Overview TDEM Inversion in EMIGMA
Jun 2022

1) Ground or Airborne data
2) Fixed Loop or Moving Loop Ground Surveys
3) Inversion Inside or Outside loop for Ground or Airborne
4) Inversion of (Hx,Hy, and/or Hz) or Inversion of (Bx, By and/or Bz)
5) Multi-location inversion for moving or fixed loop surveys
6) Multiple component inversion :
   - multiple separations
   - multiple sensor orientations (e.g x,y,z)
7) Multiple basefrequency
8) each component has individual time window selection
9) constrained inversions
10) Overparametrized (Occam) or Underparametrized Inversions
11) single or multiple starting models
12) Accurate System Response
   - precise current description
   - bandwidth controlled, instrument lowpass filters

Data format Support TDEM Inversion in EMIGMA

Dec 2017

1) Airborne Data
   - data imported either in QCTool format or ASCII columnar
   - .gdb files may be imported to QCTool for ease of import

Instruments with automatic Support

VTEM, GeoTEM, GENESIS, HeliTEM plus
AeroTEM, MegaTEM, SkyTEM, and TEMPEST (NA or African version)

However, will a little more effort by the user any instrument can be supported by the tools provided

Data format Support TDEM Inversion in EMIGMA
Dec 2017

2) Ground Data
- most instruments are supported by their native files with some details

a) Zonge .avg and .usf format
b) UTEM3, UTEM4 – Lamontamge native files
c) TERRATEM - .usf format
d) TEMFAST - .tem format
e) SMARTEM – AMIRA ascii
f) PHOENIX - .avg and .usf format
g) MTEM - .qct or SEGY
h) GEONICS - Protem files and .qct
i) CRONE - .pem or .raw format
j) WalkTEM - .usf format
k) Generic .usf and AMIRA format
l) ASCII imported and organized in QCTOOL format

Some Theoretical Comments

Time Domain inversion essentially began with W.L. Anderson at the USGS in the mid- to late 1970's eventually releasing an open source inversion code in the early 1980's. Anderson's code worked only for circular loops with an exact center point data location and utilizing a frequency to time domain transform that included an infinite bandwidth of DC to infinity and only an impulse response with a step-off current. Anderson's code reveals that he experimented with several important factors including: a finite ramp turn-off, frequency band limited responses, data outside the loop. His inversion code is of a style now often termed "Occam" inversion which implies, in this case, fixed layer thicknesses, allowing for more layers than data and weighting the inversion for a smooth model. All of this following, Parker's early work on MT inversion.

We have approached this problem with a more general theory of inversion. Since, the early 1990's we have been developing accurate layered earth models for virtually any type of EM source and any geometry. This was to meet the requirements of actual exploration projects and thus to provide both the background fields and Greens functions for our 3D, Integral Equation(IE) algorithms. In order to accurately meet these 3D simulation requirements, we had also incorporate as accurately as possible the actual system response (transmitted single) of a variety of instruments. This led to two key issues: accurate representation of the current injected into the source, accurate representation of the frequency limitations of the instruments. Having thus the ability to compute very accurately, 1D models of TDEM data, it was therefore a matter to integrate this capability into our inversion algorithms which we had been developing first for magnetic data, then gravity and 1D MT and later for 3D EM inversion and other controlled source 3D EM inversions such as CSAMT and Resistivity.

Finally, a comment on over-parameterized smooth models vs. under-parameterized rough models. Many, many 1D inversions for a variety of different EM data, use the so-called Occam inversion which allows more models parameters than data and to control this over-parameterization applying smoothing constraints. The problem with this method is that you have no accurate idea of the depth to different interfaces. While this is useful for deep earth studies where accuracy is never an issue as we will never know if the model is correct or not, this is not useful in exploration, environmental or engineering applications where accurate depths are important if possible. Thus, while we provide an inversion of this type, we focus more on an underparametrized approach. This is often termed a Marquardt approach. However, we do not utilize linear inversion approaches and so using this in our application is not really correct termed but we look for a word understood by most. In this case, we are attempted to resolve the major variations in the stratigraphy with as accurate as possible results for both resistivities and depths.

WORKFLOW

1. **CREATE a new EMIGMA database or OPEN an old database.**

(suggestion: easier to keep multiple datasets and projects in one database as easier to personal archiving)

2. Import Data
In this case, the data in file arlit1.100 contains 3 base frequencies and thus needs to imported 3 times to create 3 surveys

3. Examine the data from each base frequency
Pay careful attention to the decays to determine which channels should be used for the inversion

4. Perform some initial forward modelling using basic assumed structure,
To get a feel for the data and to use to help guide the inversions.

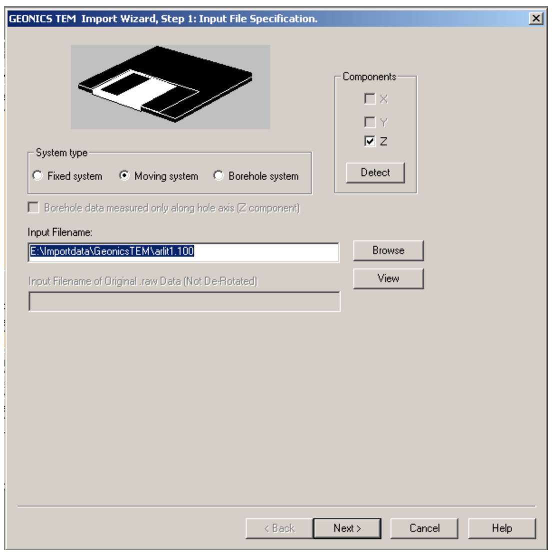
5. Perform controlled Marquardt or Occam Inversions

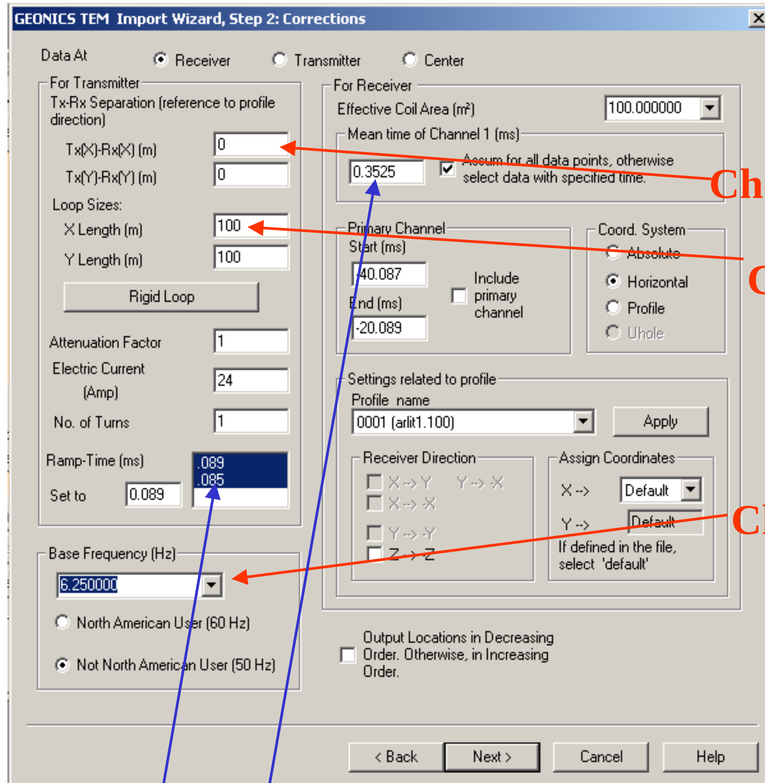
6. Create Sections

1. Open Old or Create a new EMIGMA database.

2. Import Data

3. Examine the data from each base frequency
4. Perform some initial modelling,
5. Perform controlled Marquardt or Occam Inversions
6. Create Sections





Check Rx offset from loop

Check loop size

Choose base frequency

Note: start of Ch1 will update automatically with base frequency

Note: Multiple ramp times can be imported with a common ramp time
Otherwise, ramp times can be imported separately

This example is for GEONICS TDEM data

1. Open old or Create new EMIGMA database.

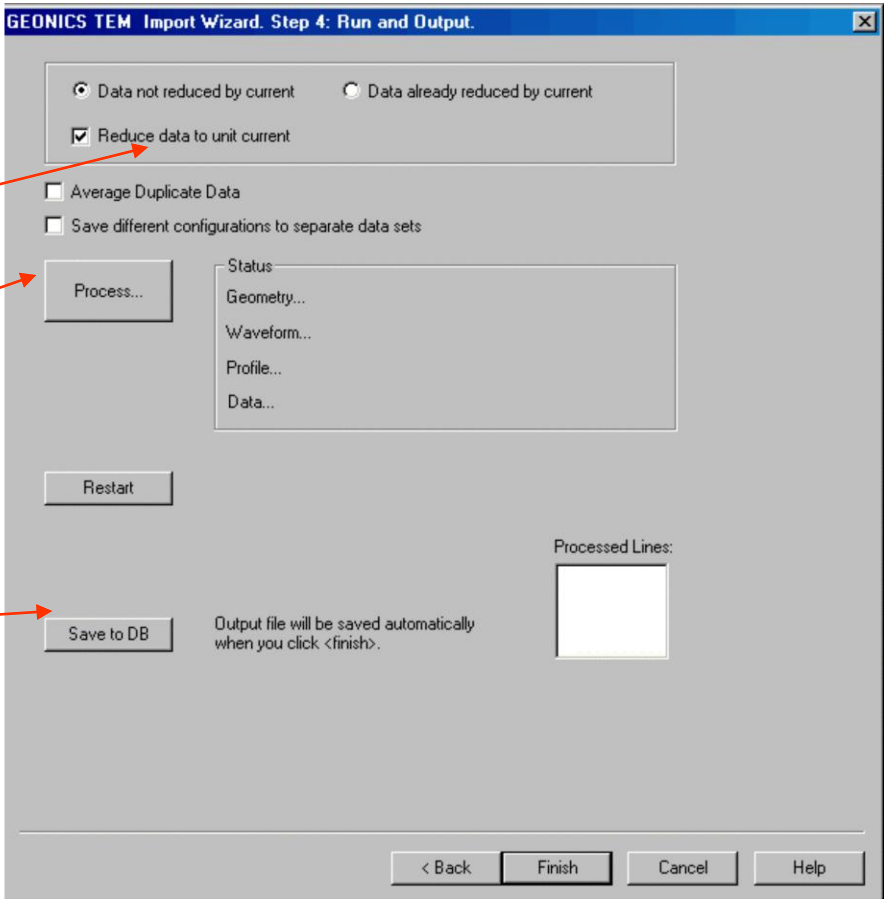
2. Import Data

3. Examine the data from each base frequency
4. Perform some initial modelling,
5. Perform controlled Marquardt or Occam Inversions
6. Create Sections

If the data consists of multiple sections with different current, then this might be useful otherwise data may have to be normalized once imported..

Click Process

Save to DB



Note: Restart will not work to import the other base frequencies
You must restart the import and repeat 2 more times to import all base frequencies

1. Create a new EMIGMA database.
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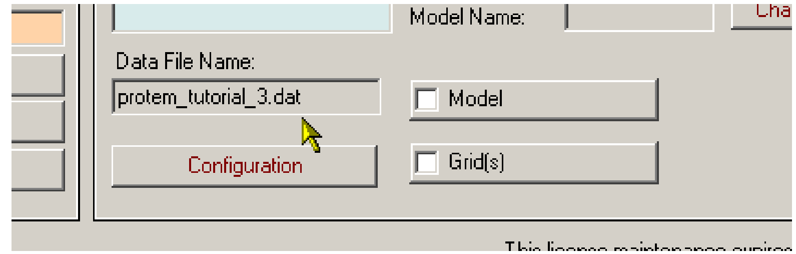
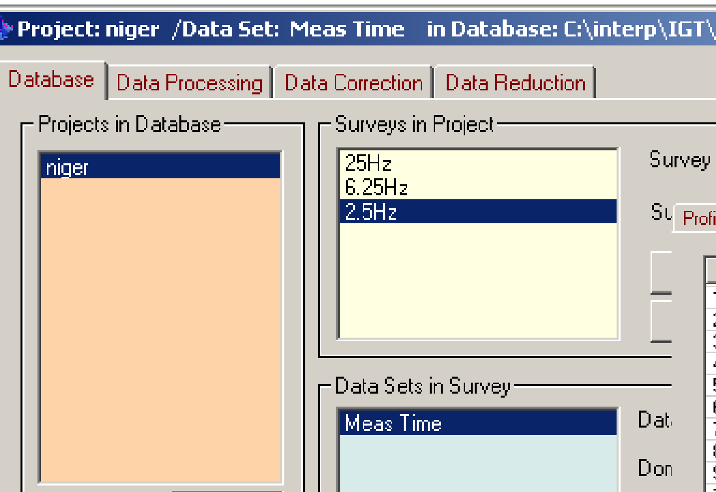
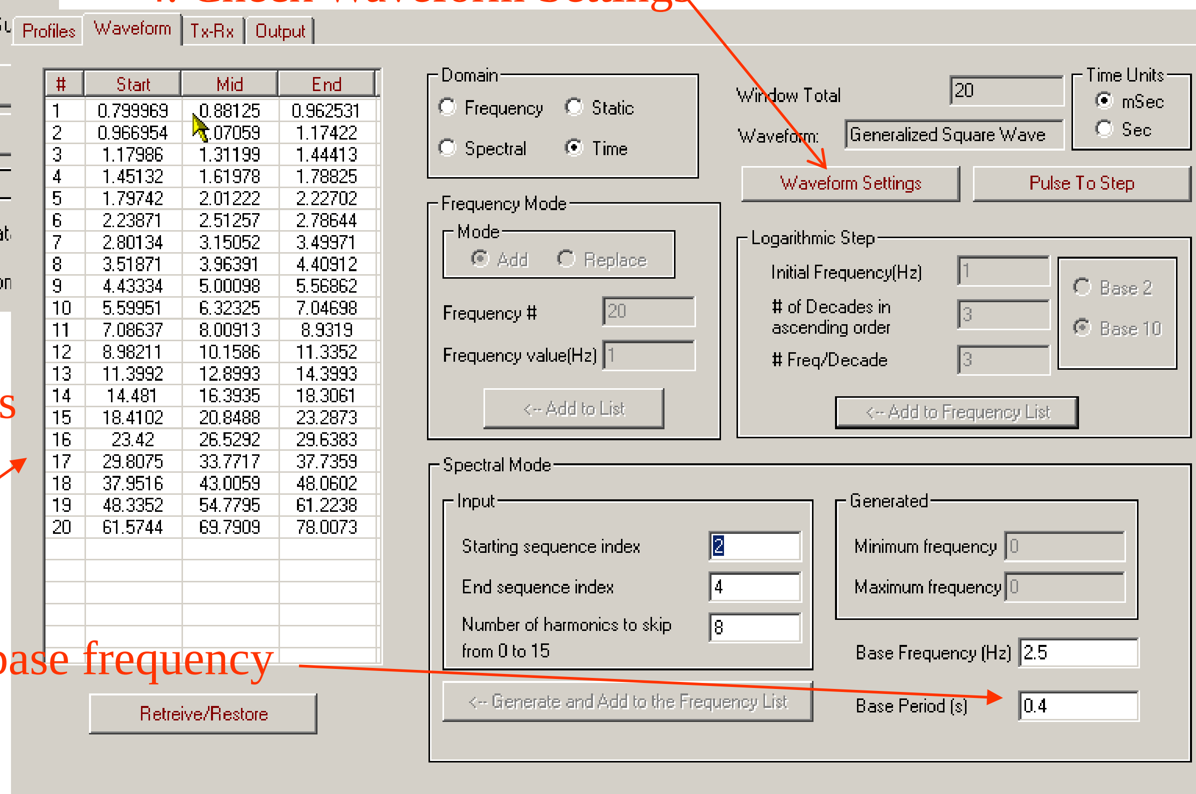


