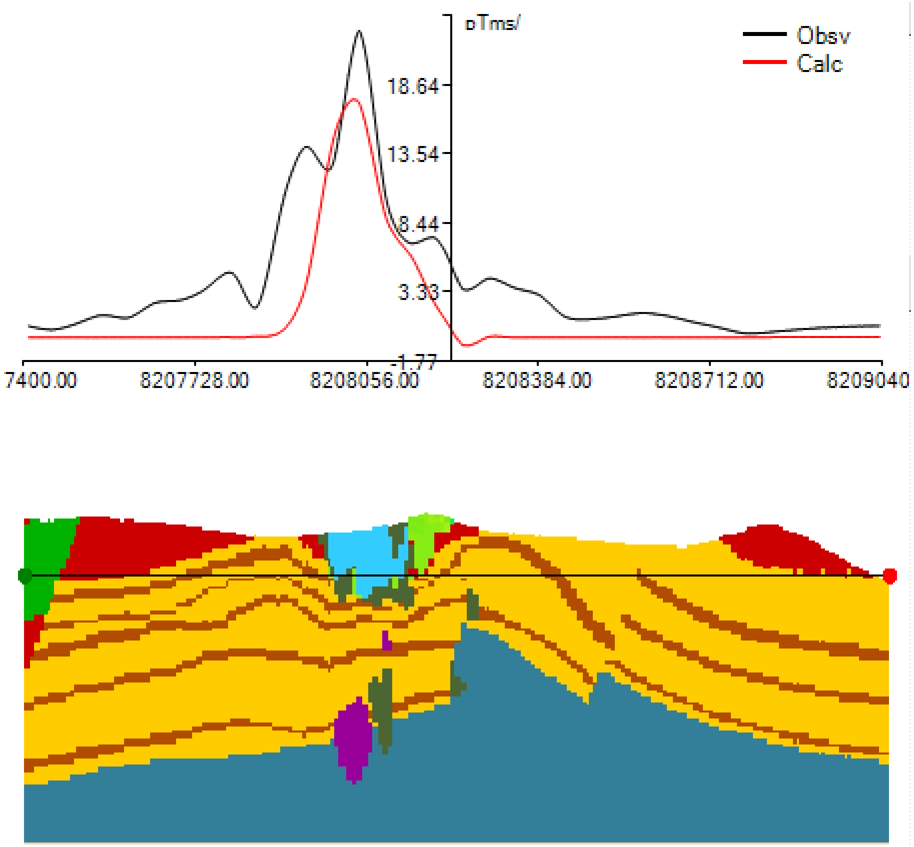
Fullagar Geophysics Pty Ltd

45 Tahune Crescent, Blackmans Bay, TAS 7052, Australia ph: +61 (3) 6229 5631

VPem3D
User Documentation



P.K. Fullagar

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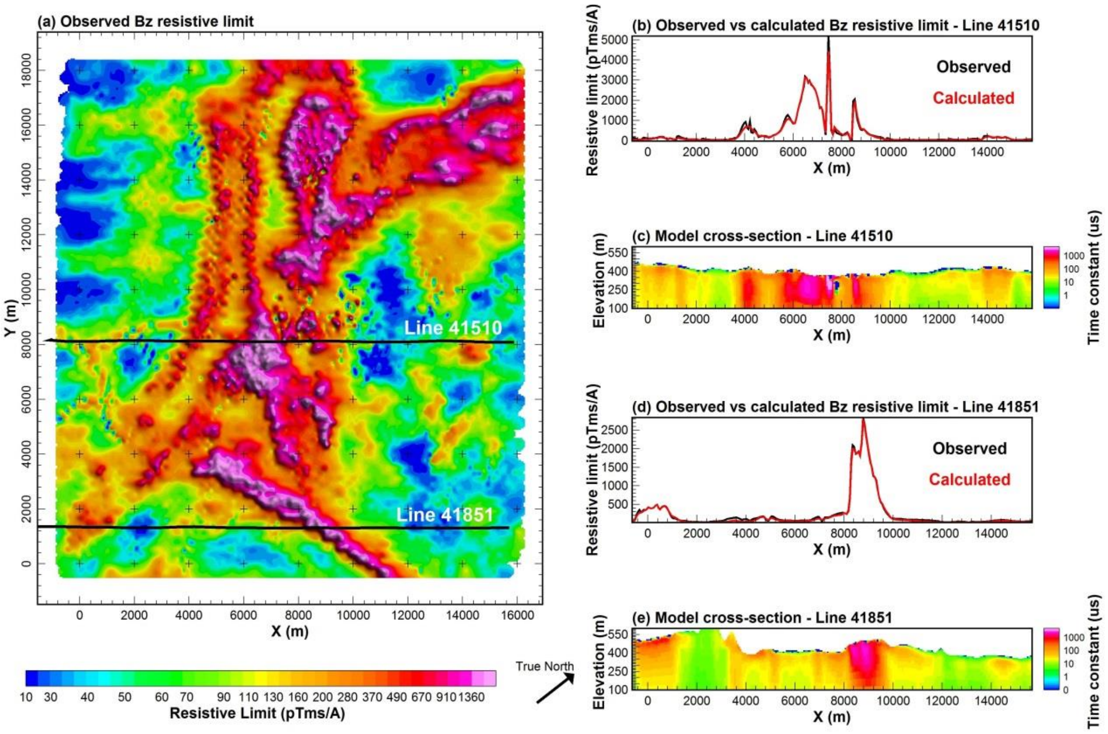
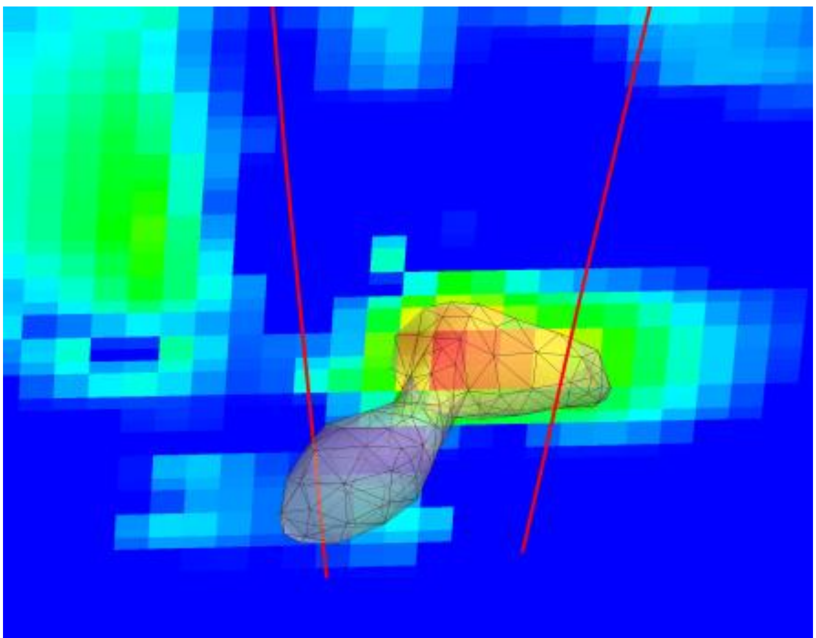


VPem3D inversion of Spectrem data from Goias, Brazil (Fullagar et al, 2014)**.**



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, D, and G.

