

Layered Earth Inversion Visual Toolkit: A Scientific Visualisation Case Study

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Abstract

Visualisation Systems are in general designed to maximise the cognitive ability of system users particularly when exposed to large sets of otherwise difficult to comprehend data, by appealing to various strengths of the human perceptual system in processing visual information. Scientific Visualisation in particular aims to present physical data in ways that facilitate the discovery and/or understanding of deterministic mechanisms or underlying cause and effect of the physical system described by the data.

This report examines the development of a Scientific Visualisation tool, which has been developed for use in conjunction with existing specialist numerical modelling software. The modelling software is typically used in an iterative fashion, with successive user specified inputs dependent on analysis of prior output. The newly developed visual tool, developed for use with Windows operating system using Borland Delphi and an object-oriented paradigm, overcomes the lack of input/output visualisation capability of the modelling software. By using the visual tool, input states can be controlled quickly and interactively through direct graphical means. The program runs the model software as a separate background process, and automatically displays model output in an interactive display. Model output consists of many thousands of data values that can be viewed simultaneously by the visual tool as a two-dimensional coloured contour. The system has been specifically designed to handle layered earth inversion data but interactive visualisation would be beneficial to other scientific applications.

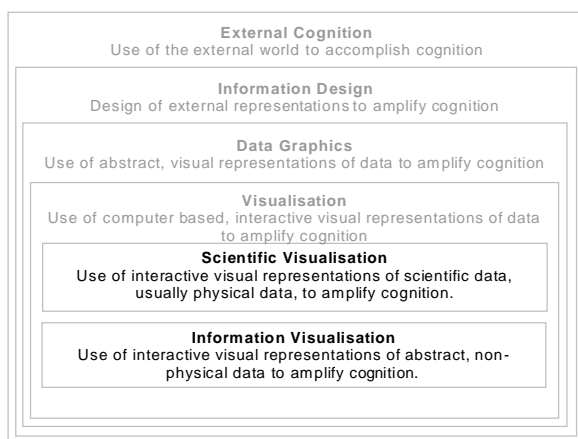


Figure 1: Visualisation in Context

1 Introduction

The conceptual framework showing the context of the field of visualisation can be seen in Figure 1 (Card, Mackinlay and Shneiderman, 1999). The framework positions visualisation within the broader established fields of external cognition (eg Norman 1993), information design and data graphics (eg Tufte 2001). The work described in this paper is primarily concerned with a subfield of visualisation known as *Scientific Visualisation* which is typically based on the observation of data resulting from the measurement of physical properties of some thing or another, often observing how these properties vary in space and or time. Information of this sort is inherently geometrical and can frequently be mapped to spatial axes. The resulting visualisations are abstractions of the underlying data, based on physical space. It is quite common that multidimensional data sets must be represented. The problem then becomes one of determining which variables should map to spatial axes, and how the other ones can be depicted in a way that makes sense to the viewer.

Figure 2 illustrates the general process of mapping data to the visual form. The human acts at each stage of the process to adjust the various transformations. The *raw data* undergoes some form of *data transformation* into *data tables*, which are relational descriptions of data that may include metadata. *Visual mappings* transform the data tables into *visual structures* which combine spatial substrates, marks and other means of graphical encoding. *View transformations* are applied to create particular *views* of these visual structures by specifying parameters such as position, scaling, clipping, distortion etc. Each type of transformation can be affected by user interaction, enabling the user to tailor the resulting visualisation to service the user's task or goal.

Raw data in some instances can be viewed directly, but for generality it is assumed the raw data is eventually (if trivially) transformed into the logical equivalent of a data table. The construction of the data table is a critical step affecting the visualisation outcome, especially when the raw data is abstract and does not contain a spatial dimension. It should be noted that the essential part of this model is the mapping between a data table, based on mathematical relations, and a visual structure, based on graphical properties to be processed by human vision. This transformation step is the one that ultimately aims to provide a cognitive advantage to the user which is not available by looking at the data or data tables alone.