2. Click configuration

4. Check Waveform Settings





1. Check database for 3 surveys

3. Check window times and base frequency

1. Create a new EMIGMA database.
2. Import Data
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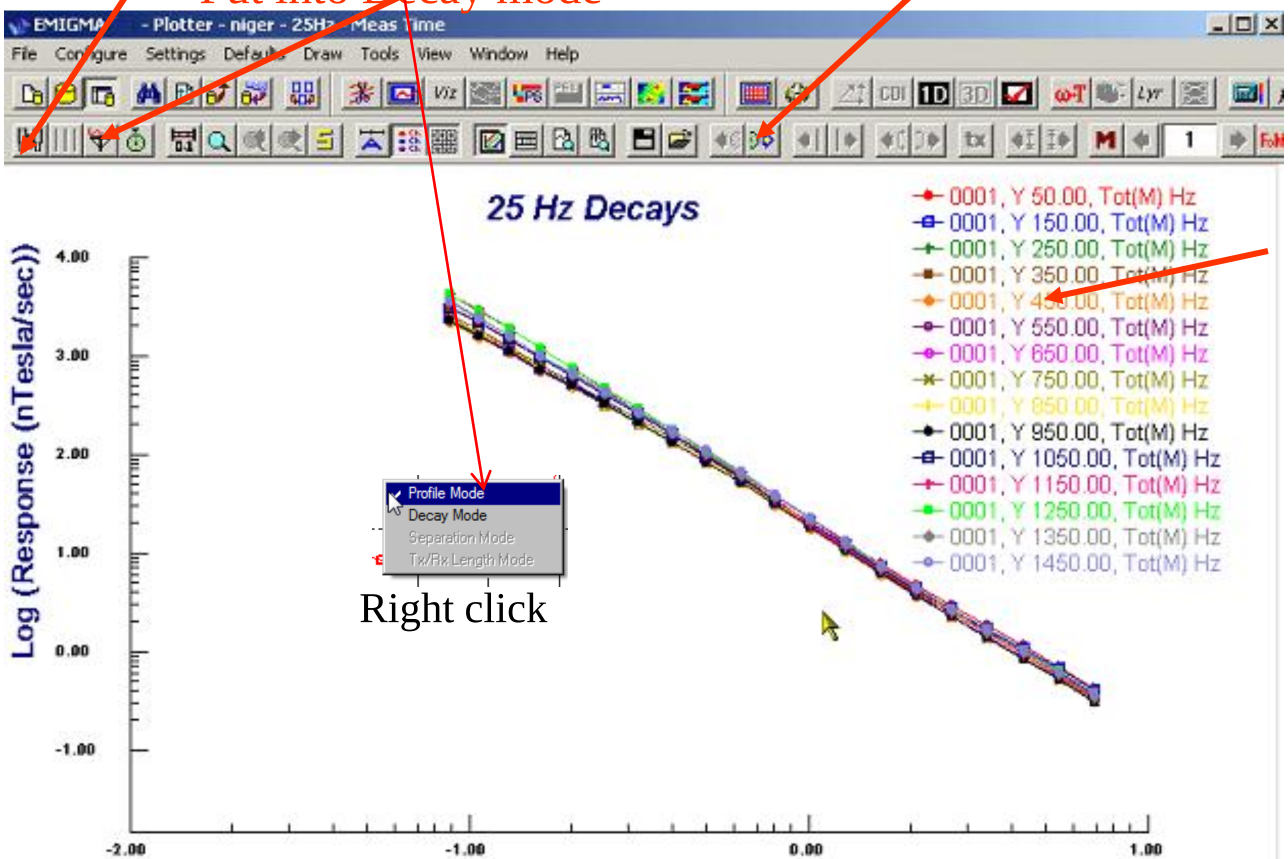
Load data set in plotter

Move up and down the line

Put into Decay mode



Right click

Select multiple data stations

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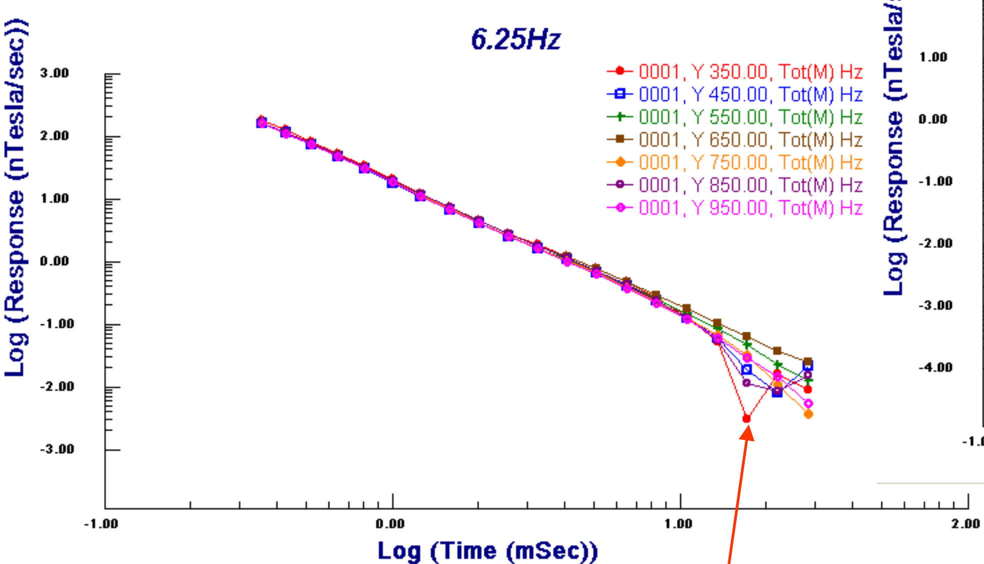

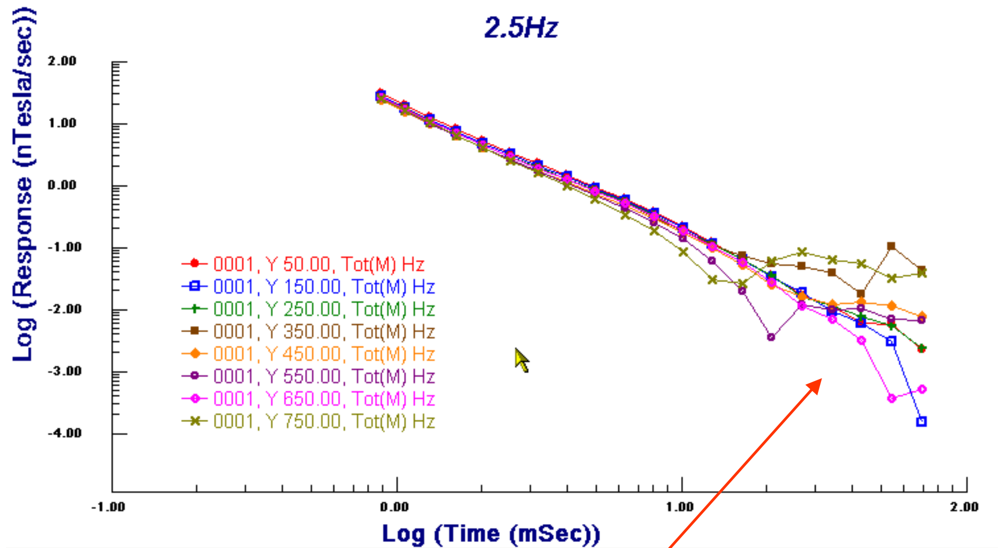

Some problems for inversion

A lot of problems for inversion

Note: theoretically, there are no sign changes for data inside the loop for a layered earth environment. This data indicates either instrument, data collection or 3D effects as issues.

1. Create a new EMIGMA database.
2. Import Data
3. Examine the data from each base frequency
4. **Perform some initial modelling,**
5. Perform controlled Marquardt or Occam Inversions
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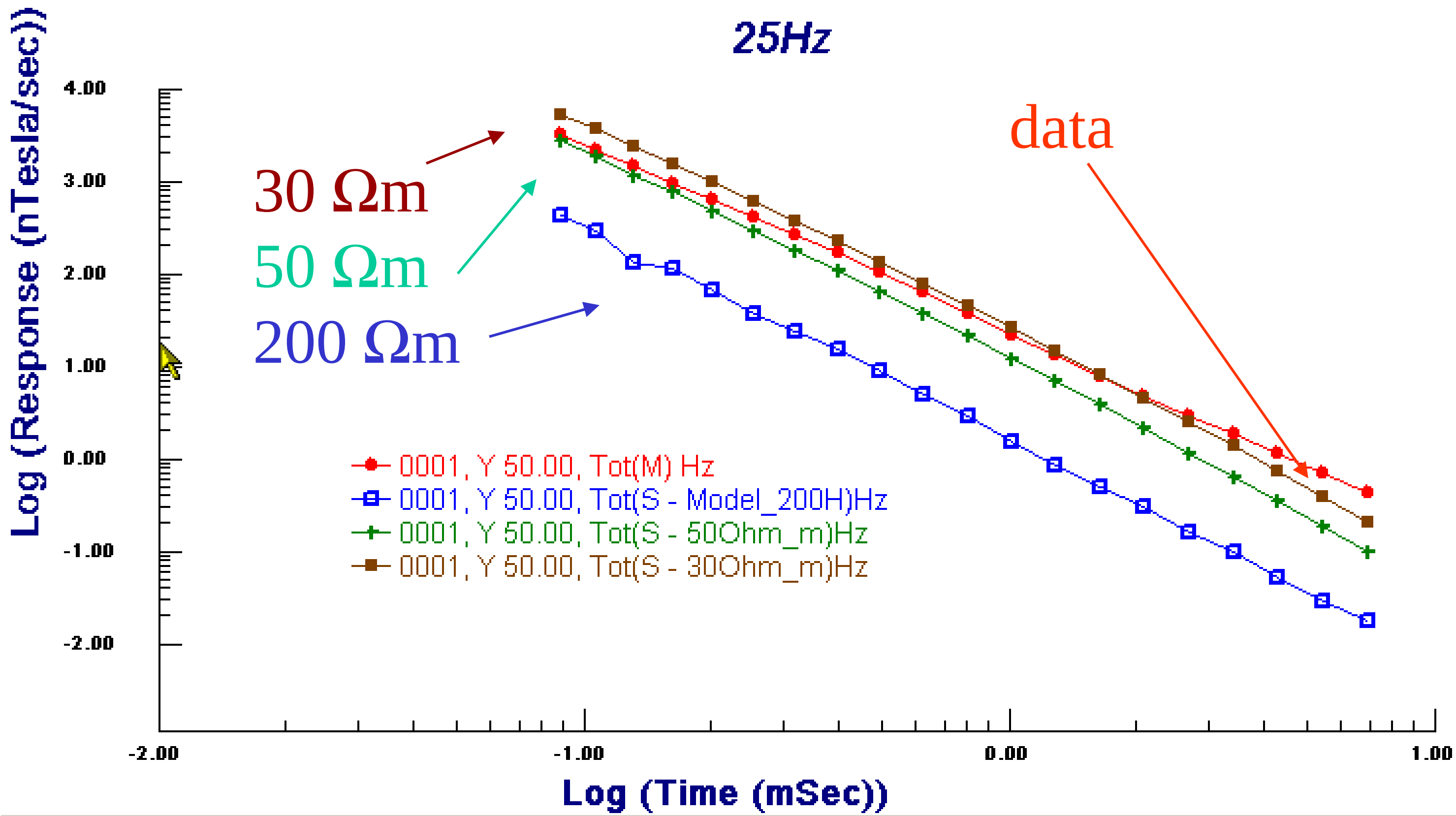
Note: *The sign of the data to be inverted should be checked with the simulation sign. If the sign is opposite, then the user can either reverse the data sign in "Data Correction" or flip the direction of current in "Configuration".*



25Hz Base frequency

1. Create a new EMIGMA database.
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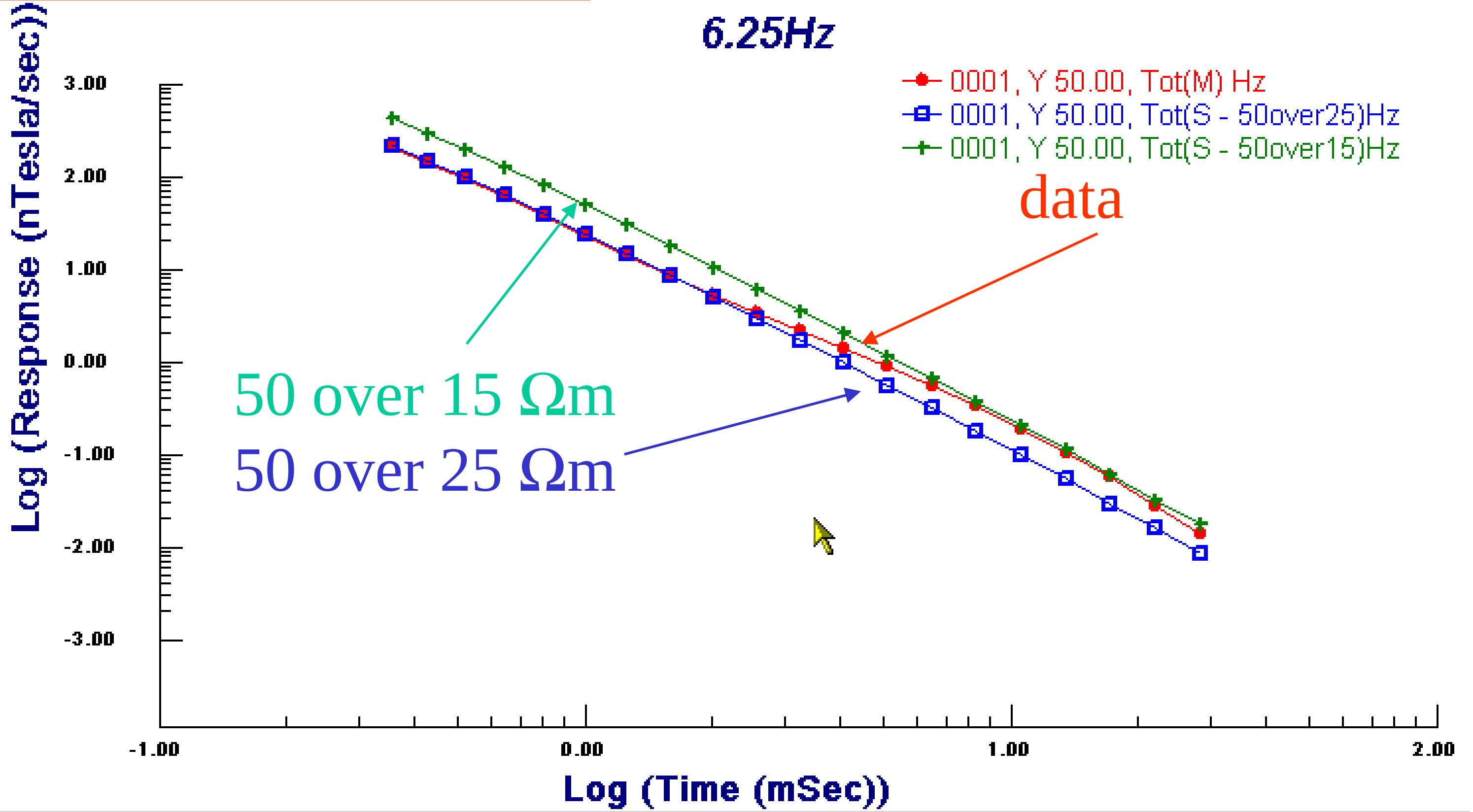

