Setting Moving FDEM systems in EMIGMA

Monday, June 23, 2025

EMIGMA Manual:
Specifying system geometry, Specify and EM/IP/Resistivity System ; Specifically: ***Specify separation, To specify the coordinate system Controlled Source Inputs*** ***entire section down to the beginning of Chapter III***

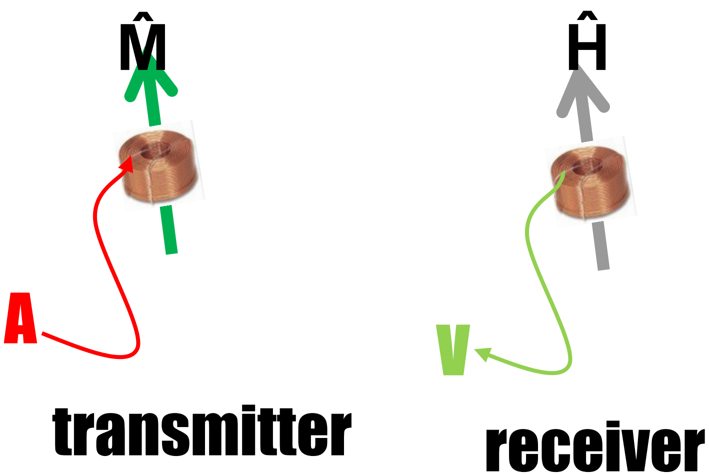
Normally, the Horizontal coordinate system is used for such systems in EMIGMA.

Coordinate system

Horizontal Coordinate System

- *direction of unit vectors change with profile direction*
- *$\hat{X}$ and $\hat{Y}$ are horizontal and $\hat{Z}$ is up.*
- *$\hat{X}$ is directed parallel to the tangent of the profile at each station.*
- *$\hat{Y}$ is perpendicular to the tangent at each station*
- *the station locations are your normal GPS or grid values*

Transmitters and Receivers

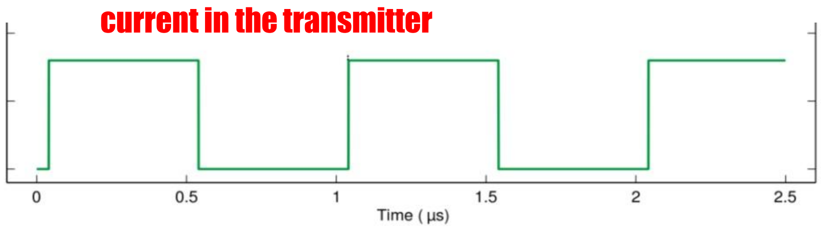


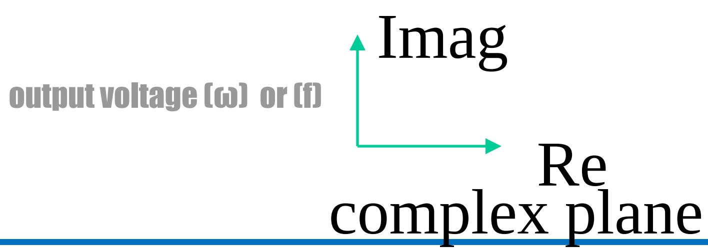
System Components

- *the transmitter and receiver are both wound coils*
- *a current is injected into the transmitter coil and this produces a magnetic moment.*
- *the magnetic field caused by the transmitter and the ground running through the receiver coil produces a voltage which is output*
- *the voltage output can be converted to a value of magnetic field coupling with the coil if desired*
- *the measured magnetic field is aligned with the moment of the receiver coil*
- *mathematically the source and receiver are defined as point electric dipoles – this is satisfactory as the coils are small with respect to the tx-rx separations*

Setting Moving FDEM systems in EMIGMA

Data Processing





Instrument Aspects

- *a square wave current of a certain frequency is injected into the transmitter*
- *the fundamental harmonic of this boxcar is extracted in the receiver which produces a real part and an imaginary part*
- *the real part is inphase with the current in the transmitter*
- *the imaginary part is out of phase with the current*

Inphase – a common name for the real part of the output
Quadrature – a common name for the imaginary part of the output

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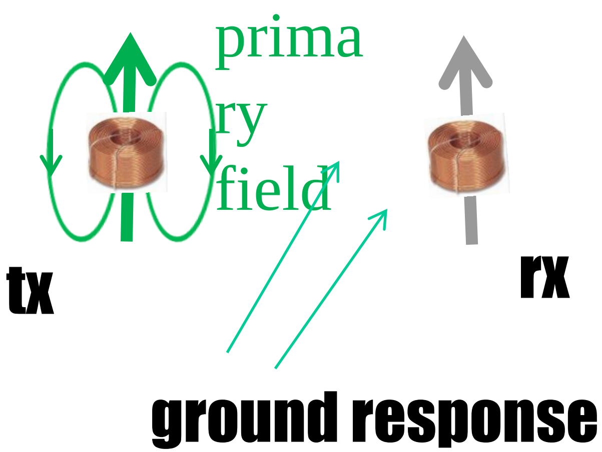
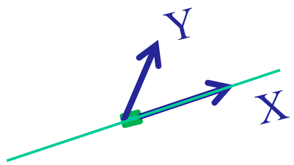
Normalization

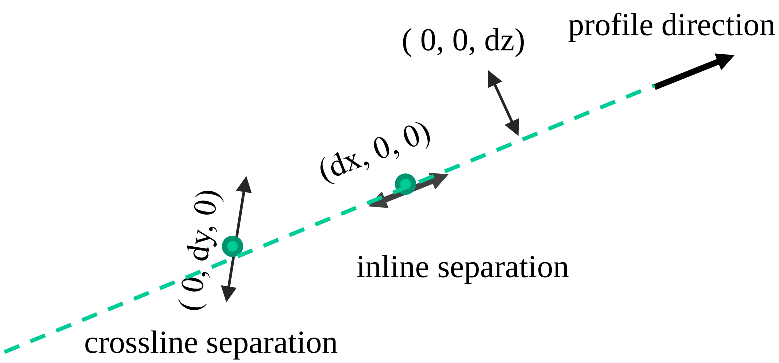


Normalization

- *the strongest field is that directly from the transmitter which contains no part of the ground response*
- *this direct (primary) field is inphase and can be computed if the coil strength and the current are known*
- *this primary field is removed from the output voltage either by computation or by the use of a bucking coil (e.g. airborne systems)*
- *the remaining voltage is the ground response*
- *the remaining or secondary voltage is then divided by the primary voltage which was previously subtracted*
- *the resulting voltage output is then dimensionless*
- *depending upon the manufacturer the resulting voltage can be adjusted to different units*

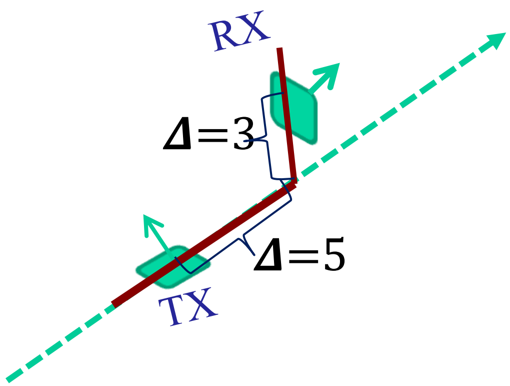
Tx-Rx separations in EMIGMA





Horizontal Coordinate System

- *direction of unit vectors change with profile direction*
- *$\hat{X}$ and $\hat{Y}$ are horizontal and $\hat{Z}$ is up.*
- *$\hat{X}$ is directed parallel to the tangent of the profile at each station.*
- *$\hat{Y}$ is perpendicular to the tangent at each station*
- *the station locations are your normal GPS or grid values but are the locations of reference point on the moving system for computations*
- *these conventions are for the source and receiver dipoles as well as the TX-RX separations*
- *separations may be defined as any (dx,dy,dz) with respect to the profile direction*
- *transmitter leads receiver is positive convention*



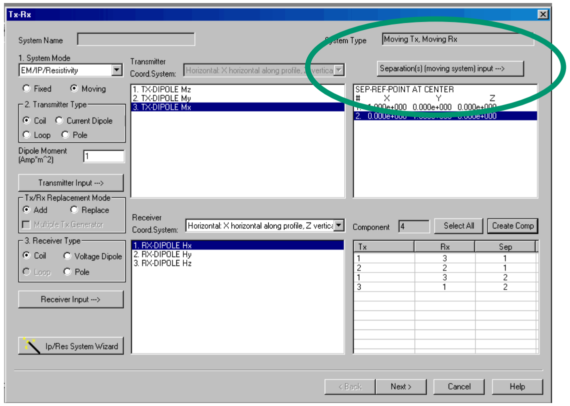
Example

- *TX is a horizontal loop or vertical magnetic dipole*
- *RX is a magnetic coil with axes in the X-direction*
- *RX is 5m in front of the TX as the system moves*
- *RX is 3m above the TX height w.r.t. altitude*
- *the Reference Points are either the TX,RX or Centre point*
- *the separation vector is the TX location vector minus the receiver location vector and is constant for the survey. Thus the software assumes a rigid TX-RX configuration*

TX(x,y,)-R(x,y,z) =(dx, dy, dz) = (-5,0,-3)

Setting Moving TDEM systems in EMIGMA

Configuration Page Example in EMIGMA



MOVING SYSTEM PLOT POINTS

MEASUREMENT REFERENCE POINT

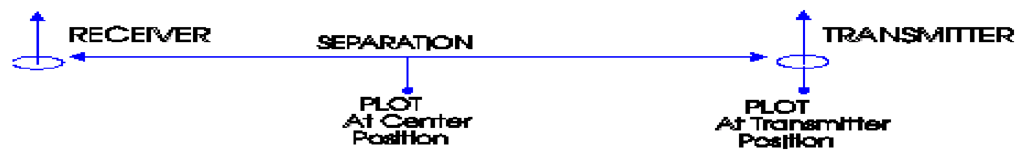


Figure 2-6

<u>The station coordinates refer to Data Reference Point on the TX-RX *frame*</u>

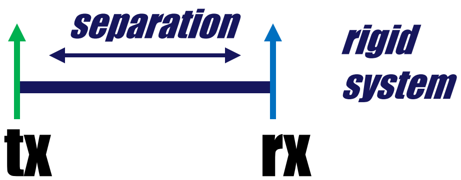
- 1: *Centre Point*   *2: Transmitter*   *3: Receiver*

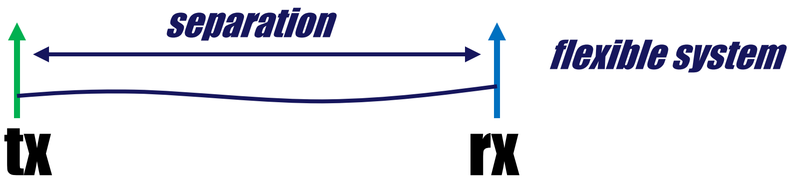
Historically, data for moving systems was referenced at the center point between TX and RX as this was inherited from resistivity surveys and is still common in Resistivity/IP today. For modern TEM systems, this is not always convenient nor suitable for interpretation. In airborne EM, the reference point is almost always at the receiver. For multi-separation TEM data, the reference point is always the transmitter. For other systems such as dipole-dipole downhole IP, the receiver is the reference point. Often it is easier to interpret 3D structure in resistivity/ip data when the data is referenced to the transmitter.

Setting Moving FDEM systems in EMIGMA

Data Processing

Normalization 2





Normalization

○ *there are two types of systems – rigid and flexible*
○ *in a rigid system, the tx and rx are housed in a rigid structure so that the separation of tx and rx is fixed – e.g. EM38, EM31, GEM2*
○ *in a flexible system, the tx and rx are independent and connected via a cable of some sort – e.g. Promis, MaxMin, EM34*
○ *in a flexible system care must be taken to ensure the cable is at the prescribed length and the coils are coplanar*

Additional Comments

○ *in an airborne system, the tx and rx and housed in a bird which is flexible during flight and thus normally a bucking coil is used to reduce and normalize to the primary response*
○ *in the PROMIS system, 3 components of the secondary field are measured simultaneously and so the coil orientation of tx and rx should be made accurately*
○ *in the older MaxMin system, one can measure Hx as well as Hz but the orientation of the receiver coils in both cases must be made accurately*

Setting Moving FDEM systems in EMIGMA

Data Units

- the raw response is always calculated according to the formula below
- *this ratio, however, can be expressed in various units as below*

$$\text{Response (Re, Im)} = \left\{ \frac{\text{Measured Voltage (Re,Im)} - \text{Primary Field}}{\text{Primary Field}} \right\}$$

InPhase Units – Percent (%), PPT, PPM

Quadrature Units – Percent (%), PPT, PPM, *apparent conductivity*

Primary Field: Theoretically, this is the direct wave from the TX to the RX or what is termed the Freespace response. If calculated this is the theoretical, low frequency field in an infinitely resistive space and thus is a real number. In practice, when bucking is applied there will be a small imaginary part to this field depending upon frequency.

Data Units Apparent Conductivity

- *it should be noted that the word "apparent" is extremely important for understanding these units*
- *this does mean actual conductivity, but rather the ratio expressed in terms of an approximate formula which represents an equivalent halfspace for the ground and not the actual ground conductivity*
- *the formula assumes a halfspace for the ground and then only one (1) term in the accurate representation from physical principles of such a system as discussed later.*

Setting Moving FDEM systems in EMIGMA

Data Units – apparent conductivity

Data Units Apparent Conductivity

○ *it should be noted that the word "apparent" is extremely important for understanding these units*

○ *this does mean actual conductivity, but rather the ration expressed in terms of an approximate formula which represents an equivalent halfspace for the ground and not the actual ground conductivity*

○ *the formula assumes a halfspace for the ground and then only one (1) term in accurate representation of such a system from physical principles*

○ *in the formula below "s" is the distance between transmitter and receiver. This formula assumes no effect from the (1/s) term in the response (far field)*

○ *if indeed the ground is a halfspace then the expression is most accurate when the induction number,*

[$\sigma \omega \mu_0 s^2$] is small

○ *this approximation is also intended when the instrument is directly upon the ground and becomes increasing incorrect very quickly as the instrument is raised above ground*

○ *in practice with commercial systems, this approximation is reasonable for systems with 1m separation (s)*

○ *the unit is useful only for non-scientists*

$$\sigma_{app} = \frac{4}{\omega \mu_0 s^2} \frac{(B)_{quadrature}}{B_{primary}}$$

Setting Moving FDEM systems in EMIGMA

Tx-Rx separations in EMIGMA

Some Examples

○ *standard horizontal coplanar inline system configuration (HCP):*

Tx – Mz ; Rx – Hz ; separation (dx, 0, 0)

[EM38 – (1,0,0) , EM31 – (3.66,0,0), GSSI – (1.219,0,0)

○ *standard horizontal coplanar crossline system configuration (HCP):*

Tx – Mz ; Rx – Hz ; separation (0, dy, 0)

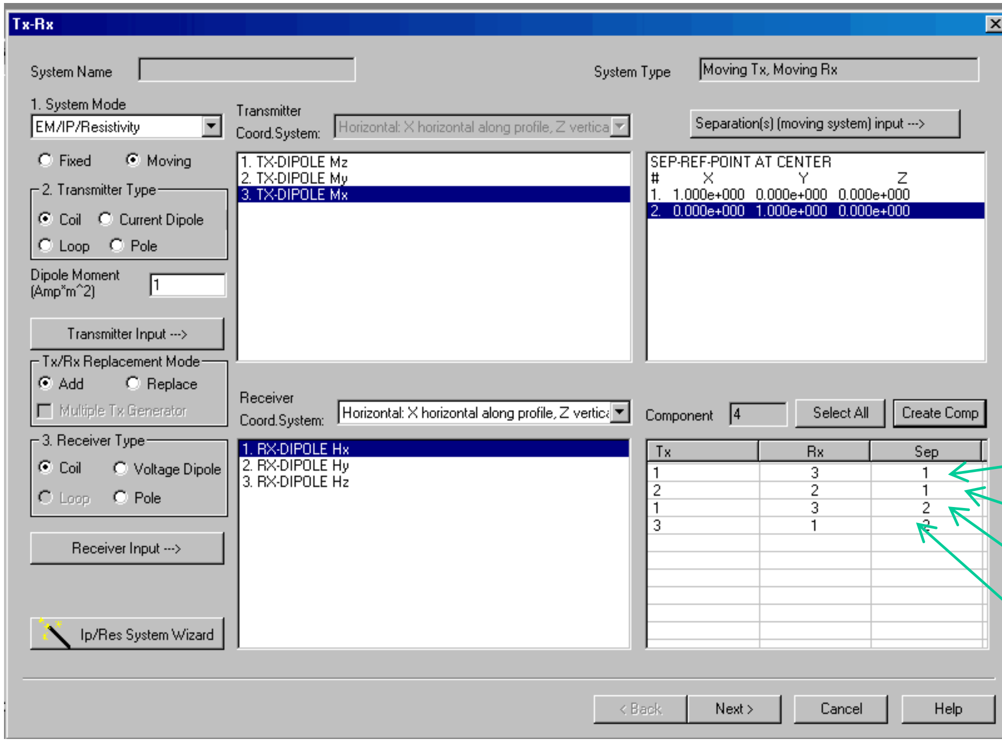
○ *standard vertical coplanar in line system configuration (VCP):*

Tx – My ; Rx – Hy ; separation (dx, 0, 0)

○ *standard vertical coplanar crossline system configuration (broadside VCP):*

Tx – Mx ; Rx – Hx ; separation (0, dy, 0)

Configuration Page Example in EMIGMA – EM38



1. Mz, Hz, (1,0,0)

2. My, Hy, (1,0,0)

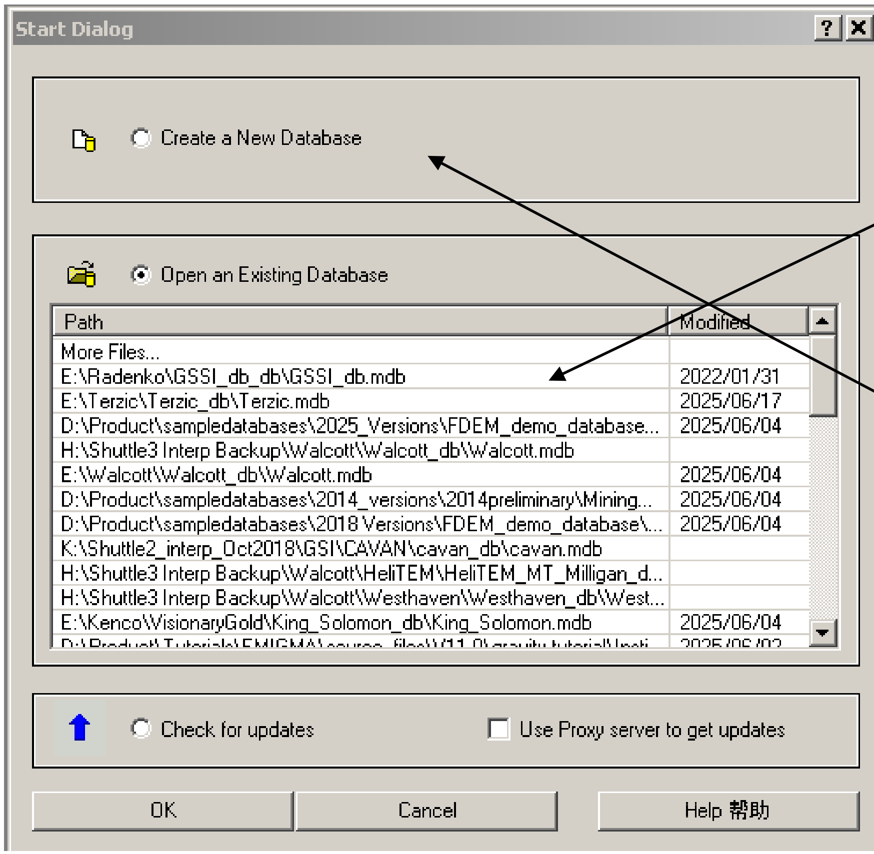
3. Mz, Hz, (0,1,0)

4. Mx, Hx, (0,1,0)

System Configurations

- ○ *1: standard HCP*
- ○ *2: standard VCP*
- ○ *3: standard HCP crossline*
- ○ *4: standard VCP crossline, broadside*

Opening a database



Select a Database

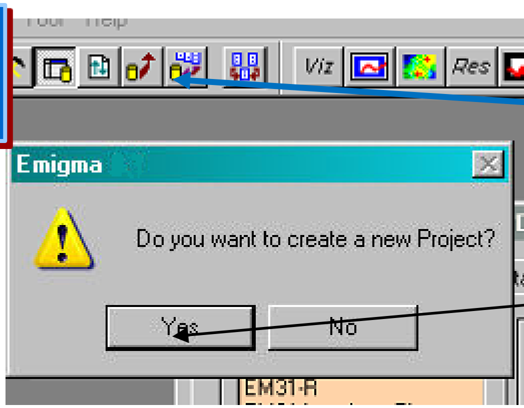
Or

Create a New Database

Note: If Creating a new database, it is recommended to put the new database in a new subdirectory

