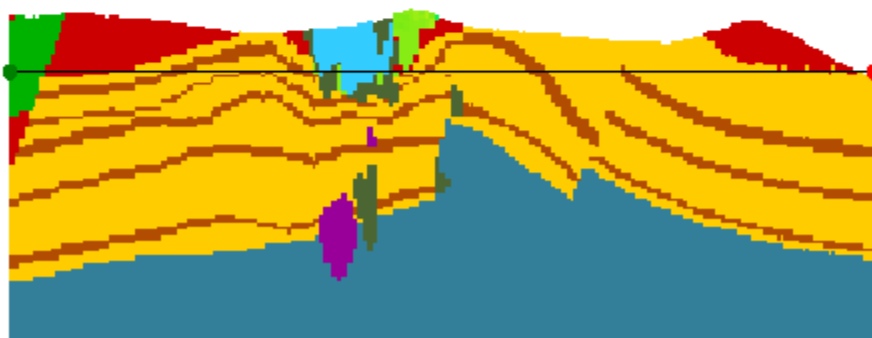
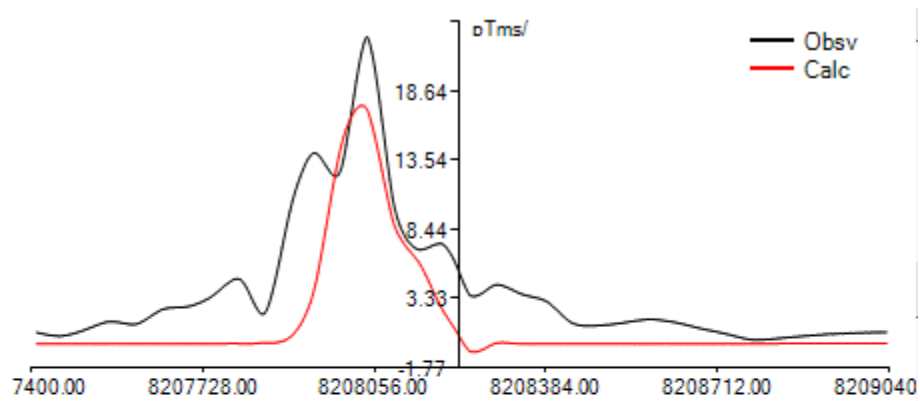


VPem3D

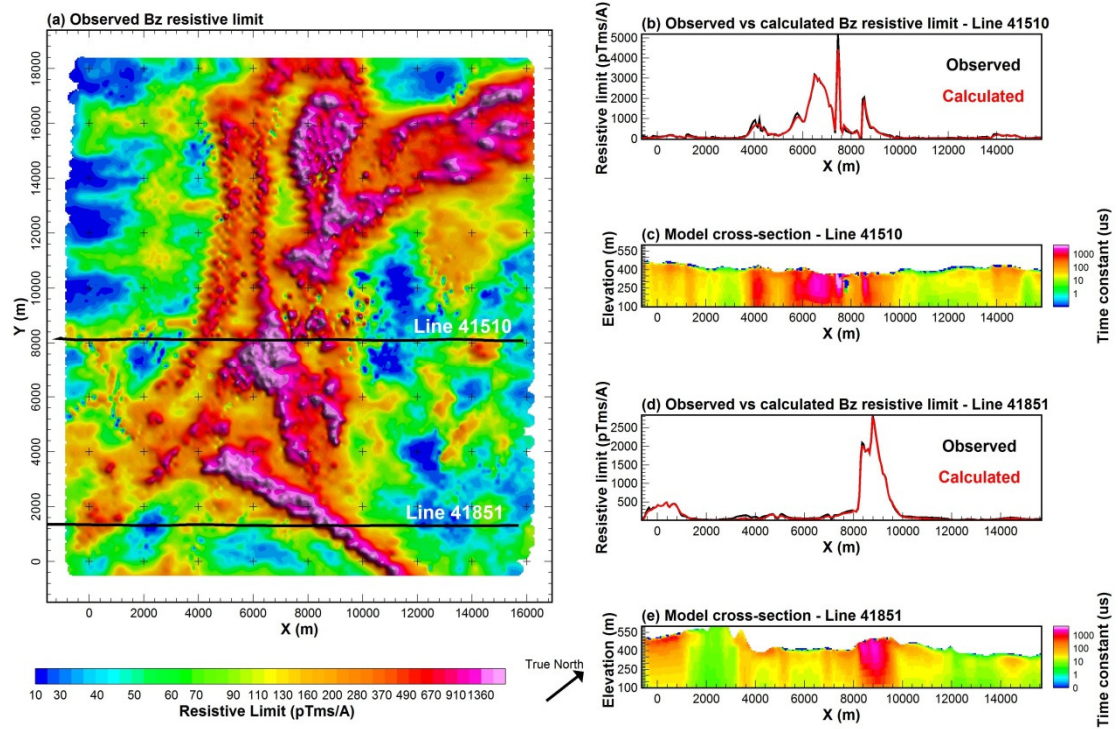
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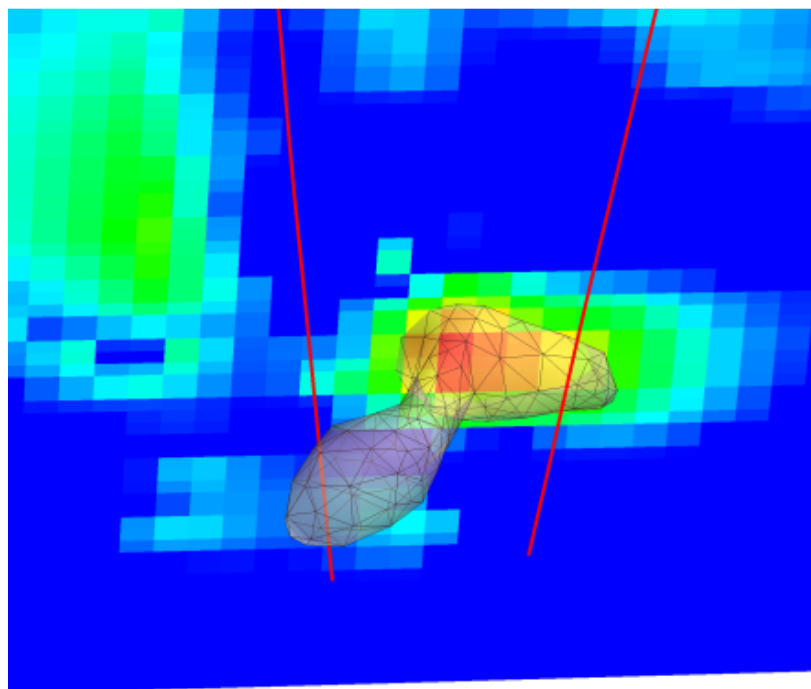
P.K. Fullagar

Version 3.35
September 2017

Frontispiece



VPem3D inversion of Spectrem data from Goias, Brazil (Fullagar et al, 2014).



VPem3D inversion of downhole TEM data from a North American nickel prospect.

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0. GETTING STARTED WITH VPem3D

VPem3D is a fast approximate modelling and inversion program for downhole, ground, and airborne transient electromagnetic (TEM) data. VPview is the user interface for VPem3D.

0.1 Installation

The install set for VPem3D can be downloaded from the Fullagar Geophysics website: www.fullagargeophysics.com. After download, double click on setup_vpem3d_v3.2_x64_Mlic.exe to install VPem3D. You will be asked for a VPem3D install password. This will be provided by your VPem3D supplier.

The install set for VPview can be downloaded from the Fullagar Geophysics website. After download, double click on setup_VPview3_0.0.4.0f.exe to install VPview. You will be asked for a VPview install password. This too will be provided by your VPem3D supplier.

0.2 Licence Activation

The licence files for both VPem3D and VPview are based on the Physical Address (aka MAC address) of your PC. To determine the MAC address, double click on the desktop icon for VPview. Email the MAC address to your VPem3D supplier.

Once you receive the licence (.REG) file from your VPem3D supplier, simply double click on it and follow the prompts. Your VPem3D and VPview licences will then be ready for use.

0.3 VPem3D documentation

Documentation for VPem3D is available from the Fullagar Geophysics website. It is also written to C:\Program Files\Fullagar\VPem3D\documentation during installation.

0.4 VPem3D sample files

Four files are required in order to run VPem3D:

- (i) a control file, defining the model and data files involved and specifying the inversion parameters;
- (ii) a model file;
- (iii) a data file; and
- (iv) a data parameter file, specifying the field components to be modelled.

Sample VPem3D files are included with the installation. They can be found in sub-directories below C:\Program Files\Fullagar\VPem3D\sample_data. There are separate folders for airborne, downhole, and ground TEM examples.

Windows imposes restrictions on the Program Files folder; it is recommended, therefore, that you transfer the sample file folders into an ordinary folder, e.g. C:\VPem3D.

In order to run the sample files:

1. launch VPview;
2. read the control (.CTL) file using the VPview *Open VP control file* option, under the *File* menu;
3. launch VPem3D using the *Run VPxx from file* option, under the *Run* menu;
4. display the results using the *Load Model* option, under the *Model* menu.

For additional information, please refer to the VPem3D documentation. Note in particular the worked examples in Appendices B,C, and D.

If you have any questions, please contact us. See our contact details on page 51.

1 INTRODUCTION

VPem3D is a fast approximate 3D modelling and inversion program for airborne, ground, and downhole transient electromagnetic (TEM) data developed in response to two related needs in mineral exploration: the need for rapid 3D inversion of large TEM data sets and the need for integrated interpretation of TEM data in concert with geological and other data. *VPem3D* is more general than 1D inversion or conductive plate modelling, but much faster than “rigorous” 3D TEM inversion programs. *VPem3D* has the potential to significantly enhance both the efficiency and effectiveness of 3D TEM interpretation, and hence to contribute to exploration success.

VPem3D converts dB/dt or B-field TEM decays to resistive limits in order to reduce run times by a factor of 10 or more relative to conventional programs. The resistive limit is the integral of the B-field decay over time. By transforming decays to “resistive limits”, the multi-channel TEM inversion problem is effectively reduced to a single channel magnetic inversion, thereby yielding a dramatic increase in speed. Each model cell contributes to the resistive limit response as a magnetic dipole. The improvement in speed is achieved at the expense of information carried by the time evolution of the decay. However, strategies have been developed to recover as much as possible of the lost information, e.g. starting conductivity models constructed from conductivity-depth images or 1D inversions. More rigorous TEM software can be employed to verify and refine the initial interpretation, if necessary.

VPem3D has been designed for geologically-constrained inversion but is also suitable for “unconstrained” inversion. One, two, or three component data can be handled, from all common configurations: in-loop or slingram, either fixed loop or moving loop. Ground and downhole data can be inverted simultaneously.

Integrated interpretation is advanced in three main ways. Firstly, inversion can be performed on a geological model, with each cell in the *VPem3D* model assigned a rock type as well as a physical property. Inverting on a geological model is a strong driver for integrated interpretation in itself, and it also delivers benefits in terms of flexibility and control during inversion. In particular it permits geometry inversion, i.e. adjustment of geological boundaries, as well as more conventional property inversion. The use of geological models not only allows geological constraints to be imposed naturally, but also introduces greater flexibility and control during inversions.

Secondly, *VPem3D* has been implemented as a new option within the existing “VP” modelling and inversion framework developed for the potential fields modelling and inversion program, *VPmg* (Fullagar et al., 2000, 2004, 2008; Fullagar & Pears, 2007). Thus *VPem3D* is the latest addition to the “VP software suite” (Figure 1.1). The advent of *VPem3D* expedites combined interpretation of magnetics, gravity, and TEM data. Model file formats and inversion styles are identical for all programs in the VP suite. The core routines for input/output, computation of derivatives, assignment of constraints, and inversion comprise the *VPshell*. The *VPshell* is linked to forward modelling routines for potential field and TEM data.

Thirdly, a user interface, *VPview*, has been developed to facilitate modelling and inversion with all the “VP” programs. *VPview* includes utilities for editing control parameters, creating simple layered models, converting TEM decays to resistive limits, and displaying models and data (both observed and calculated). *VPem3D* users also have the option (under commercial terms) of accessing the Gocad-based utilities developed for the VP suite by Mira Geoscience.

This documentation manual is comprised of seven main sections. Special technical features of *VPem3D* are briefly described in Section 2. A general introduction to *VPem3D* forward modelling and inversion is provided in Section 3. Sections 4, 5, and 6 contain general instructions for running *VPem3D* on airborne, downhole, and ground TEM respectively. *VPem3D* file formats are defined in Section 7. Example inversions for airborne, downhole and ground TEM are described in Appendices B, C, and D respectively (Sections 12, 13, and 14).

Features under development appear in **grey** text.

“VP suite” schematic

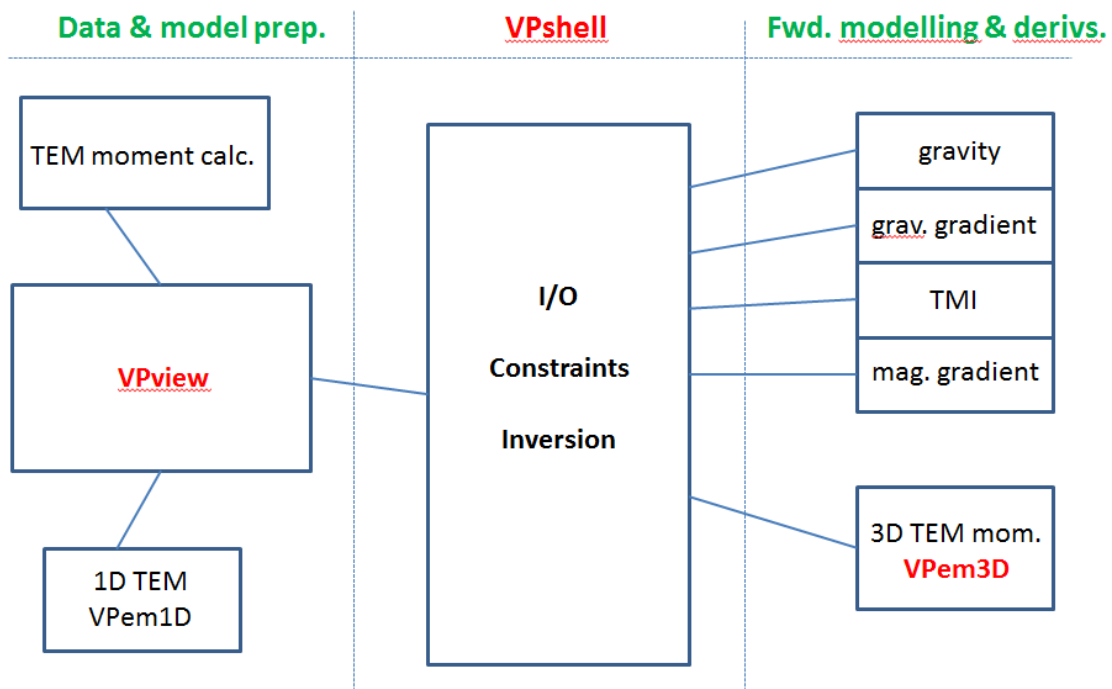


Figure 1.1: Schematic illustrating the structure of the “VP” software suite. VPem3D v2 is a specialised forward modelling module, linked to the VPshell which includes the inversion routines. VPview is the user interface.

To summarise, the **key features** of VPem3D are

- fast 3D inversion of TEM resistive limit data
- inverts airborne, ground, & downhole TEM
- can operate on geological models
- compact 3D model format
- drill hole pierce points honoured
- sharp geological contacts preserved
- conductivities are bounded
- 3 inversion styles:
 - (i) homogeneous property,
 - (ii) heterogeneous property, &
 - (iii) contact geometry
- fast steepest descent inversion algorithm
- fully compatible with VPmg, for integrated interpretation of magnetics, gravity, & TEM
- runs constrained or unconstrained inversion

Functions of **VPview**, the VPem3D user interface:

- display TEM data in plan and profile
- convert TEM decays to resistive limits
- create simple layered models
- create 3D conductivity models from CDI sections
- display topography
- cut sections and horizontal fliche plans through the 3D model
- compare observed and calculated resistive limits
- adjust inversion parameters
- edit model file parameters

-
- apply depth weights
 - launch inversions
 - export VPem3D models in UBC format or Geosoft XYZ format
 - convert homogeneous units to heterogeneous units via sub-celling

2 SPECIAL FEATURES

2.1 Inversion of geological models

Each cell in a *VPem3D* is explicitly assigned to a geological unit (Figure 2.1). Thus *VPem3D* models are geological. This is a strong driver for integrated interpretation.

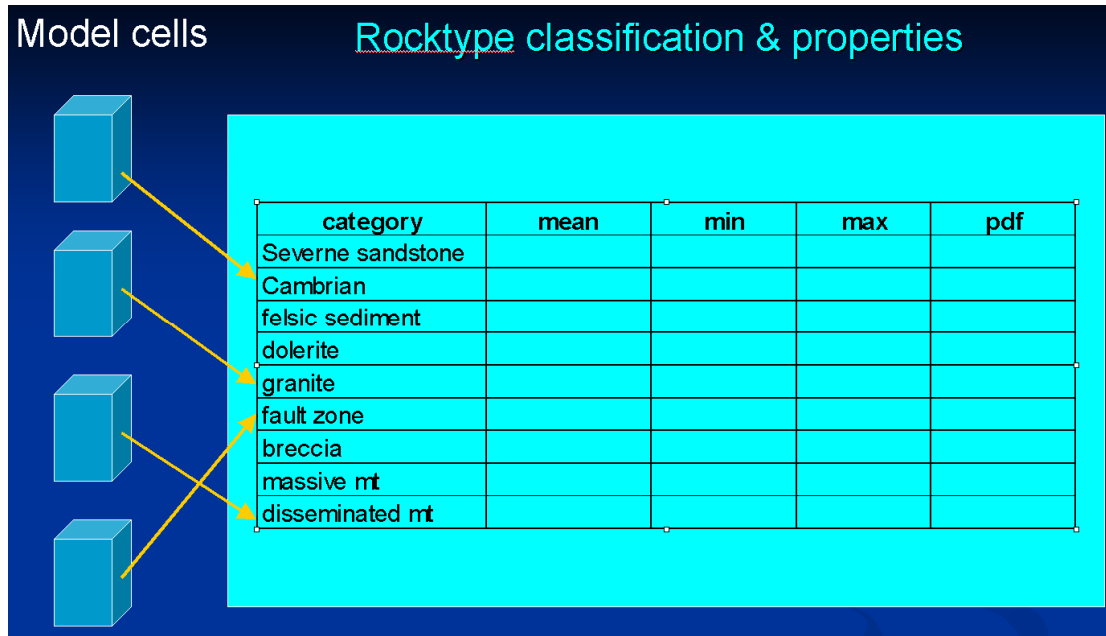


Figure 2.1: Each cell in a *VPem3D* model is assigned to a geological unit. If geology is unknown, all cells belong to the same “unknown” unit, as in conventional inversion.

The litho-stratigraphic significance of each cell is captured and carried through inversion. Final models can include sharp contacts separating different geological units. A geological unit can be broken into many spatially distinct sub-volumes, e.g. fault blocks. Each geological unit can be homogeneous or heterogeneous. All the cells comprising a particular unit share a common property if the unit is homogeneous. If a unit is heterogeneous, the properties of all its cells lie between the bounds defined for that unit.

Basement underlies the geological units. Basement cells have no internal interfaces, and extend to the base of the model (normally at great depth). Given the attenuation with depth of TEM, basement is normally assigned zero conductivity in *VPem3D* models.

Currently, the maximum number of vertical prisms allowed in any model is 15×10^6 , the maximum number of cells (or interfaces) in any prism is 350, and the maximum number of geological units is 99.

Mira Geoscience has developed Gocad utilities to export 3D geological models into *VPem3D* format, and to import *VPem3D* models into Gocad. Mira utilities are also available to impose drill hole constraints on boundaries and cells within the *VPem3D* model.

2.2 More accurate representation of surfaces

The “VP” in *VPem3D* stands for “vertical prism”, reflecting the fact that *VPem3D* models are based on close-packed vertical rectangular prisms with internal horizontal interfaces. The horizontal interfaces divide each vertical prism into cells. The cells can have arbitrary vertical dimension,

allowing the mesh to adapt to fit geological surfaces (including the topographic surface) as closely as is permitted by the lateral discretization (Figure 2.2).

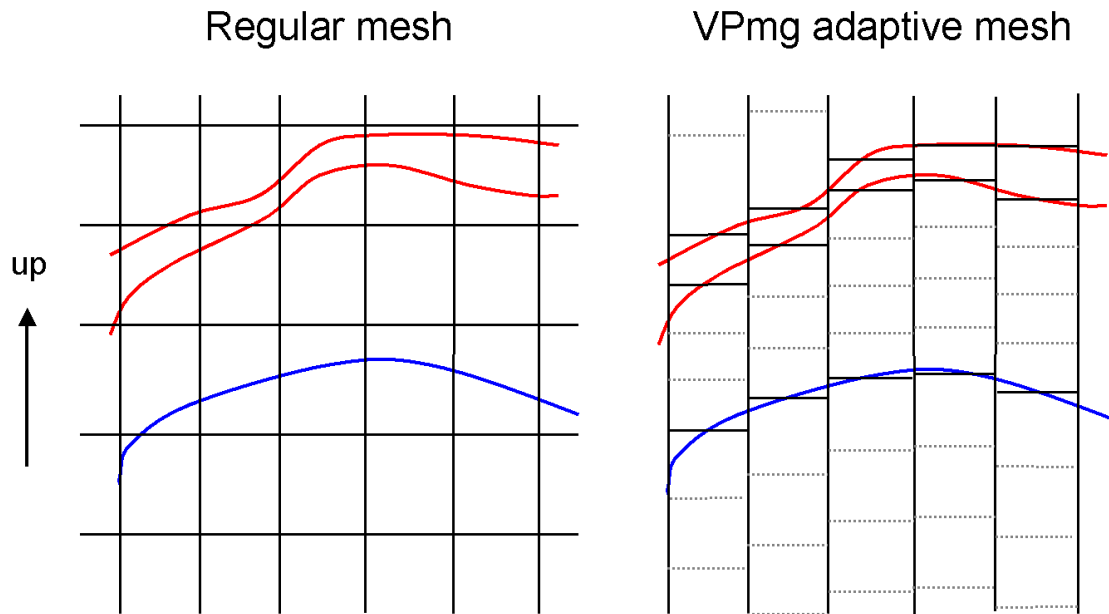


Figure 2.2: Schematic model sections illustrating the differences between a conventional regular mesh (left) and the deforming mesh implemented in VPem3D. Vertical cell dimensions are arbitrary, as required to best represent the geology. Horizontal cell boundaries snap to geological contacts (coloured) in the VPem3D mesh, whereas all boundaries are artificial in the regular mesh. Units can be sub-celled to permit internal property variations. Sub-cell boundaries are dotted in the RH panel.

Viewed in plan, VPem3D models are defined on a regular rectangular mesh, but the vertical dimension of VPem3D model cells is arbitrary. Thus a 25 cm ore intersection and a 150 m intersection of barren granite could each be represented with a single cell.

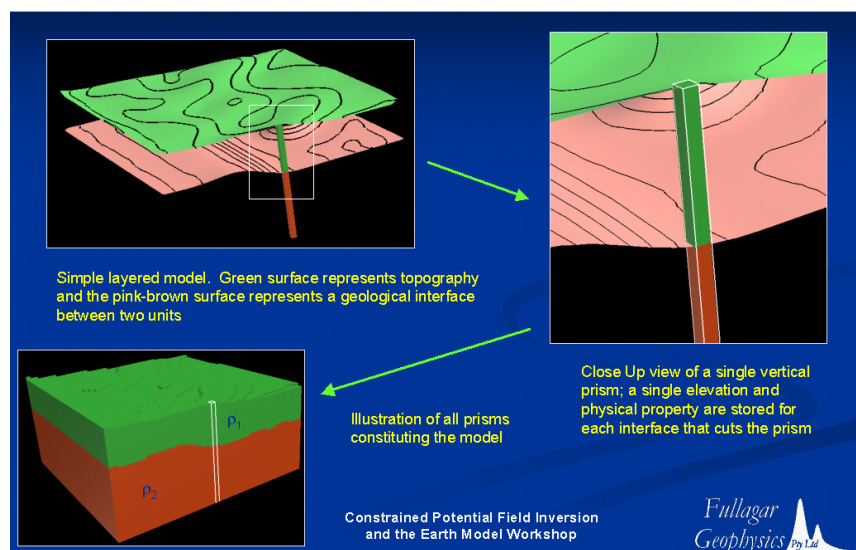


Figure 2.3: Horizontal cell boundaries are positioned within each vertical model prism to coincide with geological boundaries.

The adaptive VPem3D parameterisation has a number of advantages over uniform meshes:

1. models are more compact, with the result that model files are generally smaller and run times shorter;

2. surfaces can be represented more accurately. In particular, the top of the VPem3D model *is* the DTM.

2.3 Constraining, modifying, and recovering geological contacts

Because *VPem3D* model cells are geologically-tagged, their interfaces carry meaning as geological contacts. Therefore, it is possible to alter the shape of geological units as well as their properties via inversion (Figure 2.4).

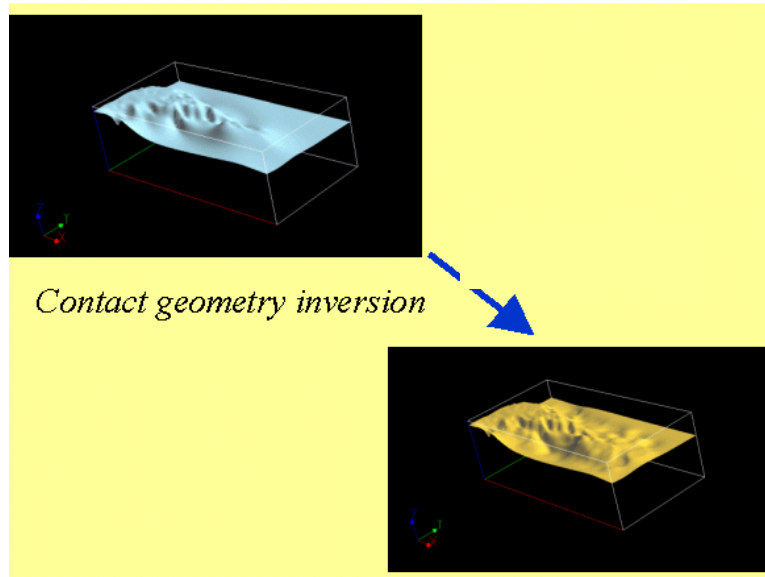


Figure 2.4: Illustration of drilling-constrained geometry inversion (after Fullagar et al, 2004). The top-limestone surface at upper left was interpreted from drill pierce points; the surface at lower right was adjusted via geometry inversion, constrained by the pierce points, in order to fit gravity data.

Contacts which have been intersected by drill holes can be held fixed, while interpreted contacts between drill holes can be allowed to vary. When inclined drill holes pass above or below “free” contacts, artificial interfaces are introduced to prevent movement of free contacts which contradicts geological logging.

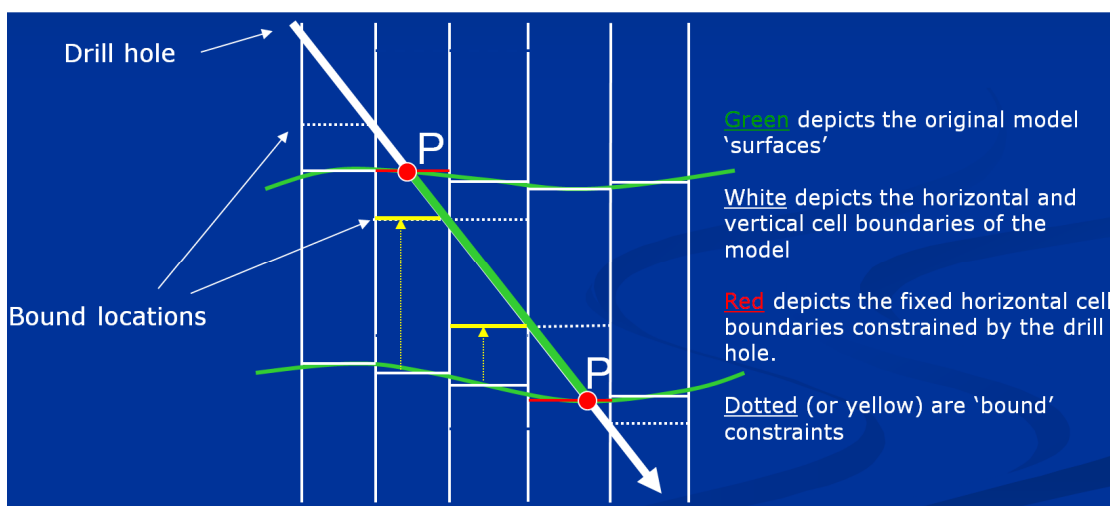


Figure 2.5: Cell boundaries intersected by drill holes are fixed during geometry inversion. Drill holes can impose bounds on the permissible movement of boundaries.

It is desirable not only to fix boundaries intersected by drill holes, but also to suppress changes in their vicinity. Otherwise, the influence of the drill hole will be confined to the fixed boundaries, which may produce “pillars” or “wells” in the inverted model. In *VPem3D*, a spherical neighbourhood is

defined, centred on each fixed boundary (Figure 2.6). By default the radius of influence, ROI, is the depth of the data point or the distance to the nearest data point, whichever is smaller. However, the user can adjust the radius of influence by means of the control file; see Section 7.1 below.

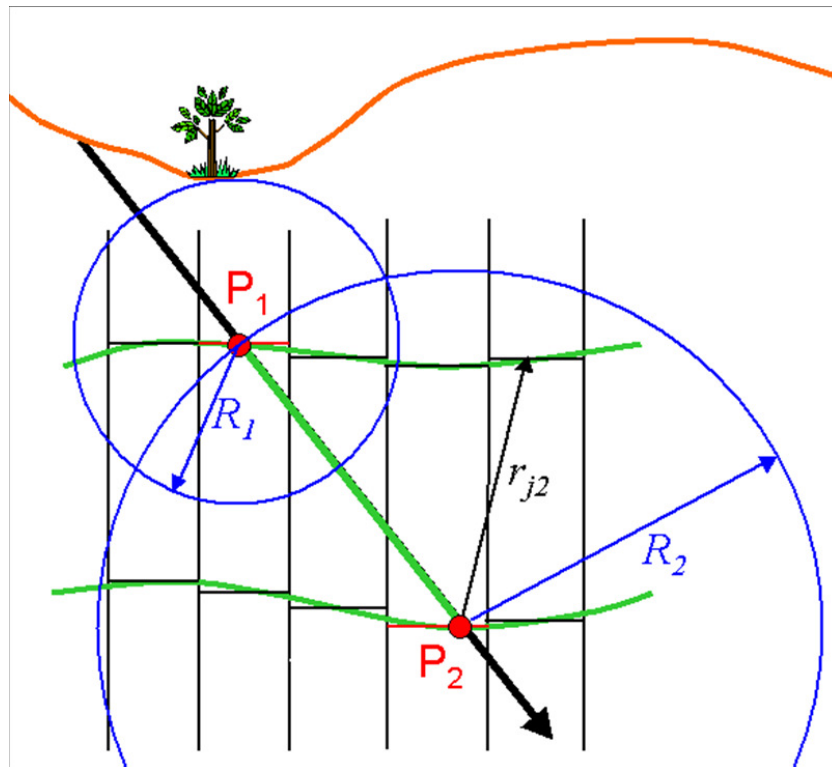


Figure 2.6: Movement of boundaries during geometry inversion is damped within a spherical volume centred on each fixed boundary.

After geometry inversion, the revised geological contacts can be recovered, i.e. the VPem3D final model can be represented in terms of surfaces. A Gocad utility has been written by Mira Geoscience to recover “layered” VPem3D models.

2.4 Geobody inversion

One special geometry inversion option is creation of a geological shape from a unit which initially has zero thickness. Although the unit has zero thickness, there is a property contrast between it and its host. Geobody inversion represents an alternative to conventional parametric inversion to define sources with simple geometric shapes.

2.5 Fast inversion of homogeneous unit properties

VPem3D inversion of homogeneous unit properties is fast because the maximum number of “active” parameters is the number of geological units in the model, even if the model is large and complex.

Upper and lower bounds can be imposed on the conductivity of each geological unit. If the upper and lower bounds are identical, the unit in question is treated as fixed and plays no part in inversion. Thus the user can control the number of active parameters.

There is no restriction on the algebraic sign of conductivity, other than that imposed by the user via choice of bounds. Therefore complete flexibility is offered in terms of modelling conductivity contrast.

2.6 Heterogeneous unit inversion

Geological units can be heterogeneous in conductivity. Homogeneous geological units can be converted to heterogeneous units either during model construction, or subsequently. During the conversion, model cells in the new heterogeneous units can be sub-divided into sub-cells. The sub-cells can have approximately equal thickness (vertical dimension), or successive sub-cells can increase in thickness by a user-specified factor. Sub-celling unrelated to model construction can be launched either from VPview or via a control file [see the description of the *itmax* parameter in Section 7.1].

Inversion of the properties of heterogeneous units produces intra-unit variations of property. Therefore, VPem3D can perform “unconstrained inversions” *a la* UBC if desired. If conventional least squares inversion is selected, the conductivity will vary smoothly, as in a UBC model. The property values of all cells within heterogeneous units are bounded by the user-specified minimum and maximum values specified in the model file header. Heterogeneous property inversion is often applied as a final stage of inversion, e.g. after homogeneous property inversion.

2.7 Compact body inversion

A variant of heterogeneous unit inversion. Defines the subset of model cells which have the greatest potential to reduce the misfit between observed and calculated data. Therefore compact body inversion tends to define discrete, deep, highly conductive volumes which can explain the measured data. Conductivity always increases in compact body inversion, so the starting model is usually zero everywhere.

2.8 Linear and non-linear resistive limit forward algorithms

The resistive limit response of a 3D conductivity distribution is computed in VPem3D by adding the magnetic dipole responses contributed by each model cell. The magnetic dipole moment for any cell is proportional to the primary field and to the time constant of the cell. The 3D resistive limit response from each can be calculated rapidly using existing VPmg magnetic forward modelling routines. The vector contributions from each cell are combined at each receiver location.

There are two forward modelling options in VPem3D: linear and non-linear. In the **linear forward algorithm**, the magnetic moment in each cell is assumed to be parallel to the primary field. This is tantamount to the assumption that the time constant is an isotropic scalar. The linear algorithm is very fast, but it takes no account of the effect of conductor shape on EM induction. The linear algorithm is always used for airborne TEM, and is an option for ground and downhole TEM.

Shape and orientation influence induction in good conductors, with the result that the magnetic moment in a cell is not necessarily parallel to the primary field (Figure 2.8). In the **non-linear forward algorithm** the effects of shape and orientation are taken into account. Separate time constants are determined for primary field excitation in the X, Y, and Z directions by slicing the model orthogonal to the axes and analysing the current domains in each slice in turn. These time constants can be regarded as the diagonal elements of a tensor, analogous to the demagnetisation tensor in conventional magnetic modelling. When the time constant tensor is applied to the primary field, the resulting dipole moment is rotated to the appropriate direction. The non-linear algorithm is slower than the linear algorithm, and is only applied to cells with conductivity greater than a threshold value, *Cmin*. The default *Cmin* value is 1 S/m. The response from less conductive cells is always computed using the linear algorithm.

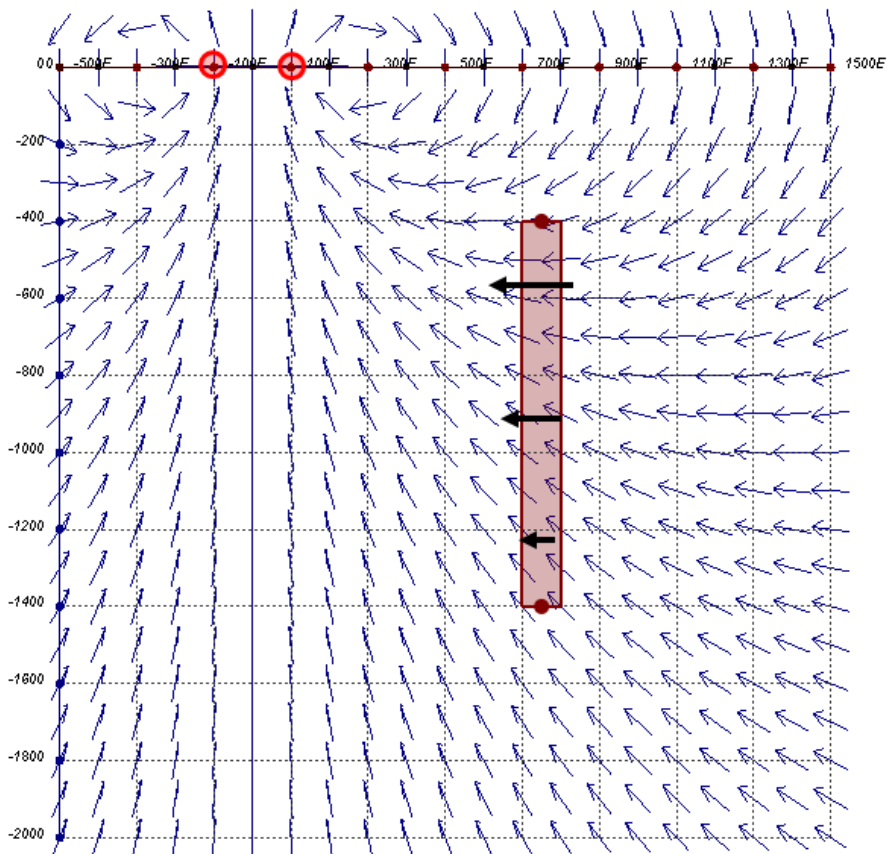


Figure 2.8: Schematic cross-section through a conductive plate (grey) excited by primary field (blue arrows) from a loop on the ground surface. Induction in the plate is dominated by the horizontal component of primary field (black arrows). Therefore “magnetisation” is horizontal, not parallel to primary field.

2.9 Modelling and inversion with a moving footprint

In airborne EM surveys, the transmitter is small in relation to the survey area. Therefore, only a minor fraction of the search volume is excited for any single measurement. This is illustrated schematically in Figure 6.2, where a hemispherical “volume of influence” is defined beneath the aircraft (hence transmitter). The term “footprint” is used to capture this idea, though the definition of footprint is not standardised: it can refer to a radius, an area, or a volume.

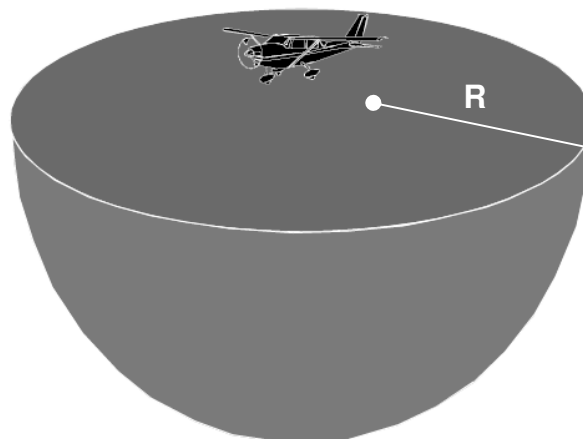


Figure 2.9: Volume of influence (or 3D footprint) for an AEM transmitter can be represented schematically as a hemisphere (after Smith & Wasylechko, 2012).

Since physically only a small fraction of the model volume is influencing the data, computationally it is advantageous to restrict attention to the subset of model cells which contribute appreciably to each measurement. In VPem3D the forward calculation of any AEM resistive limit response involves only the cells within a square prism with dimensions 400m (or 3 prism diagonal dimensions, whichever is larger). The volume of influence extends from the surface to the bottom of the model. Unlimited depth extent was adopted for two reasons, one physical and one practical. Physically, the effective depth of penetration is governed by conductivity, which is (usually) unknown; therefore it is sensible to consider the full depth extent of the model. Opting for unlimited depth extent was also expeditious because a cylindrical “footprint”, extending to the base of the model, had already been implemented in VPem3D.

2.10 Primary field from an arbitrary 3D transmitter loop

An arbitrary closed loop can be represented as a connected set of linear segments. The net magnetic field is then the vector sum of the magnetic fields associated with the individual linear current segments. An algorithm for an arbitrary piece-wise linear transmitter loop has been embedded in VPem3D. It is quite general in principle, suitable for underground loops with vertical segments as well as surface loops in rugged topography. At present the number of vertices is restricted to four. This limitation will be removed as required.

2.11 Resistive limit responses inside conductors

EM data recorded inside conductors are often erratic owing to the close proximity of the sensor to the induced currents and to local variations in conductivity. Therefore it is fairly common practice to disregard data recorded inside conductive bodies. Nevertheless, it is desirable to develop forward modelling routines capable of computing responses inside homogeneous conductors. The external resistive limit responses are modelled in VPem3D using magnetic routines. The magnetostatic routines have been extended to model resistive limits inside conductors.

Inside a highly magnetic body subjected to inducing field \vec{H}_0 , the magnetic field anomaly, $\Delta\vec{H} = \vec{H} - \vec{H}_0$, will be opposed to the inducing field owing to demagnetisation. As a result of this demagnetising field, the normal component of resultant magnetic field, \vec{H} , is discontinuous at a magnetic boundary. However, the normal component of the magnetic induction, \vec{B} , is continuous at a boundary. \vec{B} can be defined in terms of magnetic field, \vec{H} , and magnetisation, \vec{J} :

$$\vec{B} = \mu_0(\vec{H} + \vec{J}) \quad (2.1)$$

The vertical magnetic induction through the a 100m cube with vertical magnetisation is plotted in Figure 2.10. In the context of TEM modelling, the shape of the \vec{B} profile, smoothly increasing to a maximum value in the centre of the cube, captures the effect of induced current circulating in horizontal paths around the cell. Therefore, the equivalent of \vec{B} is computed at all underground measurement locations in VPem3D. This is appealing, given that \vec{B} rather than \vec{H} is the quantity measured in TEM surveys.

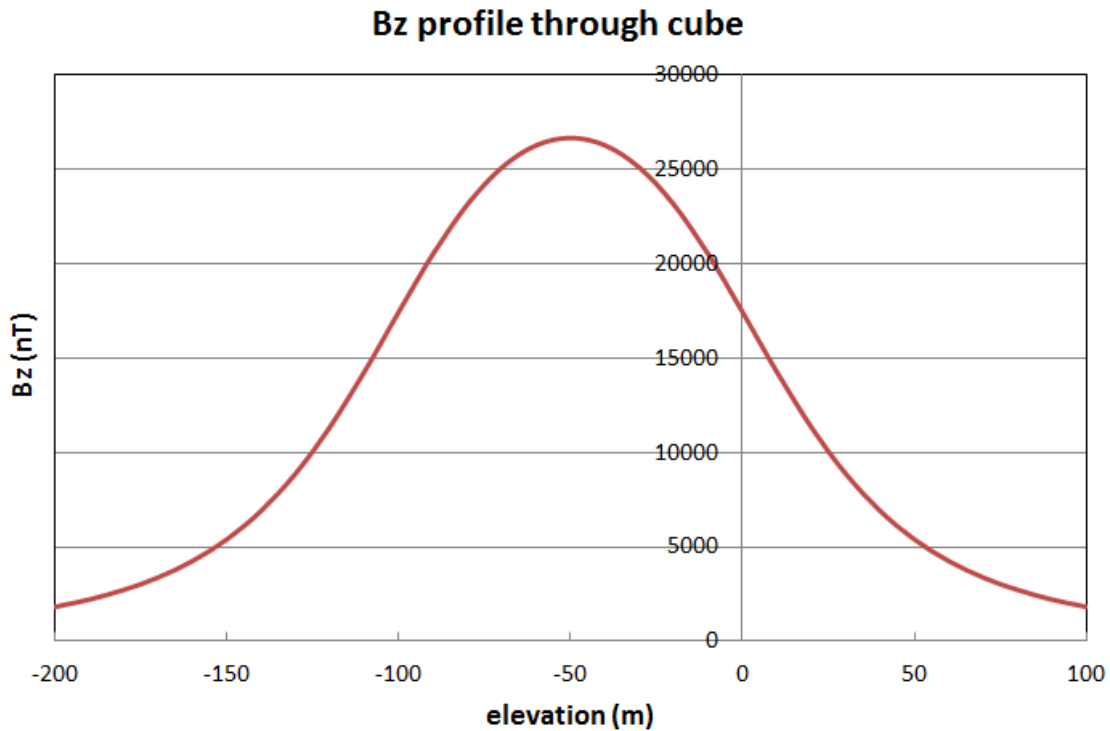


Figure 2.10: Vertical magnetic induction, B_z , profile through the centre of a 100m cube, susceptibility 1 SI, with top at RL of 0m. B_z is continuous at top and bottom of cube. Ambient field is vertical with intensity 40000nT.

2.12 Depth weighting

Depth weighting penalises model changes at shallow depths. This is often desirable, especially for ground and airborne surveys, because the receivers are most sensitive to the nearest model cells. Therefore small changes in shallow cells can have a marked effect on the data misfit. Conversely, receivers are less sensitive to deeper cells. However, in general variations at depth are of greater interest in exploration. Therefore depth weighting is intended to counteract geometrical attenuation, and hence to enable inversion to reveal possible “deep sources”. VPem3D applies depth weighting by default in geometry inversion, and user-controlled depth weighting is available as an option in heterogeneous unit inversion.

The depth weight formula used in VPem3D is as follows:

$$w(d) = \left(\frac{d + h}{d_{\max} + h} \right)^{p/2} \quad (2.2)$$

where d is the depth of a cell centre, d_{\max} is the maximum depth-to-basement in the model, p is the exponent, and h is a depth offset. h is adjusted to achieve a desired weight, w_{\max} , for the shallowest cell. The exponent varies, depending on data type. $p = 4$ for TEM resistive limits.

Thick cells exert greater influence on the inversion (have larger derivatives) by virtue of their greater volumes. Model cells often increase in thickness with depth. In such cases it may be desirable to normalise the depth weights with respect to cell thickness, i.e. to dampen the influence of thicker, deeper cells somewhat. The thickness normalised depth weights are defined by

$$w'(d) = \sqrt{\frac{\Delta_{ref}}{\Delta} \left(\frac{d + h}{d_{\max} + h} \right)^p} \quad (2.3)$$

where Δ is the cell thickness and where Δ_{ref} is a reference thickness supplied by the user.

Depth weighting can be applied to heterogeneous (sub-celled) models, as described in Section 13.8.

2.13 Conductivity weighting

3D conductivity weights (Schaa, 2010) are based directly on starting model conductivities and are less subjective than depth weights. The conductivity weights focus changes in conductive regions of the model, and penalise changes in resistive regions.

Conductivity values are mapped to weights between 0 and 1. The simplest form of conductivity weights is a linear mapping, viz.

$$w(\sigma_a) \Big|_{(x,y,z)} = 1 - \left(\frac{\sigma_a}{\sigma_{max}} \right) \Big|_{(x,y,z)} \geq 0 \quad (2.4)$$

where σ_a is the apparent conductivity at location (x,y,z) ; σ_{max} is the maximum conductivity value occurring in the model. The estimated background conductivity can be subtracted from the conductivities before calculating the weights. Conductivity weights and depth weights can be applied simultaneously. The available conductivity weighting options are described in Section 7.1 in connection with the *itmax* parameter.

2.14 Proximity weighting for fixed property cell or downhole data point

If downhole conductivity logs or core conductivity measurements are available, the conductivity can be considered known within certain “drilled” model cells. It is desirable not only to fix the conductivity in such cells, but also to suppress changes in their vicinity. Otherwise, the influence of the conductivity measurements will be confined to the fixed cells, which may be recognizable in the inverted model as “beads on a necklace”. In VPem3D, a spherical neighbourhood is defined, centred on each fixed cell (Figure 2.11). This is the same approach adopted previously for pierce points during geometry inversion (Figure 2.6). By default the radius of influence, ROI, is the depth of the data point or the distance to the nearest data point, whichever is smaller. However, the user can define the radius of influence in the control file; see Section 7.1 below.

The practical advantages of downhole TEM are the proximity of the receiver to the target, which improves the detectability (S/N), and the access to the third dimension, which improves locational accuracy. However, downhole data are a mixed blessing for inversion because the receiver becomes extremely sensitive to the conductivity and shape of the material in its immediate vicinity. Therefore, careful conditioning is required to suppress model changes adjacent to downhole measurements. It may also be necessary to filter the data prior to inversion if strong, sharp anomalies are present, especially if the model resolution is too coarse to replicate the short wavelength variations.

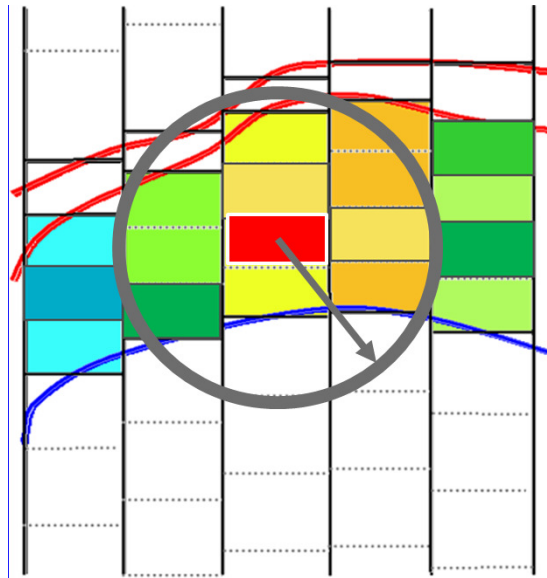


Figure 2.11: Model changes are suppressed within spherical neighbourhoods centred on each fixed property cell (coloured red).

Given the sensitivity of downhole or underground data to the host cell and its immediate neighbours, it is desirable to suppress changes within a neighbourhood of the data point. In VPem3D, a spherical neighbourhood is defined, centred on each underground data point (Figure 2.12). This is the same approach adopted previously for pierce points during geometry inversion and for fixed cells during property inversion. By default the radius of influence, R , is 2.5 times the diagonal dimension of the model prisms. However, the user can define the radius of influence in the control file; see Section 7.1 and Appendix F below.

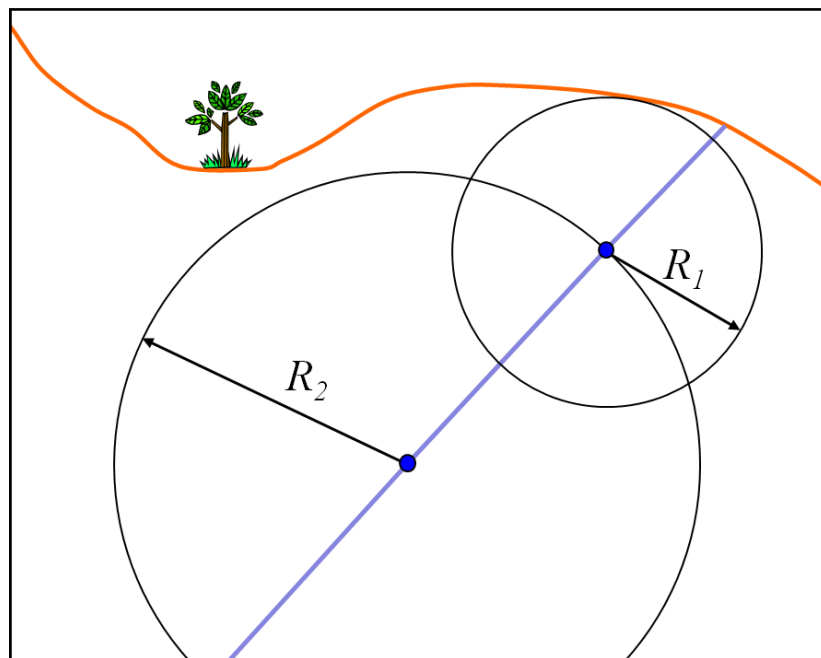


Figure 2.12: Model changes are suppressed within spherical neighbourhoods centred on each underground data point (blue dot).

The weight increases from near zero at the data point (centre of sphere) to 1 at radius R . The weight is applied to the derivatives of the underground data point with respect to changes in conductivity of the surrounding cells. The weight is small (but usually non-zero) for the derivatives of the downhole data point with respect to conductivity of the host cell; this is to enable the host cell to change during inversion, albeit in a strongly damped fashion. Clearly it is a matter of judgment as to exactly what

the minimum weight should be; currently the default 0.05. However, the user is able to define the minimum weight in the control file; see Section 7.1 and Appendix F below.

2.15 Transmitter loop wire proximity weighting

When ground or downhole TEM data are inverted, the derivatives are very high for the model cells close to loop wires, since these cells are subjected to very intense primary fields. If left unchecked, the high sensitivity to loop wires can focus model changes in the vicinity of the loop and divert attention from more geologically plausible solutions. Therefore, it is desirable to suppress changes in close proximity to transmitter loop wires. A default Tx-proximity weighting is applied by VPem3D during ground and downhole TEM inversion, to damp the derivatives associated with cells which are close to the transmitter loop wires.

In *VPem3D*, derivatives are damped during heterogeneous unit inversion of ground and downhole TEM according to the primary field intensity. The weight for the n th active cell is defined as

$$w_n = 1 - \frac{|B_{0n}| \Delta z_n}{|B_0^{\max}| + 1} \quad (2.5)$$

where Δz_n is the thickness of the n th cell, and where $|B_0^{\max}|$ is an estimate of the primary field at the centre of the transmitter loop (in pT/A). The cell thickness is applied to damp sensitivities equally, independent of cell volume.

Usually the loop proximity weights are applied in conjunction with “depth weighting” (for ground data) and “data proximity weighting” (for downhole data), since the inversion can also be compromised by high sensitivity in the vicinity of receiver locations.

2.16 Calculated data normalisation

Strictly speaking, the VPem3D rock property is time constant rather than conductivity. However, time constant is not always meaningful and is not a petrophysical property in the normal sense. The time constant of simple bodies is proportional to conductivity, but dependent on size and shape as well (Nabighian & Macnae, 1991). The constant of proportionality is also affected by the finite time interval spanned by any measured decay; ideal resistive limits are based on integration over all time. Therefore VPem3D conductivity can be regarded as proportional to conductivity, but with an unknown constant of proportionality. In exploration this somewhat elastic definition does not usually pose any serious problems because the absolute value of conductivity is generally much less important than the location and shape of the conductors.

When a starting model is derived from CDIs or 1D inversion, the VPem3D calculated resistive limits can be normalised or calibrated to conform to CDI or inverted conductivity as closely as possible. The user can elect to apply a multiplicative factor to the VPem3D calculated data in order to minimise the misfit. The application of calculated data normalisation is illustrated in Appendix E (Section 15.2).

2.17 Modelling and inversion of “total field” TEM

VPem3D can model “total field” TEM, i.e. B-field data recorded with a total field magnetometer. Specifically, VPem3D can invert sub-audio magnetic (SAM) and SAMSON data. Given that the secondary B-fields are always much smaller than the geomagnetic field, the “total field” TEM response is the component of the secondary B-field parallel to the ambient field. The transmitter can either be a closed loop or a grounded dipole. HeliSAM is treated as a variant of ground TEM, even though the data are recorded in the air.

The VPem3D polarity convention is ENU, i.e. x=East, y=North, z=Up are the positive directions. Also, current flow in the transmitter loop is anti-clockwise for VPem3D modelling, so primary B field

inside the Tx loop is up. For SAM measurements this means that a flat-lying conductor inside the loop will produce a negative anomaly in the northern hemisphere, since the secondary B-field opposes the downward oriented Earth's field.

2.18 Preferred Orientation

When the linear forward algorithm is selected, the primary field determines the “magnetisation” direction in each model cell. However, in reality the induced current in a conductor is affected by its shape as well as by the strength and orientation of the primary field. In particular, current flow in conductive plates is confined to the plane of the plate. Therefore only the primary field component orthogonal to the plate influences the induced current. In VPem3D a preferred orientation, perhaps parallel to bedding planes or to a dominant structure set, can be specified for current flow. The component of primary field orthogonal to the preferred orientation then governs the calculated resistive limit response of the model.

3 VPem3D FORWARD MODELLING & INVERSION

3.1 Forward modelling algorithms

In VPem3D, the resistive limit response is calculated as the sum of two contributions, namely a discretised 3D target response and a continuous “background” response (Figure 3.1).

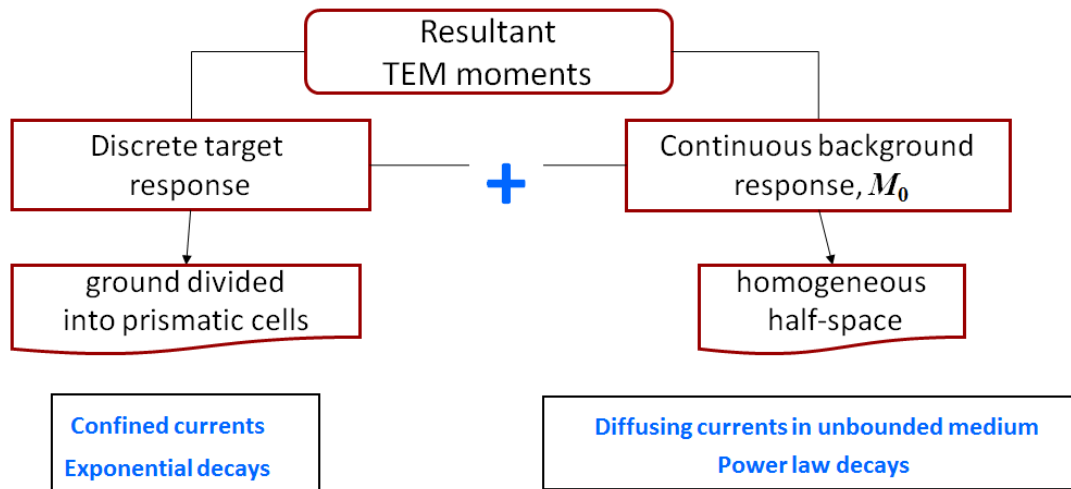


Figure 3.1: VPem3D resistive limit forward modelling schematic. Response from discretised ground is added to analytic response from homogeneous half-space.

The background response is due to the diffusion of the “smoke ring” into the host rocks. The background is assumed to be a homogeneous half-space at present. Formulae for the vertical and horizontal resistive limits on a homogeneous half-space after step shut-off of a rectangular loop are derived in Schaa & Fullagar (2012). Corresponding formulae for resistive limit components *in* a homogeneous half-space, as required for downhole TEM, were derived during the AMIRA P1022 project. [The background response is not computed for AEM at present.]

The discretised 3D model accounts for the resistive limit responses of geological conductors. The 3D target response is computed as the superposition of TEM moments from closely packed rectangular cells. Each model cell contributes to the net resistive limit response as a magnetic dipole (Figure 3.2). Dipole strength is controlled by the intensity of the primary magnetic field and the time constant of the cell.

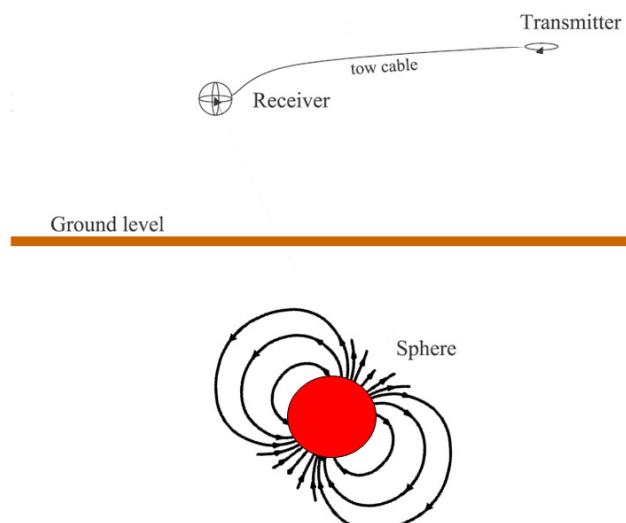
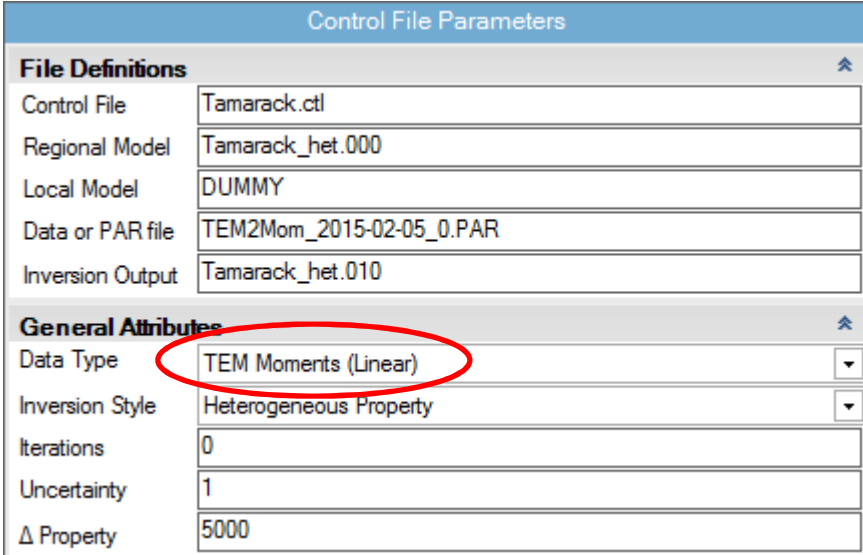


Figure 3.2: In the resistive limit, a conductive sphere produces a magnetic dipole response. This is the basis for the forward modelling algorithms in VPem3D.

There are two forward modelling algorithms in VPem3D:

- the linear scheme, which is very fast but less accurate;
- the non-linear scheme, which endeavours to account for conductor shape. The non-linear scheme is slower but more accurate. It is applied to high conductivity cells (≥ 1 S/m by default).

The user may select the linear algorithm by opting for *TEM Moments (Linear)* as the *Data Type* in the *Control File Parameters* form on the *VPview Model Definitions* page (Figure 3.2).



Control File Parameters	
File Definitions	
Control File	Tamarack.ctf
Regional Model	Tamarack_het.000
Local Model	DUMMY
Data or PAR file	TEM2Mom_2015-02-05_0.PAR
Inversion Output	Tamarack_het.010
General Attributes	
Data Type	TEM Moments (Linear)
Inversion Style	Heterogeneous Property
Iterations	0
Uncertainty	1
Δ Property	5000

Figure 3.2: Selecting the linear algorithm on the VPview *Control File Parameters* form.

In addition to their speed, VPem3D forward modelling algorithms handle zero conductivity host without difficulty, whereas more rigorous programs are often limited to a maximum contrast, e.g. $1:10^3$ for Marco.

The VPem3D forward modelling scheme has been validated against simple sphere and cube models. Gauging its accuracy has proved non-trivial since different 3D TEM programs do not necessarily agree. VPem3D and EH3DTD (UBC-GIF) resistive limit profile shapes over simple prismatic conductors are usually quite similar, but amplitudes can differ substantially. However, anomaly shape is generally more critical than amplitude for drill targeting. Anomaly shape is the key discriminant of conductor location and size, whereas amplitude is the key discriminant of conductivity. In the resistive limit, the conductivity influences the response from homogeneous bodies as a simple multiplicative factor. While achieving agreement in terms of amplitude would be desirable, for the time being VPem3D conductivity is rather elastic in absolute terms.

3.2 Inversion algorithms

VPem3D offers a great deal of flexibility for inversion of TEM, both in terms of inversion styles and constraint options (including “unconstrained”). VPem3D can invert multi-component dB/dt and B-field data sets. Downhole data from multiple holes, excited by multiple transmitter loops, can be inverted together. Ground and downhole TEM data can also be inverted simultaneously.

The aim of inversion is to achieve an acceptable degree of fit to the data, subject to geological and petrophysical constraints on the model. Inversion proceeds iteratively, i.e. by successive approximation, seeking at each stage parameter changes, Δp , which can reduce the data misfits, Δd . VPem3D solves for the model perturbation Δp using the method of Steepest Descent. The algorithm is outline in Schaa & Fullagar (2010) and Schaa (2010, Chapter 5). The steepest descent solution is very fast since no matrix inversions are performed. Forward modeling, not inversion *per se*, is the rate limiting factor in VPem3D.

Degree of fit is judged according to the magnitude of the chi-squared data norm, $L2$, and the $L1$ -data norm, defined by

$$L2 = \frac{1}{N} \sum_{n=1}^N \left(\frac{\Delta d_n}{\varepsilon_n} \right)^2 = \frac{1}{N} \sum_{n=1}^N \left(\frac{o_n - c_n}{\varepsilon_n} \right)^2$$

$$L1 = \frac{1}{N} \sqrt{\frac{\pi}{2} \sum_{n=1}^N \left| \frac{\Delta d_n}{\varepsilon_n} \right|} = \frac{1}{N} \sqrt{\frac{\pi}{2} \sum_{n=1}^N \left| \frac{o_n - c_n}{\varepsilon_n} \right|}$$

where N is the number of data, $\{o_n\}$ denotes measured data, $\{c_n\}$ denotes calculated model responses, and where ε_n is the uncertainty (standard deviation) assigned to the n th data point. The same uncertainty is currently assumed to apply to all the data. If the data uncertainties are controlled by Normal random variables with zero mean, both $L2$ and $L1$ have expected values of unity. Therefore the model is deemed “acceptable” if $L2 \leq 1$ and/or if $L1 \leq 1$.

The RMS misfit is also computed and recorded, where

$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^N (\Delta d_n)^2} = \sqrt{\frac{1}{N} \sum_{n=1}^N (o_n - c_n)^2}.$$

RMS is quoted in the data units. For an acceptable model, i.e. when VPem3D has converged, the RMS misfit should be approximately equal to ε_n .

Three inversion “styles” are offered by *VPem3D*: (i) homogeneous unit properties variable, contact elevations fixed; (ii) contact elevations variable, all conductivities fixed; (iii) heterogeneous unit properties variable, contact elevations fixed.

VPem3D can be employed for both unconstrained and constrained inversion. In unconstrained inversion, a single heterogeneous inversion run is performed, usually conditioned with depth weights and/or conductivity weights and/or by invoking compact body inversion. The conductivity of all cells can be subject to upper and lower bounds. Compact body inversion favours localised, buried, high conductivity targets. It can be used to define a target volume, which can be refined in subsequent inversion runs.

In constrained inversion a sequence of inversions is often performed. During constrained heterogeneous inversion, the starting model is normally geologically-based. The conductivity of individual cells can be subject to upper and lower bounds appropriate for the geological unit to which they belong. Individual cells can be held fixed if conductivity has been measured either downhole or on core samples. In addition, the solution can be conditioned by weights.

For the default smooth body (“least squares”) inversion, the objective at each iteration is the smallest parameter perturbation needed to halve the $L2$ data misfit. Maximum allowed perturbation size is defined in terms of absolute property change, for property inversion, or in terms of fractional change in depth, for geometry inversion. The perturbation vector is truncated if necessary.

Stochastic inversion is an option for heterogeneous property inversion. In this case, individual model cells are subjected to random property perturbations. The perturbation is accepted if it produces a reduction in misfit and if it is compatible with the expected property distribution within the geological unit.

4 MODELLING & INVERTING AIRBORNE TEM DATA

4.1 Introduction

Development of a fast modelling and inversion capability for airborne TEM involved resolution of a number of technical issues:

- Inversion speed is especially critical for AEM, given the large data volumes. Therefore, In order to maximise speed, the linear algorithm (as described in Sections 2.8 and 3.1) is employed by VPem3D for airborne EM (AEM) forward modelling. In the linear algorithm the response from each cell is controlled by the primary field at the cell centre, without reference to conductivity gradients (body shape). Slicing and domaining are not applied. The additional speed is achieved at the cost of some accuracy. However, for AEM it is arguable whether rigorous 3D inversion is always warranted, given that the objective is often regional reconnaissance rather than drill targeting. The asymmetric data coverage on most surveys (detailed along line, coarse across line) also compromises the definition of 3D geological features, even if signal/noise is favourable. Consequently the speed versus accuracy trade-off entailed in the choice of linear algorithm is attractive in many if not most cases. More sophisticated EM software can be employed to refine the interpretation of selected anomalies later, if required.
- The AEM transmitter does not excite the entire survey area at any given time. Therefore, as described in Section 2.9 above, a “moving footprint” approach has been implemented in VPem3D, similar to that employed by Cox et al (2010).
- Both transmitter and receiver positions are required, but usually only one position is recorded in the data file. Therefore, the transmitter and receiver positions are both written to the data file by AEM2Mom after computation of the resistive limit data.
- The sign of the in-line component reverses with flight direction, relative to a fixed Earth frame. Therefore, the “true” algebraic sign of the in-line component is preserved in VPem3D during modelling and inversion, but in VPview the in-line component is displayed as positive always.