6.25Hz Base frequency

1. Create a new EMIGMA database.
2. Import Data
3. Examine the data from each base frequency
4. **Perform some initial modelling,**
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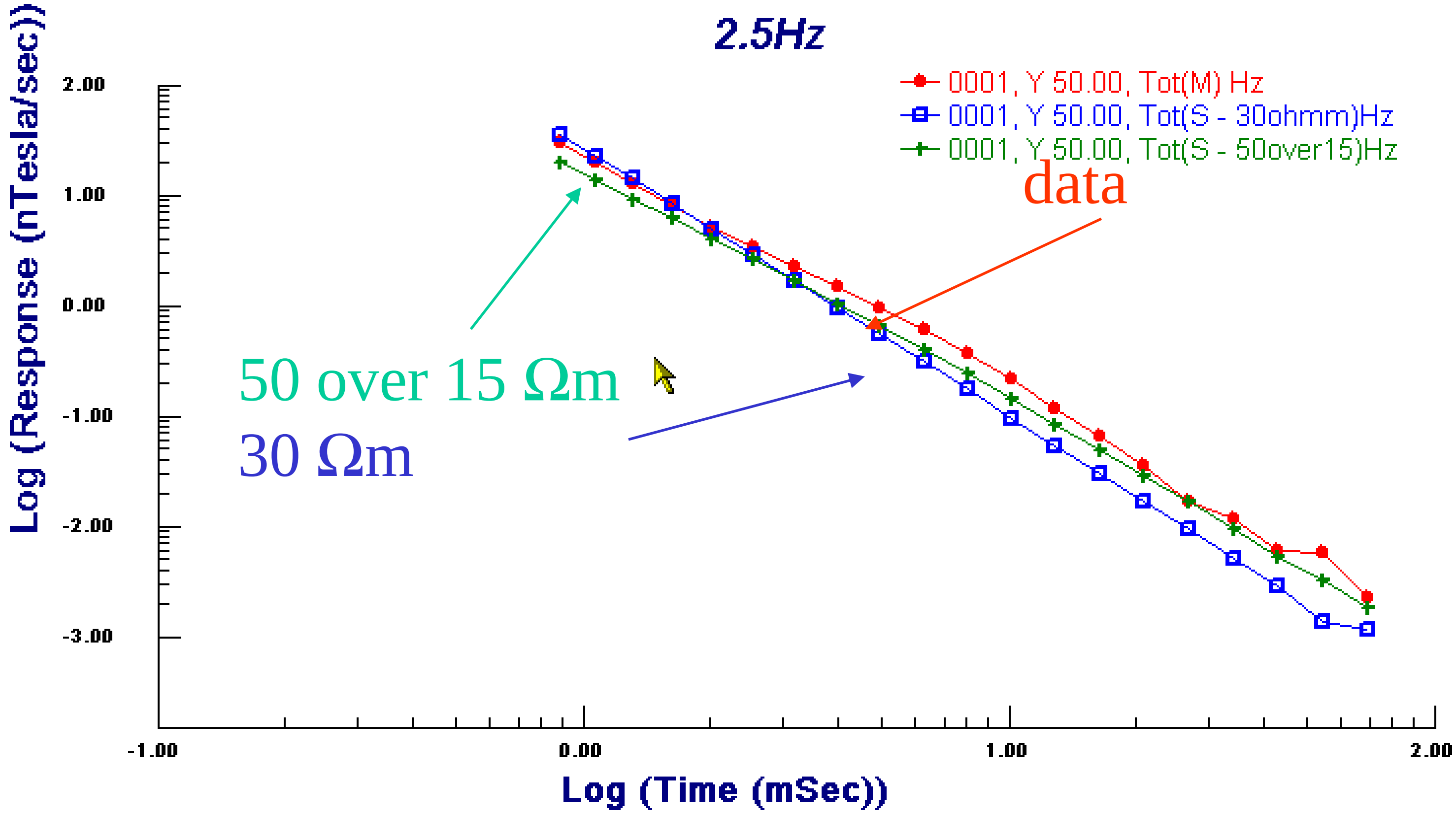
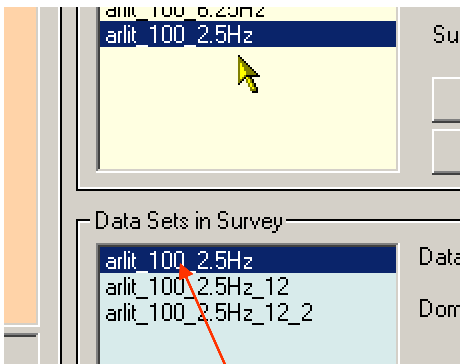
6. Create Sections

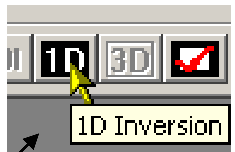


2.5Hz Base frequency

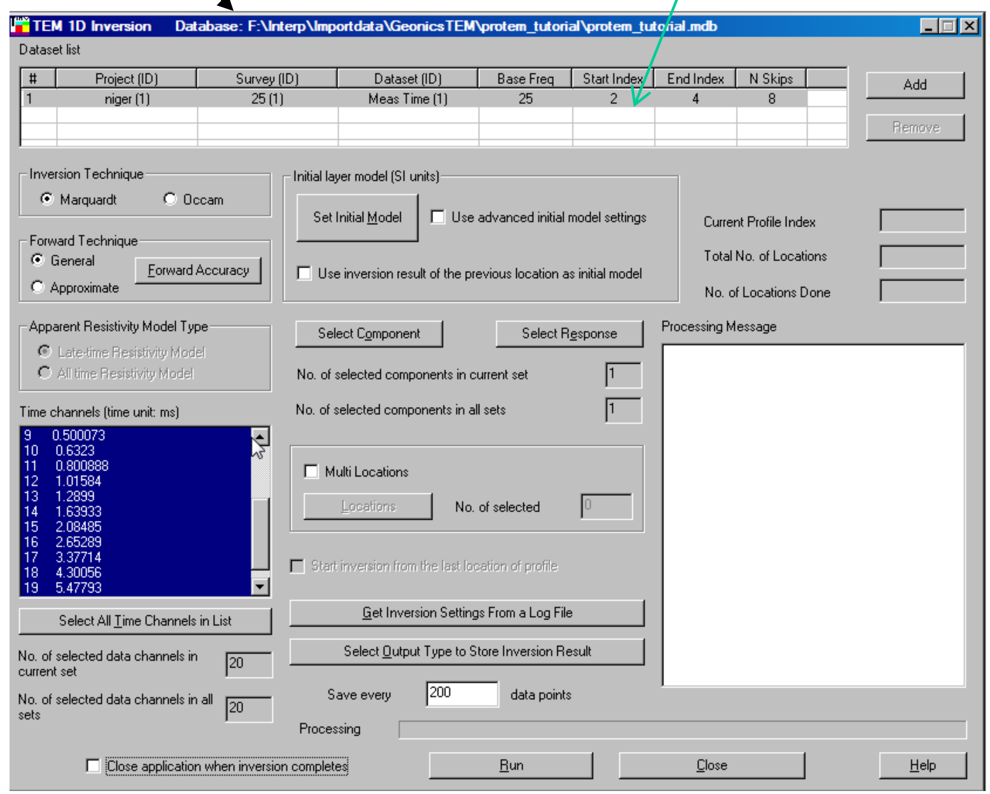
1. Create a new EMIGMA database.
2. Import Data
3. Examine the data from each base frequency
4. Perform some initial modelling,
5. **Perform controlled Marquardt or Occam Inversions**
6. Create Sections



Select survey data



Select multiple basefrequencies



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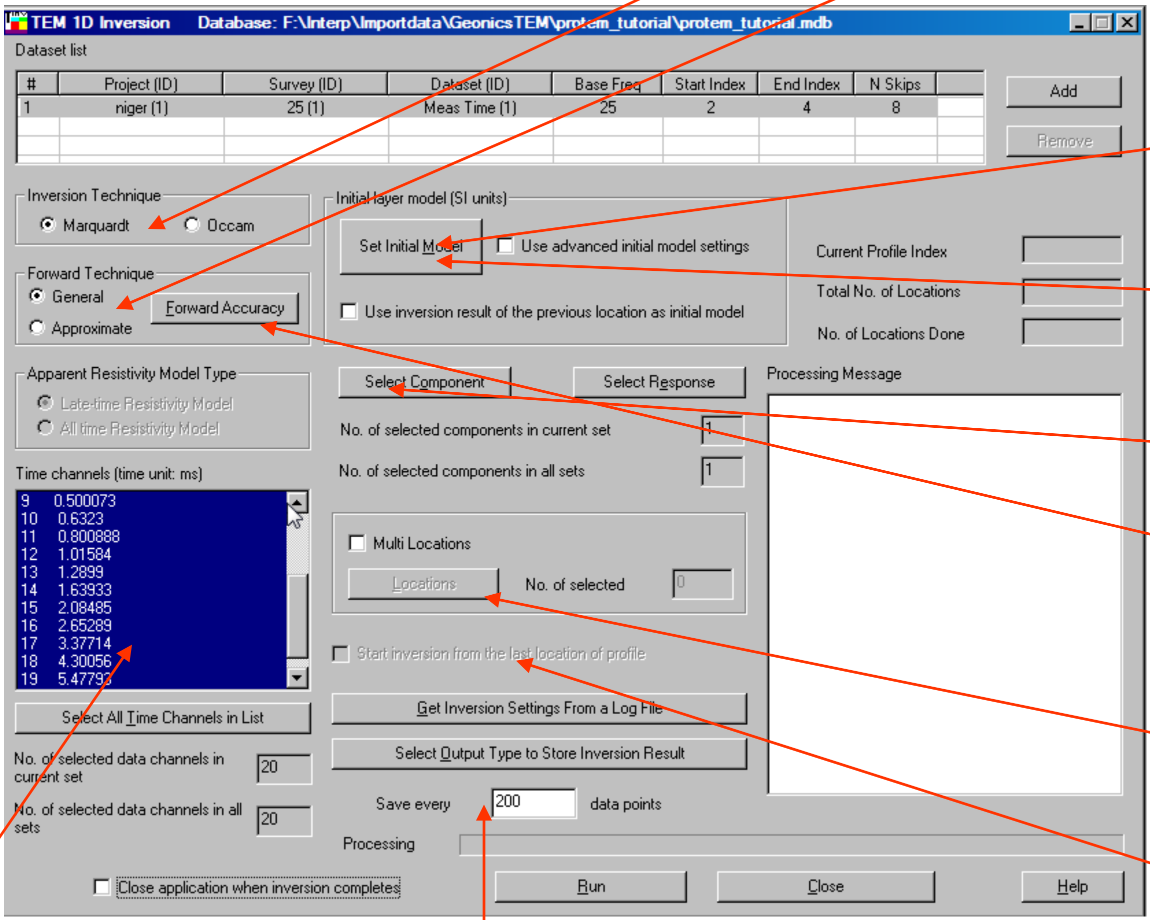
6. Create Sections

Inversion method

Forward technique



Create a Starting Model

Constrain model parameters

Select component or multiple components

Select upper bandwidth

Select multiple locations

Load inversion settings from a log file and set name for log file

Choose time windows

Set how often inversion result is saved

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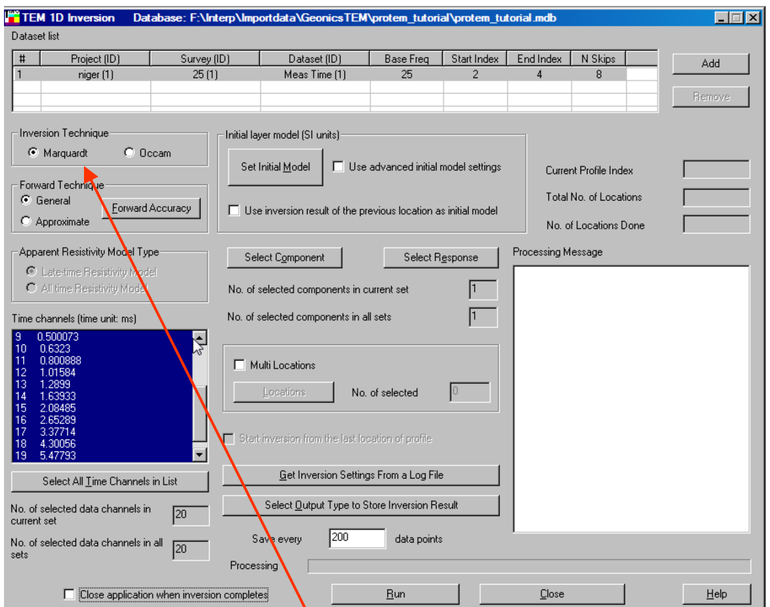

Inversion method

Inversion method:
There are 2 distinct methods which are now prevalent in geophysical inversion and both are offered here – Marquardt and Occam.