Importing Data - 1

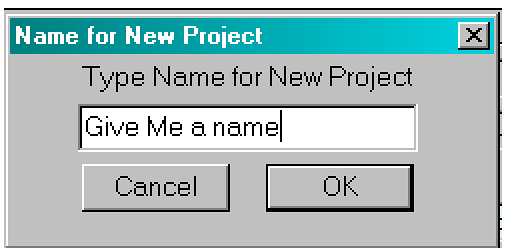
1



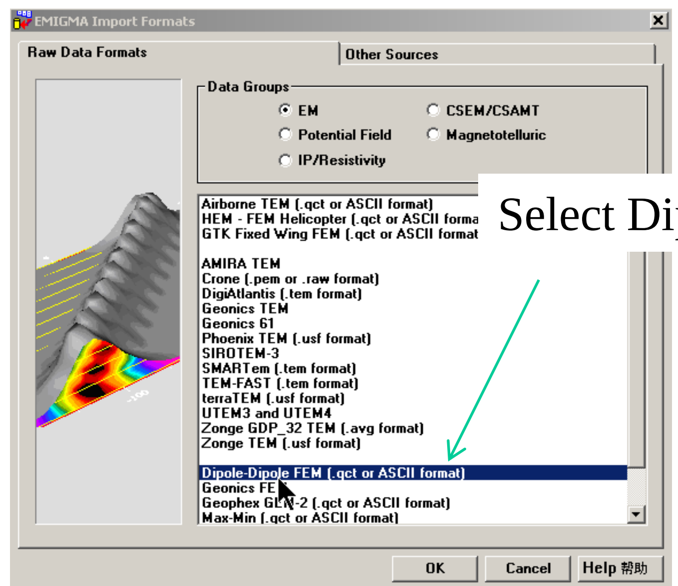
Import a dataset

Usually, Yes

2



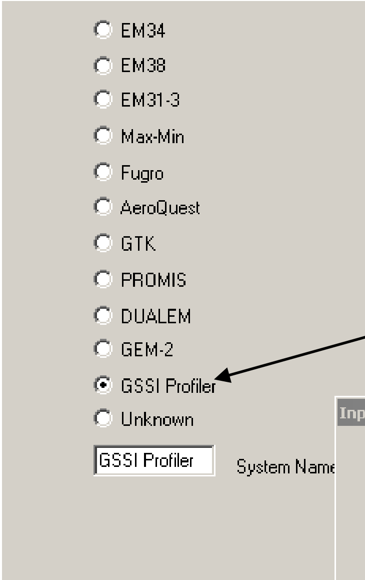
3



Select Dipole-Dipole FEM

Importing Data - 2

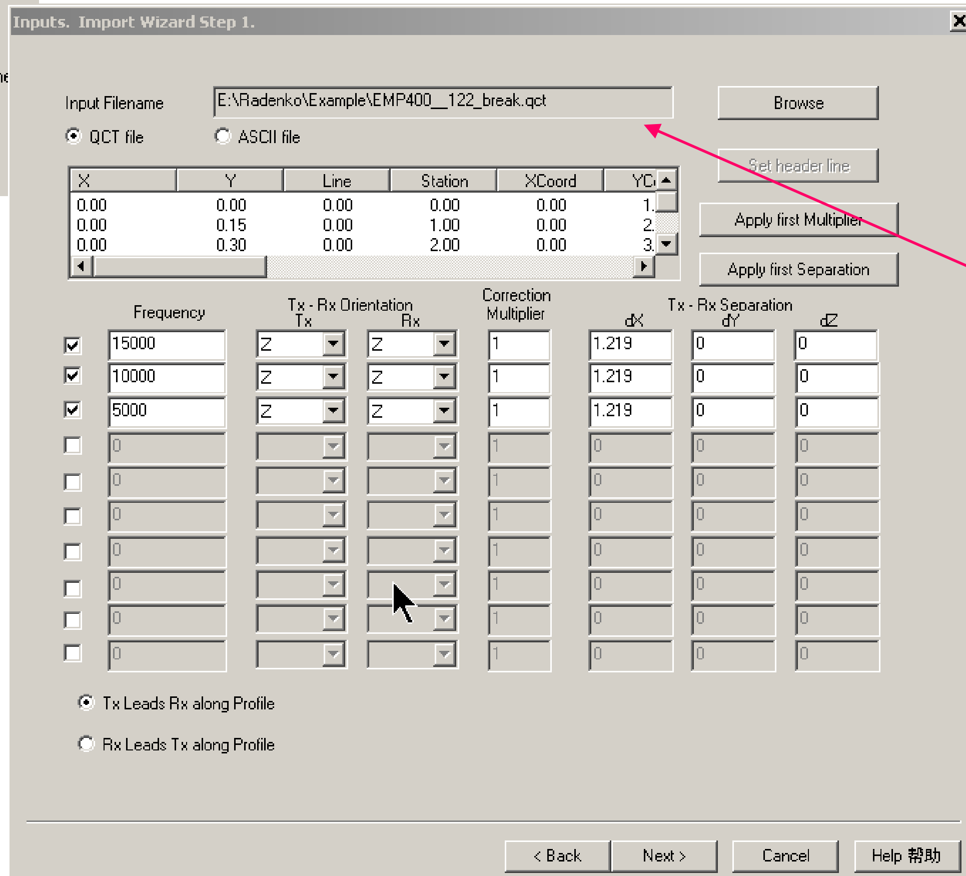
1



Select System

For other systems select *Unknown* and provide a name

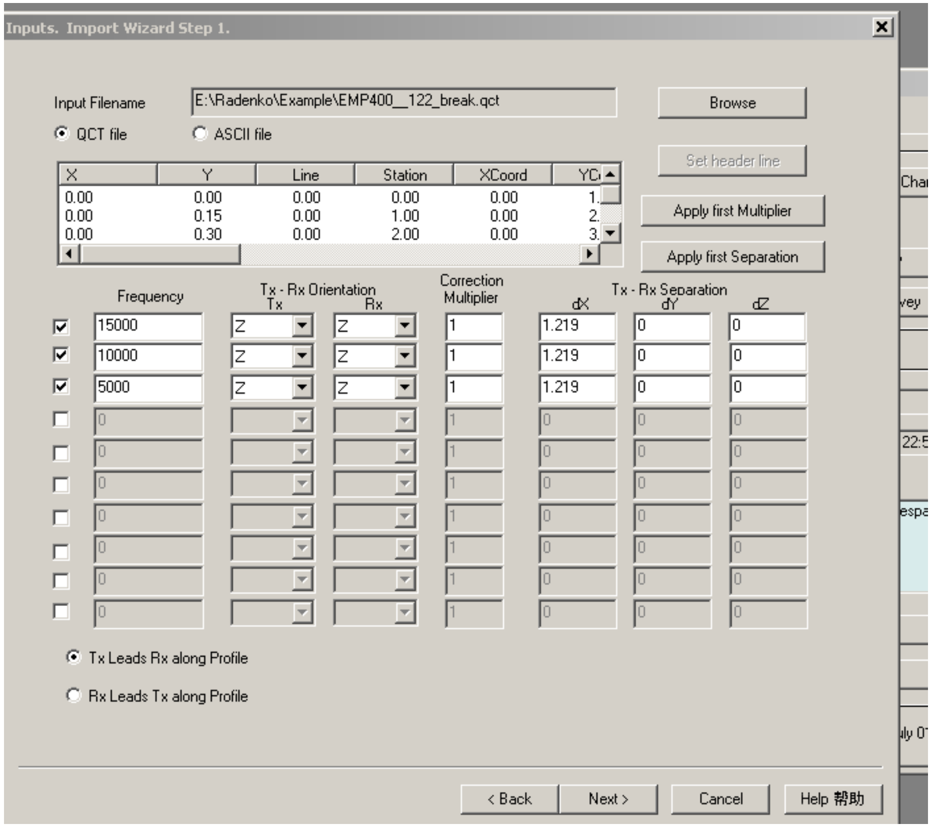
2



Browse for .qct data file

Importing Data - 3

First, import your data to QCTOOL making any changes required
Then use the .qct file for importing



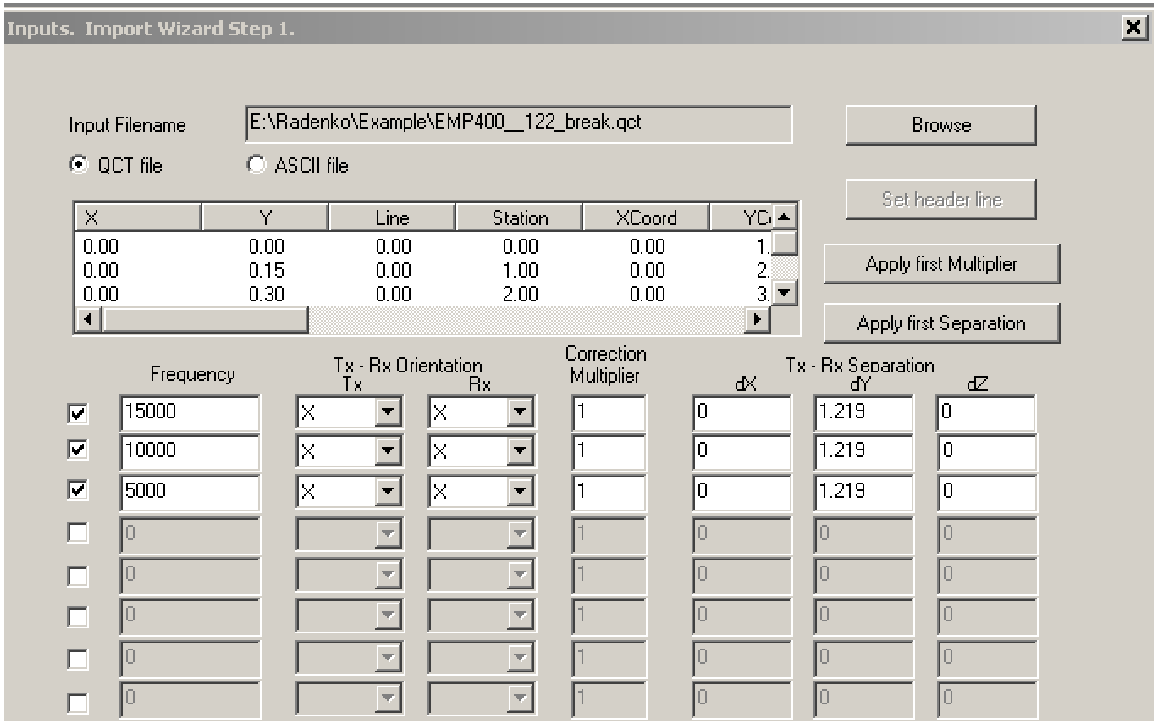
If the instrument was in the list on the first page, default settings will be made for the system configuration. Check the system configurations and alter if required.

If the instrument was not included in the list, then all settings must be made manually. Contact **support@petroseikon.com** to have your instrument added to the instrument list.

In this case, there are three instrument configurations. All three are HCP and thus the dipole settings are Z for Tx and Z for Rx. All three configurations have the same separation between Tx and Rx at 1.219m. But, each configuration is collected at a different frequency. This interface allows you to define any dipole-dipole instrument configuration.

Transmitter and Receiver location on the instrument is set by using the two choices on the lower left. If you are only considering doing 1D inversions, this issue is not relevant but for 3D modeling and 3D plate inversion this issue is critical. The Tx is usually at one end of the instrument and the Rx's are located down the instrument. Whether the instrument is carried or pulled with the Tx in the front as you move or behind is being defined by this selection.

Importing Data - 3b

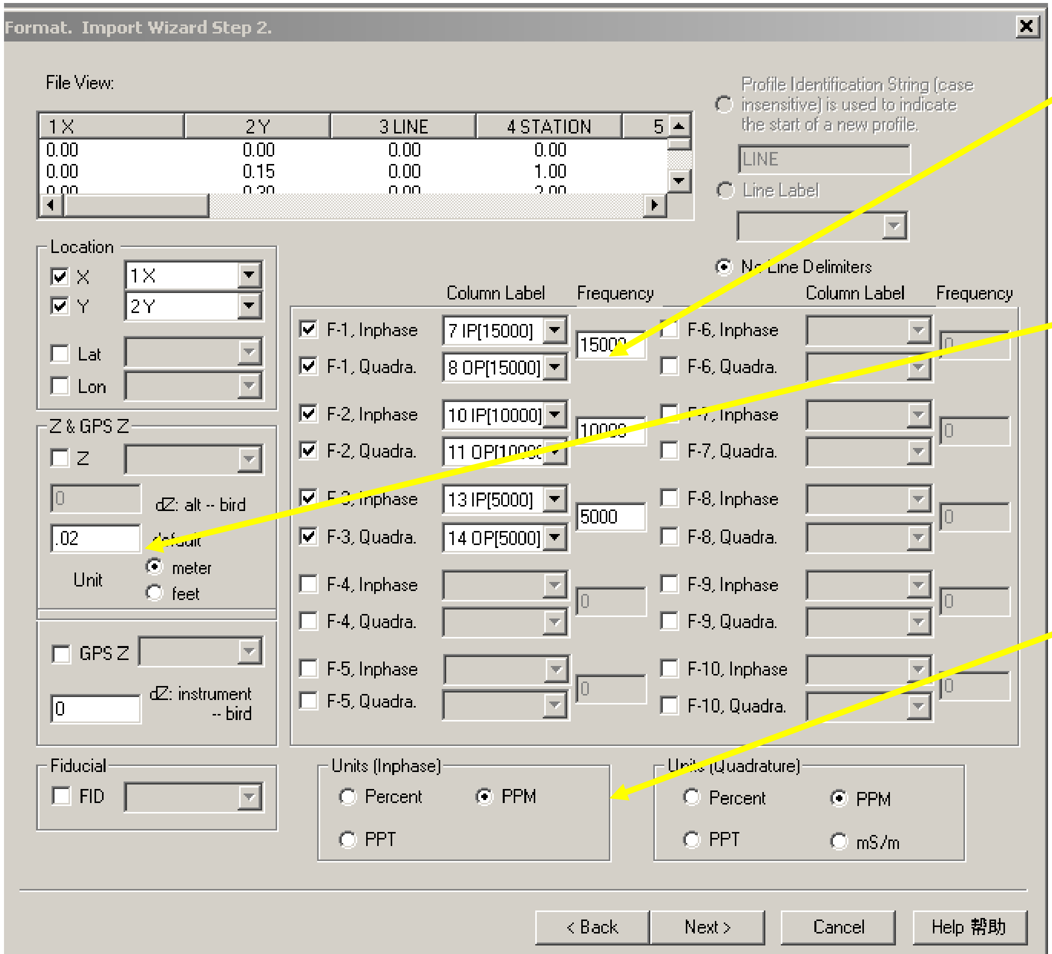


In this case, the instrument is in VCP mode with a broadside separation. Thus, the instrument is turned on it side towards the direction of movement and held perpendicular to the direction of traverse.

Note 1: Dipole orientations may be X,Y, or Z. These are in reference to the 'Horizontal" co-ordinate system (Manual). For example, Z-Z is horizontal co-planar and Y-Y or X-X or vertical coplanar. Y is perpendicular to line and X is tangential to the line.

Note 2: Separations may be dX, dY or dZ. dX is along line while dY is across line. For example, a dipole configuration with X-X and a separation of (0,dy,0) is vertical co-planar 'broadside'.

Importing Data - 4



Check that the import has recognized the columns correctly. If the instrument is not on the list, then the correct channels need be selected for each data component and IP and Quadrature.

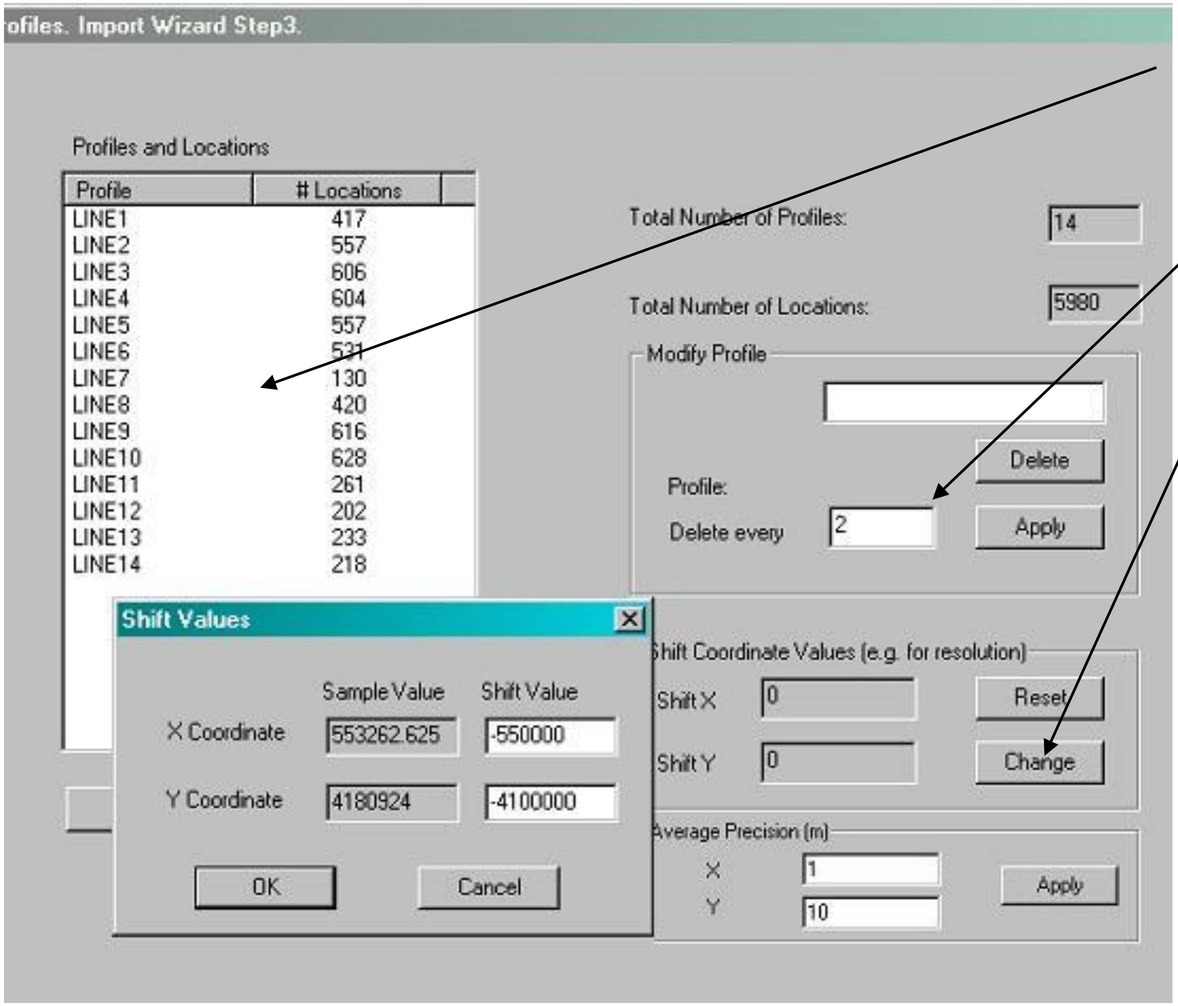
Set the height (clearance) of the instrument if there is no altimeter channel. If the instrument has GPS then a GPSZ channel should be available. Similarly for Lat/Long and station label (FID).

Check the data units for the instrument

Note:

mS/m is not an actual data unit. The data has been converted by the instrument manufacturer through an approximation to this unit. EMIGMA converts it back to the original data units. You may later display in these approximate units.

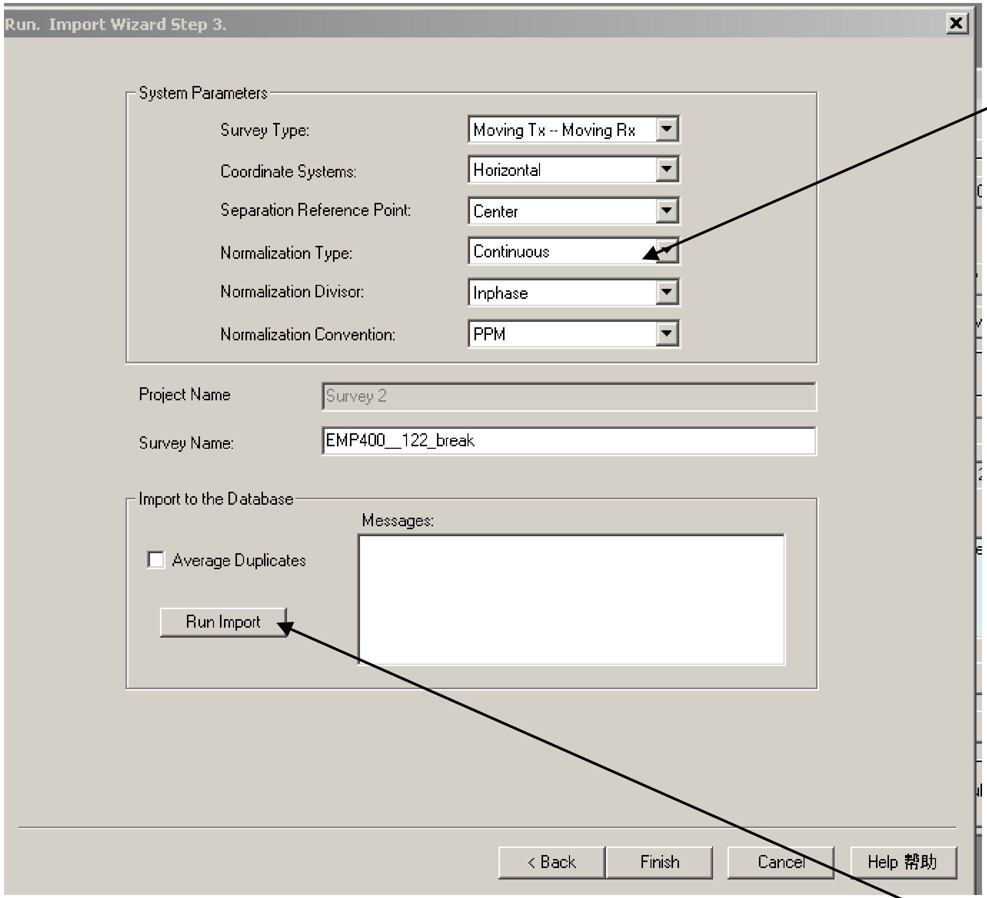
Importing Data - 5



You may choose not to import all profiles or decimate the data. But, both of these operations can be performed once imported to the database.

In addition, if you require sub-metre accuracy in your data positioning you may wish to strip off the leading numbers of the UTM positions. The import handles the coordinates in double precision but the database is a single precision data structure.

Importing Data - 6



Here, we are defining several important factors in the instrument design.

Co-ordinate System: This is not the data location coordinate system but the coordinate system associated with the moving instrument. We discussed earlier the Horizontal co-ordinate system. But, if this were a borehole instrument then the coordinate system would be Bhole.