If you have any questions, please contact us. See our contact details on page 55.

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. The technical basis for the *VPem3D* algorithm is described and illustrated in several publications: Schaa & Fullagar (2010), Fullagar & Schaa (2014), Fullagar et al (2014, 2015), and Fullagar & Woods (2016).

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 Mira Geoscience 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. In particular, layered Earth models generated with VPem1D, the Mira Geoscience 1D inversion program, can be used as starting models for VPem3D.

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, ground, and "total field" TEM are described in Appendices B, C, D, and G respectively (Sections 12, 13, 14, and 17).

Features under development appear in grey text.

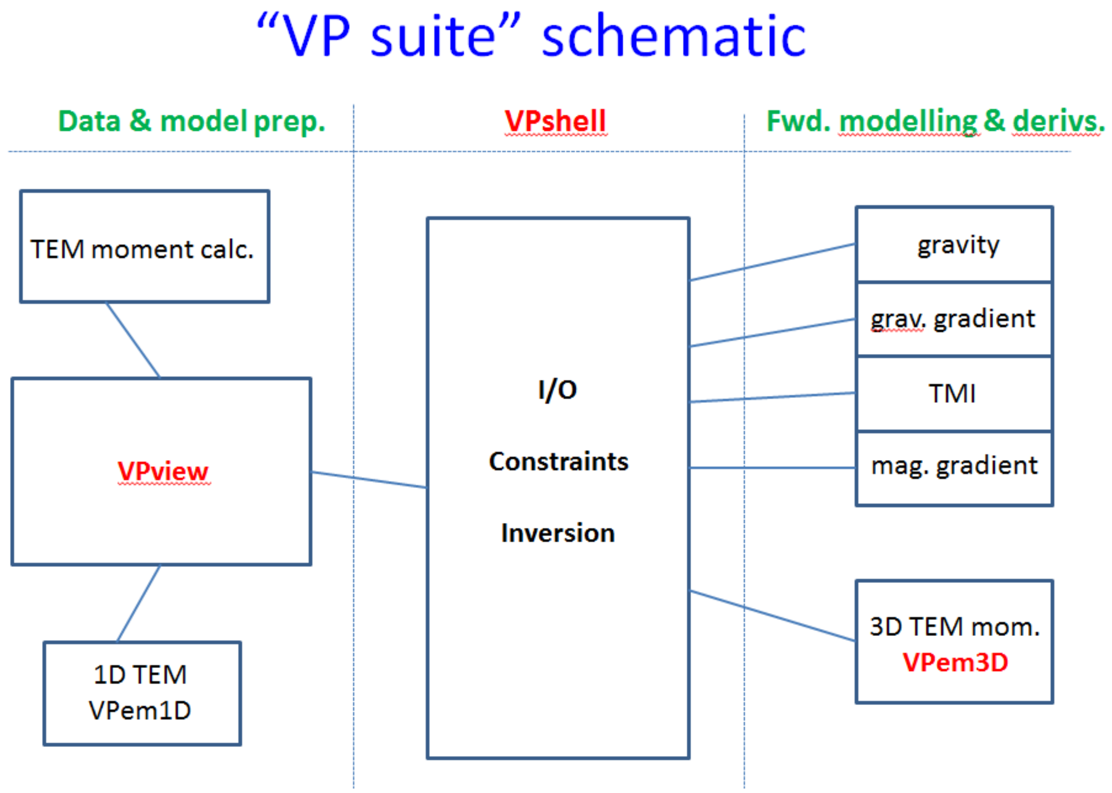


Figure 1.1: Schematic illustrating the structure of the "VP" software suite. VPem3D v2 is a specialised forward modelling module, linked to the VPshell which includes the inversion routines. VPview is the user interface.

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

- fast 3D inversion of TEM resistive limit data
- inverts airborne, ground, downhole, and "total field" 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 (including compact body option), &
  - (iii) contact geometry
- fast steepest descent inversion algorithm
- fully compatible with VPmg and VPem1D, 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 1st order moments ("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.

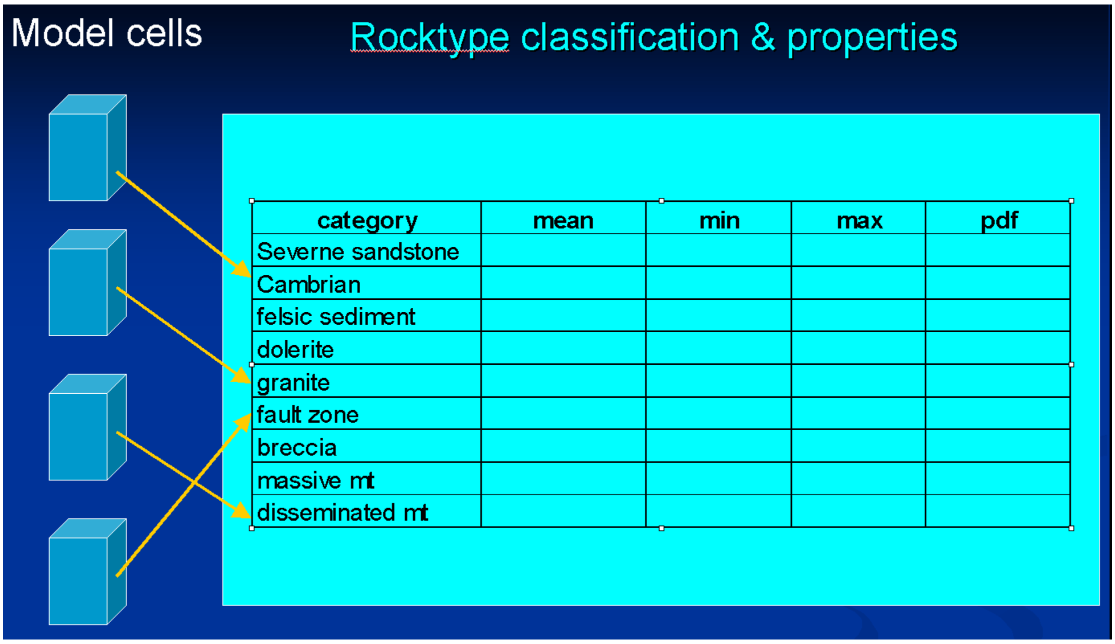


Figure 2.1: Each cell in a VPem3D model is assigned to a geological unit. If geology is unknown, all cells belong to the same "unknown" unit, as in conventional inversion.

