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Interactive inversion of transient electromagnetic data for a central-induction loop over layered earth models (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 3 MB free space, and a 1.44 MB floppy disk drive. The current version of this program requires 701,772 bytes of free XMS memory.

Software Needed

MS-DOS 3.0 or higher, and RPlot Scientific Graphics 2.05 (RSoft Inc., 1991). For information on obtaining the RPlot software, call (212) 666-0959 or Fax (212) 666-3962.

INTRODUCTION

Overview

This report is provided as a reference guide to define the user's graphical interface responses needed to perform interactive forward or inverse modeling of transient electromagnetic (EM) soundings for a central-induction loop system using an IBM compatible personal computer (PC). The forward or inverse modeling uses a one-dimensional (1-D) horizontal layered earth with parameters being the layer resistivities and thicknesses below the earth's surface.

A summary of the basic computations is given below, followed by an example using a data set generated from a known model. The program discussed in this report is named INVTCI (for INVersion of Transient Central Induction loop data).

Scope of This Guide

Ideally, a program using a graphical interface should not require a detailed reference guide, provided the user is familiar with the subject matter of the application program. A good interface 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 interface 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 95 percent reference material, with the first 5 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 the appropriate key, without pressing any additional key; i.e., <Key> is a "HotKey", and requires only a single key-stroke. The <y> or <n> key is used to answer "yes" or "no" to various questions. Other HotKey's 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 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 INVTCI.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 b: and type: copy b:*.*

To run program INVTCI from any other directory, make sure the installed directory and the RPlot directory is in the PATH statement in your AUTOEXEC.BAT file at boot time. (If necessary, 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 INVTCI for the first time.

Quick Start

To run a test problem using the data file TEST1.DAT (supplied on the distributed disk: a free-field file described in more detail later), type the command:

invtci

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>. 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 for 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 advantage in using a graphical interface program is to display prompts, user responses, and multiple forward or inverse curves drawn of all computed EM response functions. An attempt has been made in program INVTCI to minimize the amount of interactive typing required by assuming needed information about the problem that can be inferred from any observed data read; e.g., number of observations, time range, plotting scales, etc.

Forward Mode

The transient central-induction solution for an ungrounded circular loop (or an equivalent square loop of equal area) *on* the surface of a layered earth model can be developed by Fourier transforming a suitable frequency-domain function for a step function on-off bipolar current waveform. The vertical magnetic field at the loop center in the frequency-domain for a layered earth is given by Ward and Hohmann (1988, p.218-220) as

$$H_z = \tfrac{1}{2}\, Ia \int_0^\infty [1 + r_{TE}]\, \lambda^2/u_0\, J_1(\lambda a)\, d\lambda, \qquad (1)$$

where a is the circular loop radius and I is the current source. The rest of the symbols in equation (1) uses the usual notation for EM problems as defined in Ward and Hohmann (1988), and will not be repeated here.

The voltage induced in a small horizontal coil at the transmitter loop center represents the time rate of change of the vertical magnetic field. The transient response is computed during the off-time and only involves secondary currents induced in the earth. The desired transient response for any given time range is computed with a lagged-convolution Fourier transform filter developed by Anderson (1975), and an expanded-range pre-splined frequency function computed from equation (1) with a Hankel transform filter (Anderson, 1979). This approach avoids evaluating Bessel functions in equation (1), and is relatively rapid due to the fast lagged-convolution filter in the time-domain.

Some special cases using asymptotic expansions (Kaufman and Keller, 1983) are available to view responses at very late-time ranges, but should only be selected when in the Forward Mode. (See "tasy" in the OPTIONS section.) The need for late-time asymptotic expansions in the Inverse Mode is generally not required for the time ranges normally used in most surveys.

Because square loops are typically used in field operations, the radius a in equation (1) is replaced by $L/\sqrt{\pi}$, where L is the side of the loop. Also, because ideal square waveforms cannot be realized in practice, the effective ramp off-time can be accounted for by a post integration method developed by Fitterman and Anderson (1987). (See "toff" in the OPTIONS section.)

Program INVTCI has several data transformation options to agree with user defined procedures used in most field operations. The various transformations or data options available are:

a. Late-time apparent resistivity from voltage via equation (2).
b. All-time apparent resistivity from voltage via equation (3).
c. Normalized voltage/σ_1.
d. Observed voltage.
e. Observed H_z magnetic field.
f. All-time apparent resistivity from H_z-field via equation (4).
g. Late-time apparent resistivity from H_z-field via equation (5).