Marquardt Inversion:
By this name, we mean an *underparametrized* technique by which there are to be less model parameters than data. In TEM inversion, each layer consists of 2 model Parameters, namely its thickness and its resistivity.
The basement has one parameter. However, we do not use a traditional line search in the inversion proces.

Each data window consists of one datum per component (e.g. Hz or Hx) or one datum per separation.
The software restricts the number of layers in the model to be underparametrized.

Occam Inversion:
This is an *overparametrized* inversion but each layer has a fixed thickness and the inversion only inverts for resistivity.

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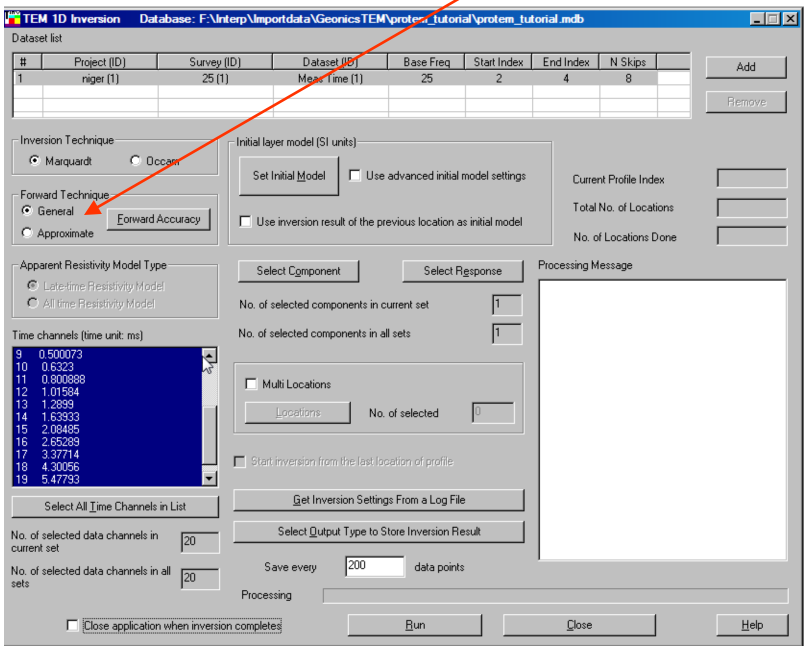
Forward technique selection



Forward Technique:

All inversion techniques consist of a series of forward models which are guided by the inversion methods to a *best* model.

Traditional TEM (TDEM) inversion has utilized an approximate technique to provide the response of the forward solution during the inversion process.
This approximation is restricted of a number of factors but most important are the location of TX and RX and the nature of the current waveform. Traditionally, the loop has been replaced by a circle of equal area and the RX was in the exact center of the loop.

The waveform was considered a perfect *impulse* response with infinite frequency bandwidth and was considered to be *causal* (i.e. turned on once and then always off). This approach is provided here by the ***approximate*** technique which can only be applied to central loop measurements.

This approach would prevent out-of-loop inversions to be effective.

General Technique: As EMIGMA is able to model fairly arbitrary loop and TX-RX configurations, we utilize our normal forward algorithms in this mode. This allows the user to utilize in-loop and out-of-loop configurations but also varying positions inside the loop. As in our forward simulations, the user should specify the bandwidth and accuracy of the transform to time-domain. In this case, we are using the true periodic waveform and attempt to reproduce the system bandwidth.

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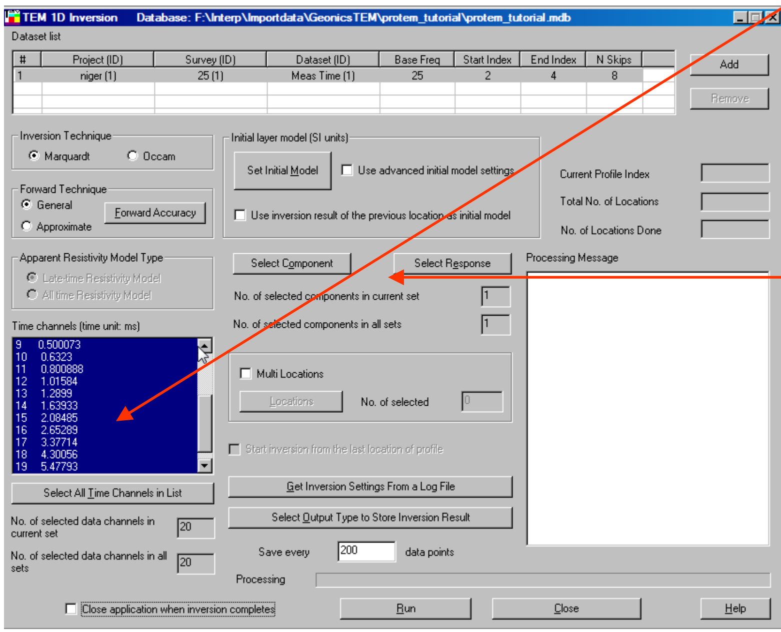

Choose time windows for inversion

After examining your data, choose which time windows you wish to utilize for inversion. The final inversion model will be simulated for all time windows for final comparison.

Inversion Controls

If you have measured more than one data component, for example Hx as well as Hz or more than one separation for a moving system then you must choose which one you wish to fit in the inversion process.

There may be more than one data response (especially when testing with synthetic data.)

As this inversion process is suitable when the ground is smoothly varying laterally, you may choose to use the previous data point's final model as the starting model for the next point. This also will speed up the process which is particularly important for airborne data.

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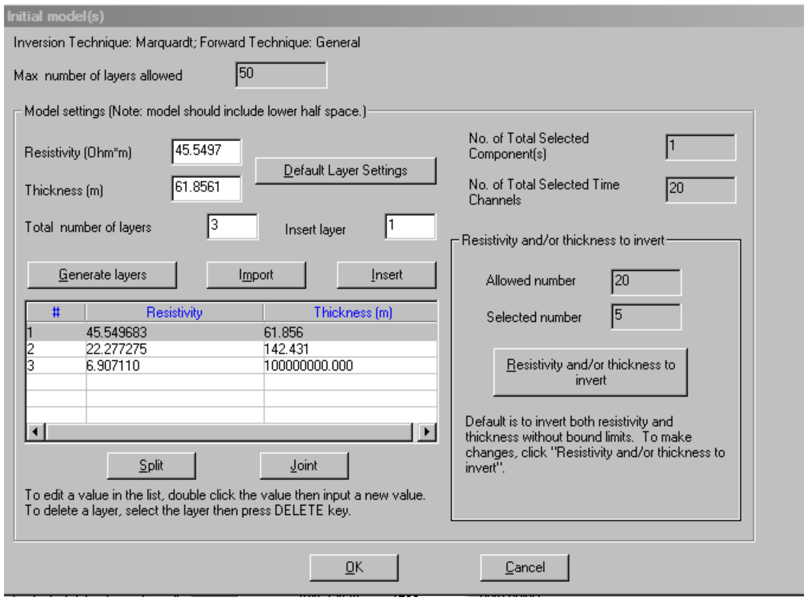
Create a Starting Model

as TDEM inversion, particularly inloop, is non-unique this can be important.



Import Layers: If you have created a forward model that you like, particularly when it is geologically appropriate, you may import it as a starting model or if you have a previous inversion that you like, you may import it as a starting model. Thicknesses and resistivities may be edited by selecting the appropriate box.

Insert a layer: You may insert additional layers at any stage.

Split a layer: Divides a layer in half to increase resolution.

Join Layers: Join 2 layers if they are not required for resolution.

Generate a Starting model:
First select how many layers in total that you would like in the model, set the initial resistivity and thickness. Then click “Generate Uniform Layers”. Then edit if required.

Editing Starting model:
After making a starting model (whether by importing or generating), the user may edit either the resistivity or the thickness of the layer. Simply double-click on the parameter setting.

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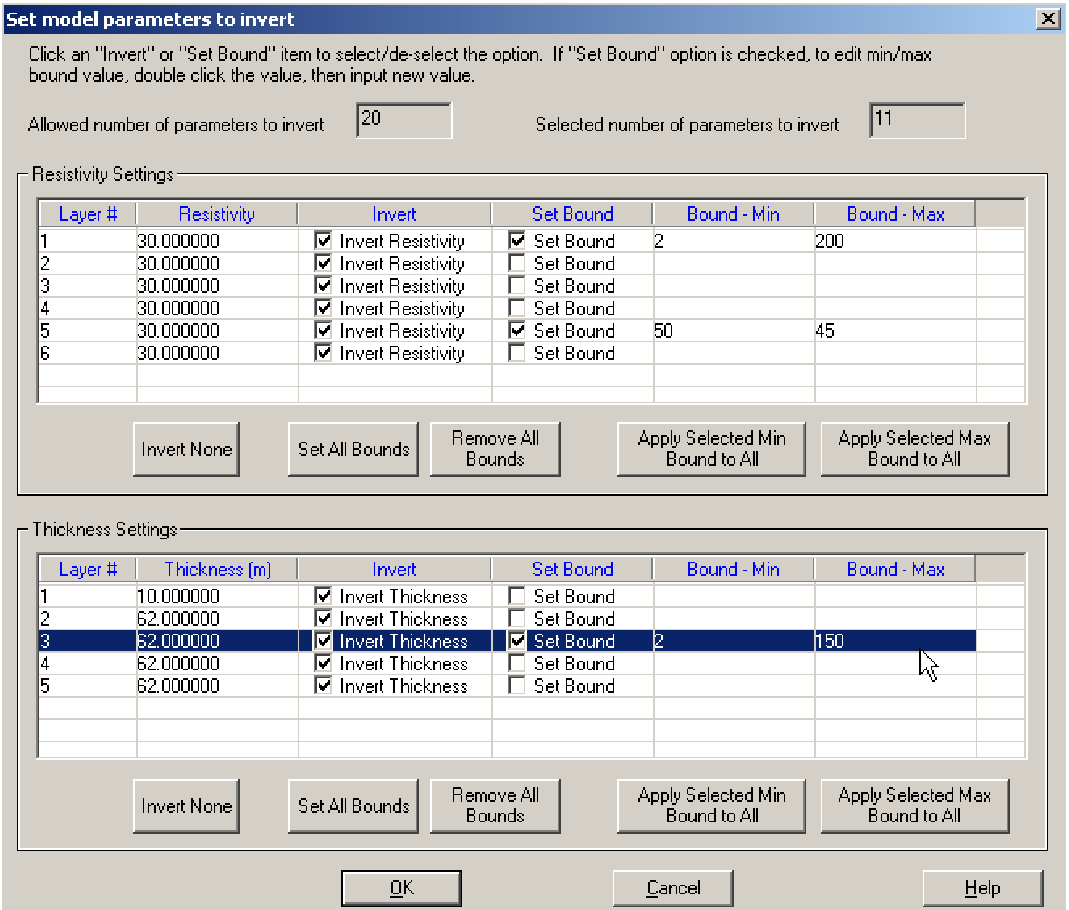
Constrain Model Parameters



Resistivity Constraints:
It is useful to constrain the layer resistivities to ranges that are realistic in the geological environment.

Thickness Constraints:
This option is only available under the Marquardt technique.
Constraining the maximum thickness can help gain resolution. Constraining the minimum is a question of geological meaningfulness.

Parameters to Invert:
If you feel a parameter is know then you choose to deselect this parameter and it will remain fixed within the inversion process.

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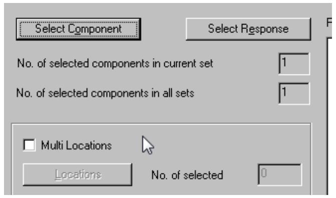
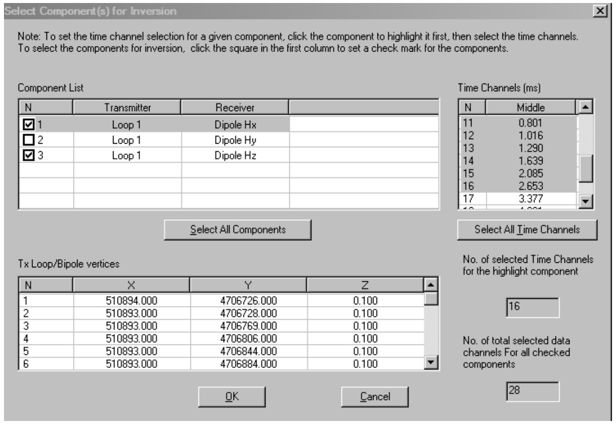
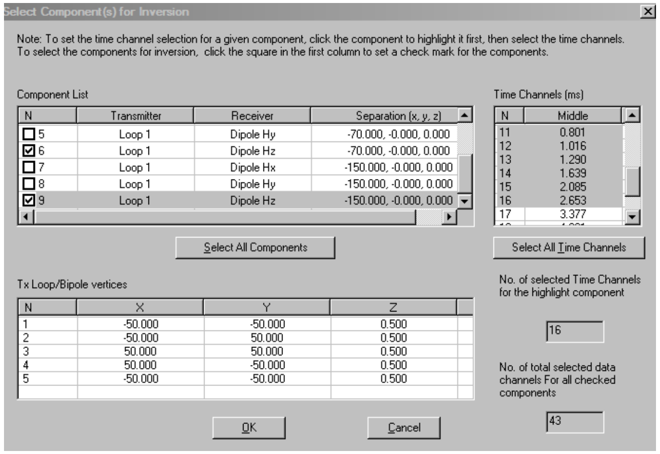
Selecting Components





Example 1: Multiple Field Components
In this case, 3 components have been collected. We have selected to invert Hx and Hz and additionally, we have specified the time channels for Hx and Hz separately.



Example 2: Multiple Field Components and Multiple Separations
In this case, there are 3 receiver offsets from the centre of the loop (i.e. separations) – 0,70,150m plus 3 field components. Here we select to use Hz at all 3 separations.

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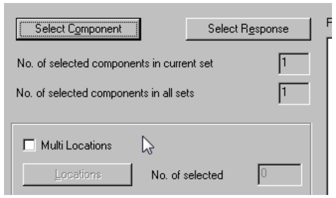
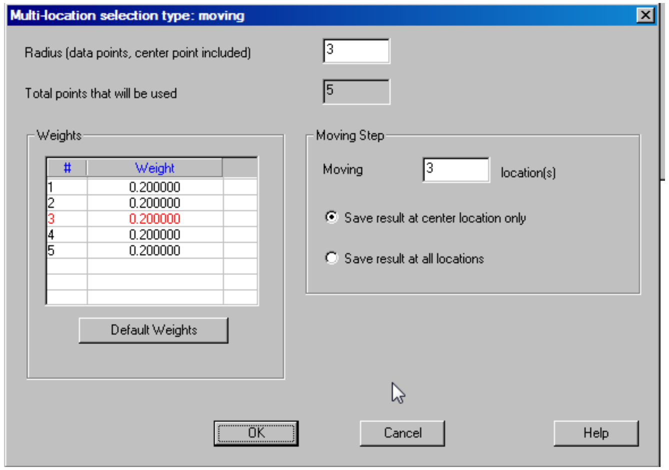
Selecting Multiple Locations



Moving multi-location spatial window

available for moving or fixed loop but only single component

If you have a need for this functionality but with multiple components, please contact us.