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).

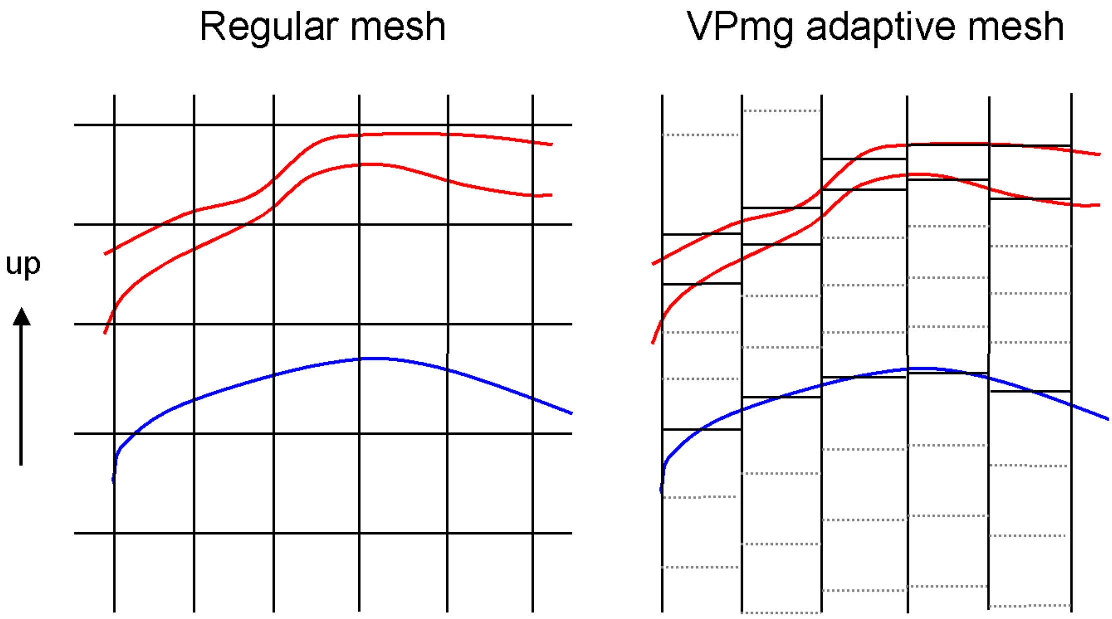


Figure 2.2: Schematic model sections illustrating the differences between a conventional regular mesh (left) and the deforming mesh implemented in VPem3D. Vertical cell dimensions are arbitrary, as required to best represent the geology. Horizontal cell boundaries snap to geological contacts (coloured) 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.

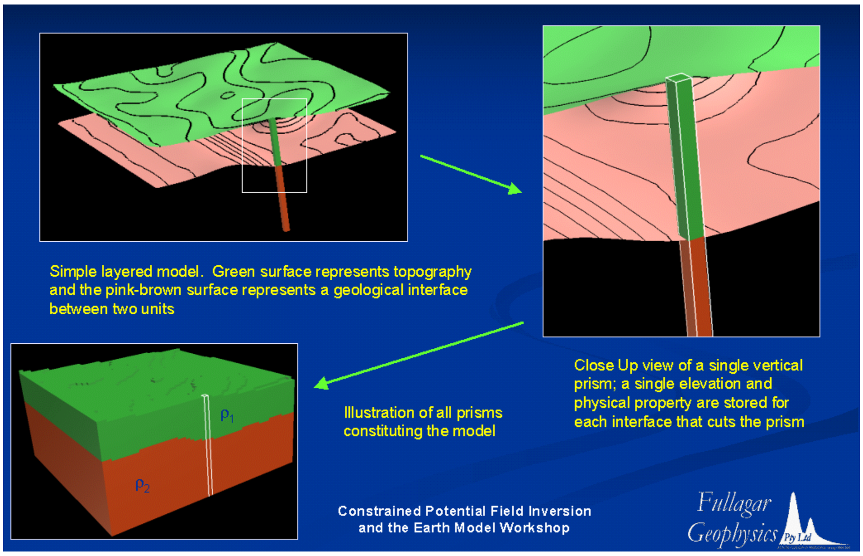


Figure 2.3: Horizontal cell boundaries are positioned within each vertical model prism to coincide with geological boundaries.

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).

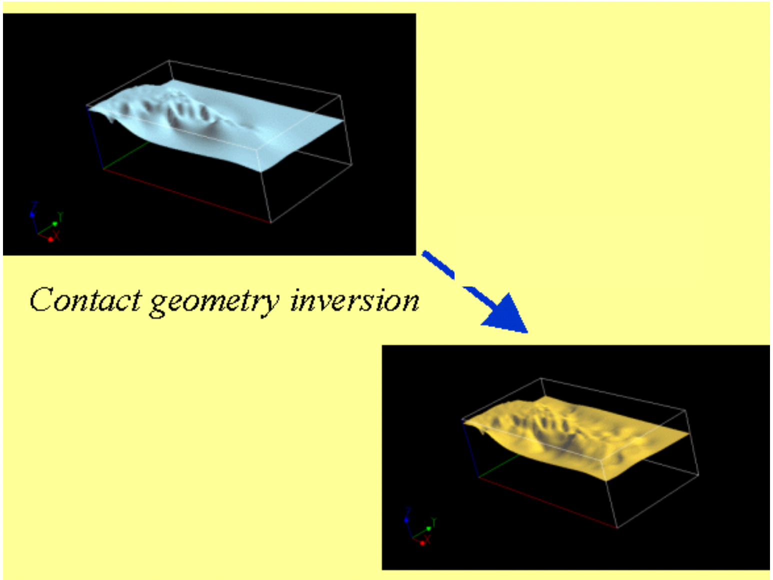


Figure 2.4: Illustration of drilling-constrained geometry inversion (after Fullagar et al, 2004). The top-limestone surface at upper left was interpreted from drill pierce points; the surface at lower right was adjusted via geometry inversion, constrained by the pierce points, in order to fit gravity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