The four stages in VPem3D modelling and inversion of airborne TEM are briefly described below. A worked example is included in Appendix B (Section 12).

4.2 Computing resistive limit data

The program, AEM2Mom converts dB/dt or B-field AEM time decays to 1st order moments (resistive limits). Survey parameters are passed to AEM2Mom in an EmaxAIR parameter file; the EmaxAIR PAR file format is defined in the EmaxAIR User Guide (see Appendix A below). If a PAR file does not exist, it can be created by means of the VPview *Prepare PAR file utility* under the *Data* menu (Figure 4.1).

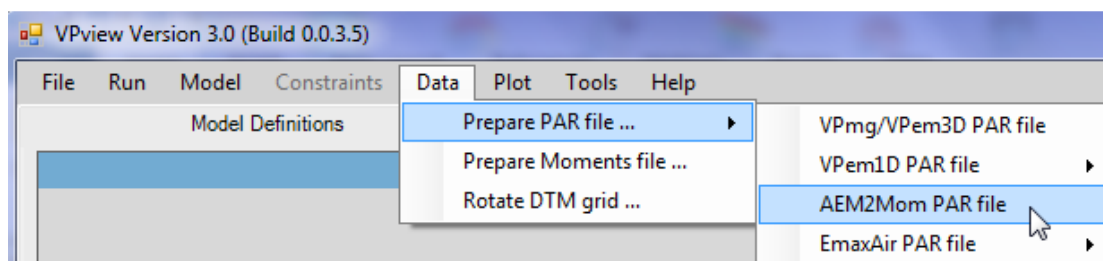


Figure 4.1: The *Prepare PAR file* utility is an option under the VPview *Data* menu.

AEM2Mom reads column ASCII data or Geosoft XYZ format (with “Line” identifiers). However, AEM2Mom does not read

- times written as hours:min.sec
- latitude and longitude if written as deg.min.sec

-
- character labels, e.g. for anomalies

Therefore, be selective if exporting from GDB to Geosoft XYZ

If AEM data are normalised with respect to primary field, the normalisation is undone by AEM2Mom in order to recover resistive limits in pTms. For example, Spectrem data are usually normalised with respect to the primary B field, and VTEM data are normalised with respect to Tx moment x Rx area, i.e. Am⁴. In order to recover resistive limits in pTms, the actual Tx moment (in Am²) is specified in the AEM2Mom PAR file.

The uncertainty is characterised in AEM2Mom by PCERR (the % error) and SDMIN (the minimum standard deviation). The standard deviation assigned to a TEM channel with measured value V is $0.01 * PCERR * |V| + |SDMIN|$. If SDMIN > 0, AEM2Mom truncates non-monotonic decays; thus V can be negative, but |V| cannot increase with time. If SDMIN < 0, AEM2Mom accepts all data provided $|V| > |SDMIN|$; thus AEM2Mom will integrate through cross-overs in this case. If less than 1/3 of the channels are included in the integration, the resistive limit is discarded. The standard deviations computed for the resistive limits are recorded in the moment data file, but are not currently passed through to VPem3D.

Both Tx and Rx positions in 3D are required for VPem3D for AEM modelling. The (X,Y) position defined in the contractor's data file refers to either Tx, Rx, or their midpoint. AEM2Mom calculates both Tx and Rx (X,Y) positions from the position provided (once its identity has been established) using the notional Tx-Rx horizontal offset, and the direction of flight. The Tx and Rx elevations are also required. Often the Tx GPS elevation is specified in the data file, in which case the Rx elevation can be computed using the notional Tx-Rx vertical offset. Sometimes the elevations can be computed by combining ground elevation with Rx altitude. If it is not possible to determine the Tx and Rx elevations, the Tx and Rx altitudes are recorded in the AEM2Mom output file, with the Rx altitude multiplied by -1. VPem3D recognises these values as altitudes, and computes the corresponding Tx and Rx elevations using ground elevations from the conductivity model.

The VPem3D model grid is oriented parallel and perpendicular to flight lines. AEM2Mom rotates the data into local coordinates, with the x-axis oriented along flight lines. The local coordinate system is defined by the #ROTATE# record in the parameter file. The #ROTATE# record is not needed if flight lines are oriented east-west, nor if flight lines are very close (say within 2 degrees) of N-S.

The Tx type and the data component(s) to be inverted are specified in the VPem3D PAR file which is created by AEM2Mom. A dipole Tx is assumed for slingram systems; the Tx coordinates are labelled VDX, VDY, VDZ in that case. For central loop systems, the Tx loop is assumed to have a finite radius, and the coordinates of the loop centre are labelled CLX, CLY, CLZ. The moment (resistive limit) data are labelled RLX, RLY, RLZ. RLX is the along-line component. The along-line components recorded in the contractor's file are assumed positive in the direction of advance. In the VPem3D data file, the along-line component polarity is fixed with respect to the Earth, i.e. changes in accordance with the direction of flight; AEM2Mom applies the required polarity changes. AEM2Mom is restricted to 2-component (Z and X) data sets at present.

The Tx moment and, for central loop systems, Tx radius must be specified either in the moment data file header or in the control file. The latest version of AEM2Mom writes the Tx moment and radius to the data file header. If using an old moment data file, without a header, the Tx moment and radius can be added to the control file via the Control File Parameters table (see below) or using a text editor. Tx moment (Am²) takes the place of "ambient field" on the 1st line of the control file and, for central loop systems, Tx loop radius (m) takes the place of inclination. See Section 7.1 below.

Control File Parameters	
File Definitions	
Control File	Fwd_calc.ctf
Regional Model	Forrestania_IR2_het.mod
Local Model	DUMMY
Data or PAR file	Forrestania_VTEMmax_AEM2Mom_late_VPem.PAR
Inversion Output	Forrestania_IR2_het.000
General Attributes	
Data Type (AEM)	TEM Moments (Linear)
Inversion Style	Heterogeneous Property
Iterations	0
Uncertainty	0.005
Δ Property	5000
Advanced Options	
Downhole Data	No
SAM Data	No
DC Level	From regional model, retain cells (-101)
Self Demag	Off
User ROI	
Parameters	
Parameter	Value
Transmitter Parameters	
Radius	17.50
Moment	0.000000E+000
Receiver Parameters	
Start Time (ms)	0.0000
End Time (ms)	0.0000

4.3 Creating a starting model

Simple layered models can be created using the *Create New Model* utility under the *Model* menu in VPview.

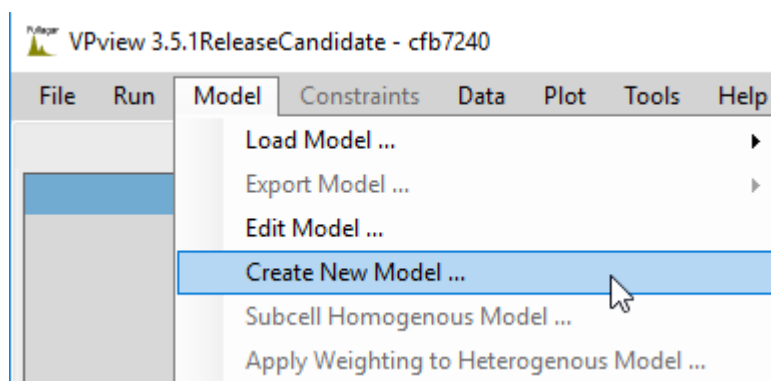


Figure 4.2: The *Create New Model* utility is an option under the VPview *Model* menu.

Model preparation involves creating a rectangular mesh (voxet) in the local coordinate system, i.e. oriented parallel/orthogonal to the flight lines. The recommended across-line dimension for model

prisms is equal to the flight line spacing. The recommended along line dimension for model prisms is half the Tx-Rx offset for slingram systems, or half the terrain clearance for central loop systems. Such prism dimensions will capture the full resolution of the survey. Ideally, the flight lines should track across prism centres.

The VPview *Create New Model* utility generates layered models, with a single cell spanning the entire thickness of each layer. Each layer (geological unit) is uniform in conductivity initially. In order to permit conductivity variations within layers, they must be converted to heterogeneous units. If geological units are defined as “Hetero” in VPview, VPem3D automatically converts them to heterogeneous units when the model is saved. If the layer thickness is greater than the specified “Cell Size”, VPem3D will divide the layer into sub-cells of the desired thickness. See section 12.3 below.

Another option is to construct a 3D conductivity starting model via interpolation of conductivity-depth images (CDIs) or 1D inversions. VPview includes utilities to construct starting models from EmaxAIR CDIs, as illustrated in Section 15 (Appendix E). Alternatively, a VPem1D model can be adopted as the starting model for VPem3D.

The simplest model, suitable for “unconstrained” inversion, is comprised of a single “host” unit overlying basement. Sub-cells in the host unit generally increase in thickness with depth, e.g. an expansion factor can be applied to the thickness of successive cells during model construction. If the Cell Size is not an integer, the decimal part is interpreted as an expansion factor. Specifically, if the Cell Size were entered as 100.1, then the thickness of successively deeper cells would increase by a factor of 1.1

Depth weighting is normally applied for “unconstrained” heterogeneous property inversion; the procedure is illustrated in Section 13.8. Conductivity weighting, which focusses changes in the conductive zones, is often beneficial if the starting model is based on CDIs or 1D inversion. Depth and conductivity weighting options are defined in Section 7.1.

Conductivity is specified in mS/m. Minimum and maximum values for each geological unit can be defined using the *Create New Model* utility. During subsequent modelling and inversion the conductivity starting values and bounds are displayed in the *Property Table* on the VPview *Model Definitions* page.

4.4 Forward calculation

Before launching inversion it is advantageous to run a forward calculation, to ensure that the starting model and flight lines are “as expected”, and to examine the degree of fit between observed and calculated data. Examination of observed and calculated profiles can reveal inconsistencies, e.g. with polarity conventions.

A control file is required for a forward calculation. The control file can be created using the VPview *New VP control file* option; see Section 12.4 below. Set the maximum number of iterations [*itmax*] to zero. Launch the forward calculation via the VPview *Run VPxx from file* option.

When modelling AEM, VPem3D identifies the measured resistive limit with Tx-Rx midpoint closest to centre of each model prism, and assigns it to the prism centre location. This data re-sampling eliminates spurious geometrical effects. The positional adjustments involved are normally of the order of the along-line sampling interval, hence small in relation to the lateral resolution of the survey. After re-sampling, VPem3D creates a new file, RESAMPLED_AEM.DAT, containing the data points at model prism centres. On subsequent runs, VPem3D will read the re-sampled data from this file.

4.5 Inversion

Adjust model geometry or conductivity, subject to constraints (if available), to optimise the data fit. Often a sequence of inversions is performed, e.g. compact body inversion followed by more conventional heterogeneous unit inversion. The inverted model file from one run can be used as the starting model file for a subsequent inversion run. However, only a single heterogeneous unit inversion is required in the “unconstrained” case.

Prior to property inversion, check the Property Table for the starting model (displayed on the VPview *Model Definitions* form) to ensure that the Min and Max conductivities for each active unit are appropriate. If the Max and Min values are identical, the unit in question will play no part in the inversion. Check too that the permitted maximum change in conductivity per iteration [Δ Property] is appropriate. If the control file parameters have been altered, launch the inversion via the VPview *Run\Run VPxx from screen* option; otherwise select the *Run\Run VPxx from file* option.

The noise level (data uncertainty) is defined in the control file in data units [pTms].

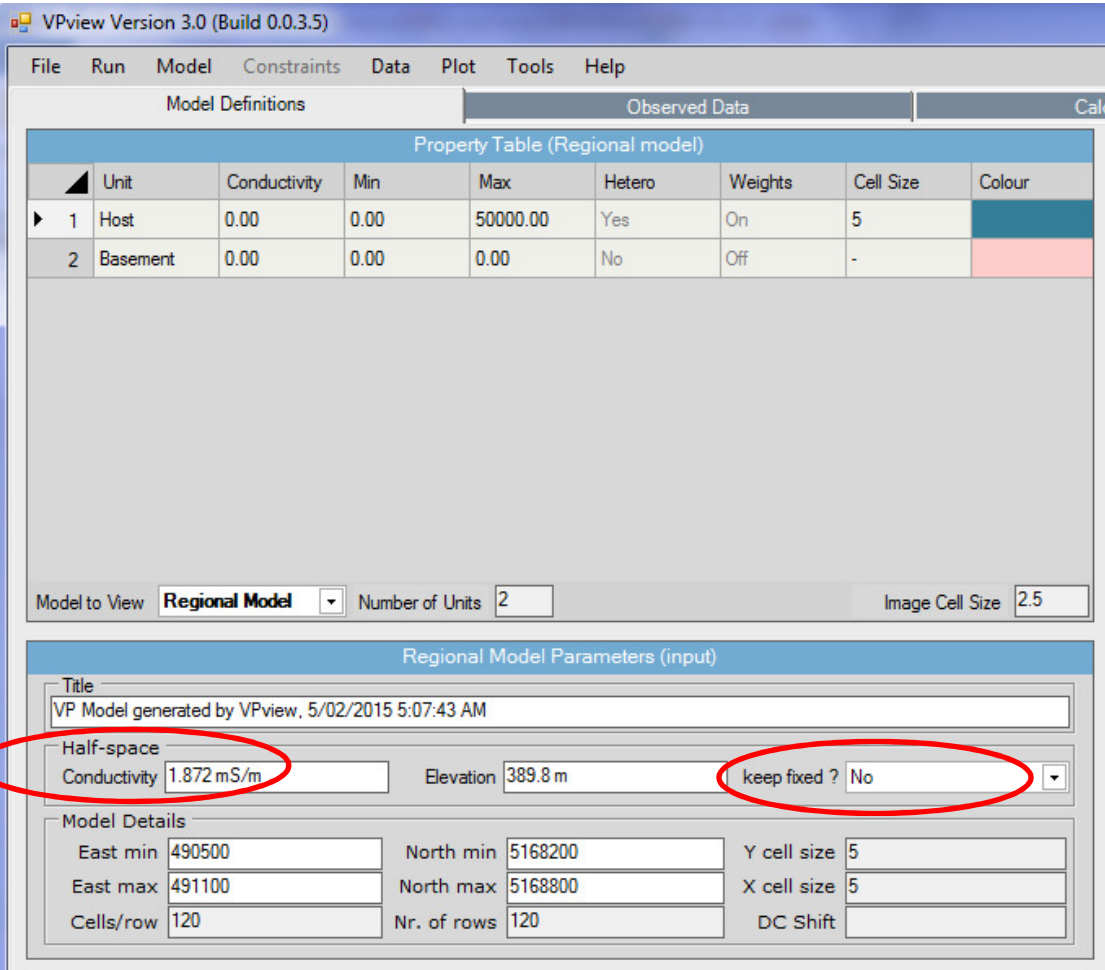
After the inversion has completed, display the model by using the VPview *Model\Load Model* option. When satisfied with the inverted model, it can be exported to UBC format via the *Model\Export model* option.

5 MODELLING & INVERTING DOWNHOLE TEM DATA

5.1 Introduction

Development of a fast modelling and inversion capability for downhole TEM involved resolution of a number of technical issues:

- The host response underground is quite different from the host response above ground. Therefore an analytic formula for the resistive response at underground locations within a homogeneous half-space was derived during the AMIRA P1022 project. The host conductivity can be specified in the *Model Parameters (input)* table at the bottom of the VPview *Model Definitions* form (Figure 5.1). The user can fix the host conductivity, or allow it to vary (in which case it is adjusted by VPem3D to minimise the L2 misfit).



The screenshot shows the VPview software interface. The main window is titled 'VPview Version 3.0 (Build 0.0.3.5)'. The menu bar includes File, Run, Model, Constraints, Data, Plot, Tools, and Help. The 'Model Definitions' tab is active, showing a 'Property Table (Regional model)' with the following data:

Unit	Conductivity	Min	Max	Hetero	Weights	Cell Size	Colour
1 Host	0.00	0.00	50000.00	Yes	On	5	
2 Basement	0.00	0.00	0.00	No	Off	-	

Below the table, the 'Model to View' is set to 'Regional Model' and 'Number of Units' is 2. The 'Image Cell Size' is 2.5. The 'Regional Model Parameters (input)' form is shown below, with the following fields:

- Title: VP Model generated by VPview, 5/02/2015 5:07:43 AM
- Half-space Conductivity: 1.872 mS/m (circled in red)
- Elevation: 389.8 m
- keep fixed?: No (circled in red)
- Model Details:
 - East min: 490500, North min: 5168200, Y cell size: 5
 - East max: 491100, North max: 5168800, X cell size: 5
 - Cells/row: 120, Nr. of rows: 120, DC Shift: [empty]

Figure 5.1: The effect of a homogeneous host can be accounted for by setting the *Half-space conductivity* to a non-zero value. The *Half-space conductivity* can either be fixed, or allowed to vary.

- The EM response inside a conductor can be markedly different from the external response. The resistive limit inside a conductor is computed as described in Section 2.12 above.
- Underground measurements are strongly affected by the material in their immediate vicinity. Therefore, property changes are damped within a spherical “volume of sensitivity” around each data point during inversion, as described in Section 2.15 above. The default radius of sensitivity is 2.5 times the diagonal dimension of the model prisms. However, the user can adjust the radius; see the description of *User_min_ROI* in Section 7.1 below.
- Display of downhole data is inescapably three dimensional in nature. Therefore VPview includes options for display of downhole data locations and profiles under the *Plot* menu.

The four stages in VPem3D modelling and inversion of downhole TEM are briefly described below. A worked example is included in Appendix C (Section 13).

5.2 Computing resistive limit data

The TEM2Mom utility converts ground and downhole TEM decays to resistive limits in pTms/A. TEM2Mom can be accessed from the VPview/Data menu.

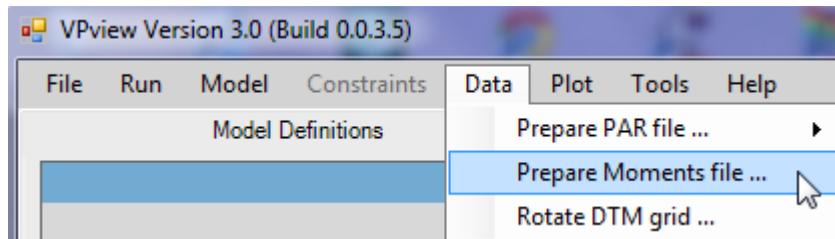


Figure 5.2: Accessing TEM2Mom from VPview

The dB/dt or B-field data are expected in TEM format, as exported by Maxwell. Include the Tx loop vertex coordinates and the drill hole collar position in the header (identified with keywords XCOLLAR:, YCOLLAR:, and ZCOLLAR:). Either direction cosines or dip and azimuth must be included in the TEM file to define the borehole trajectory.

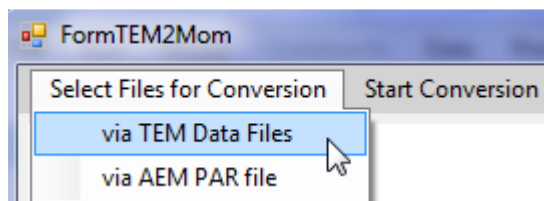


Figure 5.3: Specifying TEM file format, for downhole or ground TEM.

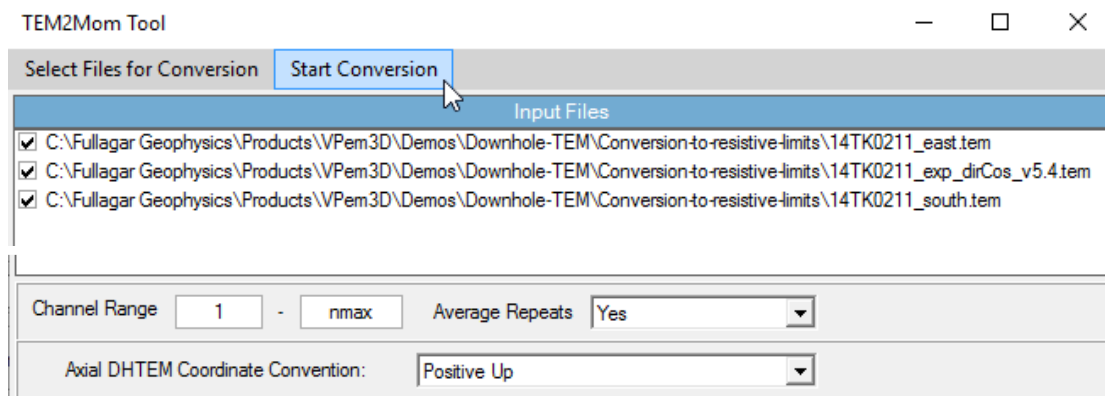


Figure 5.4: Selecting the TEM files to be processed by TEM2Mom, and the processing parameters.

The channel range (hence time interval for integration) and downhole TEM polarity convention (positive up for Crone, positive down for UTEM) can be adjusted by editing the TEM2Mom form (Figure 5.4) or via command line (see Section 7.3). Time range, and to a lesser extent waveform, affect the resistive limit amplitudes. Therefore, ensure that the channel times are identical for all TEM files selected. A warning is posted by VPview if the time range varies by more than 10 μ s.

For UTEM data the expected unit is nV/A. The primary field should be removed from the data. TEM2Mom assumes the UTEM Bx component is oriented north, By is east, and Bz is down. The

expected UTEM anomaly polarity is vertical component negative in a vertical hole passing through a horizontal plate below the centre of the Tx loop. [UTEM component identities and polarities are adjusted by TEM2Mom to conform to VPem3D conventions, i.e. Bx east, By north, Bz positive up, and in-hole Bz anomaly positive.]

TEM2Mom outputs the resistive limit components, (RLX,RLY,RLZ), in one of two column ASCII formats, as described in Section 7.2 below. The default format for downhole TEM is denoted #VPem2. However, the other format, denoted #VPem#, can be used if all the transmitter loops are rectangular. Sample #VPem# output is shown in Figure 5.5.

	RXX	RXY	RXZ	RLX	RLY	RLZ
LINE	14TK0211	exp_dirCos_v5.4	DCX=490857.80	DCY=5168536.00	DCZ=395.20	
490852.727	5168535.457	335.418	-137.8681	-13.28204	63.37446	
490849.484	5168535.076	295.551	-144.4191	-15.40307	87.97356	
490846.093	5168535.120	255.696	-115.4781	-17.14873	127.5568	
490844.477	5168535.222	235.761	-72.95573	3.554756	134.8624	
490842.855	5168535.363	215.828	68.44801	19.53473	117.1285	
490841.222	5168535.550	195.895	95.77328	11.01533	94.28712	
490839.595	5168535.778	175.963	107.5963	9.392080	93.23209	
490837.975	5168536.022	156.030	85.80414	9.002474	105.0325	
490836.334	5168536.308	136.100	65.00407	1.538284	75.99016	
490834.677	5168536.652	116.171	45.12812	2.021022	76.07790	
490833.027	5168537.037	96.243	14.98543	-16.81870	61.41261	
490831.386	5168537.427	76.314	6.718107	-31.75219	70.46153	
490829.741	5168537.828	56.386	-12.82107	-40.80534	83.23115	
490828.094	5168538.237	36.458	-56.11839	-50.39714	85.65906	
490826.475	5168538.656	16.528	-138.7791	-86.52017	113.1756	

Figure 5.5: Excerpt from the start of a #VPem# format resistive limit data file produced by TEM2Mom. (RXX,RXY,RXZ) define the receiver location. (RLX,RLY,RLZ) are the east, north, and up resistive limit components respectively. The hole ID (labelled "LINE") and collar coordinates, (DCX,DCY,DCZ), are specified on the 2nd line.

TEM2Mom rotates the components into the Earth frame coordinates using hole survey information (either dip and azimuth or direction cosines) included in the TEM file. The resistive limit ("TEM moment") data file has extension MOM.

When TEM2Mom is run from VPview, a PAR file is created to define the fields in the resistive limit data file, as required by VPem3D. The VPem3D PAR file formats corresponding to the #VPem# and #VPem2 data formats are described in Section 7.3 below. In the sample #VPem# PAR file shown in Figure 5.6, columns 4, 5, and 6 contain RLX, RLY, and RLZ data respectively.

```
#VPem#
TEM2Mom_2015-02-05_0.mom
19
-3
4      RLX
5      RLY
6      RLZ
7      LX1
8      LX2
9      LX3
10     LX4
11     LY1
12     LY2
13     LY3
14     LY4
15     LZ1
16     LZ2
17     LZ3
18     LZ4
19     STN
```

Figure 5.6: VPem3D parameter (PAR) file for #VPem# format resistive limit data file generated by TEM2Mom.

The (LXn,LYn,LZn) triplets define the coordinates for the nth Tx loop vertex. In this variant of the PAR file format, identified with #VPEM# on the first line, the Tx loop is assumed to be rectangular. If more than 4 vertices are recorded in the TEM file header, TEM2Mom computes the vertices of the best-fitting rectangular loop. Irregular (non-rectangular) loops with an arbitrary number of vertices can be accommodated via the #VPEM2 format; see Section 7.3 below.

5.3 Creating a starting model

Simple layered starting models for VPem3D can be created using the *Create New Model* utility in the VPview/Model menu.

For unconstrained inversion, the starting model can consist of a single uniform conductivity layer overlying VPem3D basement. The layer should be divided into sub-cells, i.e. converted to a heterogeneous unit, prior to running the unconstrained (heterogeneous unit) inversion, in order to capture the spatial variation of primary field. Tick the “Hetero” check box and specify the vertical dimension (Cell Size) of the sub-cells in the *Property Table* on the *Model Parameters* form.

Another option is to construct a 3D conductivity starting model via interpolation of conductivity-depth images (CDIs) or 1D inversions. VPview includes utilities to construct starting models from Emax CDIs, as illustrated in Section 15 (Appendix E). Alternatively, a VPem1D model can be adopted as the starting model for VPem3D.

If a more complicated geological model exists, Mira Geoscience has utilities to convert almost any 3D model format into VPem3D format.

Impose constraints, if available. If intending to perform geometry inversion, flag model contacts as fixed, bounded, or free depending on their geometrical relationship to existing drill holes; see Section 2.3 above. The constraint flags are defined in Section 7.4 below. If intending to perform heterogeneous property inversion, fix the conductivity of individual cells if they contain core or log values. Conductivity changes near fixed cells are suppressed by VPem3D using weights; see Section 2.15. The user can control the radius of influence; see the description of *User_min_ROI* in Section 7.1 below. Utilities written by Mira Geoscience can trace drill holes through the model and assign appropriate constraint flags.

5.4 Forward calculation

Before launching inversion it is advantageous to run a forward calculation, to ensure that the starting model, loop geometry, and drill hole geometry are all “as expected”, and to examine the degree of fit between observed and calculated data. Examination of observed and calculated profiles can identify serious inconsistencies, e.g. with polarity conventions.

The noise level (data uncertainty) is defined in the control file in data units [pTms/A].

A control file is required for a forward calculation. The control file can be created using the VPview *File\New VP control file* option. Set the maximum number of iterations [*itmax*] to zero. Launch the forward calculation via the VPview *Run\Run VPxx from file* option.

At this stage it is usually beneficial to assess the effect of a uniform host conductivity on the downhole TEM. To do so, display the *Model Parameters (input)* table on the VPview *Model Definitions* form, set the Half-space conductivity to 1 mS/m, and allow it to vary [keep fixed ? = No].

5.5 Inversion

Adjust model geometry or conductivity, subject to constraints (if available), to optimise data fit. Often a sequence of inversions is performed. The inverted model file can be used as the starting model file

for any subsequent inversion runs. However, only a single heterogeneous unit inversion is required in the “unconstrained” case.

Prior to property inversion, check the Property Table for the starting model (displayed on the VPview *Model Definitions* form) to ensure that the Min and Max conductivities for each active unit are appropriate. If the Max and Min values are identical, the unit in question will play no part in the inversion. Check too that the permitted maximum change in conductivity per iteration [Δ Property] is appropriate. If the control file parameters have been altered, launch the inversion via the VPview *Run\Run VPxx from screen* option; otherwise select the *Run\Run VPxx from file* option.

Weighting is applied automatically to suppress changes in conductivity of cells close to the transmitter wires; see Section 2.16. It may be desirable to apply depth weighting as well, to focus changes more strongly at depth, as described in Section 2.13. Control file parameter settings for depth weighting are documented in Section 7.1. Application of depth weights is illustrated in Section 13.8 below.

If performing heterogeneous unit inversion, it is usually desirable to suppress model changes close to the data points. The measured downhole TEM is especially sensitive to the conductivity of cells which contain data points. VPem3D applies “proximity weights” within a sphere centred on each data point. The default radius of influence (ROI) is 2.5 times the diagonal dimension of the model prisms. The weighting factor (applied to the conductivity derivatives) increases radially from a minimum value at the data point to 1 at the ROI. The user can adjust the ROI and the minimum weight, or disable the weighting, by adjusting the User_ROI parameter in the control file; see Section 7.1.

After the inversion has completed, display the model by using the VPview *Mode\Load Model* option. With VPem3D it is quite common to complete more than one inversion run. For example, homogeneous unit inversion followed by geometry inversion. When satisfied with the inverted model, it can be exported to UBC format via the *Mode\Export model* option.

6 MODELLING & INVERTING GROUND TEM DATA

6.1 Introduction

Development of a fast modelling and inversion capability for ground TEM involved resolution of a number of technical issues:

- In regions with appreciable topography, the transmitter loop is not planar and horizontal. Also, the non-linear forward algorithm required modification to account for the fact that some horizontal slices through the shallow portions of a model with topographic relief are partly in air.
- Ground TEM measurements are strongly affected by the material in the immediate vicinity of the transmitter loop wires; during inversion this high sensitivity must be damped, otherwise property changes will be concentrated around the wires. Therefore a “loop weighting” routine has been implemented in VPem3D, as outlined in Section 2.16 above. Depth weighting, described in Section 2.13, is normally applied as well during property inversion of ground TEM, given that the receivers are very sensitive to the conductivity of shallow cells.
- It is possible to model and invert ground and downhole data simultaneously. Also, data from hybrid TEM systems, with large fixed transmitter loops and airborne receivers, such as HeliSAM, can be inverted simultaneously with ground TEM.

The four stages in VPem3D modelling and inversion of ground TEM are briefly described below. A worked example is included in Appendix D (Section 14).

6.2 Computing resistive limit data

The TEM2Mom utility converts ground and downhole TEM to resistive limits in pTms/A. TEM2Mom can be accessed from the VPview/Data menu.

The data are expected in TEM format, as exported by Maxwell.

Care is required with component labels and polarity. There is no universal standard for ground TEM acquisition, but commonly the along-line survey component is labelled “x”. The polarity of the x-component may be positive in a nominated direction, e.g. northeast for a set of NE-SW survey lines, or polarity may be positive in the direction of advance. Similarly, the component orthogonal to the survey line is often labelled “y”. The polarity of the y-component may be positive in a nominated direction, e.g. northwest for a set of NE-SW survey lines, or it may be defined relative to the direction of advance. The user needs to understand the contractor’s conventions before attempting to invert horizontal component data.

In VPem3D the resistive limit components, (RLX,RLY,RLZ), are oriented parallel to the coordinate system adopted for the conductivity model. The model coordinate x, y, and z axes are positive towards model east, north, and up respectively. If the x and y model axes are oriented parallel and perpendicular respectively to survey lines, then RLX will relate directly to the measured x-component (assuming the contractor’s “x” is along line) provided the contractor’s polarity is “positive east”. Likewise, RLY will relate directly to the measured y-component (assuming the contractor’s “y” is across line) provided the contractor’s polarity is “positive north”. If the contractor’s polarity is linked to direction of advance, it will be necessary to reverse the polarity of RLX and RLY on some survey lines.

If the survey design includes orthogonal lines, then it will usually be necessary to alter the component labels on some lines. For example, a contractor may label the along-line component as “x” on both east-west and north-south survey lines; in this case the “x” component recorded on the north-south lines would normally relate to RLY in VPem3D.

The adjustments to labels and polarity can be made either on the contractor’s data, prior to running TEM2Mom, but it is usually more convenient to edit the PAR file and, if necessary, the ...MOM.XYZ data file generated by TEM2Mom. In order to interchange RLX and RLY, their respective columns should be swapped by editing the PAR file; the PAR file format is defined in Section 7.3 below. Only if a change of sign is required will it be necessary to edit the ...MOM.XYZ file, i.e. to multiply values by -1 for the component in question along affected survey lines.

Direction of advance can also affect the sign of the offset (SEP) between Tx and Rx in slingram surveys. The Maxwell convention is to define SEP as positive if the Tx is “in front” of the Rx. Maxwell assumes that the data are provided in chronological order, i.e. in the order they were actually measured. However, data are sometimes sorted into a different order prior to input to Maxwell, e.g. in order of increasing active coordinate. Therefore care is required in order to ascertain the contractor’s data processing conventions in order to ensure that the correct survey geometry is communicated to VPem3D.

If the survey lines are oblique in the coordinate system adopted for the VPem3D model, then VPem3D must apply a rotation to its computed “east” and “north” components in order to calculate RLX and RLY components in the contractor’s along-line and across-line directions. The rotation is performed using the bearing of the survey lines, defined in degrees clockwise from the model north direction. This angle is communicated to VPem3D via the DEC parameter, specified in the control file; see Section 7.1 below. This bearing defines the positive RLX direction for modelling and inversion. If the survey lines are oriented north-south, then DEC=0 and RLX is positive towards model north.

TEM2Mom outputs the resistive limit data in VPem3D column ASCII format, as described in Section 7.2 below. The resistive limit data file has extension MOM.

TEM2Mom also creates a PAR file, which defines the fields in the MOM file, as required by VPem3D.

6.3 Creating a starting model

Simple layered starting models for VPem3D can be created using the VPview *Create New Model* utility in the VPview/Model menu.

Usually the model mesh is oriented parallel/orthogonal to the survey lines. The recommended across-line dimension for model prisms is equal to the line spacing. The recommended along line dimension for model prisms is equal to the data spacing. Such prism dimensions will capture the full resolution of the survey. Ideally, the model prism centres should coincide with data points.

The *Create New Model* utility generates layered models, with a single cell spanning the entire thickness of each layer. Each layer (geological unit) is uniform in conductivity initially. In order to permit conductivity variations within layers, they must be converted to heterogeneous units. If geological units are defined as “Hetero” in VPview, VPem3D automatically converts them to heterogeneous units when the model is saved. If the layer thickness is greater than the specified “Cell Size”, VPem3D will divide the layer into sub-cells of the desired thickness. See section 12.3 below.

For unconstrained inversion, the model can consist of a single uniform conductivity layer overlying VPem3D basement. The layer should be divided into sub-cells, i.e. converted to a heterogeneous unit, prior to running the heterogeneous unit inversion in order to capture the spatial variation of primary field. Tick the “Hetero” check box when using the *Create New Model* utility and specify the vertical dimension (Cell Size) of the sub-cells in the *Property Table* on the *Model Parameters* form. Sub-cells in the host unit generally increase in thickness with depth, reflecting the loss of resolution. An expansion factor can be applied to the thickness of successive cells during model construction. If the Cell Size is not an integer, the decimal part is interpreted as an expansion factor. For example, if the Cell Size were entered as 100.1, then the thickness of successively deeper cells would increase by a factor of 1.1

Another option is to construct a 3D conductivity starting model via interpolation of conductivity-depth images (CDIs) or 1D inversions. VPview includes utilities to construct starting models from EmaxAIR CDIs, as illustrated in Section 15 (Appendix E). Alternatively, a VPem1D model can be adopted as the starting model for VPem3D.

If a more complicated geological model exists, Mira Geoscience has utilities to convert 3D models from all common geological modelling packages into VPem3D format.

Depth weighting, briefly described in Section 2.13 above, is often applied prior to “unconstrained” heterogeneous unit inversion; the procedure is illustrated in Section 13.8. Conductivity weighting, which focusses changes in the conductive zones, is often beneficial if the starting model is based on CDIs or 1D inversion. Depth and conductivity weighting options are defined in Section 7.1.

6.4 Forward calculation

Before launching inversion it is advantageous to run a forward calculation, to ensure that the starting model, Tx loop(s) and survey lines are all “as expected”, and to examine the degree of fit between observed and calculated data. In particular, a forward calculation provides an opportunity to check polarity of measured and calculated components; see Section 6.2.

The noise level (uncertainty) is defined in the control file in data units [pTms/A].

A control file is required for a forward calculation. The control file can be created using the VPview *File\New VP control file* option. Set the maximum number of iterations [*itmax*] to zero. Launch the forward calculation via the VPview *Run\Run VPxx from file* option.

At this stage it is beneficial to assess the effect of a uniform host conductivity on fixed loop TEM. To do so, display the *Model Parameters (input)* table on the VPview *Model Definitions* form, set the Half-space conductivity to 1 mS/m, and allow it to vary [keep fixed ? = No].

6.5 Inversion

Adjust model geometry or conductivity, subject to constraints (if available), to optimise data fit. Often a sequence of inversions is performed. The inverted model file can be used as the starting model file for any subsequent inversion runs. However, only a single heterogeneous unit inversion is required in the “unconstrained” case.

Prior to property inversion, check the Property Table for the starting model (displayed on the VPview *Model Definitions* form) to ensure that the Min and Max conductivities for each active unit are appropriate. If the Max and Min values are identical, the unit in question will play no part in the inversion. Check too that the permitted maximum change in conductivity per iteration [Δ Property] is appropriate. If the control file parameters have been altered, launch the inversion via the VPview *Run\Run VPxx from screen* option; otherwise select the *Run\Run VPxx from file* option.

After the inversion has completed, display the model by using the VPview *Model\Load Model* option. With VPem3D it is quite common to complete more than one inversion run. For example, homogeneous unit inversion followed by geometry inversion. When satisfied with the inverted model, it can be exported to UBC format via the *Model\Export model* option.

7 VPem3D FILE FORMATS

7.1 Control File (*.ctl)

Specification file that contains required filenames and some inversion parameters for a particular inversion run.

igrav	dec	inc	amb	idh	idc
iregnl	ilocal	ild			
regional.inp					
local.inp					
itmax	error	[nhet,	{uindex(j), dzsc(j), j = 1,nhet}]		
Δ depth	Δ property	User_min_ROI			
observed.dat	OR observed.par				
calculated.out					

igrav Defines the data type:

- igrav=4* : TEM moment (resistive limit) with non-linear algorithm
- igrav=3* : TEM (time decays)
- igrav=2* : vector magnetics
- igrav=1* : gravity (free-air)
- igrav=0* : magnetics (true TMI)
- igrav=-1* : gravity gradient
- igrav=-2* : magnetic gradient

igrav=-4 : TEM moment (resistive limit) with linear algorithm

dec, inc, amb Define the survey line orientation for ground TEM; define transmitter moment for airborne TEM; define the transmitter radius for central loop airborne TEM; define ambient geomagnetic field for sub-audio magnetic (SAM) TEM total field amplitude modeling and inversion [*igrav=4, idh=-4*];

For **ground TEM resistive limit**:

dec : bearing of survey lines clockwise from model grid north (deg)

For **airborne TEM resistive limit**:

inc : transmitter loop radius (m) for central loop system

amb : transmitter moment (amp*m²)

In the **sub-audio magnetic (SAM) resistive limit total field amplitude** case the definitions are as follows:

dec : magnetic declination (clockwise degrees from VP model north)

inc : magnetic inclination (degrees, negative in southern hemisphere)

amb : geomagnetic intensity (nT)

idh Distinguishes underground from above ground surveys; controls self-demagnetisation; identifies SAM total field data in TEM resistive limit case.

idh=-5 : inductive/galvanic dipole Tx; ground or airborne sub-audio magnetic (SAM) total field amplitude data computed if RLT specified in the PAR file.

idh=-4 : ground or airborne sub-audio magnetic (SAM) total field amplitude data computed for inductive (loop) Tx, if RLT specified in the PAR file.

idh=-3 : surface or airborne survey, with self-demagnetisation taken fully into account (if self-demag module has been purchased)

idh=-2 : surface or airborne survey, with self-demagnetisation factors of 1/3 in all directions everywhere.

idh=0 : surface or airborne survey

idh=1 : downhole or underground survey

idc Controls the DC level and treatment of parameters which attain their bounds

idc=100 : DC level free to change (adjusted to achieve least squares fit to data); cells which attain bounds during heterogeneous property inversion are fixed at the bound and play no further part.

idc=-100 : DC level free to change (adjusted to achieve least squares fit to data); cells which attain bounds during heterogeneous property inversion are retained, and may continue to change.

idc=101 : DC level read from end of regional model file; free to change if no DC shift recorded at end of regional model. Cells which attain bounds during heterogeneous property inversion are fixed at the bound and play no further part.

idc=-101 : DC level read from end of regional model file; free to change if no DC shift recorded at end of regional model. Cells which attain bounds during heterogeneous property inversion are retained, and may continue to change.

idc=102 : DC level read from end of local model file; free to change if no DC shift recorded at end of local model.

idc=-102 : DC level read from end of local model file; free to change if no DC shift recorded at end of local model. Cells which attain bounds during heterogeneous property inversion are retained, and may continue to change.

The *idc* parameter is not obligatory; if it is missing, the DC level is free to change, i.e. the default value for *idc* is 100.

iregnl & *ilocal* Define the model style :

iregnl=0, ilocal=1 : local model on uniform basement. The VPem3D basement property can be adjusted via homogeneous unit inversion, but not via basement only inversion. If the model is irregular in shape and does not completely fill the rectangular area bounded by *xmin*, *xmax*, *ymin*, & *ymax* [Section 8.4], the undefined prisms are assigned to the enclosing half-space. Data located above or within the undefined prisms should be deleted from the data file; the data points in question are identified in the VPem3D.LOG file.

iregnl=3, ilocal=0 : active regional model on uniform or variable basement. The VPem3D basement can be adjusted via basement only inversion, but not via homogeneous unit inversion. If the model is irregular in shape and does not completely fill the rectangular area bounded by *xmin*, *xmax*, *ymin*, & *ymax* [Section 8.4], the undefined prisms are assigned to the basement. Data located above or within the undefined prisms should be deleted from the data file; the data points in question are identified in the VPem3D.LOG file.

iregnl=3, ilocal=1 : local model incised into regional model. The incised local model must completely fill the rectangular area bounded by local model *xmin*, *xmax*, *ymin*, & *ymax* [Section 8.4]. The regional model basement cannot be adjusted via inversion. If the regional model is irregular in shape and does not completely fill the rectangular area bounded by the regional model *xmin*, *xmax*, *ymin*, & *ymax* [Section 8.4], the undefined prisms are assigned to the regional basement.

iregnl=4, ilocal=1 : complex model

ild [.nn]

Defines the inversion style. If *ild=integer.nn*, then a succession of subsets of nn% of the data will be inverted. This is a low memory option for very large inversion problems. If .nn is zero or absent, VPem3D will invert the entire data set (lying within the active model area).

ild = 0 : Basement properties variable, unit properties and contact elevations fixed.

ild = 100 : Stochastic inversion applied to basement properties; unit properties and contact elevations fixed. Basement min and max property bounds (see section 8.5 below) are regarded as the 0.15 and 99.85 percentile values for the property distribution. Thus the PDF is represented as two half-Gaussian distributions. The upper distribution for the basement has mean $dlay_{nlay}$ and sd $(dmax_{nlay} - dlay_{nlay})/3$; the lower distribution for the nth unit has mean $dlay_{nlay}$ and sd $(dlay_{nlay} - dmin_{nlay})/3$.

ild = 1 : Homogeneous unit properties variable; contact elevations, basement properties and heterogeneous unit properties fixed.

ild = -1 : Heterogeneous unit properties variable; contact elevations, basement properties and homogeneous unit properties fixed.

ild = 199 : Heterogeneous unit inversion, with only increases in conductivity allowed.

ild = 299 : Compact body inversion; contact elevations, basement properties and homogeneous unit properties fixed. Only increases in conductivity are permitted.

ild = 2 : Geometry inversion; contact elevations variable, all properties fixed.

regional.inp Model file containing regional model (optional). Enter DUMMY if no regional model.

local.inp Model file containing starting local model (optional). Enter DUMMY if no local model.

itmax

Maximum number of iterations for inversion if *itmax* ≥ 0. Set *itmax* to zero for a forward model calculation only.

If *itmax*=-1, VPem3D converts nominated homogeneous units to heterogeneous units and performs **sub-celling**. The number of heterogeneous units to be created, their indices, and their sub-cell sizes are defined by the *nhet*, *uindex*, and *dzsc* parameters.

If *itmax* ≤ -2, VPem3D computes **depth weights** and/or **conductivity weights** for a heterogeneous host unit overlying basement: *nhet*=1 and *uindex*=1. Thus these weighting options are suitable for "unconstrained" inversion. The formulae for depth weights and conductivity weights are defined in Sections 2.13 and 2.14 respectively.

itmax = -2, -21, and -22 for depth weighting only
itmax = -3, -31, and -32 for conductivity + depth weighting
itmax = -4 for conductivity weighting only.

For *itmax* = -2, the DZSC value is the standard (reference) thickness Δ_{ref} in whole metres + WMAX, where $0 < WMAX < 1$ is the maximum depth weight. So DZSC=50.95 means 50m standard thickness, with WMAX=0.95 for the shallowest cell. If DZSC is defined as a whole number, WMAX=0.9 by default.

For *itmax* = -21, depth weights are computed with no standard thickness adjustment. The mantissa (decimal part) of the DZSC value is WMAX, where $0 < WMAX < 1$ is the maximum depth weight. So DZSC=50.9 means WMAX=0.9 for the shallowest cell. The whole number part of DZSC is ignored.

itmax = -22 is a special depth weighting option available for AEM inversion only. In this case the "depth" in (2.2) is referenced to the system elevation, not the ground surface. The system elevation is defined as $(RXRL+TXRL)/2$, where RXRL and TXRL are the elevations of the Rx and Tx respectively. No standard thickness adjustment is applied in this case. The mantissa (decimal part) of the DZSC value is WMAX, where $0 < WMAX < 1$ is the maximum depth weight. So DZSC=50.9 means WMAX=0.9 for the shallowest cell. The whole number part of DZSC is ignored.

For *itmax* = -3, combined depth and conductivity weighting is applied. The DZSC value is the standard (reference) thickness Δ_{ref} in whole metres + WMAX, where $0 < WMAX < 1$ is the maximum depth weight. So DZSC=50.95 means 50m standard thickness, with WMAX=0.95 for the shallowest cell. If DZSC is defined as a whole number, WMAX=0.9 by default. The maximum conductivity set to 1000 mS/m by default.

For *itmax* = -31, combined depth and conductivity weighting is applied with user-defined maximum conductivity. No standard thickness adjustment is applied in this case. The DZSC value is the maximum conductivity in mS/m + WMAX, where $0 < WMAX < 1$ is the maximum depth weight. So DZSC=500.95 means 500 mS/m maximum conductivity, with WMAX=0.95 in the shallowest cell. If DZSC is defined as a whole number, WMAX=0.9 by default.

itmax = -32 is a special depth+conductivity weighting option available for AEM inversion only. In this case the "depth" is referenced to the system elevation, not the ground surface. The system elevation is defined as $(RXRL+TXRL)/2$, where RXRL and TXRL are the elevations of the Rx and Tx respectively. No standard thickness adjustment is applied in this case. The DZSC value is the maximum conductivity in mS/m + WMAX, where $0 < WMAX < 1$ is the maximum depth weight. So DZSC=500.95 means 500 mS/m maximum conductivity, with WMAX=0.95 in the shallowest cell. If DZSC is defined as a whole number, WMAX=0.9 by default.

For $itmax = -4$, pure conductivity weighting is applied. The DZSC value is the maximum conductivity in mS/m. So DZSC=500.9 means 500 mS/m maximum conductivity; any decimal part is ignored.

Table 7.1: Depth and conductivity weighting parameters

Weighting Type	Code	Thickness or Conductivity	wmax	itmax
Depth with normalisation	DN	thickness	yes	-2
Depth referenced to ground	DG	dummy	yes	-21
Depth referenced to system	DS	dummy	yes	-22
Conductivity	C	conductivity	no	-4
Depth (DN) and conductivity	DNC	thickness	yes	-3
Depth (DG) and conductivity	DGC	conductivity	yes	-31
Depth (DS) and conductivity	DSC	conductivity	yes	-32

error Absolute data uncertainty in data units (pTms/A) when $itmax \geq 0$. *error* is ignored if $itmax < 0$.

[nhet] Number of homogeneous units to be converted to heterogeneous units (if $itmax=-1$) or Number of heterogeneous units to be assigned depth or conductivity weights (if $itmax=-2$).

[uindex(j), dzsc(j)] If $itmax=-1$, *uindex(j)* is the index of the *j*th homogeneous unit to be converted to a heterogeneous unit, and *dzsc(j)* is the desired starting thickness of sub-cells in the corresponding heterogeneous unit. If *dzsc(j)* is an integral number of metres, the sub-cell thickness will be uniform. If *dzsc(j)* is not an integral number of metres, the shallowest sub-cell will have thickness $\text{int}\{dzsc(j)\}$, and deeper sub-cells will be progressively thicker. The decimal part of *dzsc(j)* is used to define the expansion factor. For example, if $dzsc(j)=20.2$, the shallowest cell will be 20m thick and each underlying cell will increase in thickness by a factor of 1.2.

If $itmax=-2$, *uindex(j)* is the index of the *j*th homogeneous unit for computation of depth weights. Normally depth weights are only applied to unit #1, representing a "host" unit on basement, in preparation for "unconstrained" property inversion. The maximum weight, *wmax*, in the shallowest cell is 0.9 by default; this translates into a factor of $1-wmax=0.1$ applied to the corresponding derivatives. The sub-cell thickness *dzsc(j)* is adopted as the reference thickness (used in the calculation of the depth weights). When $itmax=-2$, the *dzsc* value is interpreted as the reference thickness in whole metres + the decimal part defining *wmax* (the maximum depth weight). So $dzsc = 50.85$ means 50m reference thickness, with $wmax=0.85$.

Δdepth Maximum relative change in interface depth per iteration ($ild=2$ inversion). For example, value 0.1 permits a change of at most 10% of the depth during each iteration.

Δproperty Maximum absolute change in density (g/cm³), susceptibility (10⁻³ SI), conductivity (mS/m), or time constant (μs) per iteration ($ild=0,1, -1$ inversion).

User_ROI Defines the radius (in metres) of the "neighbourhood of influence" around underground data points or around drill hole constraints (property or geometry). The *User_ROI* parameter is optional; if it is missing, the default neighbourhood of influence" is used (2.5*diagonal cell size for property, no minimum for geometry). If $User_ROI < 1$, no proximity weights are applied around underground data points or around drill hole constraints.

For underground data points, the decimal part of *User_ROI* defines the weight applied to a cell containing a data point; thus =100.03 implies that the weight increases from 0.03 at the data point to 1 at a radius of 100m. The default minimum weight is 0.05 if *User_ROI* is not specified.

observed.dat Observed data file; format defined in Section 4.2 below.
observed.par File to define the name and format of the data file, and the data components to be inverted. The par file format is defined in Section 4.3 below.
calculated.out Model File containing final inverted model plus observed and calculated data.

7.2 VPem3D Data Files

VPem3D inverts resistive limit data. The resistive limits are computed from measured TEM decays using conversion programs, namely AEM2Mom for airborne TEM and TEM2Mom for ground and downhole TEM. The conversion programs can be launched from VPview, under the Data menu. This section describes the ASCII files generated by AEM2Mom and TEM2Mom.

RXX_n Easting (m) of receiver at location n. This is the easting in the VPem3D model coordinate system.
RXY_n Northing (m) of receiver at location n. This is the easting in the VP model coordinate system.
RXZ_n Elevation of receiver at location n (m). Thus the vertical coordinate for VPem3D data is elevation, not height above ground.
RLX_n Resistive limit east component at receiver location n in pTms (AEM) or pTms/A (ground and downhole TEM). Polarity is positive east in the VPem3D model coordinate system.
RLY_n Resistive limit north component at receiver location n in pTms (AEM) or pTms/A (ground and downhole TEM). Polarity is positive north in the VPem3D model coordinate system.
RLZ_n Resistive limit vertical component at receiver location n in pTms (AEM) or pTms/A (ground and downhole TEM). Polarity is positive up.

Each new survey line is identified with a LINE record. The syntax is

LINE Line_ID

where Line_ID is the line id.

Airborne TEM data format:

Each data record contains

RXX RXY RXZ {RLX RLY RLZ} TXX TXY TXZ

where RXX,RXY,RXZ are the easting, northing, and elevation of the receiver location, where RLX, RLY, RLZ are the east, north, and up resistive limit components, and where TXX,TXY,TXZ are the easting, northing, and elevation of the Tx centre location.

If RXZ < 0, it is interpreted as -1 * Rx altitude. In this case the Rx and Tx elevations are computed by VPem3D, using the appropriate ground elevation from the conductivity model.

The eastings and northings are defined in the VPem3D model coordinate system. This will usually be a rotated local coordinate system, parallel/orthogonal to flight lines, if the flight line direction is oblique to Earth frame north or east.

RLX, RLY, RLZ can occur in any order and needn't all be present. Z coordinates are elevations, positive up.

“Moving loop” TEM format (restricted to quadrilateral loops):

When resistive limits are recorded in this format, the PAR file begins with a #VPEM# identifier. The #VPEM# format is designed for moving loop ground TEM, but can also be used for fixed loop

ground and downhole TEM provided the transmitter loop is a quadrilateral.

Each data record contains

RXX RXY RXZ {RLX RLY RLZ} LX1 LX2 LX3 LX4 LY1 LY2 LY3 LY4 LZ1 LZ2 LZ3 LZ4

where RXX,RXY,RXZ are the coordinates of the receiver location, and

where RLX, RLY, RLZ are the resistive limit components, and

where {(LXn,LYn,LZn), n=1,4} are the easting, northing, and elevation of the transmitter loop corners. The eastings and northings are defined in the VPem3D model coordinate system. This will usually be a rotated local coordinate system, parallel/orthogonal to survey lines, if the survey line direction is oblique to Earth frame north or east.

RLX, RLY, RLZ can occur in any order and needn't all be present. Z coordinates are elevations, positive up.

The Tx loop vertices are in anti-clockwise order (as viewed from above ground).

TEM2Mom computes a "best-fitting quadrilateral" from the Tx loop vertices defined in the TEM file header.

Fixed loop format for ground and downhole TEM:

When resistive limits are recorded in this format, the PAR file begins with a #VPem2 identifier. The #VPem2 format is designed for fixed loop ground and downhole TEM. The shape of the transmitter loop is arbitrary.

Loop vertices are defined in the data file header, not repeated for each station. The number of vertices per loop is arbitrary. Tx loop vertices are in anti-clockwise order (as viewed from above ground). The following example illustrates the syntax in the header for a survey involving two Tx loops:

```
LOOP_DEF LoopAAA 5
9900 10050 100
9925 10075 115
9950 10150 110
9920 10120 120
9900 10075 130
LOOP_DEF LoopBBB 6
10900 9050 100
10925 9075 115
10950 9150 110
10920 9120 120
10900 9100 130
9980 9070 110
```

where LOOP_DEF identifies the record as the start of new loop definition, LoopAAA and LoopBBB are loop IDs, and where 5 and 6 are NVERT values, specifying the number of vertices for each loop.

After a LOOP_DEF record, the X,Y,Z coordinates of the Tx loop vertices are defined on the next NVERT records.

The data for the survey lines or drill holes is recorded after all loops have been defined. The data for all holes or lines read with the first loop must be recorded before all the data for the 2nd loop, and so on.

Each new survey line or drill hole is identified with a LINE record. The syntax is

LINE Line_ID [DCX=xcoord DCY=ycoord DCZ=zcoord] **LOOP**=Loop_ID

where Line_ID is the line or hole id, and

where xcoord, ycoord, zcoord are the collar coordinates for the drill hole [optional], and

where Loop_ID is the Tx loop id for the line or hole with id Line_ID. The eastings and northings are defined in the VPem3D model coordinate system.

Each data record contains

RXX RXY RXZ {RLX RLY RLZ}

where RXX,RXY,RXZ are the coordinates of the receiver location, and

where RLX, RLY, RLZ are the resistive limit components.

RLX, RLY, RLZ can occur in any order and needn't all be present. Z coordinates are elevations, positive up.

The #VPEM2 format is written if VPEM2 is added as a parameter on the command line for TEM2Mom.

7.3 VPem3D PAR Files

The VPem3D PAR file defines

- (i) the moment (resistive limit) data file,
- (ii) the number of components to be inverted,
- (iii) the columns in the data file where the required components reside, and
- (iv) the columns in the data file where the transmitter coordinates are recorded.

In VPem3D two AEM transmitter options are available: vertical magnetic dipole (VMD) and finite radius circular loop. For a VMD transmitter, the coordinates are labelled as VDX, VDY, VDZ in the PAR file; for a circular loop transmitter, the coordinates are labelled as CLX, CLY, CLZ.

There are two variants of the PAR file format, moving loop (#VPEM#) and fixed loop (#VPEM2).

The details of the moving loop (#VPEM#) format are as follows:

#VPEM# Identifier
data_file_name Name of the file containing the resistive limit data
nvar Number of fields (columns) in the data file; minimum *nvar* is 4, for east, north, elevation, and reading.
nch Number of data channels (or components) for modeling and inversion.
Then *nch* records of the form *column_n chid_n* where
column_n Column number for the *n*th data channel.
chid_n 3-character ID for the *n*th data channel. The legal channel identifiers resistive limit components are RLX, RLY, RLZ.
Then 12 records of the form *column_n Lid_n* where
LX_n 3-character ID for the easting of the *n*th Tx loop corner, with n=1,2,3,4.
LY_n 3-character ID for the northing of the *n*th Tx loop corner, with n=1,2,3,4.
LZ_n 3-character ID for the elevation of the *n*th Tx loop corner, with n=1,2,3,4.

The #VPEM# format is suitable for fixed loop surveys with quadrilateral Tx loops. Rectangular loops are assumed for moving loop ground TEM. TEM2Mom computes the best-fitting rectangle if more than 4 vertices are defined in the TEM file header.

The NCH parameter is negative for ground and downhole TEM, i.e. if loop coordinates are required: NCH= -1*(NUM_CMPTS + 12)

In the fixed loop (#VPEM2) data format the Tx loop vertices are recorded only once, in the data file header, not repeated for every data point. The Tx loop can be arbitrary in shape, with an arbitrary number of vertices. The #VPEM2 PAR file format is therefore simpler:

#VPEM2 Identifier
data_file_name Name of the file containing the resistive limit data
nvar Number of fields (columns) in the data file; minimum *nvar* is 4, for east, north, elevation, and reading.
nch Number of data channels (or components) for modeling and inversion.
Then *nch* records of the form *column_n chid_n* where
column_n Column number for the *n*th data channel.
chid_n 3-character ID for the *n*th data channel. The legal channel identifiers resistive limit components are RLX, RLY, RLZ.

Sensible defaults have been incorporated in TEM2Mom: #VPEM# format is always used for moving loop data, and #VPEM2 is the default format for fixed loop and downhole data. However, #VPEM# format is valid for fixed loop and downhole data if the loop is rectangular. In that case #VPEM# format can be enforced by adding "vpem" to the TEM2Mom command line.

The TEM2Mom conversion program recognises two conventions for downhole TEM (AUV) coordinates. The default case is the axial component up (A-positive-up) convention. For the A-positive-down convention, include AUV:down on the command line for TEM2Mom. The two conventions differ in terms of the identity of RLX and RLY, and the polarity of RLZ; thus a change of convention means RLX -> RLY, RLY -> RLX, and RLZ -> -RLZ.

Some TEM2Mom command line examples:

```
TEM2Mom MyData.tem VPEM
TEM2Mom MyData.tem auv:down vpem
TEM2Mom MyData.tem vpem AUV:down (same result as preceding command line)
TEM2Mom MyData.tem auv:up
TEM2Mom MyData.tem (same result as preceding command line)
```

It is also possible to control the number of channels which contribute to the resistive limits. This allows users to reject noisy late time channels or early time channels dominated by shallow conductivity. The syntax is

tem2mom <input file> CHA:5 CHB:20

where CHA and CHB denote the first and last channels accepted respectively. [The CHA channel index should be smaller than the CHB channel index even if channels are sorted in decreasing time order, e.g. for UTEM.]

The vpem, auv, and ch parameters are optional, and their order is arbitrary, except that they must follow <input file>.

7.4 "3D" Model Files (and VPem3D output files)

The VPem3D "3D format" can represent any 3D block model geology. Each vertical prism in the model can be divided into an arbitrary number of cells, and each cell can be assigned to any geological unit.

The maximum number of prisms, NPMAX, currently permitted is 1500000.
 The maximum number of cells per prism, NLINT, currently permitted is 350.
 The maximum number of geological units, NLMAX, currently permitted in 99.