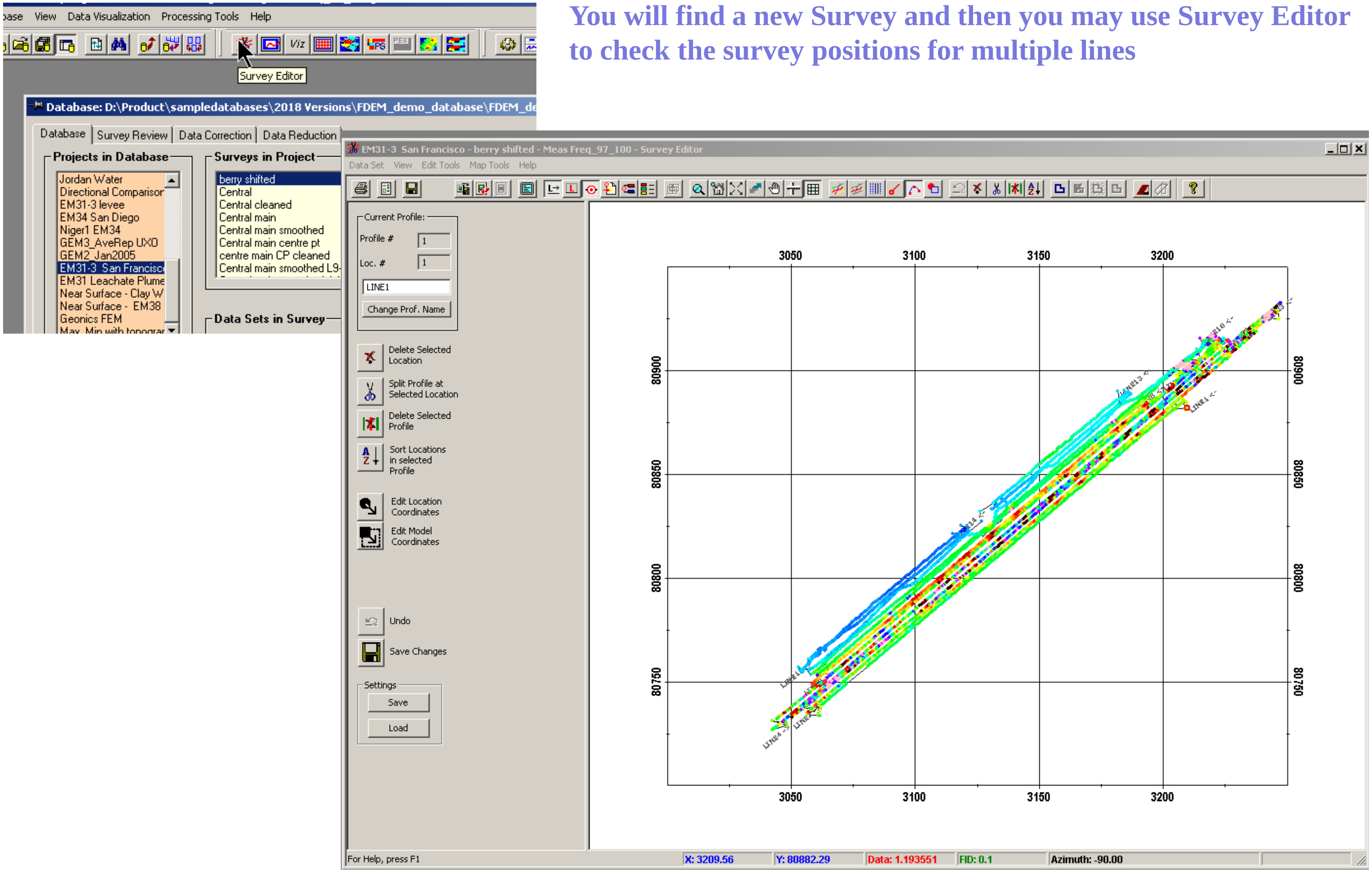
Reference Location: Here, we are defining where on the instrument the coordinates of the station are relevant. For example, are the coordinates that of the Tx, the Rx or the midpoint between Tx and Rx. In this case, there is only one TX-RX separation and thus the reference point is probably at the center. If using an EM31-R, then your data is probably positioned at a common Tx reference point. This is because the data is collected from a common Tx antennae

Normalization Divisor: Is the amplitude or inphase or quadrature of the primary field or freespace field being used as the normalizing value.

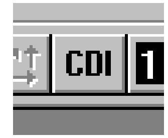
Run Import:

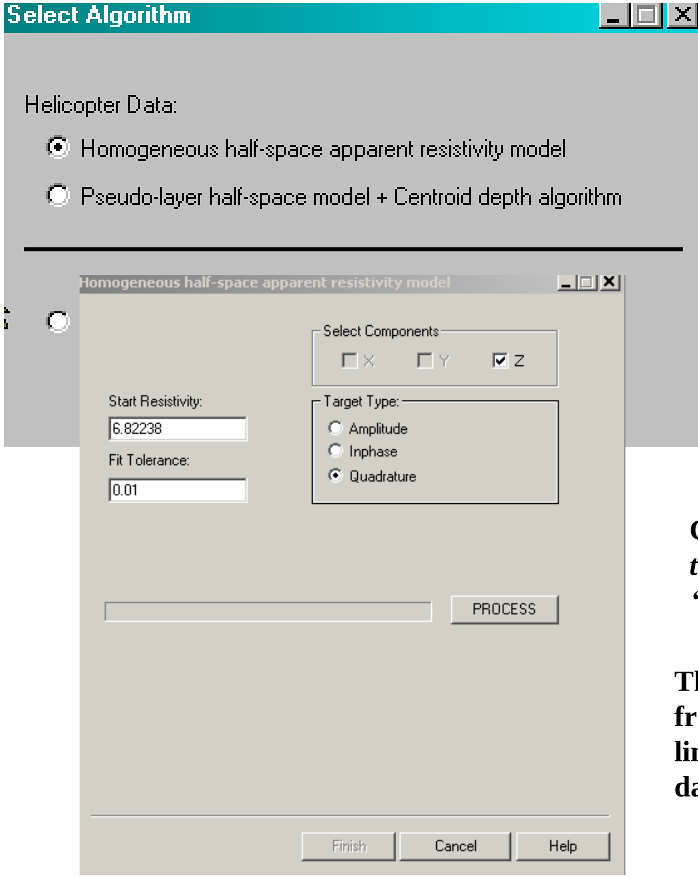
Importing Data - Final

You will find a new Survey and then you may use Survey Editor to check the survey positions for multiple lines



Calculating Apparent Resistivity



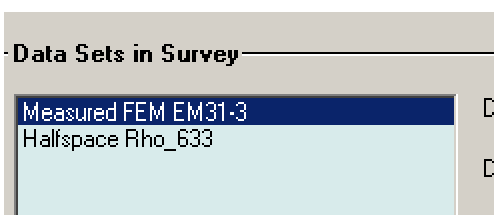


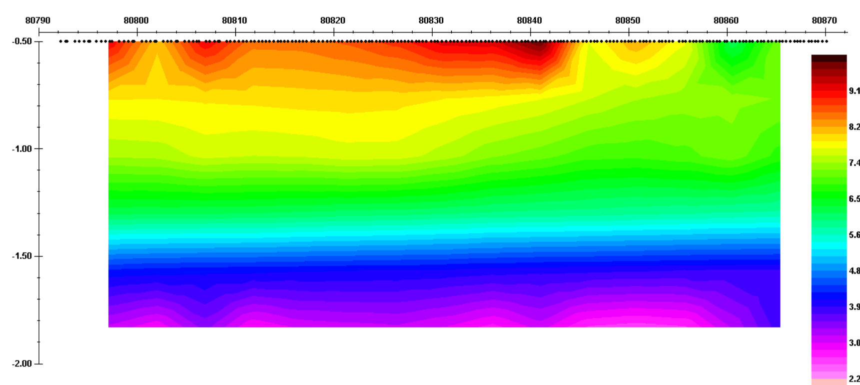
The approximation used on pg5 by several instrument manufacturers in their output data is a suitable approximation under certain very limited circumstances. In this application, for each frequency and each component, a half space inversion is performed. This inversion is not limited to elevation or ground resistivity but is only limited to approximating the response as a halfspace. This approach was widely used when towed airborne FEM dominated airborne EM exploration.

Calculate the best fitting half-space ρ_{app} for any dipole-dipole configuration and frequency, airborne or ground. This will give you a more reasonable estimate of the ground resistivity. The second option is for airborne data only, fixed wing or towed helicopter.

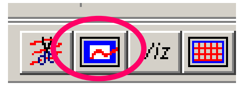
Calculate the best fitting half-space ρ_{app} choose which data elements to use. ***e.g. for EM34 then Quadrature is default. In some cases, the real and imaginary parts of the signal get 'mixed' due to calibration issues. In this case, you might try amplitude.***

This will process multiple components (ie. dipole-dipole configurations, lines and frequencies. A new dataset is output containing the apparent resistivities for all stations, lines, configurations and frequencies. [*e.g. Halfspace Rho_633*] as well as the simulated data for the halfspace. The ρ_{app} data may be loaded to the pseudosection tool.

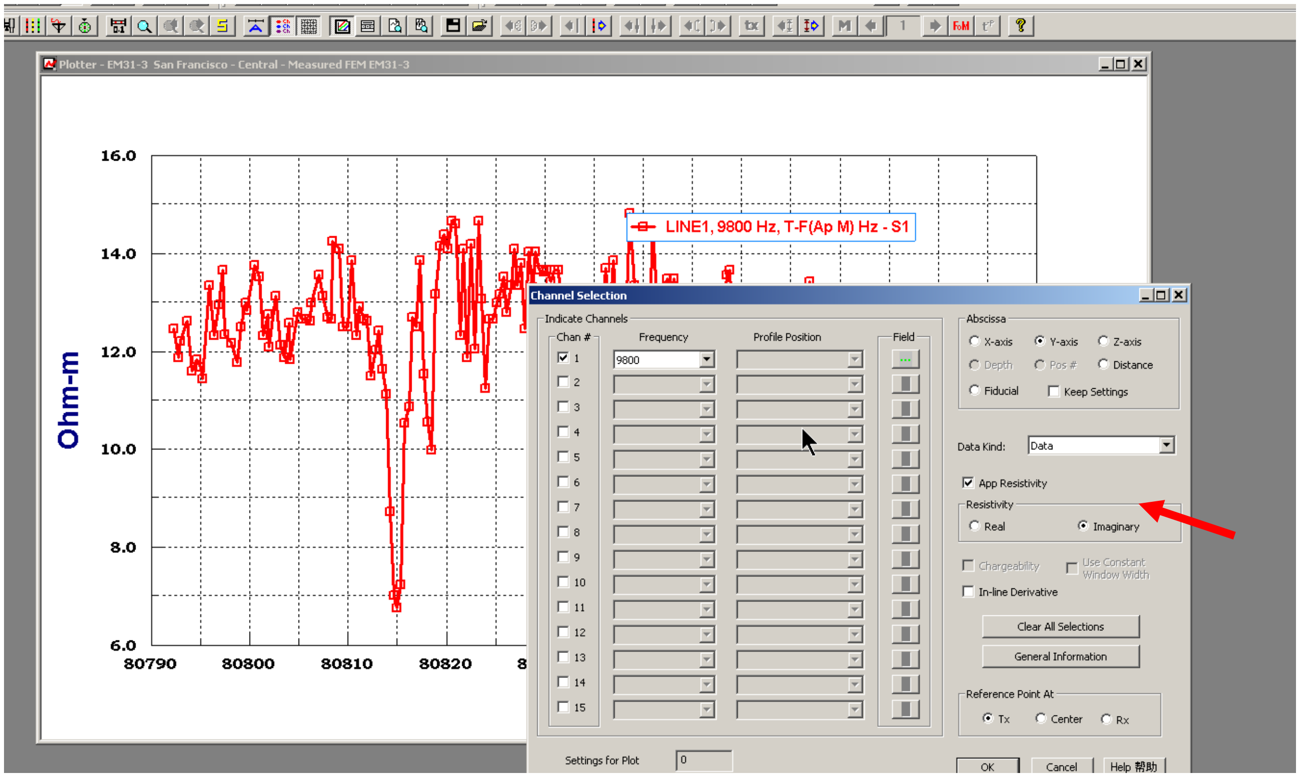




Plotting Data - 1



(*see **EMIGMA** tutorial for more details*)



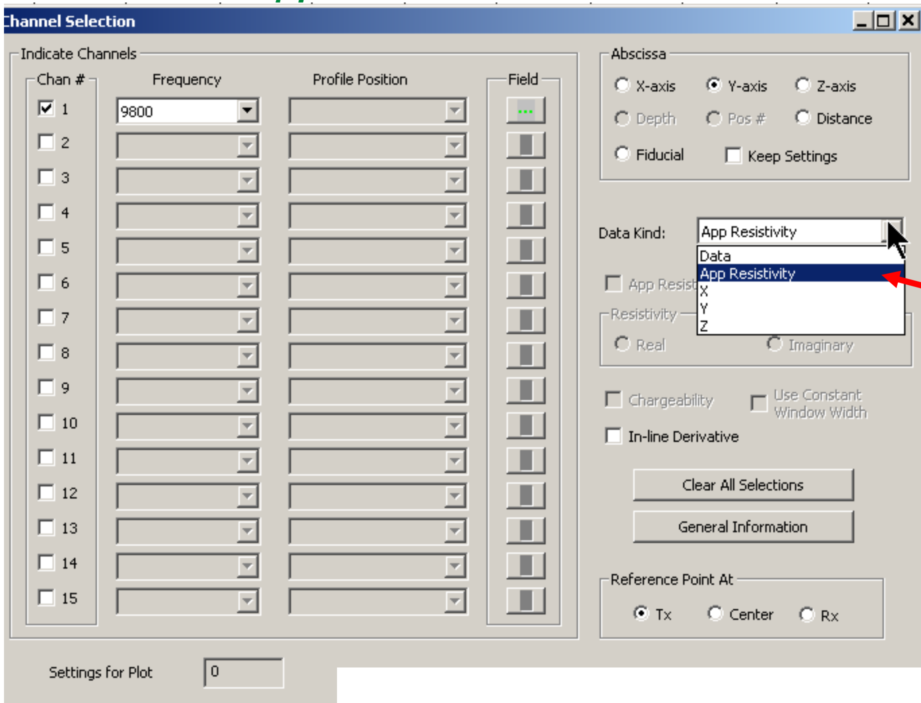
ρ_{app} display

converts normalized data to ρ_{app} through short separation algebraic formula (pg5)

for apparent conductivity display:

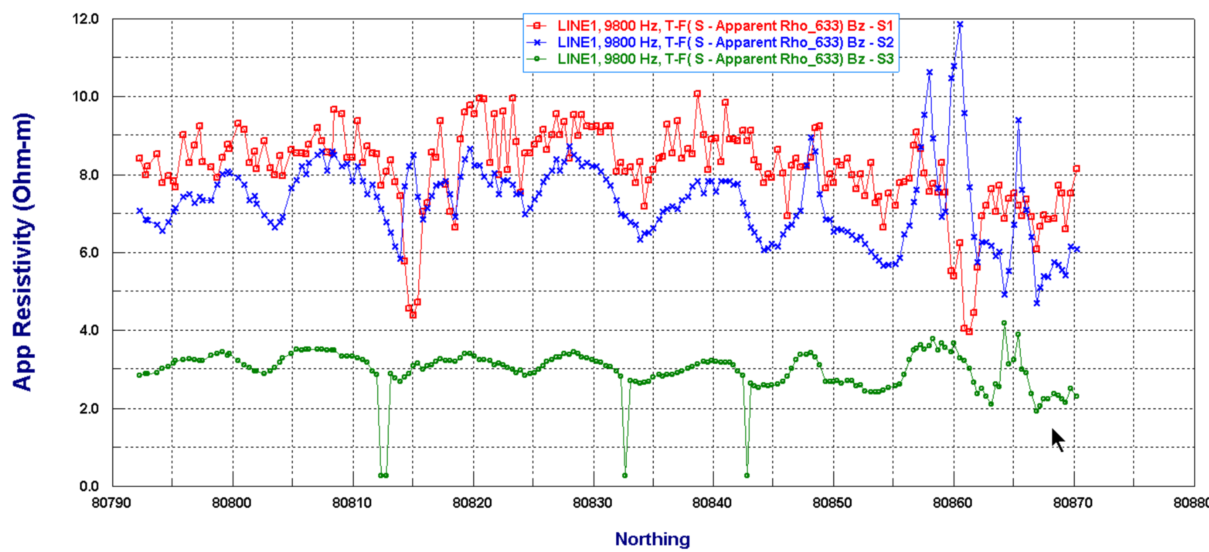
Settings ► *Custom* ► *App Conductivity*

Plotting Data - 2

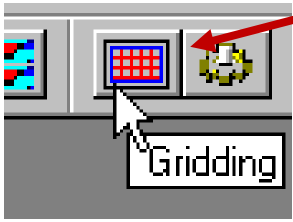


ρ_{app} display

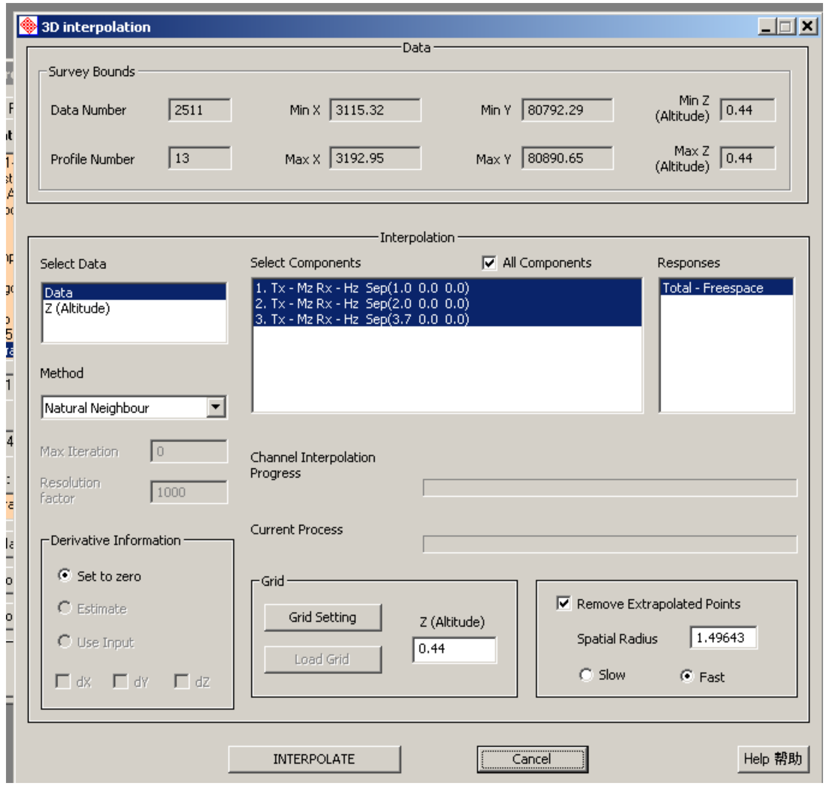
displays calculated best fit apparent resistivity



Gridding data - 1



Interpolate to Grid, *interpolate onto a regular grid*



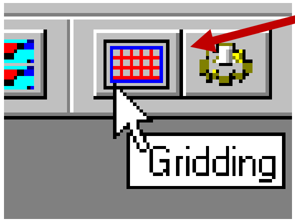
Select Components

Select Interpolation app

Select Extrapolation removal

Set Grid Settings

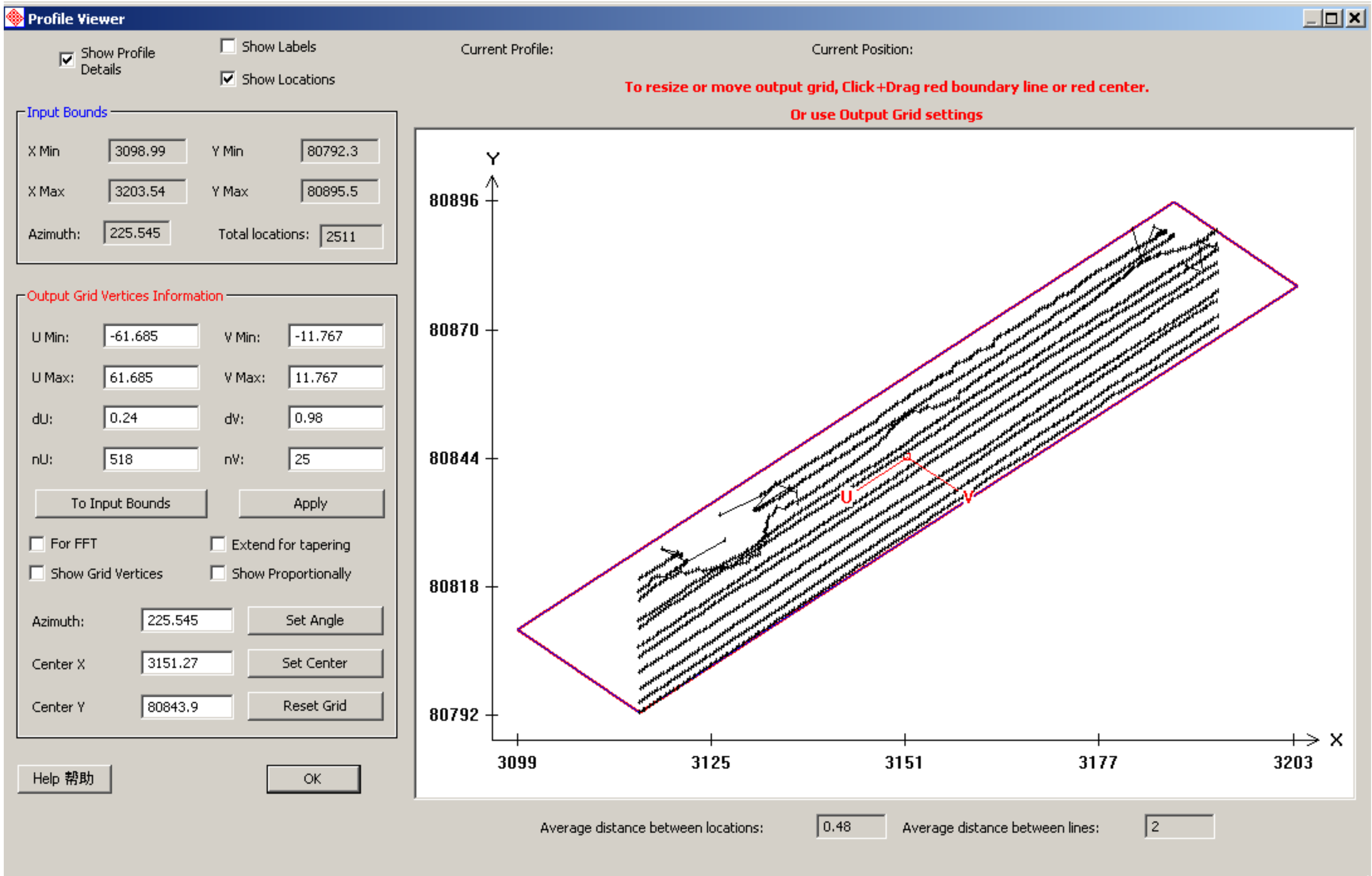
Gridding data - 2



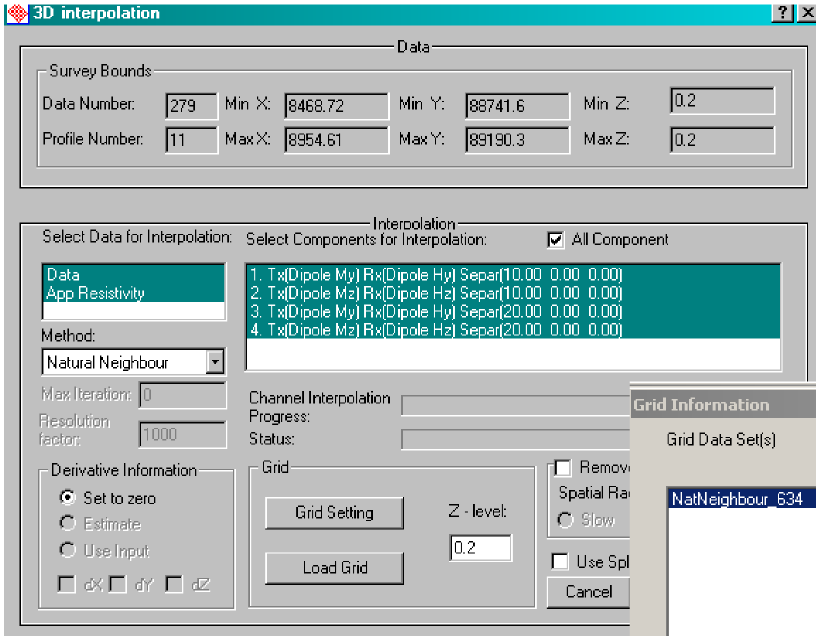
Interpolate to Grid, *interpolate onto a regular grid*