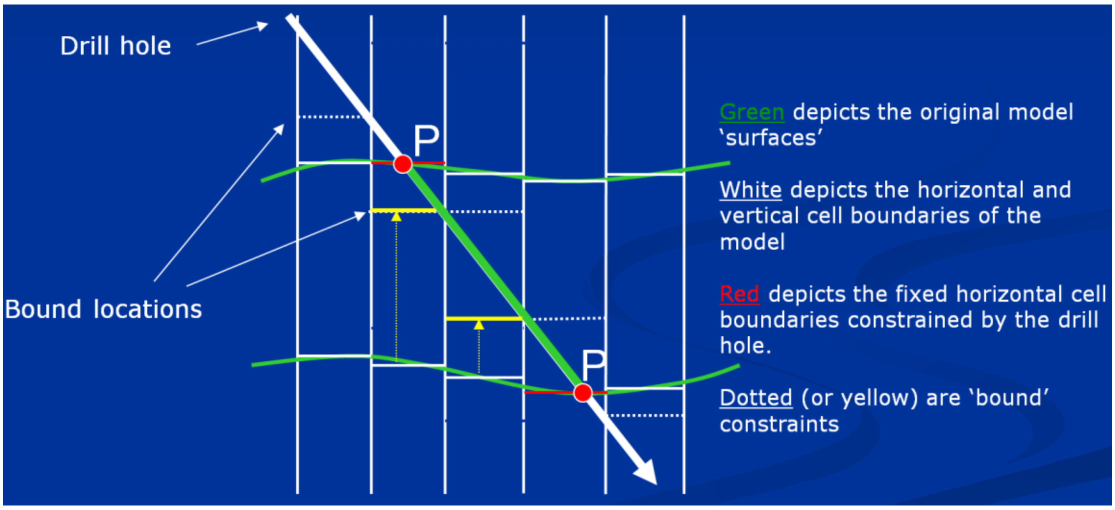


Figure 2.5: Cell boundaries intersected by drill holes are fixed during geometry inversion. Drill holes can impose bounds on the permissible movement of boundaries.

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.

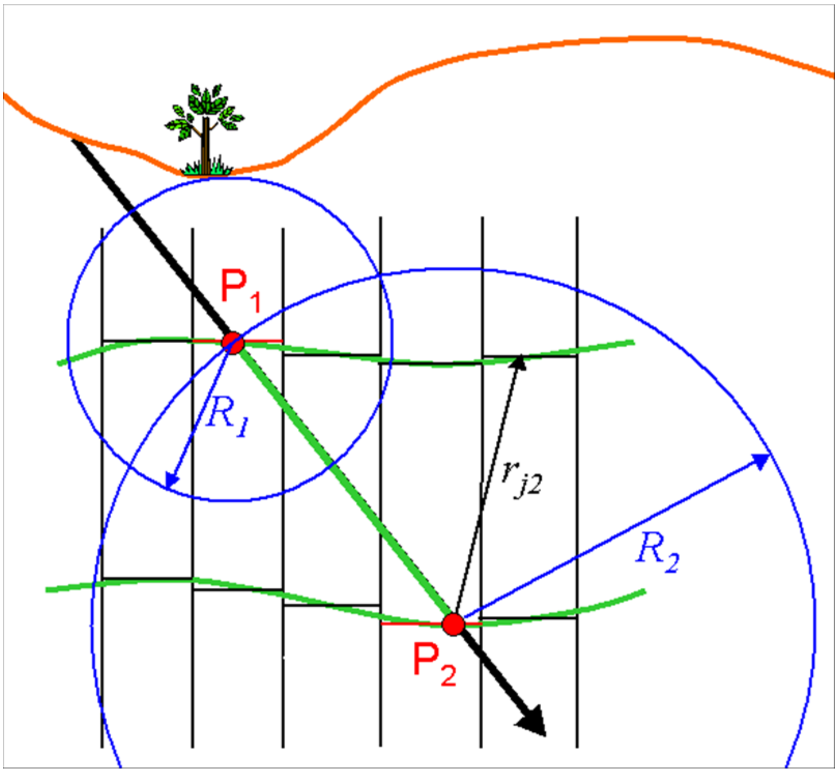


Figure 2.6: Movement of boundaries during geometry inversion is damped within a spherical volume centred on each fixed boundary.

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

Homogeneous unit (or bulk property) inversion optimises the conductivity of one or more geological units. *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. For example permitting negative conductivity can serve as a device for fitting airborne IP anomalies in some cases.

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

Compact body inversion (CBI) is a variant of heterogeneous unit inversion. As the name suggests, CBI favours solutions with small volume. Therefore CBI tends to define discrete highly conductive volumes which can explain the measured data. Compact solutions are deeper (or further from downhole data points) than larger volume solutions. Consequently, when performing CBI of airborne or ground TEM, there is not usually any need to impose depth weighting.

At each iteration, CBI first identifies the individual model cell (the “seed” cell) which can produce the greatest reduction in chi-squared misfit between observed and calculated data. It then restricts changes in conductivity (in that iteration) to the seed cell and to other cells which have a similar potential to decrease the misfit. The user has the option to limit changes to cells which are centred within a certain radius (the *Body Radius*) of the seed cell.

Compact inversion can be run for multiple iterations, to define multiple conductors, or run for a single iteration to define a volume of interest. In either case, CBI may just be the first stage; subsequently, the user may edit the volume of interest, or choose a subset of conductors, and perform additional inversions, e.g. homogeneous unit inversion &/or geometry inversion &/or conventional heterogeneous inversion.

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.