The model file is a concatenation of “data blocks”, namely the
parameter block [highlighted yellow below],
homogeneous unit block [green],
basement block [cyan],
heterogeneous unit block(s) [white], and
responses block [pink].
 There is a separate data block for each heterogeneous unit.

```
#MOD_3D#
title1
xmin      xmax      ymin      ymax
xcell      ycell
nlay      [nhet      { uindex(j),      dzsc(j),      j=1,nhet}]
dlay1     dmin1     dmax1     [Q1      dec1      inc1]     label1
dlay2     dmin2     dmax2     [Q2      dec2      inc2]     label2
.....
dlaynlay  dminnlay dmaxnlay [Qnlay  decnlay  incnlay] labelnlay
elevback  densback      ehsex
ibackg    minel      imask      distmask [elmin]
east1     north1     elev1     nlay1     elev(1)1  flag(1)1  .....elev(nlay1-1)1  flag(nlay1-1)1
east2     north2     elev2     nlay2     elev(1)2  flag(1)2  .....elev(nlay2-1)2  flag(nlay2-1)2
.....
eastn    northn    elevn    nlayn    elev(1)n  flag(1)n  .....elev(nlayn-1)n  flag(nlayn-1)n
Basement Block title
eastb1    northb1    elevb1    propertyb1      [baseb1]
eastb2    northb2    elevb2    propertyb2      [baseb2]
.....
eastbn    northbn    elevbn    propertybn      [basebn]
title3 for Heterogeneous Unit Block      nhetu      nhetc      ihu
eastc1,northc1,nheti1,{ihu(j)1,zt(j)1,zb(j)1,nsc(j)1,j=1,nheti1}{{[phet(k)1,pflag(k)1,k=1,nsc(j)1],j=1,nheti1}
eastc2,northc2,nheti2,{ihu(j)2,zt(j)2,zb(j)2,nsc(j)2,j=1,nheti2}{{[phet(k)2,pflag(k)2,k=1,nsc(j)2],j=1,nheti2}
....
eastcn,northcn,nhetin,{ihu(j)n,zt(j)n,zb(j)n,nsc(j)n,j=1,nhetin}{{[phet(k)n,pflag(k)n,k=1,nsc(j)n],j=1,nhetin}
title4 for Responses Block
eastd1    northd1    elevd1    obs1      calc1      [Bx1,By1,Bz1]      back1
eastd2    northd2    elevd2    obs2      calc2      [Bx2,By2,Bz2]      back2
...
eastdn    northdn    elevdn    obsn     calcn     [Bxn,Byn,Bzn]      backn
[DC_SHIFT dc]
[DAT_NORM dnorm]
```

Description of model parameters:

```
#MOD_3D#      3D format identifier
title1       File contents title.
xmin        Minimum easting of rectangular model area. The model prism boundaries are
            oriented north-south and east-west in an ENU Cartesian coordinate system. The
            model coordinate system may be a “local” system, i.e. rotated and/or translated from
            the “Earth system”. xmin is defined in the model coordinate system. It is the
            coordinate of the external wall of the most “westerly” boundary prism. It is xcell/2
            less than the most “westerly” prism centre.
```

<i>xmax</i>	Maximum easting of rectangular model area. The model prism boundaries are oriented north-south and east-west in an ENU Cartesian coordinate system. The model coordinate system may be a "local" system, i.e. rotated and/or translated from the "Earth system". <i>xmax</i> is defined in the model coordinate system. It is the coordinate of the external wall of the most "easterly" boundary prism. It is $x_{cell}/2$ greater than the most "easterly" prism centre.
<i>ymin</i>	Minimum northing of rectangular model area. The model prism boundaries are oriented north-south and east-west in an ENU Cartesian coordinate system. The model coordinate system may be a "local" system, i.e. rotated and/or translated from the "Earth system". <i>ymin</i> is defined in the model coordinate system. It is the coordinate of the external wall of the most "southerly" boundary prism. It is $y_{cell}/2$ less than the most "southerly" prism centre.
<i>ymax</i>	Maximum northing of rectangular model area. The model prism boundaries are oriented north-south and east-west in an ENU Cartesian coordinate system. The model coordinate system may be a "local" system, i.e. rotated and/or translated from the "Earth system". <i>ymax</i> is defined in the model coordinate system. It is the coordinate of the external wall of the most "northerly" boundary prism. It is $y_{cell}/2$ greater than the most "northerly" prism centre..
<i>xcell</i>	Dimensions of model cells in E-W direction (m).
<i>ycell</i>	Dimensions of model cells in N-S direction (m).
<i>nlay</i>	Total number of geological units, including basement, in model. <i>nlay</i> =1 for basement-only models, e.g. terrain models. If <i>nlay</i> < 0, some of the geological units are heterogeneous.
<i>nhet</i>	Number of heterogeneous units; required only when <i>nlay</i> < 0.
<i>uindex(j)</i>	Unit index for the <i>j</i> th heterogeneous unit; required only when <i>nlay</i> < 0. If <i>uindex(j)</i> < 0, the property weights (used for heterogeneous property inversion) for unit $ uindex(j) $ are read from the Heterogeneous Unit block of the model file (see below). If <i>uindex(j)</i> > 0, the property weights from the Heterogeneous Unit block are ignored.
<i>dzsc(j)</i>	Notional sub-cell dimension (m) for the <i>j</i> th heterogeneous unit; required only when <i>nlay</i> < 0.
<i>dlay_n</i>	Density, susceptibility, or conductivity of unit <i>n</i> (g/cm ³ , 10 ⁻³ SI, or mS/m respectively).
<i>dmin_n</i>	Lower limit of density, susceptibility, or conductivity in inversion for unit <i>n</i> (g/cm ³ , milli SI, or mS/m). If <i>dmin_n</i> = <i>dmax_n</i> , the property of the <i>n</i> th layer is fixed, i.e. plays no part in inversion.
<i>dmax_n</i>	Upper limit of density, susceptibility, or conductivity in inversion for unit <i>n</i> (g/cm ³ , milli SI, or mS/m). If <i>dmin_n</i> = <i>dmax_n</i> , the property of the <i>n</i> th layer is fixed, i.e. plays no part in inversion.
<i>Q_n</i>	When the linear algorithm is selected (<i>igrav</i> = -4), current flow for unit <i>n</i> is confined to planes with a preferred orientation (strike <i>dec_n</i> and dip <i>dinc_n</i>) if <i>Q_n</i> = -1. Only the primary field component orthogonal to these planes contributes to the magnetic dipole moments. No preferred orientation if <i>Q_n</i> ≥ 0.
	When the non-linear algorithm is selected (<i>igrav</i> = 4), <i>Q_n</i> = <i>Cmin</i> in mS/m, where <i>Cmin</i> is the threshold conductivity for non-linear calculations. The response from cells with conductivity < <i>Cmin</i> is computed using the linear algorithm. If <i>Q_n</i> ≤ 0 the default <i>Cmin</i> value is 999.9 mS/m.
<i>dec_n</i>	Preferred strike (clockwise angle in degrees from VP model north) of unit <i>n</i> applied during linear calculations (<i>igrav</i> = -4) if <i>Q_n</i> = -1. Ignored if <i>Q_n</i> ≥ 0.
<i>dinc_n</i>	Preferred dip (angle in degrees, clockwise down when looking in the preferred strike direction) of unit <i>n</i> applied during linear calculations (<i>igrav</i> = -4) if <i>Q_n</i> = -1. Ignored if <i>Q_n</i> ≥ 0.
<i>label_n</i>	Text description of geological unit <i>n</i> .
<i>elevback</i>	Background elevation for uniform half-space enclosing model (m). Read from regional model file if one exists; otherwise from local model.
<i>densback</i>	Background property for uniform half-space enclosing model (g/cm ³ , milli SI, or mS/m). Read from regional model file if one exists; otherwise from local model.
<i>ehsfix</i>	<i>ehsfix</i> = 1: enclosing half-space property fixed during inversion <i>ehsfix</i> = 0: enclosing half-space property variable during inversion

	Read from regional model file if one exists; otherwise from local model.
<i>ibackg</i>	<p>Background response calculation flag. Read from local model file if one exists; otherwise from regional model.</p> <p><i>ibackg</i> = 0 : active model responses (for the starting model) and background model responses (regional and enclosing half space) must be (re)calculated during the first iteration, i.e. a full forward calculation is performed at the start of the inversion.</p> <p><i>ibackg</i> = 1 : background responses read from the end of the active model file. The active model file in this case would normally be an output file generated during an earlier run of VPem3D. The active model is the local model if one exists, or the regional model otherwise. For elevation inversion (<i>ild</i>=2), setting <i>ibackg</i>=1 will mean that the exact active model responses will be calculated during each iteration, not estimated from the derivatives and parameter perturbations. This is more accurate but slower.</p> <p><i>ibackg</i> = 2 : active model responses (for the starting model) as well as the fixed background responses are read from the end of the active model file, i.e. no initial forward calculation is performed. If <i>ibackg</i> is zero initially, VPem3D re-sets <i>ibackg</i> to 2 in the output file; in that sense <i>ibackg</i>=2 is the normal setting. This approach has the advantage of speed. However, in non-linear inversion, there is some risk that the calculated data will differ appreciably from the true model responses, especially if <i>itmax</i> is large.</p> <p><i>ibackg</i> = -1 : “background” responses read from the end of the active model file relate to external elements of the model. This option was introduced to expedite modelling and inversion of sea-floor gravity data; the “external element” in this case is a layer of seawater extending from the model limits to infinity. The response of the seawater layer is computed during an earlier run of VPem3D with <i>minel</i> = -1. The “background” values read from the active model file are adopted as starting values, i.e. added to the normal background values. The RL of the EHS must equal the <i>elmin</i> value specified for the <i>minel</i> = -1 run, i.e. top of EHS coincides with the base of the extra layer. In all other respects, <i>ibackg</i> = -1 is equivalent to <i>ibackg</i> = 0.</p>
<i>minel</i>	<p>Controls the basal elevation of model prisms, below which a uniform half space is assumed. If <i>minel</i> = 0 then -25 km is adopted as the model base. If <i>minel</i> = 1, model base is at RL=0 (usually sea level); this is appropriate for terrain effect calculations. <i>minel</i> = 2 is a special test setting. <i>minel</i> = 3 for the “irregular heterogeneous layer” option [section 2.11]. If <i>minel</i> = -1, the base of the model is arbitrary, i.e. in this case <i>elmin</i> is read from the model file. This option was originally introduced for seafloor gravity, to account for the effect of the seawater at the edge of the model. In this case, <i>elmin</i> is the RL of the seafloor. The top of the “enclosing half-space” is at elevation <i>elevback</i>, as usual. The <i>minel</i> = -1 option is used in combination with the <i>ibackg</i> = -1 option if a 2-layer “enclosing half-space” is required, e.g. for seafloor gravity. VPem3D adopts the <i>minel</i> value read from the active model, i.e. from the local model file if one exists or otherwise from the regional model.</p>
<i>imask</i>	<p>Allows the user to restrict inversion to model prisms which are within a certain range, <i>distmask</i>, of data points. If <i>imask</i> = 0, a default <i>distmask</i> value is adopted by VPem3D: only prisms within the default horizontal radius <i>distmask</i> of a data point will contribute to its derivatives. If <i>imask</i> = 1, the default <i>distmask</i> applies to derivative calculations (as for <i>imask</i> = 0) and all interfaces are fixed in prisms further than the default <i>distmask</i> radius from the nearest data point during geometry inversion. For property inversion (<i>ild</i> ≠ 2), <i>imask</i> = 1 is equivalent to <i>imask</i> = 0. If <i>imask</i> = 2, the <i>distmask</i> radius is specified by the user (see below). The effect of <i>imask</i> = 2 is as for <i>imask</i> = 1, except that the horizontal “radius of influence” is prescribed by the user. VPem3D adopts the <i>imask</i> value from the local model file if one exists; otherwise from the regional model.</p>
<i>distmask</i>	<p>Radius of influence (in metres) for derivative calculations. See <i>imask</i> above. A value of <i>distmask</i> is required when <i>imask</i> = 2; otherwise the <i>distmask</i> parameter is dummy. Read from local model file if one exists; otherwise from the regional model.</p>
[<i>elmin</i>]	<p>Defines the basal elevation of model prisms, below which a uniform half space is assumed. <i>elmin</i> is used only in the special case when <i>minel</i> = -1. <i>elmin</i> is read from the active model file.</p>

<i>east_n</i>	Easting of centre point of vertical prism n. [Geological units not defined if <i>nlay = 1</i> , i.e. basement only model. See Note 1 below]
<i>north_n</i>	Northing of centre point of vertical prism n. [Geological units not defined if <i>nlay = 1</i> , i.e. basement only model. See Note 1 below]
<i>elev_n</i>	Surface elevation of top of vertical prism n. [Geological units not defined if <i>nlay = 1</i> , i.e. basement only model. See Note 1 below]
<i>nlay_n</i>	Number of cells or interfaces in prism n.
<i>elev(j)_n</i>	Elevation of interface at base of cell j within vertical prism n.
<i>flag(j)_n</i>	Flag controlling whether the interface at <i>elev(j)_n</i> is fixed or free during inversion, and defining the geological unit immediately above. Interfacial flags are floating point numbers (not integers) for the 3D models. The 3D format flags take the form $FLAG(j,n) = IFLAG(j,n) + \text{sgn}\{IFLAG(j,n)\} * \frac{INDD(j-1,n)}{100}$ <p>where <i>IFLAG(j,n)</i> denotes the 2D format integer interfacial flag, and where <i>INDD(j-1,n)</i> is the index for the geological unit assigned to the cell immediately above the interface. [Note that interface j is at the base of the (j-1)th cell.]</p> <p><i>iflag(j)_n = 0</i> : free interface (bounded above by the ground surface)</p> <p><i>iflag(j)_n = 1</i> : fixed interface, pierced by a drill hole. A contact flagged with 1 will affect parameter weighting during geometry inversion, which can in turn reduce inversion speed. Therefore use 1 flags only for drill pierce points.</p> <p><i>iflag(j)_n = 2</i> : fixed interface, constrained by the operator or by VPem3D, e.g. if <i>imask=1</i>. A contact flagged with 2 will not affect parameter weighting during geometry inversion. Use 2 flags to fix contacts which are not drilled.</p> <p><i>iflag(j)_n = -1</i> : fixed "artificial" interface, to restrict movement of a free interface during inversion. Imposed owing to a near-miss by drill hole(s)</p> <p><i>iflag(j)_n = -2</i> : fixed "artificial" interface, to restrict movement of a free interface during inversion. Imposed operator.</p> <p><i>iflag(j)_n = -3</i> : fixed "artificial" interface between sub-cells in a heterogeneous unit.</p>
<i>title2</i>	Basement section title. Must begin with the word "Basement", starting in first column.
<i>eastb_n</i>	Easting of centre point of vertical prism n.
<i>northb_n</i>	Northing of centre point of vertical prism n.
<i>elevb_n</i>	Elevation of top of basement within vertical prism n.
<i>propertyb_n</i>	Basement density (g/cm ³), susceptibility (10 ⁻³ SI), or conductivity (mS/m) within vertical prism n.
<i>baseb_n</i>	Elevation of base of heterogeneous layer in vertical prism n. Only required for the special heterogeneous layer option. See section 2.11
<i>title3</i>	Title for Heterogeneous Unit block. Must begin with the word "Heterogn", starting in first column.
<i>nhetu</i>	Number of heterogeneous units defined in this block. <i>nhetu=1</i> .
<i>nhetc</i>	Number of sub-cells in the heterogeneous unit #ihu.
<i>ihu</i>	Index (unit number) for the heterogeneous unit defined in this data block.
<i>eastb_n</i>	Easting of centre point of vertical prism n. Only prisms which contain cells belonging to one or more heterogeneous units are listed in this section of the model file.
<i>northb_n</i>	Northing of centre point of vertical prism n.
<i>nheti_n</i>	Number of intervals of heterogeneous units within vertical prism n. There may be more than one interval of a particular heterogeneous unit.
<i>ihu(j)_n</i>	Unit index identifying the jth interval of a heterogeneous unit within vertical prism n; j increases downwards.
<i>zt(j)_n</i>	Elevation of top of the jth interval of a heterogeneous unit in vertical prism n.
<i>zb(j)_n</i>	Elevation of bottom of the jth interval of a heterogeneous unit in vertical prism n.

$nsc(j)_n$	Number of cells which comprise the j th interval of a heterogeneous unit in vertical prism n . Each cell has vertical dimension $[zt(j)_n - zb(j)_n] / n$.
$phet(k)_j$	Property (density, susceptibility, or conductivity) of the k th cell within the j th interval of a heterogeneous unit in vertical prism n . Index k ranges from 1 to $nsc(j)_n$.
$pflag(k)_j$	Inversion flag of the k th cell within the j th interval of a heterogeneous unit [index $ihu(j)$] in vertical prism n . $pflag$ is of the form $ipf.nnnn$, where ipf is an integer flag and where $nnnn$ is a weight, defined to 4 decimal places. $ipf = 0$: the cell property is free to change during heterogeneous property inversion (when $ILD=-1$); $ipf = 1$: the cell property is fixed, e.g. owing to proximity to a drill hole (in which properties have been determined). The decimal part $nnnn$ of $pflag$ is a weight (an indicator of certainty); this is used to condition the inversion when $uindex(ihu(j)) < 0$, i.e. when the user defines the weights (see parameter block above). The weight ranges from zero (uncertain, i.e. free to change) to 0.9999 (very well defined, virtually fixed). If $nnnn$ is zero or absent, VPem3D default weights are applied during inversion, based on proximity to cells for which $ipf=1$, i.e. cells with fixed property.
title4	Title for Responses block. Must begin with the word "EAST".
eastd_n	Easting of measurement station n . Need not coincide with prism centre.
northd_n	Northing of measurement station n . Need not coincide with prism centre.
elevd_n	Elevation of measurement station n , on or above the ground surface. If below top of vertical prism at that location, the prism top is lowered if $idh=0$. [Downhole and underground capability not yet implemented]
obs_n	Gravity (mgal), gravity gradient (Eotvos), or TMI reading (nT) at station n .
calc_n	Calculated model response at station n , i.e. including background contribution, in mgal, Eotvos, or nT. $calc_n$ is true TMI in the case of magnetic inversion ($igrav=0$), or the selected tensor component in the case of gravity gradient inversion ($igrav=-1$).
{Bx_n,By_n,Bz_n}	Calculated magnetic components at station n , i.e. active model response without background, in nT – recorded for magnetic inversion only ($igrav=0$).
back_n	Background response from model at station n . Values are normalised, i.e. are not in mgal, Eotvos, or nT. back_n is a single scalar for gravity and gravity gradient inversion ($igrav=-1$ or 1), but the three magnetic components are recorded in the case of magnetic inversion ($igrav=0$).
dc	dc is the DC shift applied to the calculated data. The DC shift is read from the regional model when $ idc = 101$; it is read from the local model when $ idc = 102$. The value recorded in the model file is ignored if $ idc =100$; in that case the DC shift is optimised to minimize the L2 misfit. For VPem3D, dc is usually fixed as zero.
dnorm	$dnorm$ is an optional scaling factor applied to calculated resistive moments, recommended if the starting model is based on CDIs or 1D inversion. The scaling factor in effect converts conductivity to time constant. Set $dnorm$ to any positive value to activate calculated data scaling; the value of $dnorm$ is then optimised to minimise the L2 misfit. If the DAT_NORM record is missing, or if $dnorm < 0$, no scaling is applied.

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11 APPENDIX A: AEM2Mom PAR file format

The AEM2Mom parameter file format defined below is identical to the EmaxAIR parameter file format. This means that AEM2Mom can be run on an AEM data set using the same PAR file as EmaxAIR.

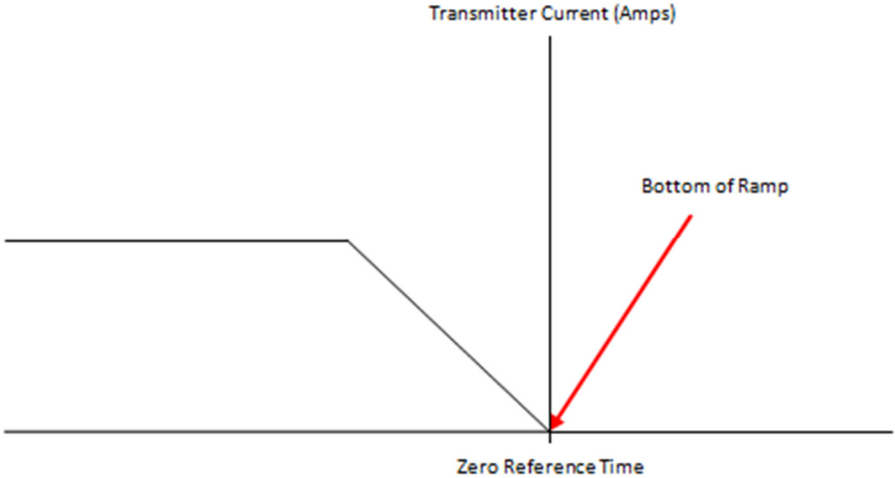
EmaxAIR requires more parameters than AEM2Mom, so some parameters in the PAR file are dummies, i.e. not used by AEM2Mom. Also, some MODE settings are different, e.g. MODE=3 and MODE=32.

0	FORMAT IDENTIFIER = #VPEM#
1	TITLE Text to describe the data being processed.
2	DATA FILENAME Column ASCII data is assumed. An arbitrary number of header or comment records are allowed, but only at the beginning of the file. These records are identified by a forward slash in the first column..
3	NVAR Total number of columns in data file.

<p>4</p>	<p>ILINE, IX, IY, IALT, IDATI, IDATF, ITXRL, IOFFX, IOFFZ, ItxCrnt, [IDEM, IRALT, IDATI2, IDATF2]</p> <p>ILINE column number containing flightline or line number; ILINE can be zero if data file is in Geosoft XYZ format (with line block identifiers)</p> <p>IX column number containing eastings.</p> <p>IY column number containing northings.</p> <p>IALT column number containing transmitter altitude (metres above ground surface).</p> <p>IDATI column number containing first TEM window to be processed; if 2 components are inverted simultaneously, IDATI refers to the along-line (X) component.</p> <p>IDATF column number containing last TEM window to be processed; if 2 components are inverted simultaneously, IDATI refers to the along-line (X) component.</p> <p>ITXRL column number containing RL of the transmitter (mASL)*. Set ITXRL = 0 if the transmitter RL is not recorded in the data file; Tx elevation computed as ground elevation + Tx altitude in that case, OR as ground elevation + Rx altitude + DEL0 if Tx altitude is not recorded in the data file (IALT=0).</p> <p>IOFFX column number containing horizontal Tx-Rx offset (m). Set IOFFX = 0 if the Tx-Rx offset is not monitored & recorded in the data file.</p> <p>IOFFZ column number containing vertical Tx-Rx offset (m). Set IOFFZ = 0 if the Tx-Rx offset is not monitored & recorded in the data file.</p> <p>ItxCrnt column number containing Tx current (amps). Used when ISTEP=-1 only. Set ItxCrnt = 0 if the Tx current is not monitored & recorded in the data file. Set ItxCrnt = 0 for ground TEM data.</p> <p>IDEM column number containing digital elevation of ground surface</p> <p>IRALT column number containing receiver altitude (metres above ground surface).</p> <p>IDATI2 Not required for inversion of single component; leave blank in that case. If 2 components are inverted simultaneously, IDATI2 is column number containing first TEM window for the vertical (Z) component.</p> <p>IDATF2 Not required for inversion of single component; leave blank in that case. If 2 components are inverted simultaneously, IDATF2 is column number containing last TEM window for the vertical (Z) component.</p> <p><i>The TEM data columns are assumed sorted in order of increasing delay time.</i></p> <p><i>Data files with up to 100 columns can be read.</i></p> <p><i>IDEM, IRALT, IDATI2, IDATF2 are optional; it is valid to omit IDATI2, IDATF2, or to omit all four of these parameters.</i></p>
<p>5</p>	<p>LMIN, LMAX</p> <p>LMIN, LMAX are the min, max line numbers to be processed. These parameters can be used to restrict processing to a subset of lines contained in the data file.</p>
<p>6</p>	<p>XMIN, XMAX, YMIN, YMAX</p> <p>XMIN, XMAX are the min, max eastings of the area to be processed. YMIN, YMAX are the min, max northings of the area to be processed. These settings can be used to restrict the areal extent of data processed by VPem3D.</p>

7	<p>IDAT, ConversionFactor</p> <p>IDAT = 1 for normalized dB/dt data (e.g. in ppm). IDAT = -1 for dimensional dB/dt data (see Table 11.1). IDAT = 2 for normalized B data (e.g. in ppm). IDAT = -2 for dimensional B data (see Table 11.2).</p> <p>Data can be multiplied by ConversionFactor to convert them to VPem3D “standard units”; see data unit column in Tables 11.1 and 11.2.</p>
8	<p>NSKIP, POSLAG</p> <p>NSKIP stations skipped between each station processed. Set NSKIP = 0 to process decays at all stations.</p> <p>POSLAG controls the positional lag adjustment. POSLAG = 1 if data coordinates refer to Tx position. POSLAG = -1 if data coordinates refer to Rx position. POSLAG = 0 if data coordinates define the Tx-Rx midpoint</p> <p><i>If POSLAG = 1 or -1, coords <u>are</u> altered to Tx-Rx midpoint. If POSLAG = 0, coords are <u>not</u> altered.</i></p>
9	<p>TXFREQ, TXMOM, RXAREA</p> <p>TXFREQ is the transmitter “fundamental” operating frequency (Hz), e.g. 0.125Hz (for 2 sec bi-polar square wave TEM data)</p> <p>TXMOM is the transmitter moment (amp.turn.m²). Enter the actual Tx moment, irrespective of whether the data are dimensional (IDAT<0) or dimensionless (IDAT>0), since AEM2Mom converts the data to pT*ms.</p> <p>RXAREA is the effective area of the receiver (turn.m²). For B-field data, (IDAT =2), RXAREA is arbitrary. Normally set it to 1.</p>
10	<p>PULSE, ISTEP</p> <p>PULSE is the duration of maximum Tx current, in microseconds. Dummy parameter for AEM2Mom.</p> <p>ISTEP = 0 for slingram configuration, with arbitrary waveform. Use this option for GEOTEM, with appropriate half-sine waveform defined in a WVF file*.</p> <p>ISTEP = 1 for 100% duty cycle waveform, slingram configuration (TEMPEST, SPECTREM)</p> <p>ISTEP = -1 for central loop configuration, with bipolar trapezoidal waveform defined by PULSE, turn-on ramp, RON, and turn-off ramp, ROFF*. Use this option for HOISTEM and Aerotem.</p> <p>ISTEP = -4 for SkyTEM, with waveform defined in a WVF file*.</p> <p>ISTEP = -5 for VTEM, with waveform defined in a WVF file*.</p> <p>*AEM2Mom processing is independent of waveform at present</p>

11	<p>MODE</p> <p>MODE = 1 for horizontal-axis receiver (normalized w.r.t. primary horizontal component if data is in ppm, i.e. IDAT>0)</p> <p>MODE = 12 for horizontal-axis receiver (normalized w.r.t. primary vertical component if IDAT>0)</p> <p>MODE = 10 for horizontal-axis receiver (normalized w.r.t. total primary field if IDAT>0)</p> <p>MODE = 2 for vertical-axis receiver (normalized w.r.t. primary horizontal component if data is in ppm, i.e. IDAT>0)</p> <p>MODE = 22 for vertical-axis receiver (normalized w.r.t. primary vertical component if IDAT>0)</p> <p>MODE = 20 for vertical-axis receiver (normalized w.r.t. total primary field if IDAT>0)</p> <p>MODE = 3 for simultaneous processing of both along-line and Z-components (normalised w.r.t. their respective primary components if IDAT>0).</p> <p>MODE = 32 for simultaneous processing of both X- and Z-components (normalised w.r.t. the primary vertical component if IDAT>0).</p>
12	<p>R, DEL0, ALTO</p> <p>R is effective Tx loop radius (metres) for central loop data (ISTEP < 0), i.e. radius of a circular loop with area = Tx area. For slingram systems (ISTEP ≥ 0), R is the notional (survey spec) horizontal Tx-Rx separation. A vertical magnetic dipole Tx is assumed for slingram configurations. R > 0 if the Tx is ahead of the Rx; R < 0 if the Tx is behind the Rx.</p> <p>DEL0 is the notional (survey spec) vertical Tx-Rx separation (metres). DEL0 > 0 if the Tx is above the Rx; DEL0 < 0 if the Tx is below the Rx.</p> <p>ALTO is the horizontal offset of the Rx from the centre of the Tx for SkyTEM (ISTEP=-4) and VTEM (ISTEP=-5) systems. Otherwise, ALTO is the notional (survey spec) Tx altitude (metres) .</p> <p><i>R and DEL0 govern the magnitude of the primary field for calculation of dimensionless data, e.g. ppm values. The actual horizontal Tx-Rx separation for the recorded data is assumed to be R, unless IOFFX is non-zero (see #4 above). Likewise, the actual vertical Tx-Rx separation is assumed to be DEL0 unless IOFFZ is non-zero (see #4 above) .</i></p> <p><i>The "actual" Tx altitude (from radar altimeter) at each station is normally read from the TEM data file.</i></p>

13	<p>T, CHW, PCERR, SDMIN</p> <p>T is midpoint time (microseconds from bottom of turn-off ramp) for the TEM channel. CHW is window width (microseconds). PCERR is percent error (%) for the TEM channel. PCERR is not currently used by AEM2Mom; enter -1, which is interpreted as a dummy value. SDMIN is minimum allowable standard deviation (TEM data units). ConversionFactor is applied to SDMIN. SDMIN is not currently used by AEM2Mom; enter -1, which is interpreted as a dummy value.</p> <p>AEM2Mom will expect $NCHAN = IDATF - IDATI + 1$ successive records in the parameter file here (refer to record 4 above), each with window midpoint time and width.</p> <p>Time origin is the <u>bottom</u> of the turn-off ramp for the most recent current pulse. Times specified in the PAR file should be adjusted if supplied times are referenced differently, e.g. measured from the top of the turn-off ramp.</p>  <p>A zero channel width, corresponding to instantaneous recorded voltages, is not valid in this version.</p> <p>PCERR and SDMIN values for individual channels defined here take precedence. Where an individual channel's error parameters are not defined (PCERR = -1), the default global values are used, viz. PCERR0 and SDMIN0 defined on record 16+ NCH (see below).</p>
13 + NCH	<p>ITMAX, PERT, TOL, IPRINT 4 dummy parameters for AEM2Mom</p> <p>ITMAX is the maximum number of iterations allowed for determination of apparent conductivity for one time window. <i>Usually 10.</i> PERT is the maximum fractional change in the conductivity at each iteration. <i>Usually 0.5.</i> TOL controls the convergence condition for cases when the data are not consistent with a homogeneous half-space response; iterations cease if the ratio of perturbation to current conductivity value is less than TOL. <i>Usually 0.01.</i> IPRINT controls the written output. If IPRINT = 0, the written output is minimal.</p>
14 + NCH	<p>IINT Dummy parameter for AEM2Mom</p> <p>IINT governs the time sampling interval, DELTA, used for convolution in the half-sine waveform cases (ISTEP=0). DELTA is defined as PULSE/IINT, in microseconds. DELTA need not correspond to the acquisition time sampling interval. A typical value for IINT is 30.</p> <p>IINT is a dummy parameter for step-current systems (ISTEP = 1, -1).</p>

<p>15 + NCH</p>	<p>SIG1, SIG1MAX 2 dummy parameters for AEM2Mom</p> <p>SIG1 is the initial conductivity estimate (S/m) for the <i>first channel</i> at the <i>first station</i>. For other stations, the starting conductivity for the first channel at a station = the apparent conductivity solution for the first channel at the previous station. The starting conductivity for the second and successive channels = the apparent conductivity solution for the previous channel. However, the starting value at a new station is not allowed to exceed SIG1MAX. If ISHARP = 2, SIG1 is the surface conductivity (see record #17+ below).</p> <p>SIG1MAX (S/m) is the maximum permitted starting conductivity at any station. This provides a degree of immunity against non-uniqueness: low signals can be due to extremely high conductivity as well as to low conductivity. If all apparent conductivities appear to be unrealistically high then try a re-run with a much smaller SIG1MAX. Conversely, if all apparent conductivities appear to be too low, re-run with a much larger SIG1MAX. If ISHARP = 2, SIG1MAX is the maximum conductivity (see record #18+ below). Normally set SIG1MAX = SIG1.</p>
<p>16 + NCH</p>	<p>PCERR0, SDMIN0 1 dummy parameter for AEM2Mom</p> <p>PCERR0 is the percentage error assumed for each recorded decay value, unless a specific PCERR value has been defined for the TEM channel (see above). The error is regarded as the standard deviation of a Normal random variable. Convergence is presumed when the 58ormalized squared misfit between the calculated and observed data values is less than or equal to unity, this being the expected value for the corresponding chi-squared random variable.</p> <p>SDMIN0 is the minimum allowable standard deviation (TEM data units), unless a specific SDMIN value has been defined for the TEM Channel (see above). Express as ppm or dimensional units according to the value of IDAT. Percentage error can become unreasonably small at late times, as the signals decay. SDMIN is an absolute error, which can be regarded as the noise floor.</p> <p>SDMIN0 If SDMIN > 0 it is not currently interpreted as a standard deviation by AEM2Mom. If SDMIN0 > 0, TEM channels within the specified range (columns IDAT1 to IDATF, and IDAT12 to IDATF2 if defined) will contribute to the resistive limits as long as the dB/dt or B values are monotonically decreasing with time. Minor increases in amplitude (up to 10% are allowed). If the decay is not monotonically decreasing, it will be truncated. If the resistive limit is based on fewer than 1/3 of the number of channels selected, it will be rejected.</p> <p>If SDMIN0 < 0, it is interpreted as a standard deviation (noise floor) by AEM2Mom. If SDMIN0 < 0, TEM channels within the specified range will contribute to the resistive limits provided their amplitude > SDMIN0 . The decay is not truncated if a channel below the noise floor is encountered. SDMIN0 must be specified in data units, consistent with the value of IDAT. AEM2Mom multiplies the SDMIN0 value by the ConversionFactor. If two components are being processed, the same SDMIN0 is applied to both. If the resistive limit is based on fewer than 1/3 of the number of channels selected, it will be rejected.</p> <p><i>PCERR0 and SDMIN0 are used as default values when individual channel PCERR and SDMIN values are not defined. Conversion factor is applied to SDMIN0</i></p>

<p>17 + NCH</p>	<p>ISHARP, ITSHEET, OutputFmt 3 dummy parameters for AEM2Mom</p> <p>ISHARP = 0 : no “sharpening” is applied.</p> <p>ISHARP = 1 : the original apparent conductivities are treated like conductances, and are differentiated to produce a final "sharpened" apparent conductivity versus depth profile.</p> <p>ISHARP = 2 : the original apparent conductivities are treated like inner products of the true conductivity with the linear sensitivity functions of Christensen (<i>Geophysics, 2002, 67, 438-447</i>). A simple inversion yields a "C-sharpened" estimate of the true conductivity versus depth. SIG1 and SIG1MAX (see record #16+ above) assume special roles when ISHARP=2; SIG1 is the surface conductivity, and SIG1MAX is the maximum conductivity allowed after sharpening. This is a more aggressive sharpening option than ISHARP=1.</p> <p>ITSHEET = 0 : homogeneous halfspace model for conductivity calculation (NORMAL USE).</p> <p>ITSHEET = 1 : thin sheet model for conductivity calculation (<i>only for Hoistem</i>, IF DESIRED).</p> <p>OutputFmt is used to control which of multiple possible output formats are created. There are four options, and each option has a numeric flag associated with it;</p> <p>option A, flag = 1 : standard “CDI” format.</p> <p>option B, flag = 2 : Geosoft XYZ format – with Line headers; one output file per flightline.</p> <p>option C, flag = 4 : Geosoft XYZ format – with flightline column but <i>no</i> Line headers.</p> <p>option D, flag = 8 : Geosoft XYZ format – suitable for array channel import to Oasis Montaj.</p> <p>Set OutputFmt equal to the <u>sum of the flags</u> that correspond to the output formats you require. For example to output three files in formats A,C,D set OutputFmt to a value of 1 + 4 + 8 = 13. To output all formats set OutputFmt to 15.</p> <p><i>A maximum value of 10 S/m is enforced if sharpening is applied, i.e. if ISHARP = 1 or 2.</i></p>
<p>18 + NCH</p>	<p>IHC Dummy parameter for AEM2Mom</p> <p>IHC is a switch for height-corrected output data. Adjusted data values are computed at a uniform ground clearance, with the Tx at the notional survey altitude, ALT0. Height-corrected data are written to a separate output file.</p> <p>IHC = 0 : no height-corrected data output.</p> <p>IHC = 1 : yes, height-corrected data output.</p> <p>IHC = -1 : yes, height-corrected data output : written in Hoistem binary BDB format.</p> <p><i>Output data units are always those defined by IDAT.</i></p> <p><i>Where a value of ConversionFactor (see parameter record #8) was used to convert the units during data import, the original input data units will be different to the output data units.</i></p> <p>The height correction is intended to suppress the effect of altitude variation as a preparatory step for generation of "time channel maps", i.e. it is purely intended to improve the interpretability of "raw" data display. EmaxAIR accounts for the survey height variation explicitly when computing the apparent conductivity, whether or not the height-correction option is turned on.</p>
<p>19 + NCH</p>	<p>RON, ROFF 2 dummy parameters for AEM2Mom</p> <p>RON is the Tx ramp turn-on time (microseconds)</p> <p>ROFF is the Tx ramp turn-off time (microseconds)</p> <p>RON and ROFF are used for Hoistem and Aerotem data. RON and ROFF are not needed (set to zero) if a waveform file is provided.</p>

20 + NCH	<p>#WAVEFORM# <filename></p> <p><filename> is the name of a WVF file containing an arbitrarily defined waveform.</p> <p>THIS RECORD IS OPTIONAL – waveform is not used by AEM2Mom</p> <p><i>If it is present then the standard waveform defined above by ISTEP, RON, ROFF will be ignored and the arbitrary waveform used instead.</i></p> <p>A waveform file is not required for Hoistem & Aerotem (ISTEP=-1) or for Tempest & Spectrem (ISTEP=1).</p> <p>The file should contain two columns separated by spaces or a comma; Time (seconds) and Current (normalised to 1 maximum).</p> <p>A WVF can be created from a Maxwell configuration (.mcg) file if available. It is desirable to reduce the time samples since processing speed will be adversely affected if the waveform is defined at a large number of points.</p>
21 + NCH	<p>#ROTATE# DEC XREF YREF IADD</p> <p><i>This record is only required if flight line coordinates are adopted</i></p> <p>DEC is the bearing of flight lines in degrees clockwise from survey north.</p> <p>XREF is the survey easting of the origin of the local coordinate system.</p> <p>YREF is the survey northing of the origin of the local coordinate system.</p> <p>IADD = 1 if XREF is added to local eastings and YREF is added to local northings; otherwise IADD = 0</p>

Table 11.1: Vpem1D parameter combinations for dB/dt systems

dB/dt system	data unit	IDAT	ISTEP	MODE	ConversionFactor	Tx Moment (Am²)	RxArea (m²)
Aerotem*	nT/s	-1	-1	2	0.001	actual	1
Geotem	nT/s	-1	0	1,2	1	actual	1
Geotem	pV/m ²	-1	0	1,2	0.001	actual	1
Geotem	ppm	+1	0	1,10,12 2,22,20	1	1	1
Hoistem	μV	-1	-1	2	1	actual	actual
Questem	nT/s	-1	0	1,2	1	actual	1
SkyTEM	μV	-1	-4	2	1	actual	actual
VTEM	pV/(A.m ⁴)	-1	-5	2	1	actual	1

*For Aerotem, RON=ROFF=pulse_duration/2 (μ s), and PULSE=0 (see Section 2.3 below)

Table 11.2: VPem1D parameter combinations for B-field systems

B-field system	data unit	IDAT	ISTEP	MODE	Conversion Factor	Tx Moment (Am ²)	RxArea (m ²)
Geotem	pT	-2	0	1,2	1	actual	1
“Hoistem”	pT/A	-2	-1	2	1	actual	1
Spectrem	ppm	+2	1	1,12,10 2,22,20	1	actual	1
Tempest	fT/(A.m ²)	-2	1	1,2	1	1000	1
VTEM	pV.ms/(A.m ⁴)	-2	-5	2	1	actual	1

12 APPENDIX B: Example Airborne TEM Inversion

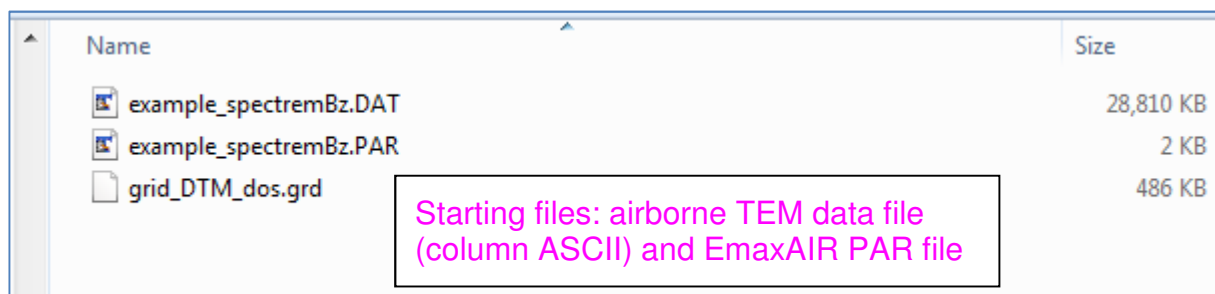
12.1 Introduction

This Appendix is intended as a guide for running VPem3D modelling and inversion of airborne TEM through the VPview user interface. The application of VPem3D is illustrated step-by-step with an example dataset using a series of annotated images with explanatory notes. It should provide enough information to guide you as you work through one of your own datasets. The airborne survey used for the example has not yet been released by the survey owners so at the time of writing the digital survey data file is not included with the guide.

The guide does not attempt to explain all of the VPview parameters. For a fuller explanation see the VPview documentation (accessible from the VPview *Help* menu).

There are various ways to set up and run VPem3D inversion on AEM data. The example used here illustrates “unconstrained” heterogeneous unit inversion with a simple uniform half-space starting model. The model cell size is relatively coarse for the purposes of this guide so that processing times are very quick. **For a high quality unconstrained inversion result the model cell size would be smaller than in this example run, and depth weighting (Section 2.13) would normally be applied.** Moreover, the starting model would often be based on 3D interpolation of CDIs or 1D inversions.

12.2 Computing resistive limit data



Name	Size
example_spectremBz.DAT	28,810 KB
example_spectremBz.PAR	2 KB
grid_DTM_dos.grd	486 KB

Starting files: airborne TEM data file (column ASCII) and EmaxAIR PAR file

The minimum files required to start modelling inversion are;

- A data file in ASCII columnar format (*.DAT example is shown on page 4).
- A parameter file (*.PAR example is shown on page 5).

The *.DAT and *.PAR files are virtually the same files that are used for EmaxAIR. The only difference is that, depending on the data, some additional parameters may be needed in the *.PAR file.

/1	2	3	4	5	6	7	8	9	10	11	12	13
/EAST	NORTH	LINE	FID	FLIGHT	SEC	DATE	ALT	DEM	X1	X2	X3	X4
98546	91164	41010	4445	7	43887		89.5	371.9	20.94	0.6	-0.24	0.03
98554.4	91174	41010	4446	7	43887		89.5	371.9	22.41	0.66	-0.25	-0.02
98562.8	91184	41010	4447	7	43887		89.5	371.9	23.31	0.66	-0.25	-0.04
98571	91194	41010	4448	7	43887		89.5	371.8	24.1	0.3	-0.25	-0.07
98579.3	91205	41010	4449	7	43888		89.5	371.6	24.77	-0.08	-0.25	-0.07
98587.4	91215	41010	4450	7	43888		89.6	371.4	25.56	0.28	-0.25	-0.07
98595.5	91225	41010	4451	7	43888		89.7	371	26.61	0.62	-0.24	-0.07
98603.5	91235	41010	4452	7	43888		89.9	370.6	27.66	0.53	-0.22	-0.07
98611.5	91245	41010	4453	7	43888		90.1	370.3	28.07	0.61	-0.2	-0.07
98619.4	91256	41010	4454	7	43889		90.2	369.7	27.95	1.14	-0.16	-0.04
98627.3	91266	41010	4455	7	43889		90.5	369.1	27.77	1.83	-0.11	-0.07
98635.1	91276	41010	4456	7	43889		90.8	368.6	27.5	2.11	-0.08	-0.07
98642.8	91287	41010	4457	7	43889		91	368	27.16	2.18	-0.05	-0.07
98650.6	91297	41010	4458	7	43889		91.5	367.4	26.56	2.17	0.08	-0.07
98658.1	91307	41010	4459	7	43890		91.9	366.7	26.02	1.82	0.22	-0.07
98665.7	91318	41010	4460	7	43890		92.4	366.1	25.53	1.41	0.34	-0.07
98673.3	91328	41010	4461	7	43890		92.8	365.6	24.84	1.38	0.48	-0.07
98680.8	91338	41010	4462	7	43890		93.3	365.1	24.11	1.39	0.52	-0.07
98688.3	91349	41010	4463	7	43890		93.8	364.6	24.15	1.71	0.38	0.07
98695.8	91359	41010	4464	7	43891		94.2	364.3	24.09	2.03	0.26	0.17
98703.1	91369	41010	4465	7	43891		94.5	364	23.96	1.87	0.13	0.17
98710.5	91380	41010	4466	7	43891		94.6	363.8	24.12	1.72	0.08	0.17
98717.9	91390	41010	4467	7	43891		94.7	363.8	24.65	1.65	0.13	0.17
98725.3	91400	41010	4468	7	43891		94.6	364	25.21	1.58	0.17	0.17
98732.6	91411	41010	4469	7	43892		94.3	364.3	25.42	1.56	0.18	0.17
98740	91421	41010	4470	7	43892		93.9	364.6	25.61	1.74	0.2	0.17
98747.3	91432	41010	4471	7	43892		93.5	365	27	1.92	0.2	0.17
98754.6	91442	41010	4472	7	43892		93.1	365.4	28.53	1.8	0.2	0.17
98761.9	91452	41010	4473	7	43892		92.5	365.9	29.08	1.68	0.21	0.17
98769.2	91463	41010	4474	7	43893		92	366.3	29.65	1.61	0.21	0.17
98776.4	91473	41010	4475	7	43893		91.6	366.8	30.46	1.53	0.27	-0.07
98783.8	91484	41010	4476	7	43893		91.1	367.1	31.27	1.46	0.32	0
98791	91494	41010	4477	7	43893		90.8	367.4	31.88	1.43	0.37	0.03
98798.3	91504	41010	4478	7	43893		90.6	367.4	32.01	1.43	0.36	-0.02
98805.6	91515	41010	4479	7	43894		90.4	367.6	32.7	1.52	0.28	-0.08
98813	91525	41010	4480	7	43894		90.3	367.6	33.41	1.61	0.18	-0.08
98820.4	91535	41010	4481	7	43894		90.2	367.6	34.12	1.53	0.18	-0.08
98827.8	91545	41010	4482	7	43894		90.1	367.6	34.83	1.53	0.18	-0.08
98835.2	91555	41010	4483	7	43894		90	367.6	35.54	1.53	0.18	-0.08

Example of the start of a *.DAT airborne (Spectrem) column ASCII data file.

The first two data records are comments (beginning with a slash) used for column header names and counters.

```

example_spectremBz.PAR x
#VPeM#
This is an EmaxAIR parameter file, with additional parameters (column numbers and rotation param
example_spectremBz.DAT
28                               !NVAR (total number of columns in data file)
3 1 2 8 17 23 28 0 0 0 9 0      !Columns numbers for:  LINE, X, Y, ALT,  first_channel, l
0 42000                          !LMIN, LMAX
-1000000 10000000 -10000000 10000000 !XMIN, XMAX, YMIN, YMAX
2 1                               !IDAT (=1 for dB/dt [2 for B] in ppm; -1 for dB/dt [-2 for
0 0                               !NSKIP, POSLAG
90 400000 1000                  !TXFREQ, TXMOM, RXAREA
3333.3 1                         !PULSE (micro.s), ISTEP
22                               !MODE (=1 for x; 2 for z; 0 for total) (=22 for normalisa
122.9 36.6 91                   !YO, DELO, ALTO (notional configuration geometry)
    21.7 21.7 -1 -1              !T (micro.s after shut-off), CHW (micro.s)
    54.3 43.4 -1 -1
    119.4 86.8 -1 -1
    249.6 173.6 -1 -1
    501.0 347.2 -1 -1
    1030.8 694.4 -1 -1
    2072.5 1388.9 -1 -1
10 0.5 0.01 0                   !ITMAX, PERT, TOL, IPRINT
256                              !IINT time samples span PULSE
0.1 1                           !SIG1, SIG1MAX (S/m)
1 1                              !PCERR, SDMIN (units as per IDAT)
0 0 15                          !ISHARP, ITSHEET, OutputFormats
0                                !IHC
800 40                          !RON, ROFF
#ROTATE# 38. 13000. 80200. 0.    !Define coordinate rotation: specify the Flightline bear

```

Depending on VPem3D processing requirements,
one or more additional column numbers may need to be specified (circled, top)
and/or data rotation may need to be specified (circled, bottom)

Example of a *.PAR parameter file. The format is defined in Appendix A.

The file is an EmaxAIR *.PAR file with some additional data column numbers defined for VPem3D, as well as an extra record at the end to define a data rotation.

Normally all flight lines to be processed have the same orientation. If tie lines are present in the *.DAT file then the range of flight line numbers specified in the *.PAR file normally excludes tie lines.

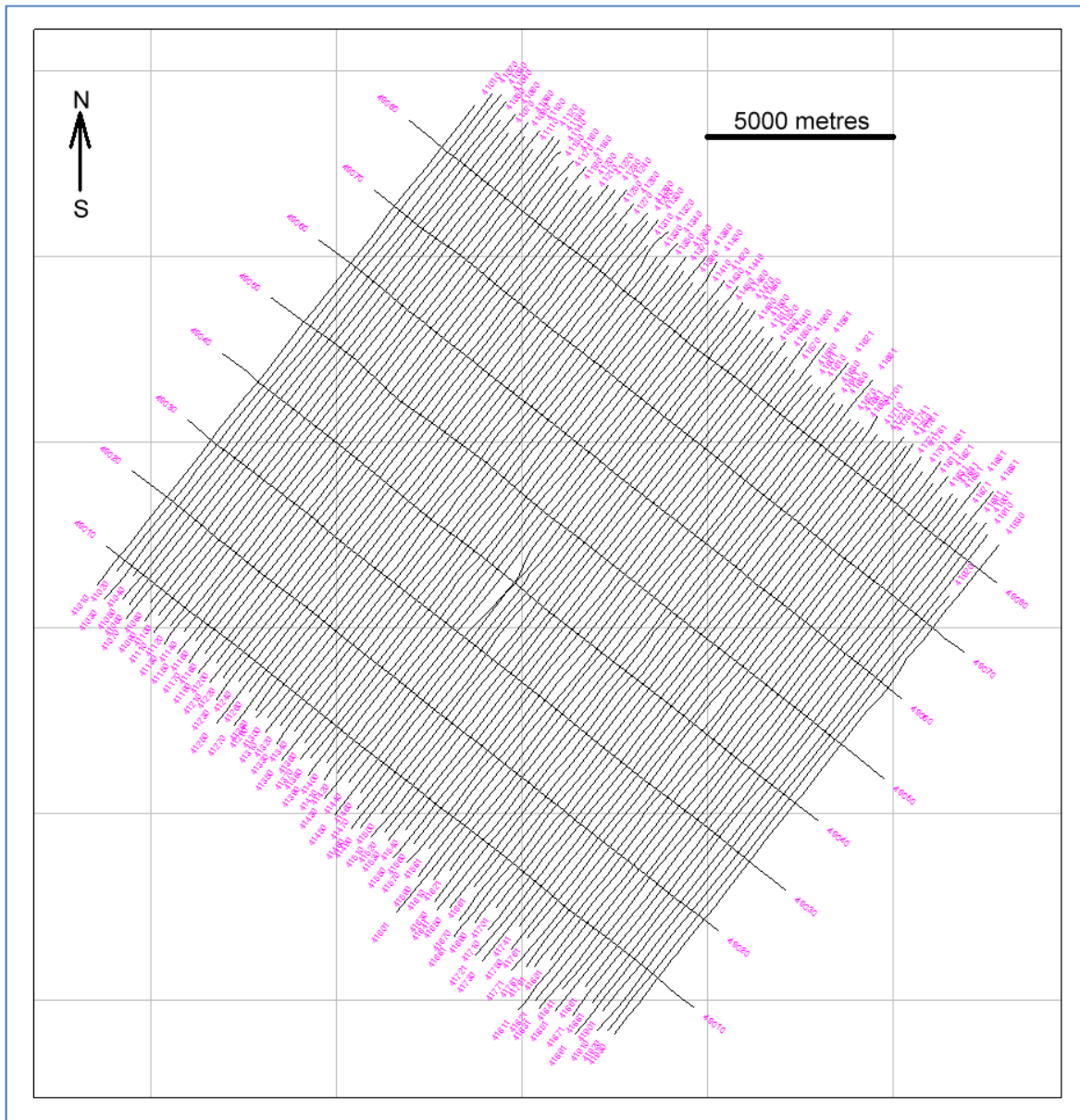
The first record is a flag to the software and may be either #VPeM# or #V3# (both are valid).

On record 5 the extra column numbers that can be defined for VPem3D are described in the VPem3D documentation. In this example there are 3 additional column numbers (0 9 0) defining the columns in the data file containing Tx_current, DEM, and Rx_altitude values. The zeros indicate that Tx_current and Rx_altitude are not actually present on the *.DAT file.

Y0 DELO ALTO define the system geometry. Y0 is the loop radius for central loop systems (ISTEP < 0) or the Tx-Rx horizontal offset for slingram systems. DELO is the vertical Tx-Rx separation. If the Tx is above the Rx, DELO > 0; if the Rx is above the Tx, then DELO is negative. ALTO is the Tx-Rx horizontal offset for SkyTEM (ISTEP = -4) and VTEM (ISTEP = -5) or a length scale for slingram systems.

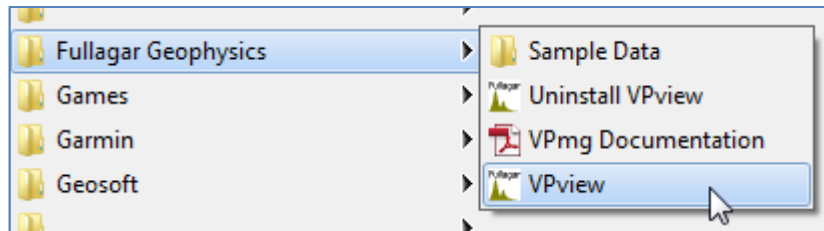
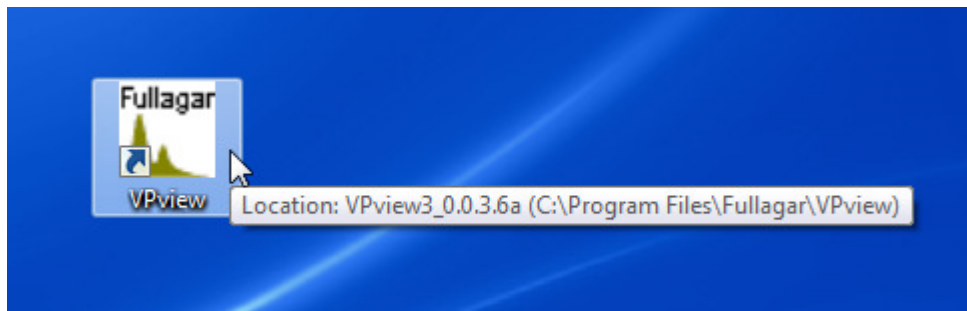
The #ROTATE# BEARING XREF YREF IADD record, defining the flight line coordinates, is optional. If a #ROTATE# record is not included then it is assumed that the flight lines are east-west. For any other flight line direction this record is required. The three parameters required to specify the rotation are flight line BEARING in degrees clockwise from survey north, and XREF, YREF (in survey coordinates) defining the origin of the flight line coordinates. Ideally, the model is oriented parallel and perpendicular to flight lines, with flight lines tracking across the model prism centres.

Therefore choose (XREF, YREF) on a flight line. If IADD=1, then XREF (YREF) are added to the flight line eastings (northings). IADD=0 otherwise, which is the recommended setting.

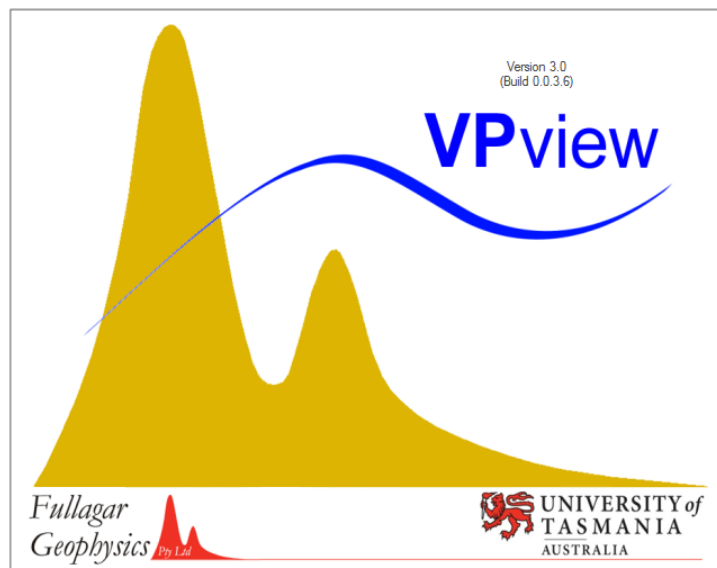


Flight line plot of the example survey.

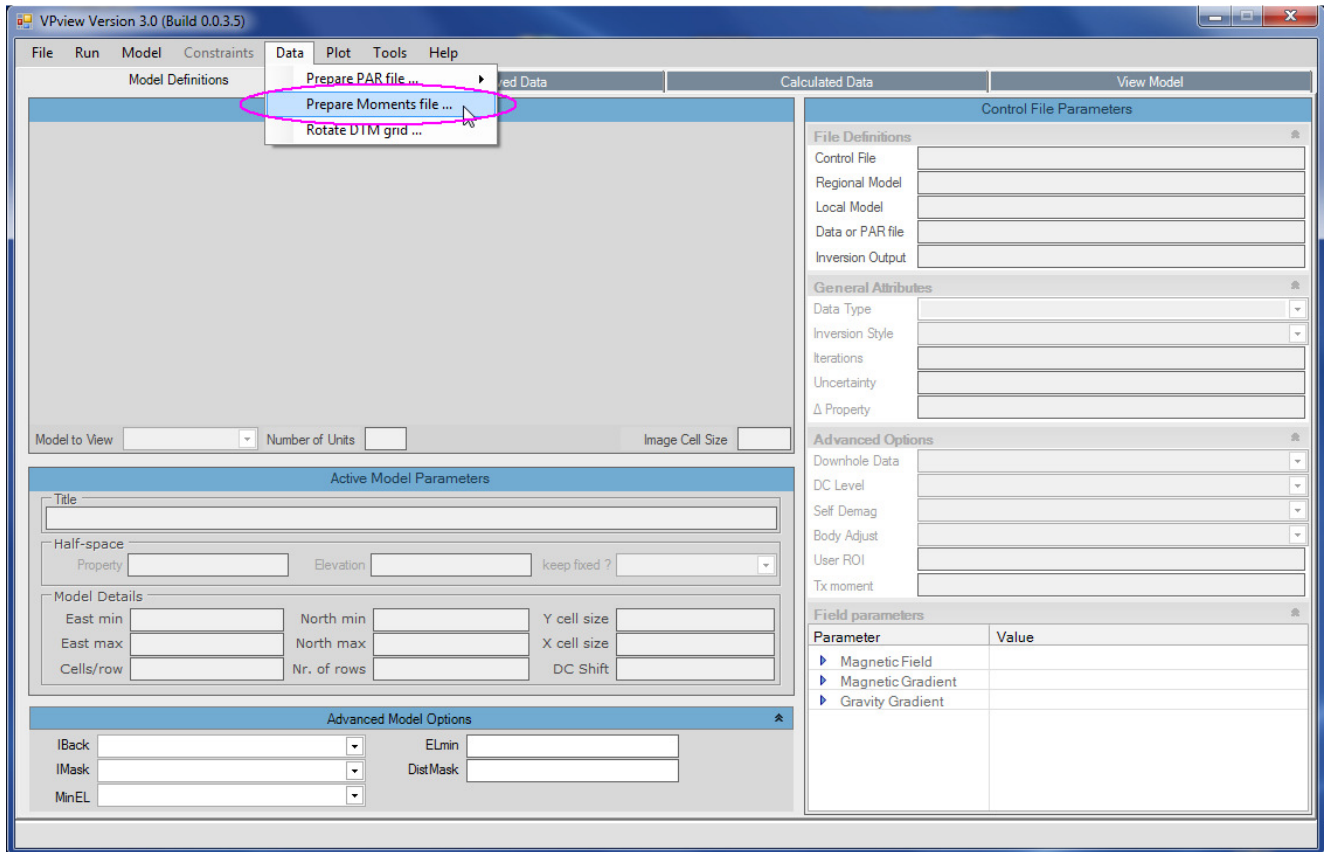
Due to the flight line bearing of 038 degrees the *.PAR file requires a #ROTATE# record (see page 5).



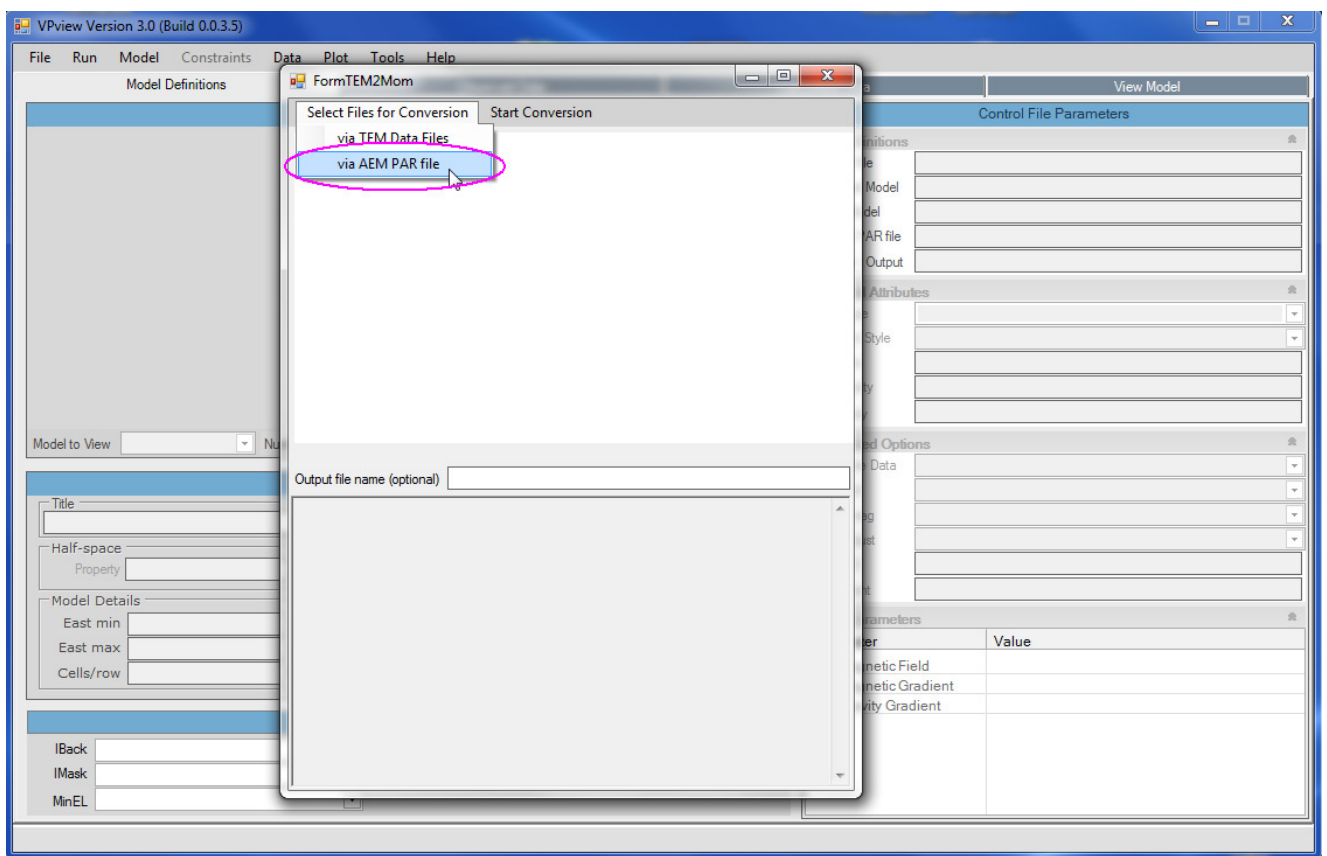
Start VPview from either the Desktop icon, or from the Windows Start → Programs menu.



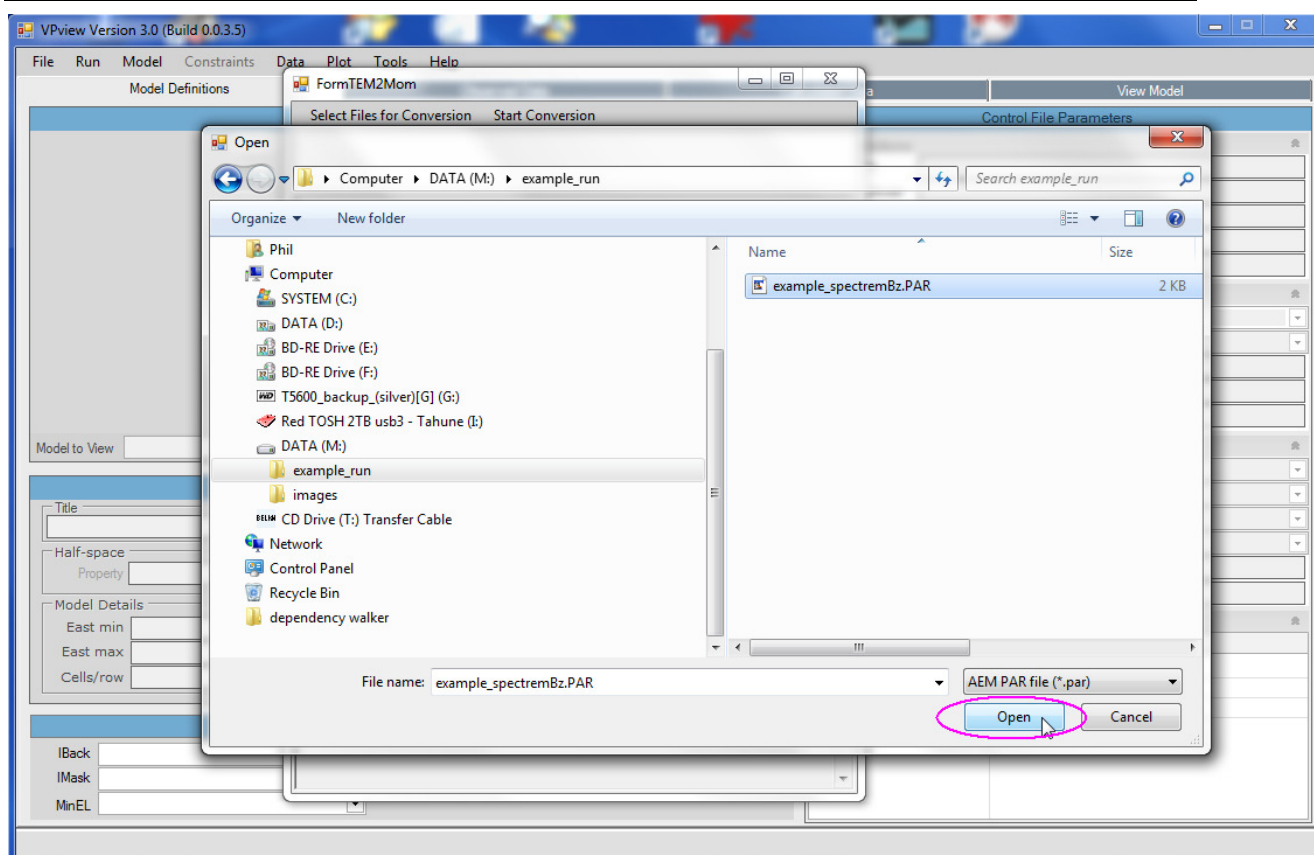
VPview splash screen



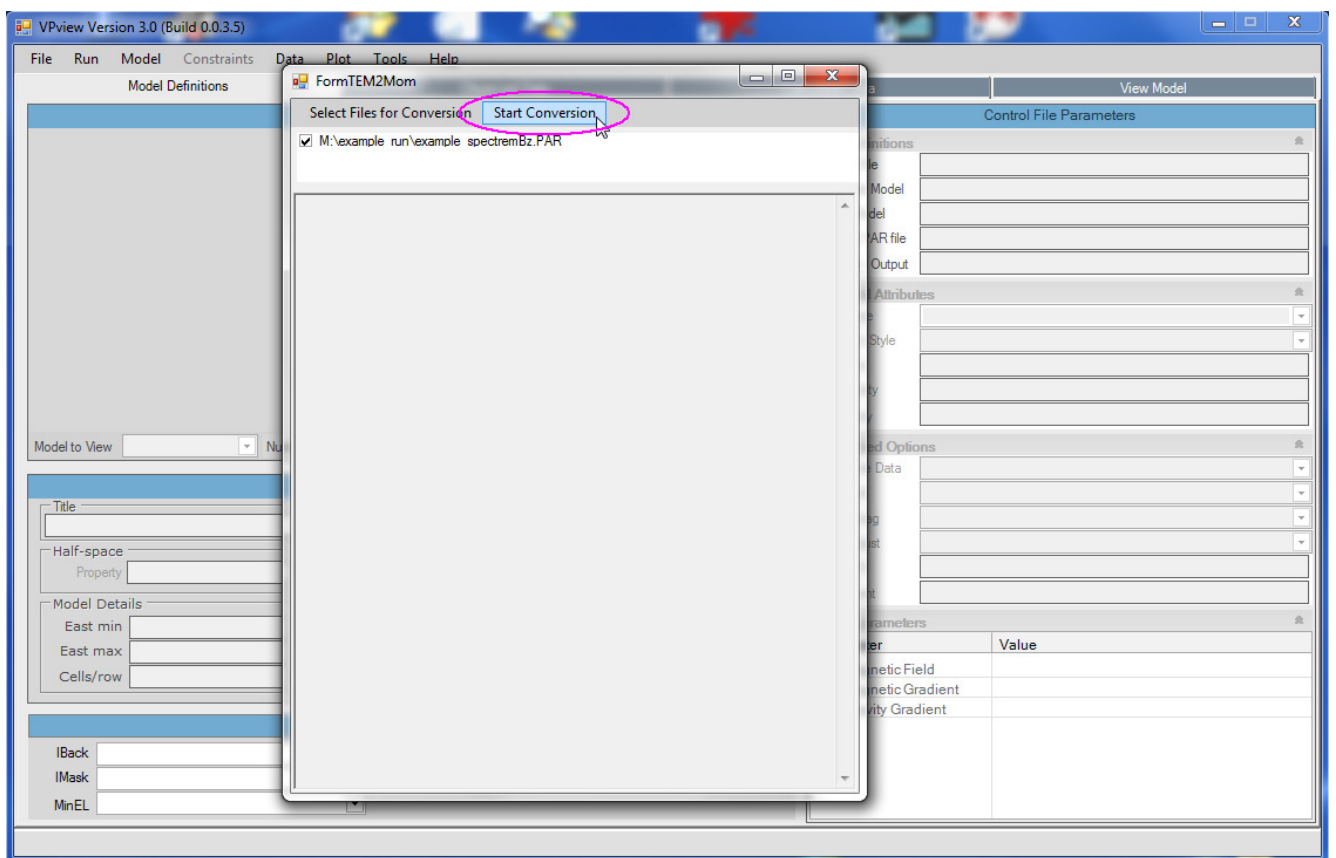
Convert the TEM decays (in the *.DAT file) into a resistive limits (TEM moments).



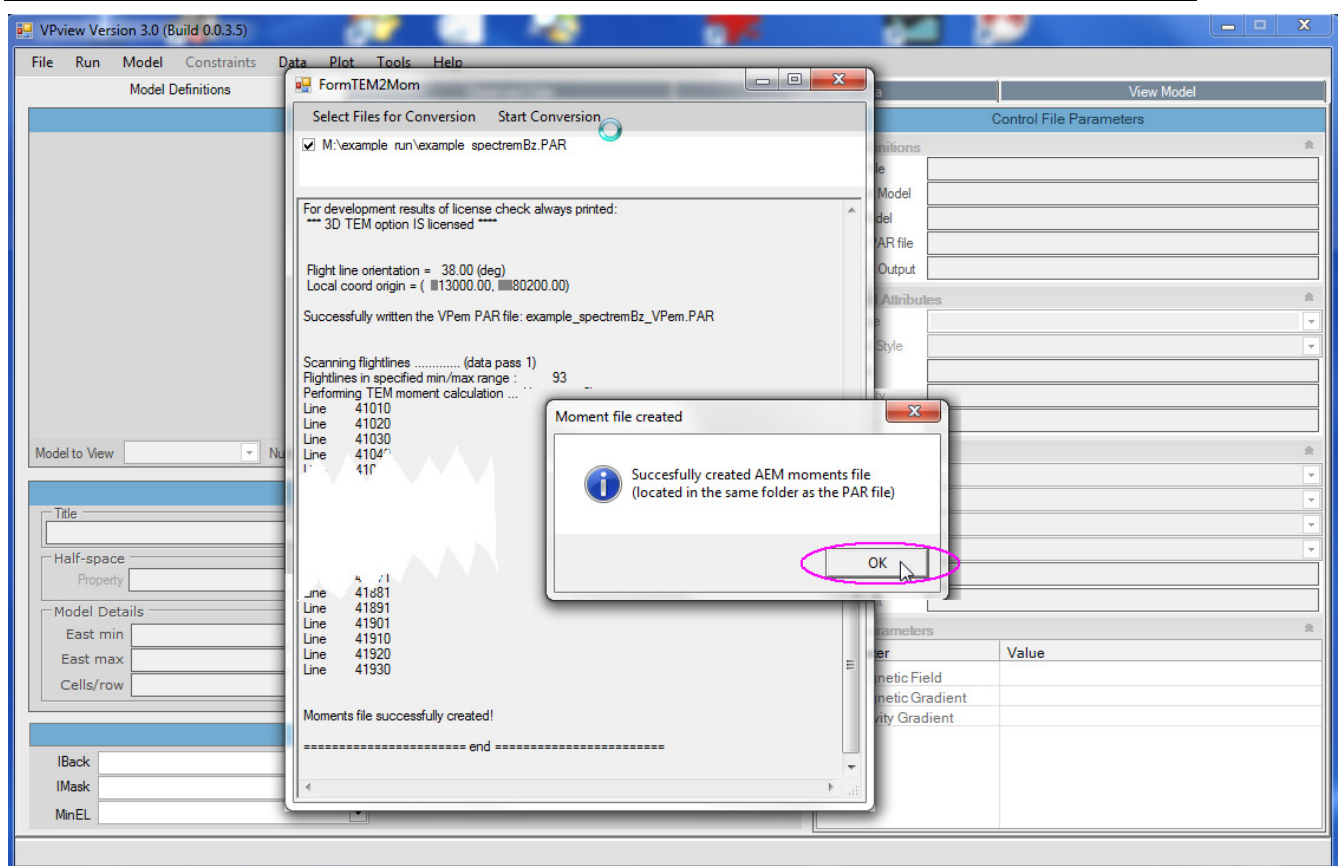
For airborne data select “via AEM PAR file”.