Selection of any transformation option is denoted by parameter "iopt" described in the OPTIONS section below. Following Ward and Hohmann (1988, p.221-222), the formulation used in the above transformations (except c, d, and e) are as follows:

a. $$\partial h_z/\partial t \approx (I\sigma^{3/2}\mu_0^{3/2}a^2)/(20\pi^{1/2})\, t^{-5/2}, \tag{2}$$

b. $$\partial h_z/\partial t = -I\left[\, 3\,\mathrm{erf}(\theta a) - 2\theta a(3+2\theta^2a^2)\exp(-\theta^2a^2)\,/\pi^{1/2}\,\right]/(\mu_0\sigma a^3), \tag{3}$$

f. $$h_z = I\left[\, 3\exp(-\theta^2a^2)/(\pi^{1/2}\theta a) + \left(1 - 3/(2\theta^2a^2)\right)\mathrm{erf}(\theta a)\,\right]/(2a), \tag{4}$$

g. $$h_z \approx (I\sigma^{3/2}\mu_0^{3/2}a^2)/(30\pi^{1/2})\, t^{-3/2}, \text{ where } \theta = \tfrac{1}{2}\,(\mu_0\sigma/t)^{1/2}. \tag{5}$$

It is important to note that the appropriate transformation option should be selected corresponding to the *same* transformation used in preparing the observed data; this is especially true in the Inverse Mode, otherwise unpredictable and/or erroneous results can occur (i.e., don't try to fit "apples" to "oranges"!).

It should be noted that I have used the quasi-static approximation (i.e., displacement currents neglected) in computing all forward EM field responses for the central-loop configuration. No tests are made for violation of this assumption in program INVTCI.

In selecting the Forward Mode, one can either generate families of curves, by varying any model parameter(s) at each interaction, or superimpose a set of computed 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 a complete data set was first selected.

The Forward Mode requires a data file giving the loop radius (a > 0 m) and the initial sounding curve transformation selection (see "iopt" in the OPTIONS section). The data file format is the same in Forward Mode as in Inverse Mode, where the starting parameters and/or options precedes any transient data records. (See the Data File Format section below for syntax details.)

Inverse Mode

The inversion method used to obtain 1-D layered earth models from central-loop transient data follows an algorithm by Anderson (1982) that 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 INVTCI.

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 or special cases, some control parameters can be overridden as described in the OPTIONS section. Also see the Data File Format section for the required input file format.

Nonlinear least-squares inversion can be time-consuming when using transient EM data for layered models, but this depends a lot on how good the initial estimate of the layer parameters are to a converging inverse solution. The problems of equivalence in multi-layer models can also cause difficulties, resulting in other or unrealistic local minimums. This is especially true when using a small bandwidth in time, typical of current transient EM measurement systems. A priori information from other methods about the geoelectric section (e.g., from DC resistivity) is also helpful if data curves do not asymptote to known values at early or late-times.

It is recommended that the fewest number of layers that can be seen as resolvable in apparent resistivity data plots be tried first. In some cases, starting with a half-space (nl=1) may be best, and then followed by subsequent runs with nl=nl+1 until the misfit error cannot be reduced any further by increasing the number of layers.

While 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 any 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 flip to the Inverse Mode option. In some cases, one could flip back to Forward Mode if unsuccessful with finding a good starting estimate for inverse modeling.

STEPS TO RUN SOFTWARE

In general, the following steps (I-V) may be used to run program INVTCI for any given forward and/or inverse problem. Step I is required initially as a preprocessing step to prepare data and options prior to a Forward and/or Inverse Mode run. 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 forward and/or inverse activity is listed. The output file has more information about the modeling, especially in Inverse Mode, and is an ASCII formatted file for possible printing later.

I. Data File Format

Program INVTCI uses an ASCII free-field format for the transient data, preceded by a required namelist record ($par ... $) containing optional parameter values that override standard default values. (See parameter default table in the OPTIONS section.)