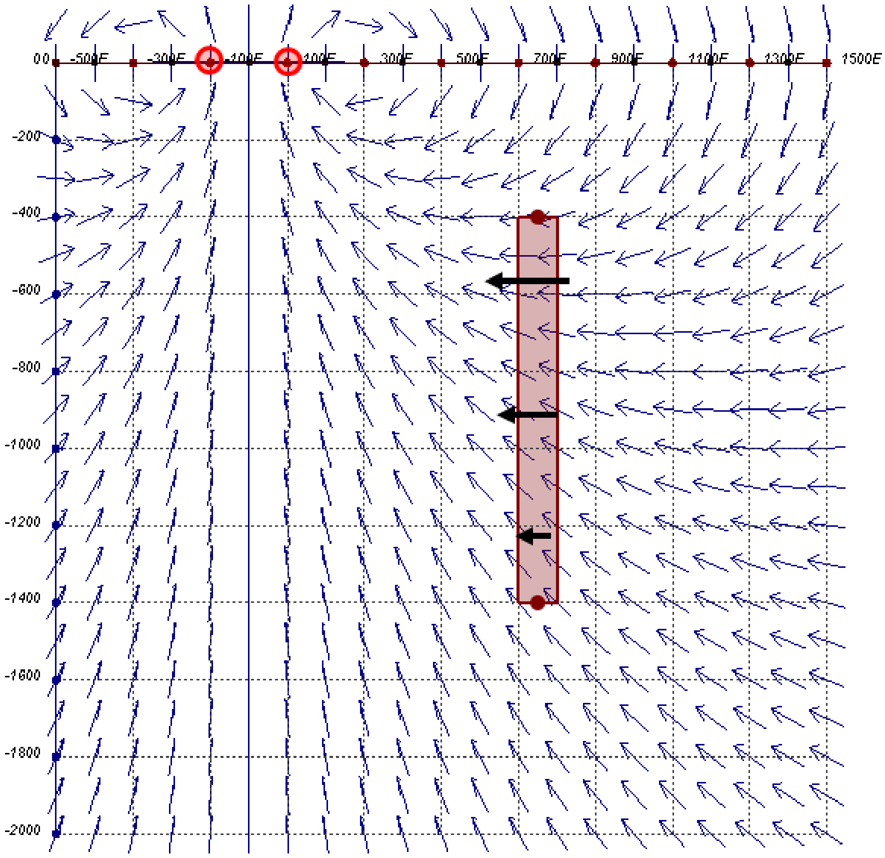


Figure 2.8: Schematic cross-section through a conductive plate (grey) excited by primary field (blue arrows) from a loop on the ground surface. Induction in the plate is dominated by the horizontal component of primary field (black arrows). Therefore "magnetisation" is horizontal, not parallel to primary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

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.

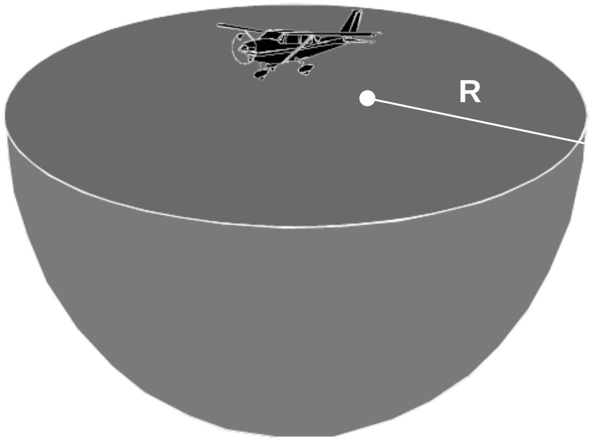


Figure 2.9: Volume of influence (or 3D footprint) for an AEM transmitter can be represented schematically as a hemisphere (after Smith & Wasylechko, 2012).

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, suitable for underground loops with vertical segments as well as surface loops in rugged topography.

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, $\vec{J}$:

$$\vec{B} = \mu_0\left(\vec{H} + \vec{J}\right) \tag{2.1}$$

The vertical magnetic induction through 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.

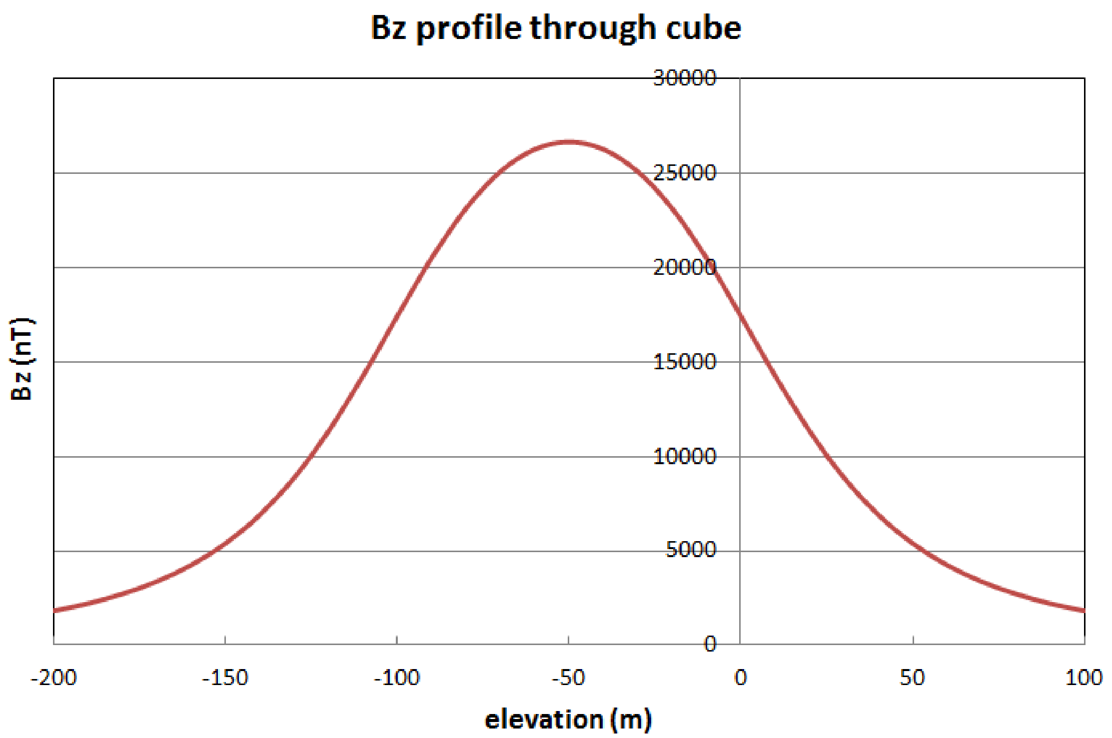


Figure 2.10: Vertical magnetic induction, B_z, profile through the centre of a 100m cube, susceptibility 1 SI, with top at RL of 0m. B_z is continuous at top and bottom of cube. Ambient field is vertical with intensity 40000nT.