Set Grid Settings

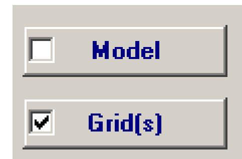
Select
- grid azimuth
- grid centre
- inline and crossline resolution



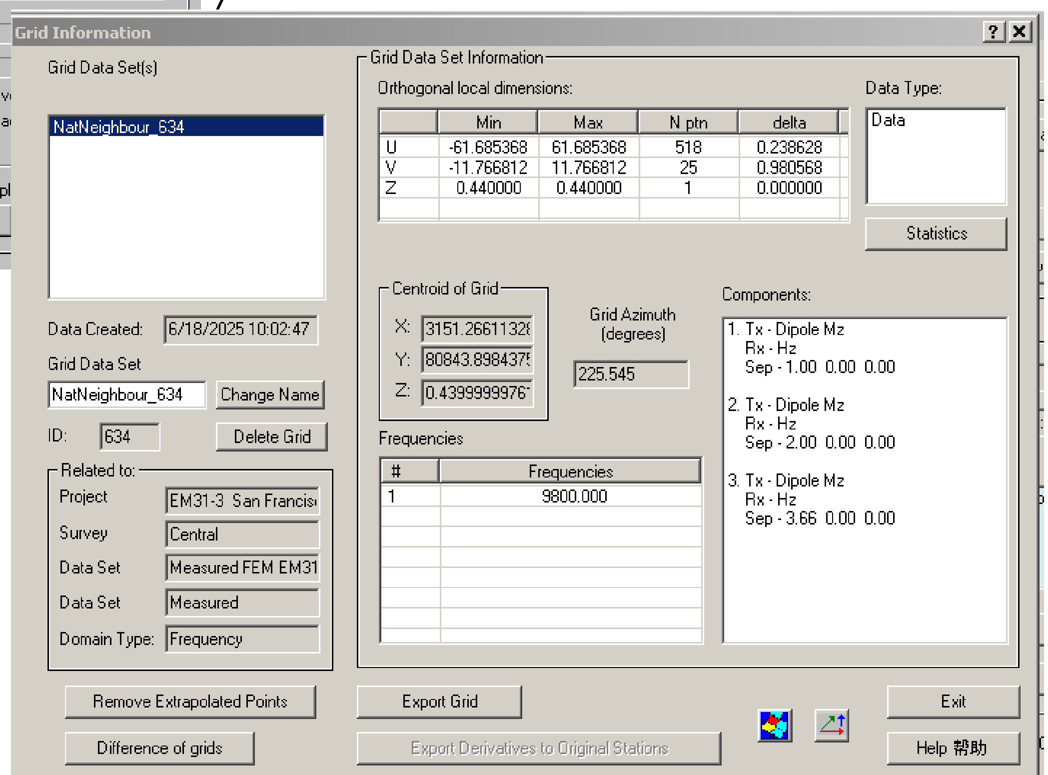
Gridding data - 3



Interpolate to grid



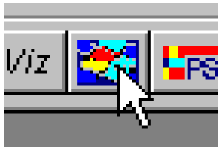
View Grids



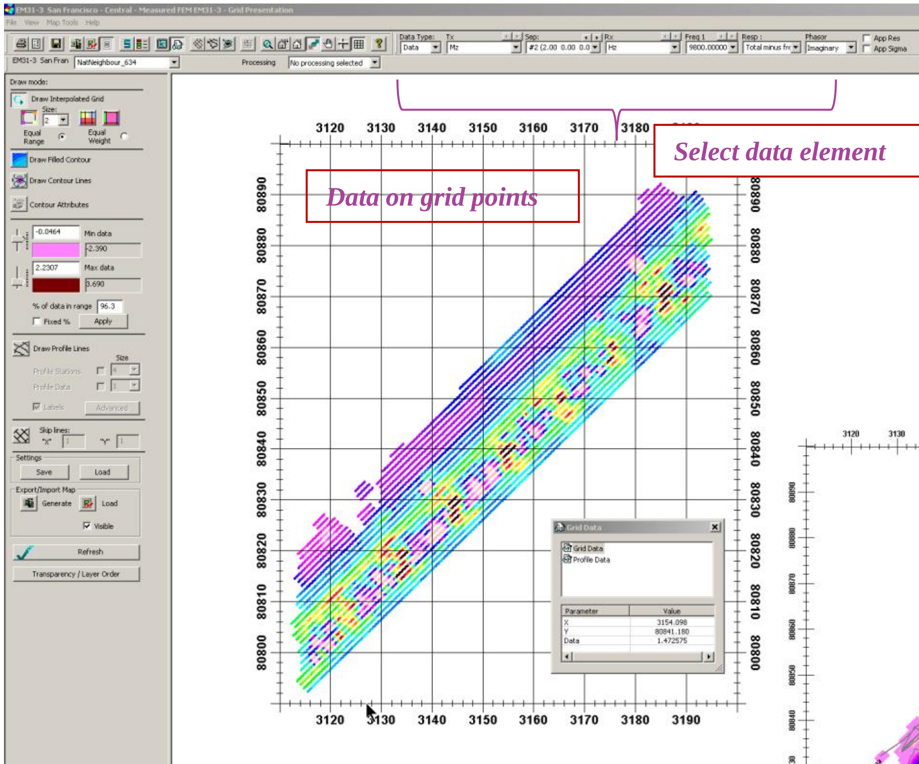
view grid characteristics
- process and export

Viewing Gridded Data - 1

EMIGMA works with multi-layered grids which means more than one data element can be stored in a grid.



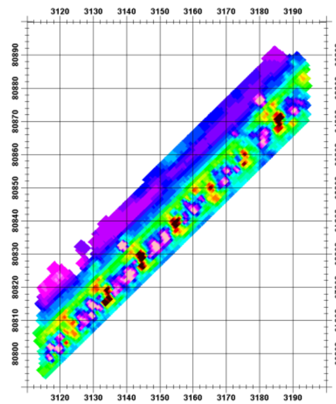
Grid Presentation



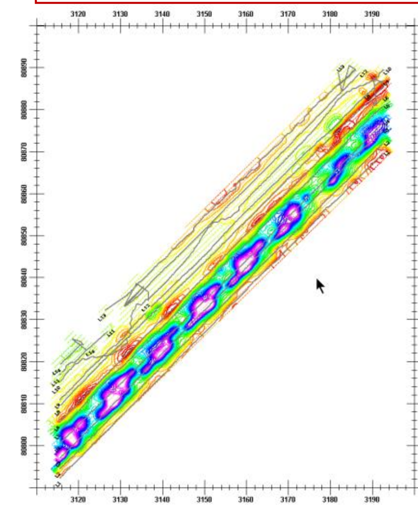
Select data element

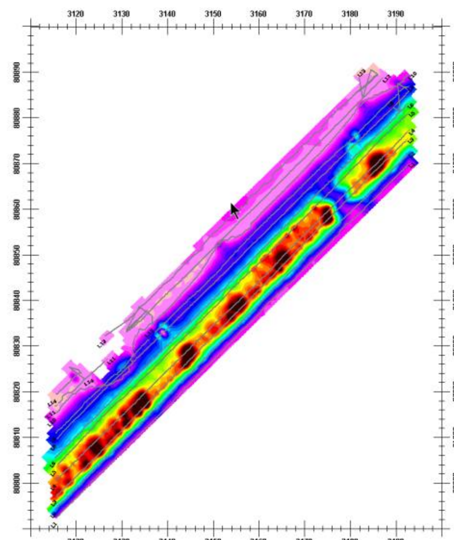
Data on grid points

Filled grid cells

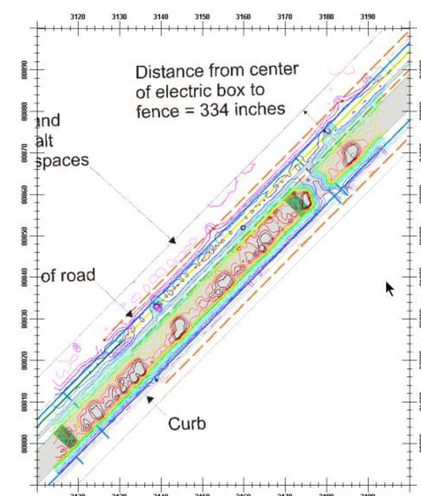


Grid points plus contour lines



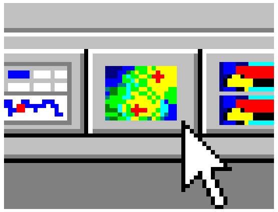


Filled Contours

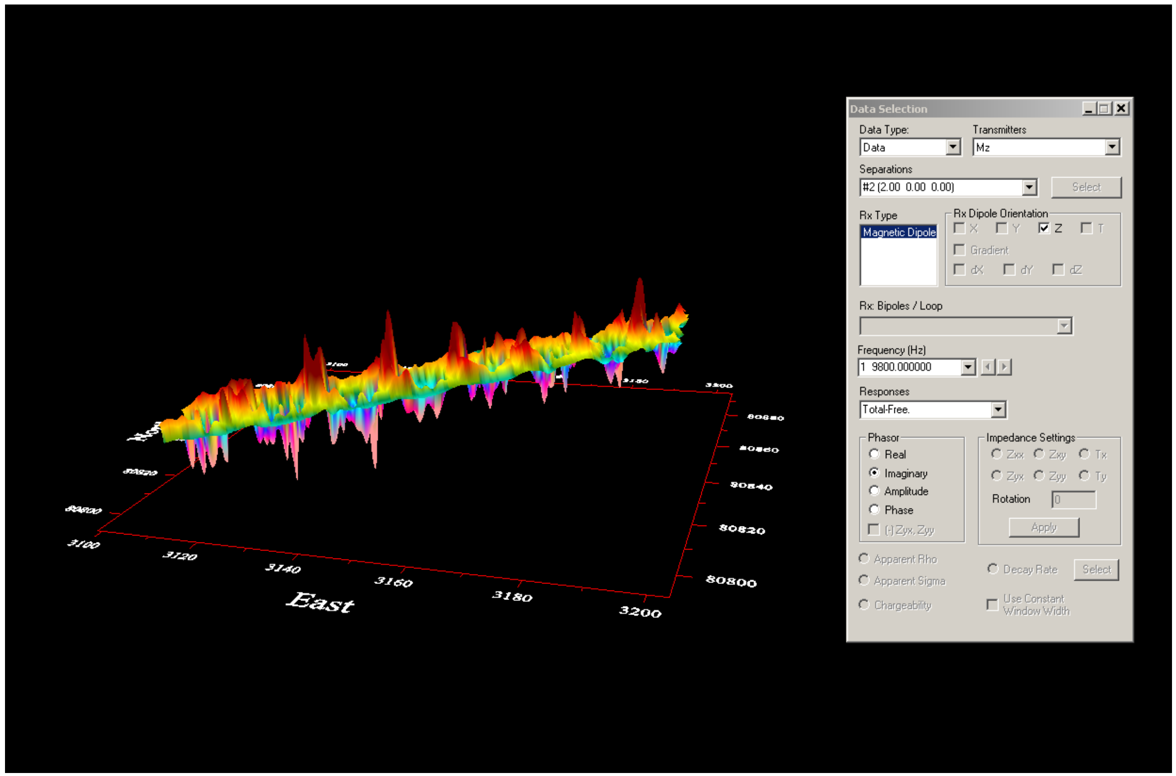


with map underlay

Viewing Gridded Data - 2

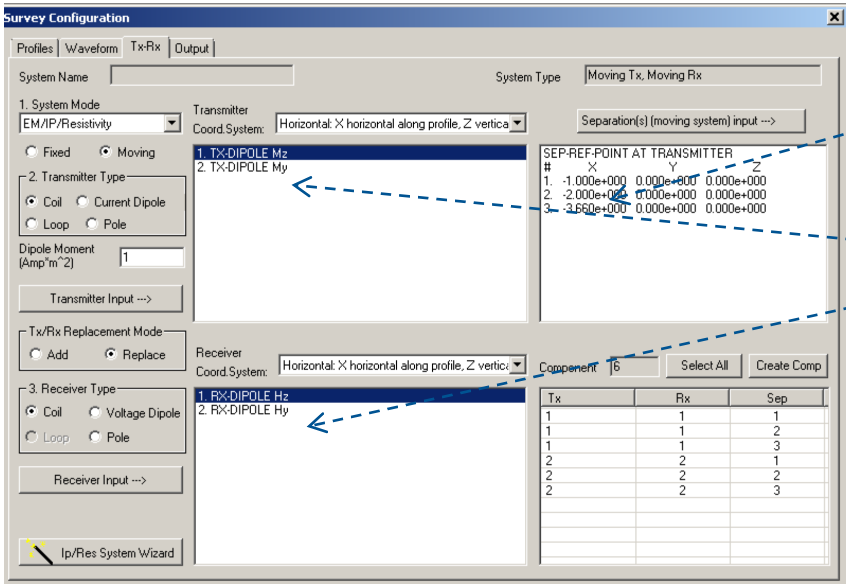


3D Contour



1D FEM Inversion – 1
System Configuration

This example is an EM31-3 survey over a levee in the southern US.



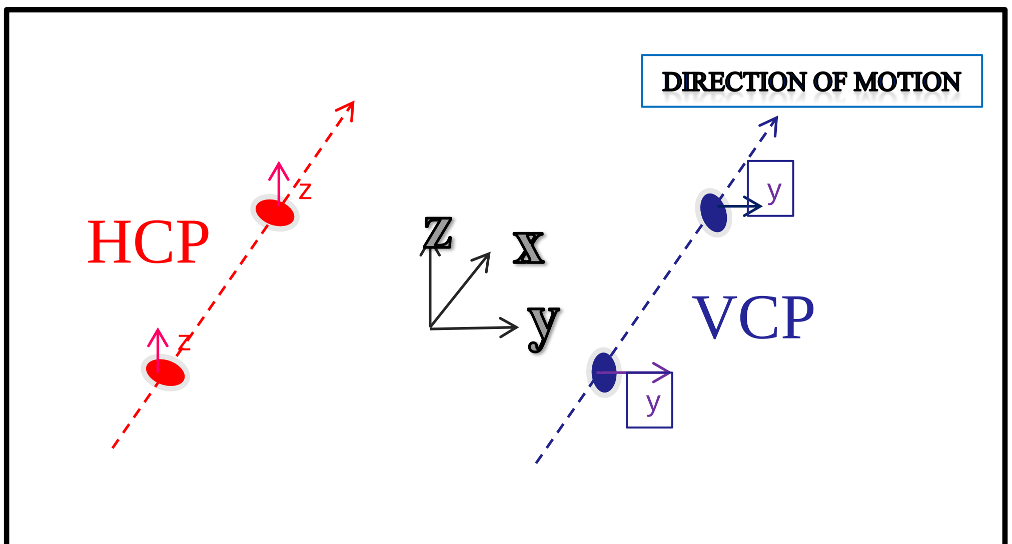
Two Tx-Rx configurations, 3 separations all at 9800Hz towed array, Tx at back of coil's cylinder

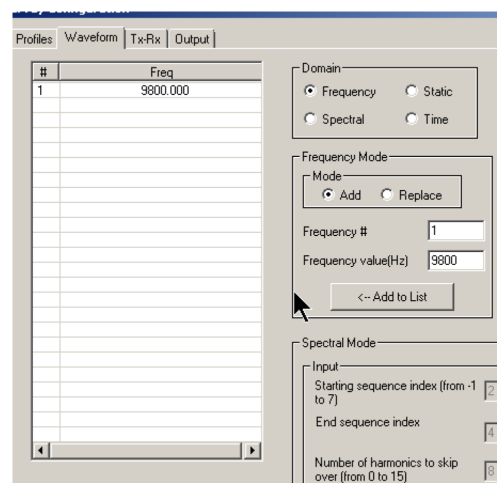
Separations – Rx leads Tx along profile station coordinates reference is at the transmitter

TX's – instrument coordinate system - HORIZONTAL RX's

COMPONENTS - ***in EMIGMA a component is the definition of physical (geometric) configuration is this case each component consists of***

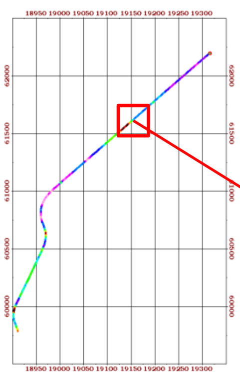
Tx_i with Rx_j with $Separation_k$

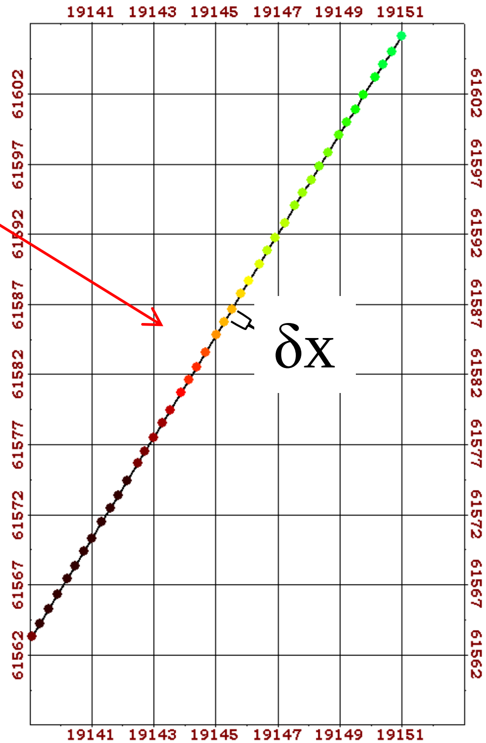




1D FEM Inversion – 2
Data Resolution

This example is an EM31-3 survey over a levee in the southern US.





A survey line is shown to the left. With the system set as horizontal, the tangent to the profile in the direction of motion is always defined as the x-direction, y is perpendicular and horizontal and z is up.

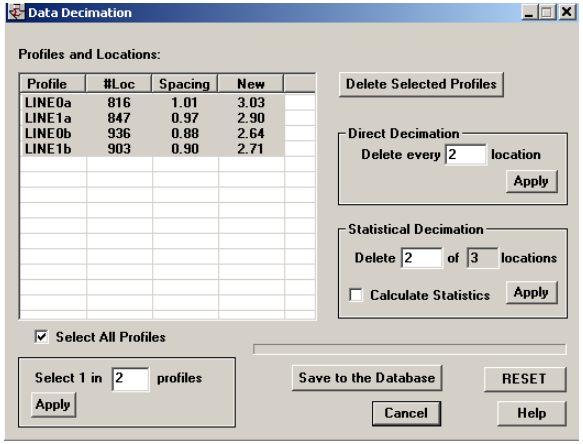
A section of the profile is zoomed into and shows the average distance between stations as δx ≈ 1. The separations between Tx and Rx are 1m, 2m, and 3.66m and the instrument is elevated at 0.42 above the ground.

Average δx ≈ 1

Statistical Decimation: The data sampling is too fine at 1m spacings particularly for the 3.66m separation configuration. In this case, we suggest applying a statistical decimation. This algorithm takes data in a moving window and estimates the mean within the window based upon a Gaussian distribution. The value at the center point in the window is replaced by the mean and the remaining stations are deleted. An error estimate can be saved for each remaining station. This is performed on all the data elements and frequencies.

Statistical Decimation: For each profile, the number of data stations and the average station spacing is given. Under *Statistical Decimation* define your window width. In this case, the window width is 3 stations and the new station spacing is provided (≈3m). If you wish to store the estimated variance then select *Calculate Statistics*.

This tool can also do standard decimation as well as decimate profiles.



This app is found in the data and model processing toolbox under Survey Editing.

1D FEM Inversion – 3

Data Calibration - A

This example is an EM31-3 survey over a levee in the southern US.