The data file syntax is (strings within [...] are optional):

```
$par a=...,iopt=...[,]
[..., ...,]
$[end]
time(1), obs(1) [,1]
time(2), obs(2) [,2]
...
time(n), obs(n) [,n]
```

The first part of the data file ($par ... $end) can be given in a single line and any starting column, but must begin with "$par" and end with "$end" or a terminating "$" symbol; i.e, the "end" in $end is optional. The namelist parameter assignments may appear in any order and on multiple lines, each separated by a "," until the namelist ends with the final $ symbol. Note that parameter a>0 (loop radius) must *always* be given, but it is also recommended that parameter iopt=[i] always be given to identify the type of transient data records following the namelist portion of the data file. Floating-point decimal values may contain an imbedded decimal point, however, decimal points should not be used in integer values (integer parameter names begin with "i" or "n" in INVTCI); e.g.,

$par a= 123.4, iopt= 2 $end

The transient data records immediately follow the namelist parameters as illustrated above. Each data record (1 to n) must contain the time (in seconds) and observed value as defined by "iopt" in the OPTIONS section. Successive data records must be given in ascending time, and in free-field format, where a "," or "blank" must be given between the time(i) and obs(i) columns. Note that a third column is optional (not read), but can be used as an observation count.

It is also helpful if the data file is named with a .DAT suffix so that one of the HotKey's will function properly--see HotKey Options below.

Several example data sets for different cases are provided with the supplied diskette, and can be listed to see how the above requirements must be used prior to forward or inverse modeling.

II. Observed Data Plot Only

This option requires a complete data file. The data points are 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). Another Mode must be selected to continue.

III. Forward Mode

There are two possible options in Forward Mode:

(1) Forward: Curves Only

This option requires only the namelist portion ($par ... $) of a data file. The main use of this option is to run program INVTCI to produce a family of forward curves without displaying discrete observed data. Because no observed data are used, the user is prompted for the minimum x-axis time (x1), maximum time (xm), and number of points per decade (nx). Selecting the <Home> key to flip to Inverse Mode is disallowed for this option. Note that several stacked or multiple curve sets are possible in this mode. To avoid extra interactive prompts for this option, the next option is advised using an existing data file.

(2) Forward: Curves & Obs.Data

This option requires a complete data file. This mode 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 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 a complete data file. This is the primary starting point using 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. Because 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 previously, many control or optional 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 INVTCI, a starting model is required. It is suggested that a minimum number of layers should be used to graphically find a "best-fit" solution. Subsequent modeling can be used to insert, or delete, additional layers as deemed necessary. When the program begins computing an inverse solution, the message

... INVTCI is running ... Please wait ...

means a pause in response time should be expected. The computation time is very dependent on the starting estimate of the layer parameters, assuming a 1-D model is appropriate for the given data. If a poor estimate is given, and for any nl > 1, the CPU-time could be large.

Observe that the updated least-squares solution will appear 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 back again to the Inverse Mode with an improved starting guess.

A special "keyboard-and-mouse" feature of the RPlot graphics system used in INVTCI allows for marking groups of data points with a BOX outline so that subsequent inverse runs will ignore all points within any marked BOX[es]. To activate this option, the following steps can be used whenever a graph is displayed on the screen:

1. Press <Alt-a> and an RPlot window appears at the bottom.
2. Press <b> key to ask for the "box" option.
3. Move the "+" cursor with the mouse to the first box corner.
4. Click the left mouse button.
5. Drag the mouse cursor to the last box corner surrounding the data points to be marked for deletion in the inversion.
6. Click the left mouse button to terminate the box.
7. Optionally, go to step 2 for marking any other box. (Up to 10 separate boxes can be marked.)
8. Press <Esc> to close the "box" option.
9. Press <y> to save the BOX[es] just constructed; if <n> is pressed, then control returns without any boxes marked; i.e., use <n> to abort this option.

Subsequent graphs will continue to show points in the marked boxes, but the calculated and plotted inverse curves will be in a reduced time range if any box contained the original first or last time points. Hence, only the points *not* marked within boxes will be used in the current inverse run. To remove the marked boxes from the graph and restore all original data points, press the <F8> key when noted in the text Message window. At this point, one could flip to Forward Mode via the <Home> key and recompute the last model over the original time range if desired.

The BOX option can also be used to reduce the time range when in the Forward Mode, but this option is primarily intended for use in the Inverse Mode, as described above.

The entire BOX procedure above can be executed at any time a graph is displayed to remove other parts of the observed data not previously excluded in an inversion run. In any case, the original data points are always restorable for inversion via the <F8> HotKey.