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:

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

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, wmax, 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

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

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.

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

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.

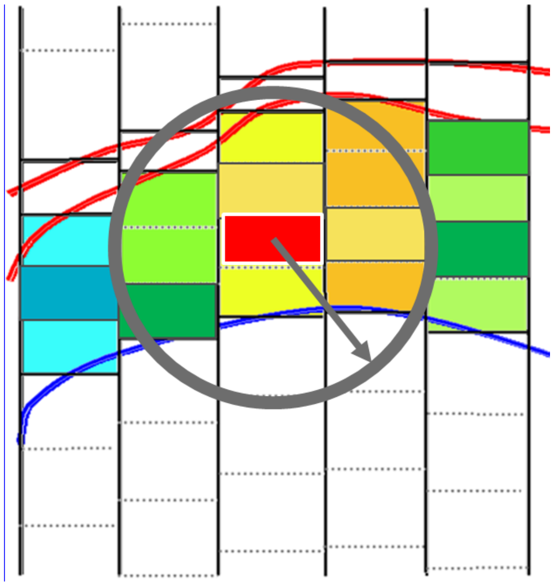


Figure 2.11: Model changes are suppressed within spherical neighbourhoods centred on each fixed property cell (coloured red).

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.

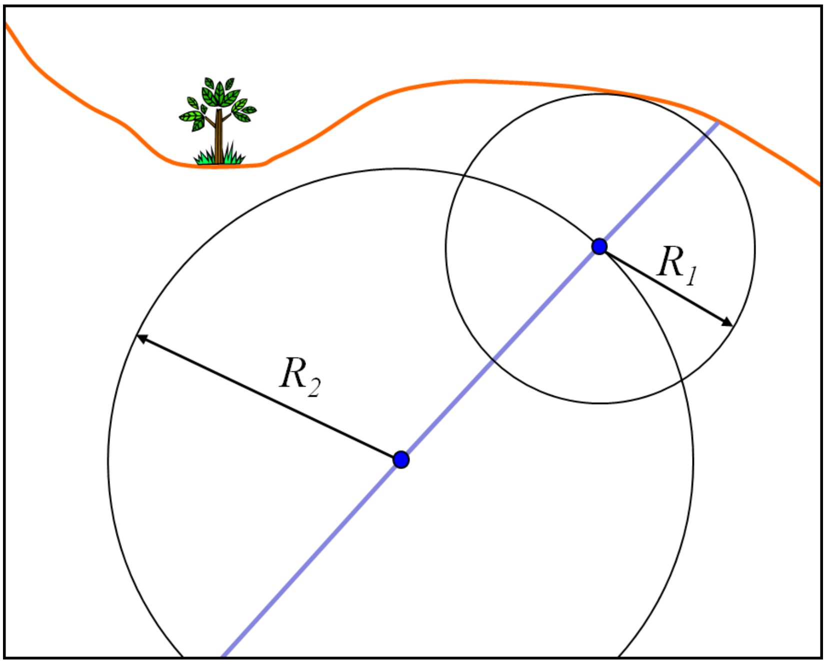


Figure 2.12: Model changes are suppressed within spherical neighbourhoods centred on each underground data point (blue dot).

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

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

where Δz_n is the thickness of the nth 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 minmise 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. In VPem3D HeliSAM is treated as a variant of ground TEM, even though the data are recorded in the air.

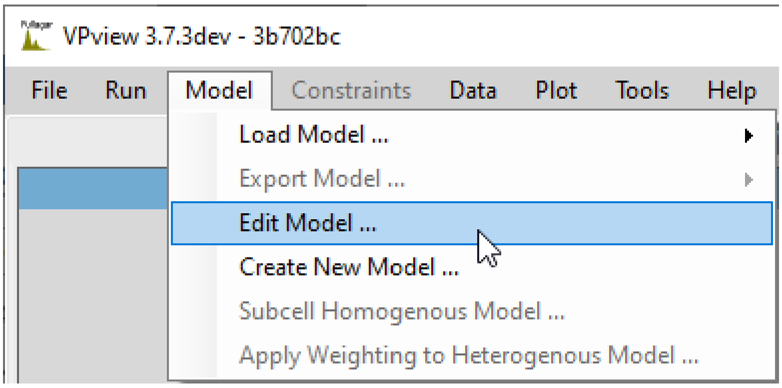
The VPem3D polarity convention is ENU, i.e. x=East, y=North, z=Up are the positive directions. Also, current flow in the transmitter loop is anti-clockwise for VPem3D modelling, so primary B field inside the Tx loop is up. For SAM measurements this means that a flat-lying conductor inside the loop will 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.

2.19 Model Editing Options

Simple model editing operations can be performed using a VPview utility in the *Model* menu, e.g. creating new “geological units” based on a conductivity threshold. In addition, discrete representations of (thick) conductive plates or ellipsoids can be inserted into VPem3D model files.



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).

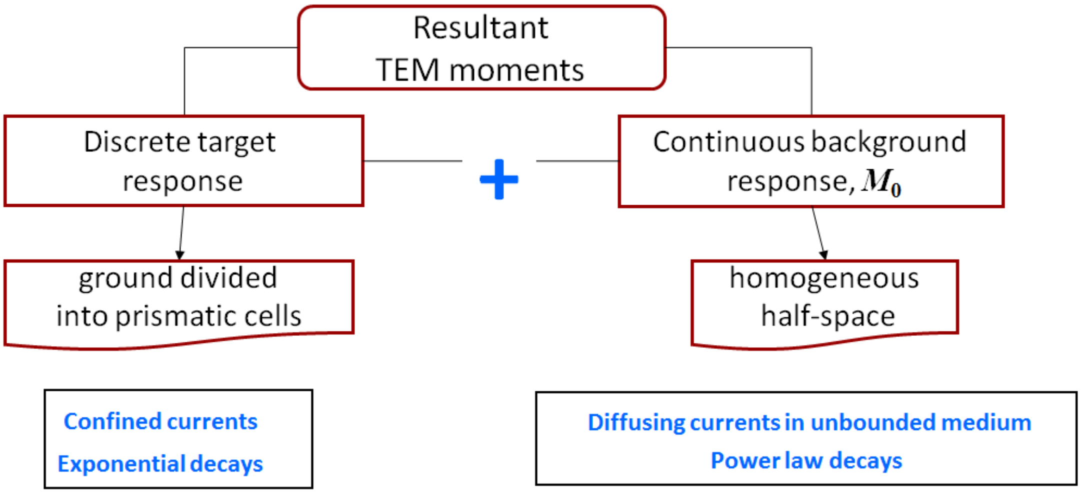


Figure 3.1: VPem3D resistive limit forward modelling schematic. Response from discretised ground is added to analytic response from homogeneous half-space.