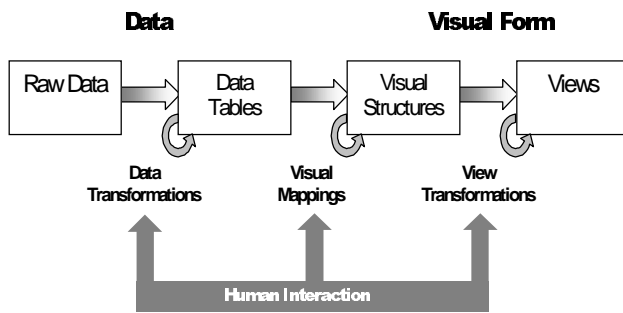


Figure 2: Process model for the data visualisation (Card et al 1999)

Haber and McNabb (1990) model the process for constructing visualisations specifically for scientific data obtained from simulation, observation or experiment. Three main phases are identified: modelling (transforming the real world problem into a well-posed mathematical one), solution (generating a reliable approximate solution to the mathematical problem) and interpretation/evaluation (establishing a causal explanation for the solution results, and forming useful conclusions). The goal of visualisation is to convert the resulting information to a form which the human perceptual system can readily understand, whilst maintaining the integrity of the information. Information in any visualisation cannot be expected to be any more reliable than each of the phases that produced it.

Scientific users have long been aware of the benefits of computer based visualisation tools for processing complex information. This is largely because physical data often readily maps directly to a spatial substrate. Tools such as tables, graphs, maps, scatter plots, contour and surface plots of spatially oriented data, etc are in common usage and may even be the primary tool for interpretation of data. With the aid of scientific visualisations, computers can be used for research and new discovery (DeFanti, Brown and McCormick 1989). Significantly improved ways of understanding and manipulating data, especially large data sets, can be obtained by computer-aided visualisation (Nielson, Shriver and Rosenblum 1990). Detecting complex phenomena becomes more achievable, for example detecting climate changes and observing weather patterns on a global basis. Fractal geometry is just one example of a significant discovery made possible only through the combination of computer processing power and visual representation (Peitgen and Richter 1986).

Computer visualisation of data has given rise to new forms of science, for instance image processing, where techniques and algorithms have been developed specifically for enhancement and measurement of features and structures present in computer based images. Image processing rearranges measured data to provide either a more appealing or more meaningful visualisation of it. Processing methods include convolution, Fourier transform, histogram equalisation, edge detection, edge enhancement, noise reduction, thresholding, segmentation, bicubic and biquadratic warping, and resampling. An excellent introduction to this field is given by Russ (1999).

This paper describes the development of a Scientific Visualisation tool which has been developed for use in conjunction with existing specialist numerical modelling software that had no interactive visual component. The value of a particular visual representation is very much dependent on the context and how it will be used. The tool described in this case study has been developed to provide rapid visualisation of layered earth inversion calculations which are a crucial step in the analysis of raw data obtained during Airborne Electromagnetic (AEM) surveys, carried out by DSTO for the purpose of environmental assessment (Vrbancich, Fullagar and Macnae, 2000). To appreciate the value of data visualisation for this purpose we begin with an introduction to the domain. The next section also provides background to the layered earth inversion engine used as the basis for this work (Fullagar 1981).

2 Background and Terminology

The Defence Science and Technology Organisation, Australia, is appraising the use of airborne electromagnetic bathymetry (AEMB) as an environmental assessment tool which could complement existing techniques used by the RAN for characterising the bathymetry (sea depth) of large expanses of Australia's inadequately charted coastal waters.

The electromagnetic (EM) technique effectively measures the electrical properties of materials contained in the earth's surface/subsurface region, including soil, rock, water, and buried conductive objects. For airborne EM (AEM) surveys, an airborne platform consisting of a helicopter or a fixed wing aircraft is used, flying at low altitude over the region of interest. The platform either tows or is fitted with various configurations of transmitter (Tx) and receiver (Rx) coils. Coil configurations are generally horizontal coplanar (transmitter and receiver coils in the same horizontal plane), or vertical coaxial (axes of the coils are in the same horizontal plane), or a combination of both. These coils are designed to generate electromagnetic signals at a number of discrete frequencies, and to detect the signals after interaction with the conductive materials in the 'ground' beneath the airborne platform.

At a given frequency, an alternating current in the transmitter coil creates an electromagnetic field that induces electrical current loops within the ground; the current loops, in turn, create a secondary electromagnetic field. Both the primary field (produced by the transmitter coil) and the secondary field induce a corresponding alternating current in the receiver coil. After compensating for the primary field (which can be computed from the relative positions and orientations of the coils), both the magnitude and relative phase of the secondary field can be measured. These can be converted to components either in-phase or out-of-phase with the transmitted field. By using both in-phase and out-of-phase (quadrature) components of signals of various frequencies as input to complicated modelling routines, it is possible to calculate the structure of the ground, in terms of a depth dependent conductivity profile at each measurement point or fiducial. Such modelling methods are known as 'Layered Earth Inversion' (LEI) techniques.