(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 INVTCI 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. <u>HotKey Options</u>

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 INVTCI (returns to DOS).
<Home>	Flip Mode (to opposite Mode: Forward <-> Inverse).
<y>	Answer "yes" (do *not* press <Enter> after <y>).
<n>	Answer "no" (do *not* press <Enter> after <n>).

<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.
<F7>	List option parameters in effect.
<F8>	Restore all marked BOX data.
<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. Any curve or individual set of curves can also be selected 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) is modified in this case. All curves can always be restored after exiting INVTCI (see POST PLOTTING OPTIONS section below).

Flip Modes

Perhaps the most useful HotKey option is to Flip Modes (<Home> key) 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 state. However, if the answer is <y> after pressing <Home>, 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.

OPTIONS

Various options available in the current version of INVTCI are listed in the table below. As mentioned in the Data File Format section, an input file is required to begin with namelist parameters within $par ... $ strings. The minimum parameter that is required is the loop radius (a>0); however, parameter "iopt" should also be given to identify the transformation used in the transient observation records that immediately follow the namelist.

For this version of INVTCI, many of the special options listed in the table below may never be needed in practice. Generally, the default values are adequate for typical observed field data. However, one may experiment (usually in Forward Mode) to see what effect some of the parameters have on transient response curves.

It should be noted that extreme time ranges can cause problems with computational accuracy, especially at very late-times. Usually, extended time ranges are of academic interest only, and are not necessary for typical field data cases. (See "tasy" below.)

The data file defined in section I must exist in the working subdirectory where INVTCI is run. Inversion control parameters in the table are set for typical cases. Refer to Anderson (1982) for a complete description of certain inversion options below.

Parameter	Default	Action of Option or Inversion Control Parameter
a	0	The circular loop radius a>0 (m) *must* always be given in the data file; if a square loop of side L is used, then set a=L/1.772 for equal area loops.
iopt	2	iopt defines the transformation option used in the data file transient observation column, where: iopt= 2: late-time apparent resistivity from voltage via equation (2); units: ohm-m iopt= 1: all-time apparent resistivity from voltage via equation (3); units: ohm-m iopt= 0: normalized voltage/σ_1 (rarely used option); units: Volts/Amp/Siemens/m iopt=-1: observed voltage; units: Volts/Amp iopt=-2: observed H_z magnetic field; units: Amps/m iopt=-3: all-time apparent resistivity from H_z field via equation (4); units: ohm-m iopt=-4: late-time apparent resistivity from H_z field via equation (5); units: ohm-m
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.

Parameter	Default	Action of Option or Inversion Control Parameter
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 to produce smooth curve plots.
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 because 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). iwt=0 will treat all data without weights in the least-squares inversion. Note iwt=1 is not allowed.
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 INVTCI. Also sp=3 is usually better than sp=4.
eps	.1E-9	Requested integration accuracy for all Fourier and Hankel transforms via digital filtering. To obtain the maximum accuracy possible, as described by Anderson (1979), set eps=0 (usually not needed).
b0	.01	Lower induction number limit in the frequency-domain to compute the pre-splined frequency response prior to Fourier transforming to the time-domain. If any b<b0 is encountered, then the limit $Re(H_z/H_{zp})=1$ is used. Sometimes setting b0≤.001 can improve accuracy at late-time.
bm	100	Upper induction number limit in the frequency-domain to compute the pre-splined frequency response prior to Fourier transforming to the time-domain. If any b>bm is encountered, then the limit $Re(H_z/H_{zp})=0$ is used. Increasing bm>100 usually will not improve accuracy at early time.