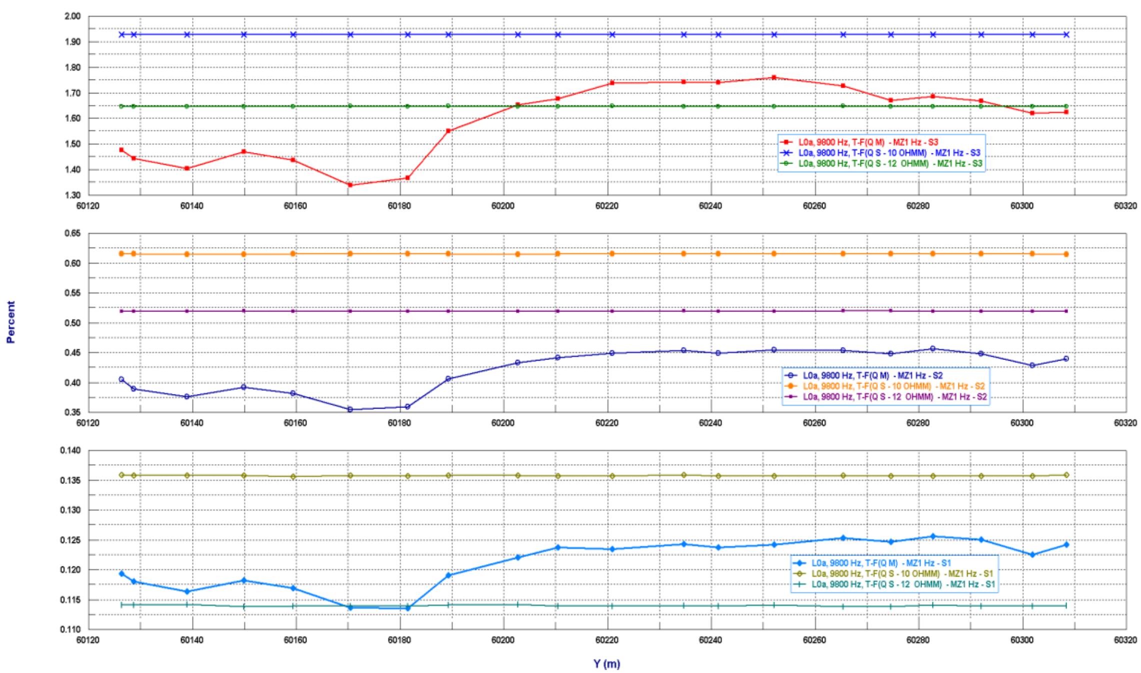
In theory, this survey would have 6 data measurements available for inversion at each station. The more data for an inversion, the higher the resolution and the greater the assurance of a correct model. Correct can be in regard both to data quality and the limitation on the number of possible models (i.e. degree of non-uniqueness).

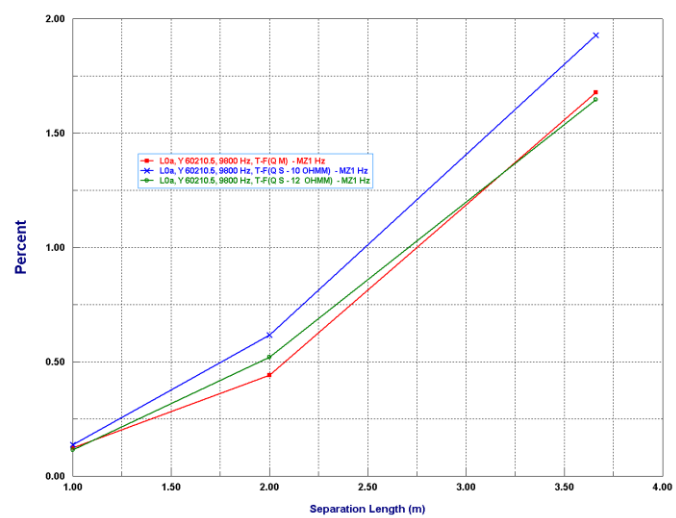
A longtime problems with FDEM systems is their tendency to become *out-of-tune*. We use this term as an analogy to a musical instrument particularly string instruments. The instruments are very sensitive to improper handling and of course, they can be returned to the manufacturer for tuning or learning to tune the equipment yourself but this is not always practical or within the user's technical capabilities.

Probably, the only practical approach is to evaluate the data calibration through some simple forward models. Such models are easily done in EMIGMA and we will use this data as an example. Initially, we would suggest taking part of line where there are no sharp obvious 3D response and then statistically decimating to get the average trend over the line.

The next step is to run a few halfspace models either staring with what you may understand already about the ground resistivity or run the CDI and use these results as a start. In the case below, we used the CDI and ran a 10Ωm and a 12Ωm halfspace model. Below, to the left, we compare the quad data and the 2 models for all separations. The 10-12 Ωm models show we are in the ball park. The figure below, to the right, shows the response comparisons as a function of the coil separation.

This study may not be entirely sufficient to check the calibration of the quadrature data but takes us to the next step where inversion is applied. However, first, we must check the IP data.





1D FEM Inversion – 3

Data Calibration - B

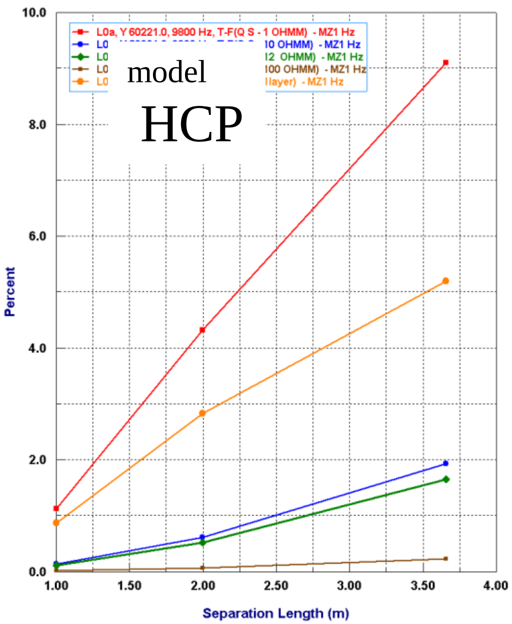
This example is an EM31-3 survey over a levee in the southern US.

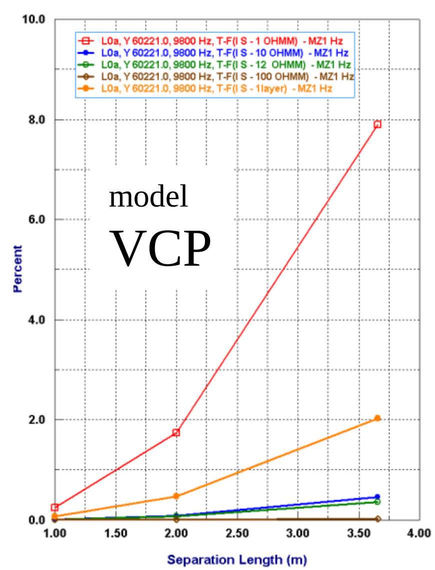
Using the Inphase (IP) is often much more difficult. Many instruments only produce IP which can be used only qualitatively.

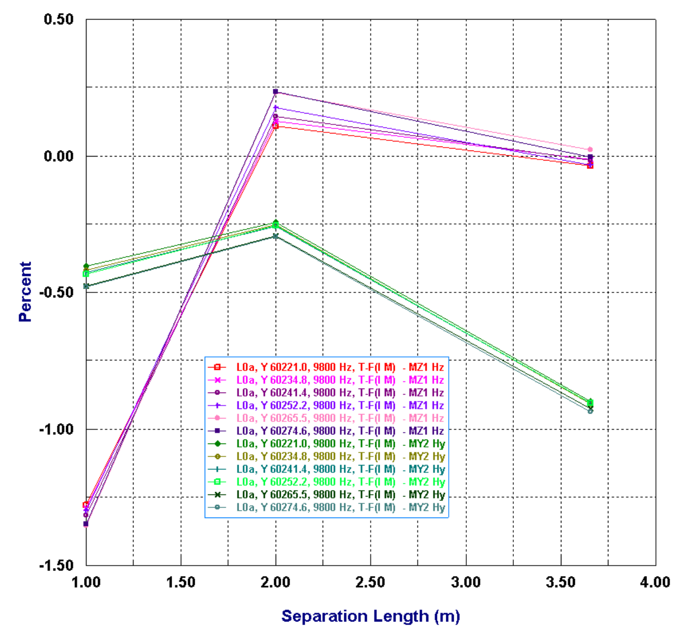
The figure at the top left is the HCP IP at 9800 Hz for the 3 separations used in this survey. The models are 1, 10, 12, 100Ωm and a layered model which is 1Ωm over 12Ωm. In the bottom centre is the same but for VCP.

As can be seen the IP responses are all positive and increase, monotonically, with separation and this is what is expected if the ground is primarily stratified. Of course, it the ground contains 3D structures whether conductive and/or magnetic this would change. The responses for the VCP are the same but the responses are slightly smaller as predicted by theory.

In the figure on the bottom right we plot the IP for all 3 separations for both HCP (pinks) and VCP (greens) at 7 stations ranging over 50m. The IP neither follows the model examples nor are the VCP and HCP related to each other as expected in a stratified earth. Additionally, the IP for both HCP and VCP start negative at the 1m separation. The VCP is negative for all 3 separations and the HCP's IP response drops to near zero for the 3.66m separation.







Data

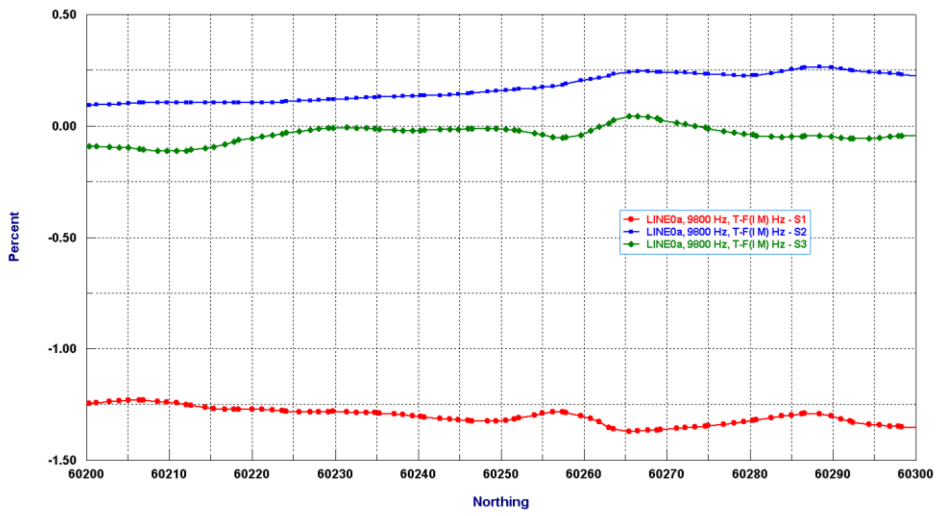
HCP & VCP

1D FEM Inversion – 3

Data Calibration - C

This example is an EM31-3 survey over a levee in the southern US.

If we plot the data IP for all 3 separations over a slightly larger distance than in the figure on the previous page, we see that there is no obvious higher dimensional response in the IP data.

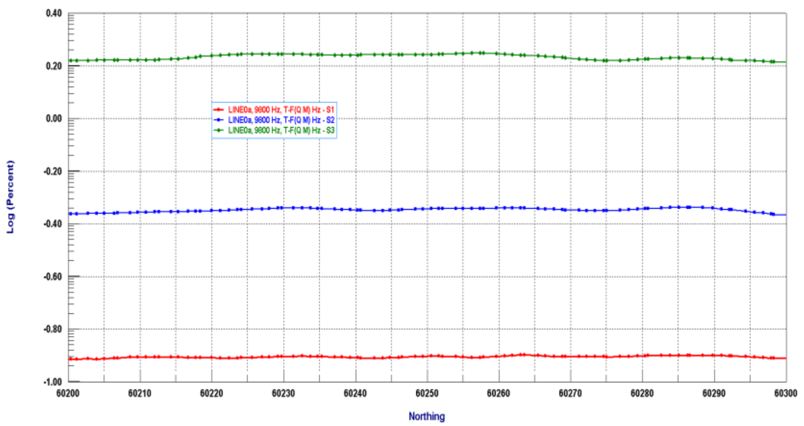


The figure on the left is the IP for the 3 separations (1m –red, 2m –blue and 3.66m green). There are not strong variations in this data over this 100m but there is a trend in both the 1m and 2m data.

The VCP data has much the same variations over this section of the line. The difference being the 3.66m separation is by far the strongest component in the VCP data while this separation is the smallest in the HCP data.

For additional confirmation, we show the quadrature data over this 100m section of the data (below). The quadrature shows a very smoothly varying 1D response.

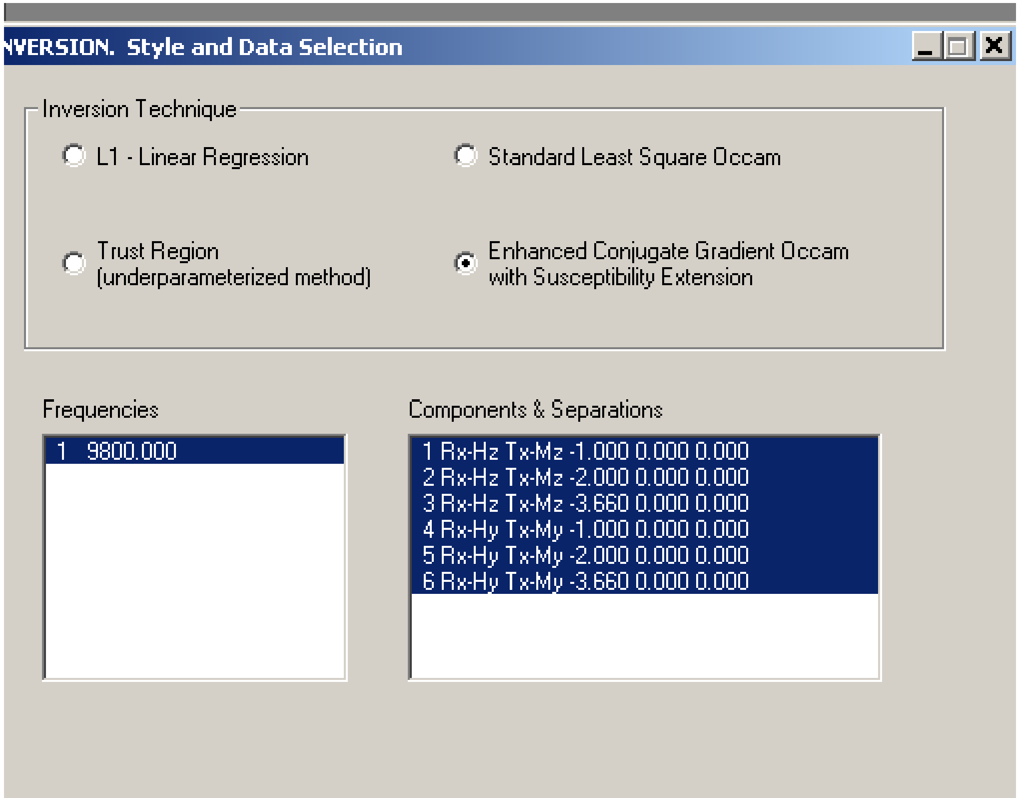
The results are similar over other sections of the survey that we have analyzed.



<u>CONCLUSION</u>: The initial analyses indicates that the 3 quadrature data elements may be used in an stratified layered earth inversion (1D) but the IP data cannot be used in such a process.

1D FEM Inversion – 4 using the tools 1

4 inversion algorithms are provided. However, the two at the top (*L1 and Standard LS Occam*) are provided primarily for student exercises.



The two choices in the bottom are

-Trust Region: steepest descent fully constrained technique

-Enhanced CG Occam – smooth model technique

Choose frequencies to use and data components to use. In this case, only 1 frequency but 6 components – 3 HCP and 3 VCP.

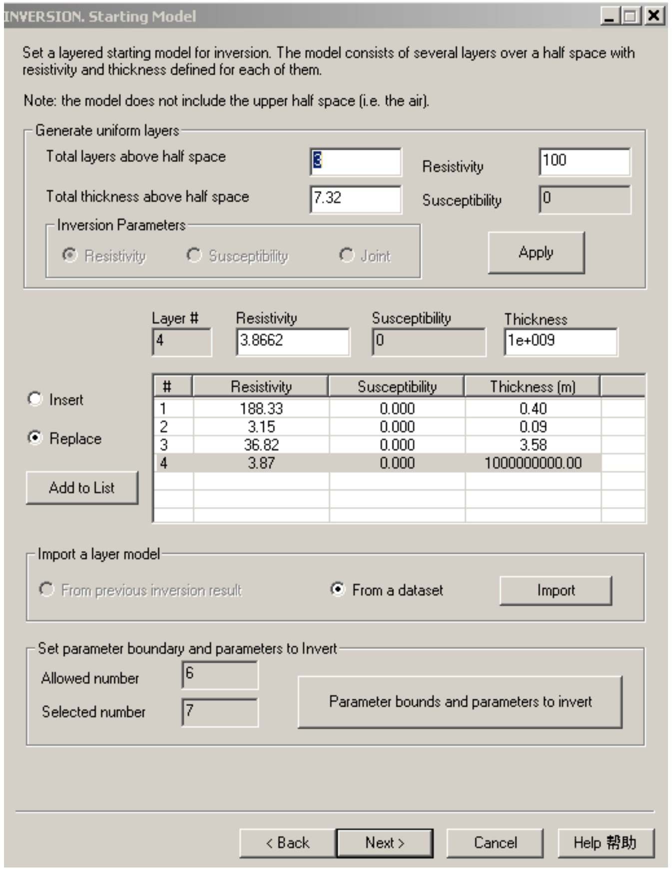
Trust Region: **thickness and resistivity are model parameters. Allows inverting for a realistic number of layers and obtaining exact depth within the limitation of data quality. This is our suggested technique as it is the technique most likely to obtain a unique solution.**

Enhanced CG Occam: **In regard to the layer thicknesses, this is a standard approach where only the resistivities are inversion parameters. This technique allows for highly over parametrized model which are thus highly non-unique solutions. Assuming the Inphase data is good, this technique can also invert for susceptibility**

1D FEM Inversion – 4 using the tools 2a

The two choices in the bottom are

-Trust Region: steepest descent fully constrained technique example



-this is the data that we have examined, previously, and will first use the Trust Region approach.

- in this case, we have imported a starting model obtained via trial forward simulations as well as trial inversion
- it is a 3 layer over a halfspace model and this model will be the starting model for each station (unless modified in a later dialogue)
- initially, we have 7 parameters to invert with 6 data. While overparametrization is allowed this increases the possibility of non-unique models.

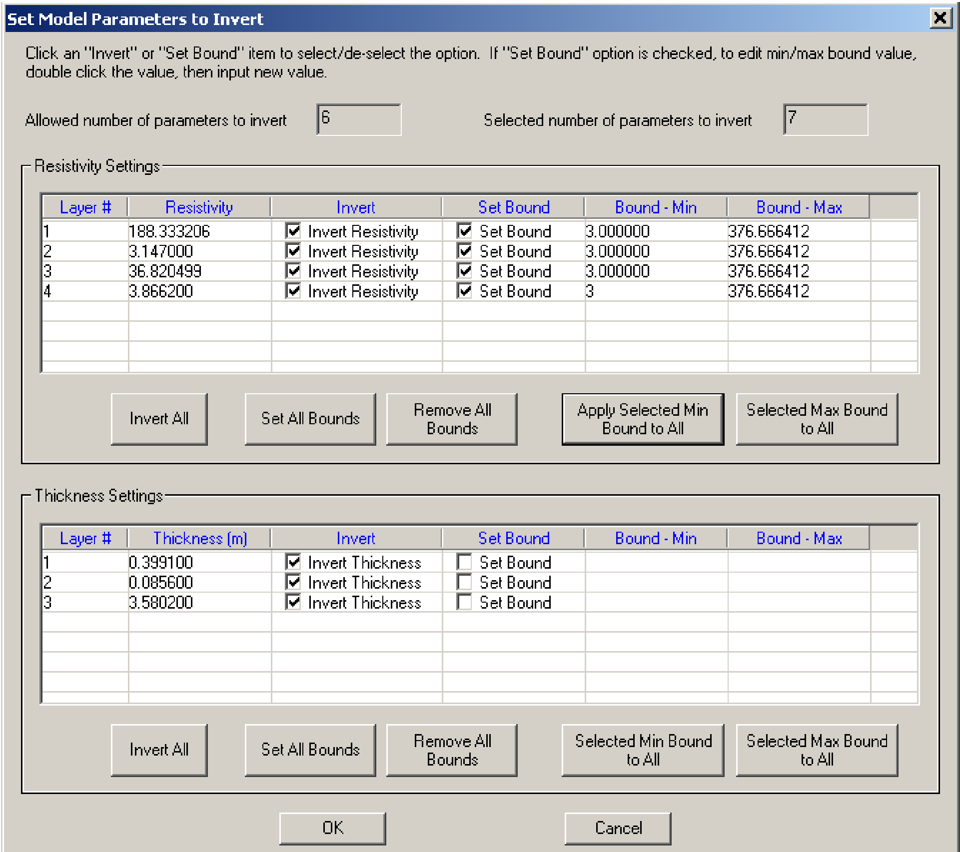
-we can now add extra controls using the

- “Parameter bounds and parameters to invert”

Trust Region: thickness and resistivity are model parameters. Allows inverting for a realistic number of layers and obtaining exact depth within the limitation of data quality. This is our suggested technique as it is the technique most likely to obtain a unique solution.

1D FEM Inversion – 4 using the tools 3a

-Trust Region: steepest descent fully constrained technique example



Of course, being able to control the inversion with known information not only improves the inversion results but increases the likelihood of obtaining a unique result. This type of data is highly susceptible to multiple models fitting the data.