Select the *.PAR file (the original or modified EmaxAIR format file).



Start the conversion.
This will run a separate conversion program named AEM2Mom.



The run of AEM2Mom finishes.
Click OK to close the message window.

Name	Size
example_spectremBz.DAT	28,810 KB
example_spectremBz.LOG	1 KB
example_spectremBz.PAR	2 KB
example_spectremBz_MOM.XYZ	21,194 KB
example_spectremBz_VPem.PAR	1 KB
grid_DTM_dos.grd	486 KB

Highlighted are the new files created by AEM-to-moments calculation

After the conversion to moments has finished, there are three new files, with extensions XYZ, PAR, and LOG. The *.XYZ and the new *.PAR files will be the input for VPem3D processing.

example_spectremBz_MOM.XYZ x									
RXX	RXY	RXZ	RLZ	VDX	VDY	VDZ	LINE	DEM	NTG1
Line 41010									
-320.435758162364				18142.1073429054		424.8000	23.60991	-197.606641244069	18137.9335F
-307.380963474516				18141.7347949718		424.8000	23.82100	-184.558107179371	18137.380F
-294.329299098243				18141.2721194719		424.8000	25.57838	-171.506442803098	18136.91F
-281.422238310612				18140.2396655402		424.7000	26.46188	-158.556439439022	18137.3
-267.652536635944				18137.9882083508		424.5000	26.48378	-144.769923109407	18140.
-254.784769858330				18139.8760172059		424.4000	26.76290	-131.903758035662	1813F
-241.917803932651				18139.6497449389		424.1000	26.45428	-119.036792109982	181F
-229.117828270577				18139.1294421081		423.9000	26.62176	-106.225968221046	18F
-216.312428495072				18138.9819709186		423.8000	26.97203	-93.4205684455410	1
-202.734519211519				18136.3393928901		423.3000	26.36994	-79.9347889263463	
-190.039927577054				18139.0837790280		423.0000	26.81250	-67.1417133101477	
-177.358538714443				18138.7137036076		422.8000	26.56468	-54.4585672225894	
-163.865181818250				18136.2427933937		422.4000	26.92969	-41.1344999167304	
-151.267559138332				18139.4284281185		422.3000	27.82056	-28.3675876464786	
-138.758052310035				18138.5120882683		422.0000	28.74772	-15.8819564256501	
-125.317285736935				18136.9069078592		421.9000	29.30103	-2.62843109718960	
-112.858243110948				18139.8545578205		421.8000	29.54548	10.0307966264390	
-100.354202159884				18139.7097502105		421.8000	28.70004	22.5218937245008	
-86.9515803499780				18137.8043520900		421.8000	27.62704	35.6904315158063	
-74.5710533347155				18140.8184801094		421.9000	27.38513	48.3050425496695	
-62.1758285055530				18140.4287541290		421.9000	27.12420	60.6586911687937	
-48.8295701594070				18139.0139334541		421.8000	27.18243	73.7604601235107	
-36.5275385671048				18142.0938816907		421.9000	24.31264	86.3304342799856	
-24.0915356927162				18142.4192169668		422.0000	28.51317	98.766437154374F	
-10.7664962407634				18140.2992565119		422.0000	30.08350	111.766292702794	
1.50691468185869				18143.7643500986		421.9000	31.07009	124.364887528949	
14.8319541335950				18141.6443896440		421.9000	31.72767	137.364743077727	
27.0555254926312				18144.7894888004		421.9000	27.05228	149.890045166978	
39.4299622164872				18145.1936251545		421.8000	26.68494	162.264481891551	
52.7432750824264				18143.4724602068		421.7000	25.08265	175.276064025984	
64.9197460098767				18146.2938343954		421.8000	23.44995	187.72533424661F	
78.2515386372179				18145.2815397661		421.6000	24.05126	200.8415689201F	
90.4566302346357				18147.7177686043		421.6000	24.85372	213.262218470F	
102.816601239329				18148.5244310045		421.4000	25.17252	225.6511209F	
116.129914105268				18146.8032660568		421.4000	26.10281	238.66270F	
128.403325027890				18150.2683596434		421.5000	27.22149	251.2612F	
140.839327902278				18150.5936949195		421.6000	25.05057	263.697300F	
153.275330776667				18150.9190301956		421.8000	24.77653	276.1333036F	
165.763838282583				18151.5606312208		422.1000	25F	288.639934F	
179.166460092489				18149.6552331003		422.3000	25F	301.80847F	
191.494482476512				18152.3530953F				314F	
203.930485350542									
216.4189928F									
227F									

Example of the start of a *.XYZ Moments data file created by AEM2Mom.
 Note that because the original survey flight lines were not east-west the coordinates on this Moments file (first two columns RXX, RXY) are now in the local rotated (flight line) coordinate system that will be used by VPem3D.

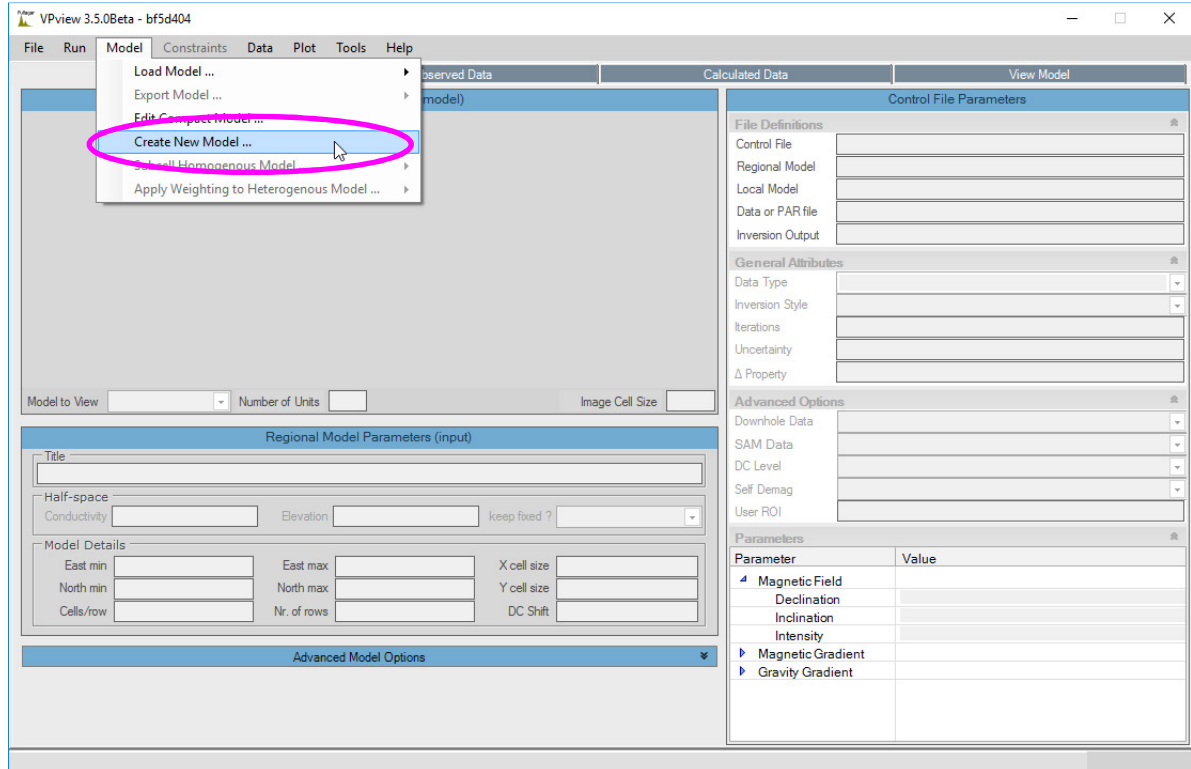
```
example_spectremBz_VPem.PAR x
#VPeM#
-----
example_spectremBz_MOM.XYZ
8   ! NVAR
-1  ! NCH
4   RLZ
5   VDX
6   VDY
7   VDZ
8   LINE

! VPem PAR file created by AEM2Mom on 2015-01-25 (yr-mo-dy)
```

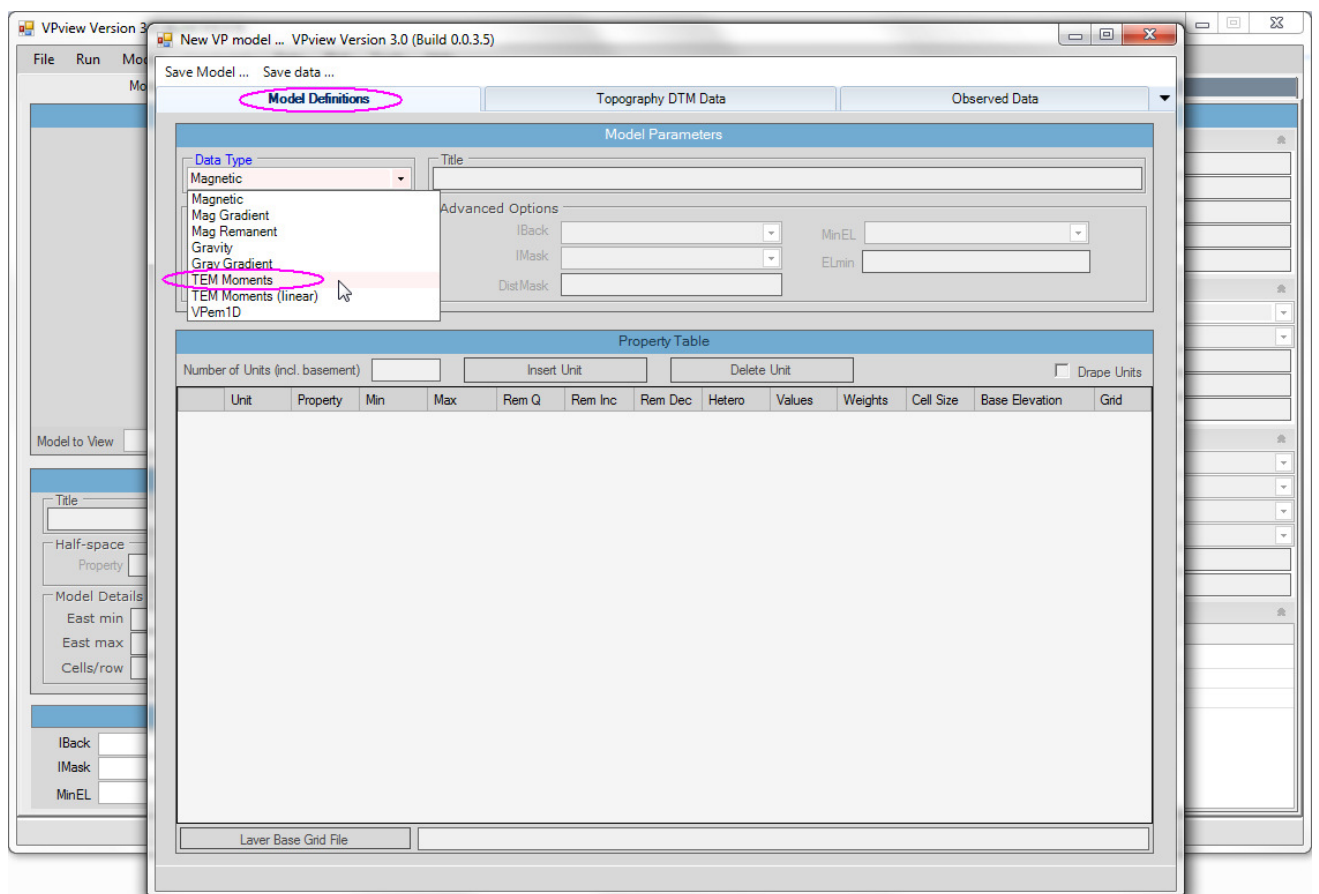
Example of a *.PAR parameter file to be used by VPem3D. This PAR file defines the format of the moments (*.XYZ) file. The VPem3D *.PAR file format is not the same as the EmaxAIR *.PAR file format. Normally you will not need to edit the VPem3D PAR file.

12.3 Create a starting model (DTM grid available)

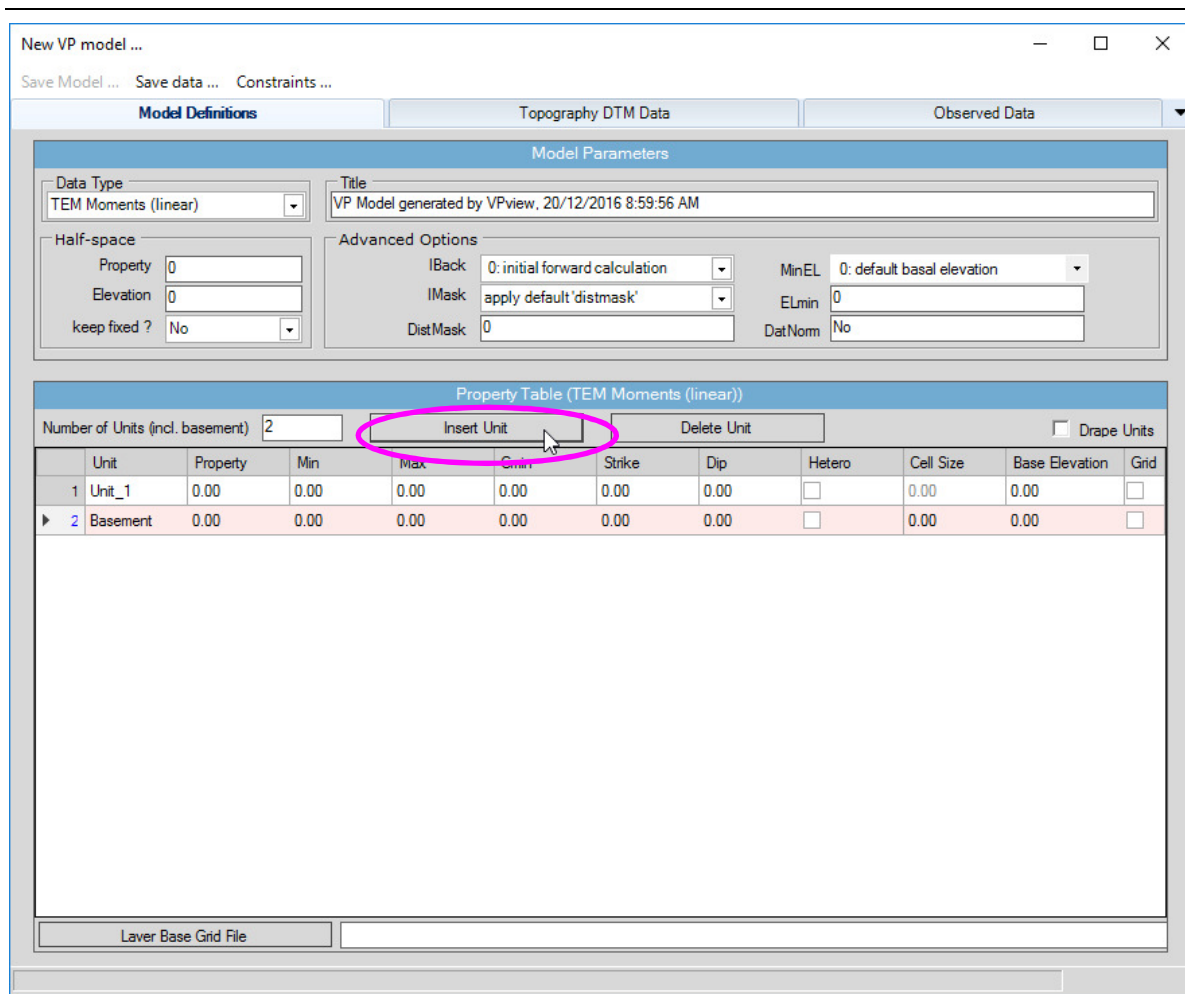
VPview includes a *Create New Model* utility under the Model menu for creating layered models. The layers span the entire model area, but layer thickness can reduce to zero, allowing discrete bodies to be represented.



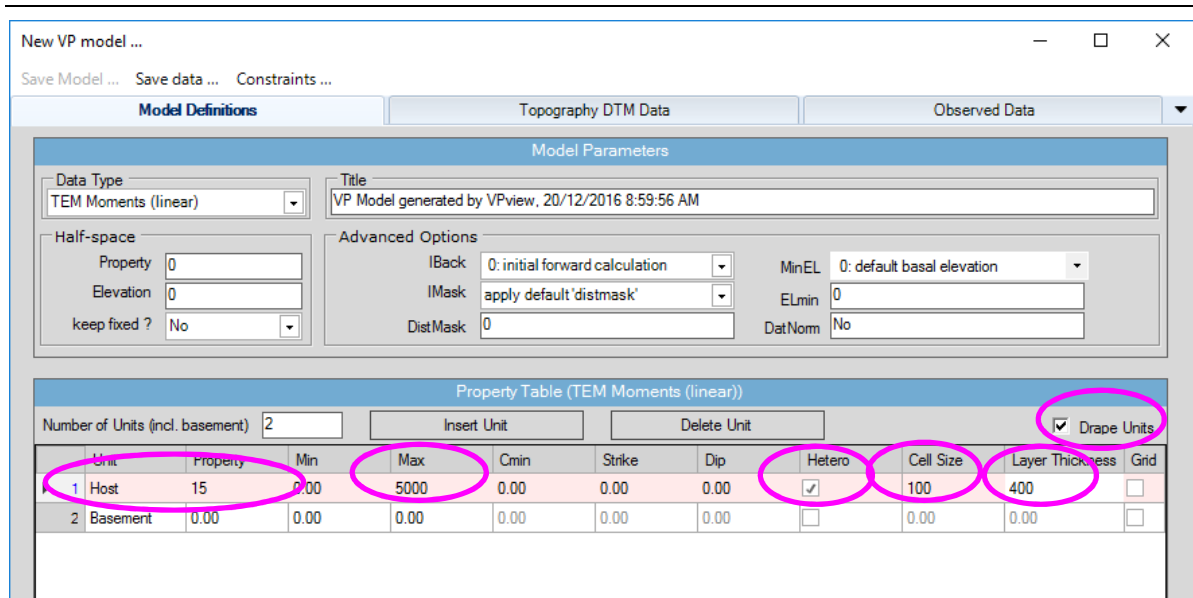
Create a layered model as a starting point for inversion.



On the *Model Definitions* form, select data type “TEM Moments”.



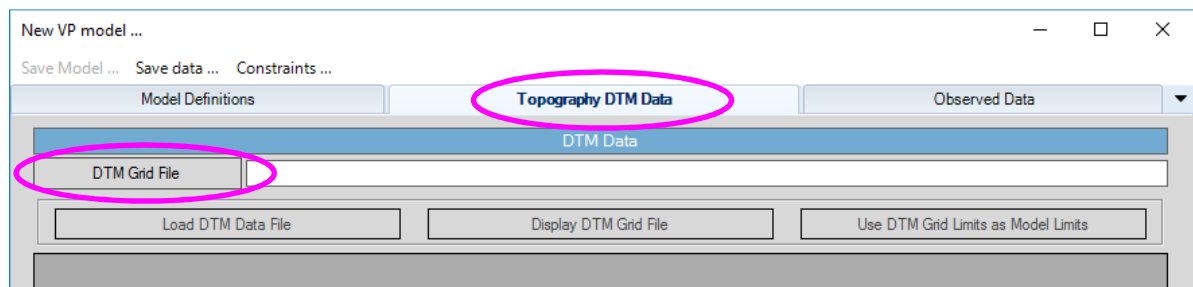
The simplest VPem3D model consists of a single layer above basement. The default name is "Unit_1".



Set parameters for the layer and basement.

In this example:

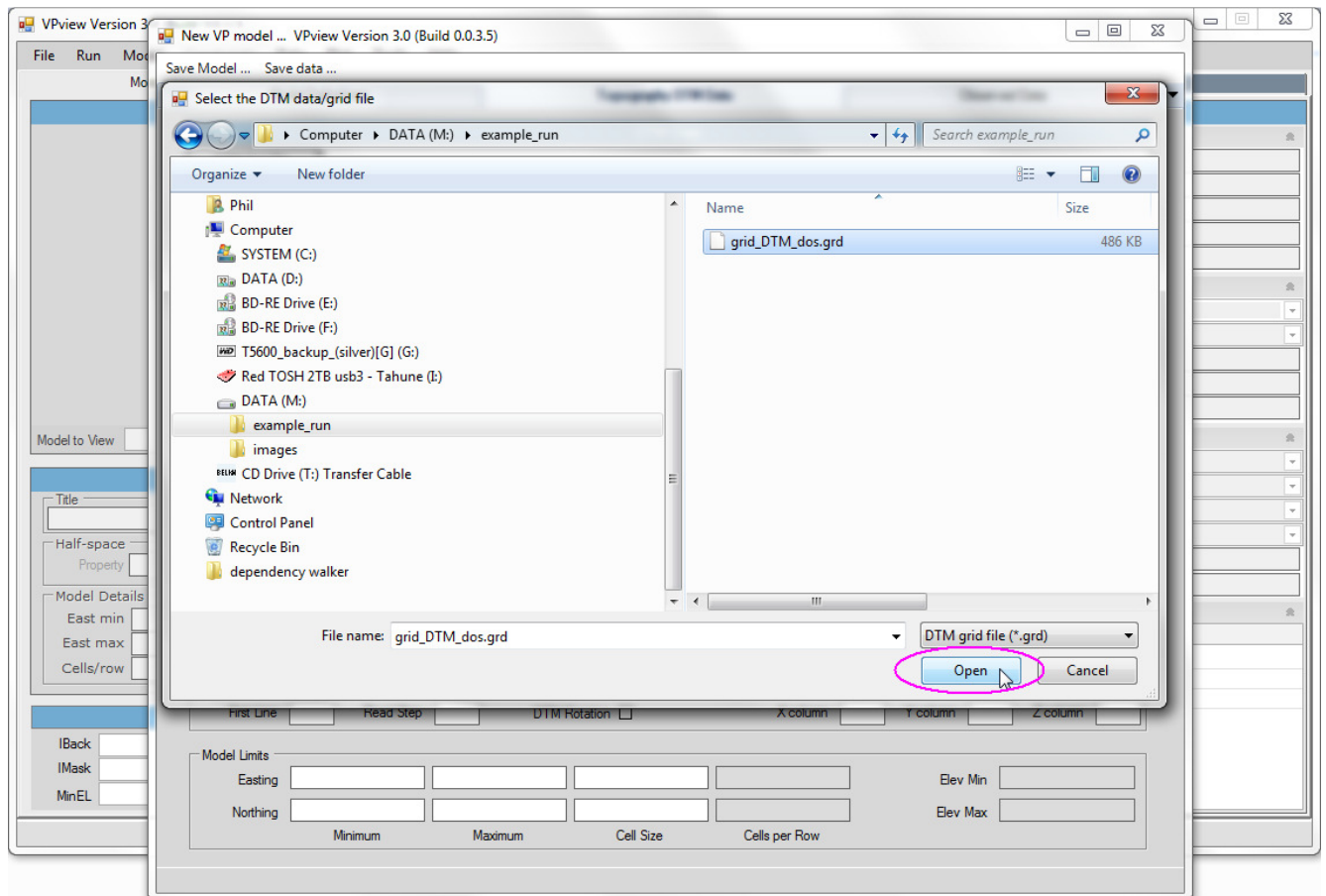
- (a) Changed the name of the added unit to “Host”
- (b) Set the starting conductivity of Host to 15 mS/m
- (c) Set the maximum conductivity for Host to 5000 mS/m
- (d) Made the Host heterogeneous (checked *Hetero* box)
- (e) Set the model sub-cell size to 100m in the Host unit (n/a for the basement). If the Cell Size is not an integer, the decimal part is interpreted as an expansion factor. Specifically, if the Cell Size were entered as 100.1, then the thickness of successively deeper cells would increase by a factor of 1.1
- (f) Specified that the Host should be Draped below the topography (checked *Drape Units* box)
- (g) Set the thickness of the Host to 400m, draped under the ground surface (n/a for the basement)



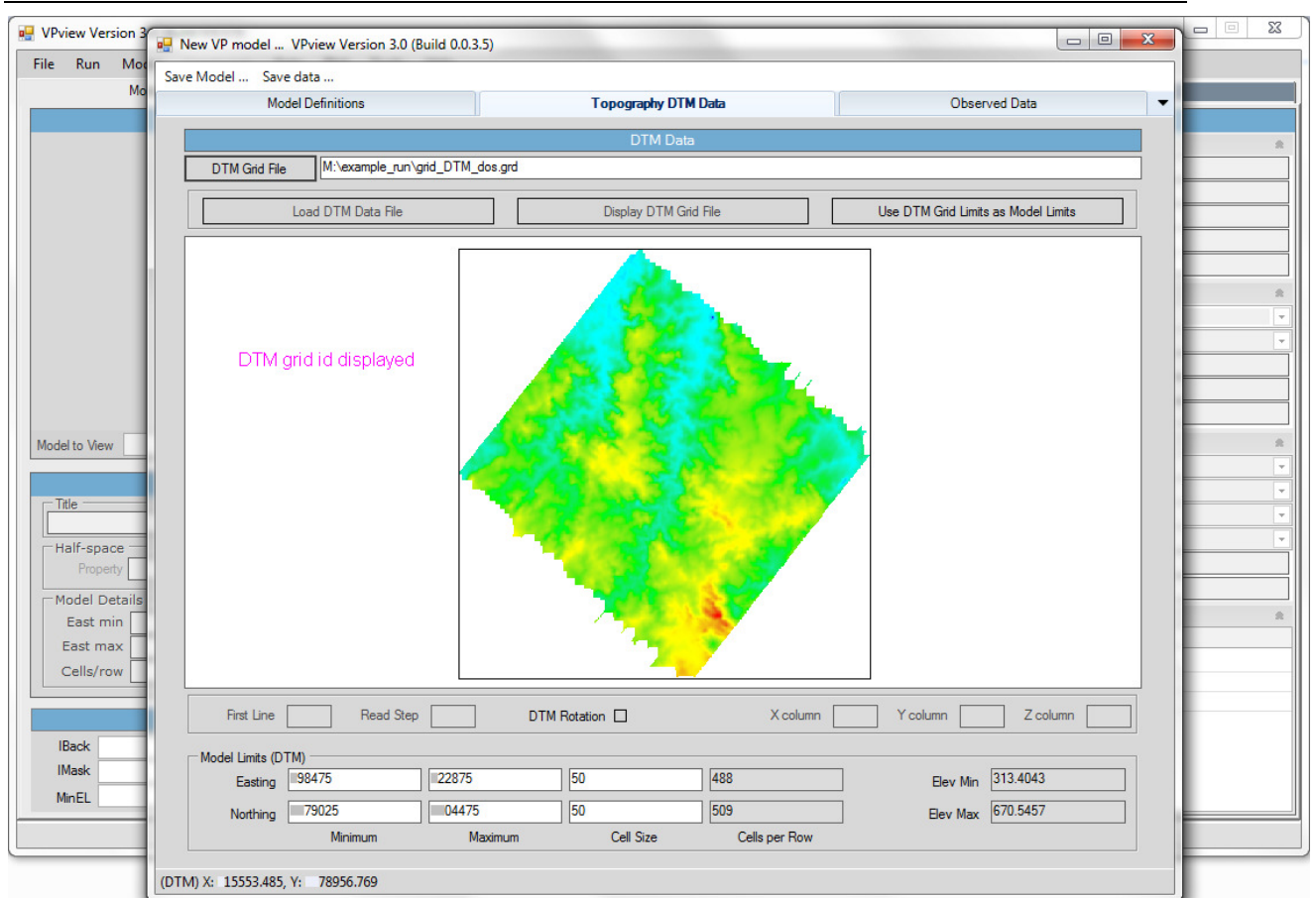
In VPem3D models, the model top coincides with the ground surface. Therefore VPview uses a DTM grid, if available, to define the model top during starting model construction. The format of the DTM grid must be Geosoft “DOS”, i.e. uncompressed GRD.

Import the DTM topography grid file.

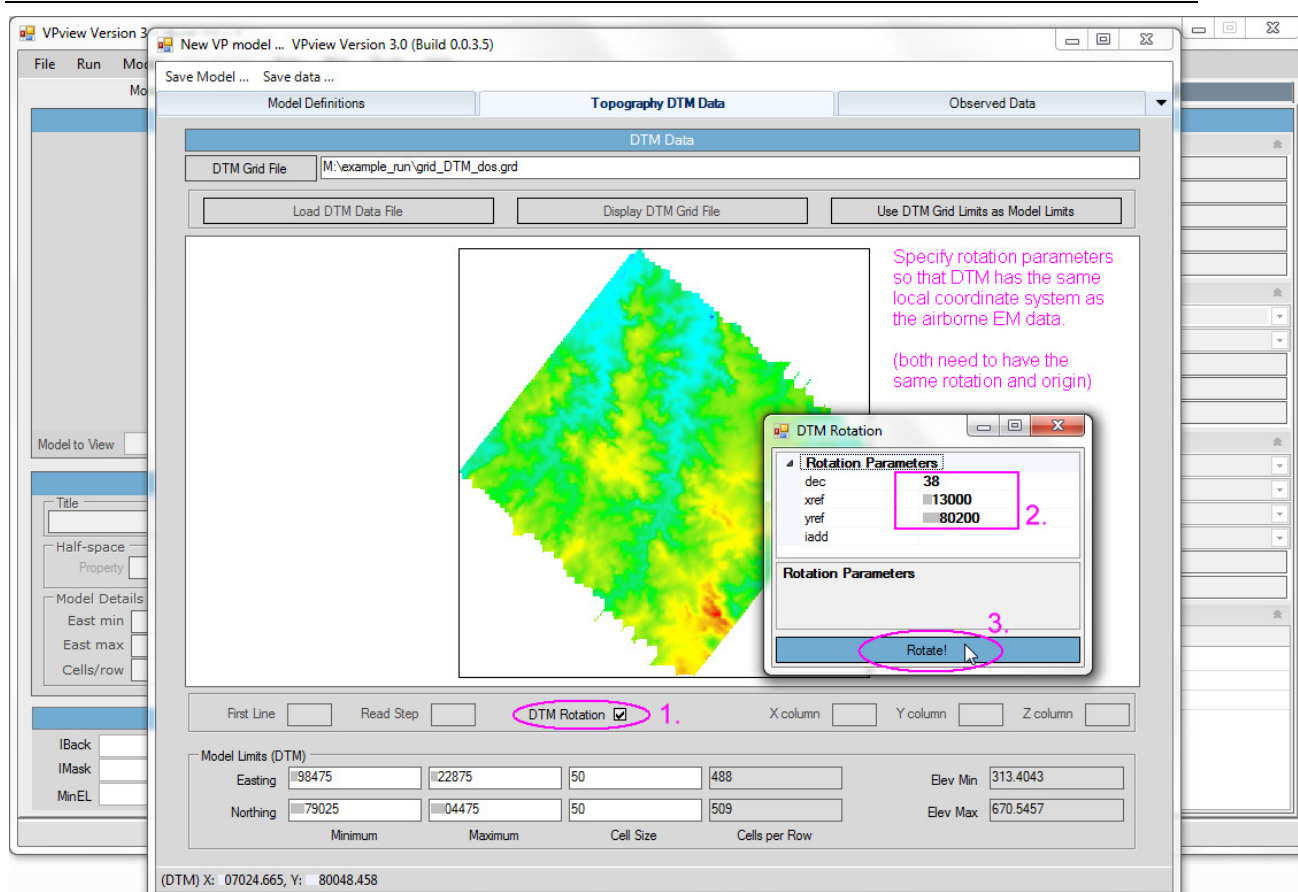
(IF YOU DO NOT HAVE A DTM GRID go to Section 12.4 below).



Open the DTM grid file.



The DTM grid file is displayed.



Specify a coordinate rotation for the DTM. Adoption of a local coordinate system parallel/orthogonal to flight lines is recommended for VPem3D.

Because the airborne TEM survey flight lines were not flown east-west, a #ROTATE# record was included in the original EmaxAIR *.PAR file to rotate the data during conversion to moments. Consequently we have to now specify the identical rotation to apply to the DTM grid.

Use the same three rotation parameters as defined in the EmaxAIR *.PAR file:

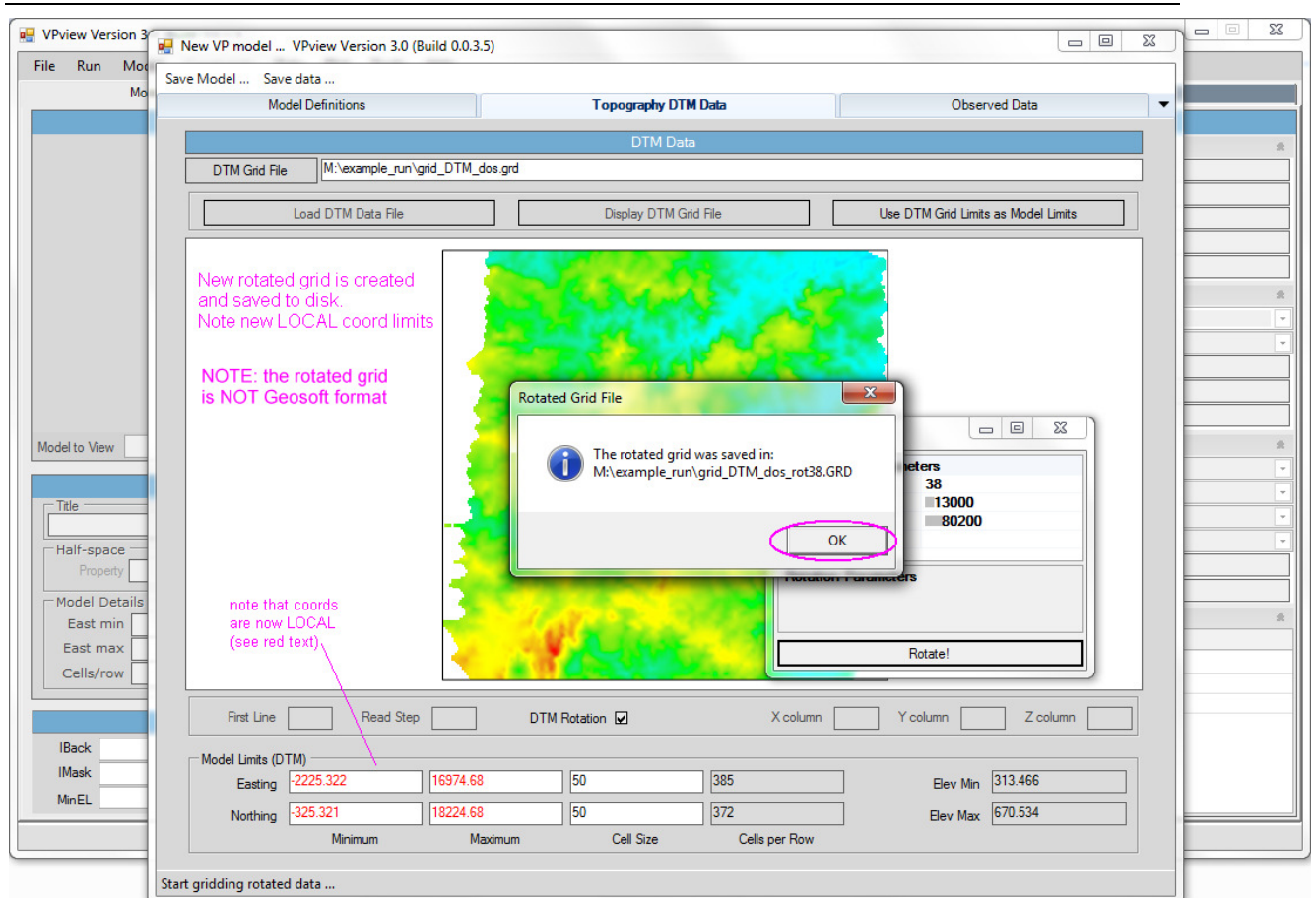
“dec” = declination = Bearing of flight lines (positive clockwise from DTM north).

“xref” = Easting reference point for rotation, i.e. easting of the origin for the local coordinate system.

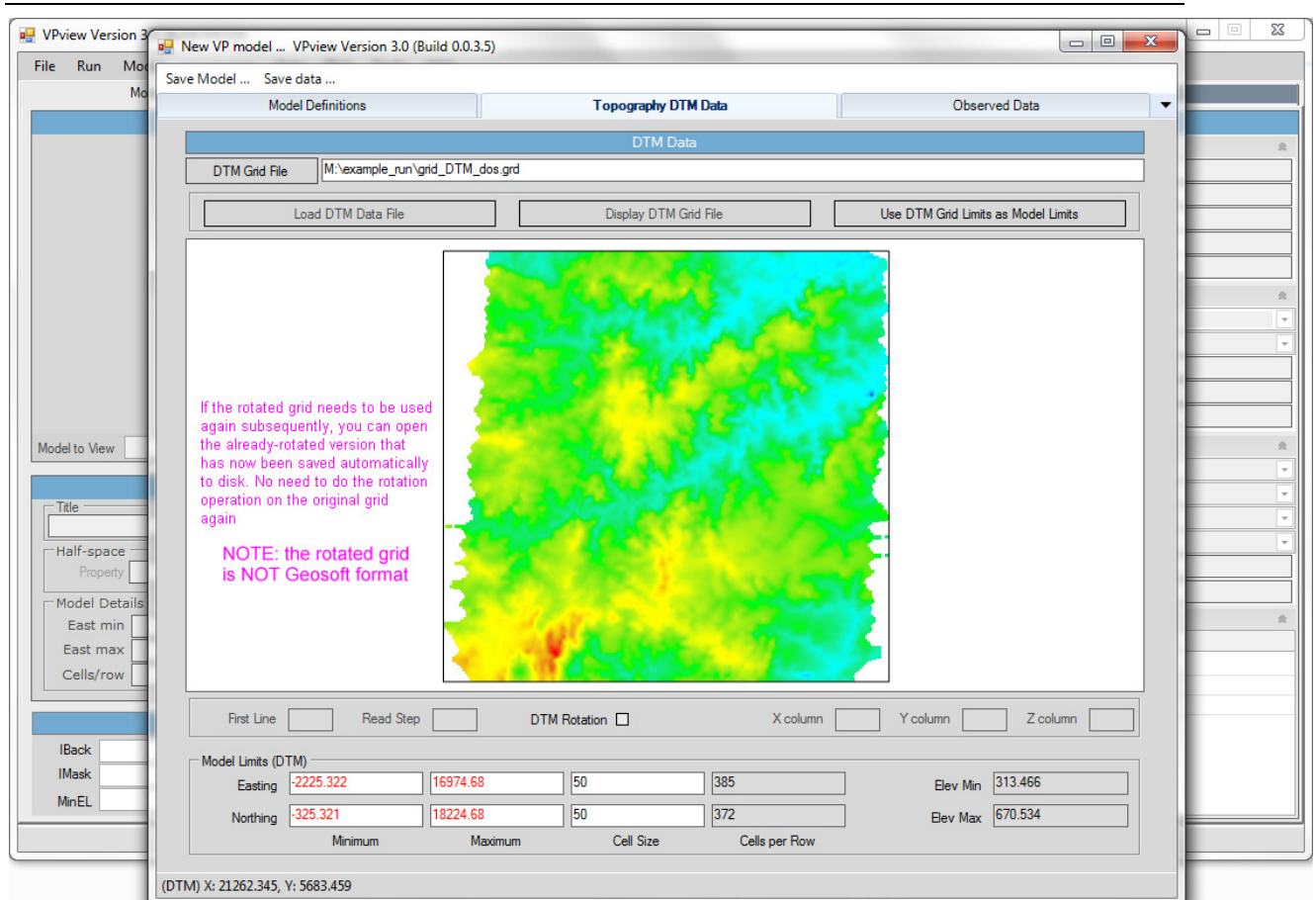
“yref” = Northing reference point for rotation, i.e. northing of the origin for the local coordinate system

“iadd” = flag for addition of (xref,yref) to rotated coordinates.

(also see Section 12.2 for comments on rotation).



- The rotated DTM grid is displayed.
- The rotated grid is automatically saved.
- Note that the coordinates are now in the rotated system.
- Click OK to close the message window.

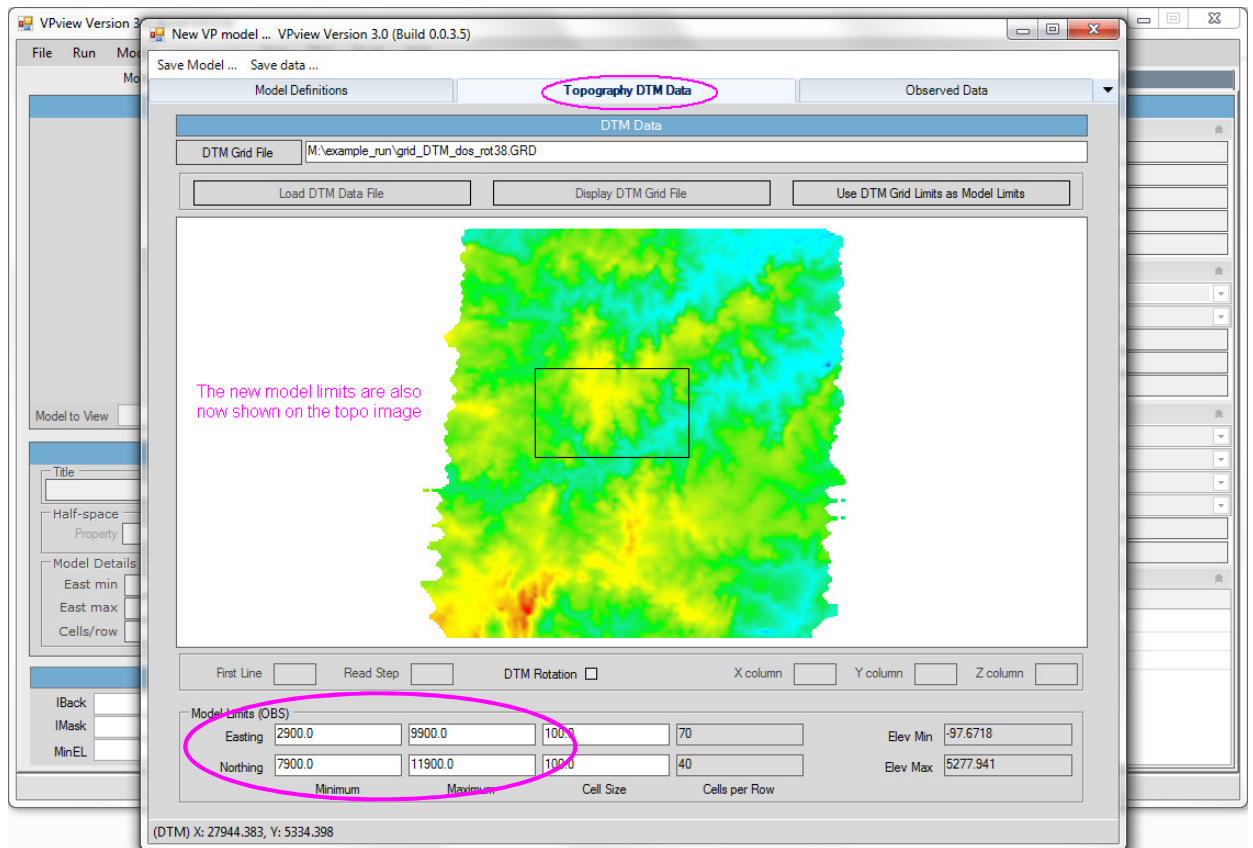


Note that you can re-use the rotated DTM grid again later if required.

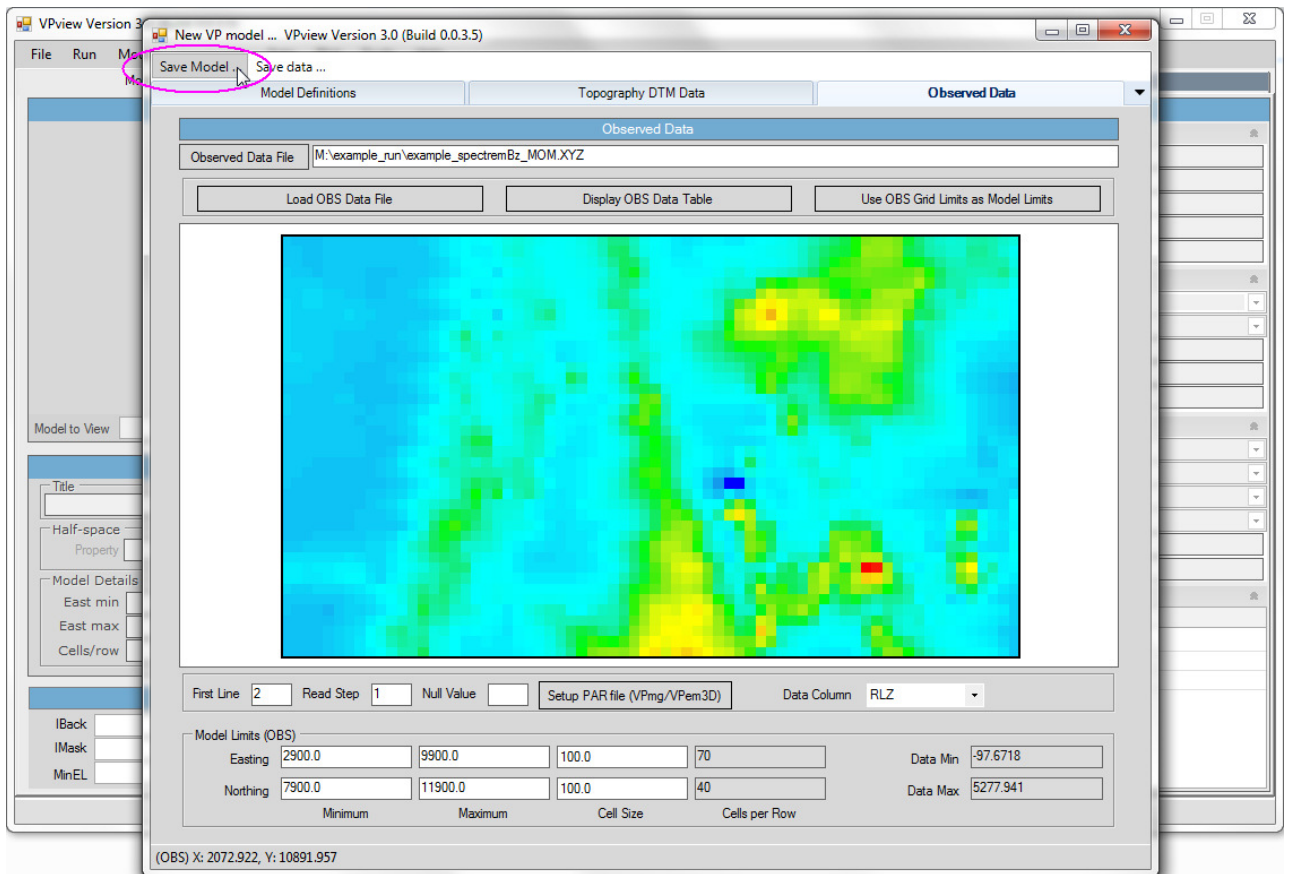
For example, you may decide to define some different starting models and need to load the DTM again, whereby you can simply load the rotated grid file and skip the rotation definition step.

Limitations to remember;

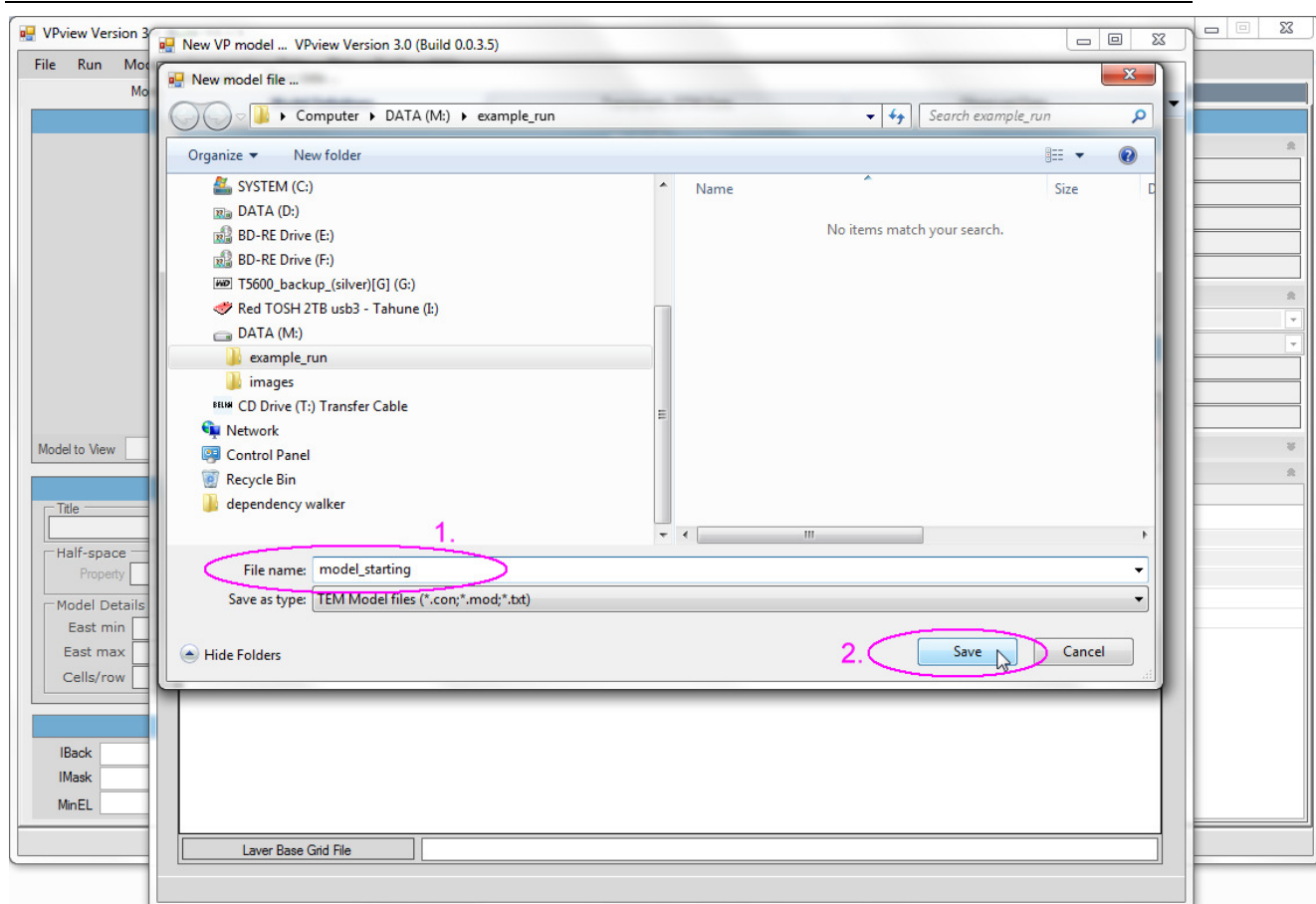
- The rotated grid file created by VPview is not in a Geosoft grid file format.
- The rotation defined in the original EmaxAIR *.PAR file for the TEM data MUST be identical to the rotation defined for the DTM grid during model creation.



- Enter the desired model limits (now in LOCAL rotated coordinates).
- Your newly defined model limits area is displayed on the DTM image



Save the model to a disk file.



Choose a suitable file name.

```
ca. C:\Windows\System32\cmd.exe

##### UPmg v8.0 (x64) #####

  3D constrained & unconstrained modelling & inversion
    of gravity, gravity gradient, ...
      IMI, magnetic gradient, ...
    & TEM (resistive limit) data.

  Fullagar Geophysics   Brisbane   Australia.

#####

=====
Create heterogeneous unit(s)
=====

Control file = subcell.ctl
Gravity data file = subcell.dat
Local model file = model_starting.con
UPmg output file = model_starting_het.mod

Active model area:   70 prisms E-W   40 prisms N-S

Total data points in active model area =           1
No. prisms filling active model area =           2800

Preliminary read through active model ...

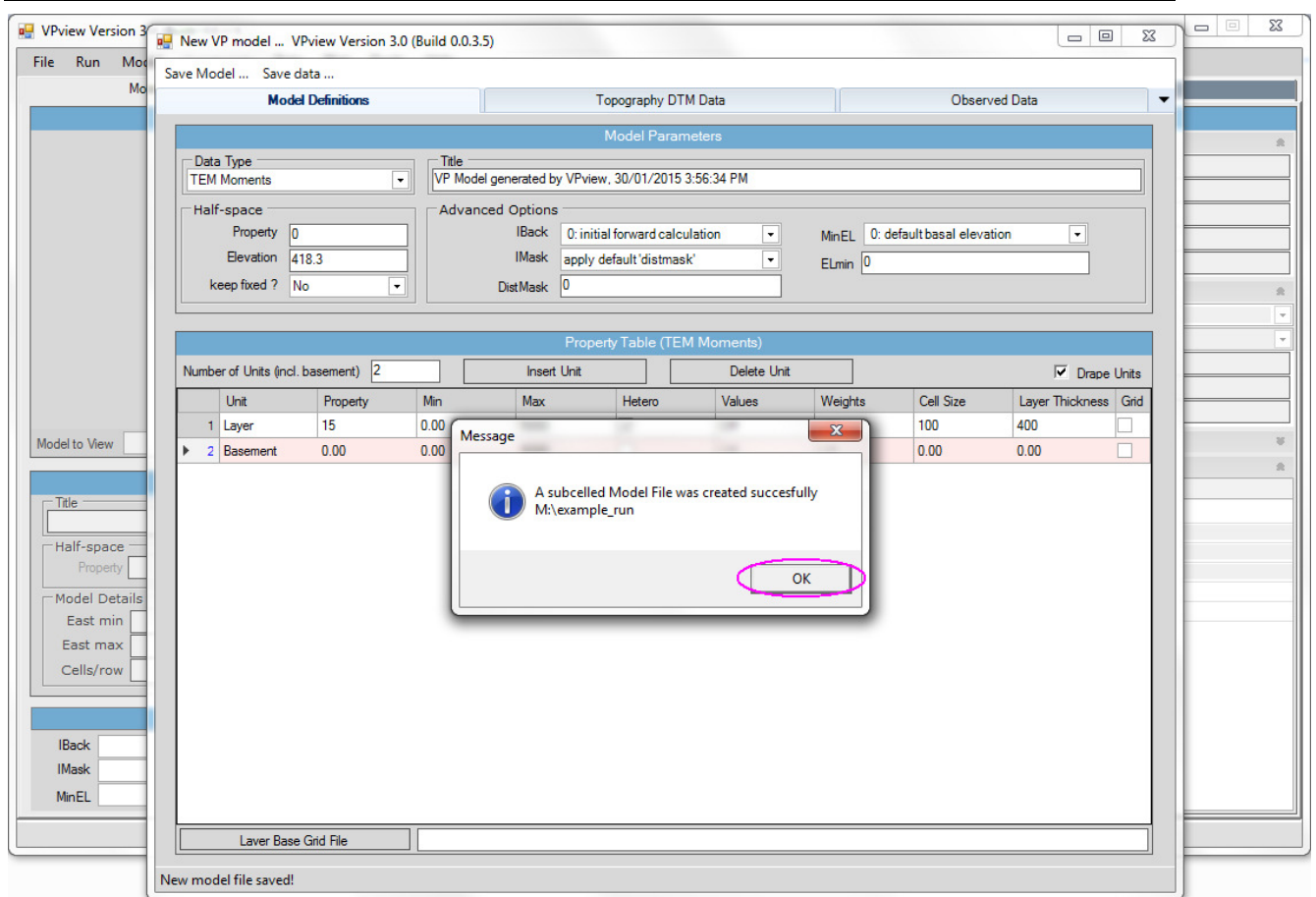
Loading the active model ...

***** Heterogeneous unit(s) created! *****

M:\example_run>_

This window can be closed after a successful run.
```

After VPview creates a homogeneous model, VPem3D sub-cells any heterogeneous units. In the example the Layer unit is sub-divided into cells 100m thick. The Command Window can be closed once the run completes.



12.4 Create a starting model (no DTM grid available)

When no DTM grid is available, VPview creates a model with a horizontal upper surface. Launch the VPview *Create new model* utility, and complete the Model Definitions form as described in Section 12.3. Then click on the Observed Data tab.

The model extents and model top elevation can be read from a dummy data file defining the corners of the model area. A 3 to 5 line dummy data file will suffice, with records of the form shown below:

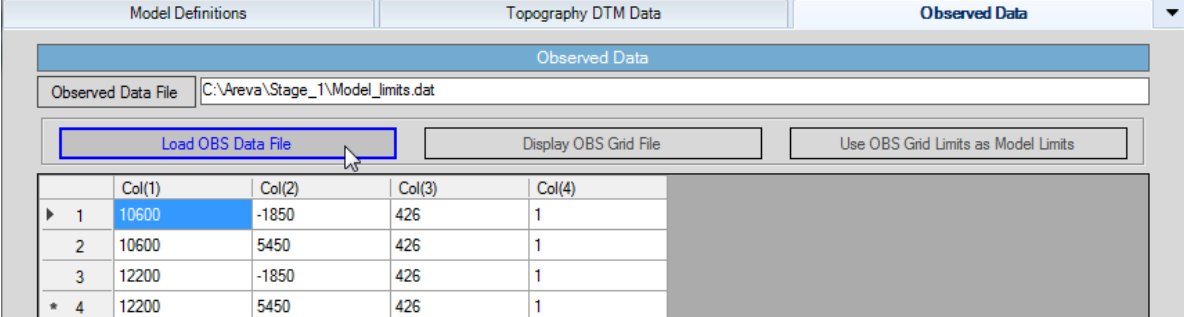
EAST NORTH ELEVATION READING

XMIN, YMIN, RL1, DATA1

XMAX, YMIN, RL2, DATA2

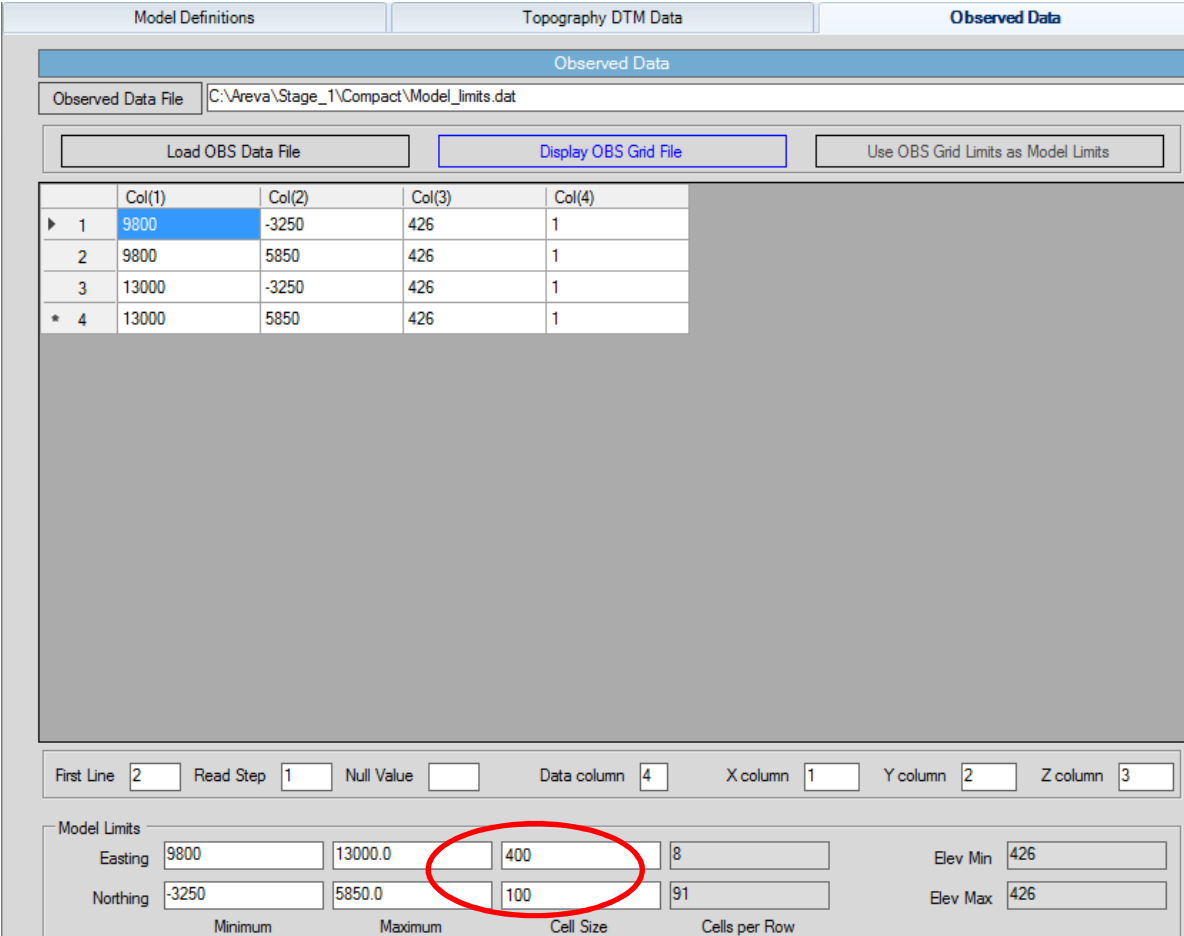
XMAX, YMAX, RL3, DATA3

The first record here is an optional header line; the elevations, RL_n, should be identical.



	Col(1)	Col(2)	Col(3)	Col(4)
▶ 1	10600	-1850	426	1
2	10600	5450	426	1
3	12200	-1850	426	1
* 4	12200	5450	426	1

Load the dummy data file by clicking on the *Load OBS Data File* button.



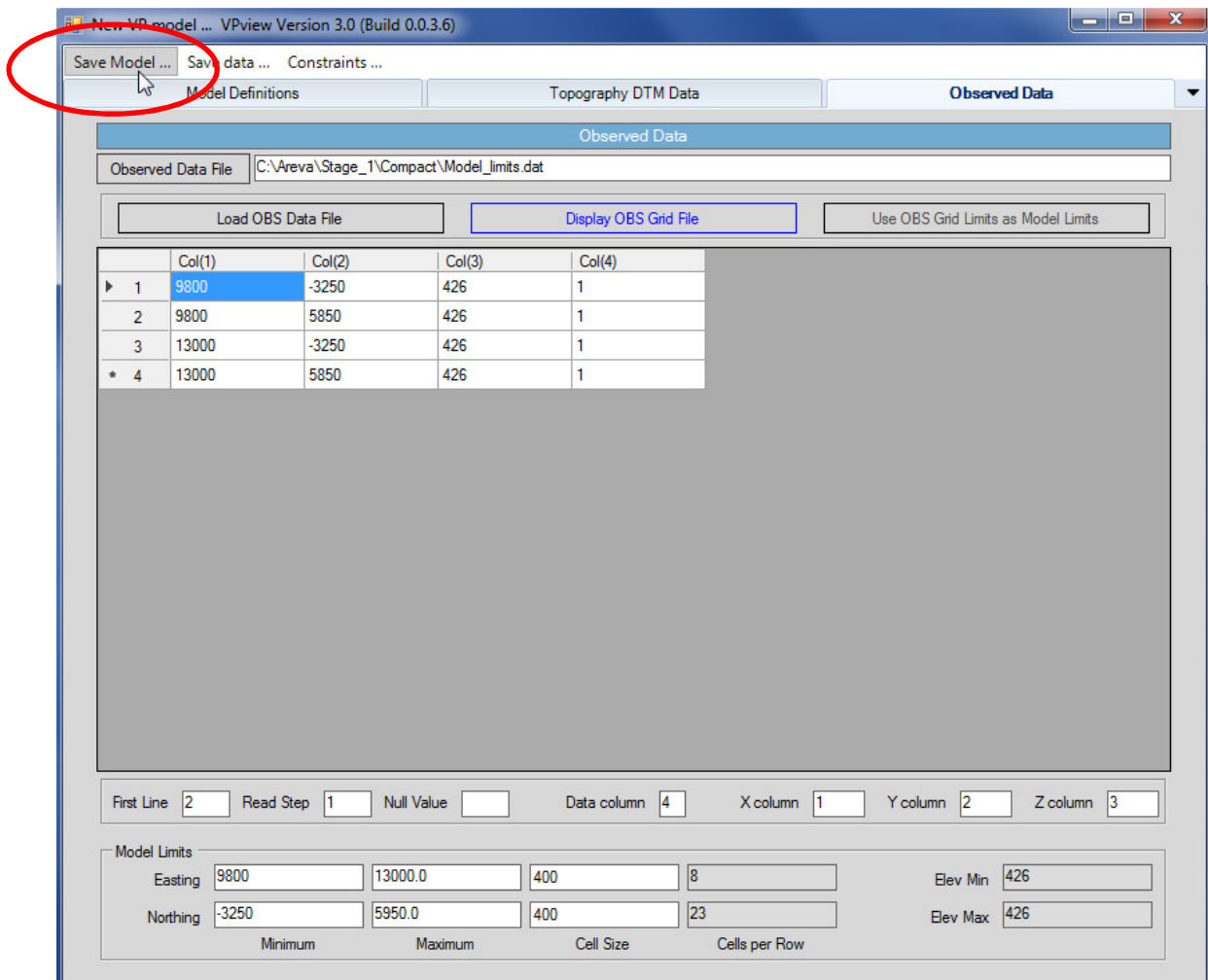
	Col(1)	Col(2)	Col(3)	Col(4)
▶ 1	9800	-3250	426	1
2	9800	5850	426	1
3	13000	-3250	426	1
* 4	13000	5850	426	1

First Line Read Step Null Value Data column X column Y column Z column

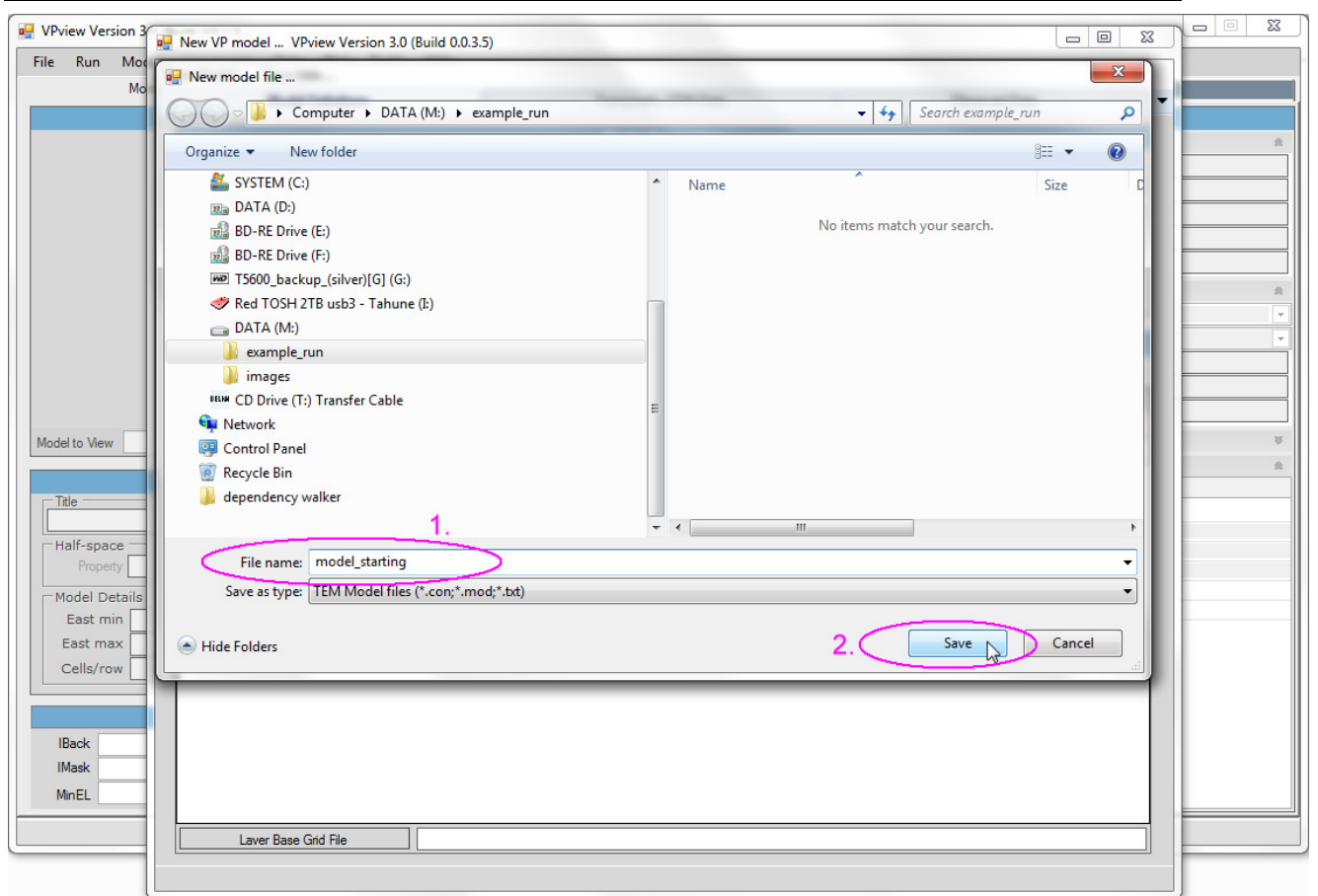
Model Limits

Easting	<input type="text" value="9800"/>	<input type="text" value="13000.0"/>	<input type="text" value="400"/>	<input type="text" value="8"/>	Elev Min	<input type="text" value="426"/>
Northing	<input type="text" value="-3250"/>	<input type="text" value="5850.0"/>	<input type="text" value="100"/>	<input type="text" value="91"/>	Elev Max	<input type="text" value="426"/>
	Minimum	Maximum	Cell Size	Cells per Row		

Enter the desired model prism dimensions.