Parameter	Default	Action of Option or Inversion Control Parameter
nb	8	Number of induction number points per decade to generate in the pre-splined frequency response function in the range [b0,bm]. nb > 8 can sometimes be used to improve accuracy of the Fourier transform response; however, nb > 20 is not recommended. (See related parameter "nbskip".)
nbskip	1	Number of induction numbers to skip in the first decade [b0,10 b0] and last decade [bm/10,bm]; e.g., when nb=10, setting nbskip=2 will use 5 points in these subintervals. The default nbskip=1 will not skip any points. When nbskip > 1 is used, only the first and last intervals are affected. This technique will save considerable time when nb is large and/or b0 is decreased, because fewer spline knots are needed to adequately define the frequency spline function in the first and last intervals.
toff	0	Transmitter ramp off-time (in seconds). The default assumes an ideal impulse response due to an instant on-off step current source. If toff > 0 s, then a post integration option is used as described by Fitterman and Anderson (1987). Note that toff > 0 is for EM-37 or 47 systems, and toff < 0 is for a Sirotem ramp of |toff| > 0 s.
tasy	0	Late-time asymptotic expansions (Kaufman and Keller, 1983) are used only when t > tasy > 0 seconds; the default tasy=0 ignores this option. Care should be exercised when choosing where tasy may be effectively used at late time. Generally, tasy > 0 should only be used in Forward Mode to generate extended late-time responses.
tearly	0	Reserved for future versions of INVTCI.
ivh	1	Reserved for future versions of INVTCI.
ihank	1	Reserved for future versions of INVTCI.

Parameter	Default	Action of Option or Inversion Control Parameter
ider	1	ider=1 uses finite difference derivatives in Inverse Mode, and is always required for this version of INVTCI. ider=0 may be used in future versions to indicate analytic derivatives are available.
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.

EXAMPLE TEST RESULTS

An example problem, using the observed data file TEST1.DAT on the supplied diskette, is listed below. File TEST1.DAT was generated from a previous Forward Mode run using a known model. To save space, only the output file (called T1.OUT), which also lists the input file contents, is shown as first run in Forward Mode (RUN 1), followed by a flip to Inverse Mode (RUN 2) after first marking the last 6 points with the BOX option (see plot below). For this example, the input file contained the namelist parameters:

$par a= 100,iopt= 2,iprt= -2,nspline= 3,niter= 10$

Only the final graphic screen plot showing the observed data and both 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 their PC if desired.

<u>Output File Listing</u>

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, consisting mainly of a few derived and input parameters, and possibly computed curve values if the default parameter iprt=-1 is not changed. 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, most of which are also used by the adaptive nonlinear least-squares algorithm (Dennis et al., 1979; 1981).

The output file listing for the above example (file name = T1.OUT) is as follows:

```
Program INVTCI  --  Forward: Curves & Obs.Data  --  DATE:  02/05/93

Obs.Data File: test1.dat