Typically, the sensor system records each frequency component simultaneously, many times per second, resulting in data points separated along a flight line by a ground distance of several metres. Successive parallel flight lines separated by distances of the order of 100m are flown in order to cover a survey region.

Following the survey measurements and initial processing of data, LEI numerical modelling can proceed. The software 'engine' for performing this step is discussed below. A more detailed description of the format and meaning of parameters in the input files are given in Appendices A and C.

It is customary to view the model output of this type as a contour diagram, see Figure 3, with the vertical axis corresponding to depth, the horizontal axis showing distance along a particular flight line, and conductivity being represented by variation in colour. These displays are called 'Conductivity Depth Images' (CDI). Several third party packages can be used to perform this step, after additional reformatting of the output data. Because a flight line is typically several kilometres, and the depth of investigation only tens of meters, there is substantial vertical exaggeration in these displays.

For AEM bathymetry surveys, the resulting image can be thought of as a vertical slice through the seawater column along the length of a flight line, illustrating channels, shoals and reefs, and submerged hazards. The water column also shows subtle variations in seawater conductivity with depth, due to salinity and temperature variations. Seabed conductivity differences can be interpreted as an illustration of varying sea-bottom types, ranging from sand through to solid bedrock.

The range of colours used to encode the variation in conductivity is often chosen to maximise the contrast between adjacent layers of different conductivity, and not for aesthetic reasons. However some flexibility needs to be maintained in this choice as each user has their own preferences, and different data sets require different mappings. There is no best overall choice for the colour mapping, it is both user and data dependent. Traditional methods such as thermal colour ranges and 'mountain-to-the-sea' colour scales have had various levels of success. Customised colour scales allow various features of the data set to be either accentuated or hidden. Tufte (2001) notes that humans do not have a natural ordering for

colours, and in many instances greyscale representations are more comprehensible.

The aim of the Layered Earth Inversion Visual Toolkit is both to provide interactive control (steering) and rapid interactive visualisation of results from execution of the Layered Earth Inversion Engine (see Section 2.1 below). Execution of the engine based on a user selected choice of modelling parameters should be facilitated, and immediate visualisation of the output in the form of a CDI image should occur. By doing this the effect of parameter adjustments can be visualised, and necessary changes made before repeated execution of the numerical engine. The program should assist the user in obtaining meaningful inversion results representing accurate estimation of conductivity variation with depth for numerous flight lines over a large survey area.

2.1 Layered Earth Inversion Engine

The layered earth inversion engine was originally written in 1980 by Fullagar (1981). In 1998 the code was extended by Fullagar under contract to DSTO to include vertical coaxial coil geometries. The Fortran 90 program has since been extensively tested against DSTO's bathymetry database, to determine accuracy and reliability of results (ground truth). During 2000, the contract was renewed to include Extremal Inversion capabilities (see below). This ongoing work has just recently been commenced.

The program is designed to perform an inversion using AEM measurement datasets as input, producing output that may be interpreted as the actual conductivity depth profile of the ground at all or a subset of the measurement points. At each measurement point used, LEI gives an optimised model that represents the conductivity of a series of layers of earth above an infinitely deep basement layer. The inversion output is the layer conductivity and thickness.

The inversion is repeated for a series of survey coordinates (fiducials) that represent a straight flight path or line. The resulting output model at each fiducial is stitched together to show varying layer thicknesses and layer conductivities that may be mapped using additional software as a 2D Conductivity Depth Image (CDI). In order to rapidly process the data no data gridding (interpolation between fiducials) is performed.