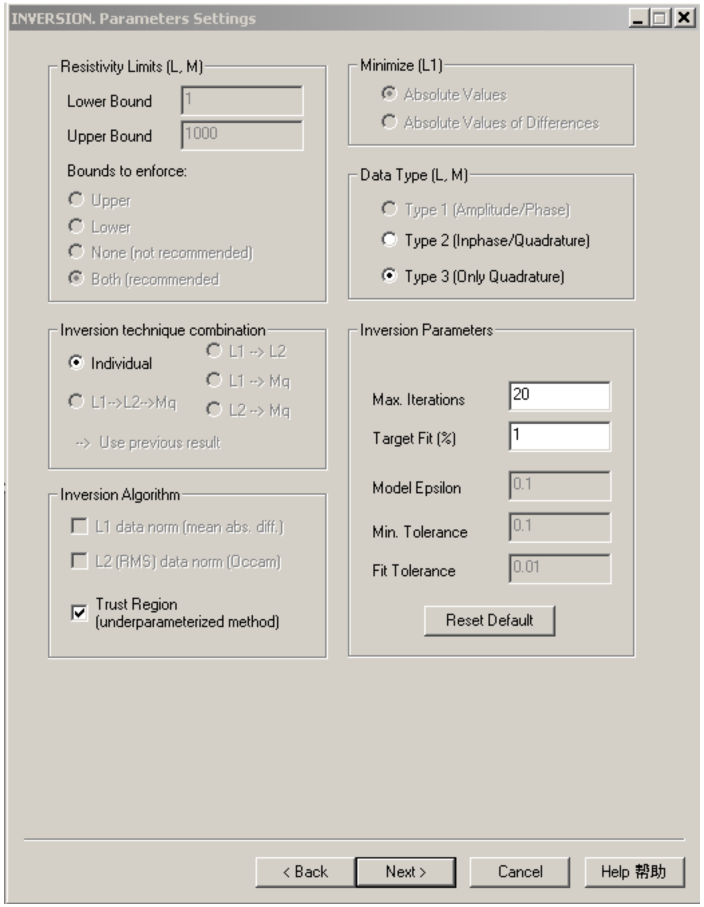
If we have knowledge of a layer's resistivity or thickness, we set that parameter's value and turn off the inversion for this parameter thus holding it fixed during the inversion.

The bounds for each parameter may be set individually, or as a group or not set at all. In this case, the minimum resistivity is set at 3Ωm and the maximum at 377Ωm. The data indicates the surface is quite resistive but the ability of the instrument to resolve higher resistivities is limited.

Trust Region: thickness and resistivity are model parameters. Allows inverting for a realistic number of layers and obtaining exact depth within the limitation of data quality. This is our suggested technique as it is the technique most likely to obtain a unique solution.

1D FEM Inversion – 4 using the tools 4a

-Trust Region: steepest descent fully constrained technique example



Trust Region: **thickness and resistivity are model parameters. Allows inverting for a realistic number of layers and obtaining exact depth within the limitation of data quality. This is our suggested technique as it is the technique most likely to obtain a unique solution.**

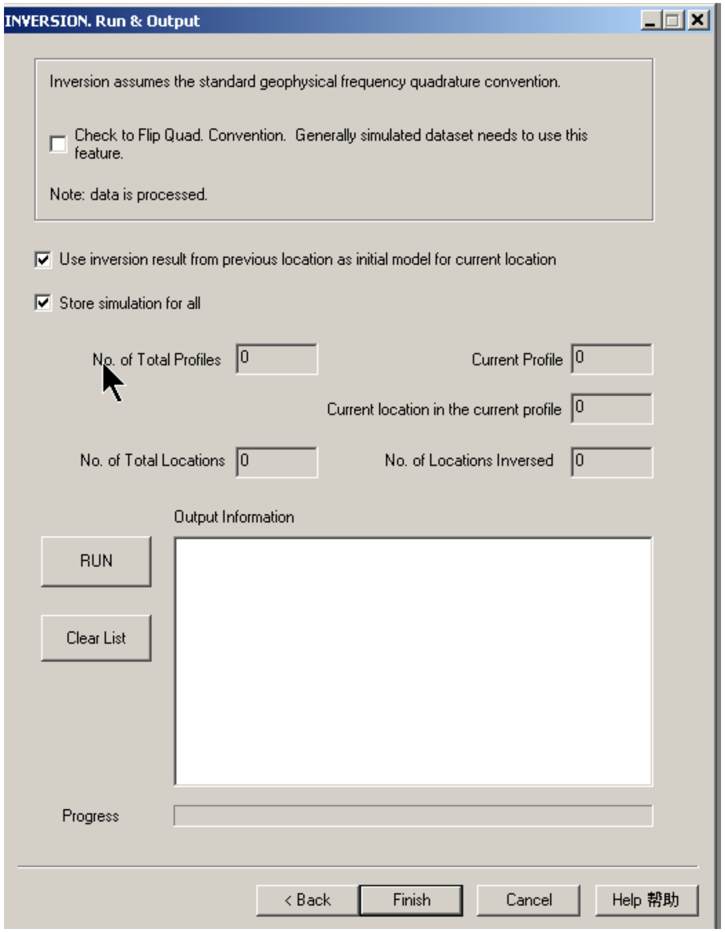
On this page, only parameters may be set. This depends upon the technique utilzied.

Here, we set ONLY quadrature as we have already determined the IN Phase is not quantitatively correct.

We also set the Maximum iterations and the desired fit. If the inversion cannot reach this level of fit, it map stop before 20 iterations.

1D FEM Inversion – 4 using the tools 5a

-Trust Region: steepest descent fully constrained technique example



Trust Region: **thickness and resistivity are model parameters. Allows inverting for a realistic number of layers and obtaining exact depth within the limitation of data quality. This is our suggested technique as it is the technique most likely to obtain a unique solution.**

-Use inversion result from previous location as starting model

- this is a 1D approach and thus we expect a smooth variation in ground resistivity. This allows to use the inversion model from the previous station for the present station as the starting model. This approach improves speed and well as the smoothness of the model along the profile

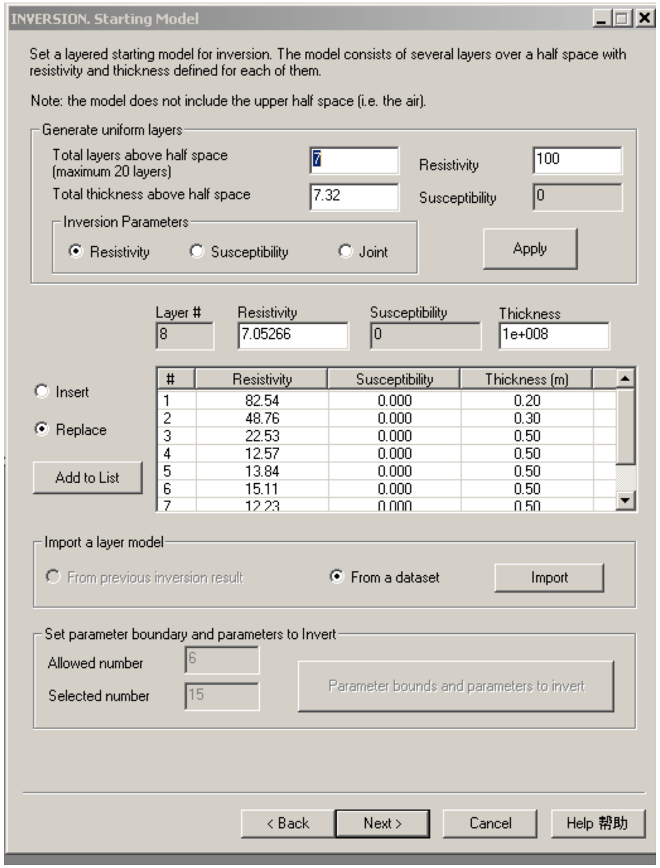
-Store simulation for all

- if this is turn on then the inversion with simulate the model for all data components and frequencies including IN Phase.

- RUN
- the inversion is applied to each station one after the other and all profiles. The results are automatically stored to the database.

Note: EMIGMA uses the standard scientific sign convention for imaginary EM data. Many geophysical instruments have historically used the opposite sign convention from the remainder of the scientific community.

1D FEM Inversion – 4 using the tools 2b



The two choices in the bottom are

-Enhanced CG Occam : over parametrized "Occam" approach.

-For this technique, the number of allowed layers is very high. But, the thickness of the layers is defined initially and does not change. Only the resistivities change in the inversion.

In this case, we have defined a starting model as 7 layers over a halfspace. The top layer is 0.2m because of the short 1m separation's sensitivity to only shallow ground and the remain layers are 0.50m in thickness. The top layers are slightly more resistive decreasing in resistivity to the basement layer. The initial layer resistivities are defined because of the apparent resistivities from the CDI and from some forward models.

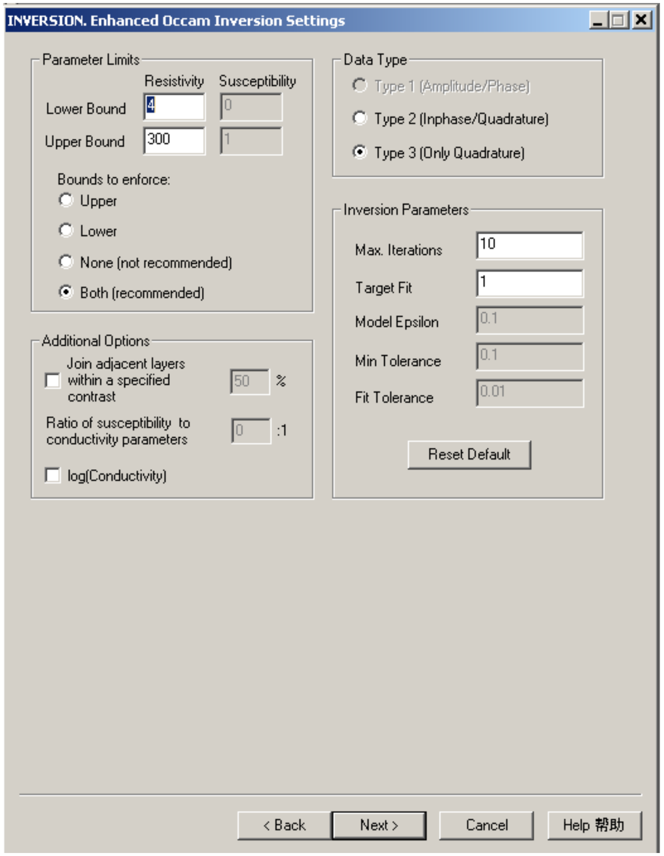
Enhanced CG Occam: In regard to the layer thicknesses, this is a standard approach where only the resistivities are inversion parameters. This technique allows for highly over parametrized model which are thus highly non-unique solutions. Assuming the Inphase data is good, this technique can also invert for susceptibility

<u>The RUN dialogue page does not differ from the Trust Region technique.</u>

1D FEM Inversion – 4 using the tools 3b

The two choices in the bottom are

-Enhanced CG Occam : over parametrized “Occam” approach.



-For this technique, the bounds on the layer resistivities cannot be selected individually but are only for all layers. Here, we define the minimum to be 4Ωm and the maximum to 300 Ωm.

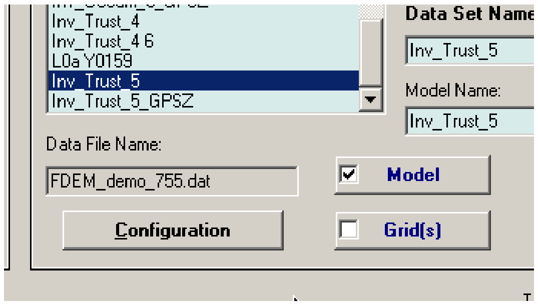
Inphase/Quadrature are only Quadrature is defined as input. Maximum Iterations and Target Fit are set by the user.

There are two other settings.
Join Adjacent Layers: as there can be many layers, it is useful to join adjacent layers into one layer during the inversion when the resistivities become close.

log(Conductivity)
If there is a wide range of conductivities/resistivities in the ground, you may want the inversion to perform inversions based on the logarithm of the conductivity.

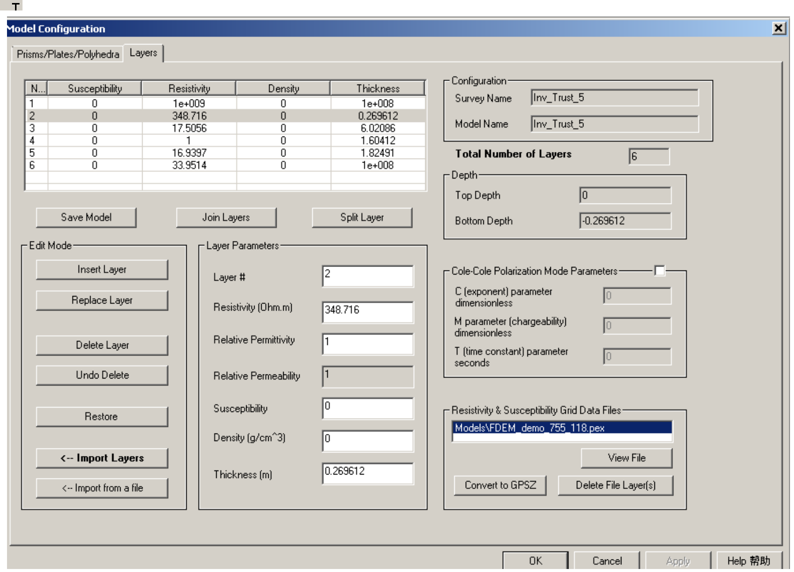
Enhanced CG Occam: In regard to the layer thicknesses, this is a standard approach where only the resistivities are inversion parameters. This technique allows for highly over parametrized model which are thus highly non-unique solutions. Assuming the Inphase data is good, this technique can also invert for susceptibility

1D FEM Inversion – 5
Examining Results



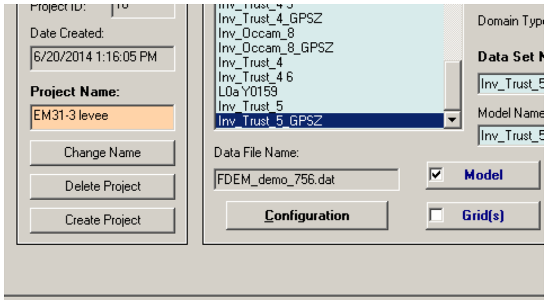
When the inversion completes, the results will be saved to the database in a new dataset. Here, for example, the inversion was the Trust technique and the model consists of a section of 4 layer over halfspace models. This data set contains the results of simulating the inversion models for comparison to the data and a structure which contains the inversion models.

If we click 'Model', the following interface opens:

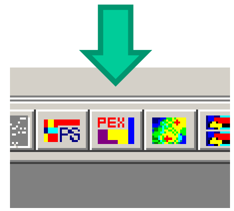


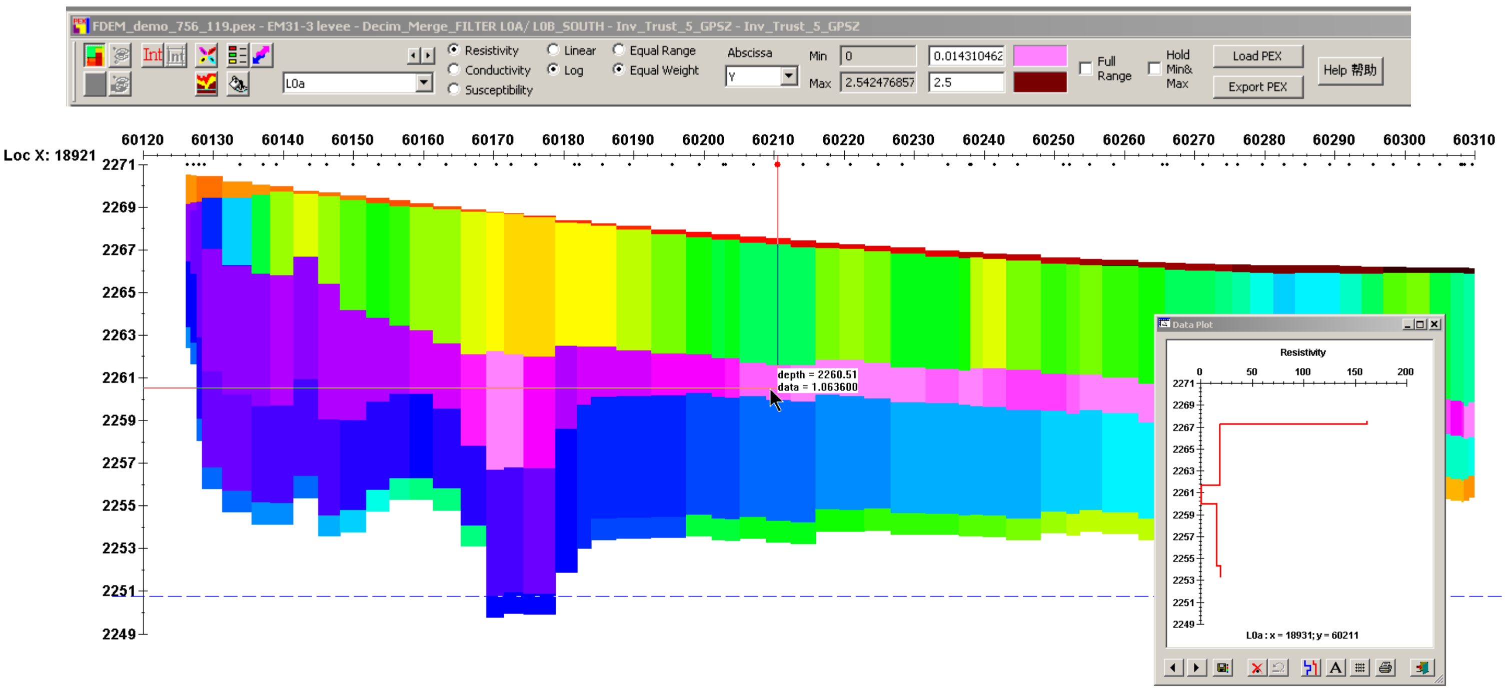
The inversion models (all stations/all lines) are stored n a .pex file which is saved to the db and is linked here for viewing. If your data file has GPS elevation or some other true elevation (not altitude), you may convert to GPSZ here. A new data file will be produced as seen in the image at the top.

1D FEM Inversion – 5
Examining Results



If we select a data file which contains a .pex File, then we may use the PEX Viewer (called the CDI viewer) .



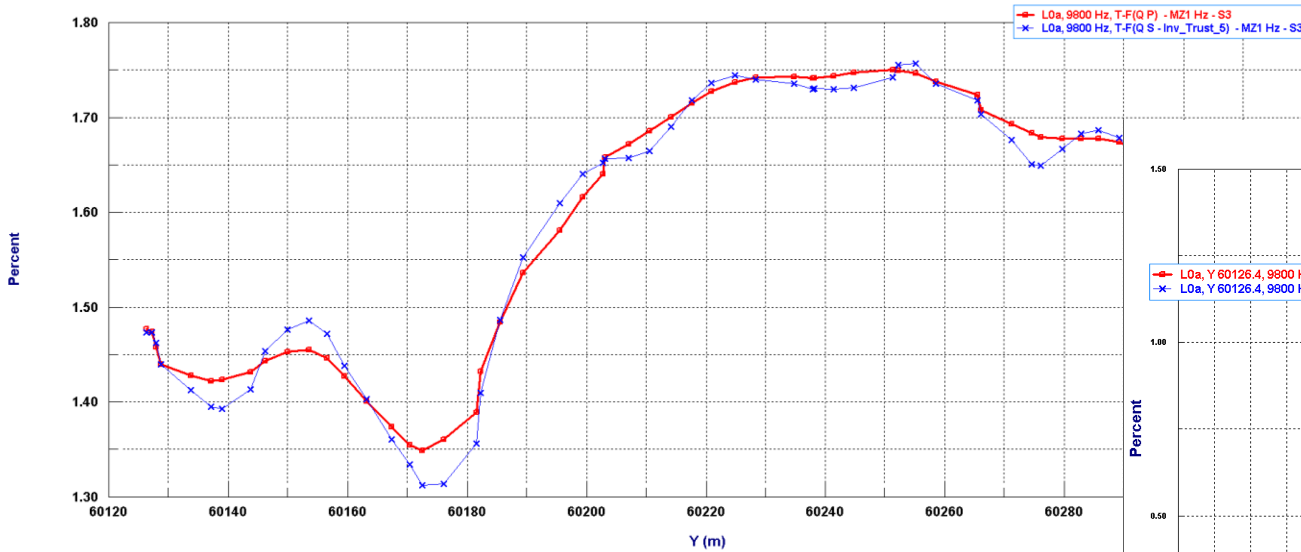


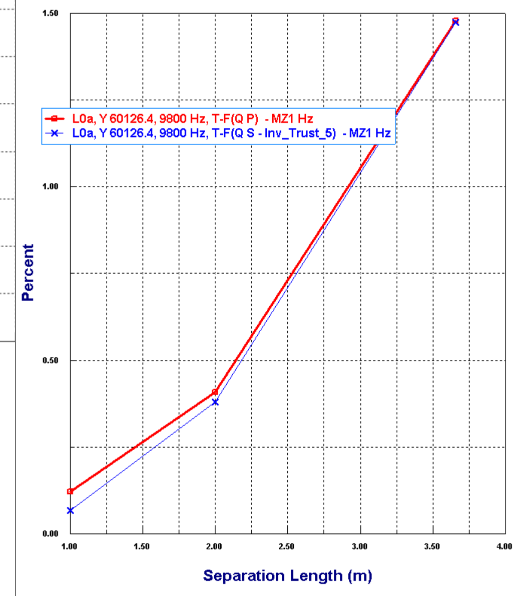
The initial display does not contour results but displays the “raw” inversion models. The small subplot is a resistivity/conductivity or susceptibility vs. depth display. If you select a point in the graph it will show depth and model data at that point. You may export the inversion results using the Export PEX button.

1D FEM Inversion – 5
Examining Results

For each data point, the response of the inversion model is computed and saved to the database in the output data file. To compare the inversion model's data to the field data, load the field data and the dataset output from the inversion to the plotter.

You may navigate through the data by separation , frequency , IP /Quadrature , etc once loaded to the plotter.