Save the model to a disk file. The model will have a flat ground surface, at the average elevation of the points in the data file, i.e. 426m in this case.



Choose a suitable file name.

```
C:\Windows\System32\cmd.exe

##### UPmg v8.0 (>x64) #####

  3D constrained & unconstrained modelling & inversion
    of gravity, gravity gradient, ...
      IMI, magnetic gradient, ...
      & TEM (resistive limit) data.

  Fullagar Geophysics   Brisbane   Australia.

#####

=====
Create heterogeneous unit(s)
=====

Control file = subcell.ctl
Gravity data file = subcell.dat
Local model file = model_starting.con
UPmg output file = model_starting_het.mod

Active model area:   70 prisms E-W   40 prisms N-S

Total data points in active model area =           1
No. prisms filling active model area =           2800

Preliminary read through active model ...

Loading the active model ...

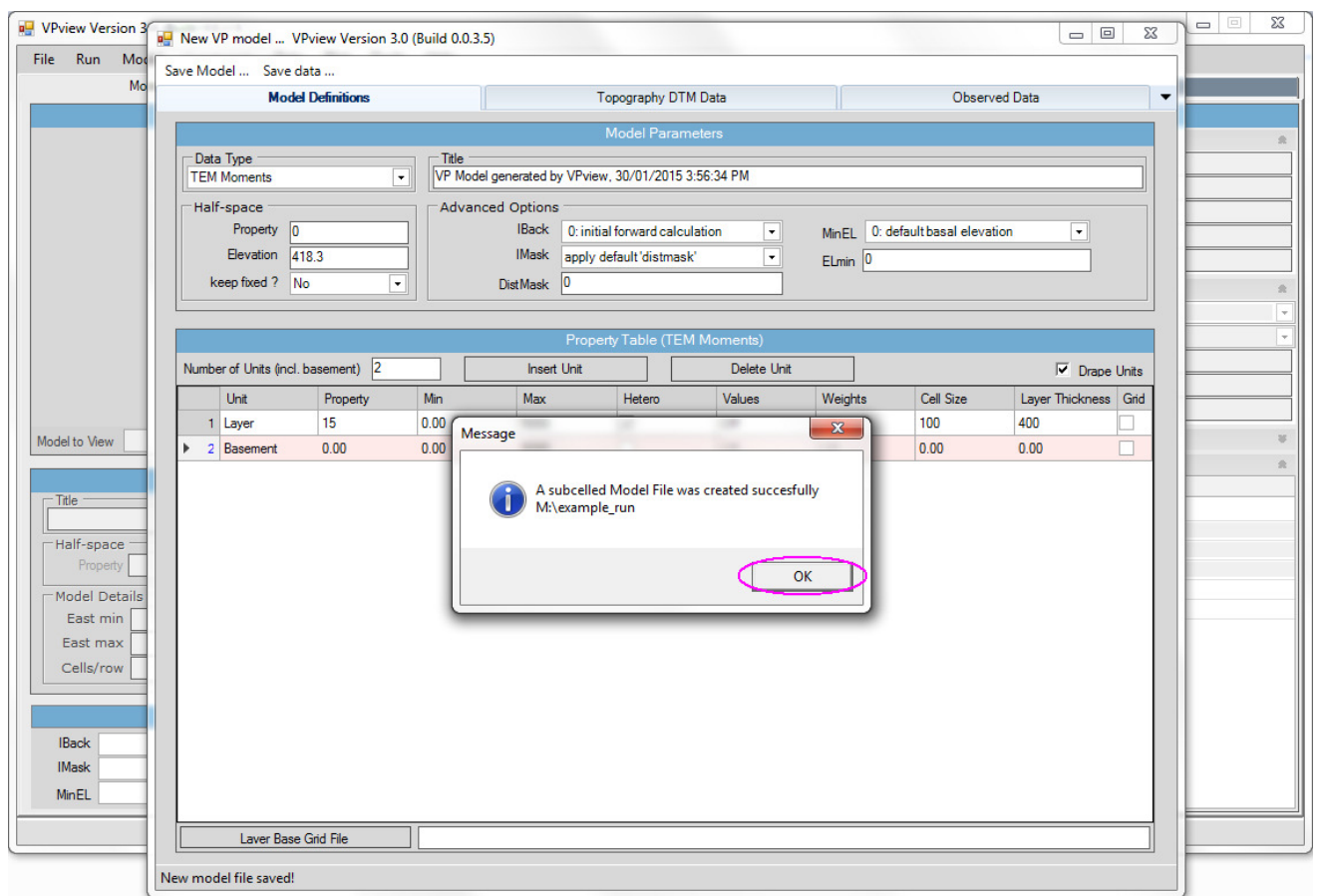
***** Heterogeneous unit(s) created! *****

M:\example_run>_

This window can be closed after a successful run.
```

After VPview creates a homogeneous model, VPem3D sub-cells any heterogeneous units. In this example the Host unit is sub-divided into cells 100m thick.

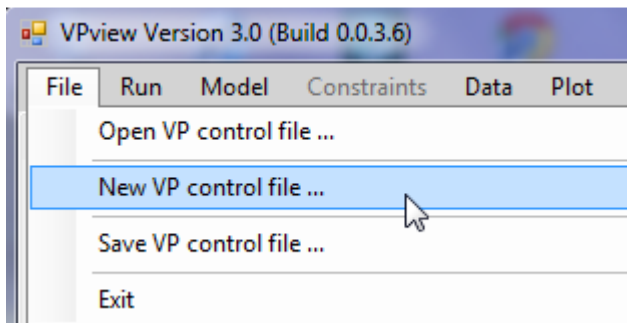
The Command window can be closed once the run completes.



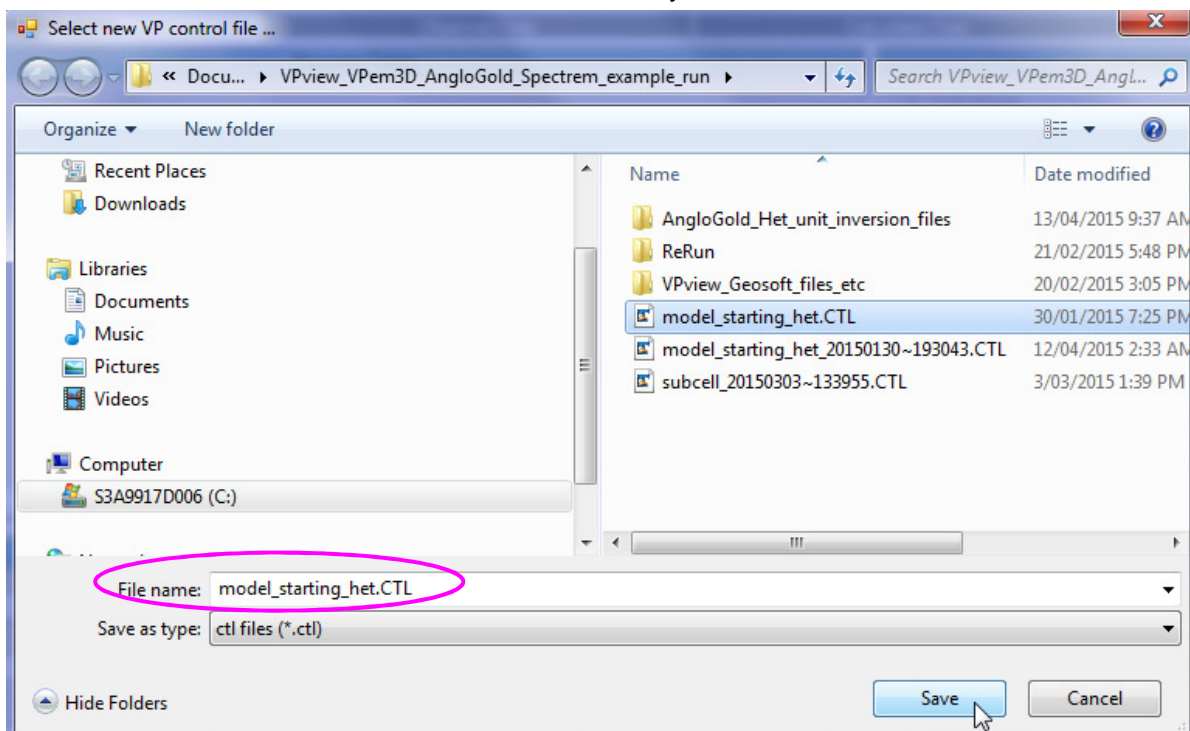
Click OK to close the message window.

12.5 Create a control file

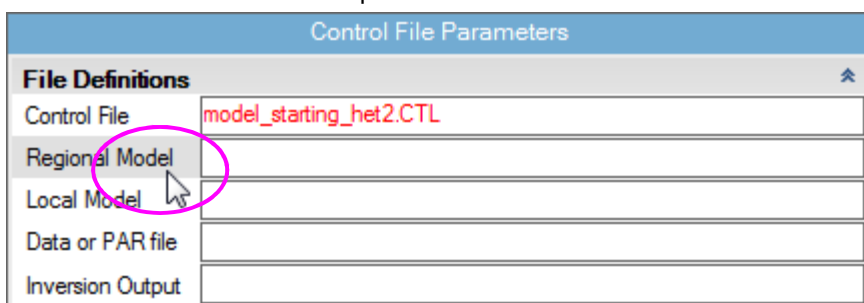
A control file is required in order to run VPem3D. If the control file does not already exist, it can be created using the *New VP control file* utility under the File menu.



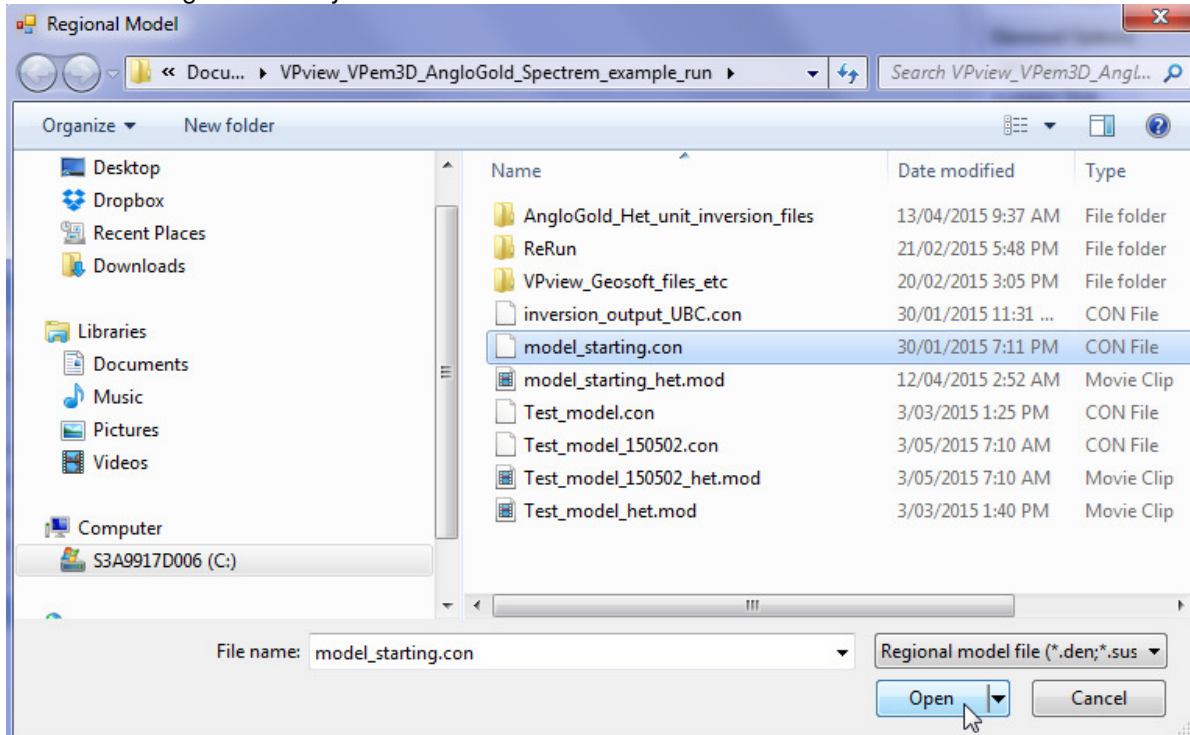
First select the project directory and choose a name for the control file. The control file has extension is CTL. In the illustration the control file already exists.



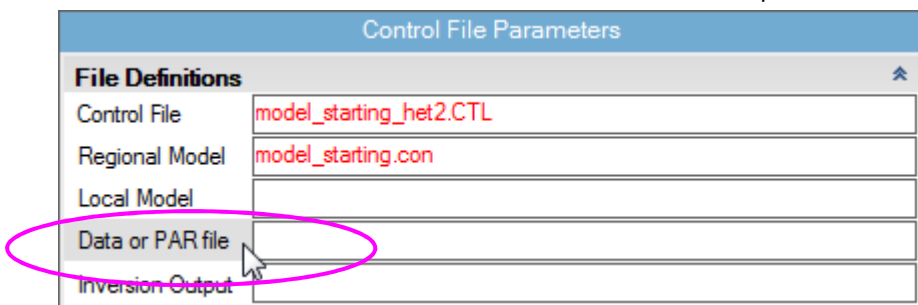
Click on a model file label to open a browse window.



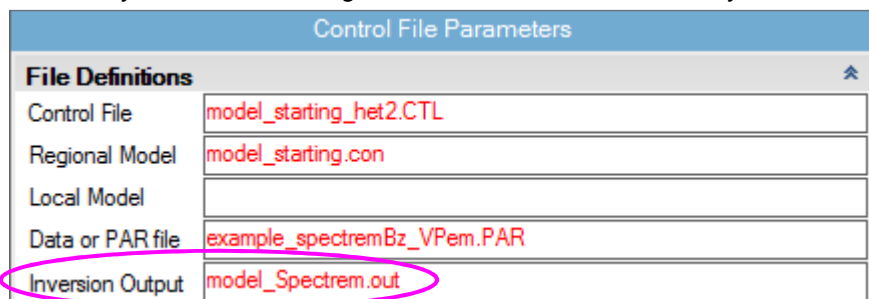
Select a starting conductivity model.



The starting model can be either regional or local. The text box for the other model can be left blank. Select a PAR file in the same fashion: click on the label to open a browse window.



The output model file will usually not already exist. Type in a name for the output file. The extension is arbitrary, but VPview recognises *.CON files as conductivity models.



Now define **General Options** settings. Use the drop down menu to select *Data Type*. TEM Moments (Linear) is the appropriate *Data Type* for airborne TEM.

General Options	
Data Type	TEM Moments (Linear)
Inversion Style	
Iterations	
Uncertainty	
Δ Property	

Use the drop down menu to select *Inversion Style*. Heterogeneous Property is the appropriate *Inversion Style* for the simple host-on-basement model created above, when the aim is to adjust the conductivity of individual model cells.

General Options	
Data Type	TEM Moments (Linear)
Inversion Style	Heterogeneous Property
Iterations	
Uncertainty	
Δ Property	

Set Iterations to zero for an initial forward calculation.

General Options	
Data Type (AEM)	TEM Moments (Linear)
Inversion Style	Homogeneous Property
Iterations	0
Uncertainty	
Δ Property	

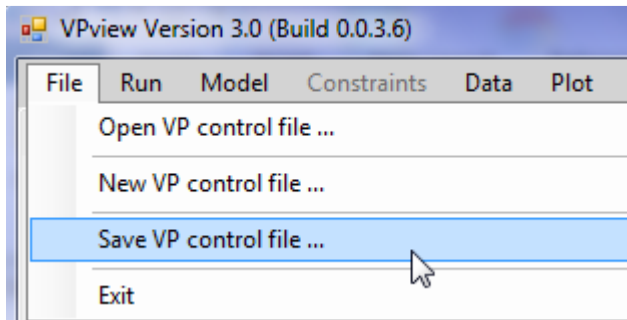
Define values for the *Uncertainty* (in data units) and the Δ *Property* (maximum conductivity change per iteration, in mS/m).

General Options	
Data Type (AEM)	TEM Moments (Linear)
Inversion Style	Homogeneous Property
Iterations	0
Uncertainty	5
Δ Property	100

In the **Advanced Options**, use the drop down menus to choose *Downhole Data* and *DC Level* settings. *Downhole Data* is "No" for airborne data. For regional models, -101 is normally the appropriate setting for *DC Level*. [The normal *DC Level* setting for local models is -102.]

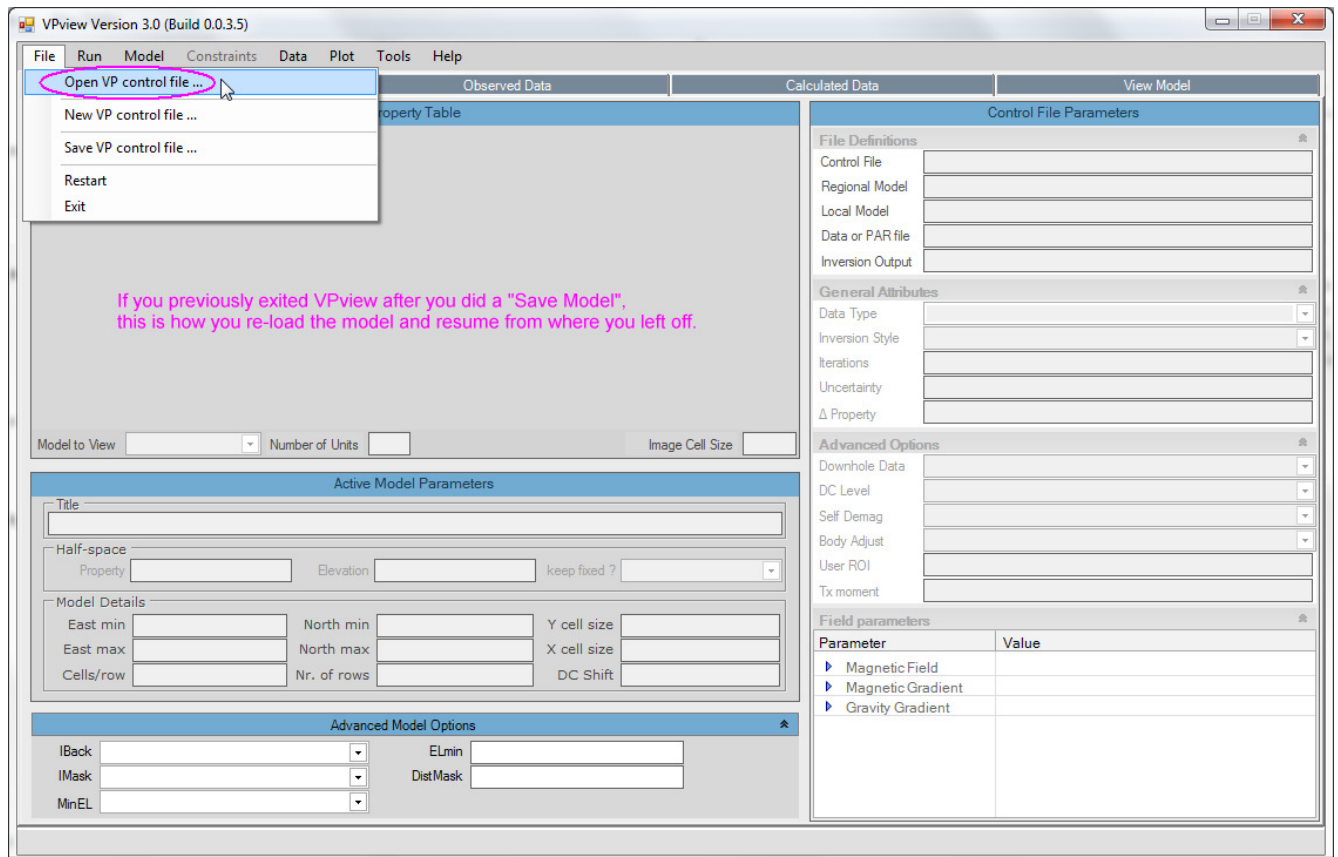
Advanced Options	
Downhole Data	No
DC Level	From regional model, retain cells (-101)
Self Demag	
User ROI	

When all fields have been populated, save the new control file using the option under *File*.

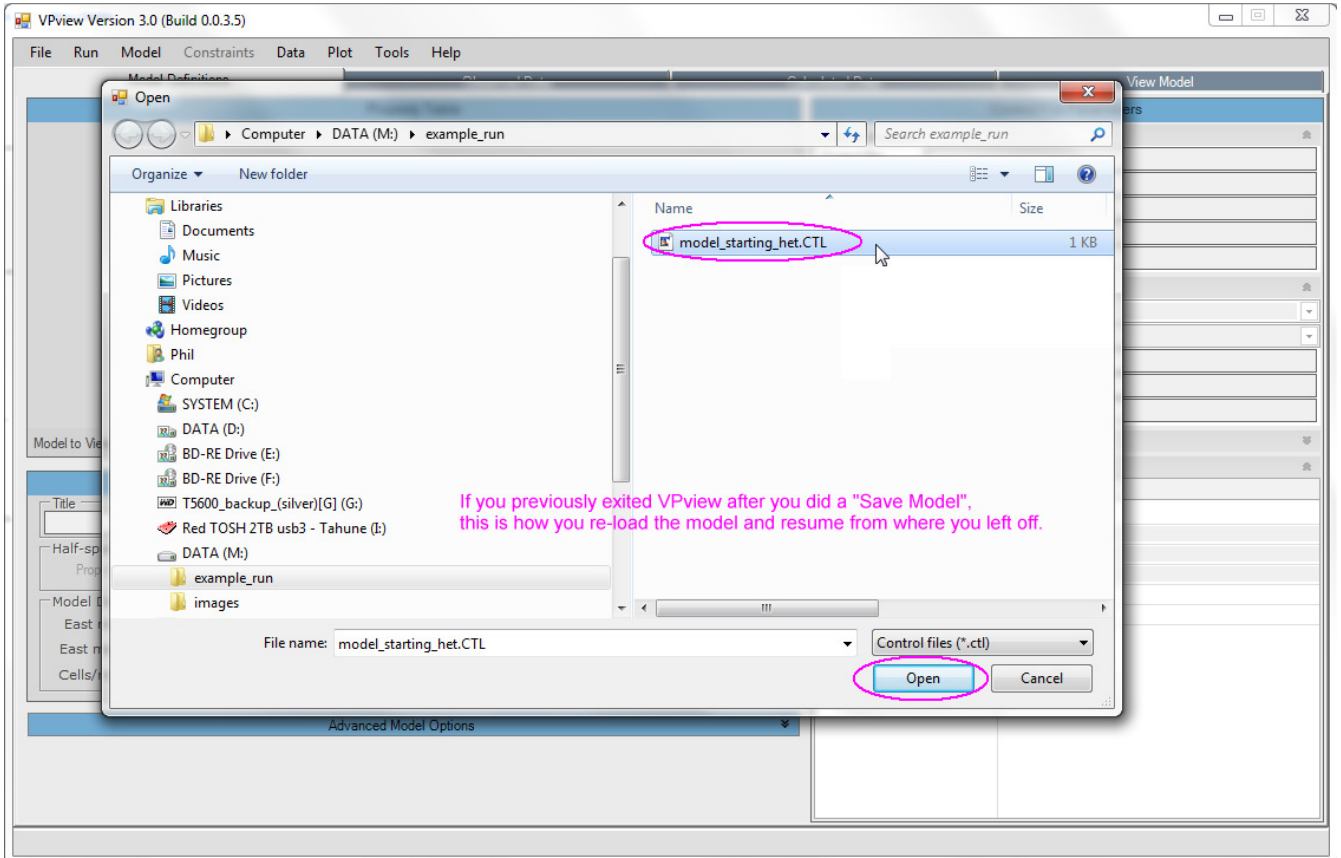


12.6 Performing a forward calculation

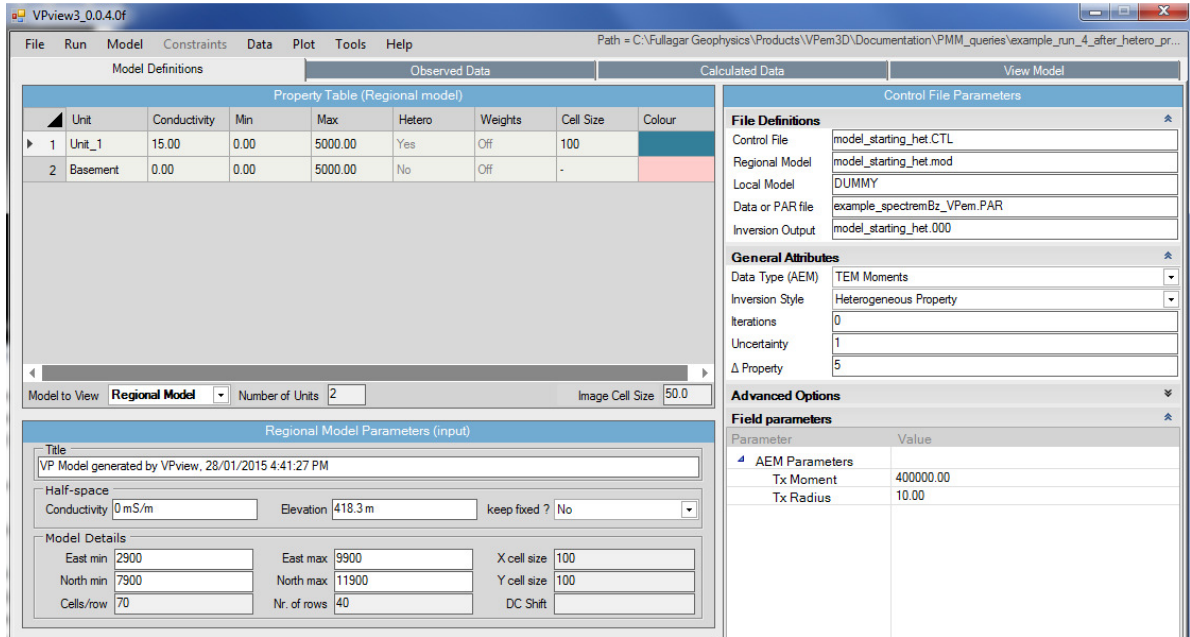
If you had exited, start VPview again and select the “Open VP control file” option under the *File* menu.



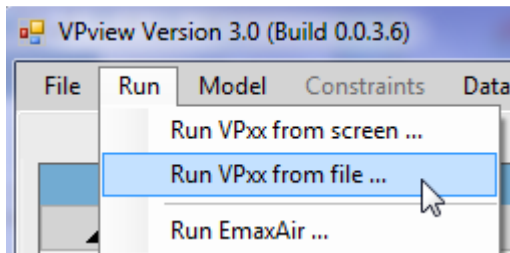
Select the desired VP control file.



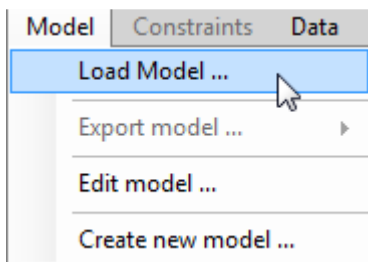
VPview displays the control file settings saved earlier.



If the saved settings are all acceptable, launch VPem3D using the “Run VPxx from file” option under the *Run* menu. If some of the settings have been edited, but not saved, launch VPem3D using the “Run VPxx from screen” option.



When the forward calculation has completed, display the starting model, and the observed and calculated data, using the “Load Model” option under the *Model* menu.



12.7 Running an AEM inversion

Once satisfied with the forward calculation, prepare to run an inversion.

The shallowest model cells are most sensitive to the AEM data. Therefore, VPem3D will preferentially introduce near-surface conductivity changes during inversion unless surficial conductivity is penalised. Development of shallow conductive zones is usually damped using depth weights (see Section 13.8). Depth weighting is recommended for heterogeneous unit inversion, though it was not applied in the example described here for the sake of brevity.

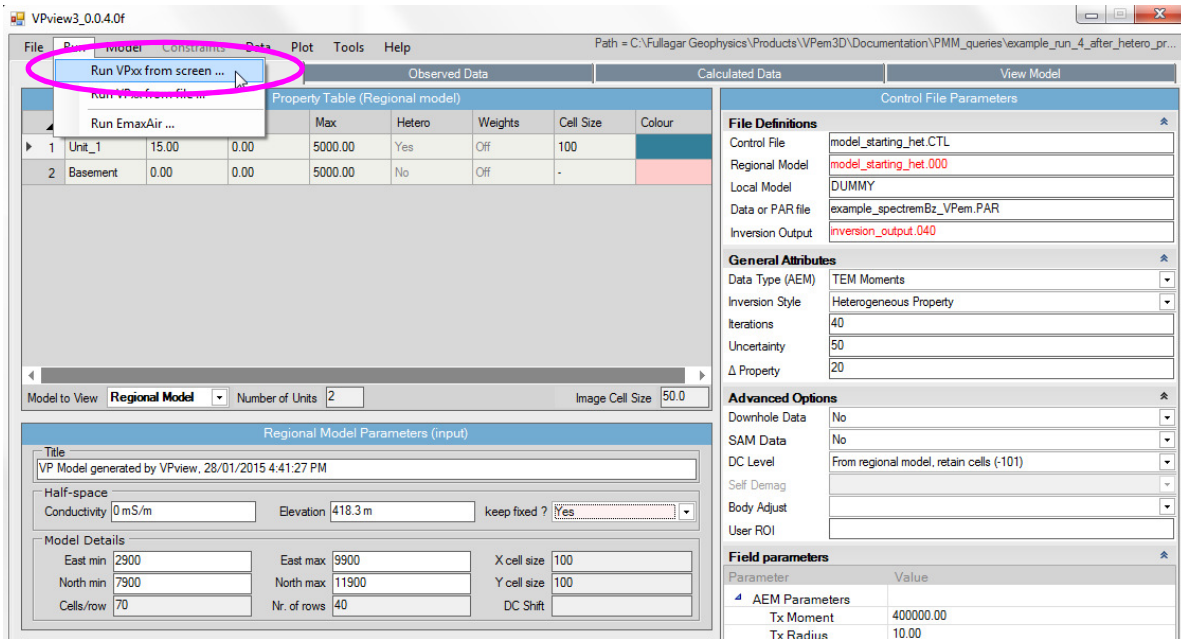
The output model from the forward calculation can become the input model for inversion; this obviates the need to re-run the forward calculation since the calculated data are recorded at the end of the model file.

Control File Parameters	
File Definitions	
Control File	model_starting_het2.CTL
Regional Model	model_starting.con
Local Model	DUMMY
Data or PAR file	example_spectremBz_VPem.PAR
Inversion Output	model_Spectrem.040
General Options	
Data Type (AEM)	TEM Moments (Linear)
Inversion Style	Heterogeneous Property
Iterations	40
Uncertainty	5
Δ Property	100
Advanced Options	
Downhole Data	No
DC Level	From regional model, retain cells (-101)
Self Demag	
User ROI	
Field parameters	
Parameter	Value
AEM Parameters	
Tx Moment	1.000000E+005
Tx Radius	10.00

Set remaining parameters in prepare for running the inversion:

- Enter a file name for the inversion output.
- Set the inversion style.
- Set the number of iterations to perform.
- Set the uncertainty level in the data (data units).
- Set the maximum permitted change in property value per iteration (mS/m).
- Set the DC Level; because the model is notionally a “regional model”, normally select the *From regional model ... (-101)* option. The DC Level is usually zero for TEM.
- Set the transmitter moment (Am^2) for the AEM system, and Tx loop radius (m) for central loop configurations by editing the **Field Parameters**.

If any fields in the control file have been edited, select “Run VPxx from screen” to start the VPem3D inversion. Otherwise, launch VPem3D via “Run VPxx from file” to use the parameters saved in the *.CTL file.



```

C:\Windows\System32\cmd.exe - vpmg_v8.exe model_starting_het_20150130~165600.CTL

##### UPmg v8.0 <x64> #####

  3D constrained & unconstrained modelling & inversion
  of gravity, gravity gradient, ...
  TMI, magnetic gradient, ...
  & TEM (resistive limit) data.

  Fullagar Geophysics   Brisbane   Australia.
#####

=====
Heterogeneous unit property inversion
=====

Control file = model_starting_het_20150130~165600.CTL
UPmg output file = inversion_output.040
Active model parameters read from control file

Active model area:   70 prisms E-W   40 prisms N-S
UPem3D resistive limit data file = example_spectremBz_MOM.XVZ

Total data points in active model area =      1437
No. prisms filling active model area =      2800

Preliminary read through active model ...

Begin enclosing half-space calculation ...

Loading the active model ...

Begin the inversion cycle ...
Number of inversion parameters =      11200

Begin forward calculation for active model ...
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
**** EHS property modification does not work if EHS property is zero

***** ITER = 0
After 0 iterations: DC shift = 0.00 pTms/A   RMS misfit = 697.28 pTms/A
L1 misfit = 0.129533E+02   L2 (chi-squared) misfit = 0.194478E+03
Expected value = 1 for both L1 & L2

Begin calculation of derivatives ...
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

**** EHS property modification does not work if EHS property is zero

***** ITER = 1
After 1 iterations: DC shift = 0.00 pTms/A   RMS misfit = 355.24 pTms/A
L1 misfit = 0.561824E+01   L2 (chi-squared) misfit = 0.504787E+02
Expected value = 1 for both L1 & L2

**** EHS property modification does not work if EHS property is zero

***** ITER = 34
After 34 iterations: DC shift = 0.00 pTms/A   RMS misfit = 118.74 pTms/A
L1 misfit = 0.143538E+01   L2 (chi-squared) misfit = 0.563948E+01
Expected value = 1 for both L1 & L2

**** EHS property modification does not work if EHS property is zero

***** ITER = 35
After 35 iterations: DC shift = 0.00 pTms/A   RMS misfit = 118.37 pTms/A
L1 misfit = 0.142681E+01   L2 (chi-squared) misfit = 0.560427E+01
Expected value = 1 for both L1 & L2

***** Stalled inversion *****

***** Final model not acceptable *****

M:\example_run>

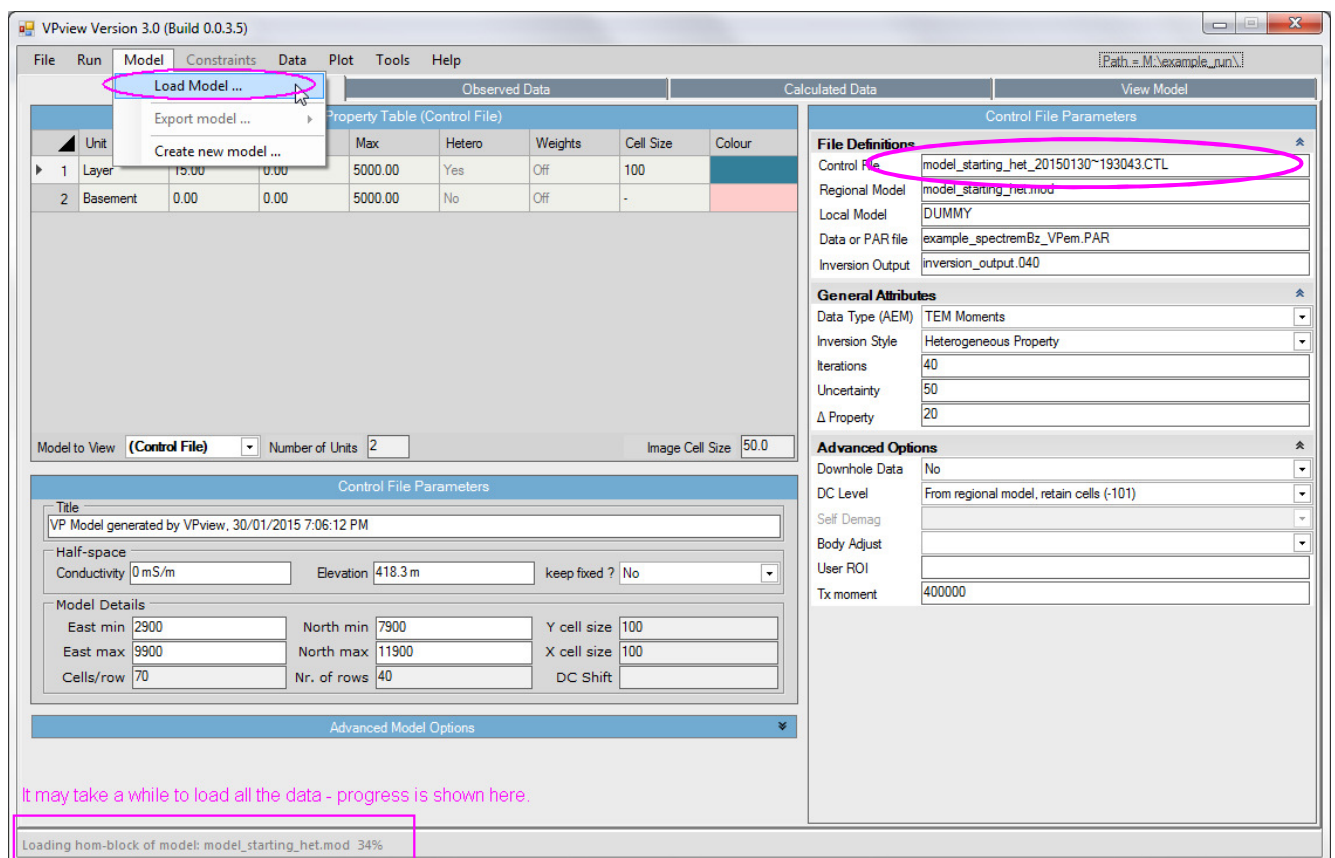
```

VPem3D inversion progress is displayed in a Command Window.

Name	Size
example_spectremBz.DAT	28,810 KB
example_spectremBz.LOG	1 KB
example_spectremBz.PAR	2 KB
example_spectremBz_MOM.XYZ	21,194 KB
example_spectremBz_VPem.PAR	1 KB
FIXED_CELL.LK	0 KB
grid_DTM_dos.grd	486 KB
grid_DTM_dos_rot38.GRD	560 KB
inversion_output.040	926 KB
inversion_output.040.DMF	0 KB
model_starting.con	148 KB
model_starting_het.CTL	1 KB
model_starting_het.mod	679 KB
model_starting_het.mod.DMF	0 KB
model_starting_het_20150130~193043.CTL	1 KB
RESAMPLED_AEM.DAT	131 KB
TIME_CONST.TMP	0 KB
VPMG.LOG	30 KB

Highlighted are the new files after the first VPem3D inversion run

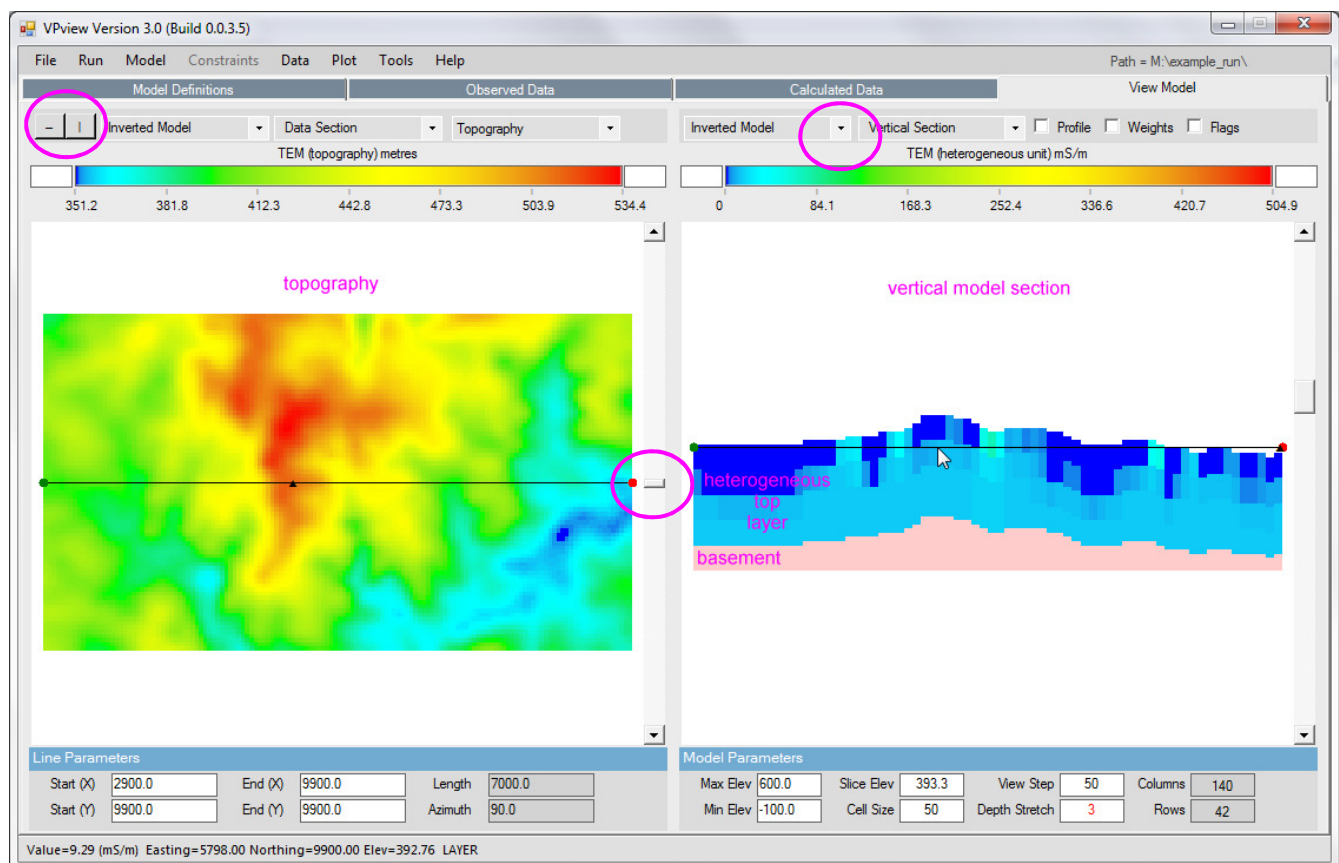
New files created after the VPem3D inversion run has completed.



Load the model into memory.

The progress of various data load stages is shown at the bottom left of the VPview window.

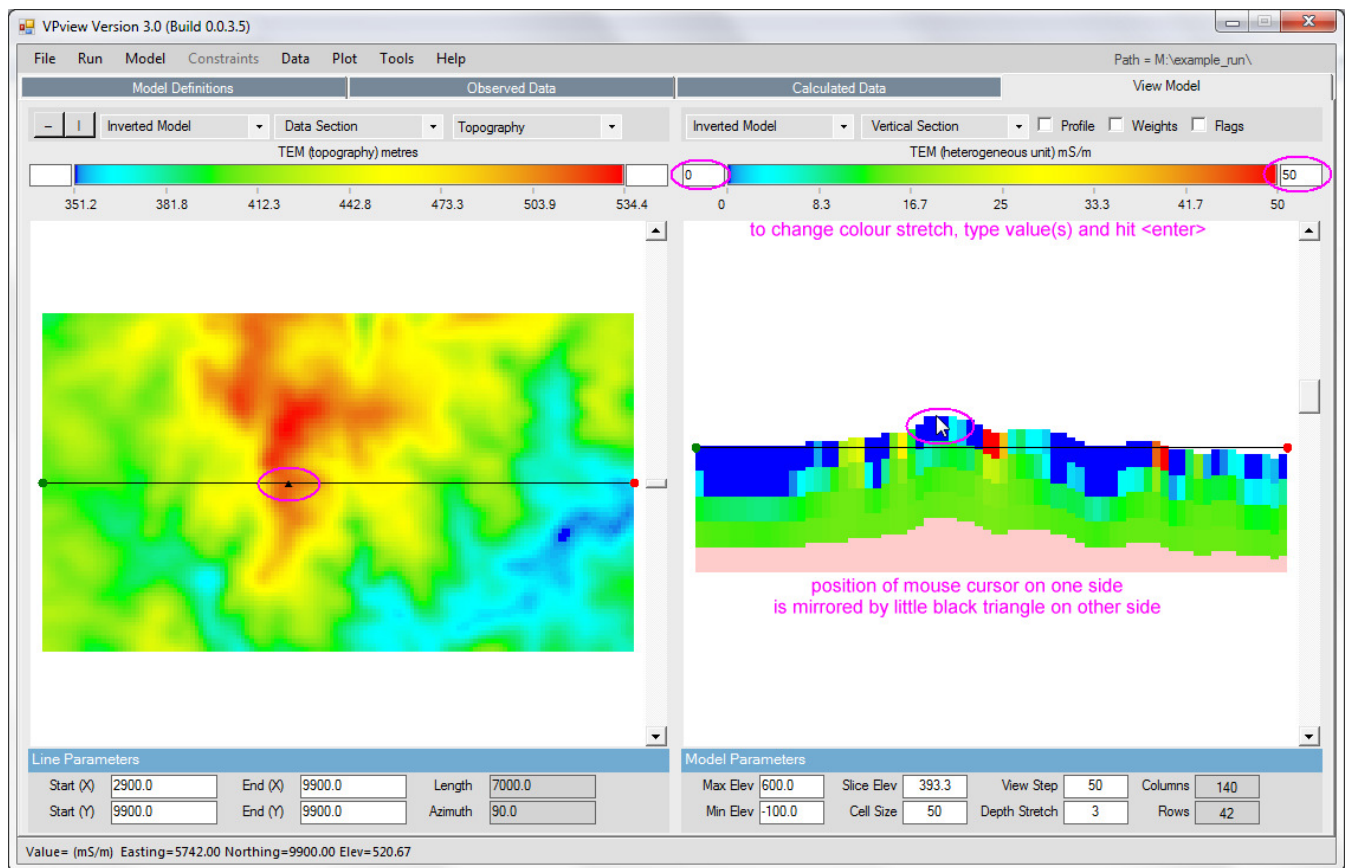
Note that a new Control File is created when VPem3D is run "from screen". The date and time are appended to the original control file name in this case.



When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the inverted model is displayed in the right panel. The user can toggle between section views of the starting (Initial) and output (Inverted) models using the drop-down menu above the RH panel.

The black line in the LH panel shows the position of the vertical section; it can be adjusted using the scroll bar. Toggle buttons in the top RH corner of the VPview window switch the display line from E-E to N-S orientation. Oblique sections can be displayed by clicking and dragging the red and green knobs at either end of the section line

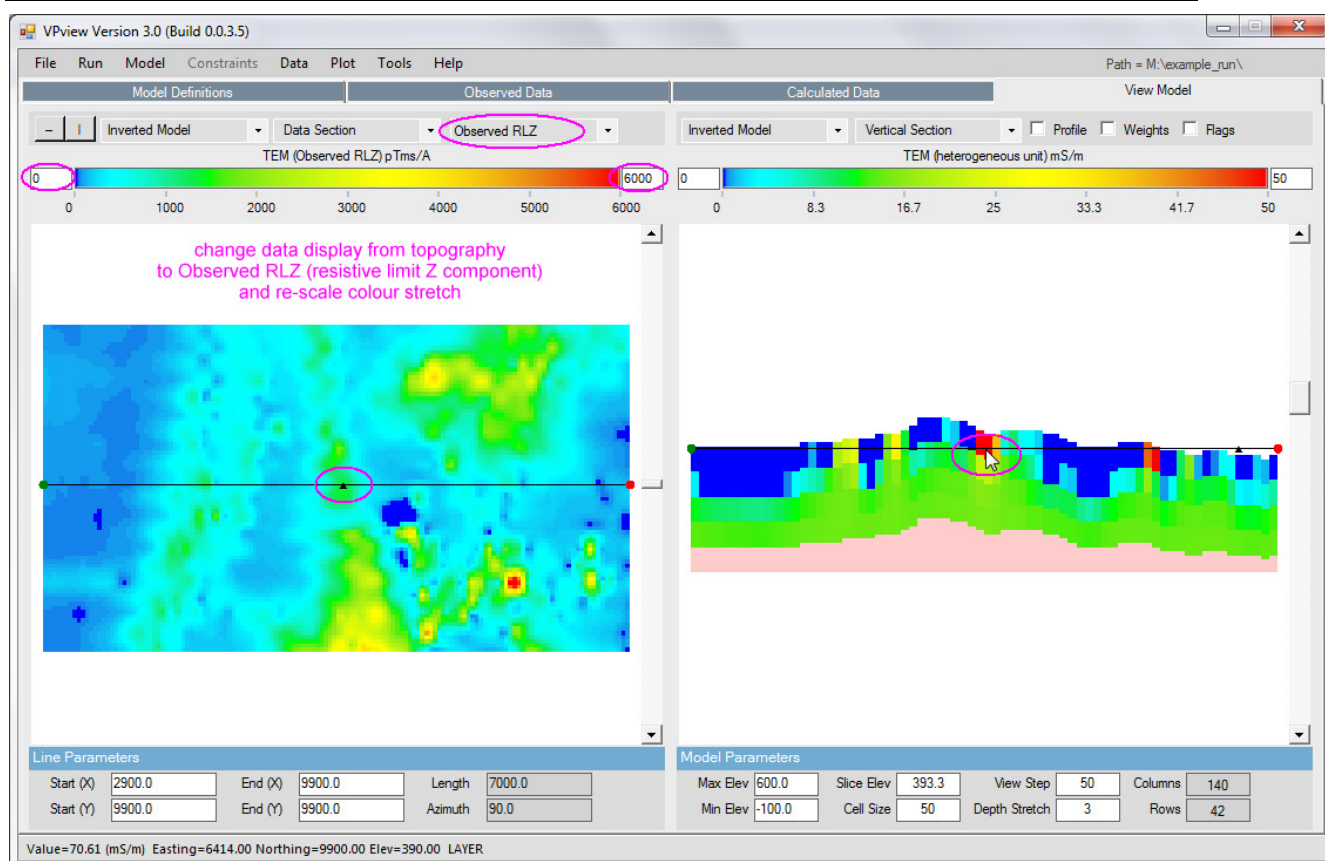
Note that because of the coordinate rotation used in this example (Section 12.3), the coordinates are in the LOCAL rotated (flight line) system.



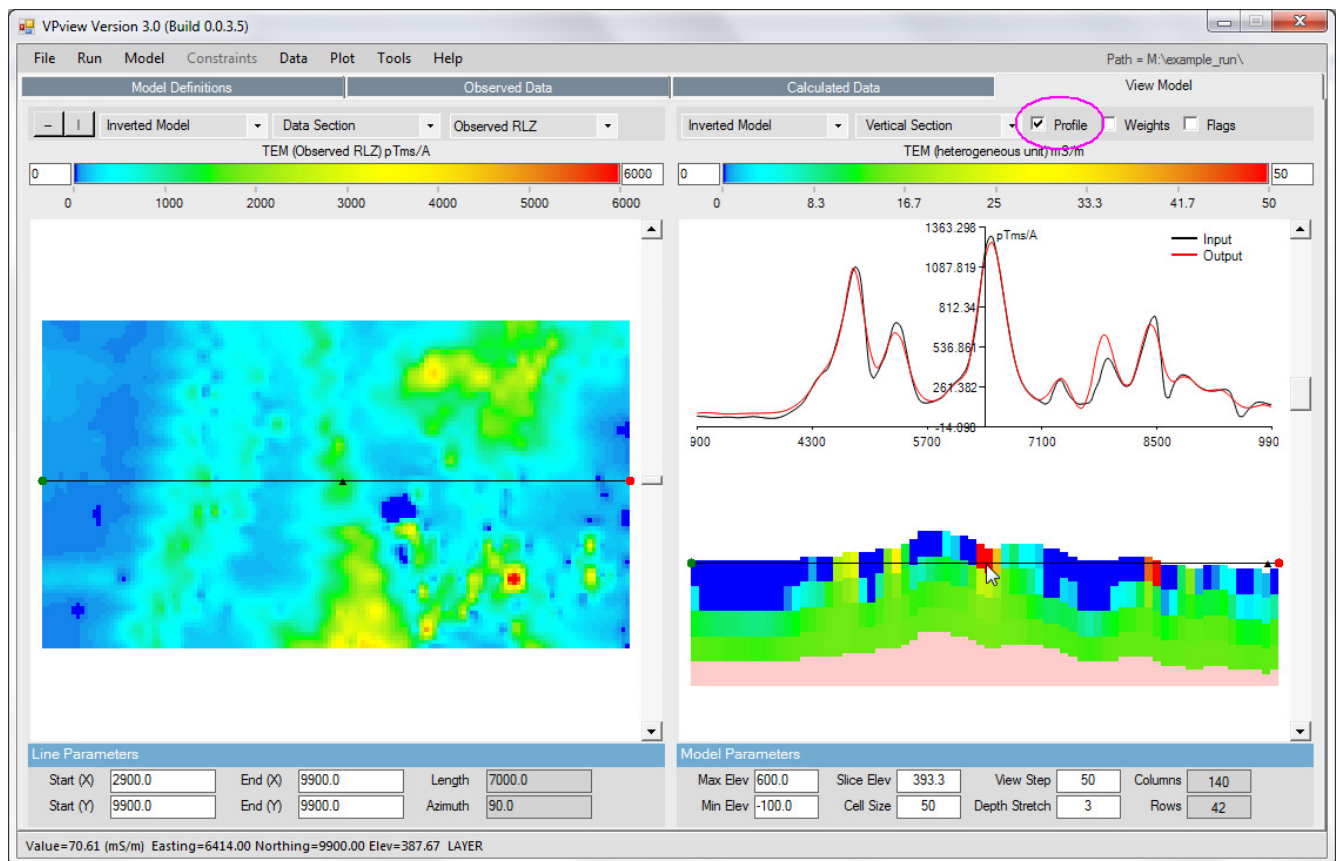
The cursor positions on left and right displays shadow each other.

For example if the mouse cursor is moved along the vertical section (right) a little black triangle shadows this position on the DTM image (left). The shadowing works the same way if the mouse cursor is moved over the left image.

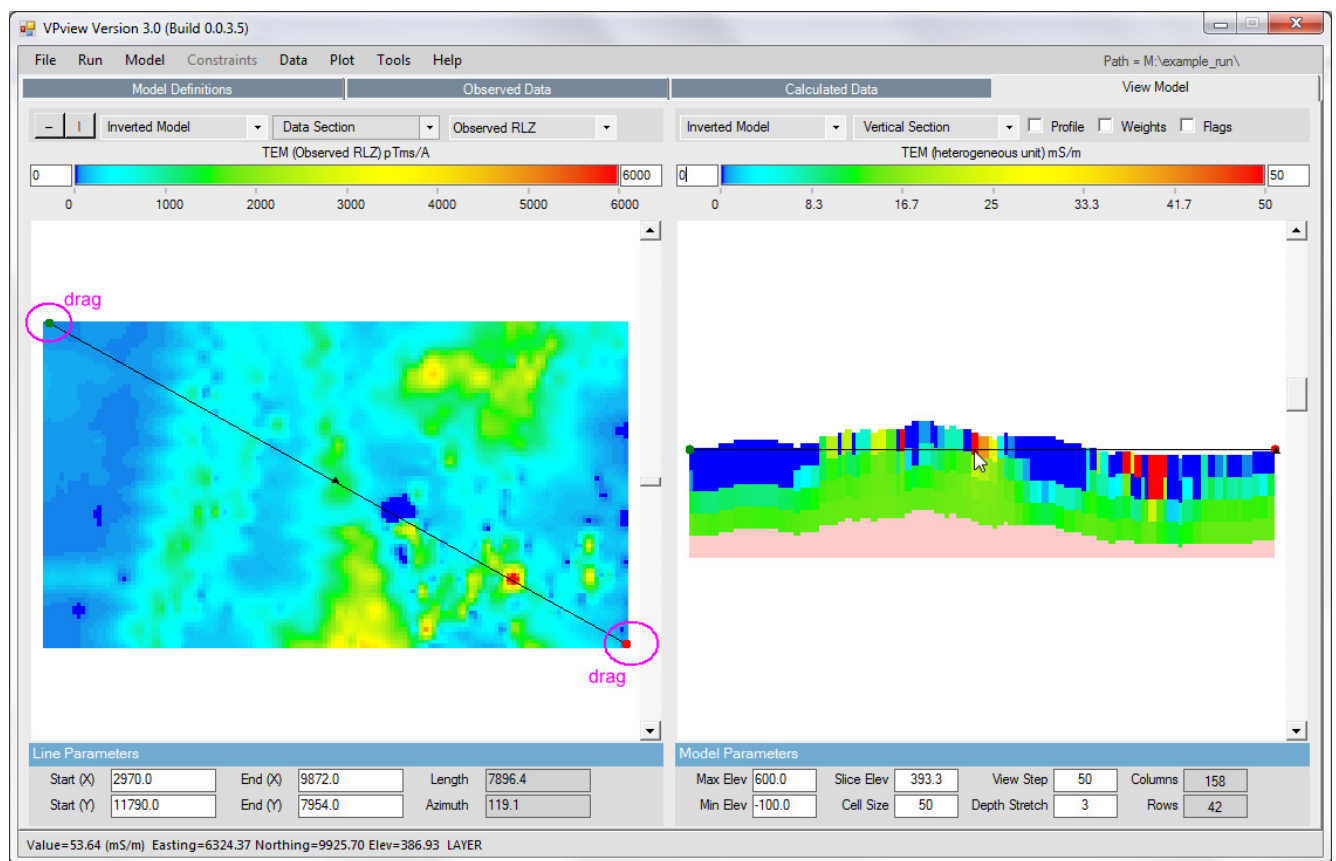
The colour stretch can be altered by entering min and max values then hitting Enter.



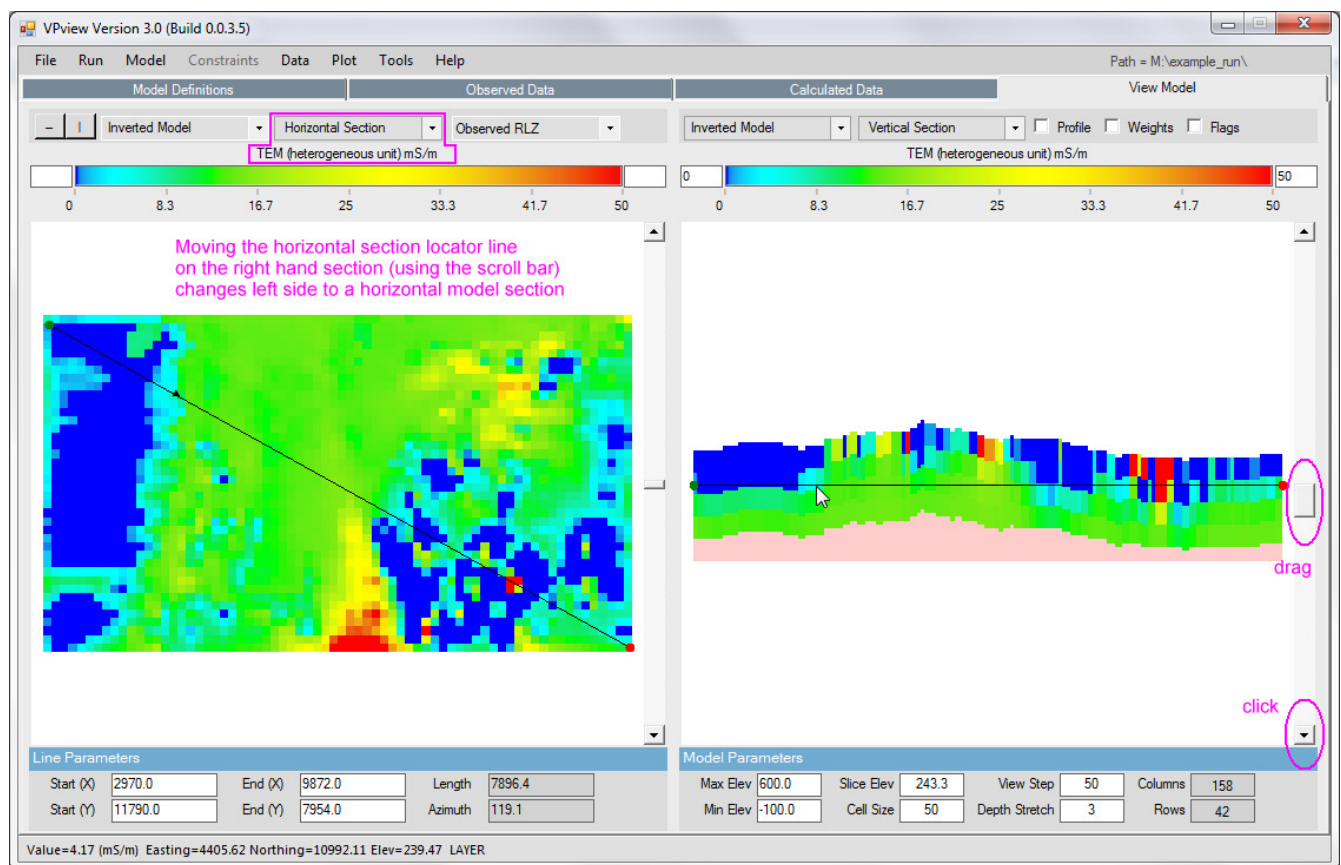
Here the left panel display has been changed from DTM to Observed Data by selecting “Observed RLZ” from the pull-down list. The colour stretch has also been reset to 0 – 6000 mS/m.



A profile display of observed (black) and calculated (red) data can be displayed above the vertical section by checking the Profile box.



The position and orientation of the displayed section can be changed by dragging the ends of the black line on the plan view (left). The cursor positions on left and right still shadow each other.



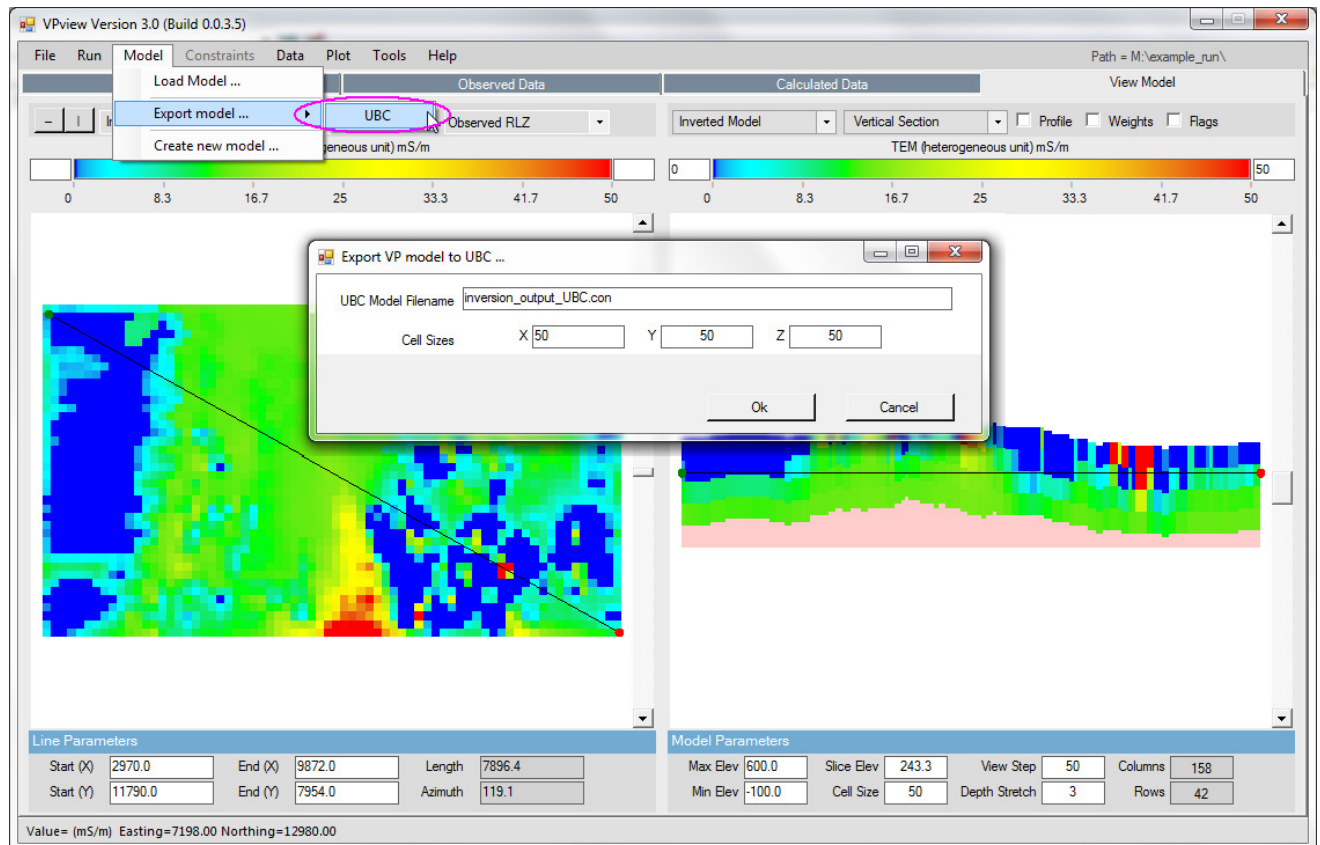
Here the left panel display has been changed from Observed Data to a horizontal section through the inverted model at the elevation indicated by the black line through the vertical section in the RH panel. The elevation of the horizontal section can be changed by adjusting the scroll bar on the vertical section view (right).

12.8 Exporting the inverted model

The inverted VPem3D model can be exported into a UBC model file or a Geosoft XYZ file. The export options will be expanded in the future.

One option is to convert the VPem3D model to point conductivity values at cell centres, which can then be gridded, e.g. using Geosoft. A program to do this has recently been developed (available on application). If the model is defined in rotated (flight line) coordinates, the program converts the cell centres to original survey grid coordinates.

Export to UBC model format is described below.