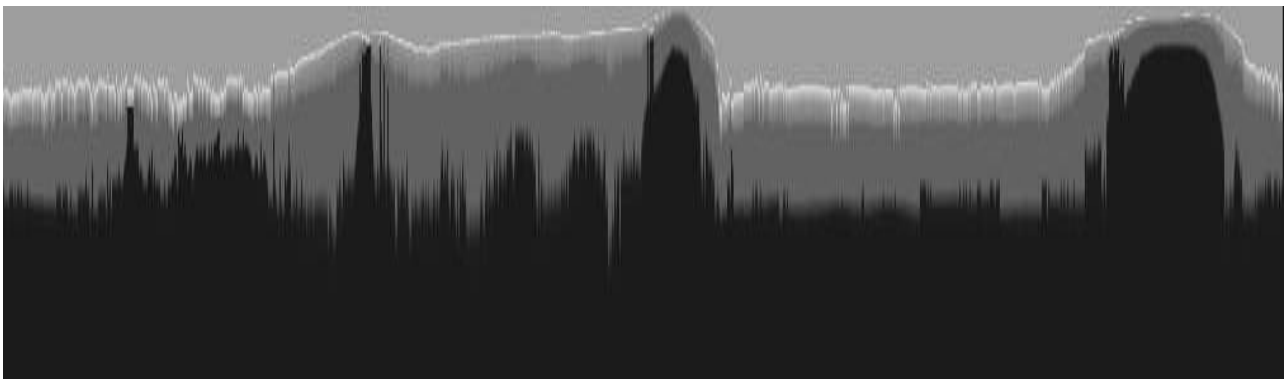


Figure 3: A Conductivity Depth Image

There are several important options in the layered earth inversion process, some of which include the following:

- The number of layers in the model can be varied, or fixed
- The conductivity range for each layer can be specified
- Inverting for depth with fixed conductivity values, 'depth-only inversion'
- Inverting for conductivity with fixed layer depths, 'conductivity-only inversion'
- Depth-only inversion followed by conductivity-only inversion
- The number of in-phase and quadrature electromagnetic data channels to use

The inversion takes as initial parameters an estimated layer model, specifying the location (depth) of conductivity boundaries as well as maximum and minimum conductivity values for each discrete layer. This model of the conductivity strata can be used as a starting point/boundary conditions for the calculations.

Inversion can be used to estimate the depth of each of the conductivity boundaries, keeping the conductivity of each layer fixed, or may estimate the conductivity of each layer keeping the depth fixed. Estimation of both conductivity and depth is also possible.

Extremal Inversion involves performing inversion as above, but also estimating valid upper and lower bounds (extremes) for the fitted parameters. The new inversion process, currently under development, will not only provide an optimised choice of parameters for minimum misfit error, but also provide a range of parameter values (ie models) that can meet certain error misfit criteria. This extremal inversion process aims to provide a range of models that can fit the data, not just a single model. This can then be used to determine the relevance of certain parameters, for example, the range of a layer thickness for a deeper layer may be very large which implies that the data cannot be used to constrain the layer thickness. Thus the model would be unrealistic to include such a layer.

All program input and output occurs through the use of formatted ASCII text files. On successful completion of an inversion the program terminates.

3 Developing an extended visual toolkit

As described in Section 1, the program will be used to steer and analyse output from repeated execution of a pre-existing numerical inversion program, in order to establish meaningful interpretation of Airborne Electromagnetic survey flight line data.

Numerous possible variations in inversion input parameters can lead to a multitude of CDIs for a given flight line, and there are numerous flight lines that cover a survey area. Presently each combination of input parameters must be written to a separate text file using

the format as described in Appendix D. This process in itself is prone to error especially after repetition.

The existing method of visualising the inversion data output is to import the data into a geophysical data processing software package (such as Geosoft/Oasis Montaj), then perform a lengthy series of database manipulations and gridding to produce the CDI. The whole process is tedious and time consuming. New visualisation software will prevent needless repetition of this process, whilst providing direct control over the parameters affecting inversion.

Thus the visualization software developed to support the layered earth inversion must execute the inversion, allowing for parameter choices and choice of input data channels, and provide a CDI image based on the output. The inversion will be repeated for different parameters, inversion procedures (depth-only, etc.) and/or data channels so that a series of CDIs can be used to determine the preferred choice of modelling parameters and to determine how many data channels are required and if any data channels degrade the quality of the CDI. Figure 4 shows a number of screens used to accept different input parameters. Currently, the user has to work with an awkward ASCII file and a file layout specification to be able to make changes. By providing a well-structured and user-friendly interface to change the input parameters the task is easier and less error-prone. In the case of determining shallow water depths, the CDI should represent water thickness and seabottom characteristics such as sediment layers and thicknesses possibly above bedrock. Once a suitable CDI is produced with the preferred parameters etc, the ASCII data can then be imported, massaged and gridded using more advanced third party products to produce a final CDI. The need to easily modify parameters is a common problem in areas of science where numerical methods are in use. The availability and ease of use of Rapid Application development (RAD) software development tools address this need by providing an interactive visual component to non interactive style scientific programs.