<Obs.Data>:    RUN =  0    FILE(s) = t1.*
-----------------------------------------------

   Time (s)      App.Res. (ohm-m)  i

 0.1000000E-04  0.4079508E+03      1
 0.1584893E-04  0.3164655E+03      2
 0.2511886E-04  0.2666889E+03      3
 0.3981071E-04  0.2413056E+03      4
 0.6309573E-04  0.2341057E+03      5
 0.1000000E-03  0.2518468E+03      6
 0.1584893E-03  0.2922912E+03      7
 0.2511886E-03  0.3213145E+03      8
 0.3981072E-03  0.2490592E+03      9
 0.6309574E-03  0.1593062E+03     10
 0.1000000E-02  0.9907311E+02     11
 0.1584893E-02  0.6172331E+02     12
 0.2511887E-02  0.3919678E+02     13
 0.3981072E-02  0.2566203E+02     14
 0.6309574E-02  0.1749941E+02     15
 0.1000000E-01  0.1240511E+02     16
 0.1584893E-01  0.9121110E+01     17
 0.2511887E-01  0.6976101E+01     18
 0.3981072E-01  0.5569378E+01     19
 0.6309574E-01  0.4610967E+01     20
 0.1000000E+00  0.3950132E+01     21

 &PAR A=100.000,TOFF=0.000000,TEARLY=0.000000,TASY=0.000000,EPS=0.100000E-09,
RFACTOR=100.000,HFACTOR=10.0000,B0=0.100000E-01,BM=100.000,NB=8,
NBSKIP=1,IOPT=2,IVH=1,IPRT=-2,NSPLINE=3,NITER=10,IWT=2,SP=3,IDER=1,
IHANK=1 &END

<forward>:    RUN =  1    FILE(s) = t1.*
----------------------------------------------
nl= 2 x1=  0.1000000E-04 nx=    5 xm=  0.1000000     a=   100.0000

rho()=
   0.2500000E+03  0.3000000E+01
h()=
   0.1500000E+03

RUN=  1  CPU=    1.700 (s) =   0.028 (m)

Program INVTCI  --  Inverse: Initialize & Start --  DATE:  02/05/93

<inverse>:    RUN =  2    FILE(s) = t1.*
----------------------------------------------
```

```
n=          15     k=           3     ip=          0     m=           1
iwt=         2     ider=        1     iprt=       -2     niter=      10
sp=          3

parameter lower bounds: bl=

 0.99999997E-05  0.10000000E-02  0.10000000E+02

initial parameters: b=

 0.40000002E-02  0.33333334E+00  0.15000000E+03

parameter higher bounds: bh=

 0.10000000E+01  0.10000000E+03  0.10000000E+05
** itr_tci (ider=0) or nl2sno (ider=1) called **


    i     initial x(i)       d(i)

    1     0.632088E-01     0.182E+04
    2     0.576806E-01     0.233E+03
    3     0.118659E+00     0.756E+03

   it    nf       f          df         cosmax      var

    0     1  0.182E+03             0.763E+00
    2     3  0.519E+02  0.274E+02  0.906E+00  0.117E+02
    4     5  0.261E+00  0.351E+01  0.583E+00  0.119E+02
    6     7  0.491E-06  0.121E-03  0.734E+00  0.120E+02
    8     9  0.410E-07  0.243E-07  0.652E+00  0.488E+01
    9    10  0.410E-07 -0.266E-07  0.652E+00  0.595E+01

***** x-convergence *****

function      0.410119E-07  variability   0.594509E+01
func. evals       10        grad. evals        9
grad. norm    0.187195E+00  cosmax        0.652401E+00

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

    1     0.706992E-01     0.129E+04     0.165E+00
    2     0.706993E-01     0.165E+03    -0.308E-01
    3     0.138350E+00     0.668E+03    -0.821E-01

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

row  1    0.8139E-14
row  2    0.5243E-13  0.7157E-12
row  3   -0.9917E-14 -0.1176E-12  0.3503E-13

** rmserr=  0.10544730E-02  ave|%res.err|=  0.591363E-03

covariance matrix
 1  0.8139E-14
 2  0.5243E-13  0.7157E-12
 3 -0.9917E-14 -0.1176E-12  0.3503E-13

correlation matrix
 1  0.1000E+01
 2  0.6869E+00  0.1000E+01
 3 -0.5873E+00 -0.7429E+00  0.1000E+01
```