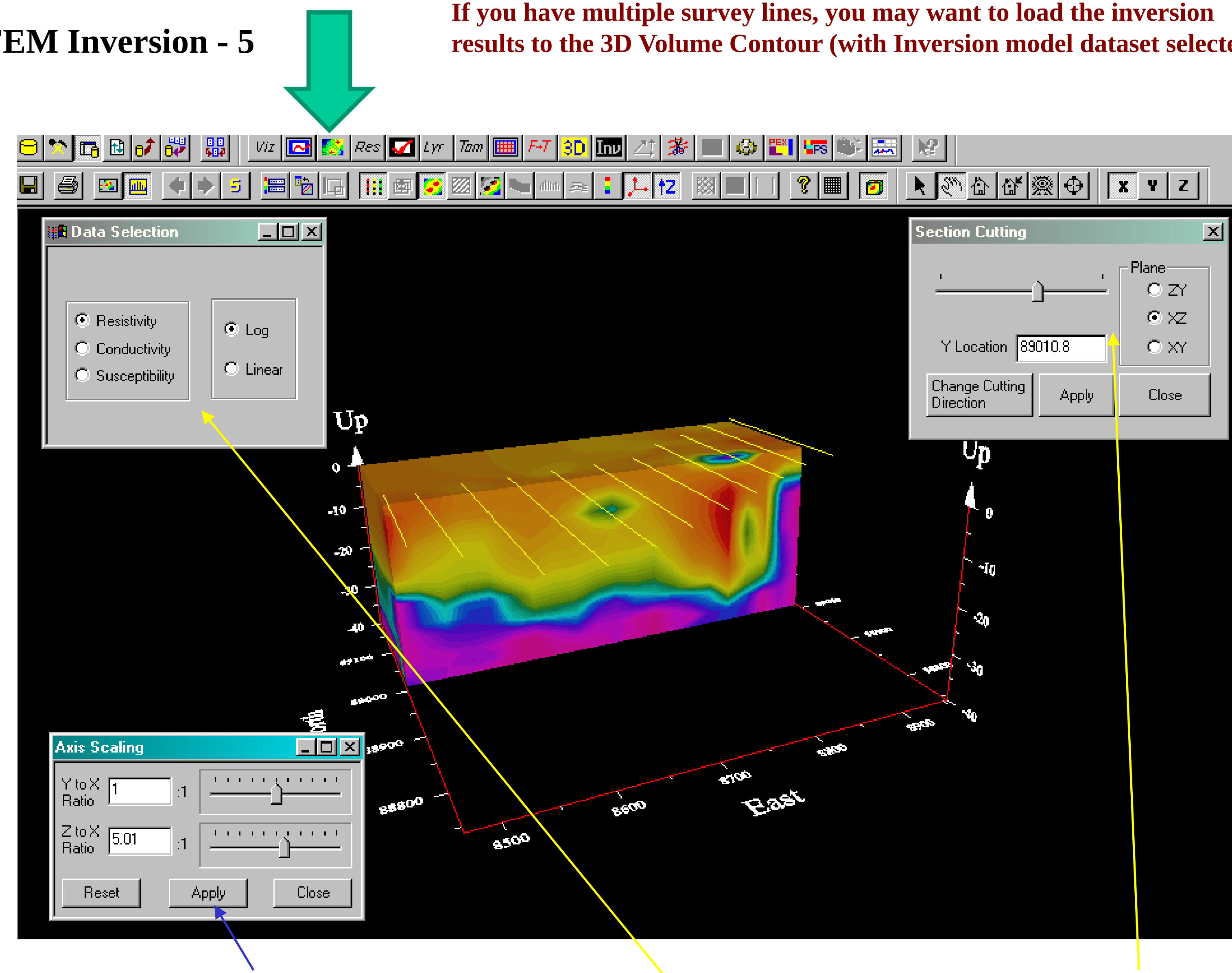




Using your right mouse, you may switch to separation mode or frequency mode if there are multiple frequency.

1D FEM Inversion - 5

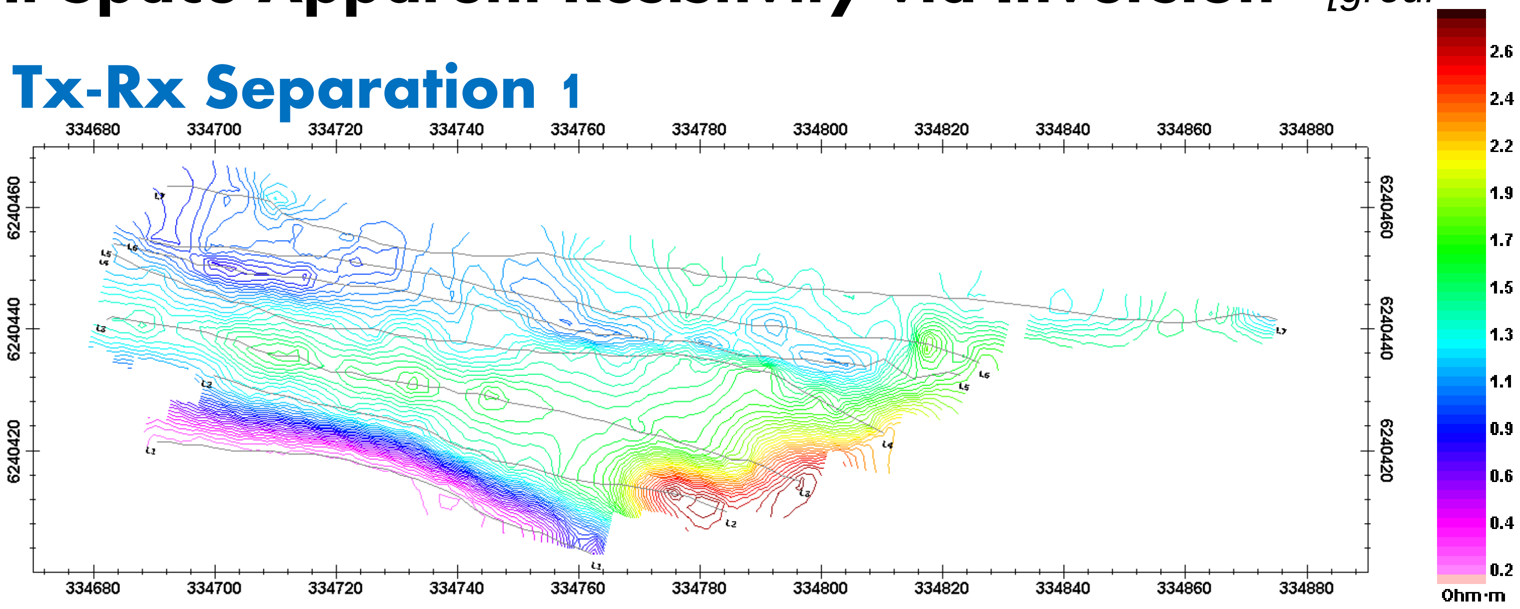
If you have multiple survey lines, you may want to load the inversion results to the 3D Volume Contour (with Inversion model dataset selected)



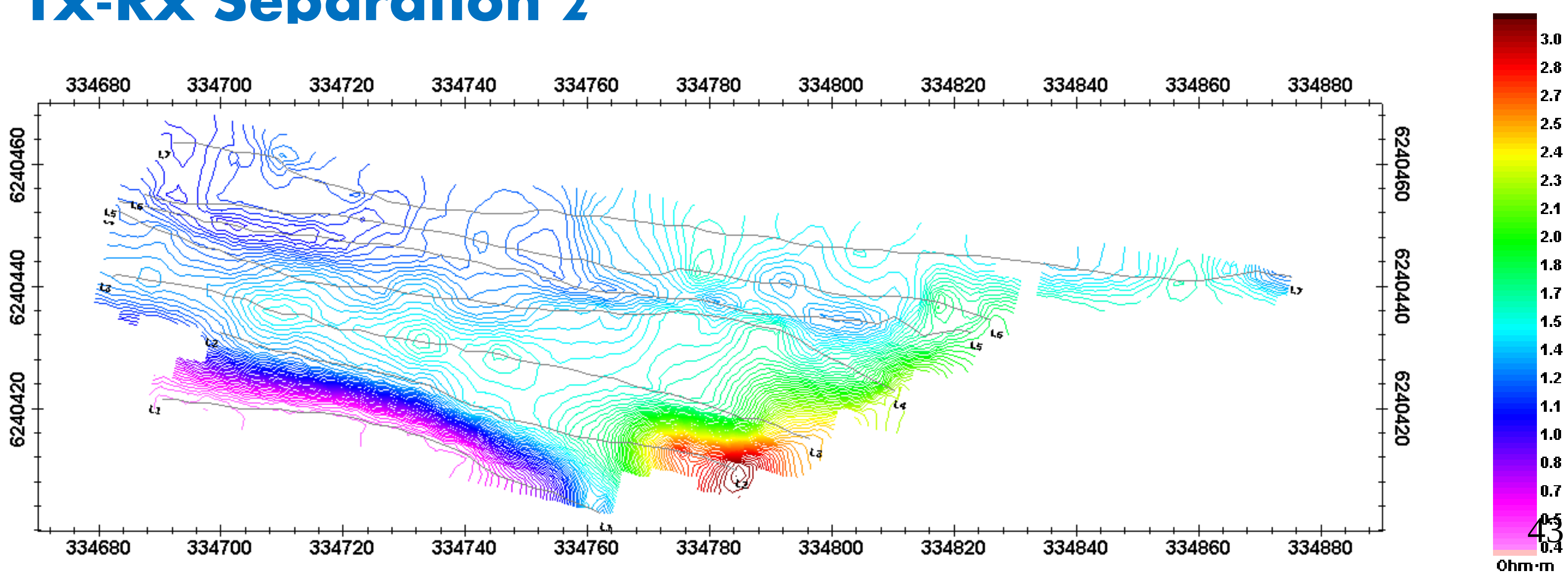
Axis Scaling **Model Units** **Section Cutting**

Half Space Apparent Resistivity via Inversion *[ground clearance 0.9m*

Tx-Rx Separation 1

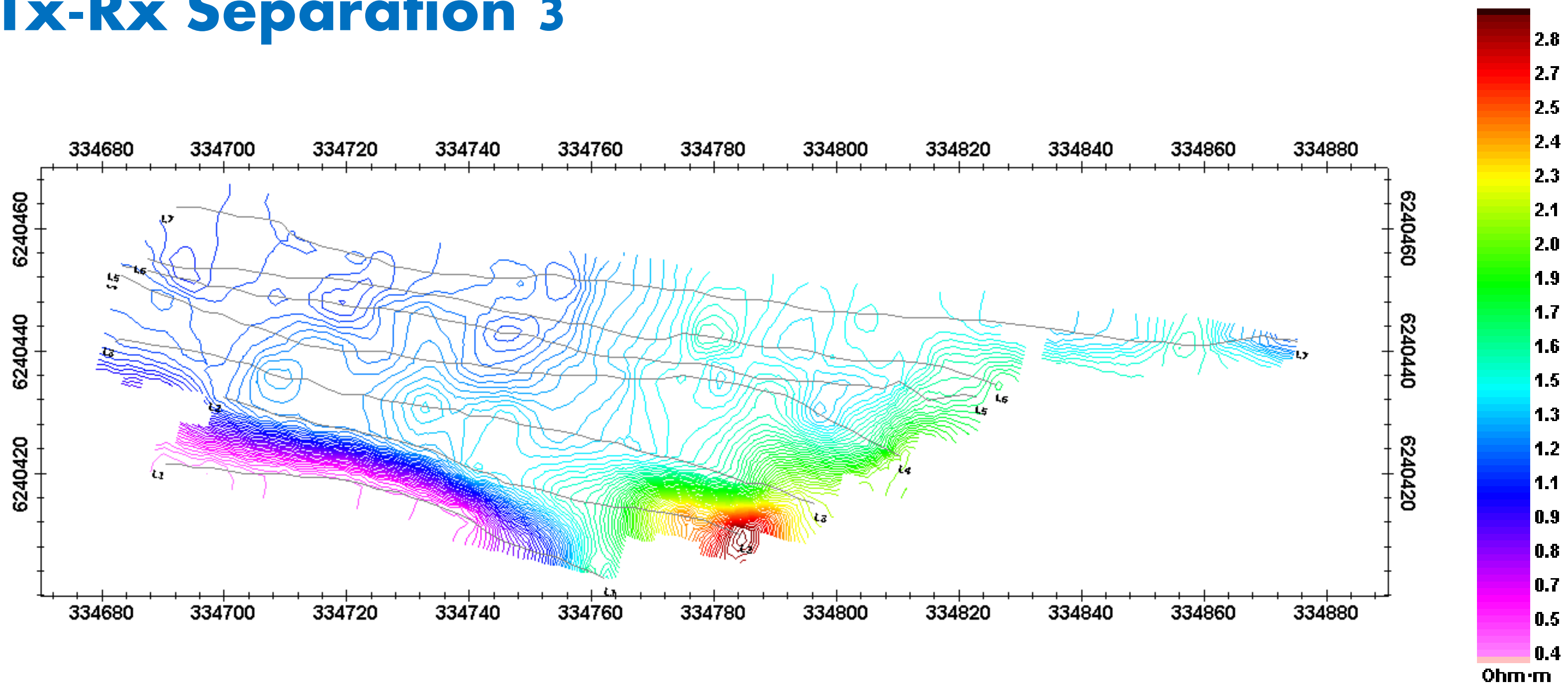


Tx-Rx Separation 2



Half Space Apparent Resistivity via Inversion *[ground clearance 0.9m*

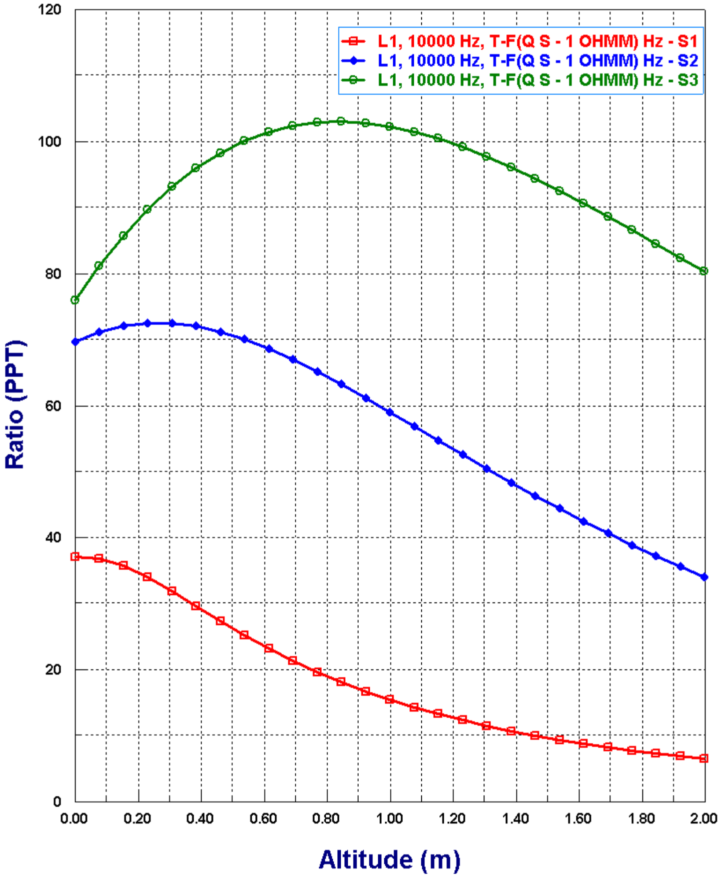
Tx-Rx Separation 3

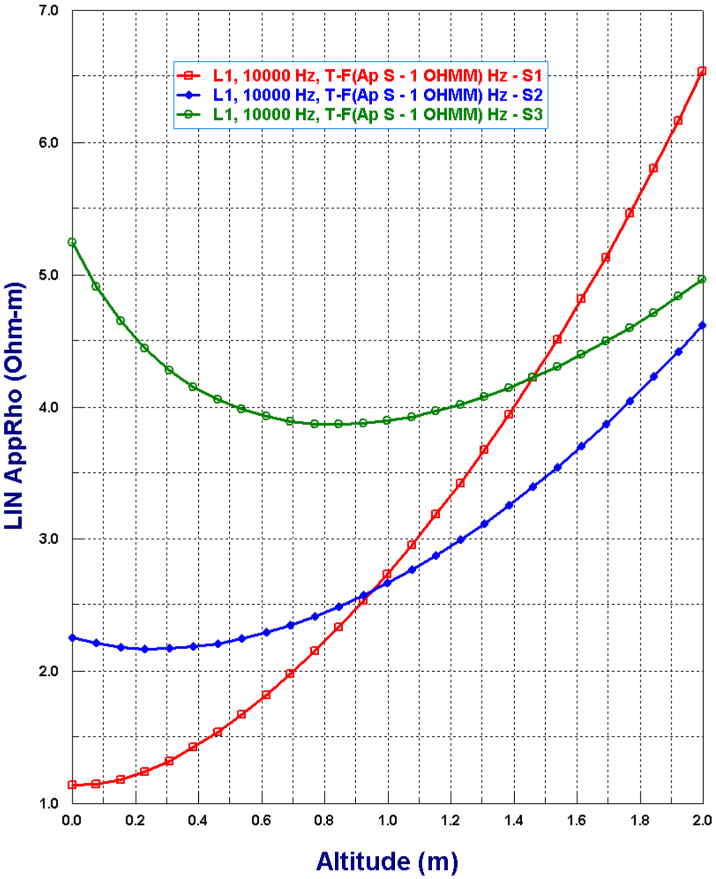


The majority of the data indicates between 1 and 1.5 Ωm. The eastern edge resistivities rise to 2-3 Ωm while the southern line indicating resistivities comparable to saline brine (<0.4 Ωm).

CMD Ground Clearance Dependence

Quadrature Response vs. Altitude [*Normalized Response*]



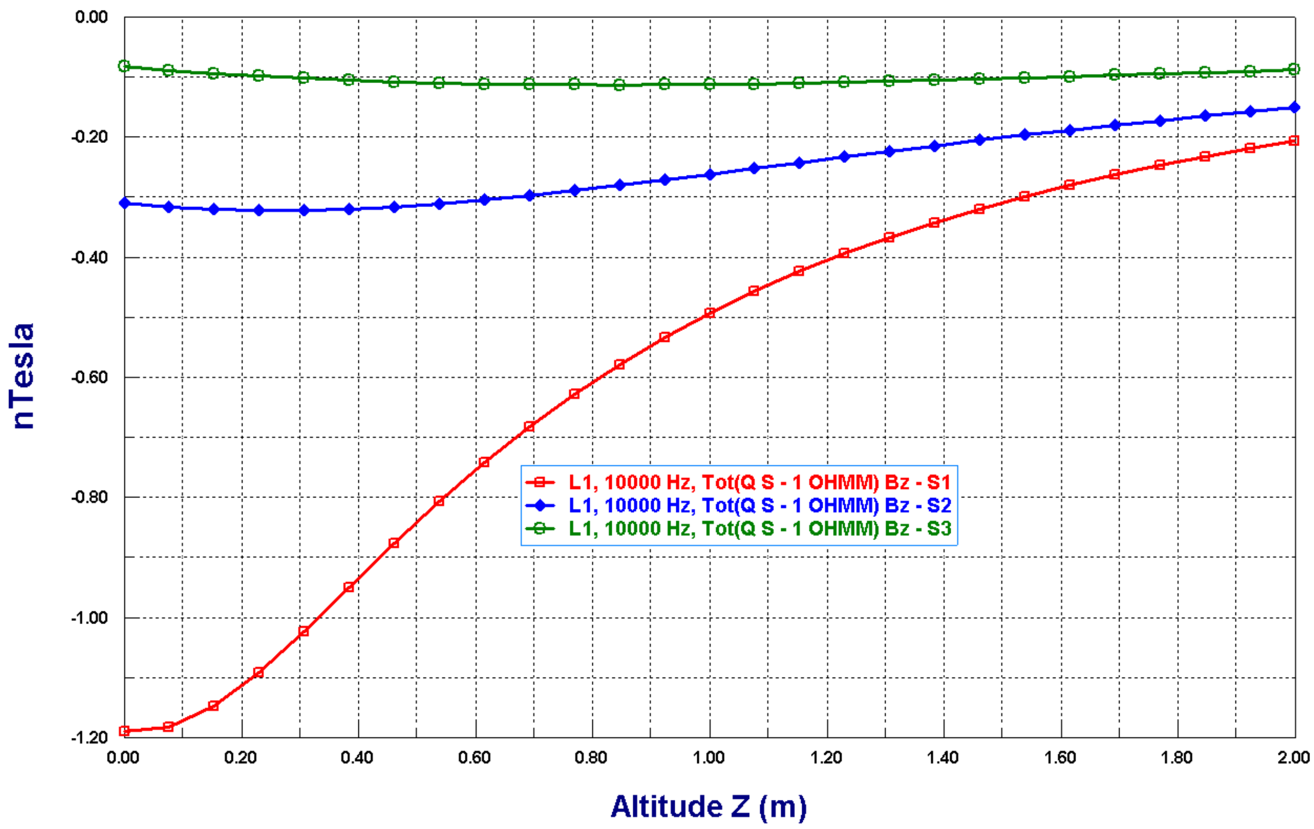


Response to a 1Ωm halfspace for 3 coil separations as function of elevation above ground
Quad/FS (PPT) on left , LIN Apparent Resistivity Approximation on right

NOTE: These are in the units output by the instrument. They are normalized units. Normalized by the direct/primary/freespace field. The responses are somewhat deceptive as the primary field for the data decreases rapidly with greater separation distances.

CMD Ground Clearance Dependence

Quadrature Response vs. Altitude [*Unnormalized*]



Response to a 1Ωm halfspace for 3 coil separations as function of elevation above ground. This assumes a unit area for both TX and RX. Thus, in this case, nTesla is equivalent to nVolts.

Depending upon the manufacturer, they may stored in the instrument the primary field in the instrument and subtract this from the measured voltage before normalizing. However, for this instrument and at this frequency, there is virtually no primary field.

CMD Ground Clearance Dependence

Inversion, Non-Unique Models and Effects of Coil heights

1. Inversion – the inversion utilizes the 3 coil separations and the instrument height to produce models which fit either the Quadrature (OP) data or the OP and Inphase (IP) data.