The visualisation software for extremal inversion should perform the same procedure as outlined above, however there needs to be a method for visualising the range of models. A single CDI is not capable of displaying the full meaning of an extremal inversion. Figure 5 shows how multiple CDIs can be displayed to provide a range of models. As evident in Figure 5, the concept of visualising a range of models is not straightforward and is currently under investigation. It is intended that this toolkit be readily extended in the future using Visualisation principles to assist the user in understanding the results from an extremal inversion.

3.1 Toolkit Specification

The basic functions of the program can be categorised as follows:

- **Parameter Display:** Display Layered Earth Inversion parameters graphically, using as input the data file described in Appendix D.

- **Parameter Modification/Update:** Enable Layered Earth Inversion parameters to be changed interactively
- **CDI Display:** Display multiple Conductivity Depth Images using as input the LEI engine output data file as described in Appendix A.

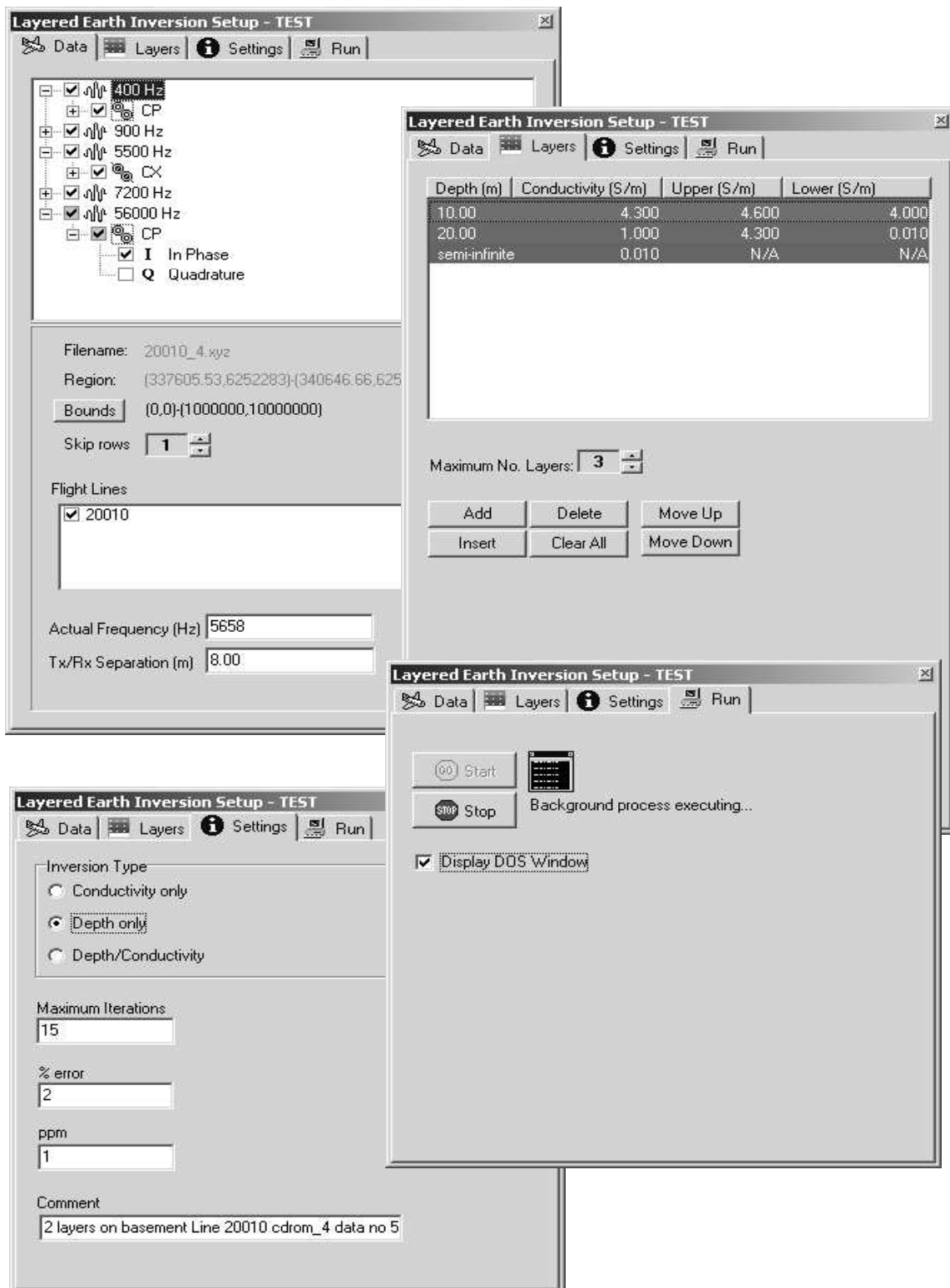


Figure 4: Screens in our prototype system which allow for easy manipulation of parameters

- **Inversion Execution:** Execute the Layered Earth Inversion using the displayed inversion parameters
- **Extremal Inversion Display:** In the future, display extremal inversion results in a readily comprehensible manner

The program should be designed to allow error free repetition of the above actions

Each of these functions is described in more detail in Section 3.5.

3.2 Intended Users