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.

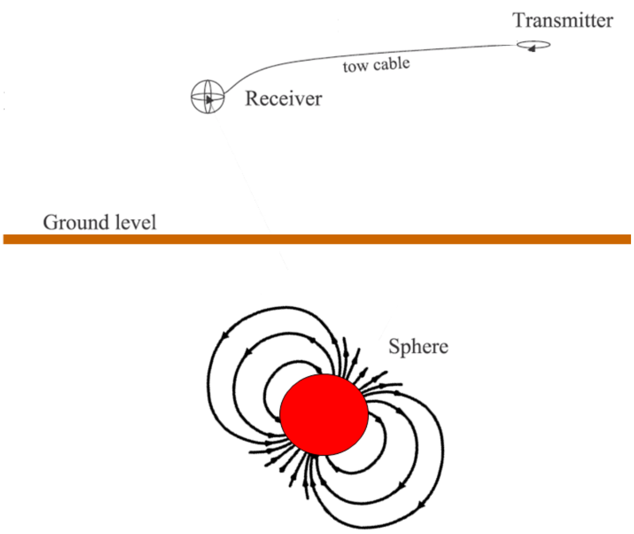


Figure 3.2: In the resistive limit, a conductive sphere produces a magnetic dipole response. This is the basis for the forward modelling algorithms in VPem3D.

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 3.3).

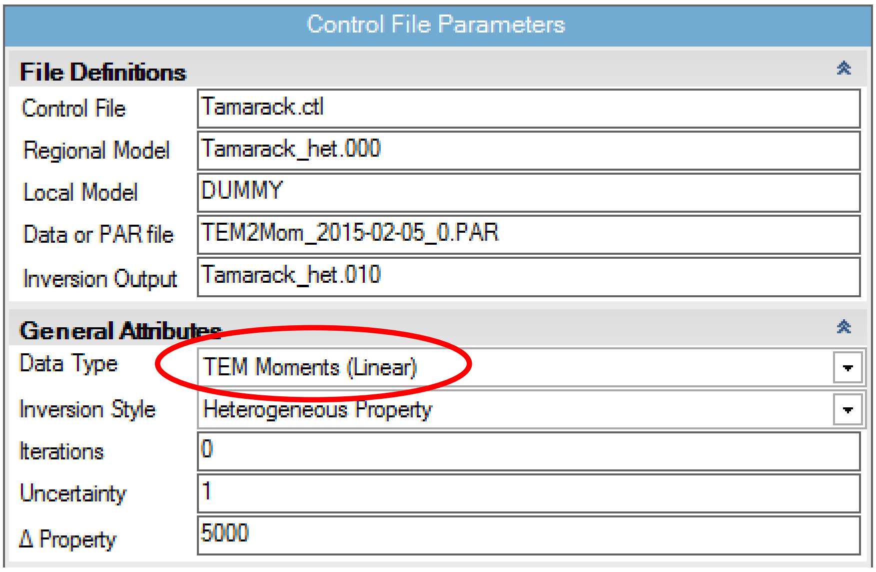


Figure 3.3: Selecting the linear algorithm on the VPview *Control File Parameters* form.

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, $\Delta \boldsymbol{p}$, which can reduce the data misfits, $\Delta \boldsymbol{d}$. *VPem3D* solves for the model perturbation $\Delta \boldsymbol{p}$ using the method of Steepest Descent. The algorithm is outlined 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 nth data point. The uncertainty can vary from one station to another. 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 $L2 \le 1$ and/or if $L1 \le 1$.

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. However, the RMS misfit is not a reliable indicator of acceptability if the standard deviations vary from station to station. The inversion algorithm minimises the $L2$ norm.

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. Unconstrained heterogeneous inversion is 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 may be used to define a relatively large volume of interest, 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. Changes to the model are suppressed by weights within a neighbourhood of influence centred on fixed cells, as described in Section 2.14.

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.

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).

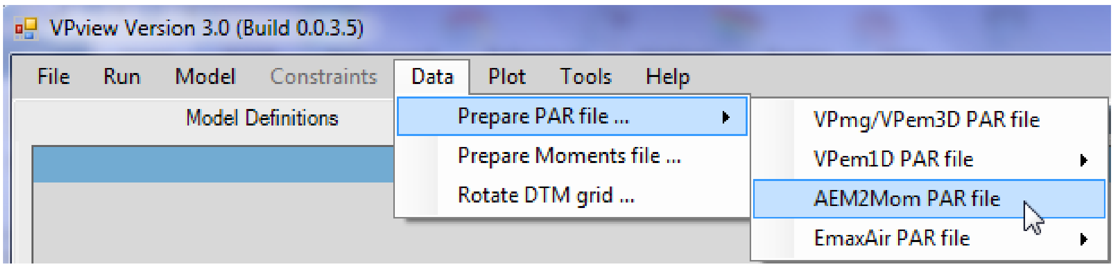


Figure 4.1: The *Prepare PAR file* utility is an option under the VPview *Data* menu.

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. Am^4. In order to recover resistive limits in pTms, the actual Tx moment (in Am^2) is specified in the AEM2Mom PAR file.