2. Non-unique models: There is not necessarily one correct model and most often there are multiple models which correspond to the data. Thus accurate data and accurate altitude (ground clearance) are extremely critical

example: Some FEM instruments have only 1 frequency and one coil separation and only OP data. In this case, there will be a best fitting half space model but also many other models which fit the data. This is the basic nature of EM as even if there are multiple strata, the combined effect of reflections and transmissions at strata interfaces can be interpreted with multiple models if there is only 1 data element at a station. There are several methods which are tried to overcome this limitation but they will also provide multiple fitting models as most are means to deal with geological and other noise. Only one measurement will provide additional information and that is to turn the instrument vertical and measure HCP but with a vertical separation.

3. Effect of Coil Height: On page 4, we see that the responses of the 3 separations peak at different altitudes. On page 5, we see this effect as well but other than for the shortest separations, the variations with height in absolute terms are not so dramatic. There are 3 important criteria which cause these variations:

a) Fall off TX field: *The TX coil is very small and thus the field from the TX which causes the response falls off very rapidly with height both above and below the ground. Thus raising the instrument above the ground decreases the strength of the source field below ground not only decreasing the depth of penetration.*

b) Induction of Secondary Currents: *When the field from the TX (source field) interacts with a ground which is conductive (or permeable), secondary currents are induced in the ground (ie. Faraday's principle). The responses of these secondary source fields are what the instrument is designed to measure in both the IP and OP components although these responses may not be all of the response in the IP. These production of these currents are dependent upon a number of factors (e.g. frequency, conductivity and source field factors). The source field factors are primarily its strength but also its spatial distribution as the source field spreads out as it falls off with distance (somewhat like a flashlight). Thus, although the strength of the source field diminishes with height above ground , it also spreads out.*

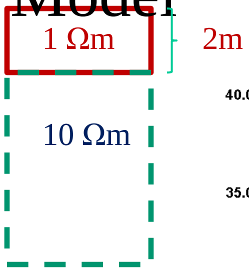
c) Effect of RX coil height: *The area of the RX coil is also very small and elevating this receiver from the sources of ground currents causes a significant reduction in response. The ground currents radiate an EM field which also falls away with distance and also spreads out becoming more diffuse with height above the ground.*

CMD Ground Clearance Dependence

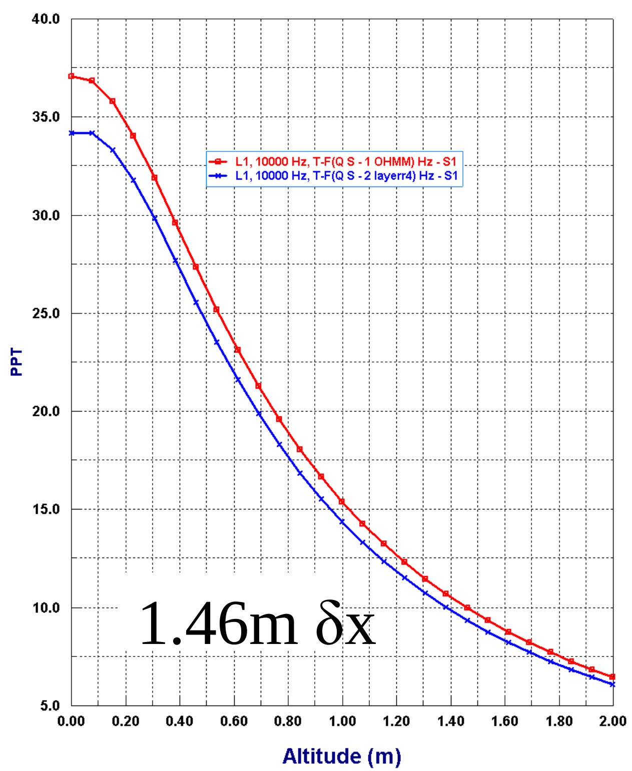
Inversion, Non-Unique Models and Effects of Coil heights

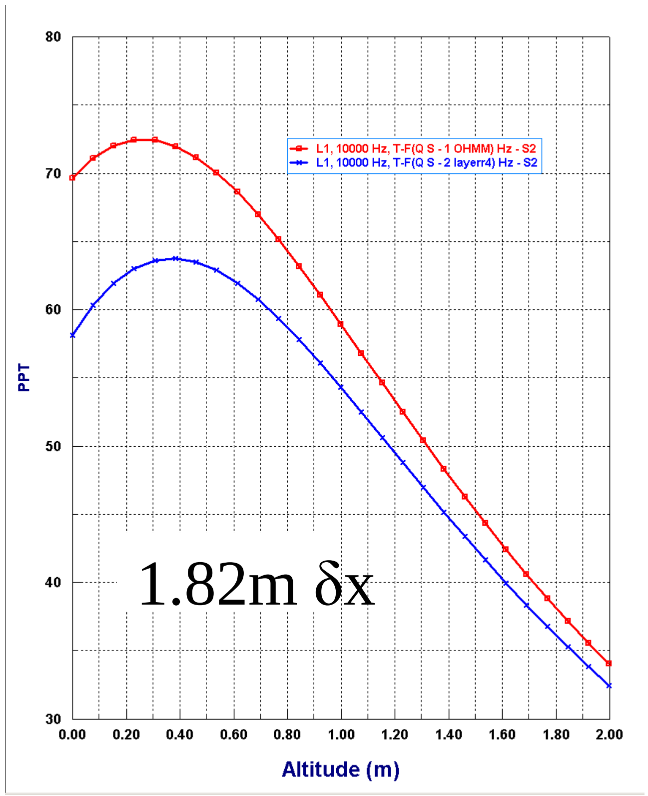
Simulation Examples

Model



Example 1: layer over a halfspace – HCP OP



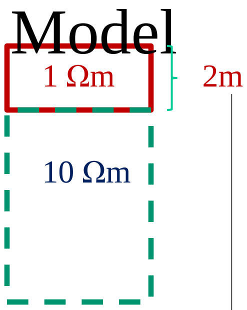


1. Effect of Height response amplitude – In general, as the instrument is elevated the instrument loses the ability to detect the resistive strata. With the VCP mode, the situation is slightly worse. On the left, the response for the short separation over a 1Ωm halfspace is compared to our example model as the instrument is raised above ground. On the right is the same but for the middle separation measurement.

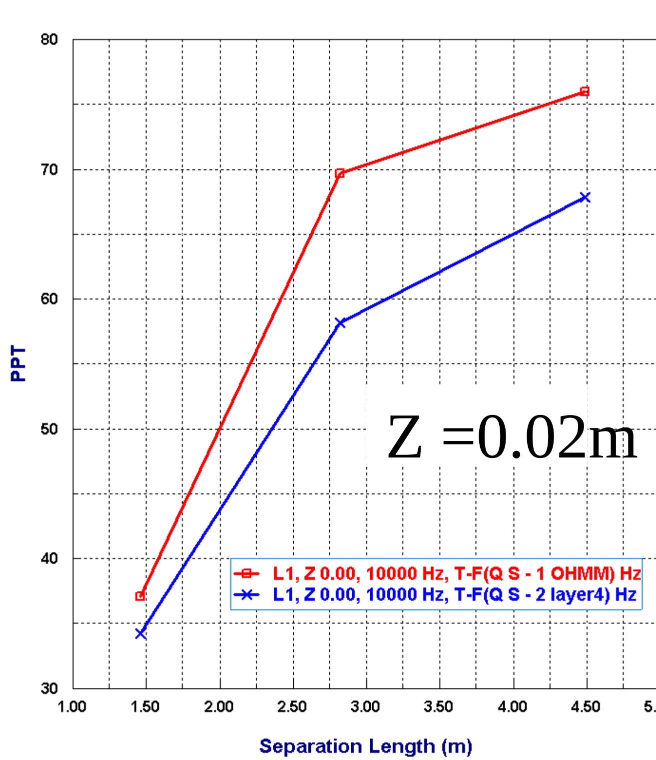
CMD Ground Clearance Dependence

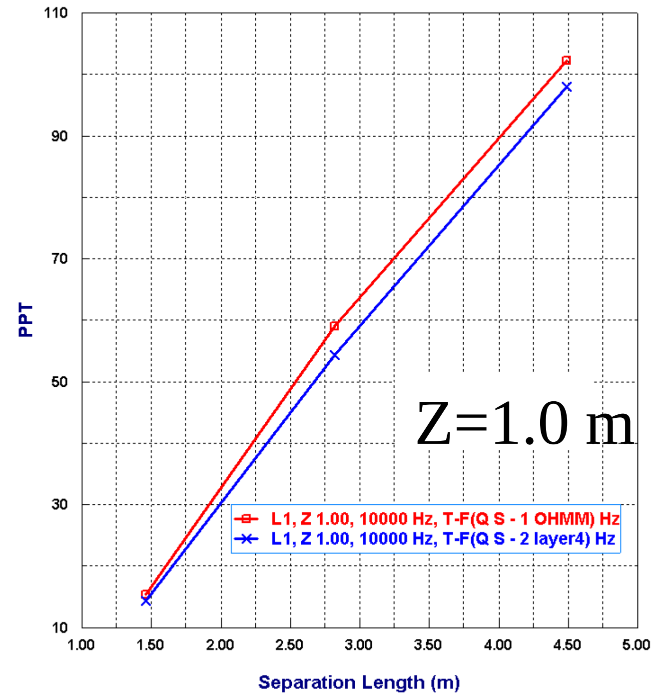
Inversion, Non-Unique Models and Effects of Coil heights

Simulation Examples



Example 1: layer over a halfspace – HCP OP





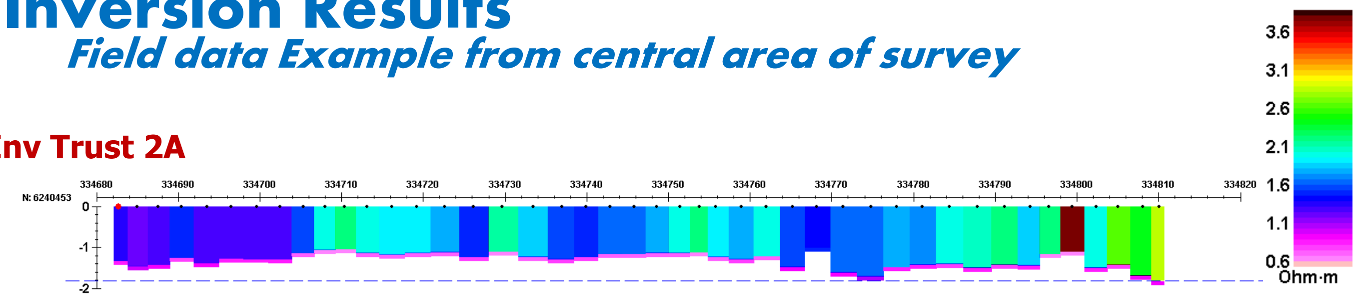
2. Effect of Height relative response– Another important issue in regard to the height of the instrument is the relative responses of the 3 separations. To the left, is the relative responses of the 1Ωm and the example model for the 3 separations at ground level while on the right is the same but when the instrument is elevated to 1m above ground. At ground level, the short separation is roughly half of the wider separations while at an elevation of 1m, the short separation is many times smaller than the other two and the middle separation is now about 60% of the largest separation.

CMD Ground Clearance Dependence

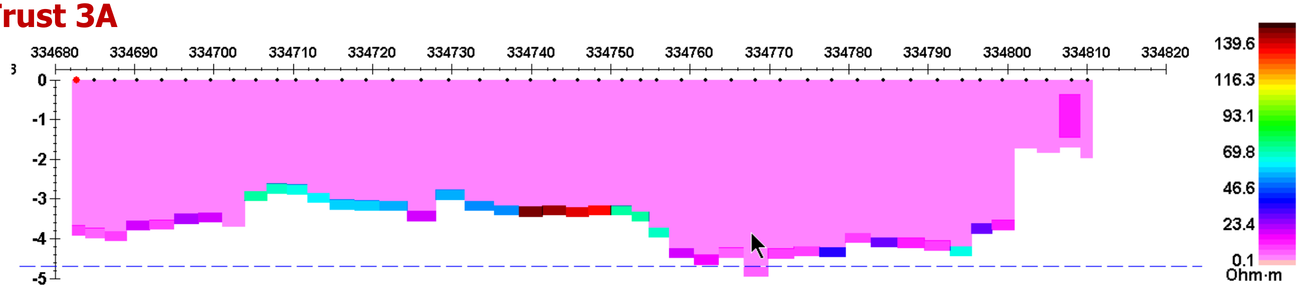
Inversion Results

Field data Example from central area of survey

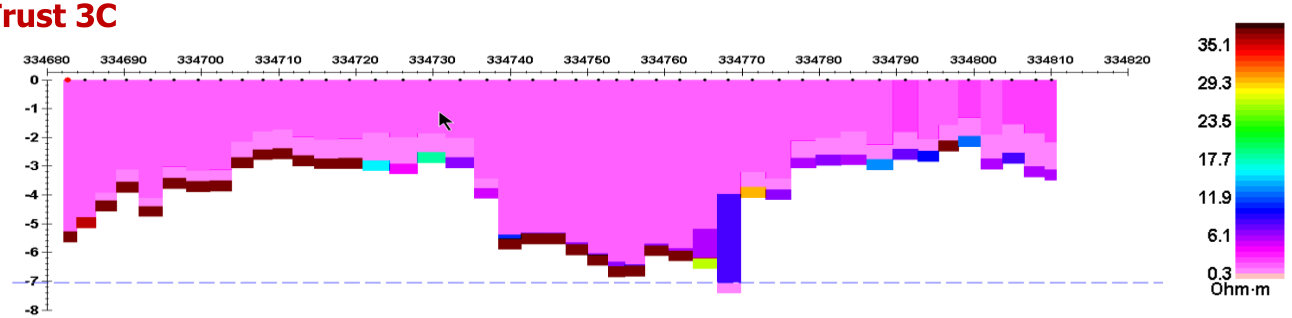
Inv Trust 2A



Inv Trust 3A



Inv Trust 3C

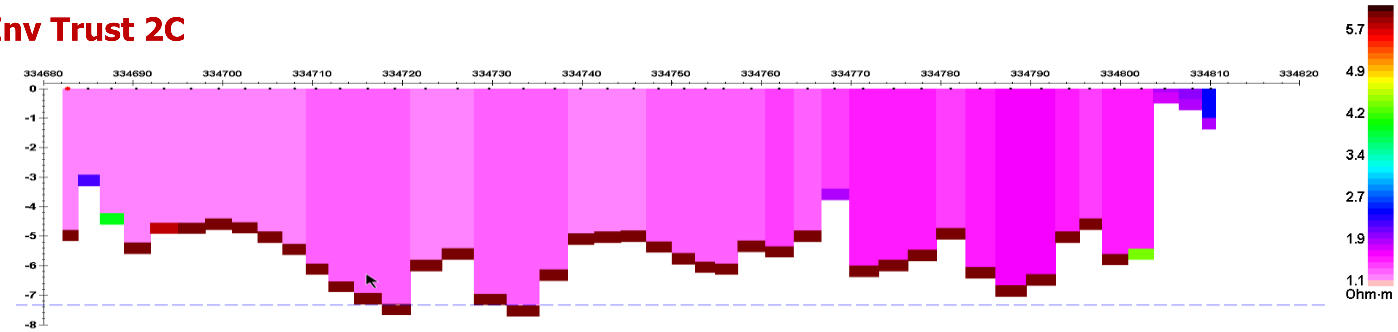


Model *InvTrust 2A* is a layer over halfspace model while *InvTrust 3A* and *3B* are 2 layers over a halfspace. For the first two models, all 3 separations were used but only OP data while in the third used 3 separations and IP and OP data. This technique can invert for thickness as well as resistivity. Thus, the depth of the model is NOT pre-determined.

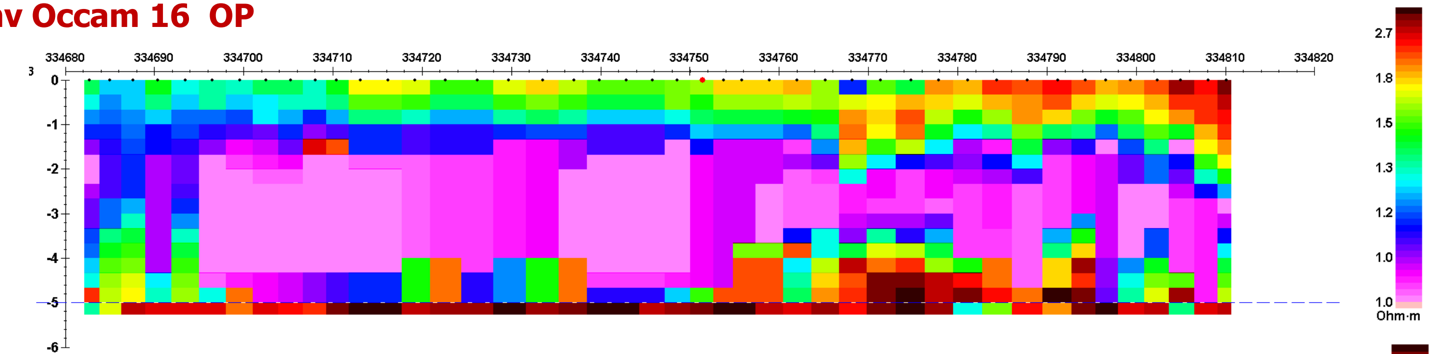
CMD Ground Clearance Dependence

Inversion Results
Field data Example

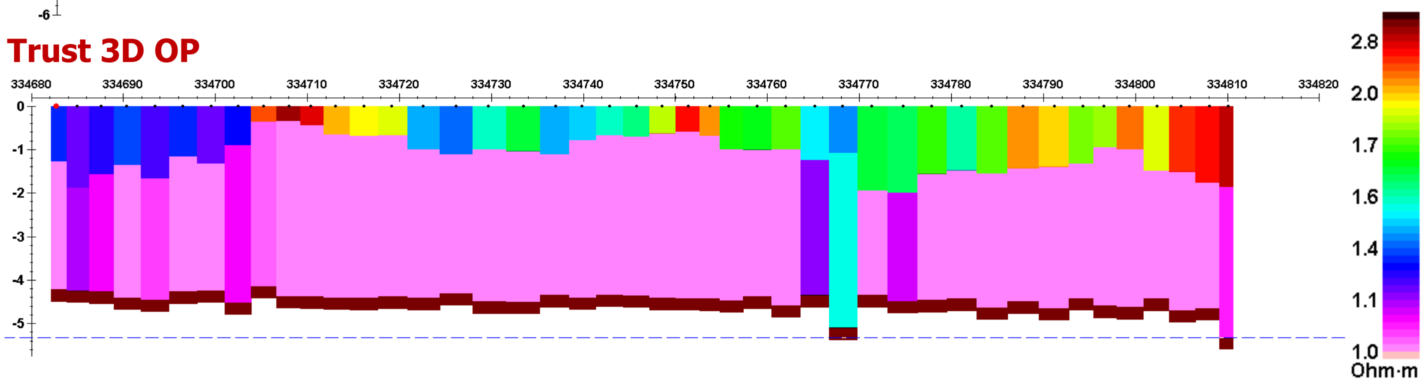
Inv Trust 2C



Inv Occam 16 OP



Inv Trust 3D OP

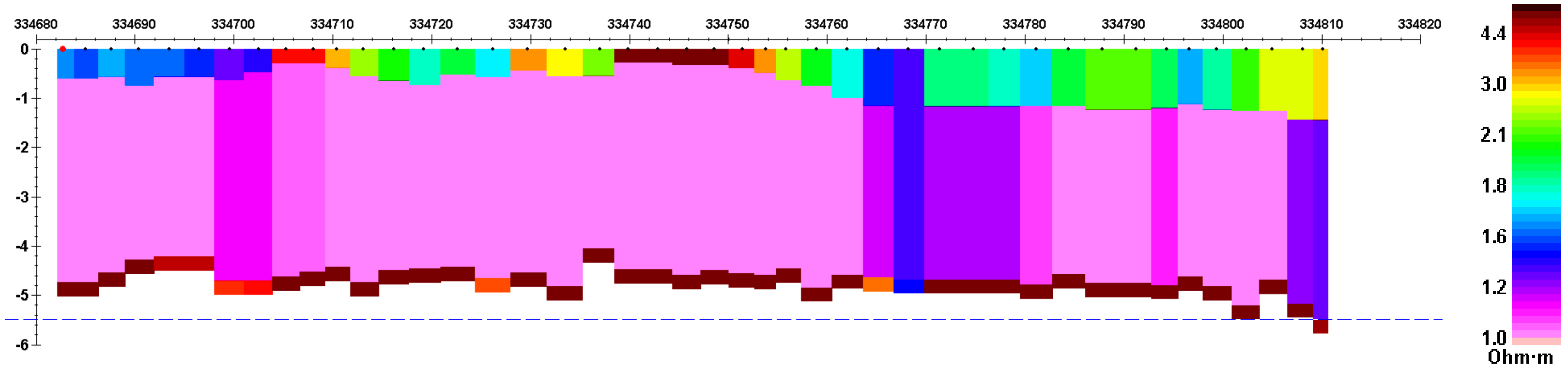


Model *InvTrust 2A* is a layer over halfspace model using 3 separations and IP and OP. *InvOccam16OP* is a 15 layer over a halfspace using defined thicknesses of 0.33m with a minimum resistivity of 1Ωm, 3 separations and only OP. *InvTrust3DOP* is a 2 layer over halfspace with a minimum resistivity of 1Ωm and a maximum of 5Ωm but thicknesses are not constrained. All 3 separations are used and only OP is used.

CMD Ground Clearance Dependence

Inversion Results
Field data Example

Inv Trust 3E OP 2SEP



InvTrust3DOP 2SEP is defined exactly as the model on the bottom of pg9 but uses only the 2 larger separations. The results are little different from *InvTrust3DOP which uses all 3 separations.* These results are confirmation of the synthetic model results and discussion on pg7.

CMD Ground Clearance Dependence

Inversion Results
Field data Example

The inversion models' simulated response compare to the measured data very similarly for all stations. Below, are shown for one station, the quadrature response of the data at the 3 separation distances compared to the quadrature response of all 7 models. The data fits for those inversions which utilized the IP data as well as the OP are slightly poorer. On the right, the 5 model results using only OP are shown. The closest fit to the two wider separations is the last model which uses only these separations.