The users of the software have a scientific background and are capable of interpreting the output data as well as making decisions affecting performance of the underlying complex numerical algorithm. However, the user will be operating the program continuously for extended periods of time, with the intention of analysing large quantities of data. For this reason the program should provide clear feedback and display its current state in a readily identifiable unambiguous way. The user's physical, mental and perceptual workload should be reduced to enable concentration on the desired complex goal in accordance with Human Computer Interaction principles.

The users have familiarity with Windows operating system, and are accustomed to direct manipulation interfaces in general.

3.3 General Constraints

The program will run on a standalone desktop or notebook PC using Microsoft Windows 95, 98, NT or 2000.

3.4 Dependencies

The program is to integrate with existing numerical software as described in Section 2.1. The program should interface with the DOS based numerical engine without its alteration.

3.5 Functional Requirements

3.5.1 Parameter Display

Display Layered Earth Inversion parameters graphically, using as input the data file described in Appendix D

- All LEI parameters as described in Appendix D to be displayed
- Prewritten parameter files as described in Appendix C to be read and displayed
- Graphical display of parameters to be used where appropriate, allowing rapid comprehension of current parameter settings by user

3.5.2 Parameter Modification/Update

Enable Layered Earth Inversion parameters to be changed interactively

- All parameters as described in Appendix D to be updated easily by user
- Parameter files as described in Appendix D to be saved to disk and/or renamed
- User specified EM data file (Appendix B) to be from any directory on computer
- Only appropriate parameter options for the currently selected EM dataset should be enabled
- An interactive editor for layer depth and conductivity selection to be used
- Simple interactive selection of transmitter/receiver geometries and In Phase/Quadrature components to be provided