Example 1: Multiple Data Locations Moving Window This is an airborne example with only Hz collected at every survey point. Here we use a 5 point window for joint inversion with the data location window moving 3 survey locations along the profile for each inversion thus providing an overlapping inversion window.

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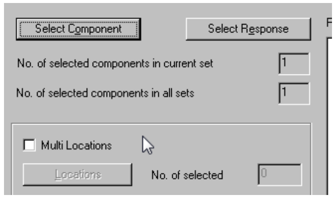
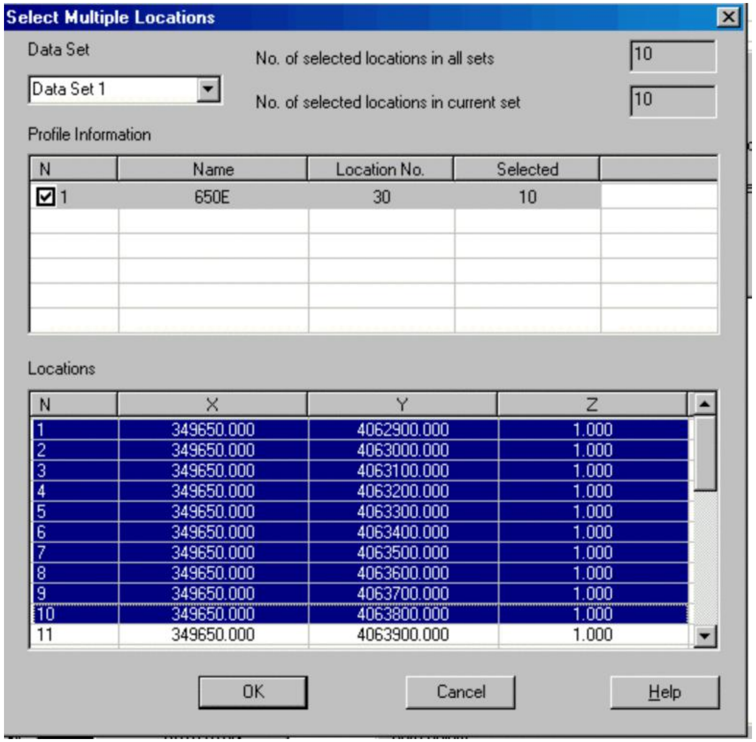
Selecting Multiple Locations





Multi-stations fixed spatial window

available for multi-component, and multi-separations

Example 2: Multiple Data Locations
In this case, we have a single profile, and 30 stations with Hx,Hy,Hz measured. We select Hx,Hz each with their own time windows and then

Multi-Locations -> Fixed-multi-location selection

then we have selected 10 of the datapoints on the profiles for a joint inversion. Note: for the simple mode, all components and all stations use the same time windows.

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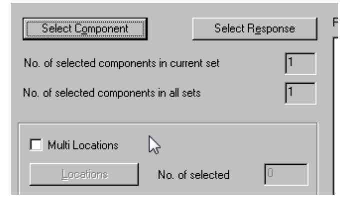
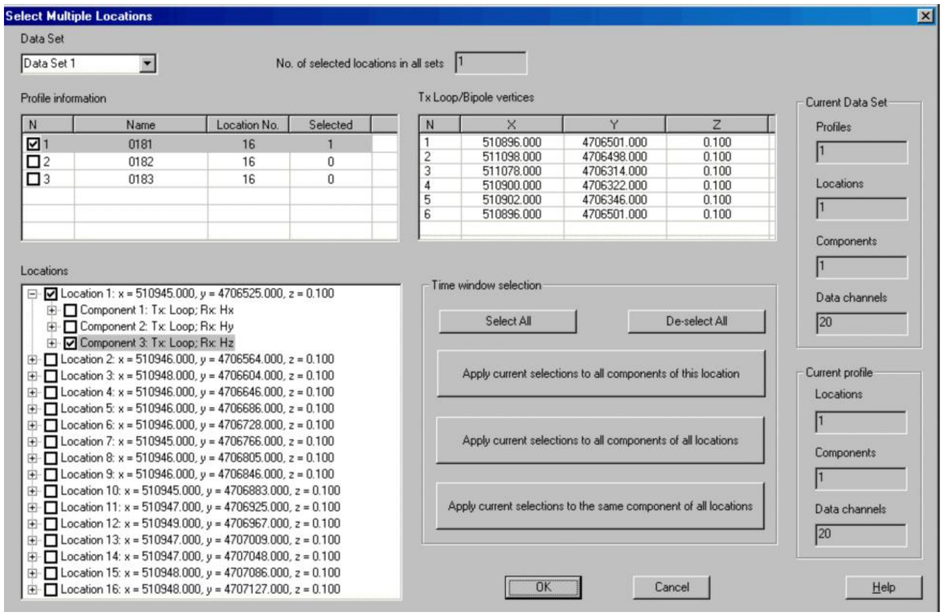
Selecting Multiple Locations



Multi-stations fixed window Advanced Mode

available for multi-component, and multi-separations, *multiple data stations*



Example 3: In Advanced Mode, each component at each station can be adjusted for specific time window.

Uses: *suggestions*

a)determination of best layered model prior to 3D modeling

b)finding layered stratigraphy for different regions in a large survey

c)comparing to moving window inversions

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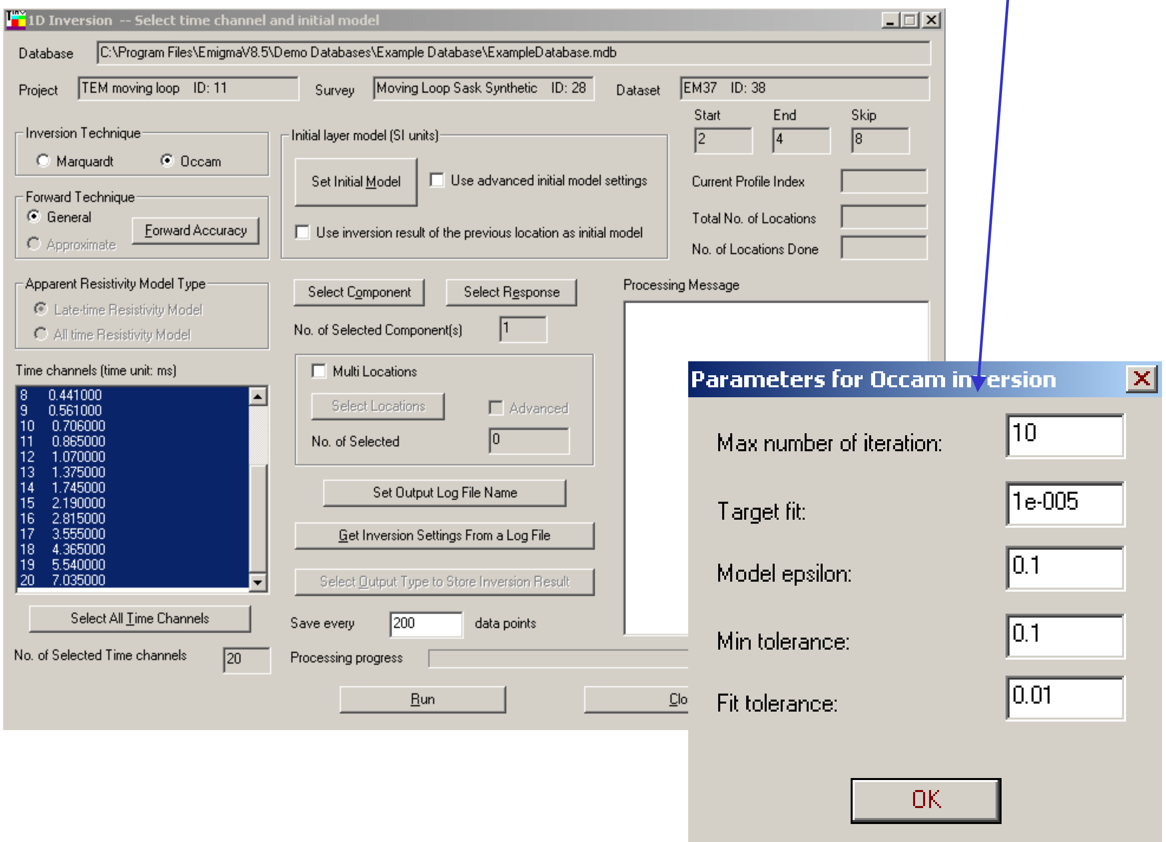
Executing the Inversion

Upon clicking Run, a window will pop-up. Unless the user is familiar with these items then it is suggested that the defaults be maintained. The OCCAM selections are shown here.



Number of Iterations: A higher value will help ensure accuracy but execution times increases

Target Fit: The residual between the estimated data under the best model and the measured data.

Model epsilon: Occam is a smooth inversion and the model epsilon controls the smoothness.

Min tolerance: Specifies how accurately the search algorithms determine minima in the fit.

Fit tolerance: Specifies how close to determine the final fit.

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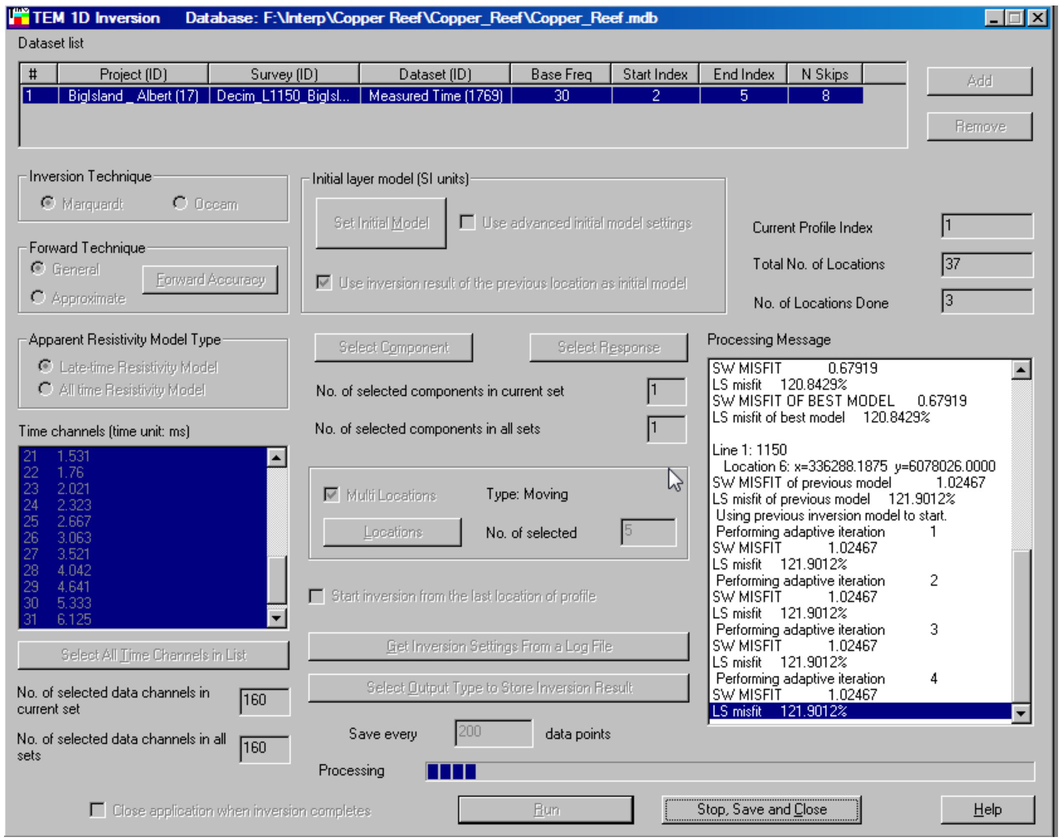
Executing the Inversion



Finally, click the Run button. The total number of data points in all the profiles will be shown as well as the number of data points completed to the right. The right corner (white) window shows each data point's progress.

NOTE: When the inversions are running, you may minimize the window and the processing will run in the background allowing you to continue to work on the computer. Any extra CPU cycles will be used by the inversion process. For some datasets containing 10's of thousands 100's of thousands of data points, the process may take many hours.

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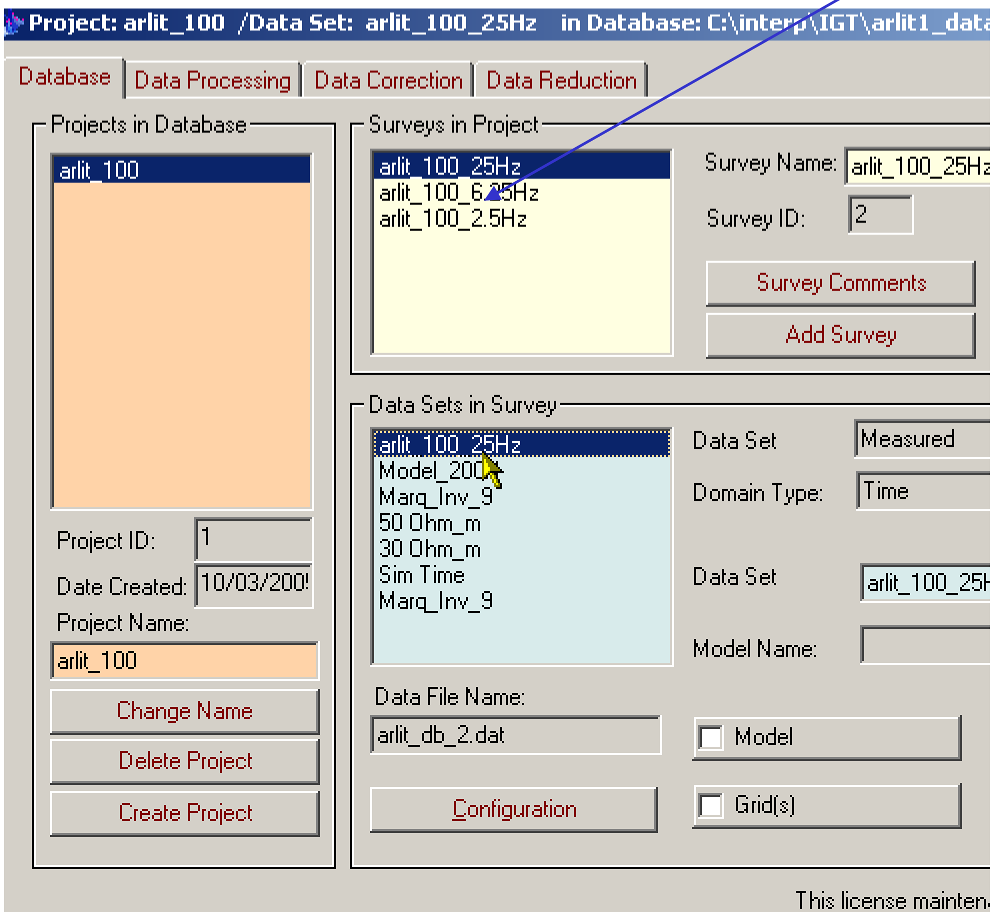
6. **Create Sections**

Inversion Evaluation

After import, there will be several surveys. In this case, 3 surveys , one for each base frequency



In each survey, there will be several data sets after modelling, inversion and processing. In this case, we have performed several ½ space models and 2 inversions. Each of the forward models, has a new data set containing the simulated data under the model. Similarly, each inversion contains a new dataset containing the simulated data set under the inversion model (for each point) and attached to that data set is the inversion model.