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

 1  0.5000E-02  0.9022E-07  0.1276E-05  0.1276E-03
 2  0.5000E+00  0.8460E-06  0.1197E-04  0.1197E-02
 3  0.2000E+03  0.1872E-06  0.1353E-05  0.1353E-03

===============================================================================
INVERSE SOLUTION SUMMARY:     RUN =  2     FILE(s) = t1.*

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

 1   0.1999996E+03 (0.128E-03)    0.1999994E+03 (0.135E-03)    0.1999994E+03
 2   0.1999995E+01 (0.120E-02)
===============================================================================

RUN=  2  CPU=   61.900 (s) =    1.032 (m)


END of RUN(s).  Date & Times:
----------------------------
 02/05/93

   Start = 09:43:02.43
    Stop = 09:47:21.07

Elapsed =     4.311 (m)
CPU Sum =     1.060 (m) -- for all RUNs
```

Discussion of Results

Several comments concerning the interactive run and above output file listing are noted as follows:

1. The main menu Mode "Forward: Curves & Obs.Data" was selected.
2. The observed data file name was TEST1.DAT (selected output files named T1.*).
3. The observed data contained n=21 data points in the range [.1e-4,.1] s.
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	250	150
2	3	

5. After step 4 finished, I marked the last 6 points using the BOX option described previously so that points greater than .01 s would be excluded in the next run. I then pressed the <Home> key to Flip Modes from forward to inverse. Here I answered <y> to continue, and also answered <y> to use the last model (RUN 1) as a starting model for the inversion (RUN 2). Note that I could have modified any parameters before starting RUN 2, but the RUN 1 curve looked somewhat near to the observed data points. I then pressed <Enter> to begin the inversion for RUN 2.

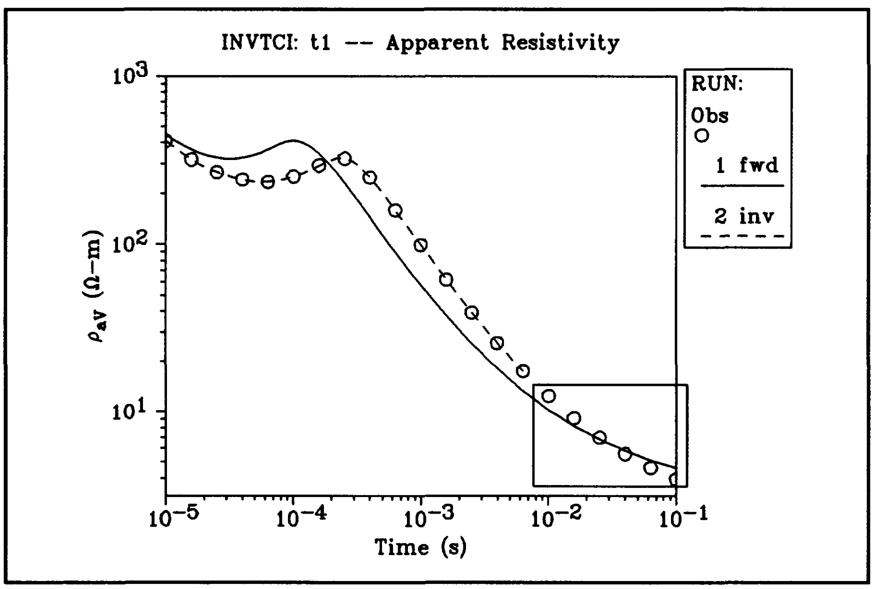
6. The inverse solution for RUN 2 was displayed in the Layered Model window as:

nl	rho	h	
1	199.9996	199.9994	
2	1.999995		0.0 % misfit

Note that 7-figures are printed to handle most ranges, but not all decimal places are always significant. Provided convergence was obtained, the output file gives parameter standard and percent errors, but these are linear statistics for a nonlinear least-squares solution. When nl ≥ 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.

For this example, the previously known model parameters listed above were recovered almost exactly, even when the last 6 points were excluded in RUN 2. Note that the computed curve for RUN 2 ended at time < .01 s, but I could have extended the calculated curve by removing the marked box (via <F8>), flipped back to Forward Mode (via <Home>), and computed an extended forward curve. This example shows that, in this case, the late-time boxed data were really not needed to completely recover the known model.

7. The final graphical displays showing the observed data, RUN 1 forward curve, and RUN 2 inverse solution (calculated curve), are 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 few 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.

8. More details on the inverse solution for RUN 2 are given in the output file T1.OUT under the heading: "INVERSE SOLUTION SUMMARY". The summary lines are located in the above output file listing between parallel "===...===" lines.

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 for RUN 2, the fit is almost perfect because a forward model data set was used in the inverse run without adding any random noise.

I leave it as an exercise for the user (if desired) to see what would happen trying nl=1 or 3 after RUN 2. In this case, I would suggest using the main menu Mode "Inverse: Modify & Restart" with output file T1.OUT as a Restart file, and select the inverse solution for RUN 2 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 INVTCI 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 three "real observed data" files taken from a field survey at Medicine Lake, California, and published by Anderson et al. (1983). These files are supplied as additional test data that was previously interpreted using another method, and can be used to further test program INVTCI for comparison purposes (or for practice). The following additional data files are provided on the supplied diskette:

File Name	From Anderson et al. (1983)
STA1.DAT	Medicine Lake Sta.1, p.12-13
STA3.DAT	Medicine Lake Sta.3, p.14-15
STA6.DAT	Medicine Lake Sta.6, p.20-21

It may be instructive to try your hand at using any of the above "real data sets" without looking at the previously determined least-squares solutions published by Anderson et al. (1983). The Medicine Lake data used large square loops with $L=1500$ feet (457.2 m) on a side, so that $a=L/\sqrt{\pi}=257.947$ m is used in the data files. The all-time data transformation from voltage (iopt=1) was used, which may help in estimating ρ_1 in a starting model.

When plotted, Sta.1 and 3 data show possibly 4-layers, whereas Sta.6 may only have 3-layers. However, Sta.6 also shows a strong 3-D effect at late-time, and as pointed out by Newman et al. (1987, p.900), the data should be truncated at the lowest point, just before the rapid rise that may be due to a 3-D body, before using 1-D interpretation methods. This approach has been tried and the truncated 1-D fit for Sta.6 was republished by Anderson (1988, p. 14-15) using a 4-layer model.

Conclusions About Inversion

I would like to point out that "real" field data measured over a limited time range that contains instrumental noise would always make finding proper (or acceptable) least-squares solutions much more difficult than in the above synthetic example. In many cases, it may be necessary to hold some parameters fixed that cannot be sufficiently resolved due to insufficient data or when fitting 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., 1991)