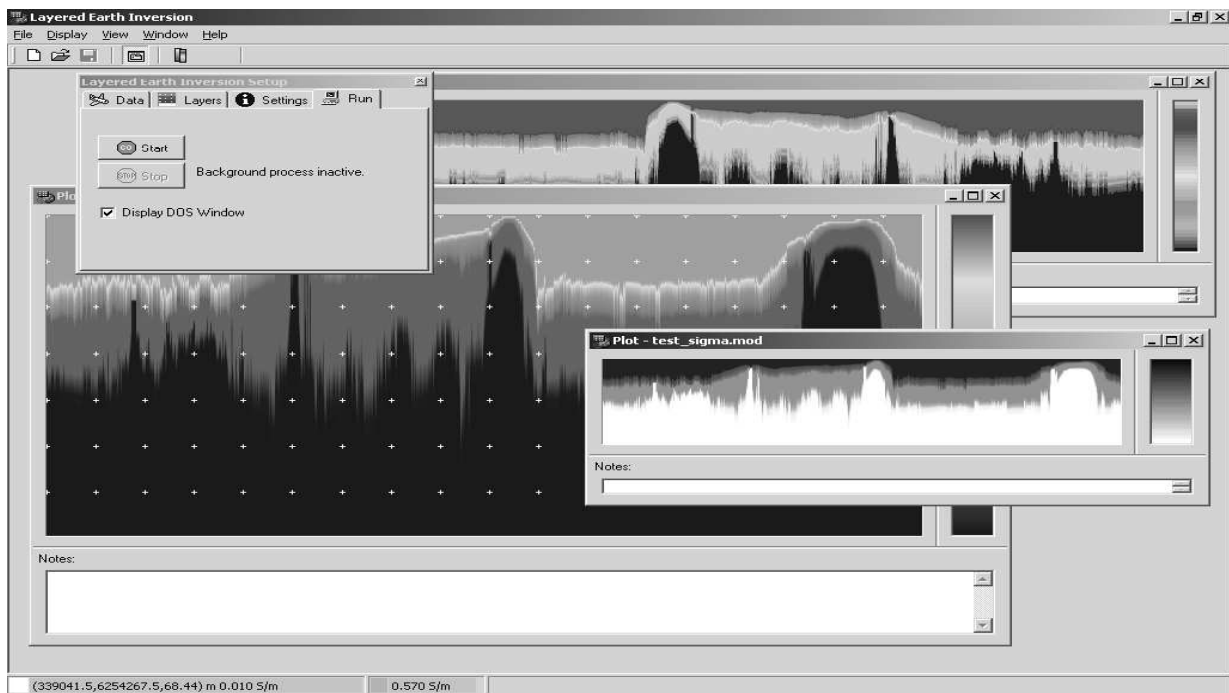


Figure 5: Visualising several models

3.5.3 Inversion Execution

Execute the Layered Earth Inversion engine using the displayed inversion parameters

- Layered Earth Inversion program AEMXZD.EXE runs as a separate process without ability for shared data
- Input and output data files are described in Appendices.
- Control over execution and termination of the LEI program to be provided
- Operational status of inversion program to be displayed
- Repeated execution of LEI program should be straightforward, requiring minimal effort by user
- All temporary files in LEI program working directory to be removed on termination/completion of process
- Automated renaming of output files based on user selected filename and path preferences for each inversion run.
- Execution follows additional constraints given in Appendix B.

3.5.4 CDI Display

Display multiple Conductivity Depth Images using as input the LEI engine output data file.

- Display multicoloured Conductivity Depth Images
- Data for the CDI is of the form given in Appendix D
- Interpolation of data in files to show smooth raster images
- Multiple CDIs to be viewed simultaneously
- Images should be resizable
- CDI to be saved to disk in a common standard raster graphics format
- CDI is to be viewed in mirrored form if desired by user, corresponding to left-to-right or right-to-left fiducial sorting
- Each image to be displayed using a potentially different colour palette.
- Colour palette files obtained from Geosoft/Oasis Montaj to be used
- Dynamic display of fiducial number, geographical location, depth and conductivity values at each data point
- Grid lines to be overlaid on images or hidden as required by user
- Area for text comments about each image is to be provided

3.5.5 Extremal Inversion Display

In the future, display extremal inversion results in a readily comprehensible form.

4 Conclusion

This paper has presented a specification for and description of a visual toolkit that can be used for layered earth inversion modelling. Although software had previously been developed to support the modelling, the system was not interactive and thus was not sufficiently flexible, as parameter adjustment is a key feature of obtaining valid results. The need to repeatedly prespecify parameters textually, and the slow processing of text output using several third party applications, was not only frustrating but likely to result in less than optimal results.

The combination of specialist preexisting non-interactive and non-visual software for numerical modelling, and purpose built interactive visualisation software, enhances the user's speed and ability in obtaining and interpreting complex data.

However, this situation is not unique. Using contemporary programming tools, relatively simple but highly effective visualisation solutions could be quickly developed for a vast number of other scientific applications that currently do not readily support interactive visualisation.

5 References

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Appendix A - Description of Model Output File (SIGMA.MOD)

Data is sorted primarily according to fiducial, in direction of flight line as appears in input file.

Data for each fiducial is in turn sorted by increasing depth. There is in general a different number of data points per fiducial, since various layer depths are not the same for each.

ASCII column data in free format. Assumed order of data fields is:

Flightline #
Easting (m)
Northing (m)
Depth (m)
 <Not used>
Conductivity (mS/cm)
 <Not used>
 <Not used>

Appendix B - Description of AEM Data Input File (*.XYZ)

ASCII column data in free format.

Data for successive flight lines follows on from data for previous flight lines.