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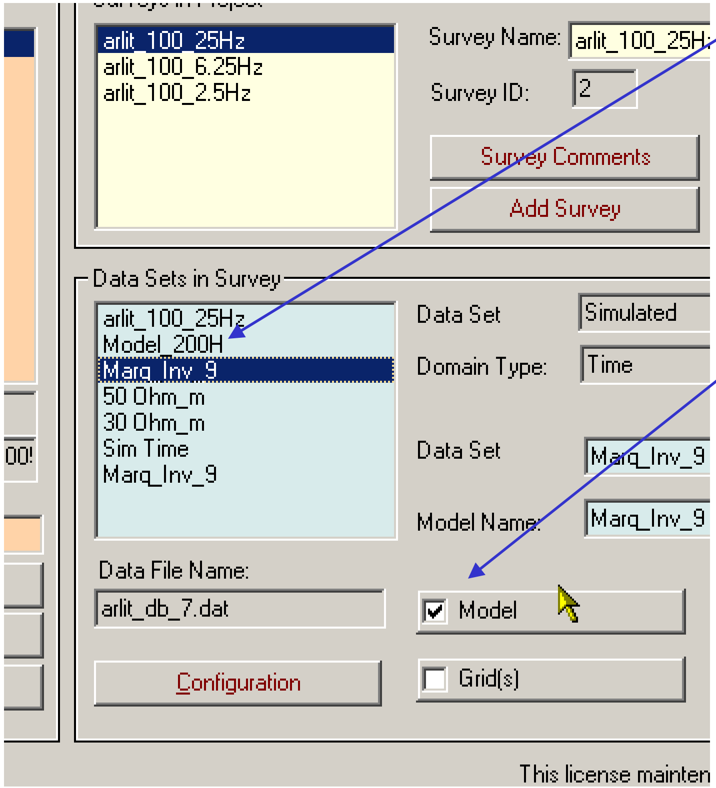
6. **Create Sections**

Inversion Evaluation

An inversion is selected. You will note the "Model" button is checked.



If the model button is clicked…

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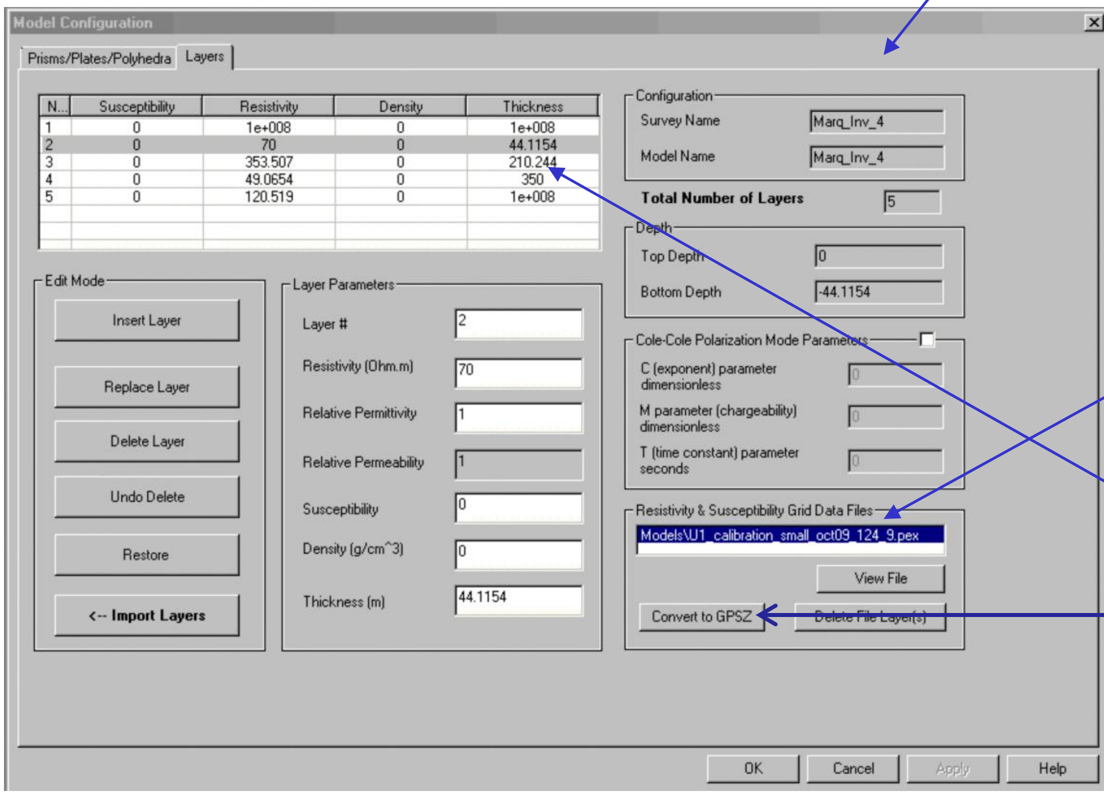
6. **Create Sections**

Inversion Evaluation

a window will open



Attached to the database, in a subdirectory called “Models”, are the inversion results in a simple ASCII XYZ file (*.pex) which may be viewed here. This file may easily be imported to another application although graphical viewing tools are provided within EMIGMA.

The 1D model for the final data point is also included.

The inversion may be adjusted w.r.t. GPS elevation in order to view in conjunction with topography. This is available ONLY when GPSZ is imported with the data.

To view the results in EMIGMA close the window.

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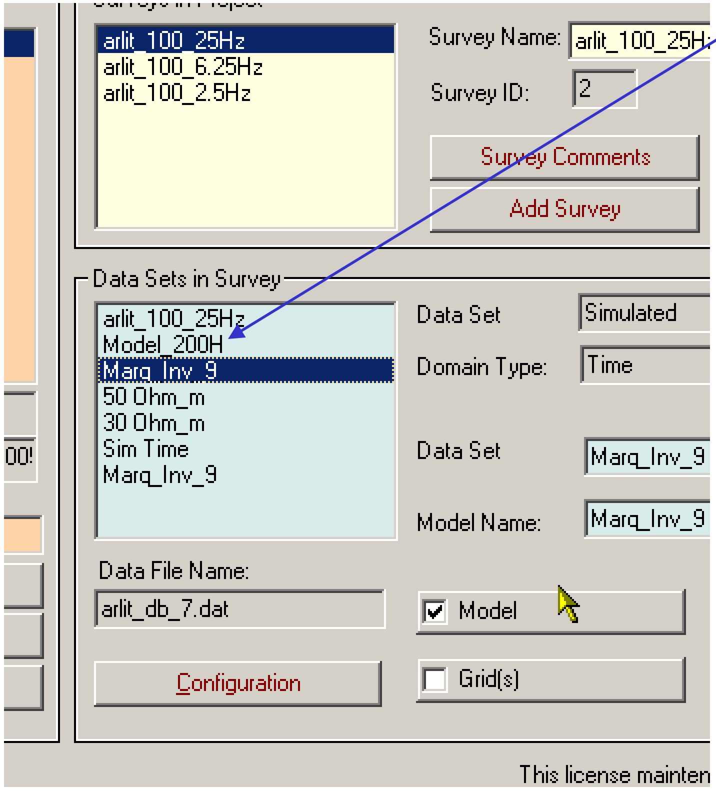
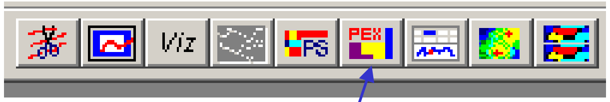
6. **Create Sections**

Inversion Evaluation

Select the inversion.





Choose CDI Viewer to graphically view the results

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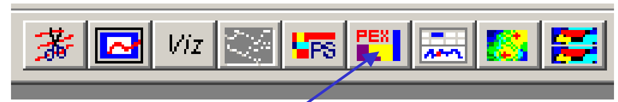
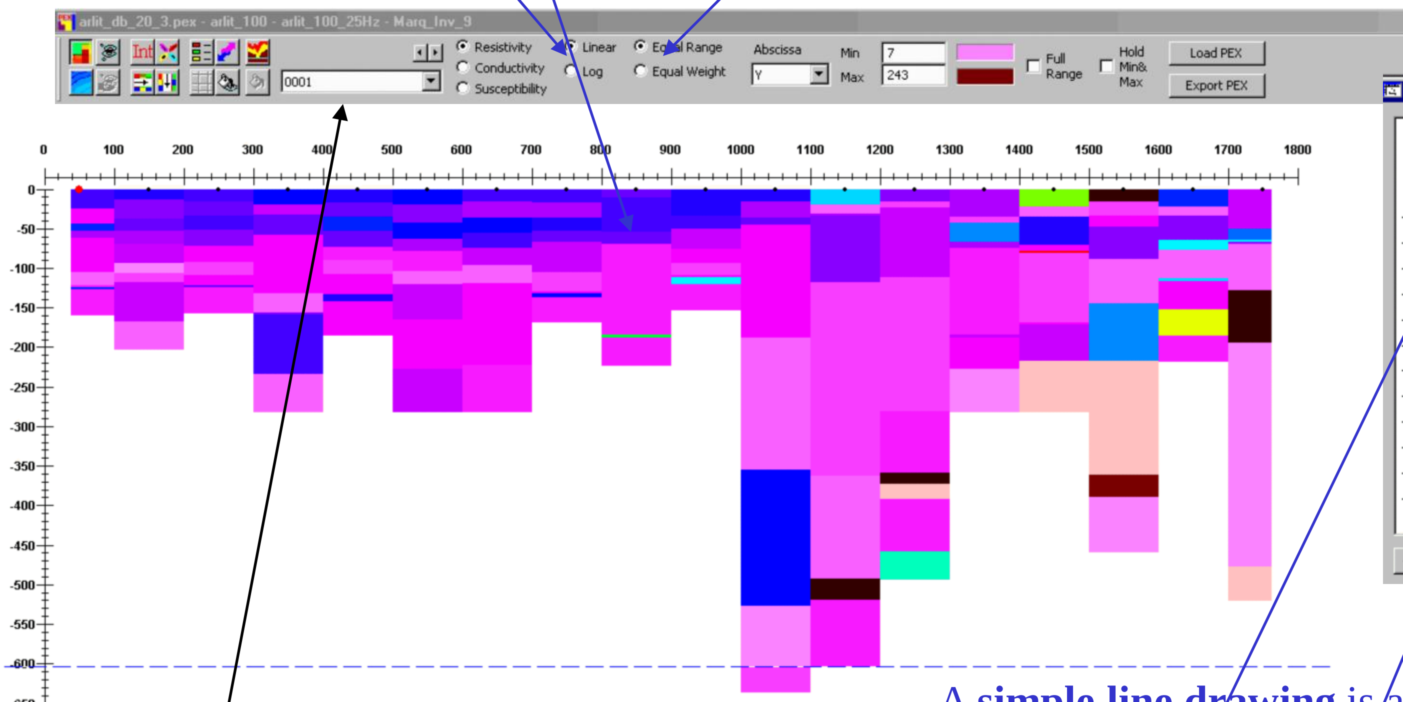
6. **Create Sections**

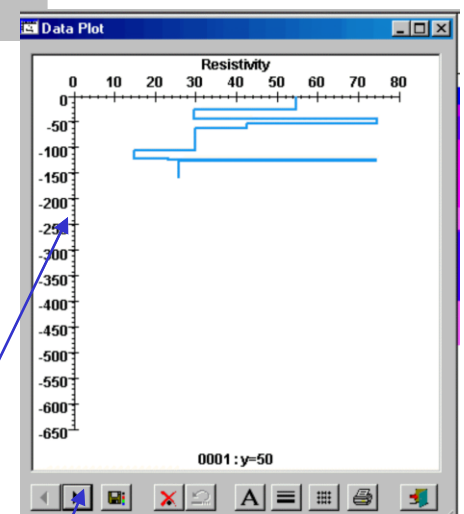
Inversion Displays



Choose CDI viewer to graphically view the results

The results for each **data point** are shown (without interpolation) initially in **linear(Resistivity)** with **Equal Range** display.

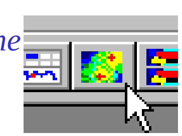




If there is more than one line then **other lines** may be selected.

A **simple line drawing** is also provided and you may **step** along the profile.