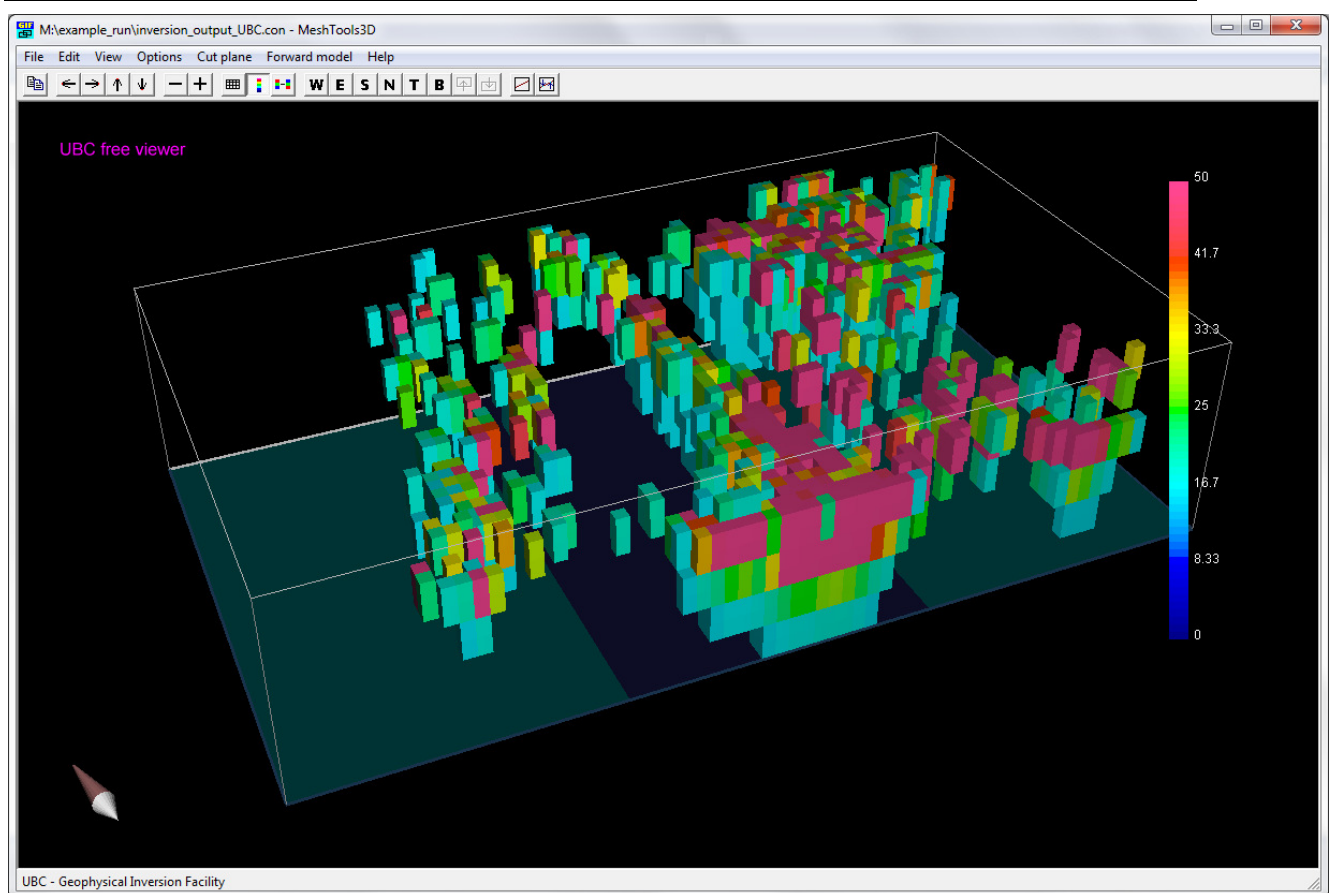


Choose a cell size suitable for 3D display. In the example the model cells are 100m cubes but for 3D display we've chosen to export at half that dimension.

Name	Size
example_spectremBz.DAT	28,810 KB
example_spectremBz.LOG	1 KB
example_spectremBz.PAR	2 KB
example_spectremBz_MOM.XYZ	21,194 KB
example_spectremBz_VPem.PAR	1 KB
FIXED_CELL.LK	0 KB
grid_DTM_dos.grd	486 KB
grid_DTM_dos_rot38.GRD	560 KB
inversion_output.040	926 KB
inversion_output.040.DMF	0 KB
inversion_output_UBC.con	1,652 KB
inversion_output_UBC.msh	1 KB
model_starting.con	148 KB
model_starting_het.CTL	1 KB
model_starting_het.mod	679 KB
model_starting_het.mod.DMF	0 KB
model_starting_het_20150130~193043.CTL	1 KB
RESAMPLED_AEM.DAT	131 KB
TIME_CONST.TMP	0 KB
VPMG.LOG	30 KB

Highlighted are the new files after exporting UBC model

The two new files created for the UBC model.



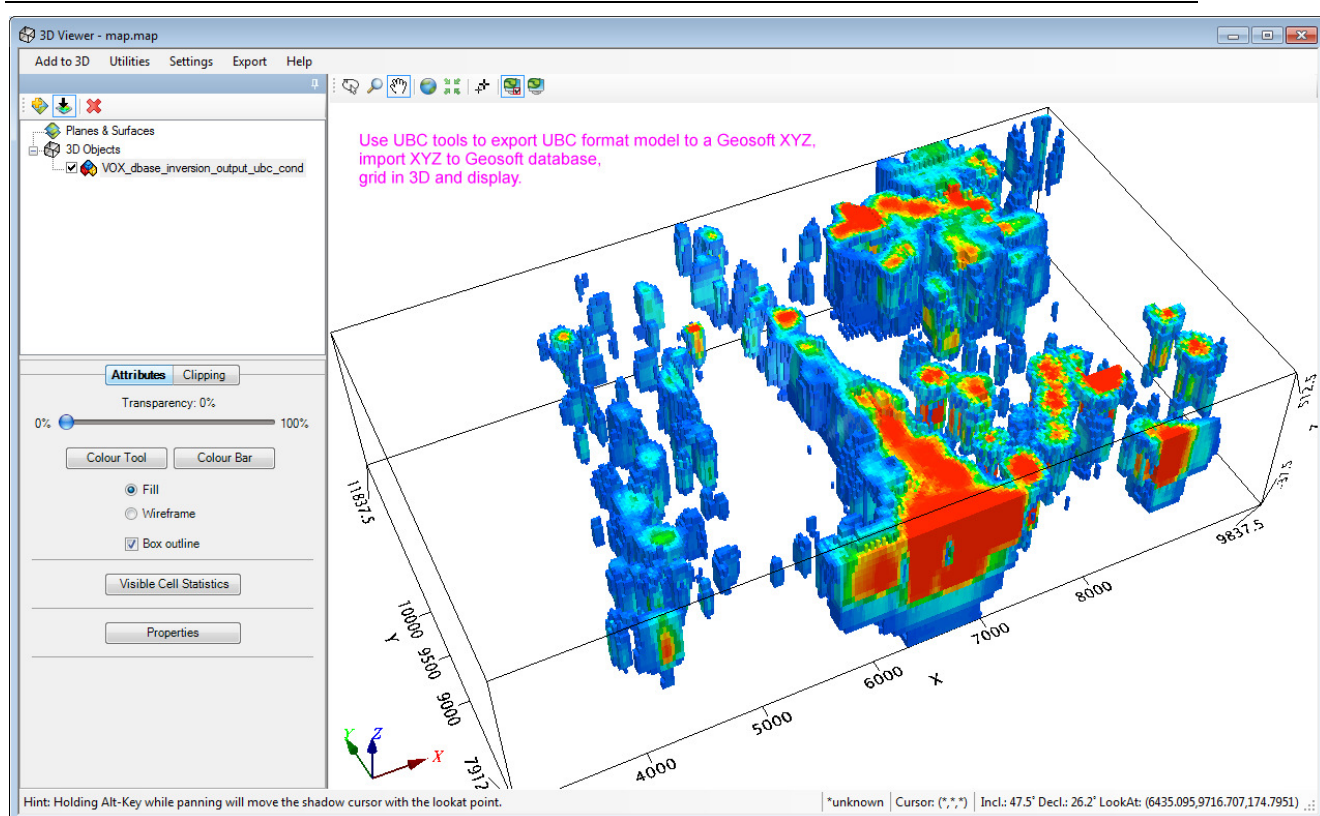
The University of British Columbia (UBC) provide a free program for viewing UBC 3D models.

This program is called “**UBC_MeshTools3d.exe**” and can be downloaded from;

http://gif.eos.ubc.ca/software/utility_programs

under the heading “3D models/meshes”.

The exported UBC model is shown in the illustration above using the UBC viewer.



The exported UBC model can also be displayed in Geosoft.

Note that if a coordinate rotation was applied prior to inversion (Section 12.3) then the exported model is still in LOCAL rotated coordinates.

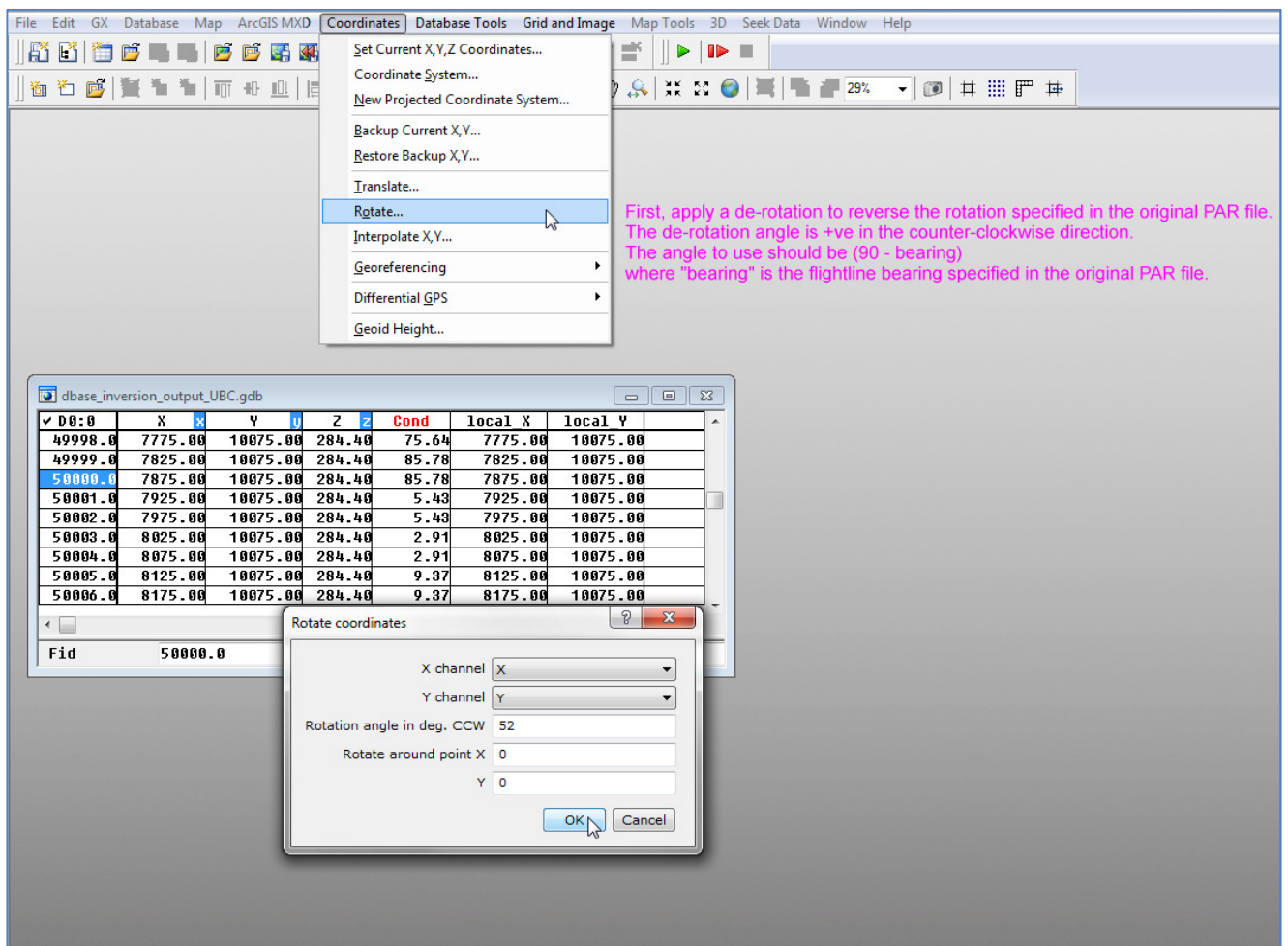
There are two ways to import the model into Geosoft:

- (a) A direct import of the UBC model to a Geosoft voxel. This runs IMPUBCVOX.GX, or can be accessed through the Geosoft menu 3D → Voxel_Conversions → UBC_to_voxel. [Some versions of Geosoft, for example 7.2.1, give an error when this import is attempted. The alternative import method described next can be used if the direct import fails].

- (b) Export the UBC model to an ASCII XYZ file, then import into a Geosoft database and perform 3D gridding there to create a new Geosoft voxel. At present this is also the preferred method to use if you want to “de-rotate” the local coordinates back to the original coordinate system.

To use this method;

- Use the free program called “**UBC_model2xyzval.exe**” which can be downloaded from; http://qif.eos.ubc.ca/software/utility_programs under the heading “3D models/meshes”.
- Run this free program to generate an XYZ file which contains the four columns E, N, Depth, Conductivity for the model. Import this XYZ file to a Geosoft database.
- If the imported data is still in LOCAL rotated coordinates the following three illustrations show how to “de-rotate” back to original coordinates.



Once the XYZ file is imported into a Geosoft database, "de-rotate" the coordinates in two stages. First, reverse the angular rotation.

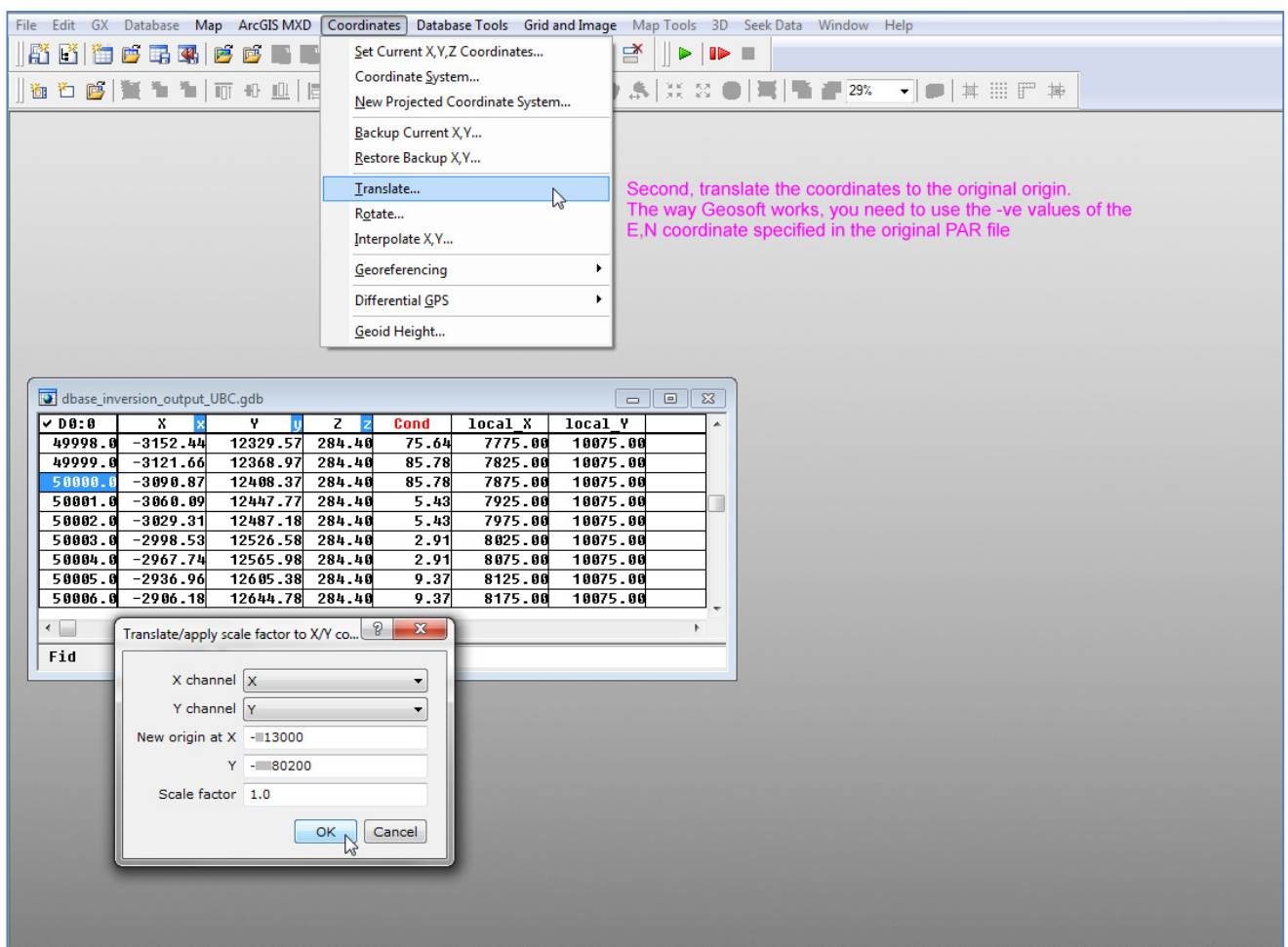
The angle of rotation in Geosoft is measured as positive in the counter-clockwise direction from the local east axis;

it is not simply the negative of the flight line bearing specified in the original PAR file.

The correct angle needed to reverse the rotation is 90 MINUS the flight line bearing used previously. In this example it is $90 - 38 = 52$ degrees.

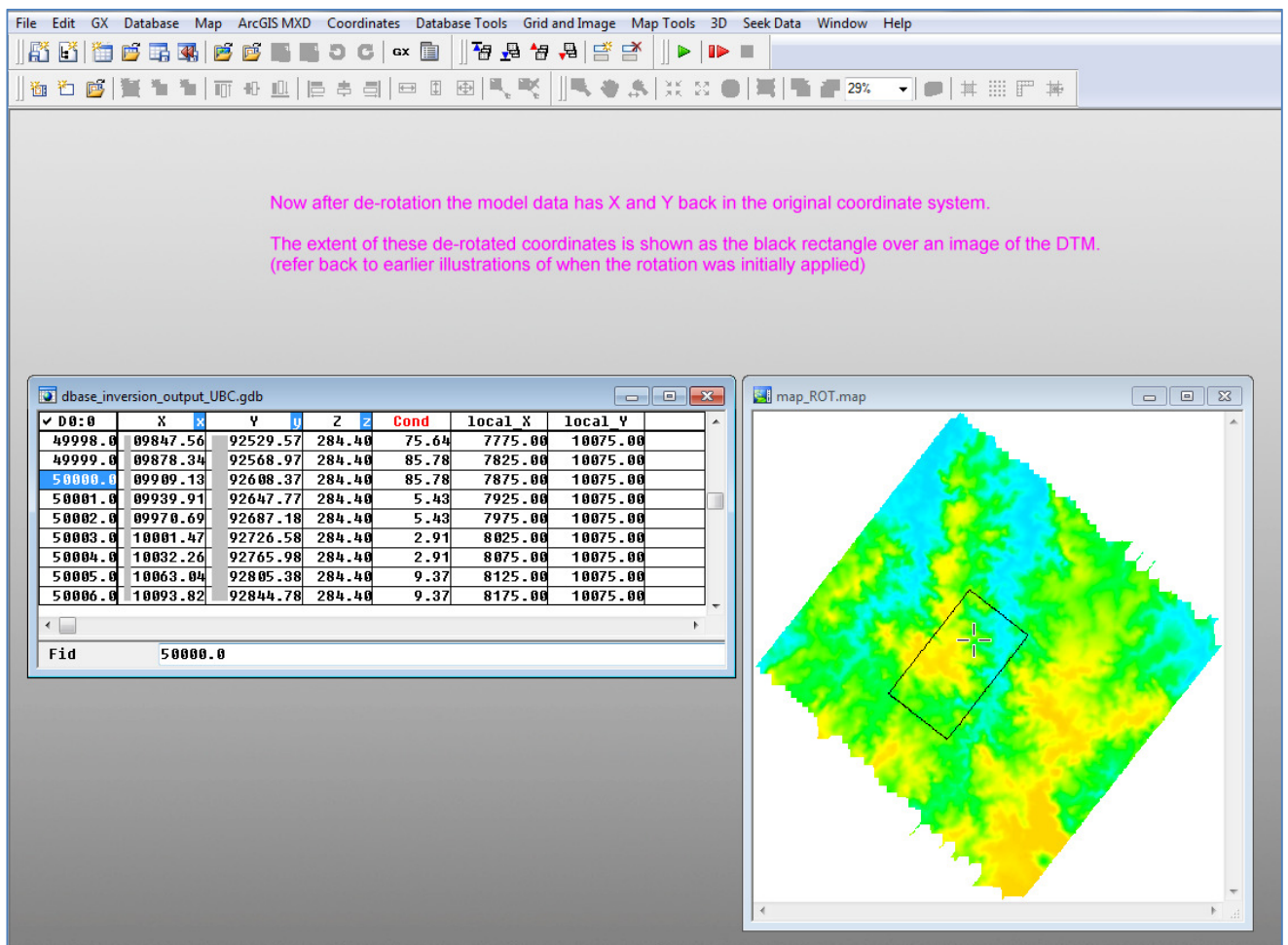
At this stage the Geosoft rotation should be done around point X=0, Y=0.

[Note that in the illustration above the X and Y channels have been copied to new channels local_X and local_Y prior to applying the rotation. This is not a requirement, but it may be useful should a de-rotation be done incorrectly and you need to restore the X and Y channels before attempting the de-rotation again].



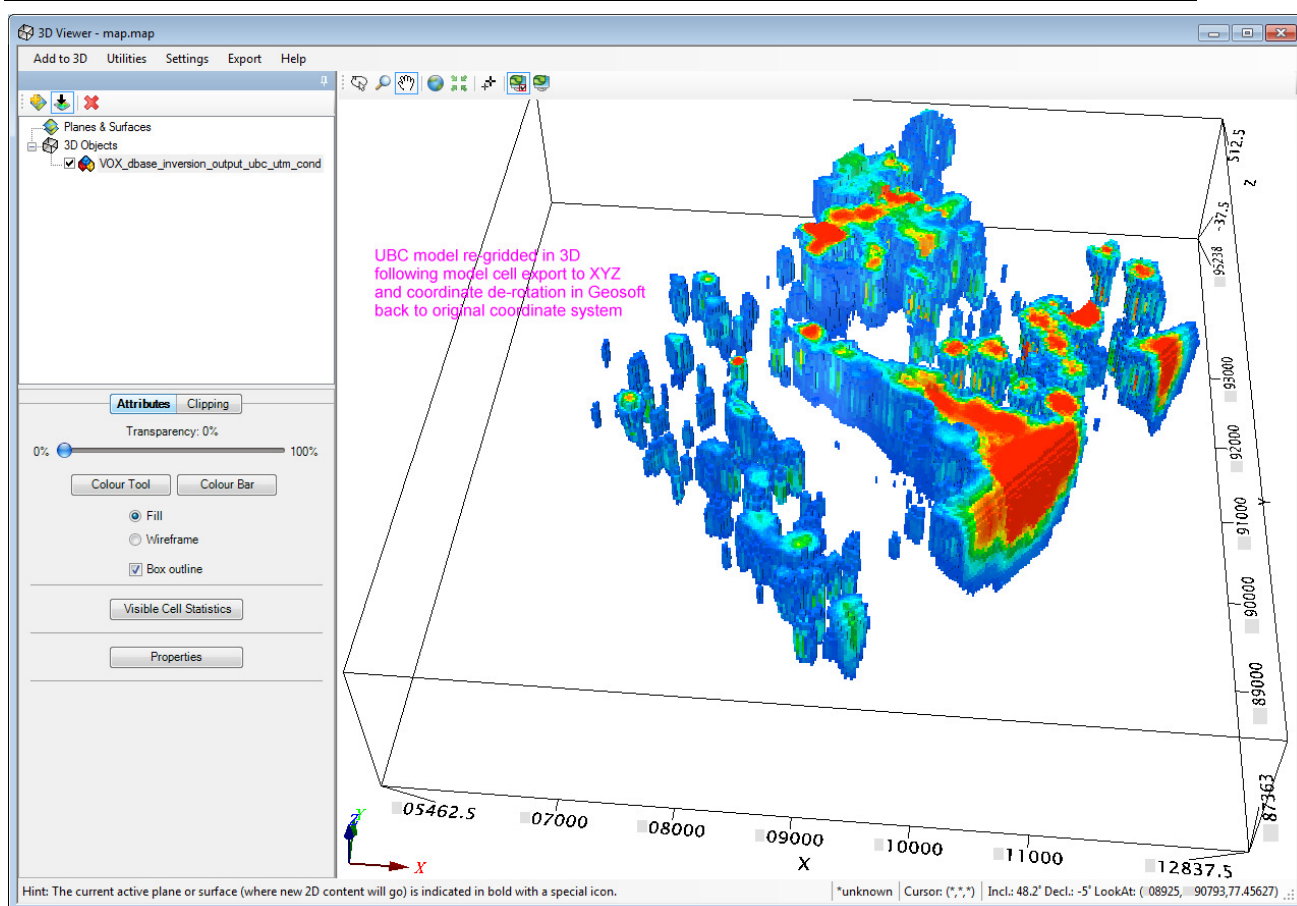
Second, move the de-rotated coordinates back to the correct origin.

The new X,Y origin for this Geosoft translation should be set to the NEGATIVES of the E,N values specified for the rotation in the original PAR file.



Now the de-rotation is complete.

The X and Y channels are now in the original coordinate system. To demonstrate this, in the above illustration the new de-rotated X,Y limits in the database are shown as the black rectangle superimposed on the original (un-rotated) grid image of the DTM, here displayed in Geosoft.



Finally a 3D Geosoft Voxel can be created and displayed in the original un-rotated coordinate system.

13 APPENDIX C: Example Downhole TEM Inversion

13.1 Introduction

This Appendix is intended as a guide for running VPem3D modelling and inversion of downhole TEM through the VPview user interface. The application of VPem3D is illustrated step-by-step with an example dataset using a series of annotated images with explanatory notes. It should provide enough information to guide you as you work through one of your own datasets. The downhole data used in the example is available on application.

The guide does not attempt to explain all of the VPview parameters. For a fuller explanation see the VPview documentation (accessible from the VPview *Help* menu).

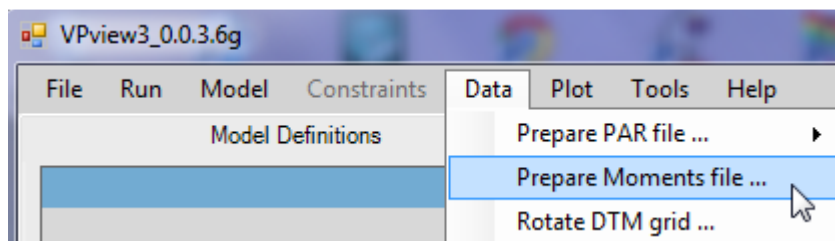
There are various ways to set up and run VPem3D inversion on downhole TEM data. The example used here illustrates conventional (smooth) heterogeneous unit inversion for data from two holes, excited by two Tx loops. The starting model comprised a 30m-thick conductive Cover layer overlying a zero conductivity uniform half-space.

13.2 Computing resistive limit data

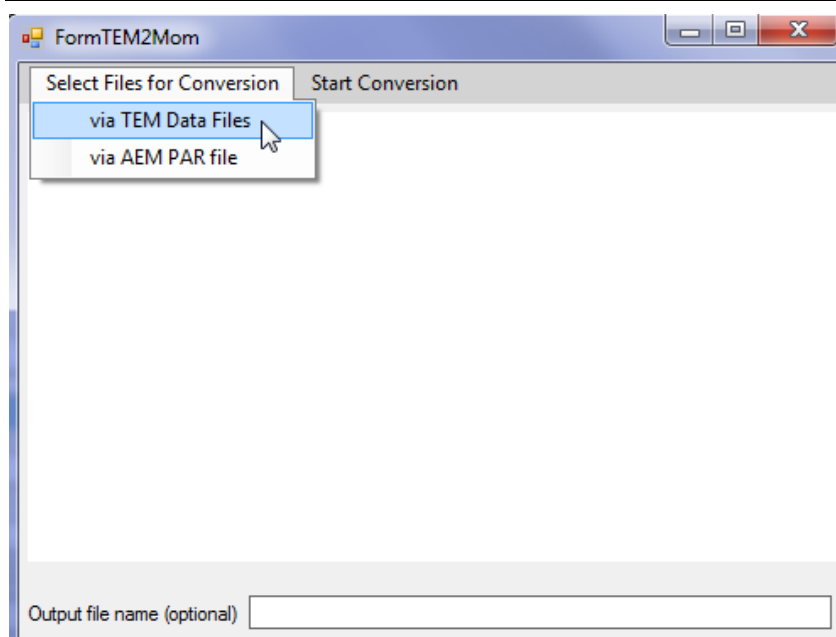
VPem3D operates on TEM resistive limit data. Therefore time decays must be integrated prior to VPem3D modelling and inversion. Downhole TEM data is expected in either Crone PEM format or TEM format as exported from Maxwell.

```
TEM File Created by MAXWELL
LINE:East, 116 Spt=BoxDecayStr INSTRUMENT:CRONE DATATYPE:TEM CONFIG:DOWNHOLE UNITS:(nV/A.m2) BREQ:5.000 CURRENT:15.000 TXAREA:192000.000 LSIDE:438.178 OFFTIME:50.000 &
ONTIME:150.000 DUTYCYCLE:50.000 TURNON:0.000 TURNOFF:1.500 RXAREAA:6500.000 RXAREAU:2800.000 RXAREAV:2800.000 XCOLLAR:1120.450 YCOLLAR:279.890 ZCOLLAR:388.520 ATLANTISPROBENO: &
TXTURNS:1.000 TXMMOMT:2880000.000 BFIELD:NO RXDIPOLE:YES TXDIPOLE:NO TIMINGMARK:51.500 PROJECT: PROSPECT: CONTRACTOR: CLIENT: &
TENEMENT: "DATE:FEBRUARY_09_2010" RECEIVER:Crone RXSENSOR: ATLANTISPROBENO: TRANSMITTER: COMMENT1: COMMENT2: &
LOOP:EAST &
LVXK:890.50 LV1Y:112.00 LV1Z:390.78 &
LV2X:890.50 LV2Y:607.00 LV2Z:390.78 &
LV3X:1310.00 LV3Y:607.00 LV3Z:390.78 &
LV4X:1310.00 LV4Y:112.00 LV4Z:390.78
/TIMES(msec)=0.0560,0.0740,0.0980,0.1320,0.1780,0.2360,0.3140,0.4200,0.5600,0.7440,0.9880,1.3120,1.7440,2.3180,3.0780,4.0880,5.4280,7.2060,9.5700,12.6600,16.0500,22.7000,32.7000,42.7000
/TIMESWIDTH(msec)=0.0160,0.0200,0.0280,0.0400,0.0520,0.0640,0.0920,0.1200,0.1600,0.2080,0.2800,0.3680,0.4960,0.6520,0.8680,1.1520,1.5280,2.0280,2.7000,3.4800,3.3000,10.0000,10.0000,10.0000
EAST NORTH LEVEL ELEV DIST STATION DIP AZIMUTH COMPONENT CH1 CH2 CH3 CH4 CH5 CH6 CH7 CH8 CH9 CH10 CH11 CH12
1107.072 273.139 309.936 309.936 0 80 79.204 243.224 U 151.9665 141.674752 125.986411 102.879469 75.531867 47.692689 22.880447 0.002722 -0.00038 -2.500324 -2.745535 -1.092775
1107.072 273.139 309.936 309.936 0 80 79.204 243.224 A 1033 854.200598 677.702384 509.173539 368.55276 259.24014 176.62135 115.5249 72.35937 43.211175 24.229372 12.455231
1107.072 273.139 309.936 309.936 0 80 79.204 243.224 V -171.133 -134.94417 -86.941174 -0.005073 0.000631 16.971246 37.72974 36.25140 27.11587 18.343891 10.354039 4.782929
1103.793 271.452 290.279 290.279 20 100 79.376 242.779 U 131.9332 122.430984 108.177739 87.378255 62.796763 37.648858 14.170012 0.001139 -0.00094 -5.118162 -3.97121 -1.714571
1103.793 271.452 290.279 290.279 20 100 79.376 242.779 V -173.355 -136.85731 -87.014019 -0.003873 0.000881 24.60832 48.809169 41.36288 31.341258 20.46688 11.548857 5.35621
1103.793 271.452 290.279 290.279 20 100 79.376 242.779 A 1003.555 898.064448 671.571772 509.056479 370.68851 261.30697 177.77411 115.7842 72.099524 42.81024 23.907839 12.264973
```

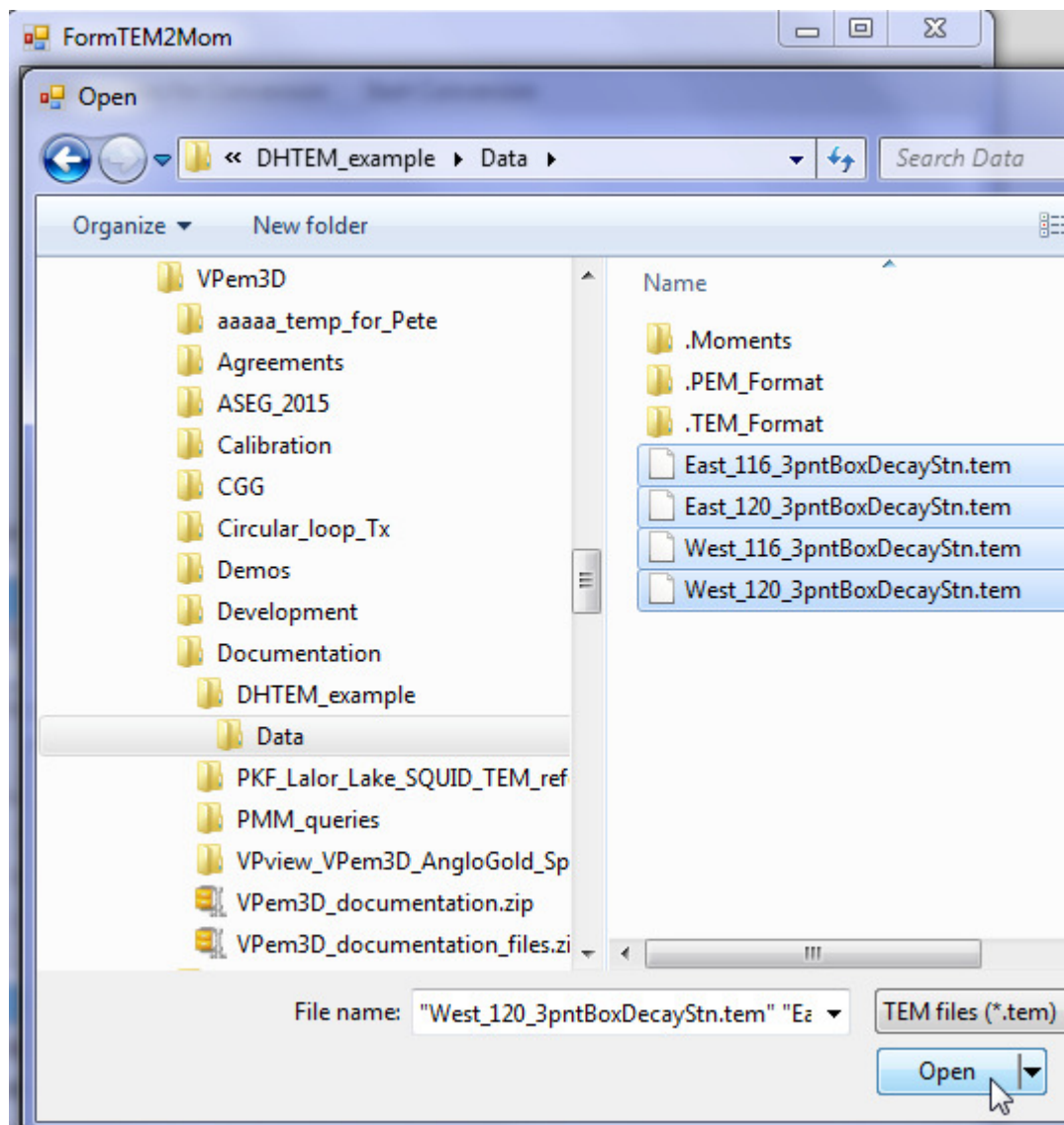
First few lines of a downhole TEM file generated by Maxwell. Tx loop vertices (LVnX, LVnY, LVnZ) are included in the header. Drill hole trajectory is defined by the DIP and AZIMUTH fields.



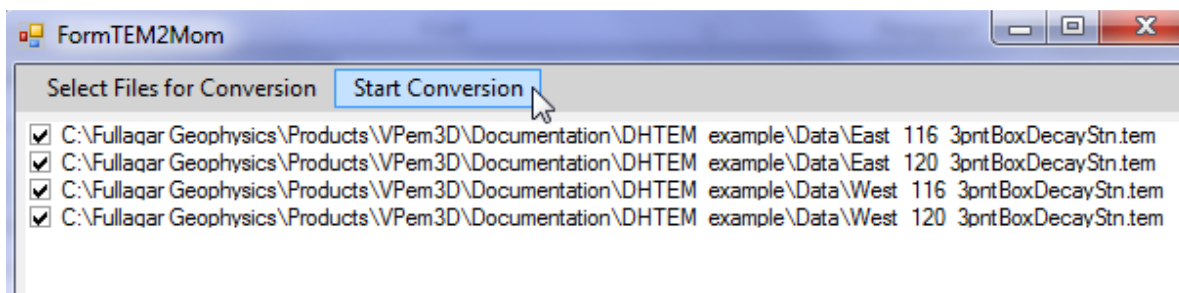
Accessing the data conversion programs under the VPview *Data* menu.



Select TEM2Mom for conversion of downhole TEM data.



Select the required downhole TEM files.



Launch TEM2Mom.

Note that TEM2Mom will include all the TEM channels in the integration when computing the resistive limits. This is not desirable if the decay degenerates into noise at late times. The number of channels included in the integration can be controlled from VPview, as described in Section 5.2. Channel range is also selectable via command line parameters; see Section 7.3.

The time range, and to a lesser extent waveform, affect the resistive limit amplitudes. Therefore, ensure that the channel times are identical for all TEM files selected.

/RXX	RXY	RXZ	RLX	RLY	RLZ	LX1
LINE East116-3pntBoxDecayStn	DCX=1120.45	DCY=279.89	DCZ=388.52			
1107.072	273.139	309.936	11.252381	0.033305	65.125480	890.500
1103.793	271.452	290.279	10.347227	-7.432527	62.259993	890.500
1100.527	269.860	270.612	11.315240	-12.841831	61.222507	890.500
1097.321	268.278	250.934	12.935338	-20.216700	59.541316	890.500
1094.040	266.848	231.257	24.949750	-19.415057	51.855048	890.500
1090.918	265.307	211.562	18.113156	-14.457164	46.930657	890.500
1087.775	263.831	191.866	3.123378	4.242888	43.317196	890.500
1084.659	262.360	172.165	-7.407505	10.863081	44.006544	890.500
1081.625	260.908	152.450	-13.857340	13.400572	46.925400	890.500
1078.556	259.502	132.737	-9.562922	5.538072	57.275988	890.500
1075.503	258.208	113.013	-3.911181	-2.336431	59.892367	890.500
1072.462	256.891	93.290	-0.122855	-3.351693	64.185405	890.500
1069.426	255.595	73.564	2.951704	-1.438932	67.327081	890.500
1067.891	254.986	63.702	2.435958	-2.755956	68.483076	890.500
1066.362	254.384	53.838	4.193255	0.517080	69.482199	890.500
1064.843	253.831	43.969	7.081366	-1.949481	74.797970	890.500
1063.313	253.312	34.100	10.012638	-5.542330	77.964995	890.500
1061.811	252.762	24.229	17.424003	-15.178773	80.462397	890.500
1060.304	252.222	14.358	19.223487	-23.253554	80.964078	890.500
1058.817	251.683	4.484	29.174693	-36.291945	81.854153	890.500
1057.352	251.142	-5.393	32.373011	-36.300904	81.724165	890.500
1055.871	250.640	-15.270	32.701882	-48.290716	80.640008	890.500

LX1	LX2	LX3	LX4	LY1	LY2	LY3	LY4	LZ1	LZ2	LZ3	LZ4	STN
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	80.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	100.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	120.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	140.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	160.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	180.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	200.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	220.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	240.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	260.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	280.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	300.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	320.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	330.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	340.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	350.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	360.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	370.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	380.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	390.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	400.000
890.500	1310.000	1310.000	890.500	112.000	112.000	607.000	607.000	390.780	390.780	390.780	390.780	410.000

First few lines of a resistive limits (“TEM moments”) file produced by TEM2Mom are shown above. This file is in #VPem# format. RXX, RXY, RXZ are the receiver coordinates. RLX,RLY,RLZ are the resistive limit x-, y-, and z-components in pTms/A. LXn, LYn, LZn are the coordinates of the nth vertex of the Tx loop. TEM2Mom now defaults to #VPem2 format for downhole TEM, but #VPem# can be used if the Tx loop is rectangular; TEM2Mom computes the best fitting rectangle from the loop vertex coordinates recorded in the TEM file header.


TEM2Mom creates a VPem3D PAR file as well as a resistive limit data file:

```
#VPEM#  
TEM2Mom_2015-07-10_0.mom  
19  
-3  
4 RLX  
5 RLY  
6 RLZ  
7 LX1  
8 LX2  
9 LX3  
10 LX4  
11 LY1  
12 LY2  
13 LY3  
14 LY4  
15 LZ1  
16 LZ2  
17 LZ3  
18 LZ4  
19 STN
```

The PAR file defines the data file and its format. In this PAR file all three resistive limit components are identified, therefore modelling and inversion will be applied to 3 components.

To restrict inversion to two components, delete the record defining the column for the unwanted component, and reduce the number of channels from 3 to 2:

```
#VPEM#  
TEM2Mom_2015-07-10_0.mom  
19  
-2  
4 RLX  
6 RLZ  
7 LX1  
8 LX2  
9 LX3  
10 LX4  
11 LY1  
12 LY2  
13 LY3  
14 LY4  
15 LZ1  
16 LZ2  
17 LZ3  
18 LZ4  
19 STN
```



13.3 Create a starting model (DTM grid available)

In VPem3D models, the model top coincides with the ground surface. Therefore VPview uses the DTM grid, if available, to define the model top during starting model construction. The format of the DTM grid must be Geosoft “DOS”, i.e. uncompressed GRD.

The procedure for model construction when a DTM grid is available is the same for downhole TEM as for airborne TEM. Therefore refer to Section 12.3 above.

After sub-celling, it may be desirable to apply depth weighting; see Section 13.8 below.

13.4 Create a starting model (no DTM grid available)

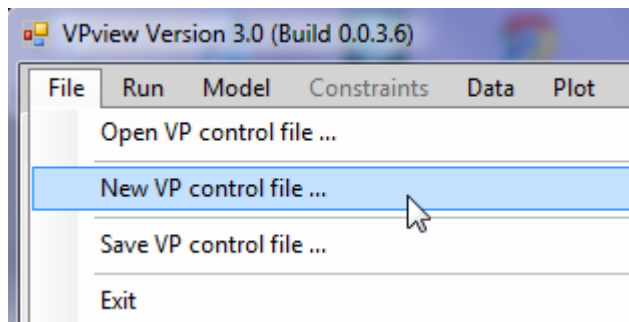
When no DTM grid is available, VPview creates a model with a horizontal upper surface. The Create New Model utility needs to know the model extents and cell sizes. The model extents can be derived from a dummy data file defining the corners of the model area. A 3 or 4 line dummy data file will suffice, with records of the form shown below:

```
EAST NORTH RL DATA
XMIN, YMIN, RL1, DATA1
XMAX, YMIN, RL2, DATA2
XMAX, YMAX, RL3, DATA3
```

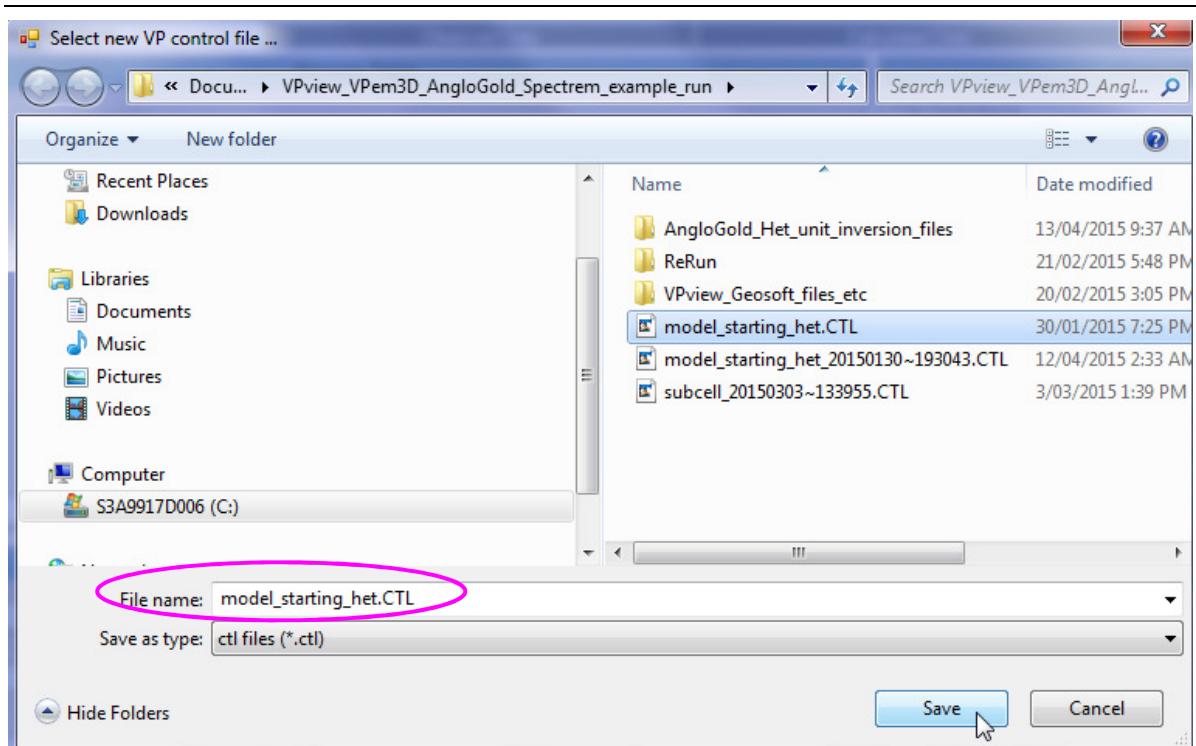
The procedure for model construction when no DTM grid is available is the same for downhole TEM as for airborne TEM. Therefore refer to Section 12.4 above.

13.5 Create a control file

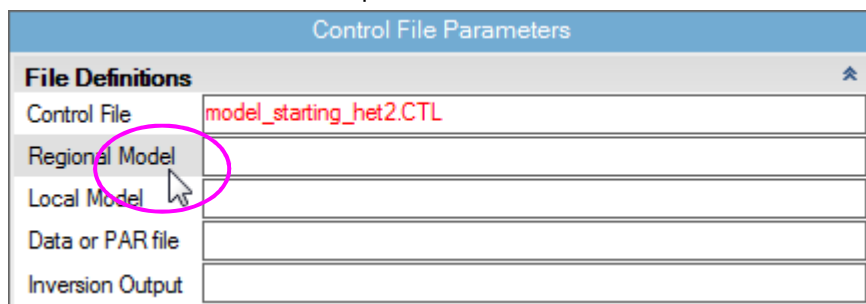
A control file is required in order to run VPem3D. If the control file does not already exist, it can be created using the *New VP control file* utility under the File menu.



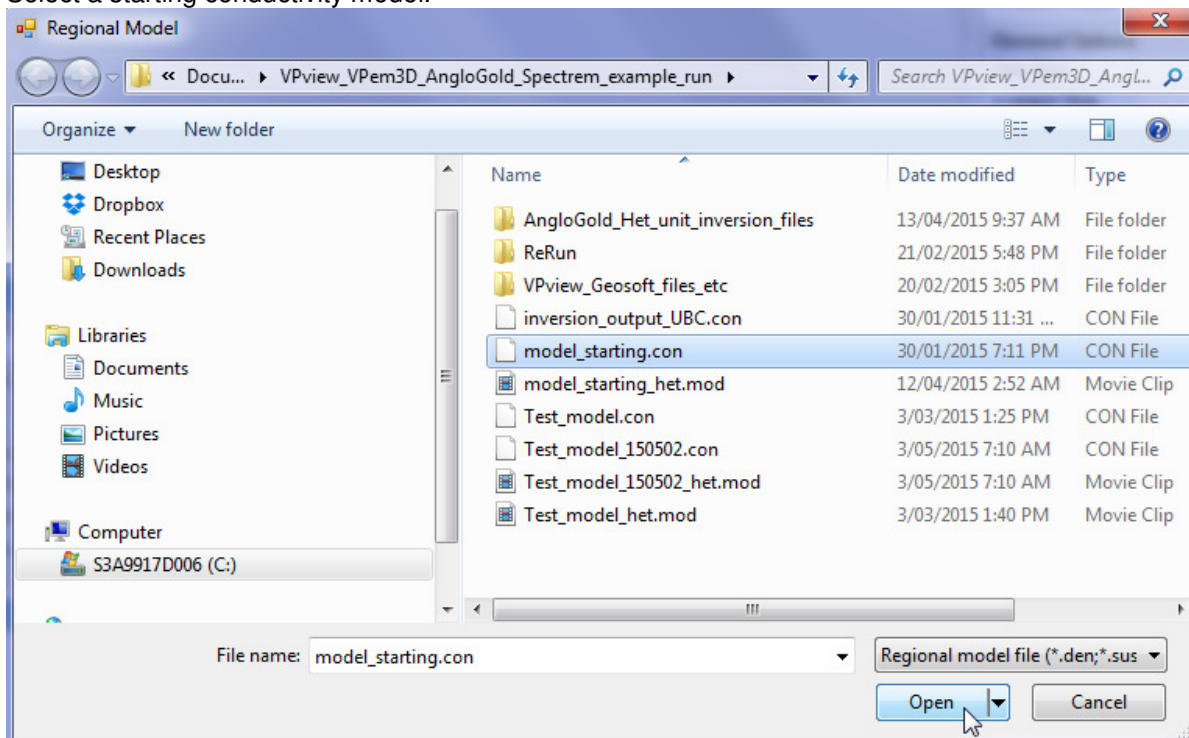
First select the project directory and choose a name for the control file. The control file has extension is CTL. In the illustration the control file already exists.



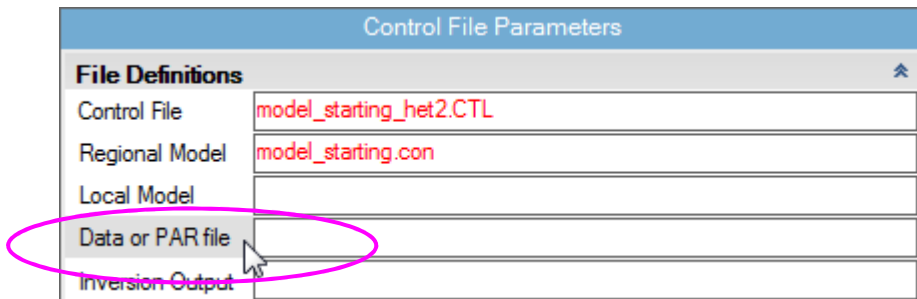
Click on a model file label to open a browse window.



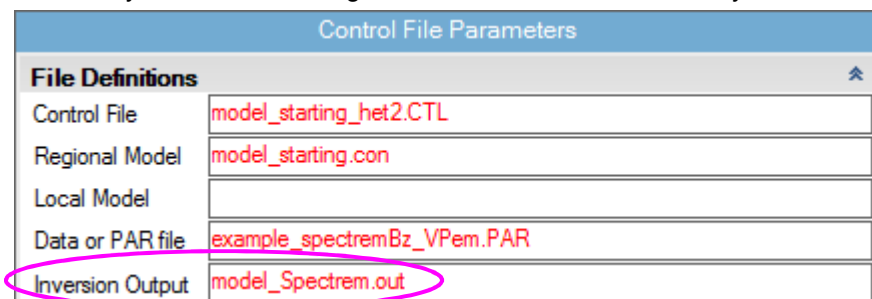
Select a starting conductivity model.



The starting model can be regarded as either regional or local. The text box for the other model can be left blank. Select a PAR file in the same fashion: click on the label to open a browse window.



The output model file will usually not already exist. Type in a name for the output file. The extension is arbitrary, but VPview recognises *.CON files as conductivity models.



Now define **General Options** settings. Use the drop down menu to select *Data Type*. TEM Moments (Linear) is the appropriate *Data Type* for most downhole TEM inversion runs.

General Options	
Data Type	TEM Moments (Linear)
Inversion Style	Defines the data type (igrav)
Iterations	
Uncertainty	
Δ Property	

Use the drop down menu to select *Inversion Style*. Heterogeneous Property (either smooth or compact) is the most common *Inversion Style* for downhole TEM, since the aim is usually to adjust the conductivity of individual model cells.

General Options	
Data Type	TEM Moments (Linear)
Inversion Style	Heterogeneous Property
Iterations	Defines the inversion style (iid)
Uncertainty	
Δ Property	

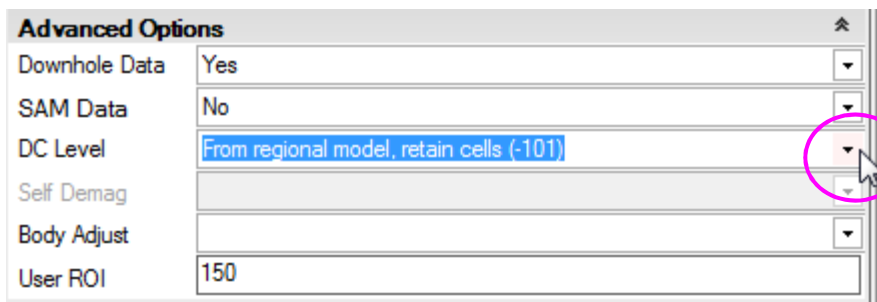
Set *Iterations* to zero for an initial forward calculation.

General Attributes	
Data Type	TEM Moments (Linear)
Inversion Style	Heterogeneous Property
Iterations	0
Uncertainty	
Δ Property	

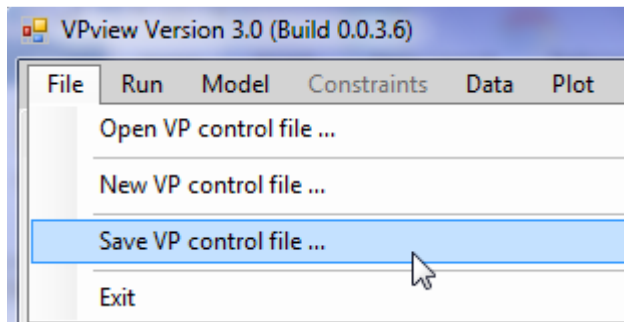
Define values for the *Uncertainty* (in pTms/A) and the *Δ Property* (maximum conductivity change per iteration, in mS/m).

General Attributes	
Data Type	TEM Moments
Inversion Style	Heterogeneous Property
Iterations	0
Uncertainty	5
Δ Property	100

In the **Advanced Options**, use the drop down menus to choose *Downhole Data* and *DC Level* settings. *Downhole Data* is “Yes” for downhole TEM data. For regional models, -101 is normally the appropriate setting for *DC Level*. This fixes the *DC Level*, which is added to all calculated data, to the value recorded at the end of the regional model file; it is almost always zero for downhole TEM. [The normal *DC Level* setting for local models is -102, to fix the *DC Level* to the value recorded at the end of the local model file.] Enter the desired *User ROI* (radius of influence). *User ROI* controls the data proximity weighting around underground receiver positions, as described in Section 2.15. In this case changes to the conductivity will be suppressed inside a sphere of radius 150m centred on each data point.



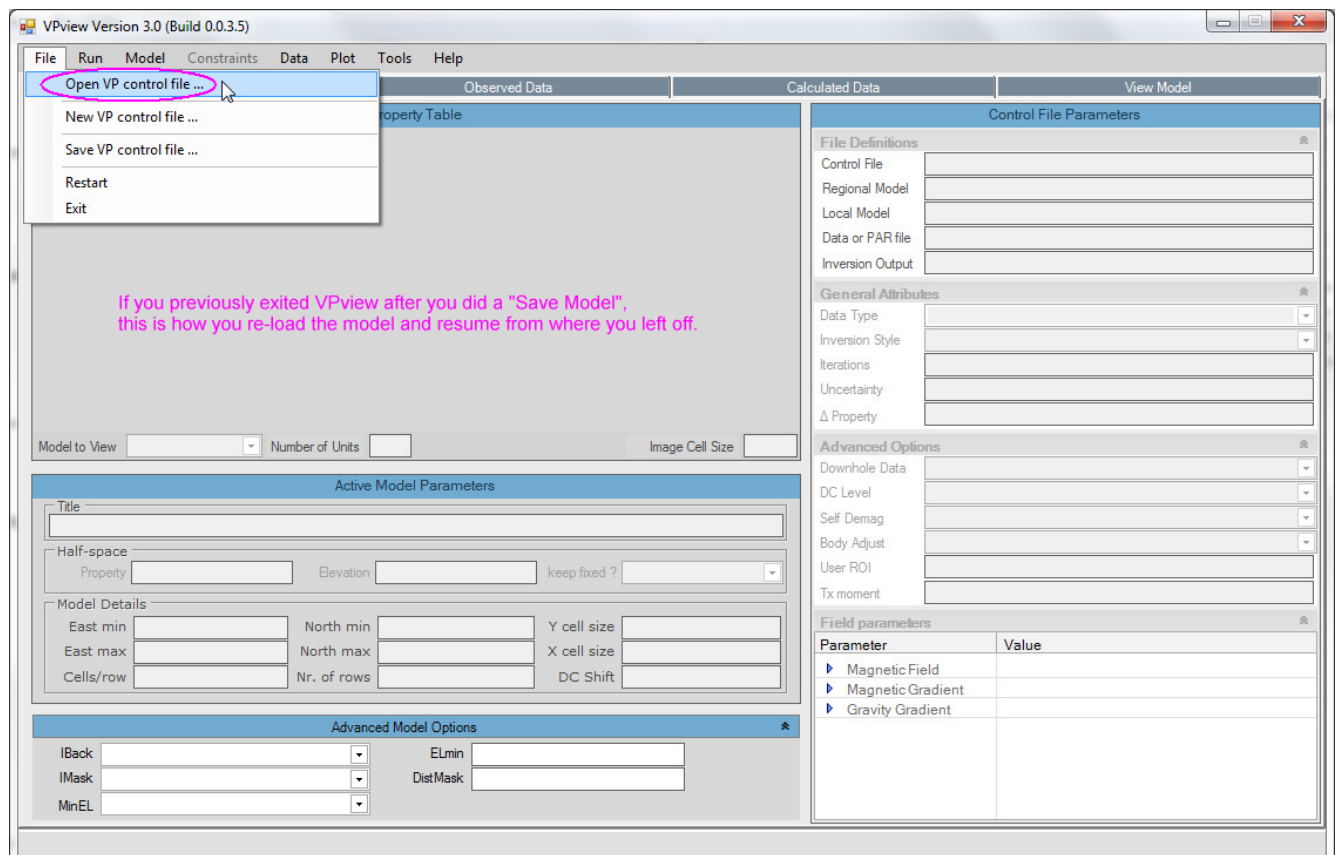
When all fields have been populated, save the new control file using the option under *File*.



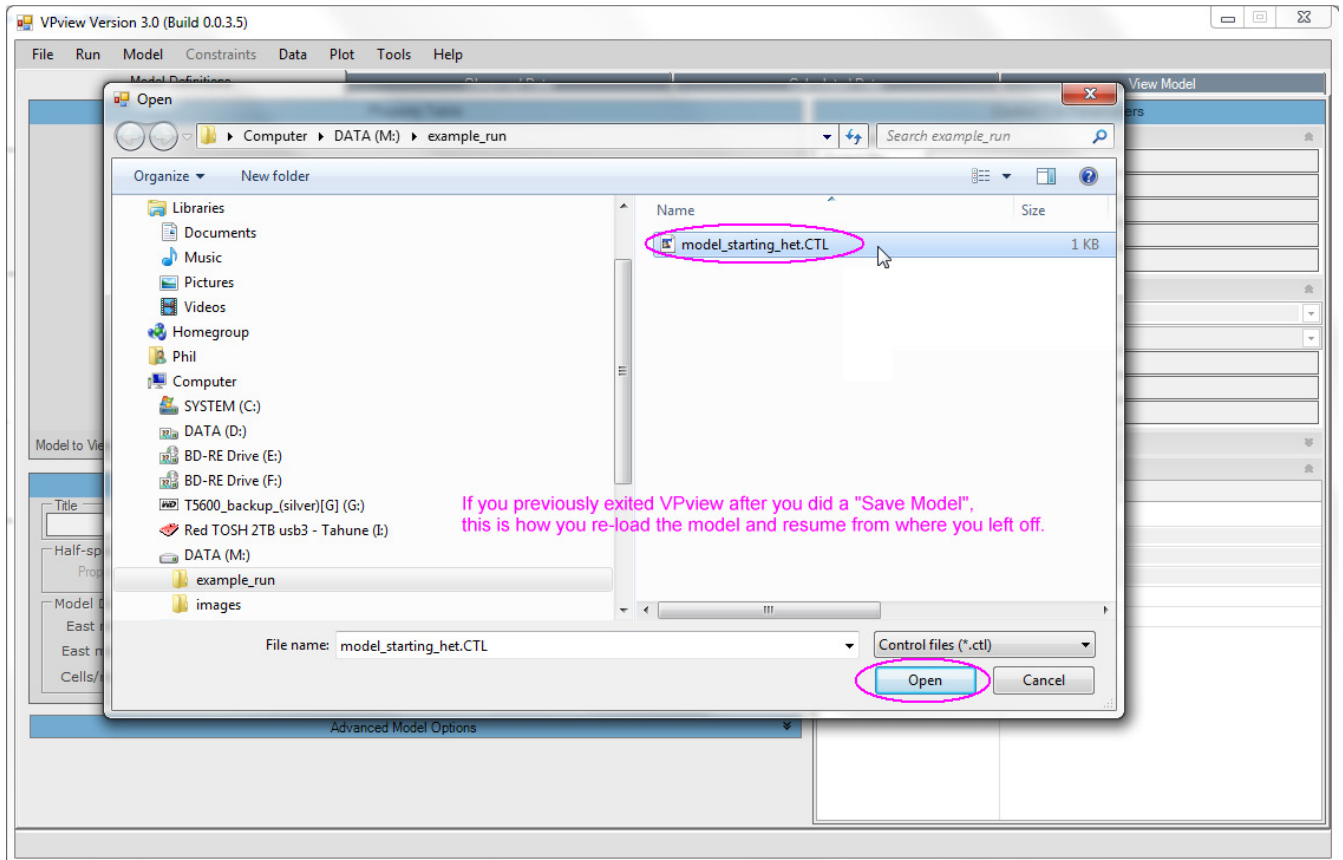
13.6 Performing a forward calculation

Before launching an inversion it is always desirable to run a forward calculation, and to examine the starting model and the initial fit between observed and calculated data.

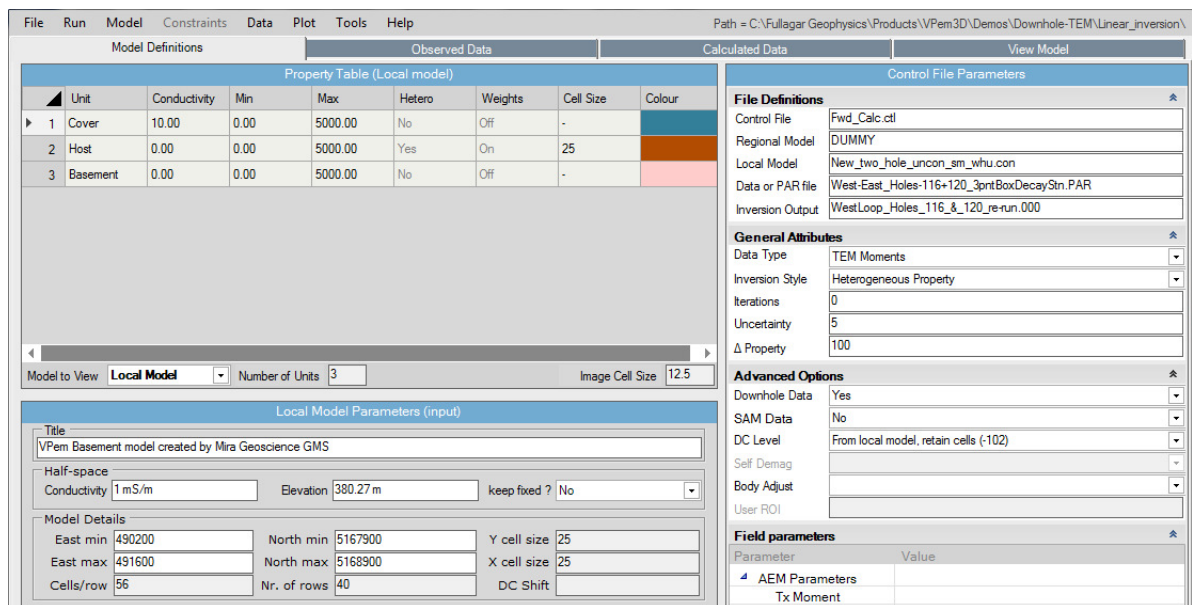
If you had exited, start VPview again and select the “Open VP control file” option under the *File* menu.



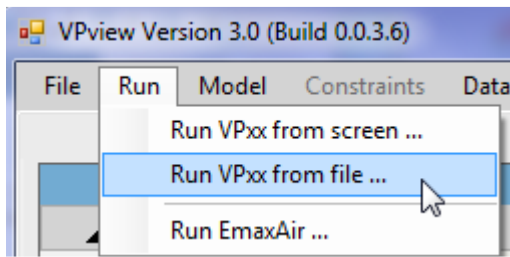
Choose the desired VP control file.



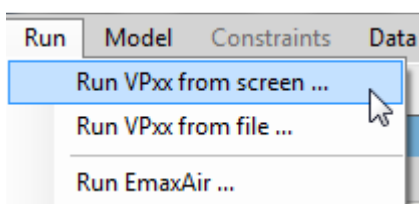
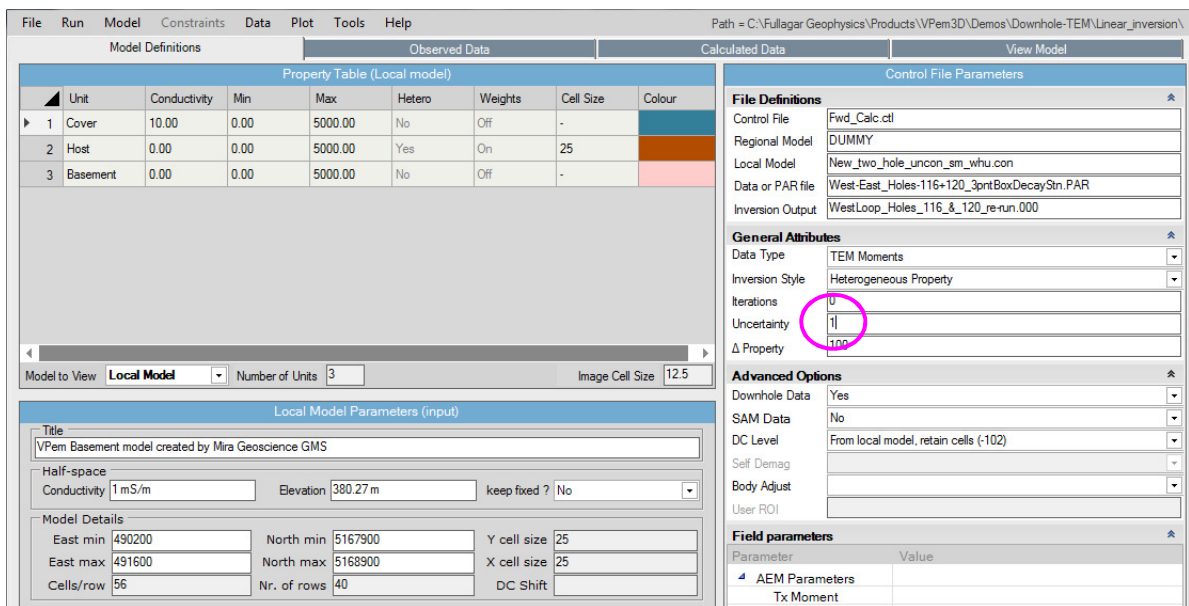
VPview displays the model file header information and control file settings. Cells in the Host unit are 25m cubes.



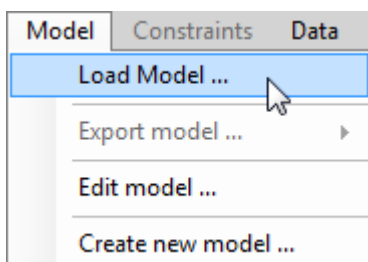
If the saved model parameter and control settings are all acceptable, launch VPem3D using the “Run VPxx from file” option under the *Run* menu.