Header lines as specified in the parameter input file (Appendix C) will be skipped.

Assumed order of column data fields is:

X Easting (m)
Y Northing (m)
FID Fiducial number
LONG longitude (decimal degrees)
LAT latitude (decimal degrees)
RXALT receiver height (m)
BIRDHT 'Bird' height (m)

[CPI400]
 [CPQ400]
 [CXI900]
 [CXQ900]
 [CPI7200]
 [CPQ7200]
 [CXI5500]
 [CXQ5500]
 [CPI56K]
 [CPQ56K]

DEPTH depth (m)

Where CP stands for CoPlanar coil data, 'CX' stands for CoaXial coil data, 'I' stands for In-phase and 'Q' stands for Quadrature components.

The fields enclosed by [] are optional.

Appendix C - Execution of the LEI Engine "AEMXZD.EXE"

Designed for operation under DOS command line, the LEI engine reads the input file "AEMXZD.INP" from the program's executable directory, locating the data input file specified within (Appendix D).

After reading the input data, the inversion process proceeds according to the parameters specified by the user in the parameter input file.

Various comments about the progress of the inversion appear on screen during execution.

On successful completion, several output files are created:

fit.out, aemxzd.out, aemxzd.krn, aemxzd.mat, aemxzd.mod, aemxzd.log, sigma.mod, depth.mod, dummy.dat, newdat.dat

The main file of interest is 'sigma.mod' which contains data for presentation as detailed in Appendix A.

Appendix D - Description of Parameter Input File (AEMXZ.INP)

ASCII data in free format, arranged by line.

End of line style comments are preceded by '!' character.

Double precision numbers may take the exponent form eg '-1.0D2' to mean -1.0×10^2 etc.

See the following example for more explanation of the fields.

The key parameters for inversion are

- Starting model conductivities and depths
- Perturbation size, controlled by DLNMAX (typically between 0.02 and 0.2).
- Magnitude of standard deviations, controlled by PCERR and SDMIN.
- Selection of frequencies and data, controlled by NW, IP flags, & Q flags.

AEMXZ run desc	!Title string for run, first line of file
20010_4.xyz	!Input file name
0 10000	!LMIN,LMAX = min,max
	!flight line number
0 1000000 0 10000000	!XMIN,XMAX = min,max
	!easting;
	!YMIN,YMAX = min,max
	!northing
2. 1.	!PCERR (assumed % error),
	!SDMIN (minimum


```

!permissible sd, c.f. noise
!level)

5 7      !NSKIP # stations skipped
         !between inversions,
         !NHEAD # header lines in
         !data file

4.D0     !SIG1=basement
         !conductivity (S/m)

2        !NW=no. frequencies for
         !inversion

328 8 1 1 !#1 FREQ(Hz), coil sepn
         !(m), InPhase*,
         !Quadrature*

.
.
.
7337 8 1 0 ! #NW FREQ(Hz), coil sepn
         !(m), InPhase*,
         !Quadrature*
         !*where flag=1 if
         !measurement influences
         !inversion;
         !      flag=0 otherwise.

4 13 20 1 ! NL=no. layers above
         !basement in starting model
         ! NLMAX=max. no. layers
         !in final model (layers are
         !split as inversion proceeds)
         ! ITMAXC=max. no. iterations
         ! ITYPE=1 for conductivity
         !inversion
         !      =2 for depth
         !inversion
         !      =3 for depth then
         !conductivity inversion.

0.1D0 0  !DLNMAX=max.
         !logarithmic perturbation
         !at each iteration ( $\delta\sigma/\sigma$  or
         ! $\delta z/z$ )
         ! IPRINT=1 for
         !comprehensive output
         !(AEMXZ.OUT)
         !      =0 for reduced
         !output.

0        !FLAPP=0 (do not alter)

0.1D0 0 0.D0 0 1 !DELZ=0.1, NSD=0,
         !X1FIN=0
         !IBASE=0, IKERN=1 (do
         !not alter)

4 3 5    !Layer #1 conductivity,
         !min, max (S/m)
4 3 5    !Layer #2 conductivity,
         !min, max (S/m)
4 3 5    !Layer #3 conductivity,
         !min, max (S/m)

.
.
.
4 3 5    !Layer #NL conductivity,
         !min, max (S/m)

4 10 25 50 !Startingmodel layer
         !interface depths (m)

```