Note: If multi-lines are available the 3DContour may be used to provide an interpolated 3D volume



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4. Perform some initial modelling,
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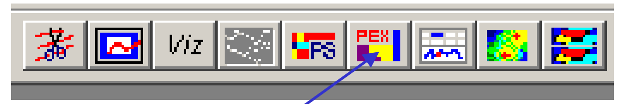
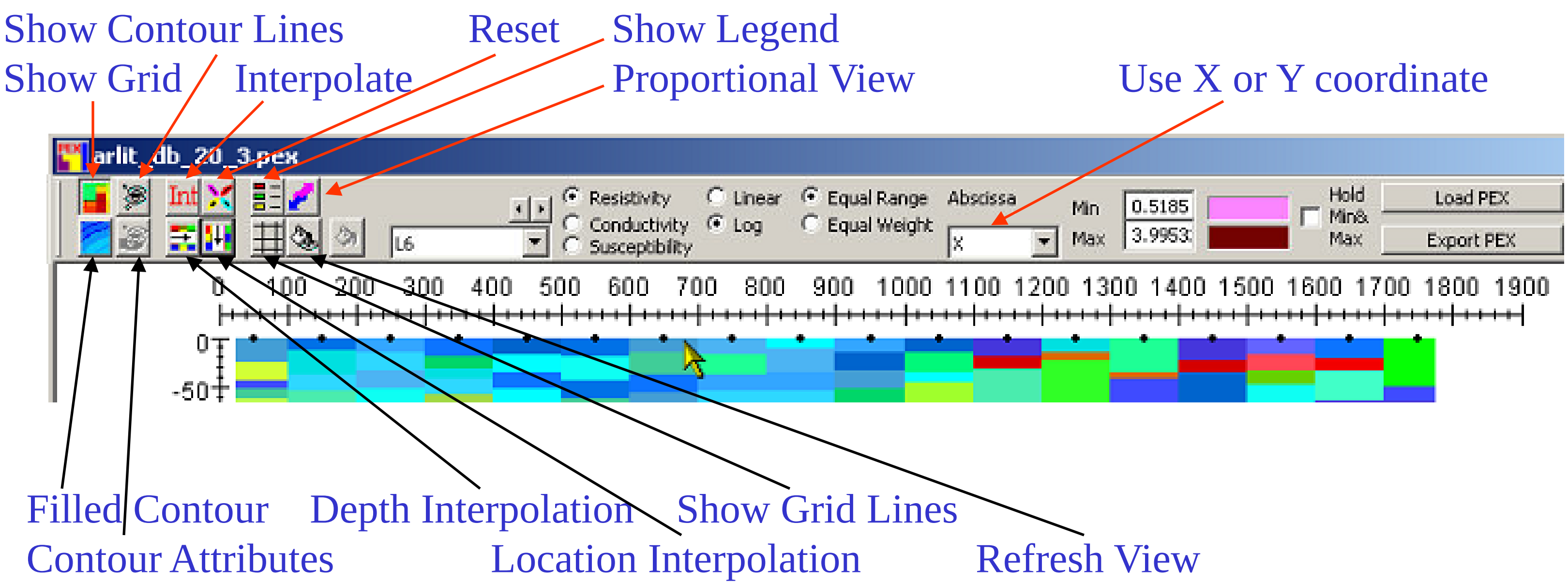
6. **Create Sections**

Inversion Displays



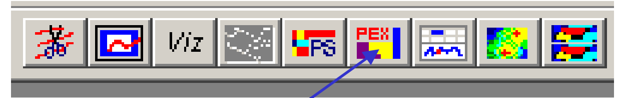
Choose CDI viewer to graphically view the results



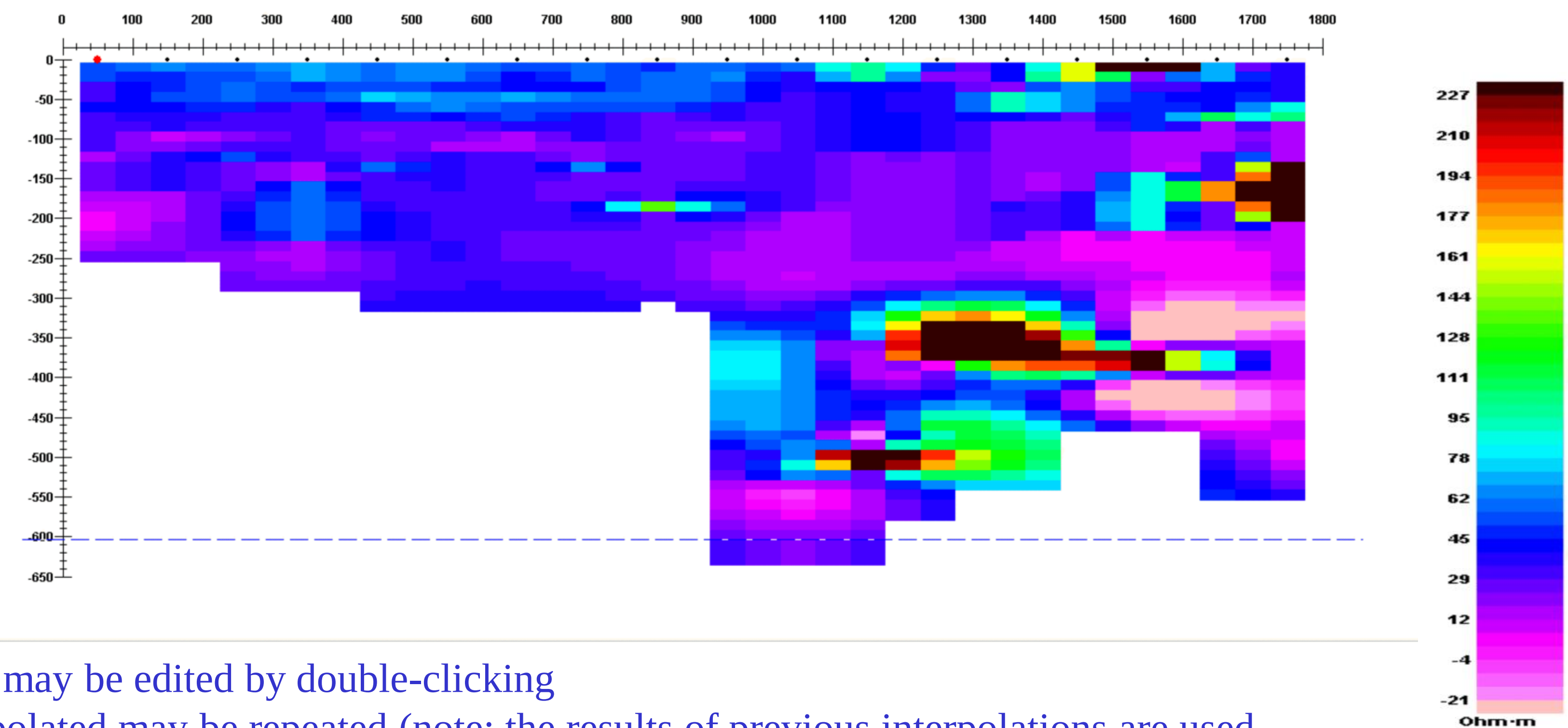
Equal Range: color intervals are equal in size
Equal Weight: color intervals are equally distributed in data
Min: Any data values below Min will be displayed as the color to the right of the edit field
Max: Any data values above Max will be displayed as the color to the right of the edit field

1. Create a new EMIGMA database.
2. Import Data
3. Examine the data from each base frequency
4. Perform some initial modelling,
5. Perform controlled Marquardt or Occam Inversions
6. **Create Sections**

Inversion Displays



Choose CDI viewer to graphically view the results



Axes may be edited by double-clicking
Interpolated may be repeated (note: the results of previous interpolations are used in the next interpolation so use with care.)
Legends turned on and controlled by double clicking the legend

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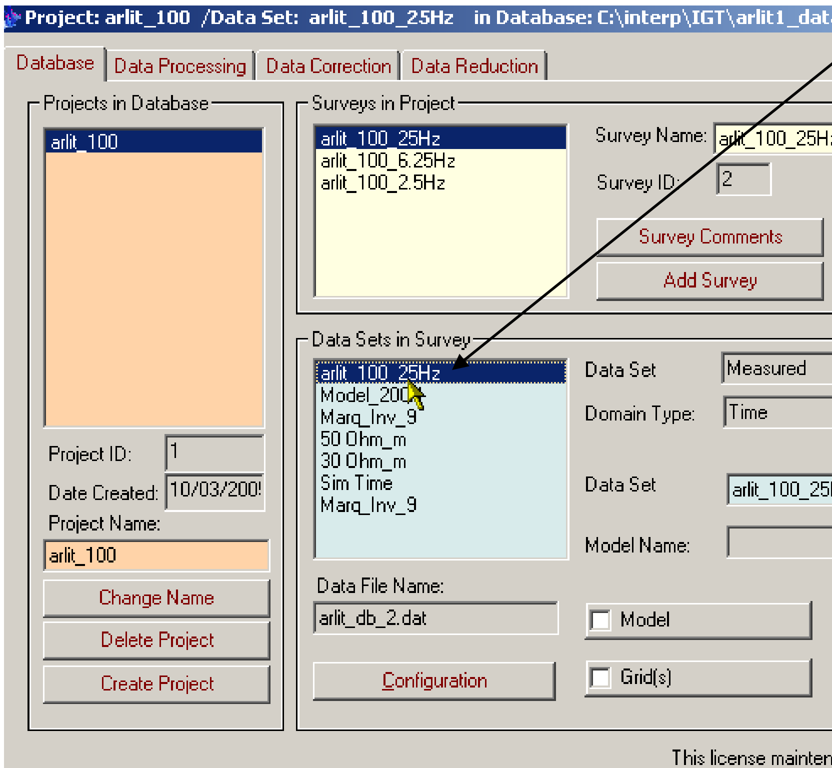
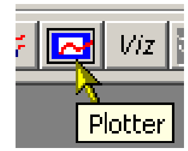
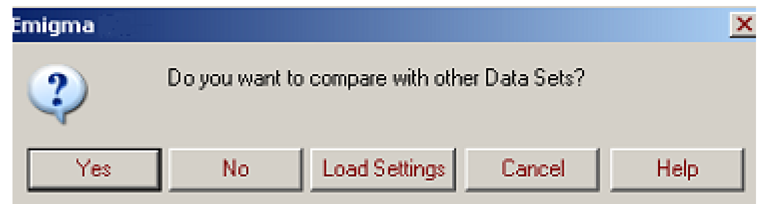
6. **Create Sections**

Inversion Evaluation



To assess the success of the inversion, select the measured data and then select the plotter.





Select "Yes"

1. Create a new EMIGMA database.
2. Import Data
3. Examine the data from each base frequency
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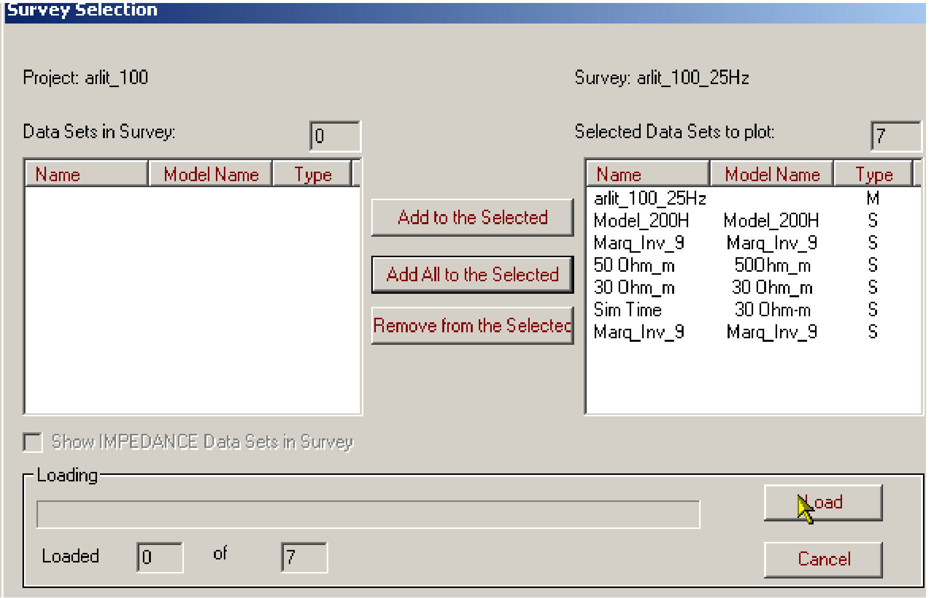
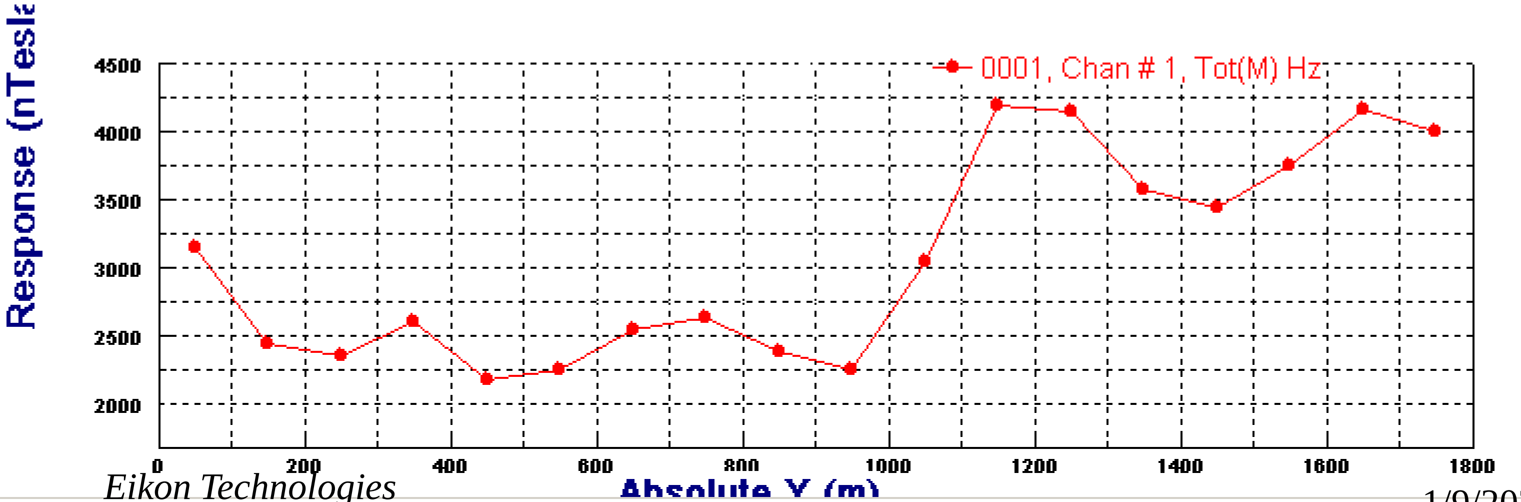
6. **Create Sections**

Inversion Evaluation

Select the data sets required for comparison and then "Load"



All selected data sets are then loaded to the plotter application and the plot appears showing the the first channel of the measured data.