If some of the settings have been edited, but not saved, launch VPem3D using the “Run VPxx from screen” option. A new control file is created in that case, with the date and time appended to the original control file name. Here the Uncertainty has been changed, so VPem3D is run “from screen”.

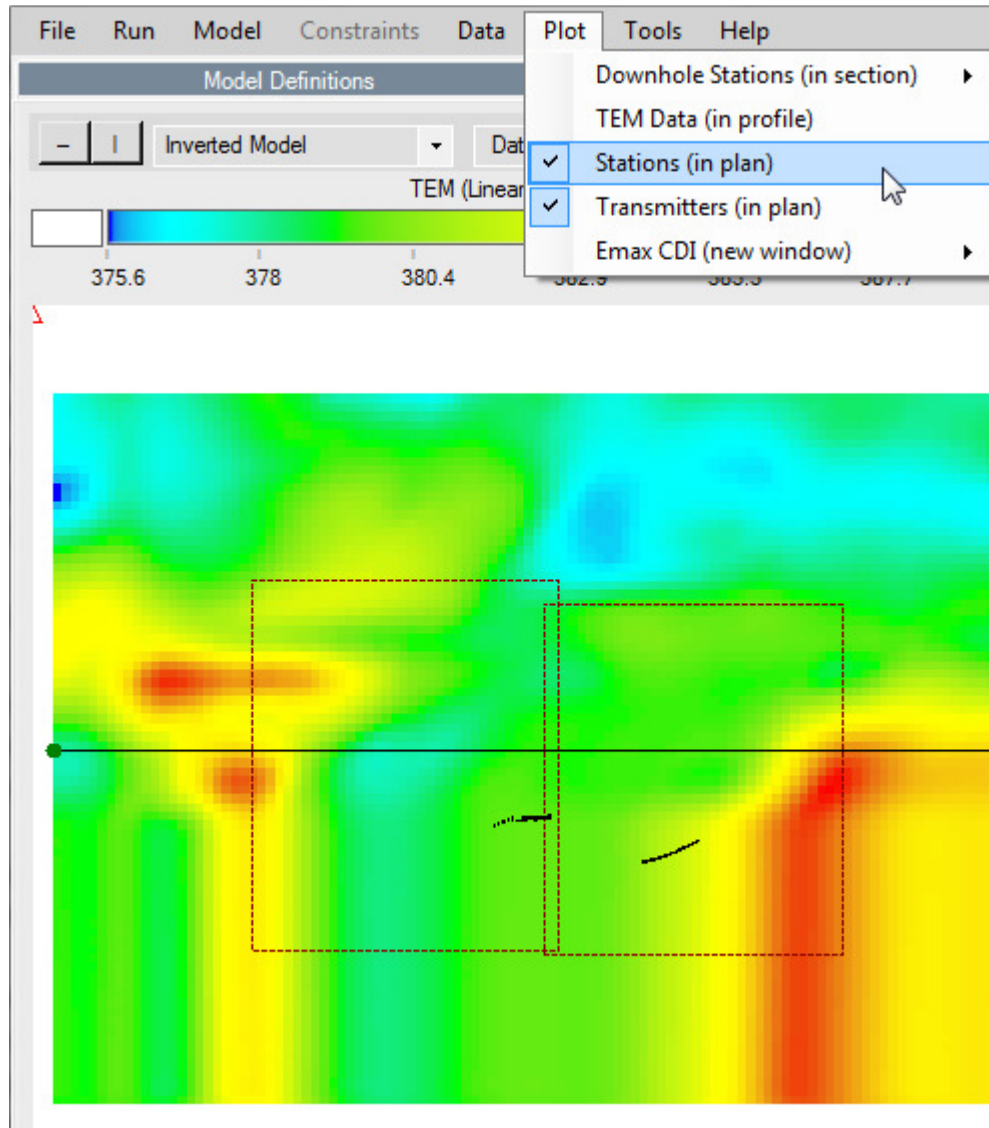


After the forward calculation has completed, load the model and data using the *Load Model* option under the *Model* menu, as shown.

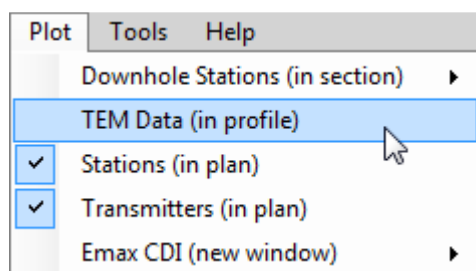


When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the model is displayed in the right panel. The black line in the LH panel shows the position of the vertical section; it can be adjusted using the scroll bar. Toggle buttons in the top RH corner of the VPview window switch the display line from E-W to N-S orientation. Oblique sections can be displayed by clicking and dragging the red and green knobs at either end of the section line.

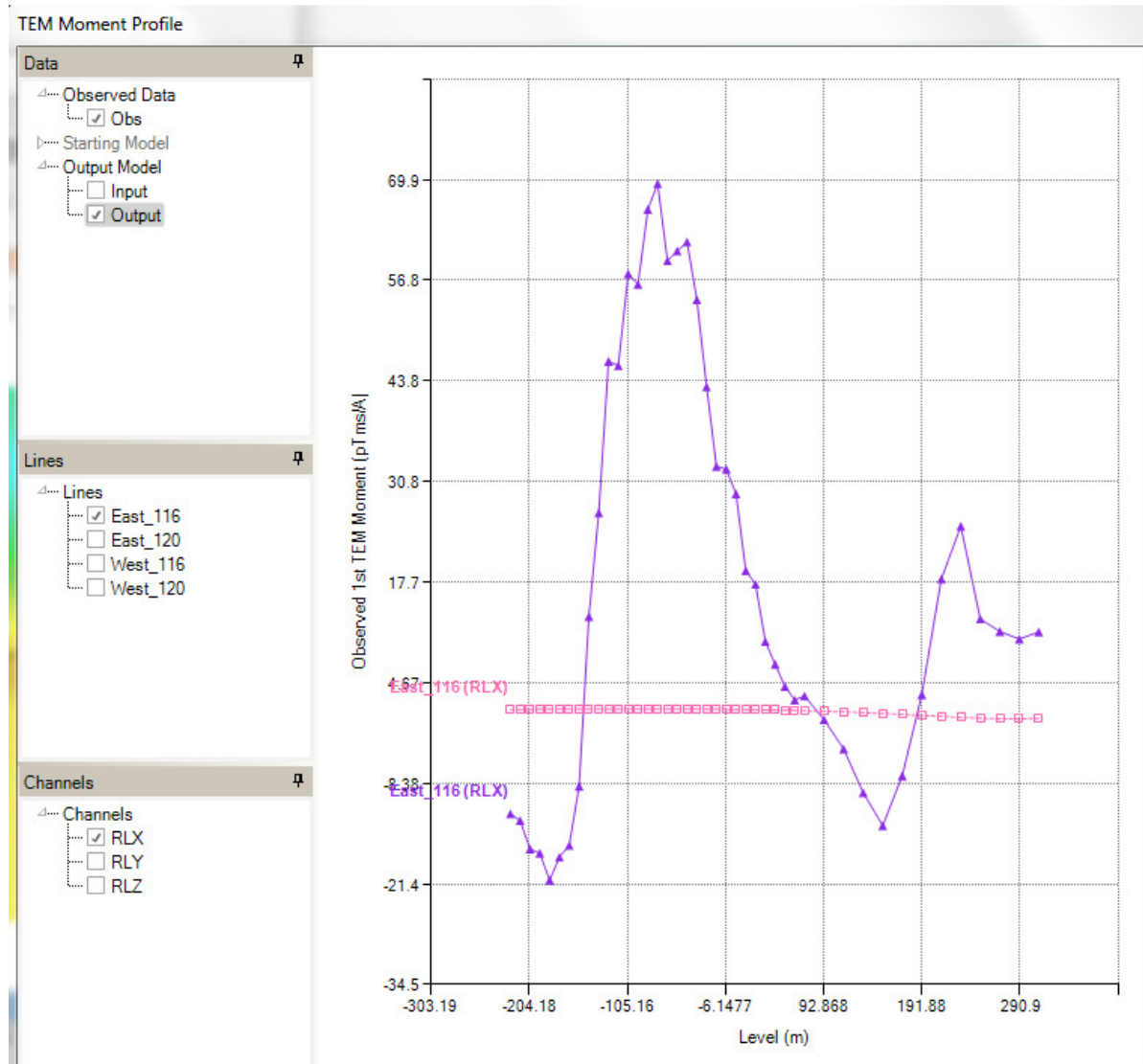
There are different options for displaying the model and data. For example, the downhole data locations can be projected in plan. Transmitter loops can also be displayed (dashed red).



The downhole TEM can be plotted in profile.



The user can compare observed and calculated (“Output”) data for each drill hole (“Line”) and each resistive limit component (RLX, RLY, RLZ).

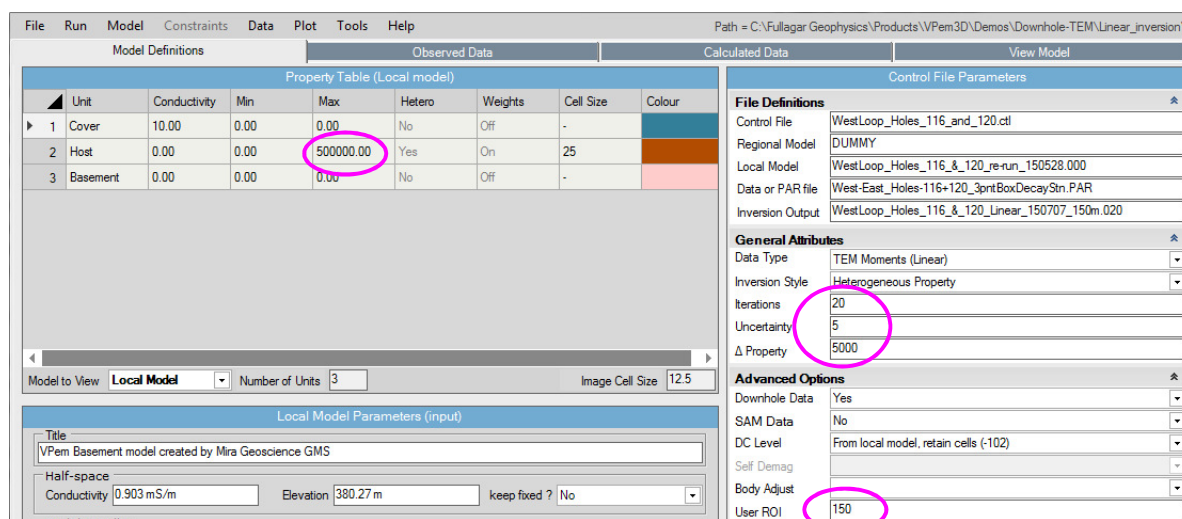


13.7 Running a Downhole TEM inversion

Once satisfied with the forward calculation, prepare to run an inversion:

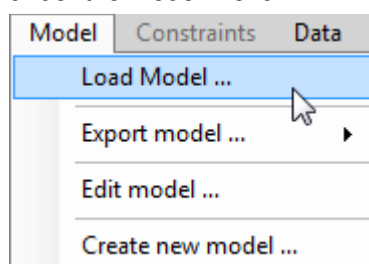
- the output model from the forward calculation becomes the input model for inversion; this obviates the need to re-run the forward calculation since the calculated data are recorded at the end of the model file.
- specify the number of iterations to perform.
- set the uncertainty level in the data (pTms/A)
- set the maximum permitted change in property value per iteration (mS/m); this is often large for base metal environments.
- ensure that the maximum conductivity (upper bound) is sufficiently large in the active unit; here it is 500000 mS/m.
- check that the radius of influence around data points (*User ROI*) is suitable. If the data include in-hole as well as off-hole anomalies, a non-zero “minimum weight” is recommended, i.e. a *User ROI* with non-zero decimal part, to enable the conductivity of cells containing data points to vary. For example, *User ROI* = 150.05 means that the radius of influence is 150m, and the weight increases linearly with distance from 0.05 at the data point to 1 at radius 150m.

If any fields in the control file have been edited, select “Run VPxx from screen” to start the VPem3D inversion. Otherwise, launch VPem3D via “Run VPxx from file” to use the parameters saved in the *.CTL file.



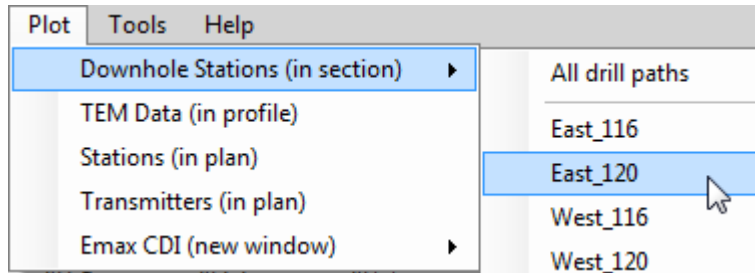
Details of the inversion, including data misfit, are displayed in a command window and recorded in a LOG file. The LOG file has the same name as the Inversion Output file, with extension .LOG.

After inversion has completed, read the model and data into VPview using the *Load Model* option under the Model menu.

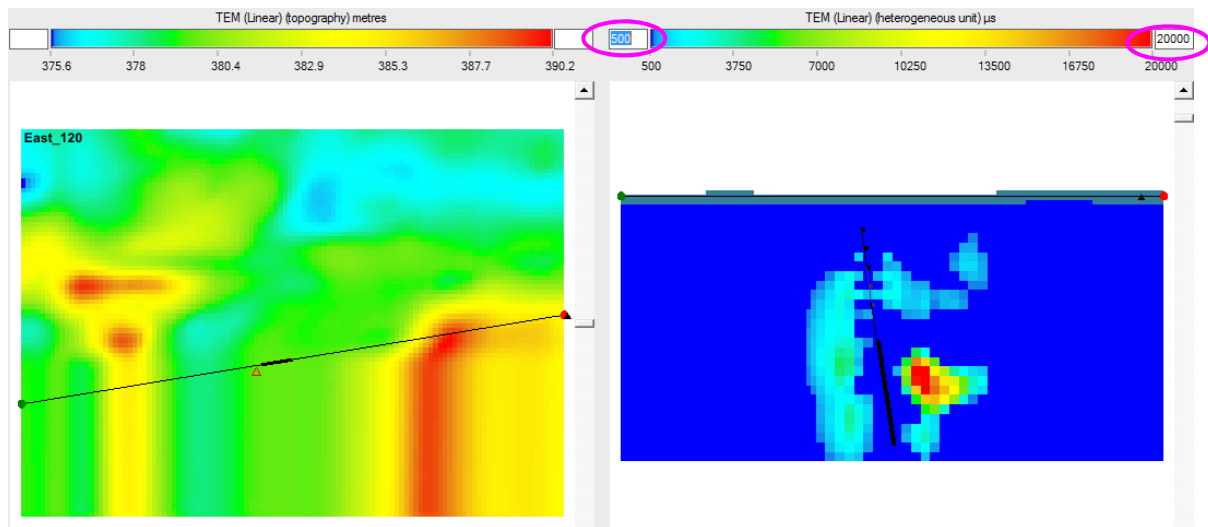


When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the inverted model is displayed in the right panel. The user can toggle between section views of the starting (Initial) and output (Inverted) models using the drop-down menu above the RH panel. The black line in the LH panel shows the position of the vertical section; it can be adjusted using the scroll bar. Toggle buttons in the top RH corner of the VPview window switch the display line from E-W to N-S orientation. Oblique sections can be displayed by clicking and dragging the red and green knobs at either end of the section line

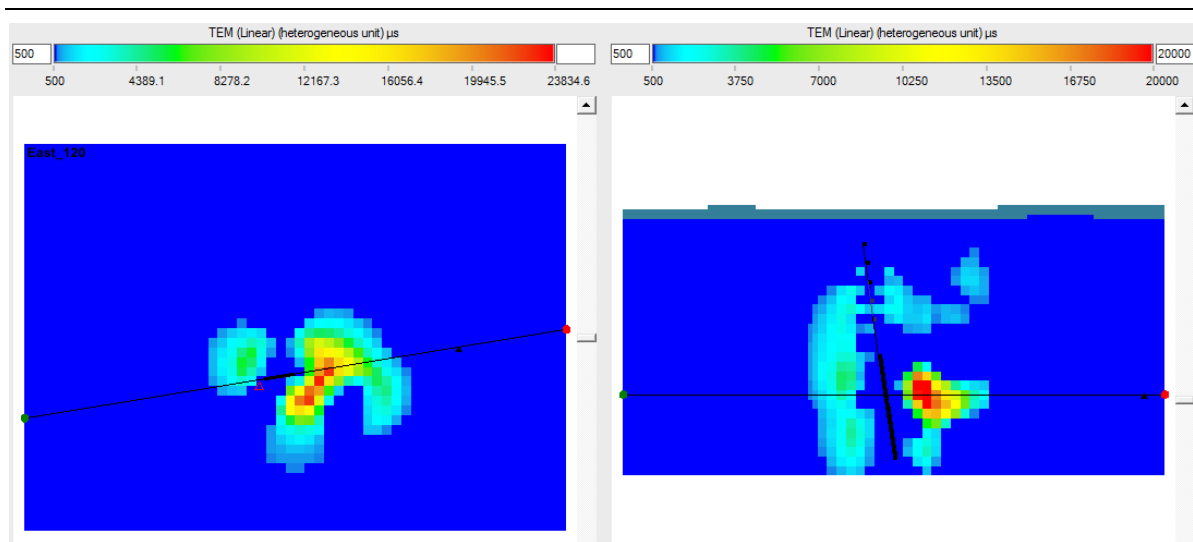
There are several options for model and data display. For example the model can be displayed in the vertical section which most closely captures a drill hole using the *Downhole Stations (in section)* option under the Plot menu.



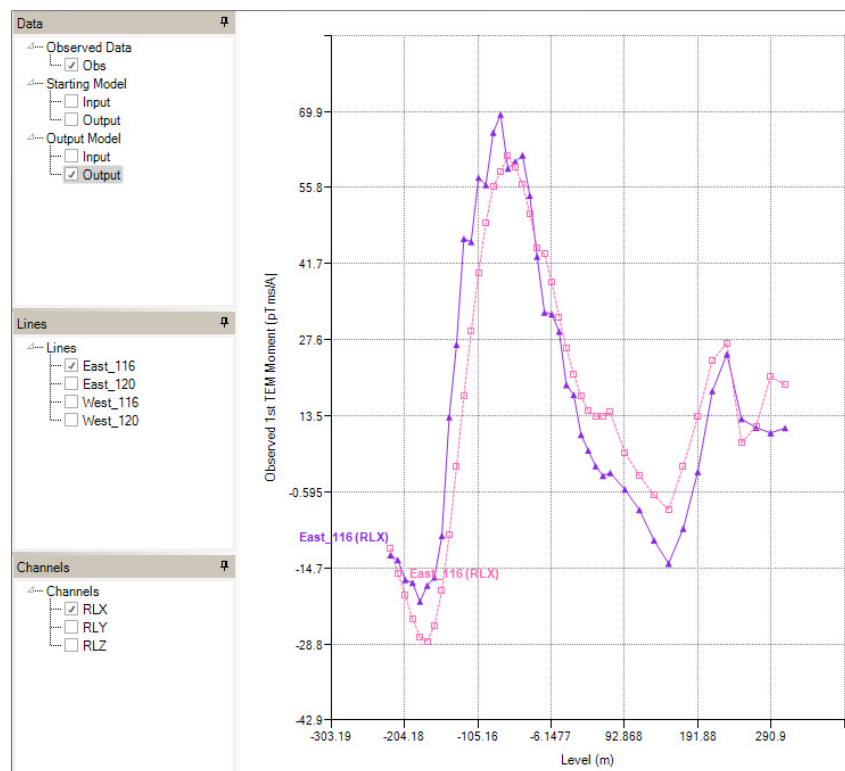
Vertical model section through plane which best captures hole East_120. Receiver positions in the RH panel are coloured black if located in the display section, grading to lighter shades of grey as their offset from the section increases. The colour stretch for the conductivity can be altered by entering min and max values in the boxes at the ends of the colour bar and then hitting Enter.



A horizontal section through the conductivity model is displayed here in the LH panel, at the elevation defined by the black line though the vertical section in the RH panel.

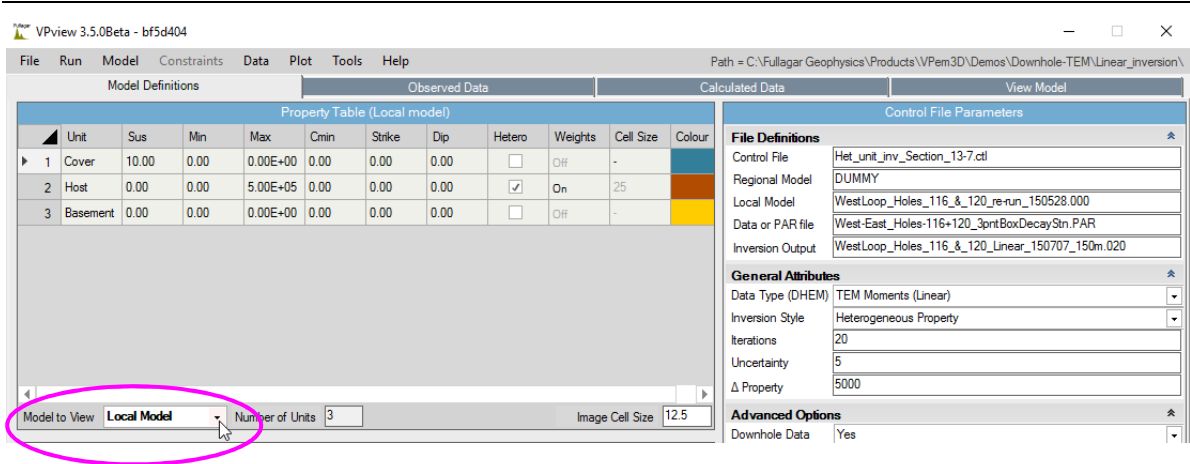


The observed and calculated data can be compared in profile for each loop and each resistive limit component.

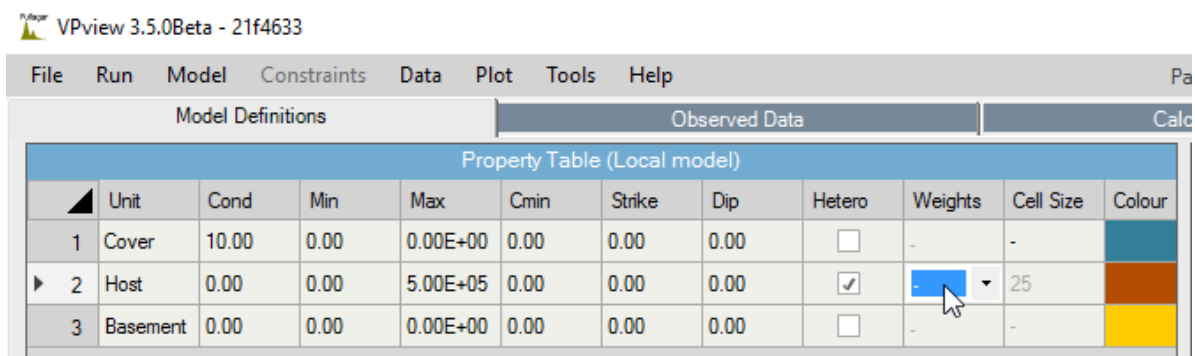


13.8 Applying Depth Weights

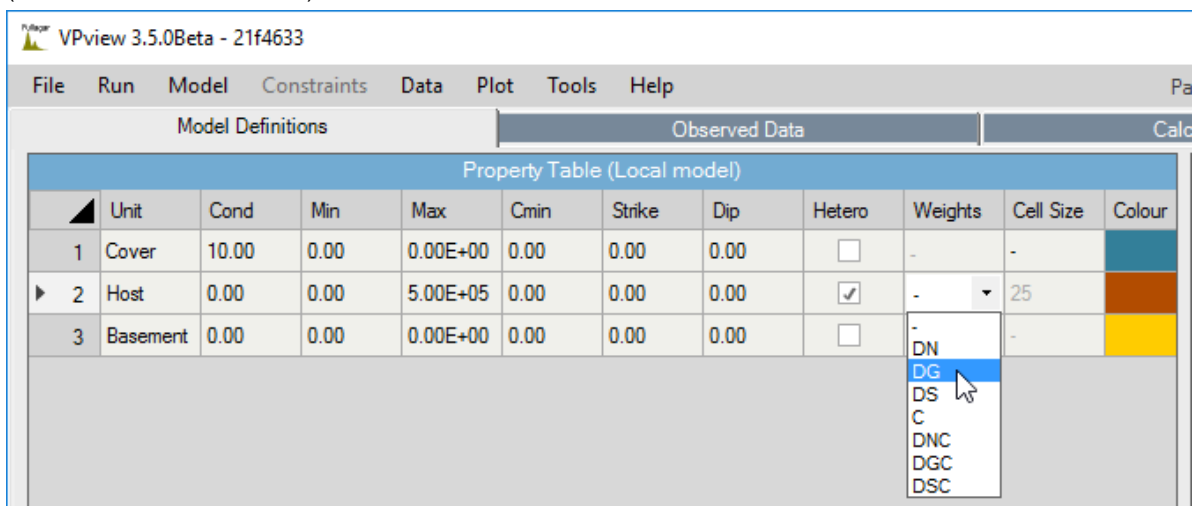
It is often beneficial to apply depth weighting prior to downhole TEM inversion, to suppress development of conductive zones close to loop wires on the ground surface. First select the model to be weighted, by choosing the *Model to View*. The Local Model is selected in this case.



Click the Weights cell in the Property Table for the unit to be weighted; the Host unit has been selected in this case.



Choose the required weighting option; DG is selected here, i.e. depth weighting referenced to the ground, without cell size normalisation. This and other options are described in Section 7.1 (summarised in Table 7.1).



VPview 3.5.0Beta - 7ec2748

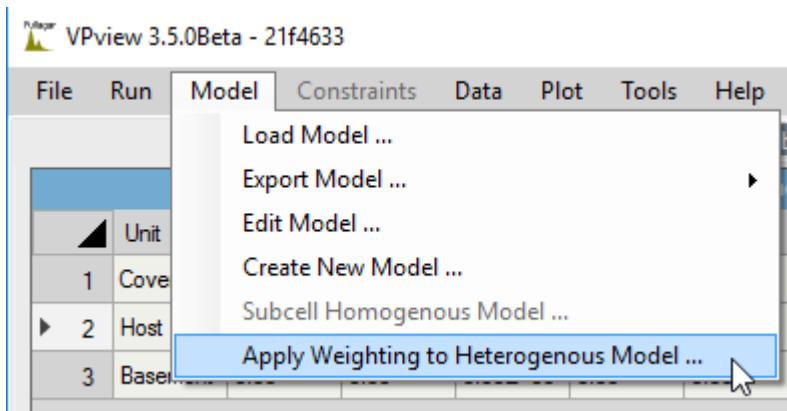
File Run Model Constraints Data Plot Tools Help

Model Definitions Observed Data Calc

Property Table (Local model)

Unit	Cond	Min	Max	Cmin	Strike	Dip	Hetero	Weights	Cell Size	Colour
1 Cover	10.00	0.00	0.00E+00	0.00	0.00	0.00	<input type="checkbox"/>	-	-	
2 Host	0.00	0.00	5.00E+05	0.00	0.00	0.00	<input checked="" type="checkbox"/>	DG	25	
3 Basement	0.00	0.00	0.00E+00	0.00	0.00	0.00	<input type="checkbox"/>	-	-	

With the type of depth weighting defined, the *Apply Weighting to Heterogeneous Model* option becomes active under the *Model* menu.



Now enter wmax, which controls the weights applied in the shallowest cells in the unit(s) being weighted. The wmax default value is 0.999. Click on OK when ready.

Weighting Parameters

Parameter	
Maximum Weight	0.99

Ok Cancel

The depth weights are inserted in the model file by VPem3D. A command window displays some run details.

```

C:\Windows\System32\cmd.exe
=====
Assign depth weights to heterogeneous unit(s)
=====

Control file = "deleteme04227.ct1"
VPem3D output file = WestLoop_Holes_116_&_120_re-run_150528_wgt.000

Active model area:   56 prisms E-W   40 prisms N-S

Total data points in active model area =           3
No. prisms filling active model area =          2240

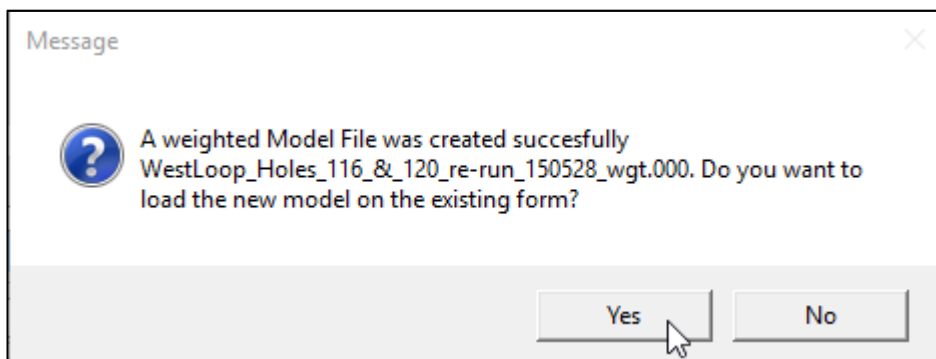
Preliminary read through active model ...

Loading the active model ...

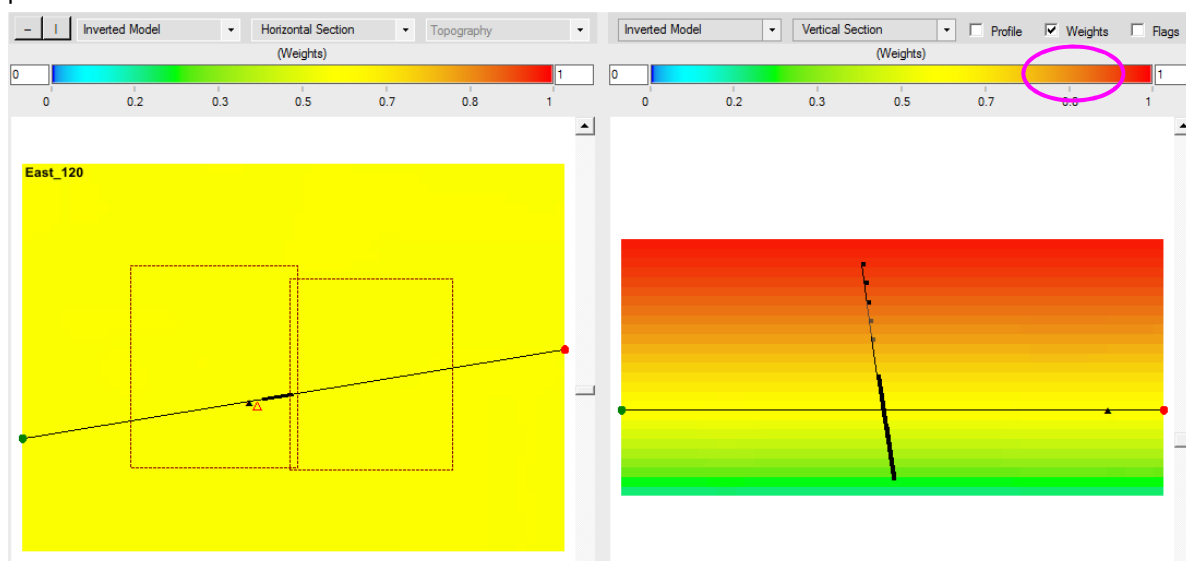
***** Depth weights applied to heterogeneous unit(s)! *****

```

Once depth weighting is finished, the user can elect to replace the unweighted model with the weighted model as the starting model in the control file.



If the weighted model has been adopted as the starting model then, after a Load Model operation, the depth weights can be displayed by checking the Weights panel above the section in the RH panel.



Depth weighting can also be applied via control file. A control file for application of depth weighting to Unit 2 is shown below, with parameters controlling depth weighting coloured red. For explanation of these parameters see Section 7.1.

```
-4 0 0 0 1 -102
0 1 -1
DUMMY
WestLoop_Holes_116_&_120_re-run_150528.000
-2 5.0 1 2 25.99
0 5000 150
West-East_Holes-116+120_3pntBoxDecayStn.PAR
WestLoop_Holes_116_&_120_Linear_150707_wtd.con
DEPTH WEIGHTING
```

14 APPENDIX D: Example Ground TEM Inversion

14.1 Introduction

This Appendix is intended as a guide for running VPem3D modelling and inversion of ground TEM through the VPview user interface. The application of VPem3D is illustrated step-by-step with an example dataset using a series of annotated images with explanatory notes. It should provide enough information to guide you as you work through one of your own datasets. The ground TEM data used in the example is available on application.

The guide does not attempt to explain all of the VPview parameters. For a fuller explanation see the VPview documentation (accessible from the VPview *Help* menu).

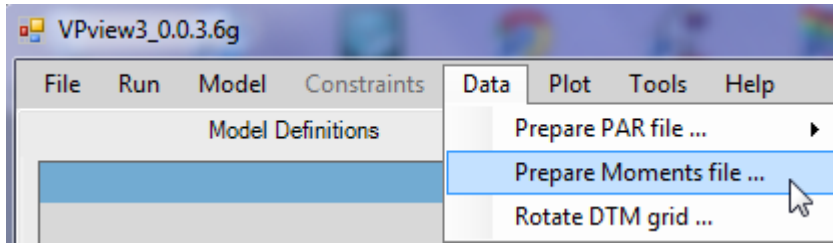
There are various ways to set up and run VPem3D inversion on ground TEM data. The example used here illustrates compact body (heterogeneous unit) inversion for fixed loop B-field (SQUID) data. The starting model was a zero conductivity uniform half-space.

14.2 Computing resistive limit data

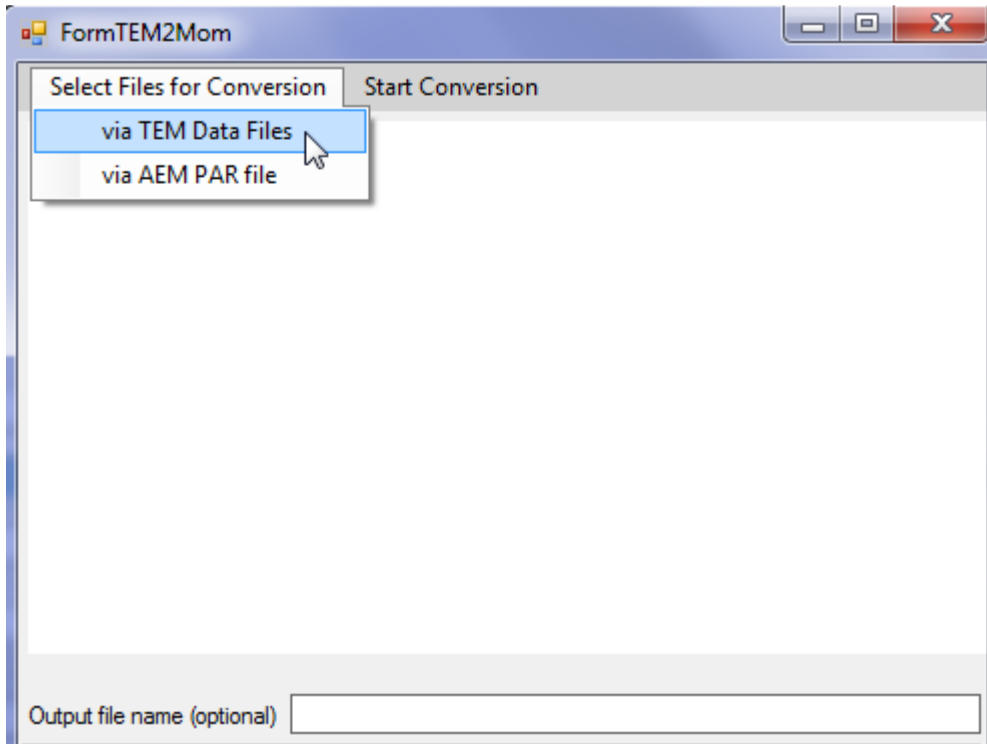
VPem3D operates on TEM resistive limit data. Therefore time decays must be integrated prior to VPem3D modelling and inversion. Ground TEM data are expected in TEM format as exported from Maxwell.

```
-----
TEM File Created by MAXWELL
LINE:2650Emerged INSTRUMENT:SMARTEM DATATYPE:TEM CONFIG:FIXEDLOOP DIP:-90.000 AZIMUTH:180.000 UNITS:(pT/A) BFREQ:0.500 TXAREA:1.000 LSIDE:1.000 &
OFFTIME:500.000 ONTIME:500.000 DUTYCYCLE:50.000 TURNON:0.000 TURNOFF:0.550 RXAREA2:-1.000 RXAREA3:-1.000 RXAREAY:-1.000 LOOP:2 TXTURNS:1.000 BFIELD:YES &
RXDIPOLE:YES TXDIPOLE:NO TIMINGMARK:500.550 DATE:26/02/2010 RECEIVER:SMARTEM RXSENSOR:Squid_JD433_JD423 TRANSMITTER:Geonics &
LOOP:Tx_loop_2_east &
LV1X:3060.00 LV1Y:4630.00 LV1Z:302.97 &
LV2X:3060.00 LV2Y:6100.00 LV2Z:304.80 &
LV3X:3960.00 LV3Y:6100.00 LV3Z:301.75 &
LV4X:3960.00 LV4Y:4630.00 LV4Z:302.67
/TIMES(ms)=0.0995,0.1245,0.1540,0.1910,0.2375,0.2950,0.3660,0.4545,0.5645,0.7005,0.8695,1.0800,1.3405,1.6640,2.0660,2.5645,3.1840,3.9530,4.9075,6.0925,7.5635,
/TIMESWIDTH(ms)=0.0250,0.0310,0.0380,0.0480,0.0590,0.0740,0.0920,0.1130,0.1410,0.1750,0.2170,0.2700,0.3350,0.4160,0.5160,0.6410,0.7960,0.9880,1.2270,1.5230,1.
EAST NORTH LEVEL ELEV STATION COMPONENT GAIN NSTACKS CURRENT DELAY NOISE CHI
2650.000 4400.000 0.000 0.000 4400.000 Z 20.000 32.000 28.000 0.040 7.050708e-02 9.308700
2650.000 4400.000 0.000 0.000 4400.000 X 20.000 32.000 28.000 0.040 2.243731e-01 -6.474900
2650.000 4400.000 0.000 0.000 4400.000 Y 20.000 32.000 28.000 0.040 6.345461e-02 -4.101300
2650.000 4600.000 0.000 0.000 4600.000 Z 20.000 32.000 28.000 0.040 6.982963e-02 12.484000
2650.000 4600.000 0.000 0.000 4600.000 X 20.000 32.000 28.000 0.040 1.541877e-01 -10.468000
2650.000 4600.000 0.000 0.000 4600.000 Y 20.000 32.000 28.000 0.040 7.252344e-02 -7.621500
2650.000 4800.000 0.000 0.000 4800.000 Z 20.000 32.000 28.000 0.040 2.624838e-01 17.323000
2650.000 4800.000 0.000 0.000 4800.000 X 20.000 32.000 28.000 0.040 5.768154e-02 -2.631100
2650.000 4800.000 0.000 0.000 4800.000 Y 20.000 32.000 28.000 0.040 2.496894e-01 -4.135500
-----
```

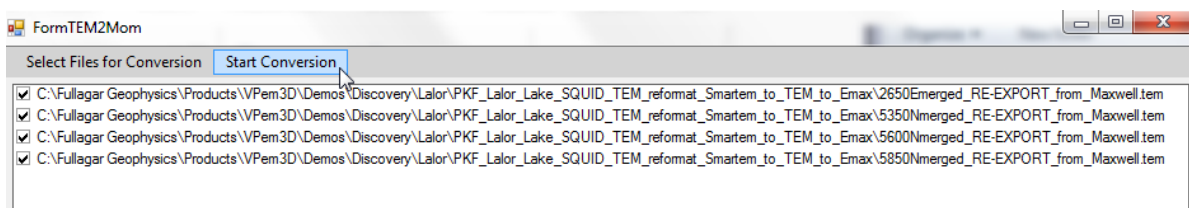
First few lines of a fixed loop TEM file generated by Maxwell. Tx loop vertices (LVnX, LVnY, LVnZ) are included in the header.



Accessing the data conversion programs under the VPview *Data* menu.



Select TEM2Mom for conversion of ground TEM data.



Select TEM files to be processed, and launch TEM2Mom.

Note that TEM2Mom will include all the TEM channels in the integration when computing the resistive limits. This is not desirable if the decay degenerates into noise at late times. Channel range can be controlled via VPview, as described in Section 5.2.

/RXX	RXY	RXZ	RLX	RLY	RLZ	LX1
LINE 2650	Emerged_RE-EXPORT_from_Maxwell					
2650.000	4400.000	0.000	-42.007508	-18.607364	96.414886	3060.000
2650.000	4600.000	0.000	-46.588278	-20.161316	105.928131	3060.000
2650.000	4800.000	0.000	-57.081968	-7.067485	118.994922	3060.000
2650.000	5000.000	0.000	-46.119928	-5.251457	132.924657	3060.000
2650.000	5200.000	0.000	-30.778636	-14.385764	141.096918	3060.000
2650.000	5400.000	0.000	-16.099575	-15.336972	158.385442	3060.000
2650.000	5600.000	0.000	-12.051035	-25.397266	173.616447	3060.000
2650.000	5800.000	0.000	0.485558	-24.539042	200.013863	3060.000
2650.000	5900.000	0.000	15.079994	-36.870351	212.113514	3060.000
2650.000	6000.000	0.000	39.577938	-42.664333	216.783955	3060.000
2650.000	6100.000	0.000	73.655603	-54.487060	201.096124	3060.000
2650.000	6200.000	0.000	80.197510	-72.826896	169.754661	3060.000
2650.000	6300.000	0.000	80.802562	-74.928008	141.744498	3060.000
2650.000	6400.000	0.000	80.494354	-60.934204	114.747733	3060.000
2650.000	6600.000	0.000	62.562604	-66.999431	83.543175	3060.000
2650.000	6800.000	0.000	49.731643	-56.002449	73.806536	3060.000
2650.000	7000.000	0.000	39.776864	-49.687555	55.863636	3060.000

The first 7 columns in the resistive limits (“TEM moments”) file produced by TEM2Mom for line 2650E. RXX, RXY, RXZ are the receiver coordinates. In this case the receiver elevations were subsequently changed to 300m, consistent with the assumed elevation of the ground surface.

The LXn, LYn, LZn values in columns 7 – 18 are the coordinates of the nth vertex of the Tx loop. The Tx loops are treated as rectangular here; TEM2Mom defines the best-fitting rectangle. However, arbitrary Tx loops can be handled; see Section 7.2 above.

RLX, RLY, RLZ are resistive limit components in pTms/A. **Care is required interpreting the horizontal components.** By convention, the along-line component is deemed the x-component by most contractors during acquisition. However, in VPem3D the x-component is the east component. Therefore, for a north-south survey line, contractor’s x-component is the VPem3D y-component, and contractor’s y-component is the VPem3D x-component (with polarity reversed, assuming a right-handed coordinate system). Clearly, it is important to establish what naming and polarity conventions have been adopted by the contractor.

This sample data set comprises 3 east-west lines and 1 north-south line, 2650E; east, west, north, and south refer to the VPem3D model coordinate system which in this case is rotated from the Earth system. In order to create a single data file for all four lines, it is necessary to edit the moment data for 2650E:

5. Re-label column 4 as “RLY”.
6. Re-label column 5 as “RLX”.
7. Multiply the data in column 5 by -1.
8. Transpose columns 4 and 5, so that column 4 contains the new RLX data and column 5 contains the new RLY data.

After these edits, the component labels and polarity will be consistent for all 4 survey lines. The edited data file for 2650E is shown below:

/RXX	RXY	RXZ	RLX	RLY	RLZ	LX1
LINE	2650	Emerged_RE-EXPORT_from_Maxwell				
2650	4400	0	18.607364	-42.007508	96.414886	3060
2650	4600	0	20.161316	-46.588278	105.928131	3060
2650	4800	0	7.067485	-57.081968	118.994922	3060
2650	5000	0	5.251457	-46.119928	132.924657	3060
2650	5200	0	14.385764	-30.778636	141.096918	3060
2650	5400	0	15.336972	-16.099575	158.385442	3060
2650	5600	0	25.397266	-12.051035	173.616447	3060
2650	5800	0	24.539042	0.485558	200.013863	3060
2650	5900	0	36.870351	15.079994	212.113514	3060
2650	6000	0	42.664333	39.577938	216.783955	3060
2650	6100	0	54.487060	73.655603	201.096124	3060
2650	6200	0	72.826896	80.197510	169.754661	3060
2650	6300	0	74.928008	80.802562	141.744498	3060
2650	6400	0	60.934204	80.494354	114.747733	3060
2650	6600	0	66.999431	62.562604	83.543175	3060
2650	6800	0	56.002449	49.731643	73.806536	3060
2650	7000	0	49.687555	39.776864	55.863636	3060

Although 3-component SQUID data were recorded, the transverse (contractor y-component) data were noisy. Therefore only two components were inverted, namely the vertical component, RLZ, and the east component, RLX. [The east component constitutes the along-line component for the 3 east-west lines, but the transverse component for the north-south line, 2650E.] The VPem3D PAR file for the two component (east and vertical) inversion is shown below. Note that there are two active channels [-2 on record 4] and that there is no reference to column 5 [line with "5 RLY" has been deleted].

```
#VPEM#
TEM2Mom_2015-07-10_0.mom
19
-2
4 RLX
6 RLZ
7 LX1
8 LX2
9 LX3
10 LX4
11 LY1
12 LY2
13 LY3
14 LY4
15 LZ1
16 LZ2
17 LZ3
18 LZ4
19 STN
```

14.3 Create a starting model (no DTM grid available)

When no DTM grid is available, VPview creates a model with a horizontal upper surface. The *Create New Model* utility needs to know the model extents and cell sizes. The model extents can be derived from a dummy data file defining the corners of the model area. A 3 or 4 line dummy data file will suffice, with records of the form shown below:

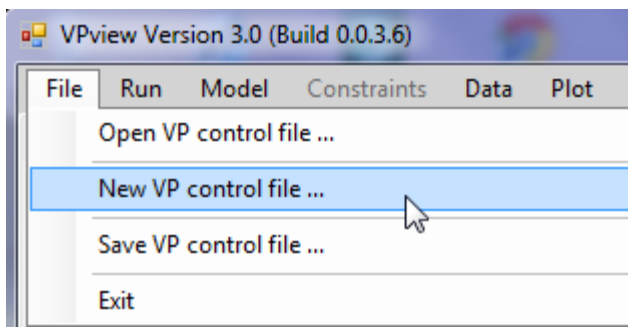
```
EAST NORTH RL DATA
XMIN, YMIN, RL1, DATA1
XMAX, YMIN, RL2, DATA2
XMAX, YMAX, RL3, DATA3
```

The procedure for model construction when no DTM grid is available is the same for ground TEM as for airborne TEM. In this case the ground surface was assumed perfectly flat, at an elevation of 300m. Therefore refer to Section 12.4 above.

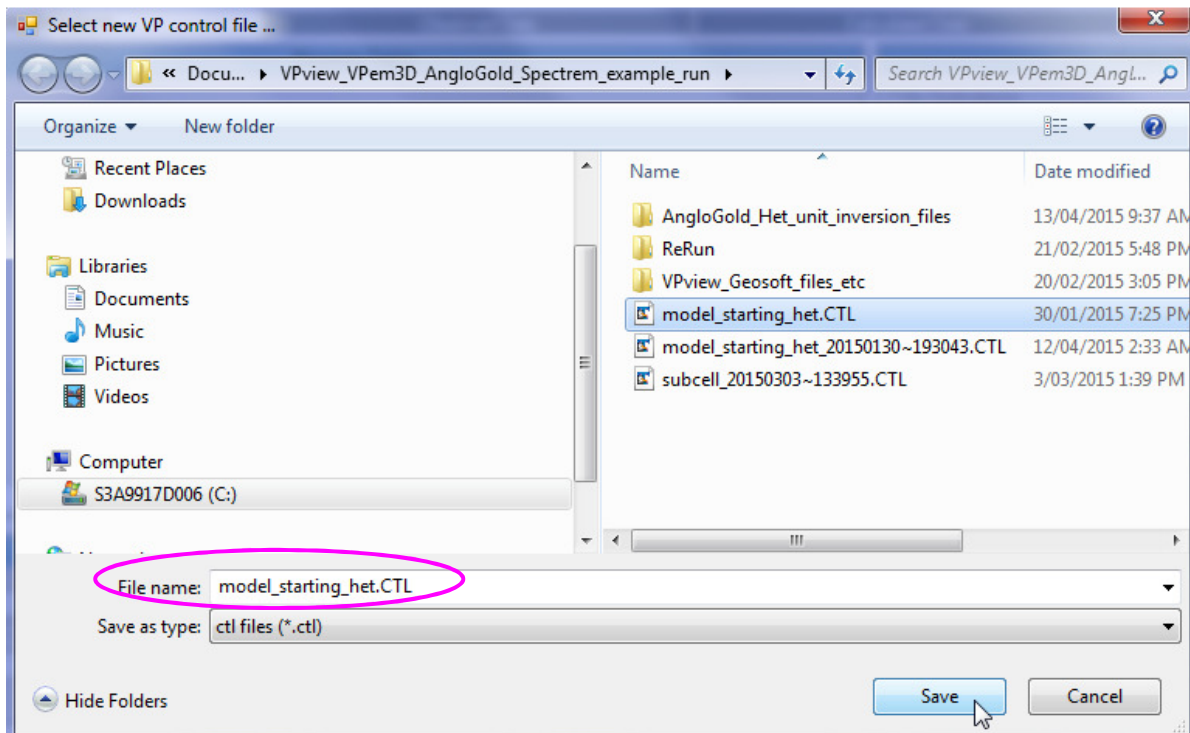
The east-west ground TEM survey lines were 250m apart, with readings every 100m. Therefore, the model prisms dimensions were set as 100m E-W by 250m N-S. The model resolution is therefore too coarse to resolve 100m-spaced data along the north-south line, 2650E. However, the station spacing is actually 200m for most of line 2650E.

14.4 Create a control file

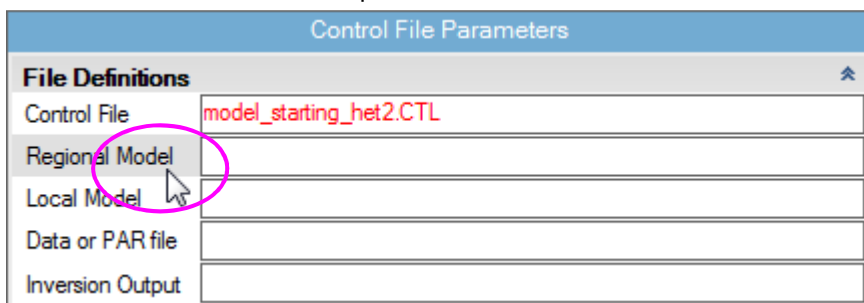
A control file is required in order to run VPem3D. If the control file does not already exist, it can be created using the *New VP control file* utility under the File menu.



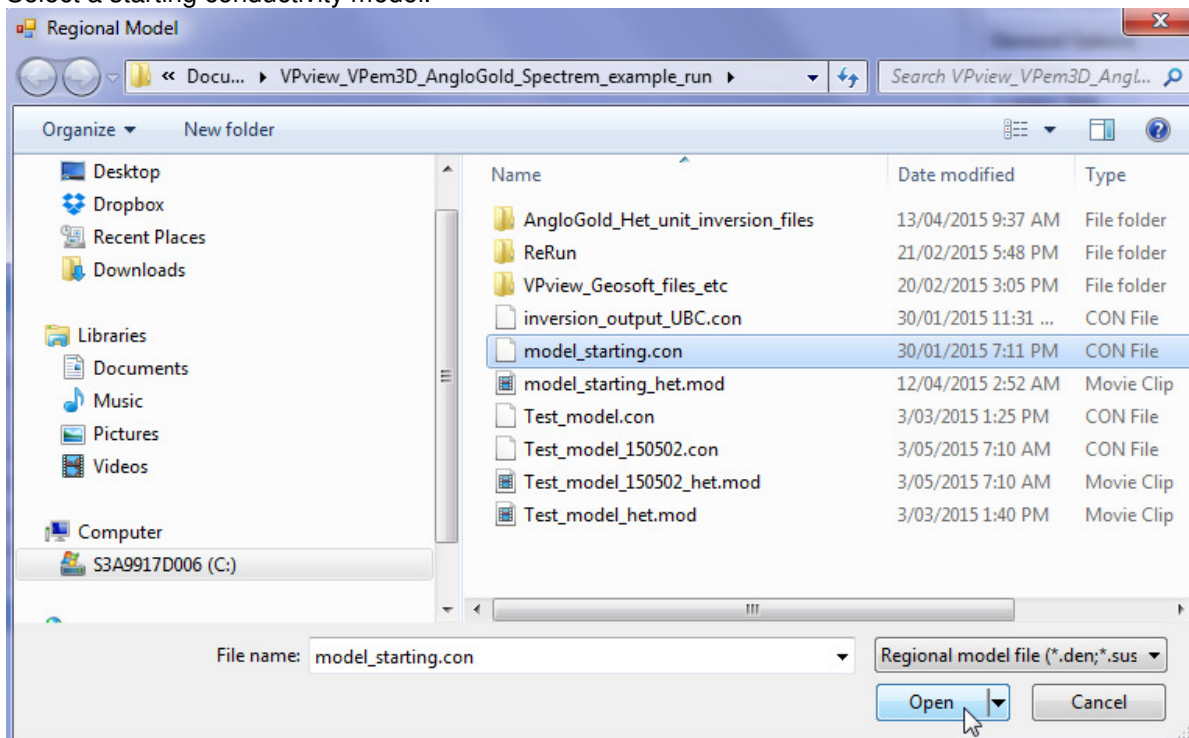
First select the project directory and choose a name for the control file. The control file has extension is CTL. In the illustration the control file already exists.



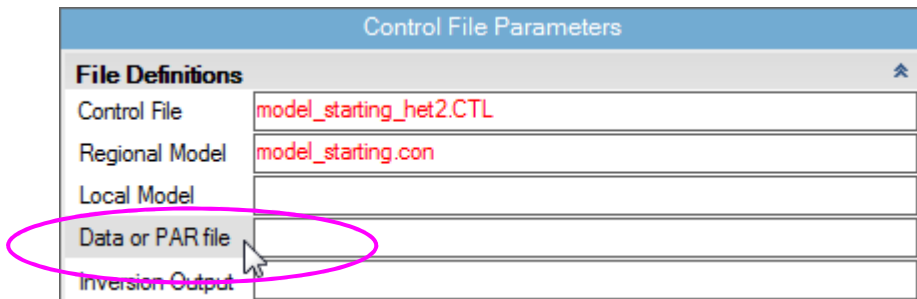
Click on a model file label to open a browse window.



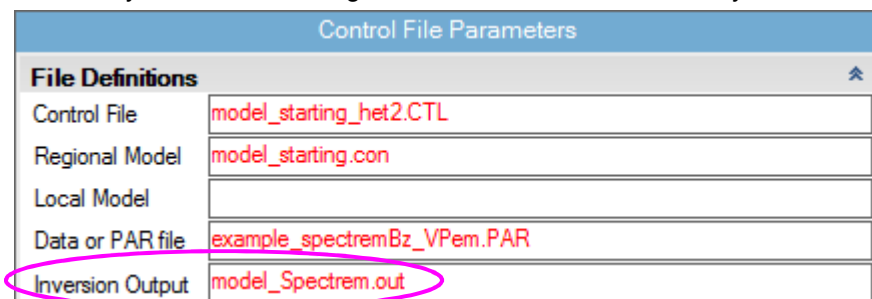
Select a starting conductivity model.





The starting model can be regarded as either regional or local. The text box for the other model can be left blank. Select a PAR file in the same fashion: click on the label to open a browse window.





The output model file will usually not already exist. Type in a name for the output file. The extension is arbitrary, but VPview recognises *.CON files as conductivity models.






Now define **General Options** settings. Use the drop down menu to select *Data Type*. TEM Moments (Linear) is the appropriate *Data Type* for most downhole TEM inversion runs.

General Options	
Data Type	TEM Moments (Linear) 
Inversion Style	Defines the data type (igrav) 
Iterations	
Uncertainty	
Δ Property	



Use the drop down menu to select *Inversion Style*. Compact body inversion, which is a form of heterogeneous inversion, is selected here.

General Attributes	
Data Type (TEM)	TEM Moments (Linear) 
Inversion Style	Heterogeneous Property (compact body) 
Iterations	Basement only
Uncertainty	Homogeneous Property
Δ Property	Geometry Inversion
Advanced Optio	Heterogeneous Property
	Stochastic Heterogeneous
Field parameter	Stochastic Basement
	Heterogeneous Property (increase only)
	Heterogeneous Property (compact body)

Set *Iterations* to zero for an initial forward calculation.

General Attributes	
Data Type (TEM)	TEM Moments (Linear) 
Inversion Style	Heterogeneous Property (compact body) 
Iterations	0 
Uncertainty	
Δ Property	

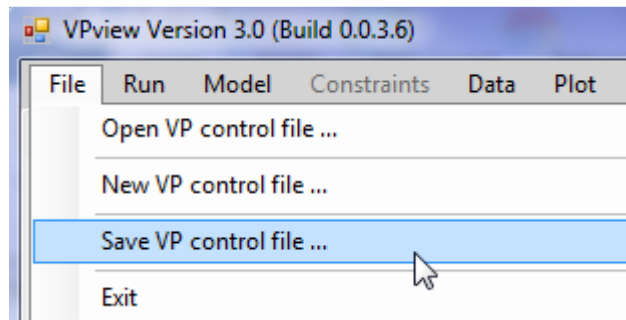
Define values for the *Uncertainty* (in pTms/A) and the Δ *Property* (maximum conductivity change per iteration, in mS/m). Δ *Property* is normally set very high for compact body inversion.

General Attributes	
Data Type (TEM)	TEM Moments (Linear) 
Inversion Style	Heterogeneous Property (compact body) 
Iterations	1
Uncertainty	10
Δ Property	500000

In the **Advanced Options**, use the drop down menus to choose *Downhole Data* and *DC Level* settings. *Downhole Data* is “No” for ground TEM data. For regional models, -101 is normally the appropriate setting for *DC Level*. This fixes the *DC Level*, which is added to all calculated data, to the value recorded at the end of the regional model file; it is almost always zero for ground TEM. [The normal *DC Level* setting for local models is -102, to fix the *DC Level* to the value recorded at the end of the local model file.] The *Body Adjust* box can be left blank.

Advanced Options	
Downhole Data	No
SAM Data	No
DC Level	From regional model, retain cells (-101)
Self Demag	
Body Adjust	
User ROI	

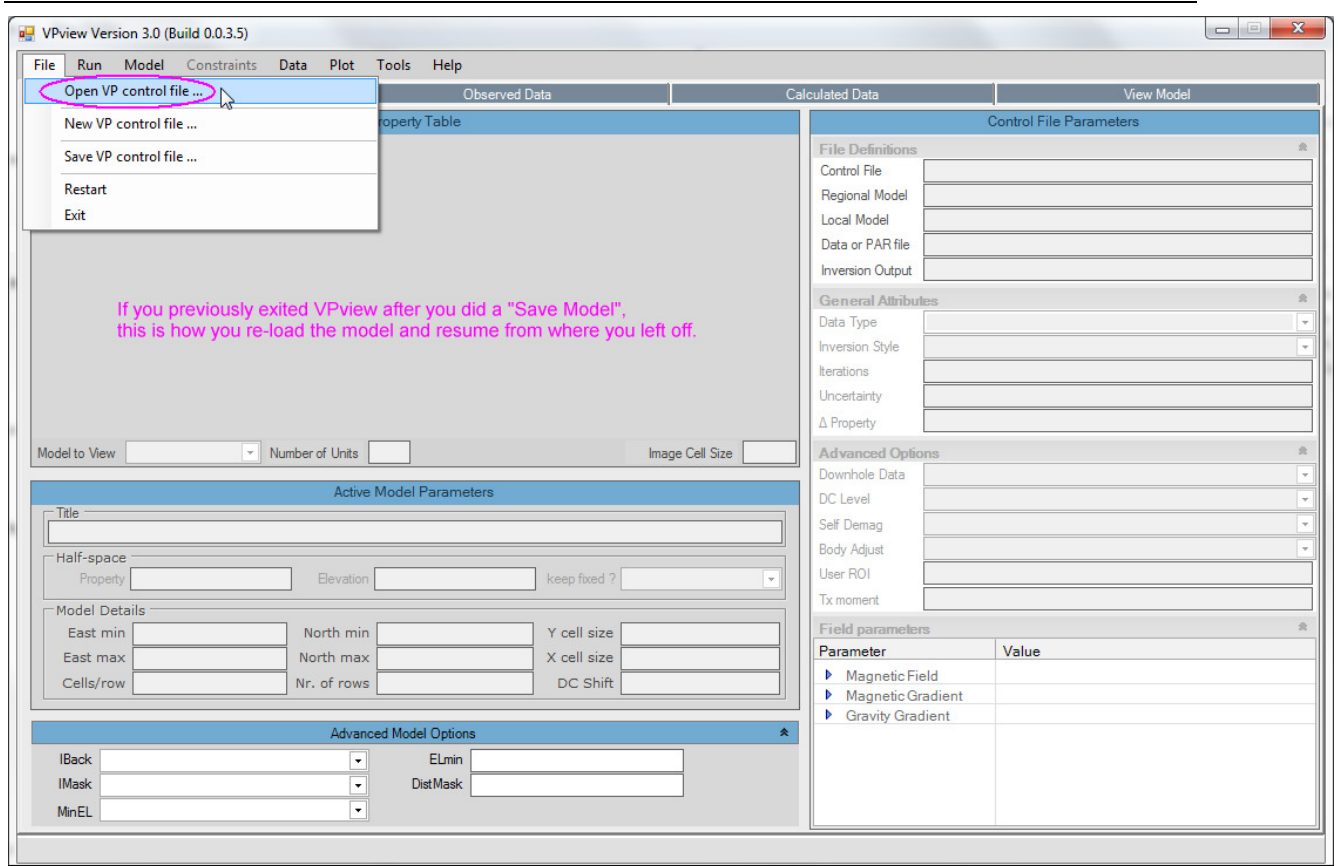
When all fields have been populated, save the new control file using the option under *File*.



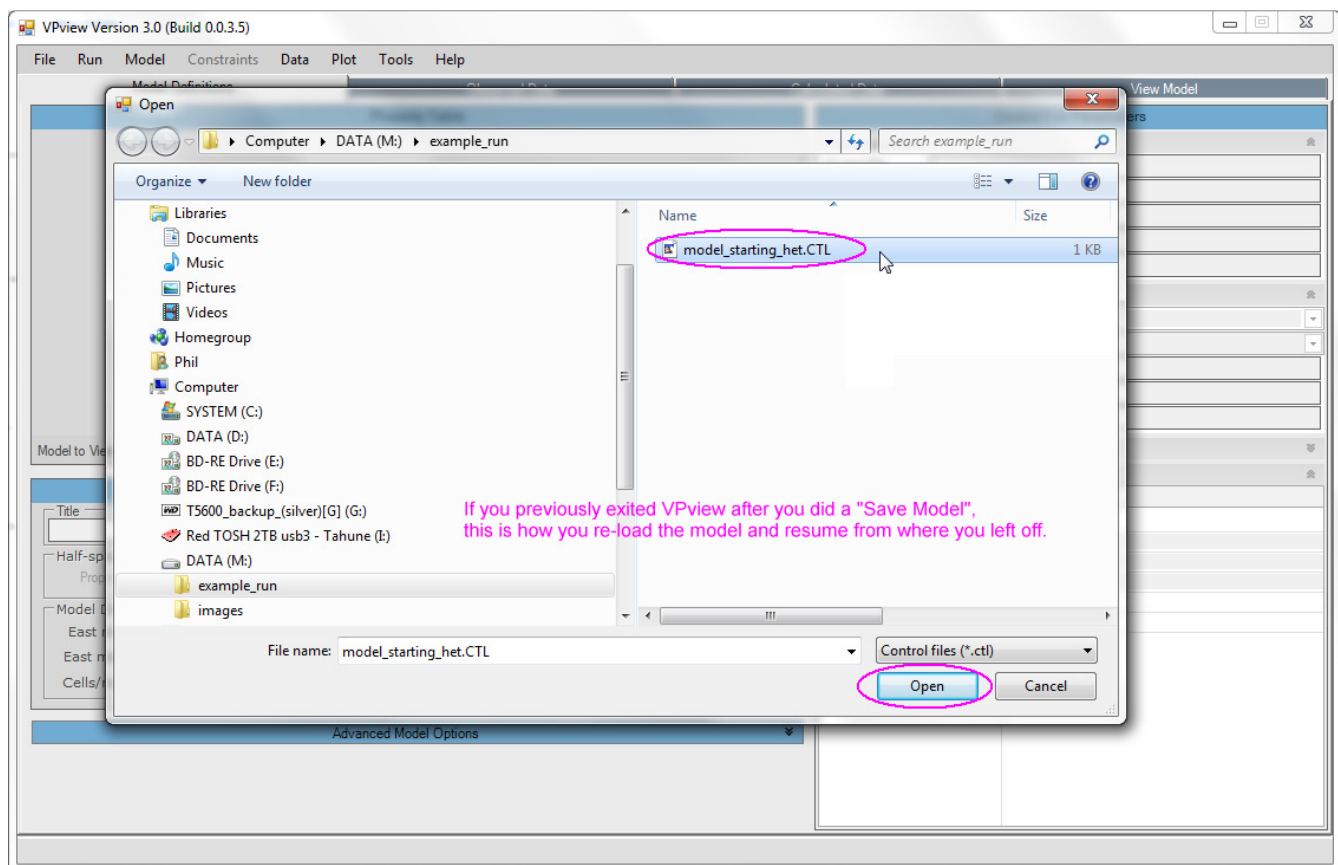
14.5 Performing a forward calculation

Before launching an inversion it is always desirable to run a forward calculation, in order to examine the starting model, check loop geometry and data locations, and assess the initial fit between observed and calculated data.

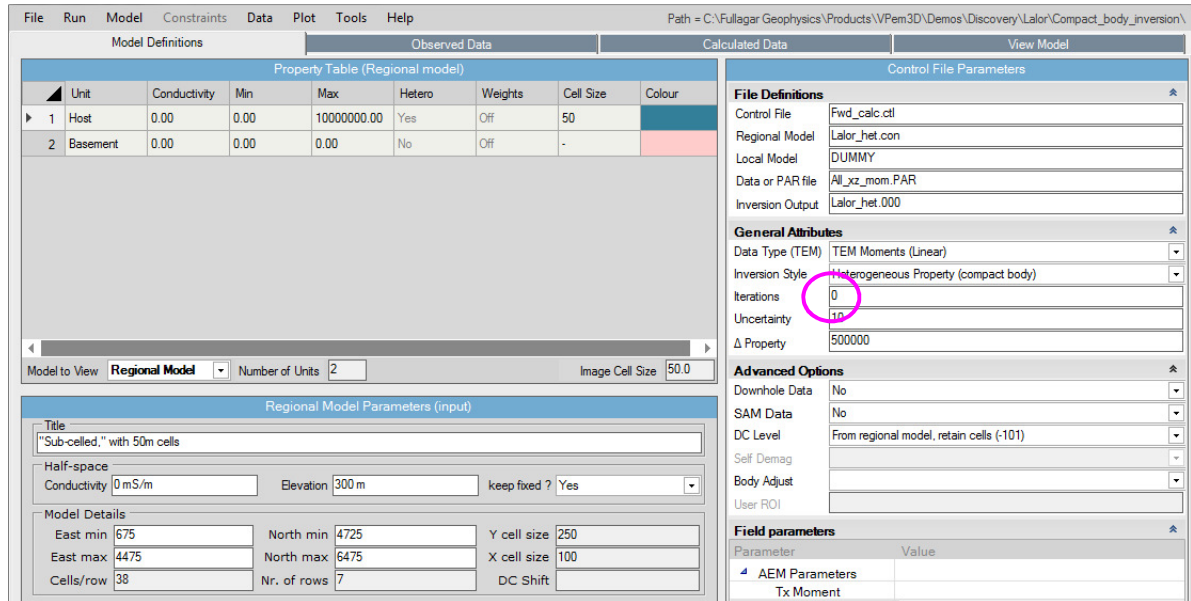
If you had exited, start VPview again and select the "Open VP control file" option under the *File* menu.