Various post plotting capabilities are easily provided using the RPlot Graphical Package. After a final curve plot is obtained from INVTCI 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 INVTCI 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 -- RPlot control file
[prefix].000 -- copy of obs.data points for RPlot
[prefix].001 -- possible splined curves for RUN 1
[prefix].002 -- possible splined curves for RUN 2
... etc ...

The above RPlot file with a suffix .PCS is automatically generated by program INVTCI 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 INVTCI. For example, to just view the very last graphic screen(s) after exiting INVTCI, simply type:

plot @[prefix]

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 INVTCI. Thus, all curves that were deleted while running INVTCI can easily be replotted after exit by removing the ! on all RUN lines (near the end of the file). Instead of commenting out a complete line, any line can be edited or deleted for special effects; e.g., in the above example plots in this report, the .PCS file was modified by removing the line:

/tb'Press <AnyKey> to Continue'

One very useful RPlot post plotting option is the ability to import a final graphic file from INVTCI directly into most word-processing files for IBM compatible PCs. RPlot can generate an HPGL, CGM, or EPS formatted file for this purpose. For example, the comment line !/pf in the .PCS file can be changed to /pf; then issue the plot command "plot @[prefix]" again to produce an HPGL file with the suffix .PLT; this file can then be imported directly into WordPerfect, or other word processors. An alternate way to produce the .PLT file is to issue the command "plot /pf @[prefix]". When issuing a plot command with the /pf switch, the graphic screen will be blank while the .PLT file is created. Again, refer to the RPlot User's Manual for more information.

TROUBLESHOOTING

A multitude of built-in error messages are provided by program INVTCI. 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 usually followed 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.

<u>Some Specific Error Messages and Possible Solutions</u>

{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 is:

<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 that the "=" character must always be used here.

When [un]fixing a layer parameter, the correct syntax is:

[-]<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 that the "=" character cannot be used here.

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

Only keys listed in the Message window can be pressed. Generally, this error occurs when <y>, <n>, or another <[key]> 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 INVTCI), 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 INVTCI, file names without the "." separator are not allowed, because 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 (".PCS" suffix) is to avoid any conflicts with RPlot 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 by 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}: x(i,1)< =0 (time(i) must be > 0 s)
{Error}: x(i,1) not increasing (i.e., time(i) must increase as i=1,n increases)

These errors all pertain to an invalid or unknown observed data file. See the section STEPS TO RUN SOFTWARE (Free-field Observed Data Files) for the proper file syntax usage. Also, list any of the *.DAT files on the supplied diskette for examples of correctly ordered data sets.

Other Undocumented Problems

If other undocumented errors occur using INVTCI with seemingly proper observed data files, 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 INVTCI 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 interactive inversion using a 386 (or 486) 32-bit PC.

ACKNOWLEDGMENTS

I would like to thank Louise Pellerin and Duff Stewart, both from the USGS, for their review comments. Many of their suggestions for improvement to the this report were adopted.

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

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

Lahey F77L-EM/32 (Version 5.01)
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., 1991) without needing additional plotting graphics in the source file INVTCI.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 (INVTCI.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 INVTCI.EXE is the RPlot Graphics Package available from RSoft Inc. (1991), phone (212) 666-0959 or FAX (212) 666-3962.

Method of Ordering

The source and executable code for program INVTCI (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 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 1.44 MB (high-density) diskette for this report:

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

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

TEST1.DAT -- Test data for the example problem in this report.
STA1.DAT -- Medicine Lake observed data from Anderson (1983, p.12-13)
STA3.DAT -- Medicine Lake observed data from Anderson (1983, p.14-15)
STA6.DAT -- Medicine Lake observed data from Anderson (1983, p.20-21)

T1.OUT -- Output file from the example problem in this report.
T1.PCS -- RPlot control file from the example problem.
T1.000 -- RPlot Obs.Data file from the example problem.
T1.001 -- RPlot RUN = 1 file from the example problem.
T1.002 -- RPlot RUN = 2 file from the example problem.

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