1. Create a new EMIGMA database.
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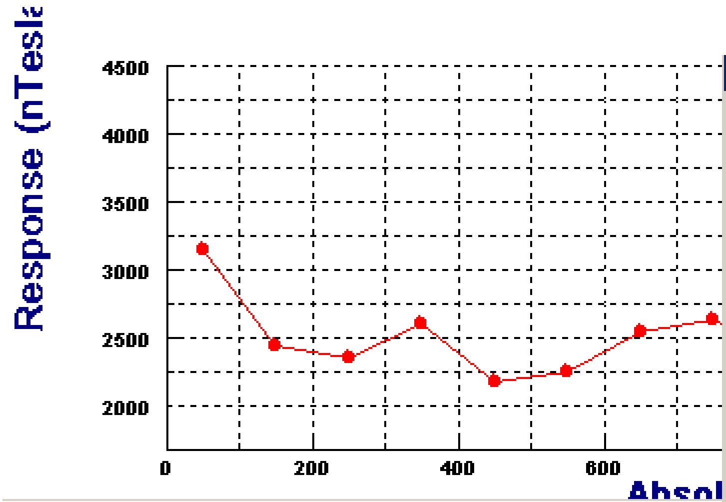
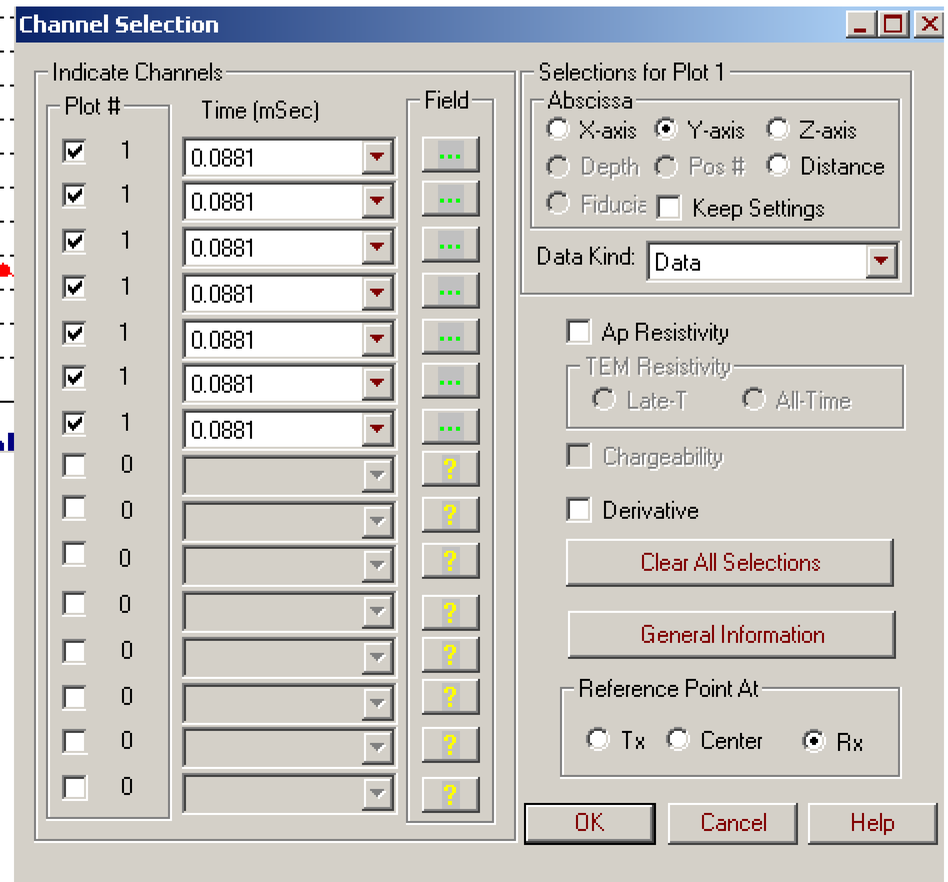
6. **Create Sections**

Inversion Evaluation

The user may select other data sets to plot by simply clicking on the plot.



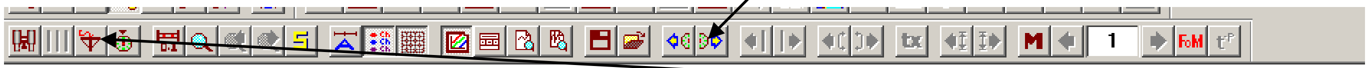


Select for the 2nd plot, the same time window and then modelled on inverted data.

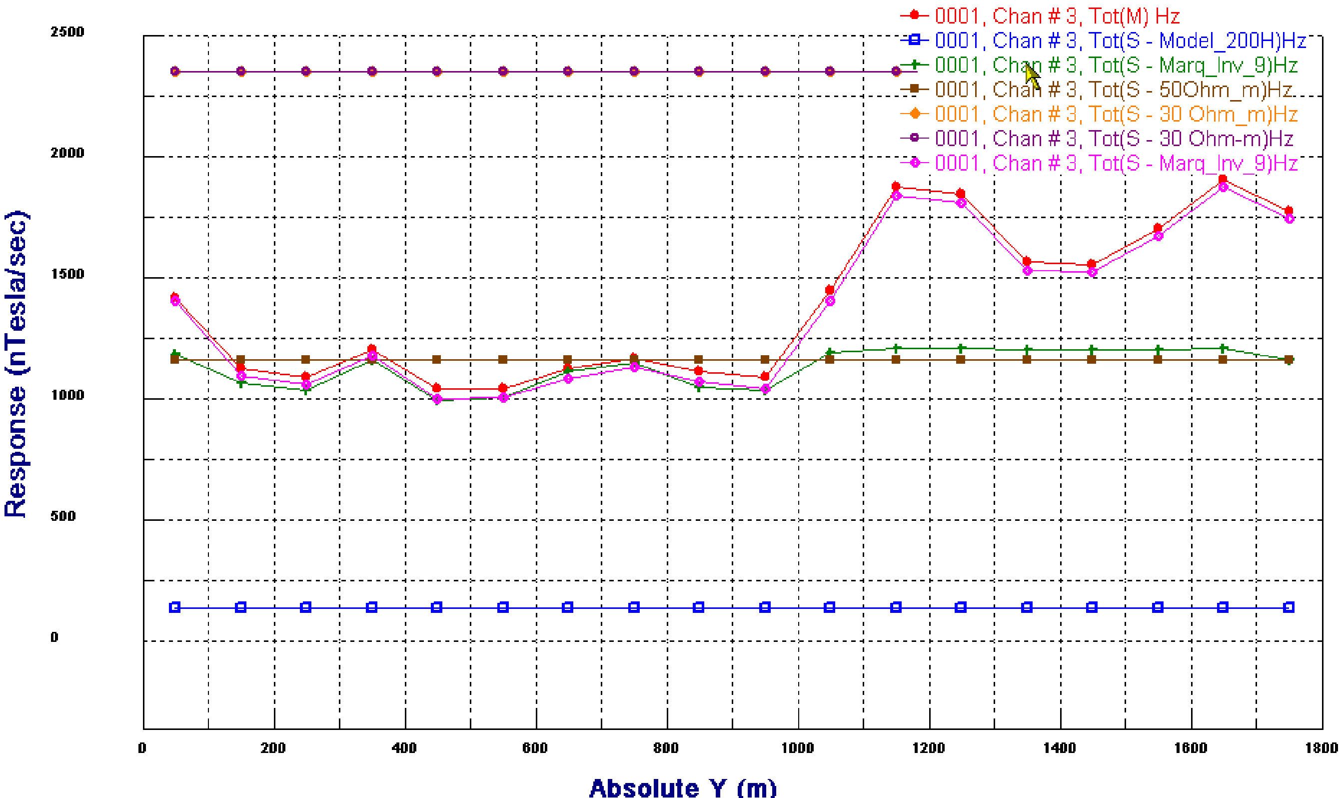
1. Create a new EMIGMA database.
2. Import Data
3. Examine the data from each base frequency
4. Perform some initial modelling,
5. Perform controlled Marquardt or Occam Inversions
6. **Create Sections**

Inversion Evaluation

Here, multiple plots are shown for various inversions and models in "Profile" mode. The user may step through time windows by simply clicking the arrow.



To show in "Decay" mode use the "Domain" button or right-click and choose Decay



1. Create a new EMIGMA database.
2. Import Data
3. Examine the data from each base frequency
4. Perform some initial modelling,
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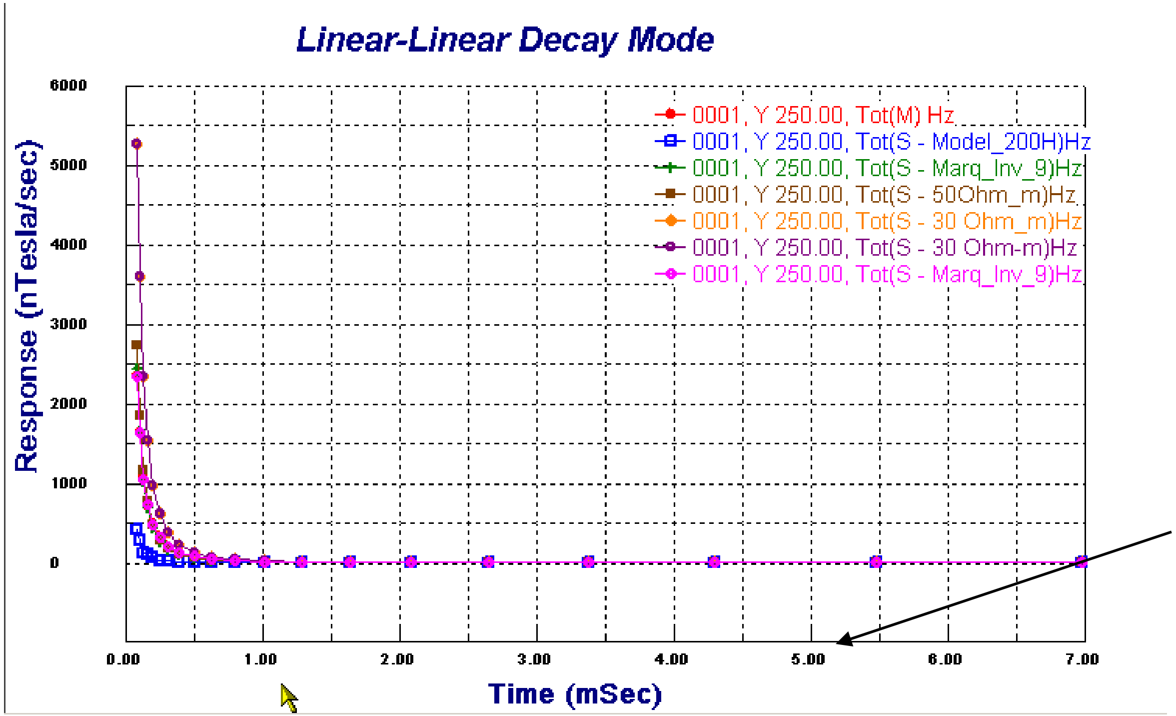
6. **Create Sections**

Inversion Evaluation

Here, decays are compared for a single data point in linear-linear mode. The user may move to other data points by simply clicking the arrows.



The step-time function of the arrows is now converted to step position.

It is useful to compare in a variety of log or linear modes. This functionality is accessed by double-clicking either axis.

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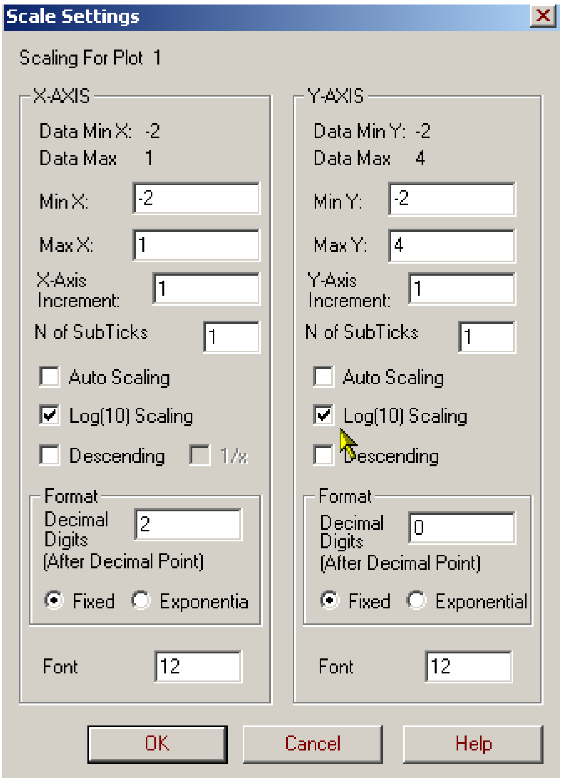
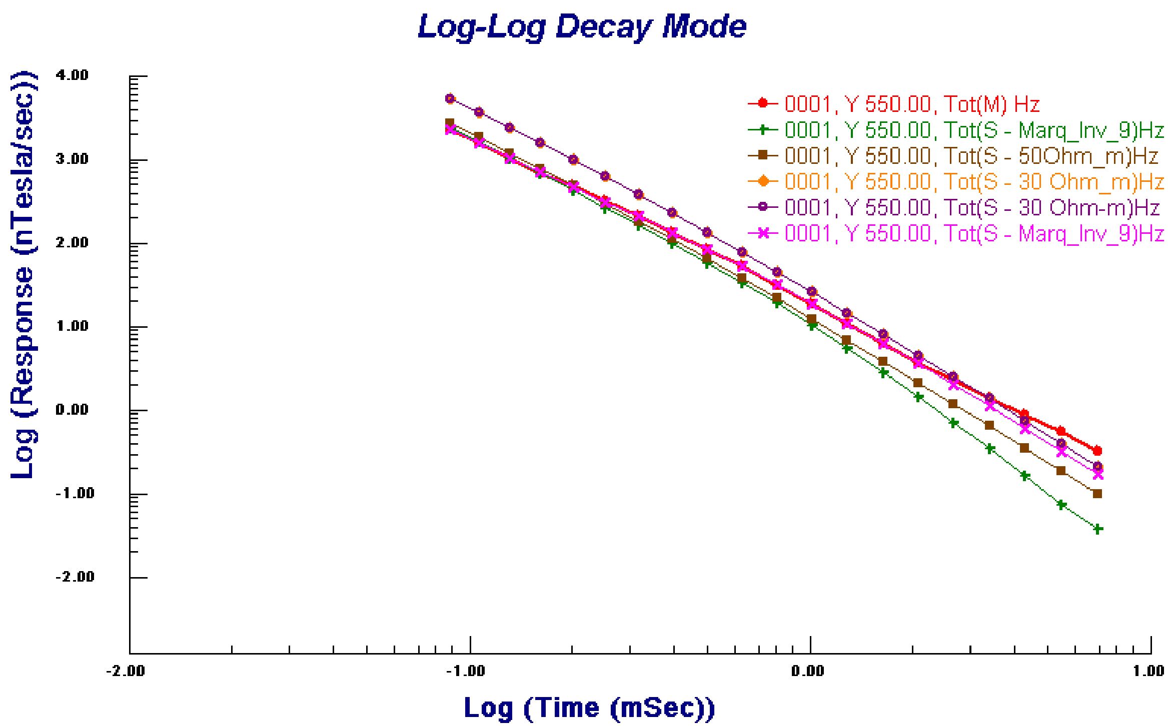
6. **Create Sections**

Inversion Evaluation

Here, we select log(time) vs log(amplitude)..





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1D-Time Domain Inversion Incorporating Various Data Strategies with a Trust-Region Method

2011. Ruizhong Jia, L.J. Davis and R.W. Groom. 10th CIGEW Workshop

Enhancing Model Reliability from TEM Data Utilizing Various Multiple Data Strategies

2007. Ruizhong Jia, R.W. Groom. SAGEEP.

On Time-Domain Transient Electromagnetic Soundings, Extended Abstract

2005. Ruizhong Jia and Ross Groom. SAGEEP.

These papers are available from our download site , http://www.petroseikon.com/resources/technical.php

A variety of other references may be found at the end of each of these papers.