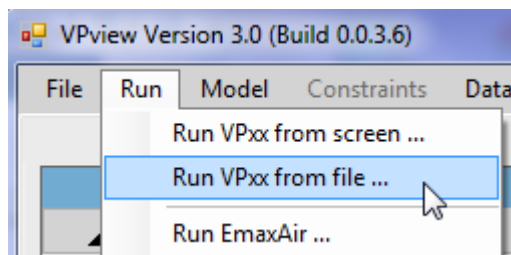
Choose the desired VP control file.



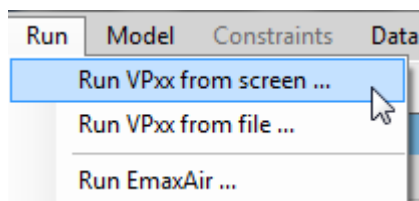
VPview displays the model file header information and control file settings. Cells in the Host unit are 100m E-W x 250m N-S x 50m vertically.



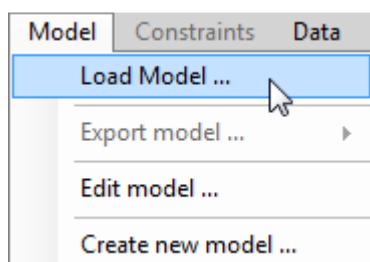
If the saved model parameter and control settings are all acceptable, launch VPem3D using the “Run VPxx from file” option under the *Run* menu. Iterations should be zero for a forward calculation.



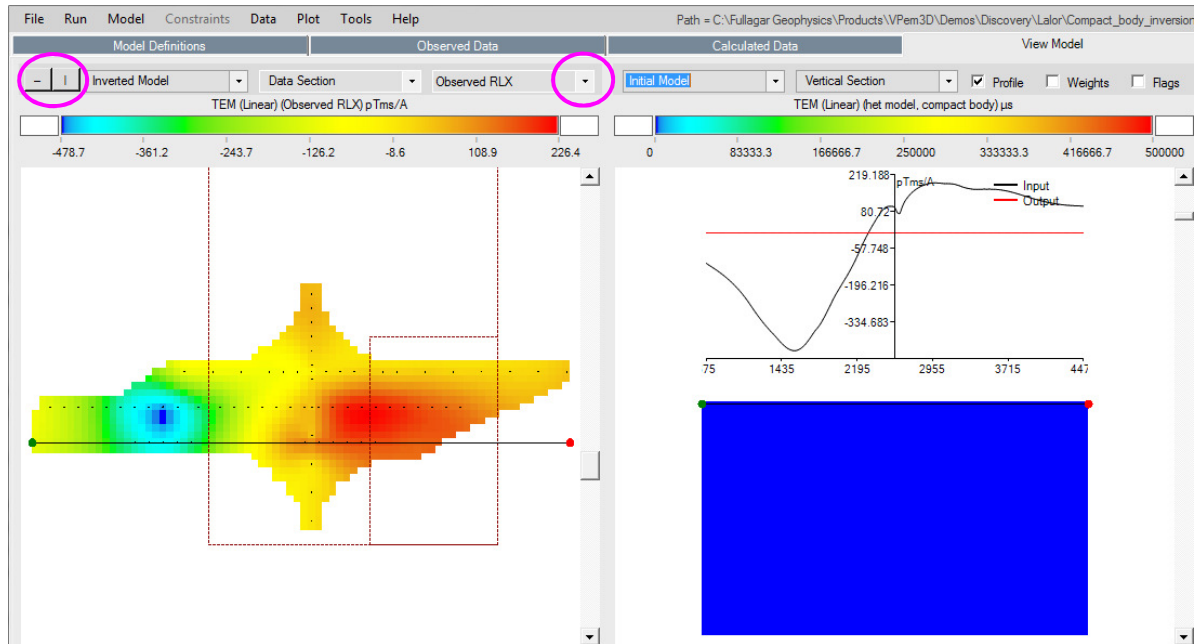
If some of the settings have been edited, but not saved, launch VPem3D using the “Run VPxx from screen” option.



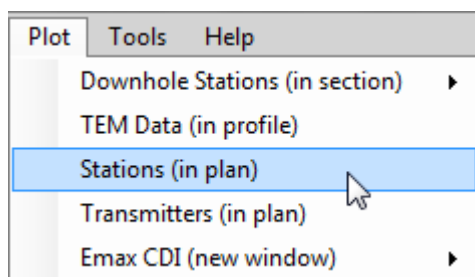
After the forward calculation has completed, load the model and data using the *Load Model* option under the *Model* menu, as shown.



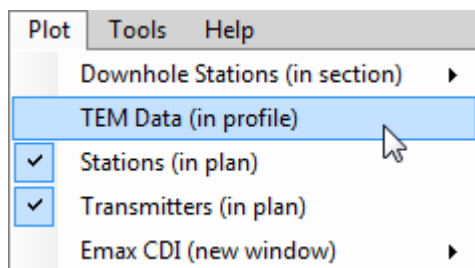
When the model first loads, the ground topography is displayed in the left panel; different quantities can be selected for display from the drop down menu above the LH panel. The observed east resistive limit component (RLX) is displayed below. The black line on the LH panel shows the position of the vertical section through the model which is displayed in the right hand panel. Its position can be adjusted using the scroll bar beside the LH panel. Toggle buttons in the top LH corner of the VPview window switch the display line from E-W to N-S orientation. Oblique sections can be displayed by clicking and dragging the red and green knobs at either end of the section line. The observed (black) and calculated (red) data are plotted above the model section at right when the *Profile* box is checked. Note that VPview interpolates data over the entire model area; therefore the profiles should be interpreted with caution.



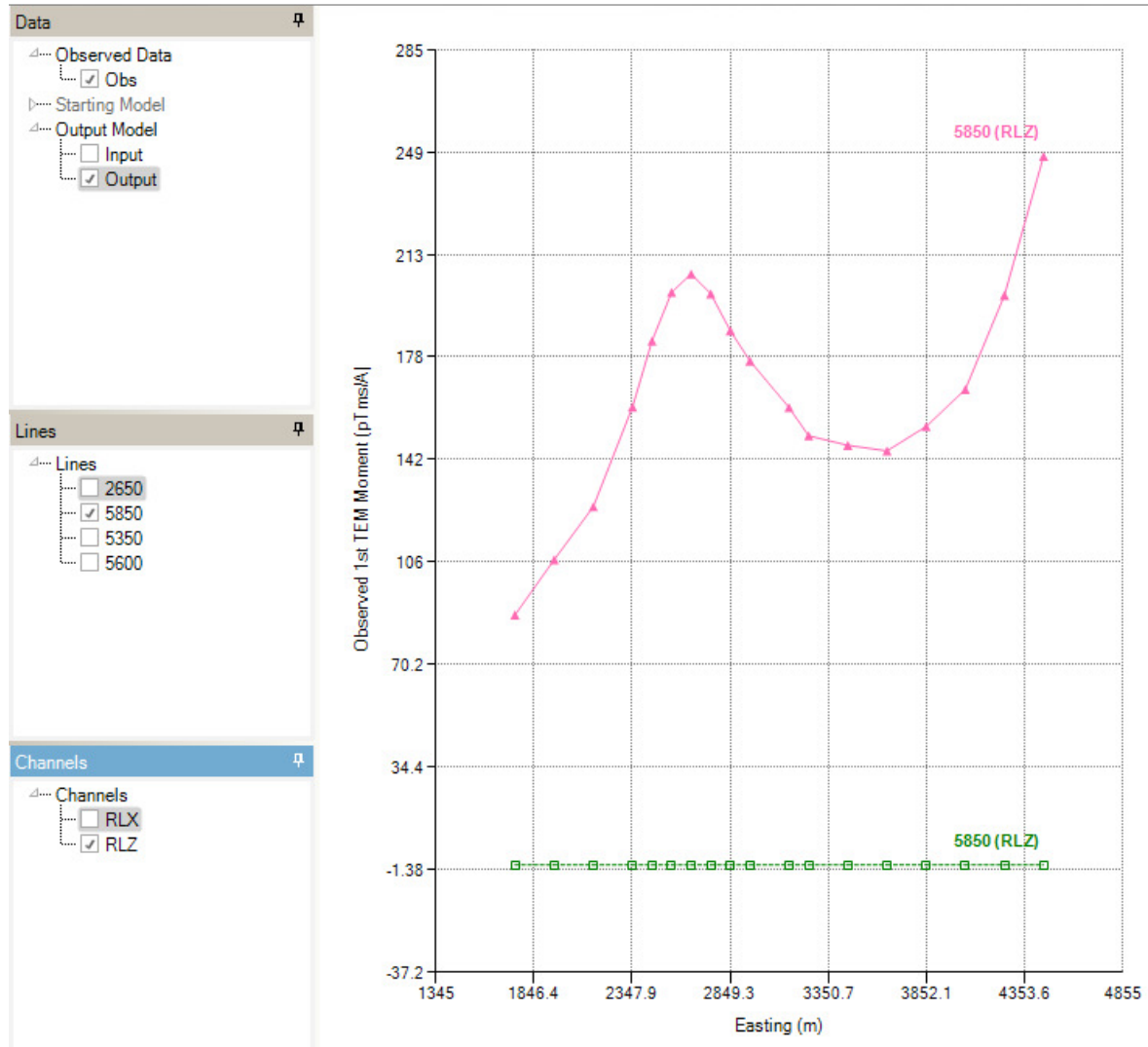
The black dots on the LH panel mark receiver locations; these are displayed using the *Stations (in plan)* option under the *Plot* menu. The red dashed lines trace the Tx loops; these are displayed using the *Transmitters (in plan)* option.



The resistive limit components can be plotted in profile in a separate window.



The user can compare observed and calculated (“Output”) data for each Line and both resistive limit components (RLX, RLZ). Here RLZ profiles are plotted for Line 5850N. The calculated values are zero for the starting model (zero conductivity everywhere)



14.6 Running a ground TEM inversion

Compact inversion usually involves 3 stages:

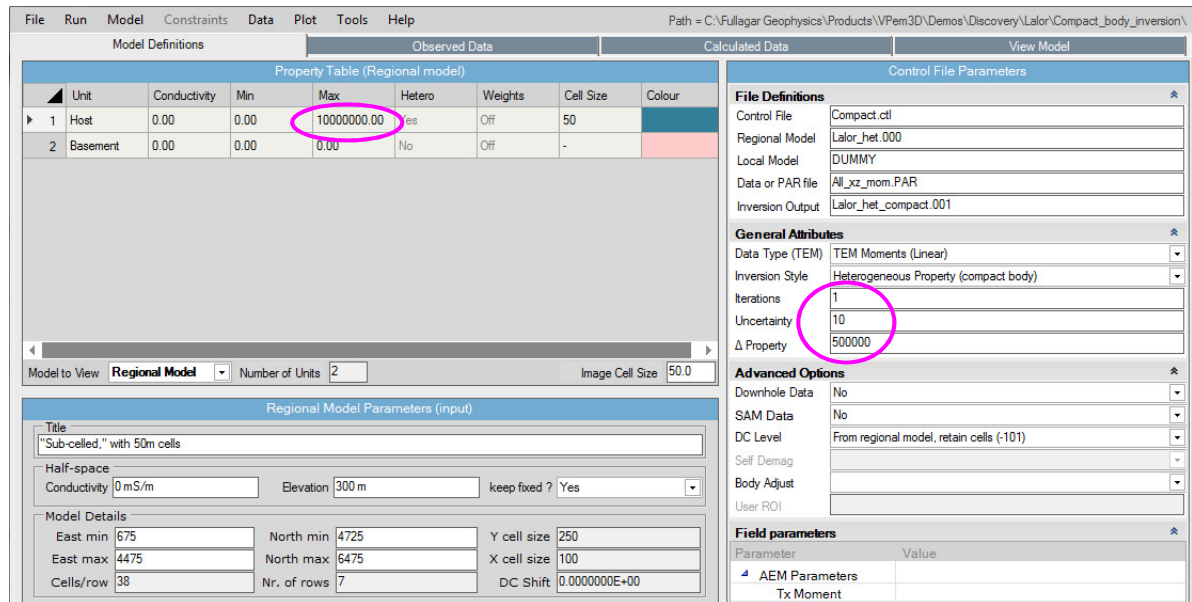
- An initial delineation of a volume of interest
- Editing of the volume of interest
- Homogeneous unit inversion &/or heterogeneous unit inversion of the edited volume.

Once satisfied with the forward calculation, prepare to run a first inversion to define the volume of interest:

- the output model from the forward calculation becomes the input model for inversion; this obviates the need to re-run the forward calculation since the calculated data are recorded at the end of the model file.
- specify the number of iterations to perform; sometimes a single iteration of compact body inversion is sufficient to define a volume of interest.
- set the uncertainty level in the data (pTms/A)

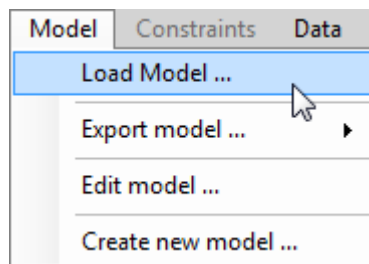
- set the maximum permitted change in property value per iteration (mS/m) to a very large for compact body inversion; here it is 5×10^5 mS/m.
- the maximum conductivity (upper bound) should be extremely large in the active unit for compact body inversion; here it is 10^7 mS/m.

If any fields in the control file have been edited, select “Run VPxx from screen” to start the VPem3D inversion. Otherwise, launch VPem3D via “Run VPxx from file” to use the parameters saved in the *.CTL file.

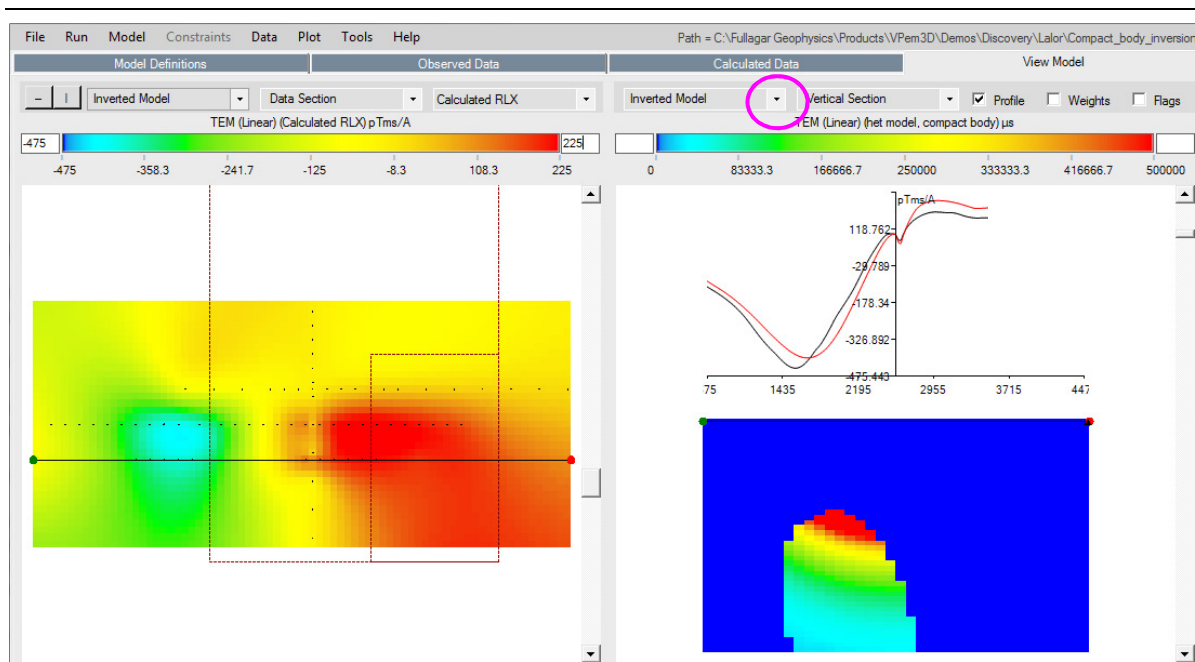


Details of the inversion, including data misfit, are displayed in a command window and recorded in a LOG file. The LOG file has the same name as the Inversion Output file, with extension .LOG.

After inversion has completed, read the model and data into VPview using the *Load Model* option under the Model menu.



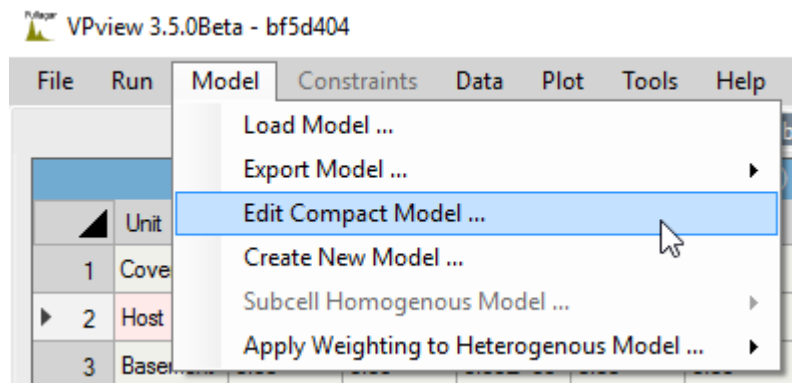
When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the inverted model is displayed in the right panel. The user can toggle between section views of the starting (Initial) and output (Inverted) models using the drop-down menu above the RH panel. The black line in the LH panel shows the position of the vertical section; it can be adjusted using the scroll bar, just right of the image. Toggle buttons in the top LH corner of the VPview window switch the display line from E-W to N-S orientation. Oblique sections can be displayed by clicking and dragging the red and green knobs at either end of the section line.



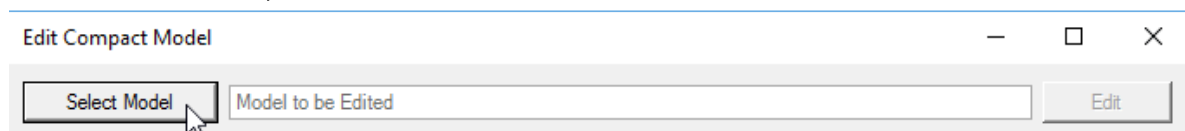
The compact inversion has defined what looks like an intrusive, with conductivity decreasing markedly with depth. Depending on the context and objectives, the user may wish to edit this conductive volume, e.g. to focus attention on the highly conductive, uppermost part. An utility is available under the Model for some simple editing operations.

The volume preserved by the editing program can be restricted by conductivity, easting, northing, depth, and thickness. In this example only the cells with conductivity $> 4 \times 10^5$ mS/m were retained.

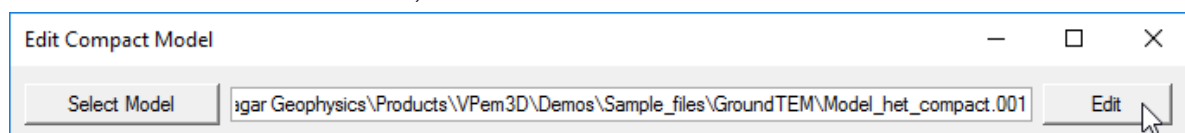
First, select the Edit Compact Model option.



Click on Select Model, and browse for the model file to be edited.



Choose the model file to be edited, and click on Edit.



In this case a new model is created, consisting of two units: a zero conductivity host unit and a unit with uniform conductivity of $PMIN = 4 \times 10^5$ mS/m comprised of all cells in the inverted model which originally had conductivity $> 4 \times 10^5$ mS/m, All the subcell boundaries have been preserved. The edited model file has the same root name as the file presented to EDIT MODEL, but with extension .edt.

ca. C:\Windows\System32\cmd.exe

```

**** EDIT MODEL ****

Generate heterogeneous (sub-celled) output model? (Y/N)
y

Cells with property > PMIN are included in the compact body.

If PMIN < 0, property is zeroed ...
... outside volume of interest, ...
... unchanged inside volume of interest

PMIN can be defined in absolute terms ...
... or as a percentage of the maximum property.
If as percentage, write as value followed by %

Enter minimum acceptable property value, PMIN:
400000

Enter min,max Easting for new hmgs unit
-10000,10000

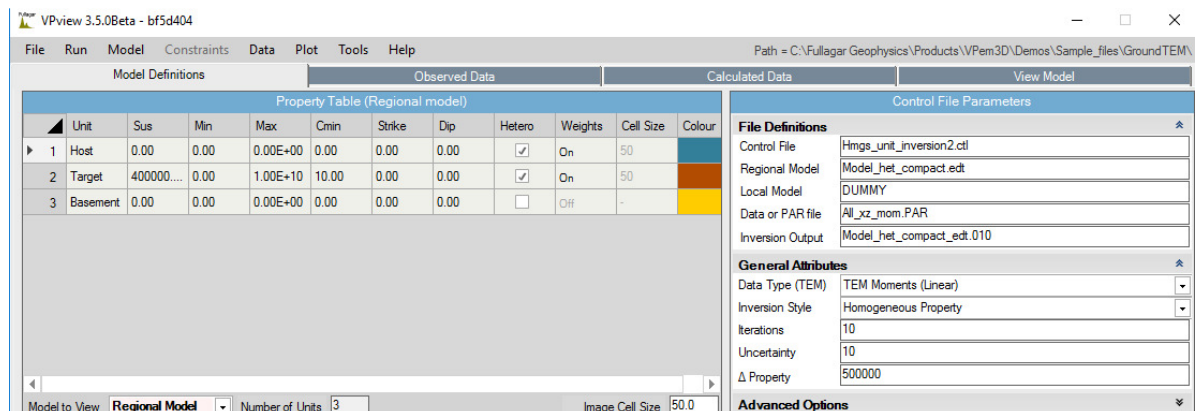
Enter min,max Northing for new hmgs unit
-10000,10000

Enter min,max Depth for inclusion in new hmgs unit
0,5000

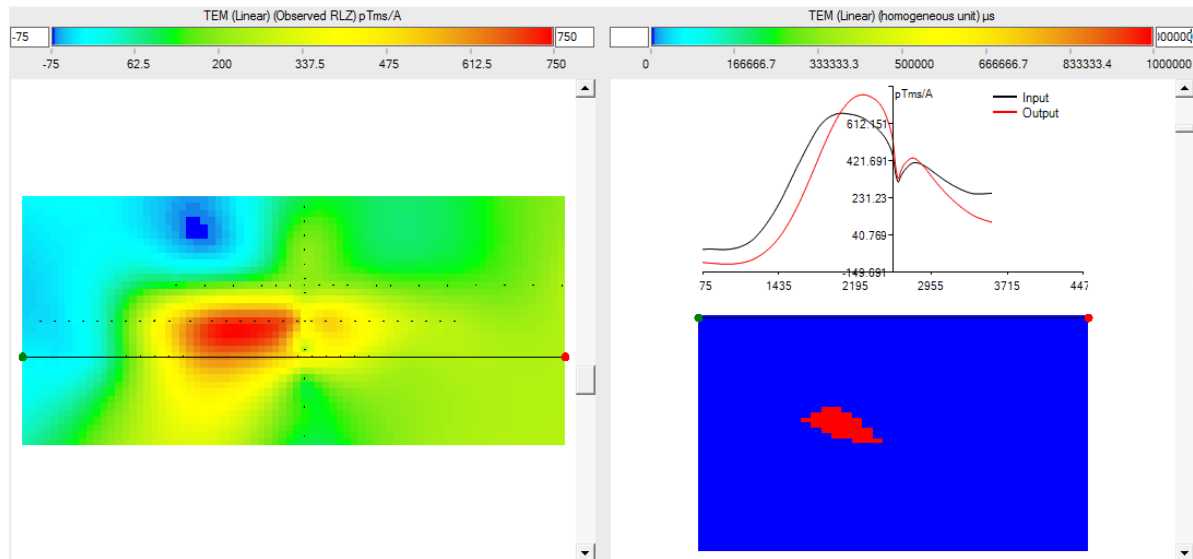
Enter maximum Thickness for the new hmgs unit
1000

```

After editing, the volume of the conductor is much smaller than the original conductive volume. Therefore a homogeneous unit inversion was run in order to optimise its conductivity, i.e. minimise the misfit the observed and calculated data.



A section through the edited and optimised model is shown below, with vertical component (RLZ) resistive limit profiles. The optimal conductivity was about 1000 S/m. This first-pass 3D conductivity model was generated in a total inversion time (for compact body inversion + editing + homogeneous inversion) of less than 10 seconds on a notebook PC. Additional inversions can now be performed, e.g. geometry inversion.



15 APPENDIX E: Create a starting model via 3D interpolation of CDIs

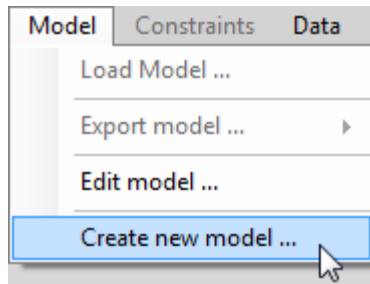
15.1 Introduction

VPem3D inversion of airborne and ground TEM is sometimes for 3D refinement of preliminary interpretations based on 1D inversions or CDIs. If 1D inversion has been performed using VPem1D, the inverted VPem1D model can serve as the starting model for VPem3D. When the preliminary interpretation is based on CDIs, a VPem3D starting model can be constructed by interpolating the CDI sections in 3D. [Such a model can also serve as the starting point for VPem1D inversion.]

Utilities are included in VPview to perform 3D interpolation of EmaxAIR CDIs. The construction of a 3D conductivity model from CDIs is illustrated in this Appendix.

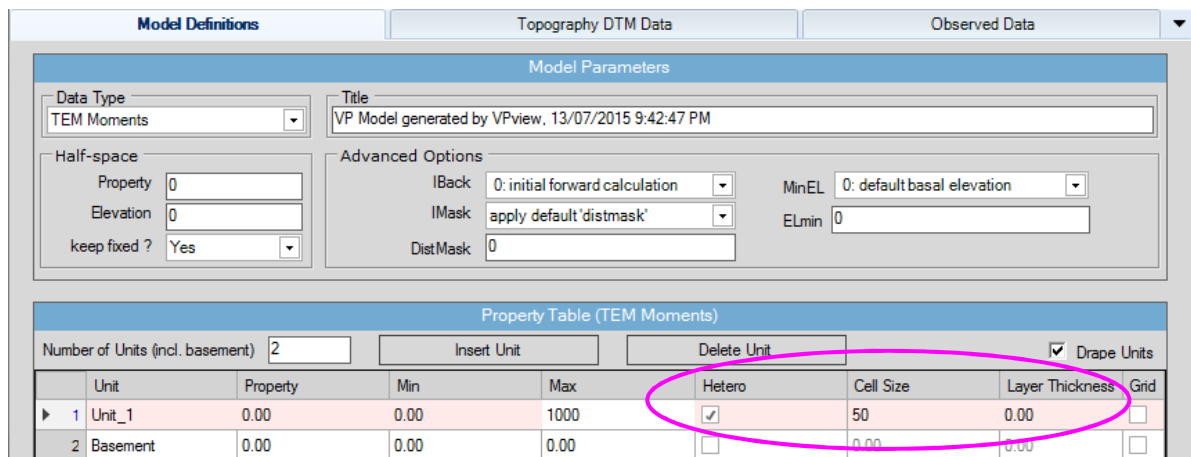
After construction of a starting model from CDIs or 1D inversions, it is usually desirable to apply calculated data normalisation (described in Section 2.17), in order to calibrate the VPem3D property (notionally time constant) against an independent conductivity. The application of calculated data normalisation is also illustrated in this section.

15.2 3D Interpolation of EmaxAIR CDIs



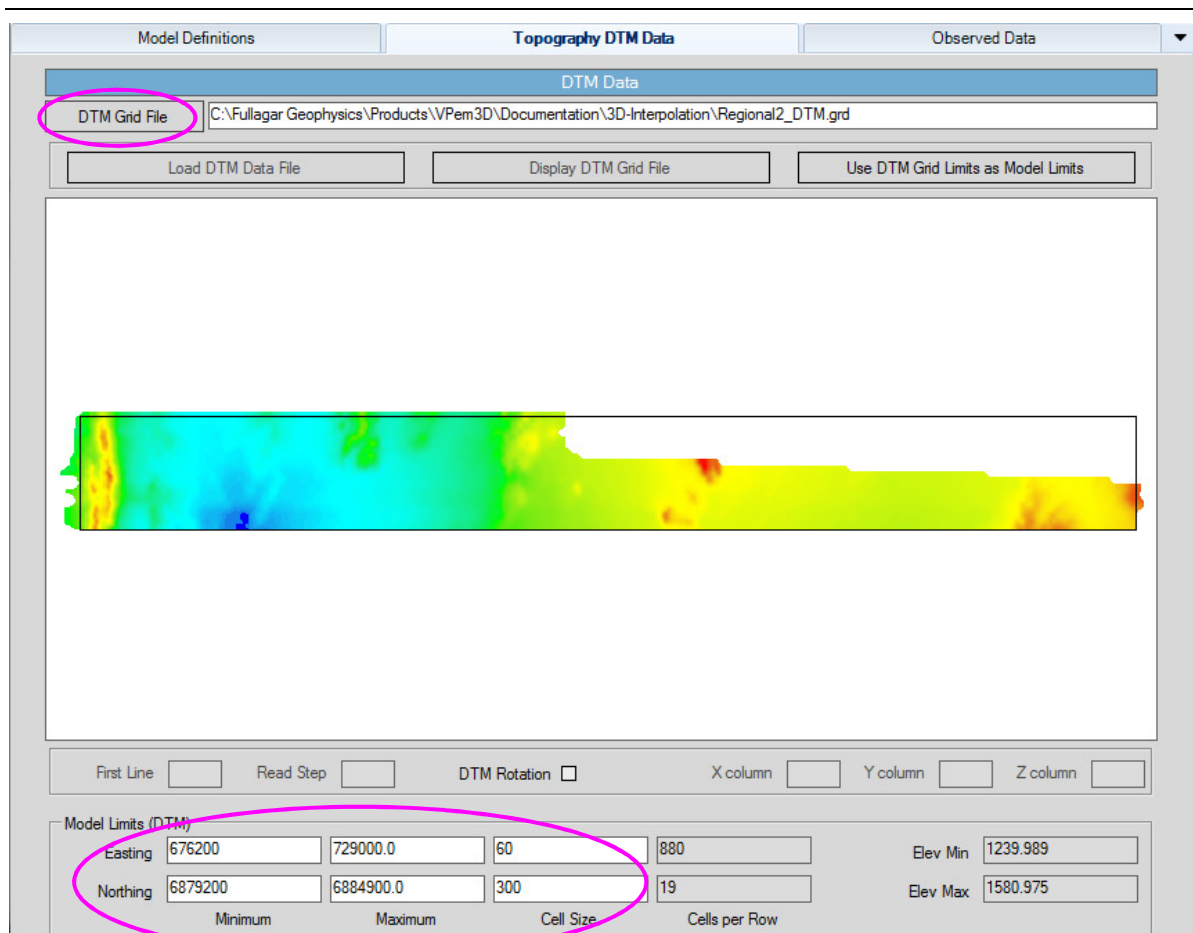
Select the *Create New Model* option from the Model menu.

On the *Model Definitions* form define a single layer (host unit) on a basement. Click on the *Hetero* check box, and define the desired vertical cell dimension (*Cell Size*). The *Layer Thickness* can be left as zero initially.

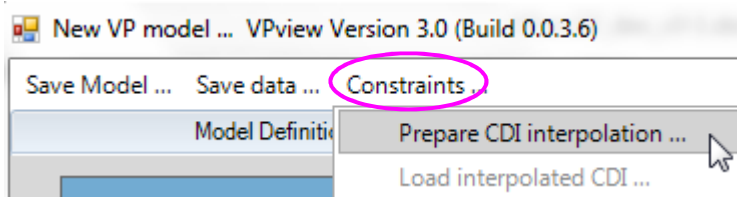
A screenshot of the 'Model Definitions' form. The 'Model Parameters' section includes 'Data Type' (TEM Moments), 'Title' (VP Model generated by VPview, 13/07/2015 9:42:47 PM), 'Half-space' (Property: 0, Elevation: 0, keep fixed?: Yes), and 'Advanced Options' (IBack: 0: initial forward calculation, IMask: apply default 'distmask', DistMask: 0, MinEL: 0: default basal elevation, ELmin: 0). The 'Property Table (TEM Moments)' section shows a table with 2 units. The first unit, 'Unit_1', has a 'Hetero' checkbox checked, a 'Cell Size' of 50, and a 'Layer Thickness' of 0.00. The second unit, 'Basement', has a 'Hetero' checkbox unchecked, a 'Cell Size' of 0.00, and a 'Layer Thickness' of 0.00. A pink oval highlights the 'Hetero' checkbox and 'Cell Size' for 'Unit_1'.

Property Table (TEM Moments)								
Number of Units (incl. basement)		Insert Unit		Delete Unit		<input checked="" type="checkbox"/> Drape Units		
	Unit	Property	Min	Max	Hetero	Cell Size	Layer Thickness	Grid
▶ 1	Unit_1	0.00	0.00	1000	<input checked="" type="checkbox"/>	50	0.00	<input type="checkbox"/>
2	Basement	0.00	0.00	0.00	<input type="checkbox"/>	0.00	0.00	<input type="checkbox"/>

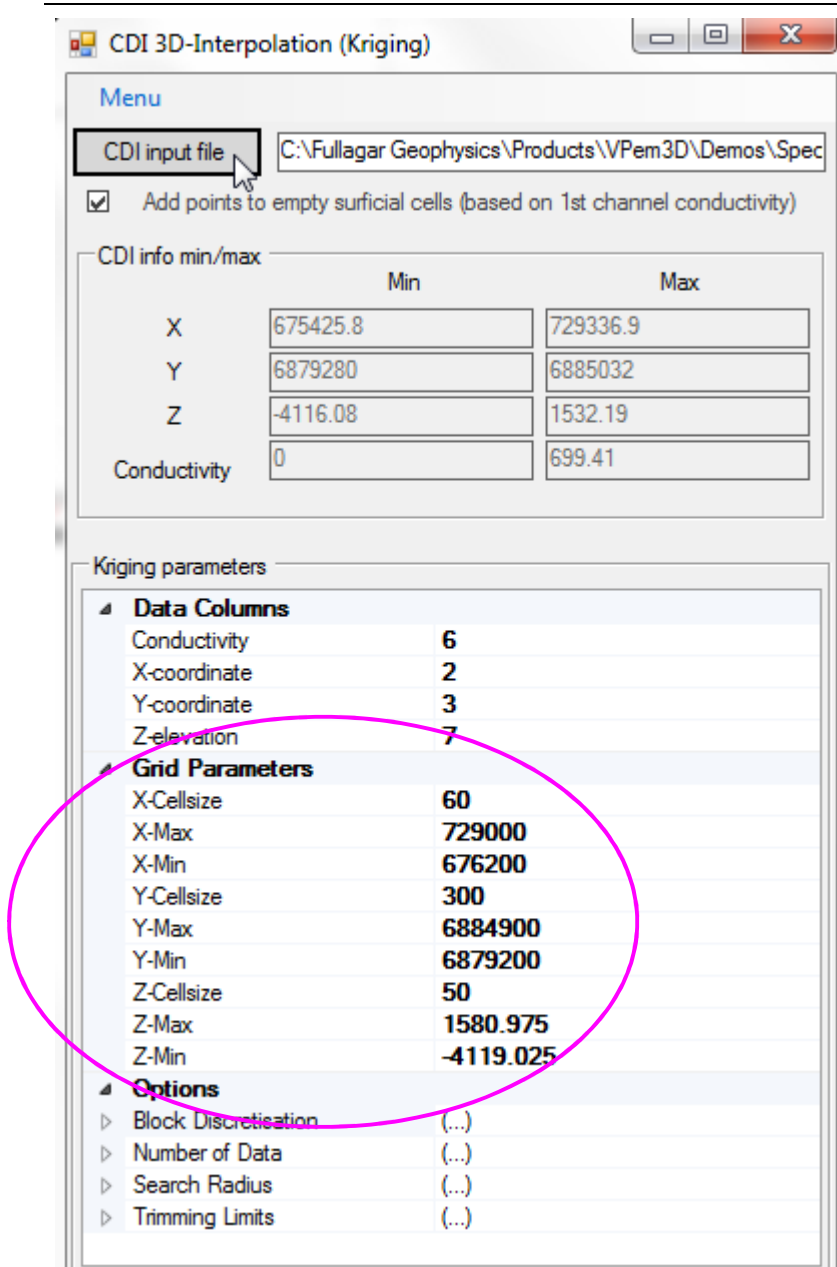
Select the *DTM Grid File* on the *Topography DTM Data* form. Edit the model limits and horizontal cell dimensions (east and north *Cell Size* values). The easting and northing extents must be exact multiples of the corresponding cell sizes.



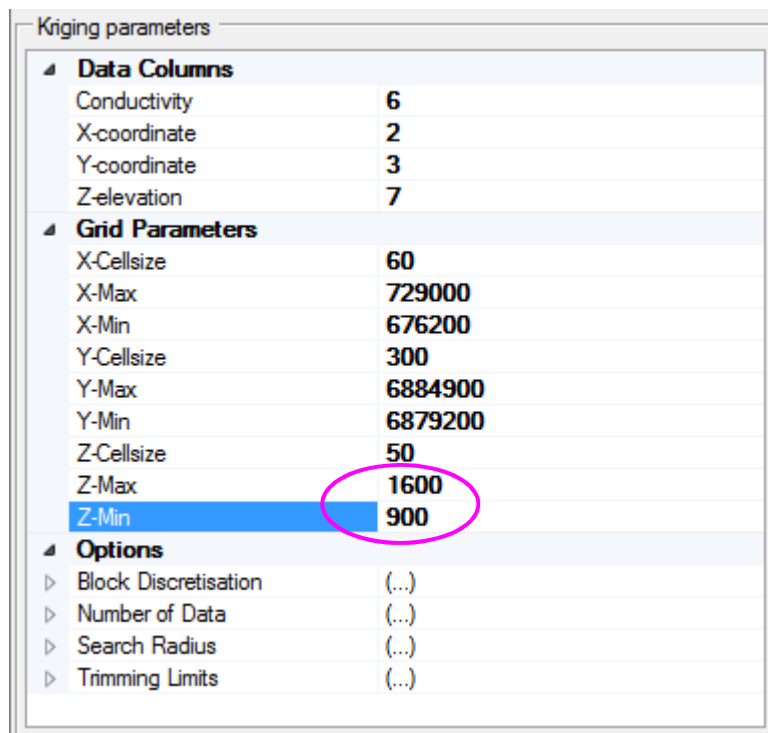
Now select the *Prepare CDI interpolation* option under the *Constraints* menu. The depths should increase monotonically with delay time; any “depth reversals” should be edited from the CDI file.



Select the EmaxAIR CDI input file; it usually has extension CDI. The model extents and prism dimensions (*Cellsize* values) are automatically passed from the *DTM Topography Data* form. The Z-Max value is the maximum elevation from the DTM file; the Z-Min value is the minimum elevation from the CDI file.



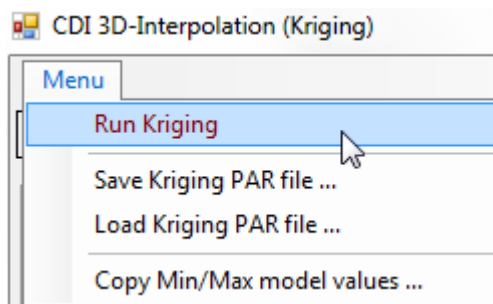
Define the vertical extent of the model grid. In particular, ensure that the Z-Min value is sensible; in this example the original Z-Min elevation is excessively low, i.e. well beyond the penetration of the TEM system. The Z-Min value defines the elevation of the base of the 3D model. The kriging is performed within a rectangular prism, defined by the X- and Y- model extents, and by the Z-Max and Z-Min values.



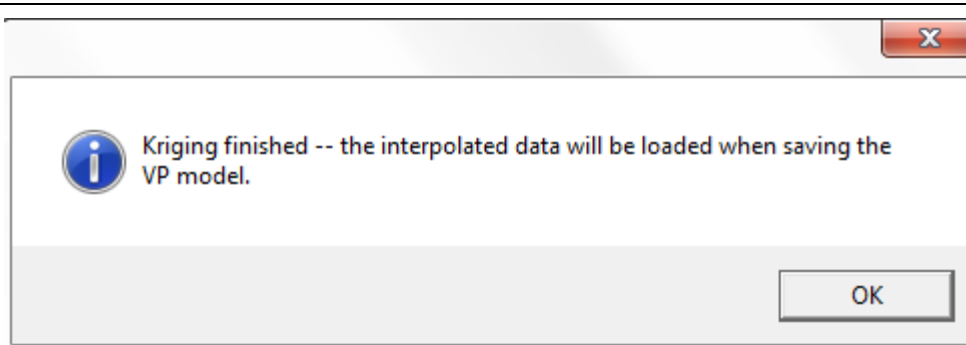
The basal elevation of the model (Z-Min value) is automatically transcribed to the Property Table on the Model Definitions form.

Property Table (TEM Moments (linear))								
Number of Units (incl. basement)		Insert Unit		Delete Unit		<input type="checkbox"/> Drape Units		
	Unit	Property	Min	Max	Hetero	Cell Size	Base Elevation	Grid
▶ 1	Unit_1	0.00	0.00	1000	<input checked="" type="checkbox"/>	50	900.00	<input type="checkbox"/>
2	Basement	0.00	0.00	0.00	<input type="checkbox"/>	0.00	0.00	<input type="checkbox"/>

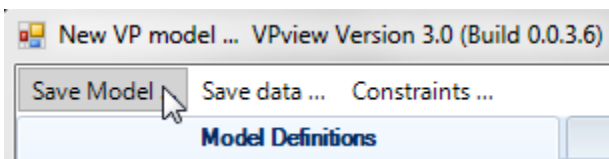
Now perform the kriging: click on *Run Kriging*. A DOS command window will open. The kriging may take a minute or two, depending on the model volume, cell dimensions, and spatial density of (conductivity,depth) points from the CDI file.



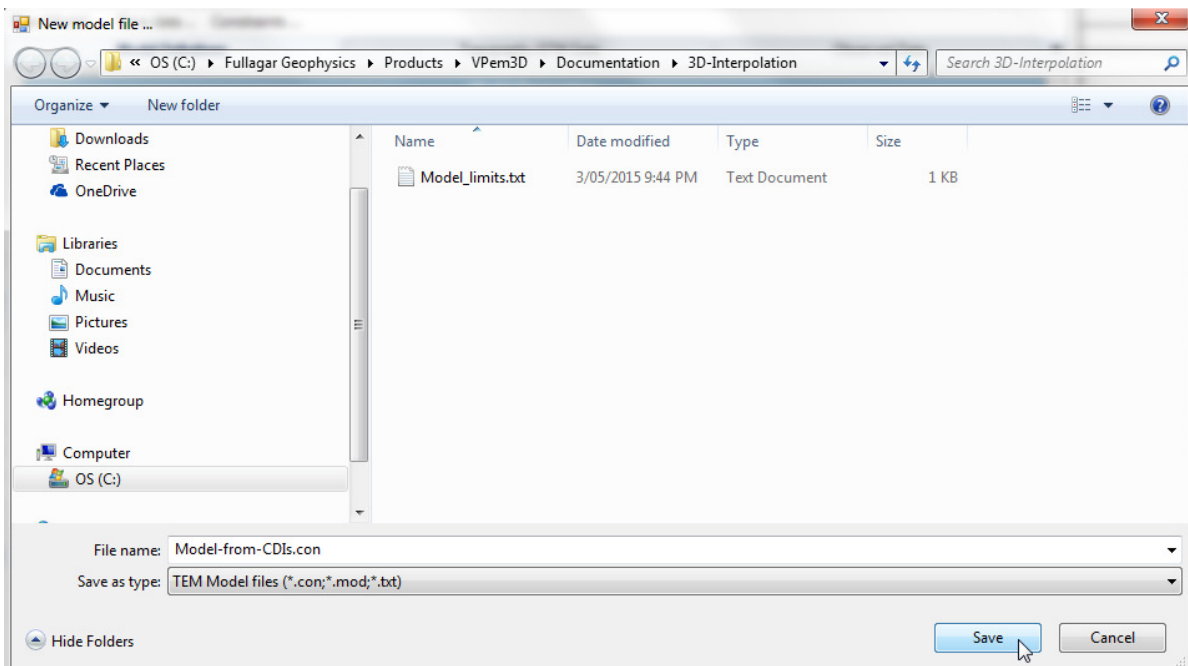
When the kriging has completed, this message is displayed:



Finally, save the model

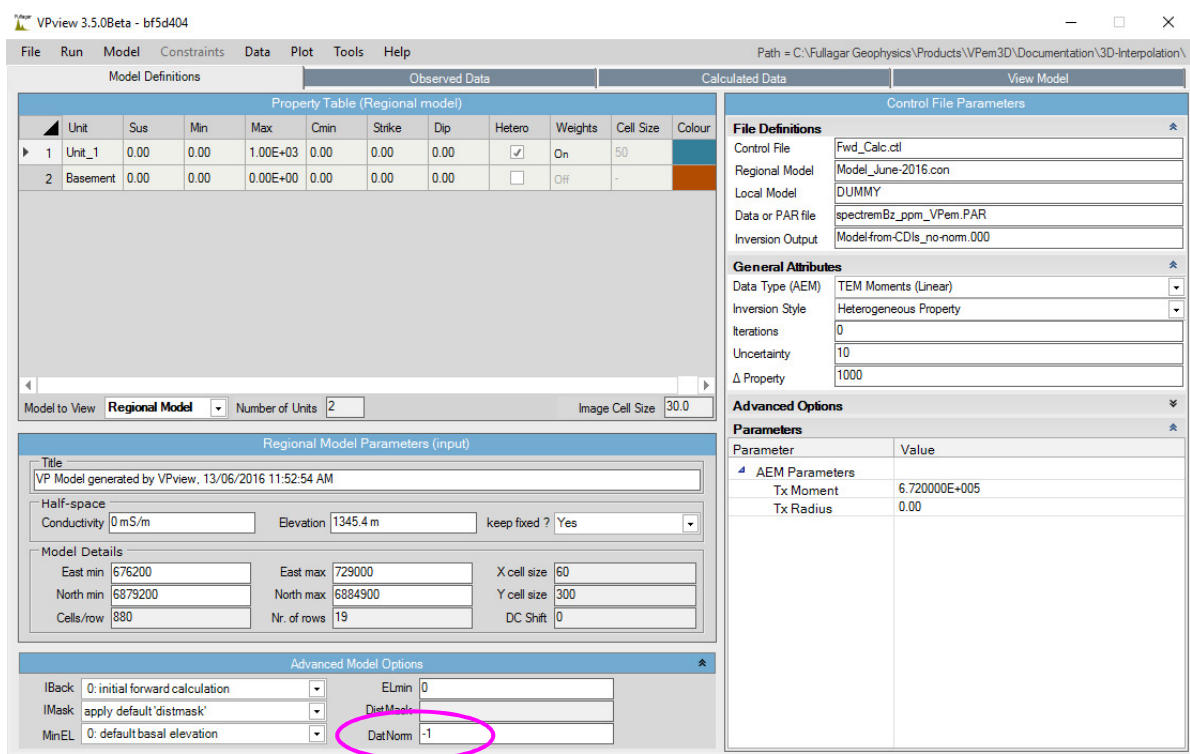


Choose a suitable model file name.

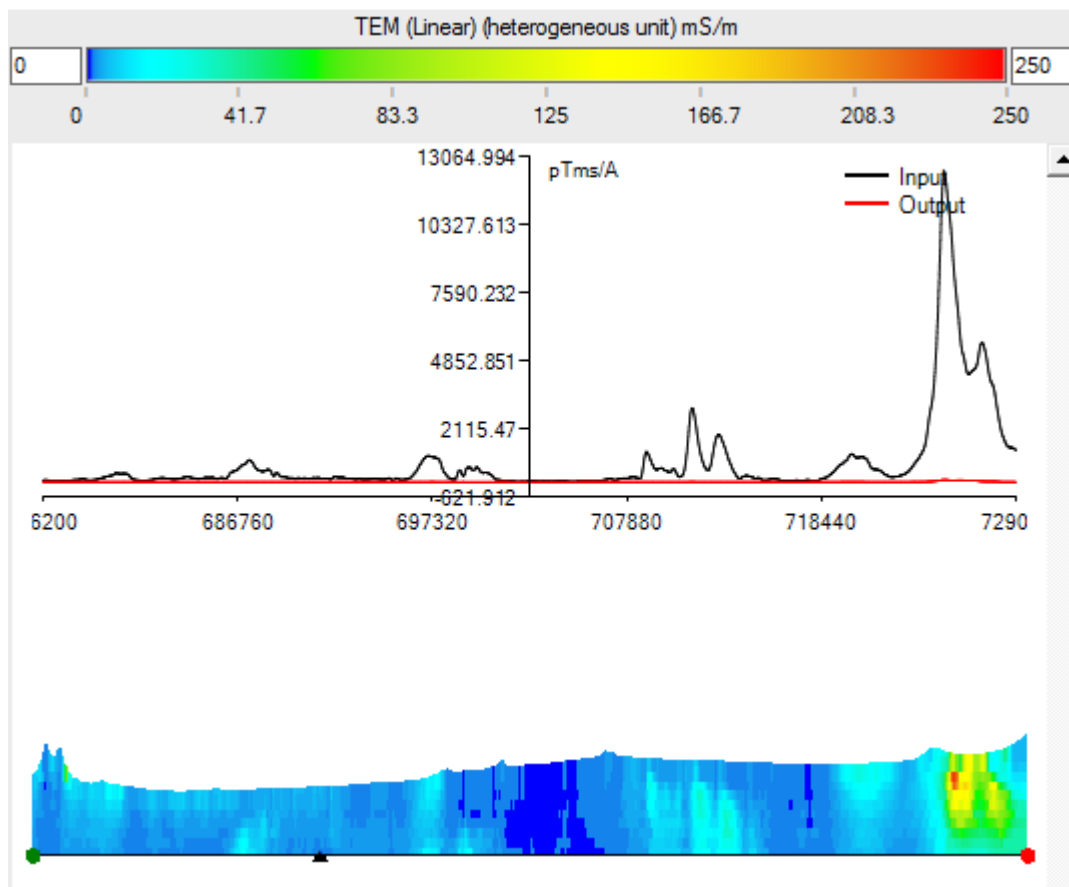


Given a starting model based on CDIs or 1D inversions, it is usually desirable to normalise the forward calculations so that the VPem3D model property is as close as possible to (apparent or inverted) conductivity. As explained in Section 2.16, the VPem3D model property is actually time constant, which is proportional to conductivity.

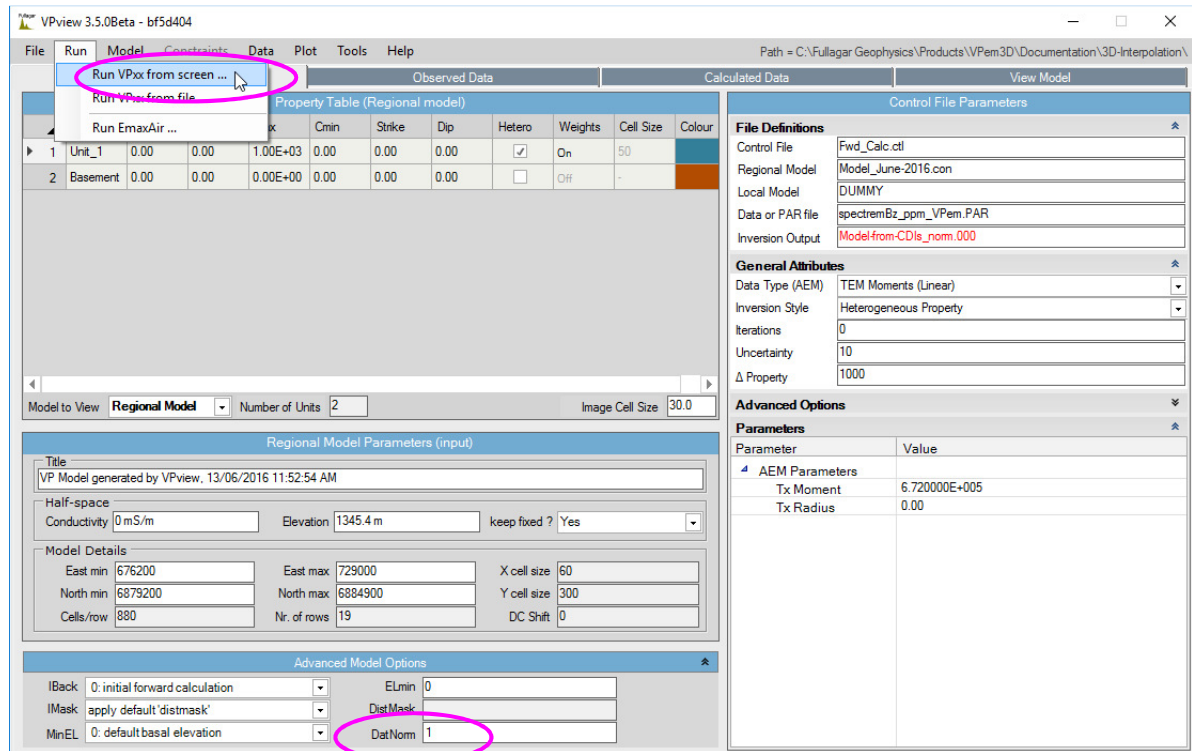
Calculated data normalisation is controlled by the *DatNorm* parameter, defined in the *Advanced Model Options* section of the VPview *Model Definitions* form (see below). Normalisation is not applied if *DatNorm* < 0. The default value of *DatNorm* is -1.



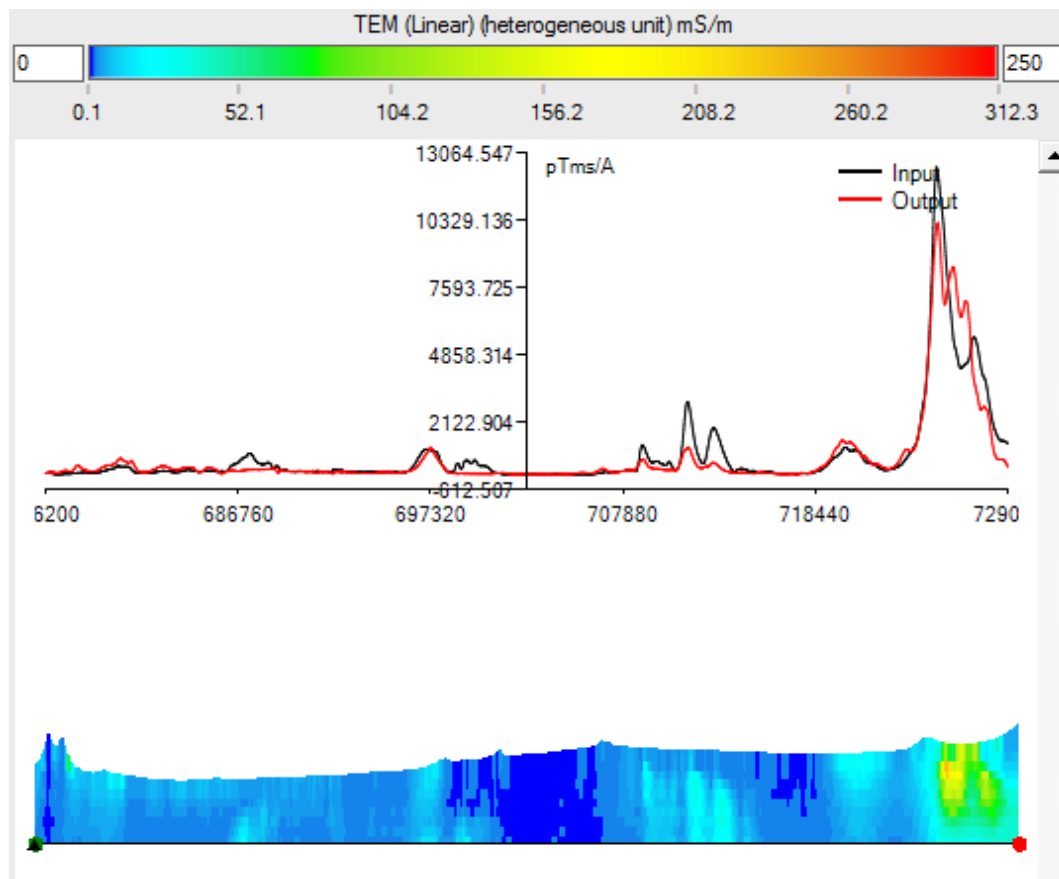
A section through the model after forward calculation without normalisation is shown below. The RMS misfit was 1340 pTms.



The forward calculation was then repeated, with $DatNorm = 1$.



The same section through the model after forward calculation with normalisation is shown below. The RMS misfit was reduced to 570 pTms.



16 APPENDIX F: VPem3D Downhole Data Proximity Weighting

Downhole or underground data are very sensitive to the conductivity of nearby model cells, especially the cell within which they reside. It is usually desirable to damp the conductivity derivatives of cells within a “radius of influence” around downhole data points; otherwise the model changes may be very localised at and near the data points.

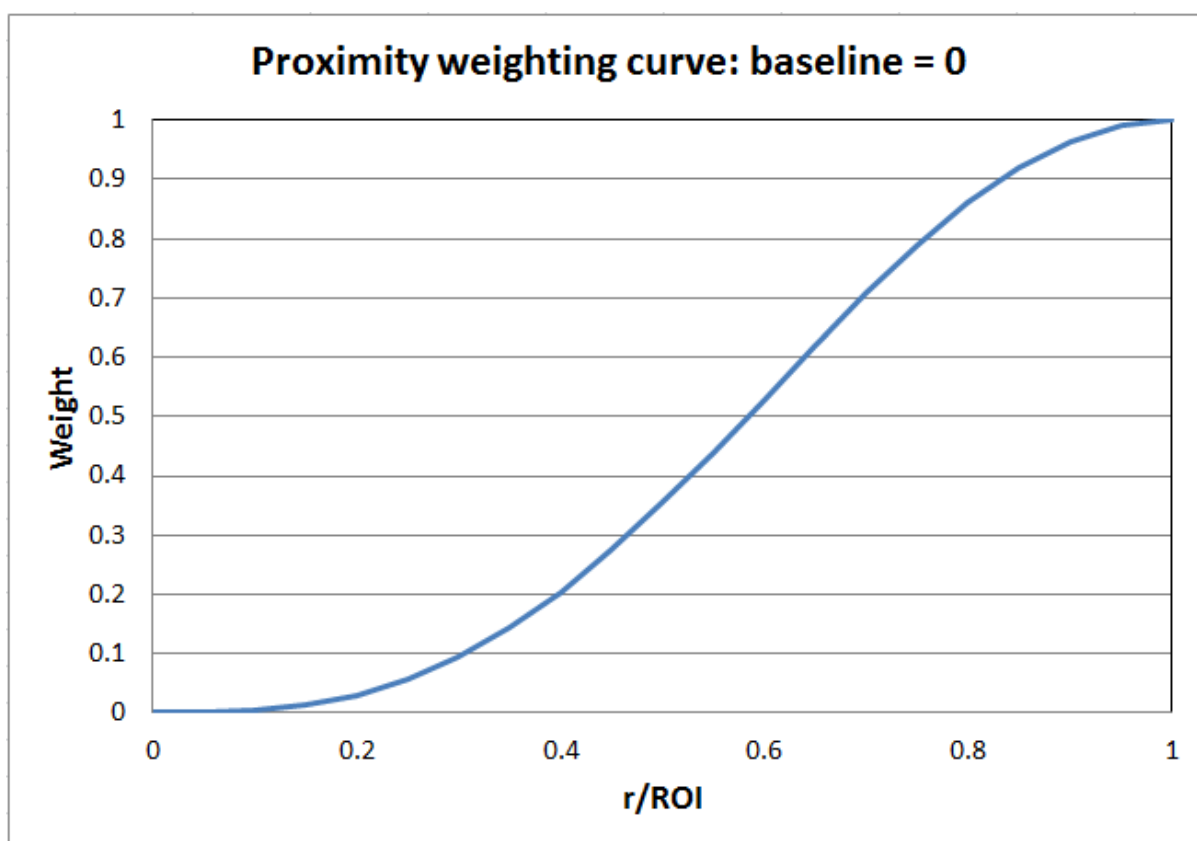
In VPem3D the damping is controlled by two parameters, namely the radius of influence, ROI, and the baseline weight, w_0 . These parameters are specified in the control file, on the record containing the Δdepth and $\Delta\text{property}$ parameters which govern perturbation size (Section 7.1). The syntax is

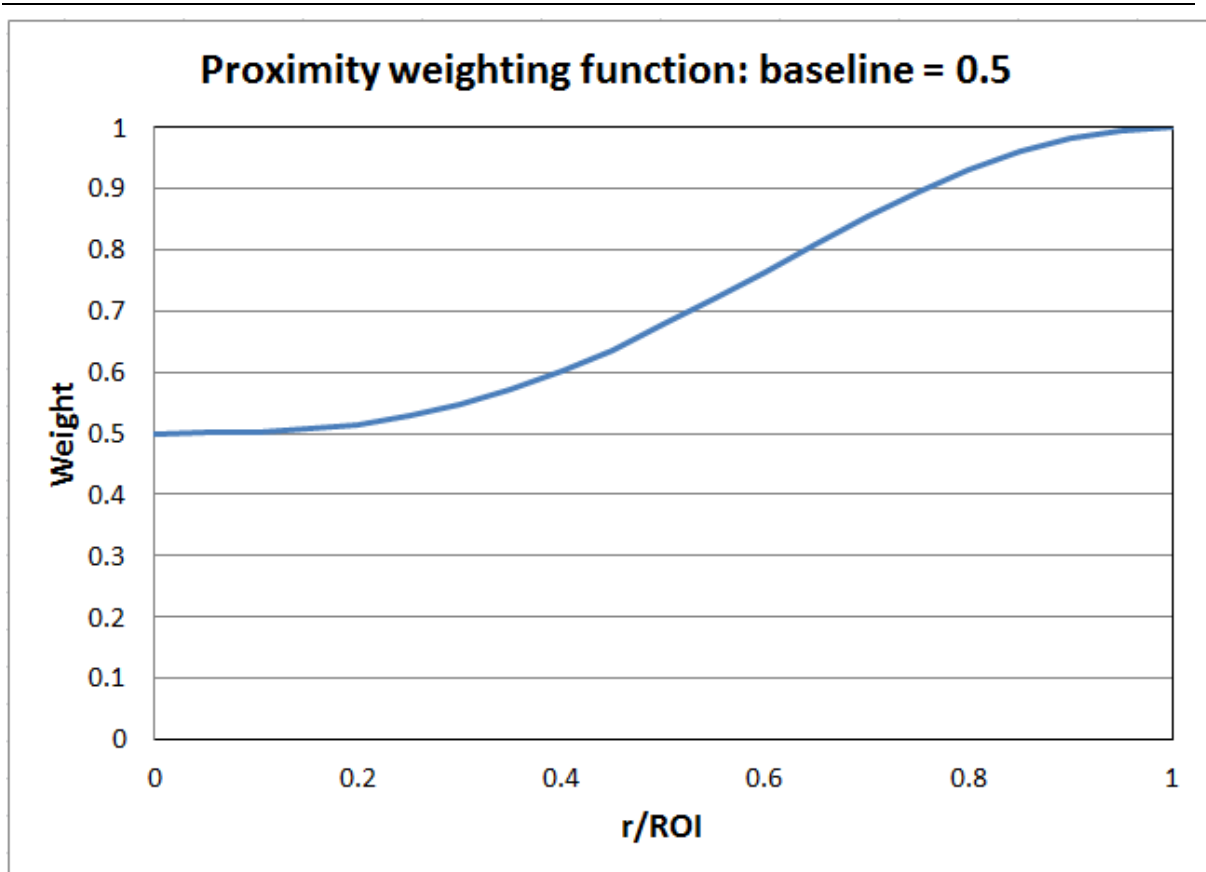
Δdepth $\Delta\text{property}$ ROI+ w_0

where ROI is the radius of influence in whole metres, and

w_0 is the baseline weight applied right at a data point ($0 \leq w_0 < 1$).

The two parameters are entered as a single floating point number; for example, for a radius of influence 20m and a baseline weight of 0.45, ROI+ w_0 = 20.45. Thus ROI is restricted to integral metres. The weighting function is illustrated below for baseline weights of 0 and 0.5. The horizontal axis is scaled to represent the variation in weights over the entire radius of influence; r denotes distance from a data point.





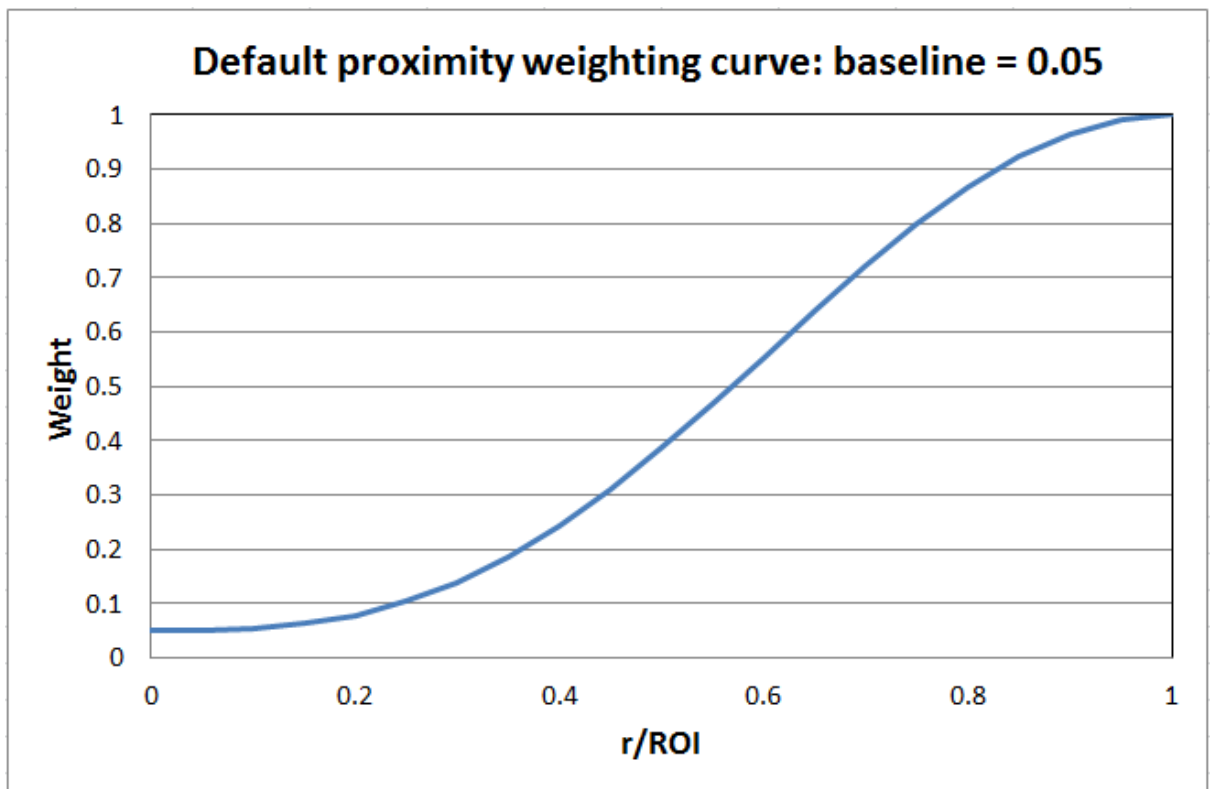
Special cases:

1. Default proximity weight curve. If ROI and w0 are not specified in the control file, VPem3D applies default values:

Default ROI = 2.5 * DL, where DL is the diagonal dimension of model prisms

Default w0 = 0.05

The default weighting curve is illustrated below.



2. No proximity weighting. To disable data proximity weighting, set ROI = 0 in the control file. In this case the weight is unity everywhere. Setting $w_0 = 0.99$ for any ROI has virtually the same effect. Thus the weighting becomes more pronounced as w_0 decreases.