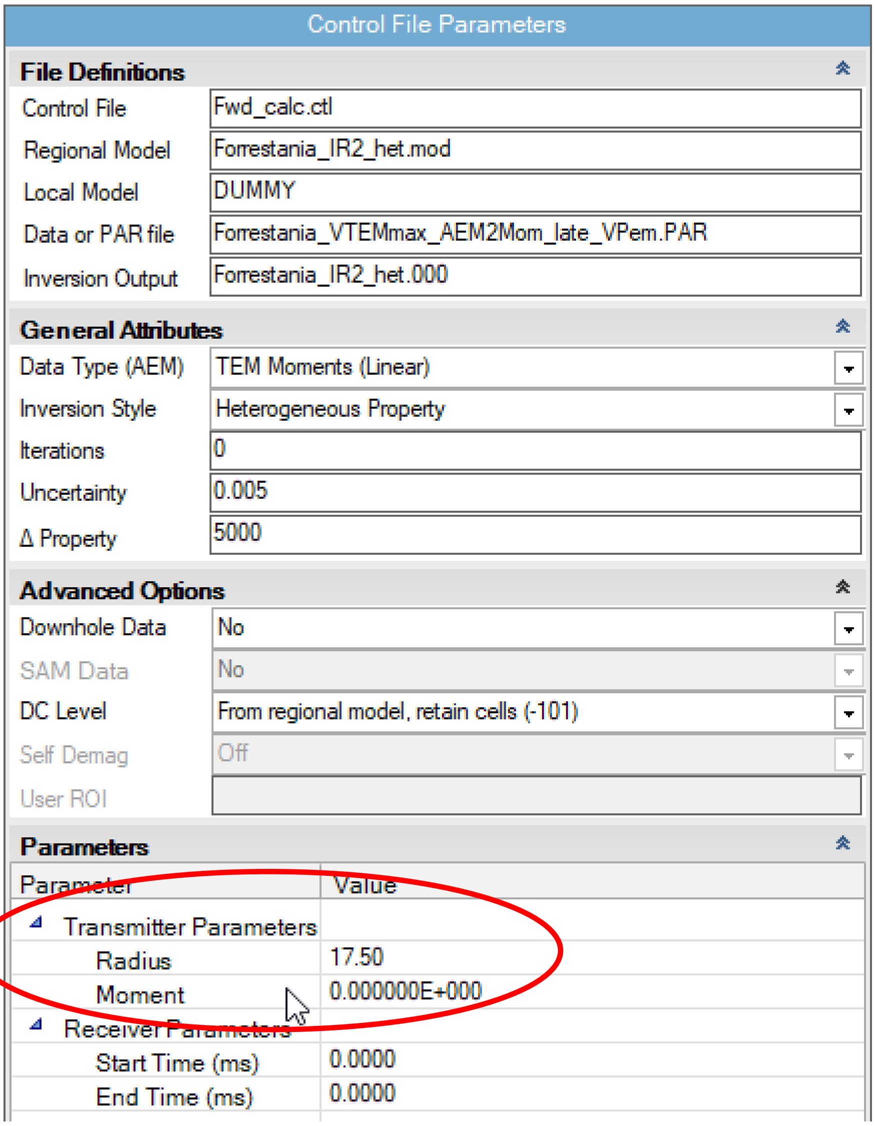
The uncertainty is characterised in AEM2Mom by PCERR (the % error) and SDMIN (the minimum standard deviation). The standard deviation assigned to a TEM channel with measured value V is 0.01*PCERR*|V| + |SDMIN|. If SDMIN > 0, AEM2Mom truncates non-monotonic decays; thus V can be negative, but |V| cannot increase with time. If SDMIN < 0, AEM2Mom accepts all data provided |V| > |SDMIN|; thus AEM2Mom with 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.

Both Tx and Rx positions in 3D are required 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 usually 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. Rotation parameters are defined in Section 11.

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.

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 (Am^2) 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.



4.3 Creating a starting model

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

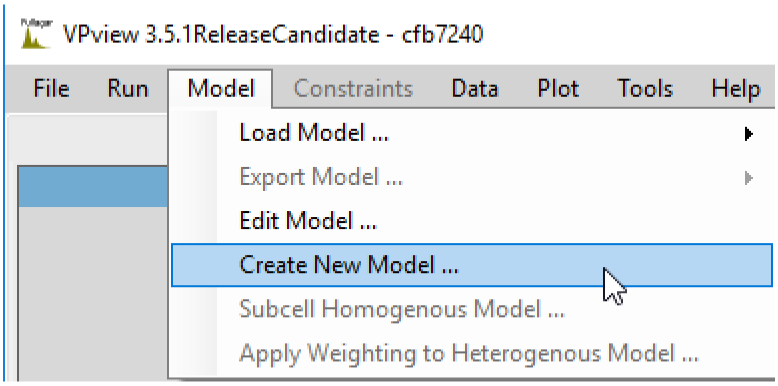


Figure 4.2: The *Create New Model* utility is an option under the VPview *Model* menu.

Although not essential, normal practice is to create the model in the local coordinate system, i.e. with model cell sides 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.

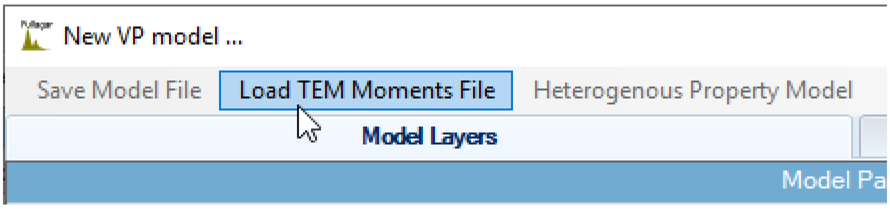
Another option is to construct a 3D conductivity starting model via interpolation of conductivity-depth images (CDIs) or 1D inversions. VPview includes utilities to construct starting models from EmaxAIR CDIs, as illustrated in Section 15 (Appendix E). Alternatively, a VPem1D model can be adopted as 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 specified as 100.1 in the control file, 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.

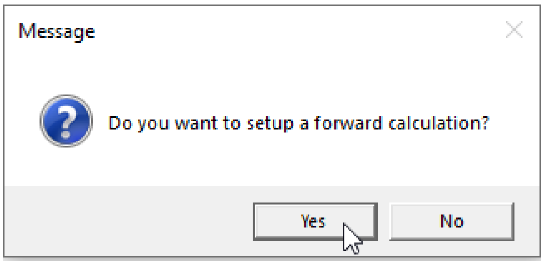
If the user specifies the moment ("resistive limit") data file when running the *Create New Model* utility, VPview inserts default model parameters into the Model Parameters table, based on information in the data file header. These defaults are suitable for unconstrained inversion, for a single host unit on basement. For further details, see the worked example in Section 12.3.



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. VPview can create a control file at the end of a *Create New Model* process.



Alternatively, 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.

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.

A global noise level (uncertainty) can be defined in the control file in moment data units [pTms/A]. Alternatively, individual sds can be defined in the moment file. The individual errors will be adopted by VPem3D if the VPem3D PAR file includes entries for RLXE, RLYE, and/or RLZE, except when all the sds in the moment data file are zero.

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).

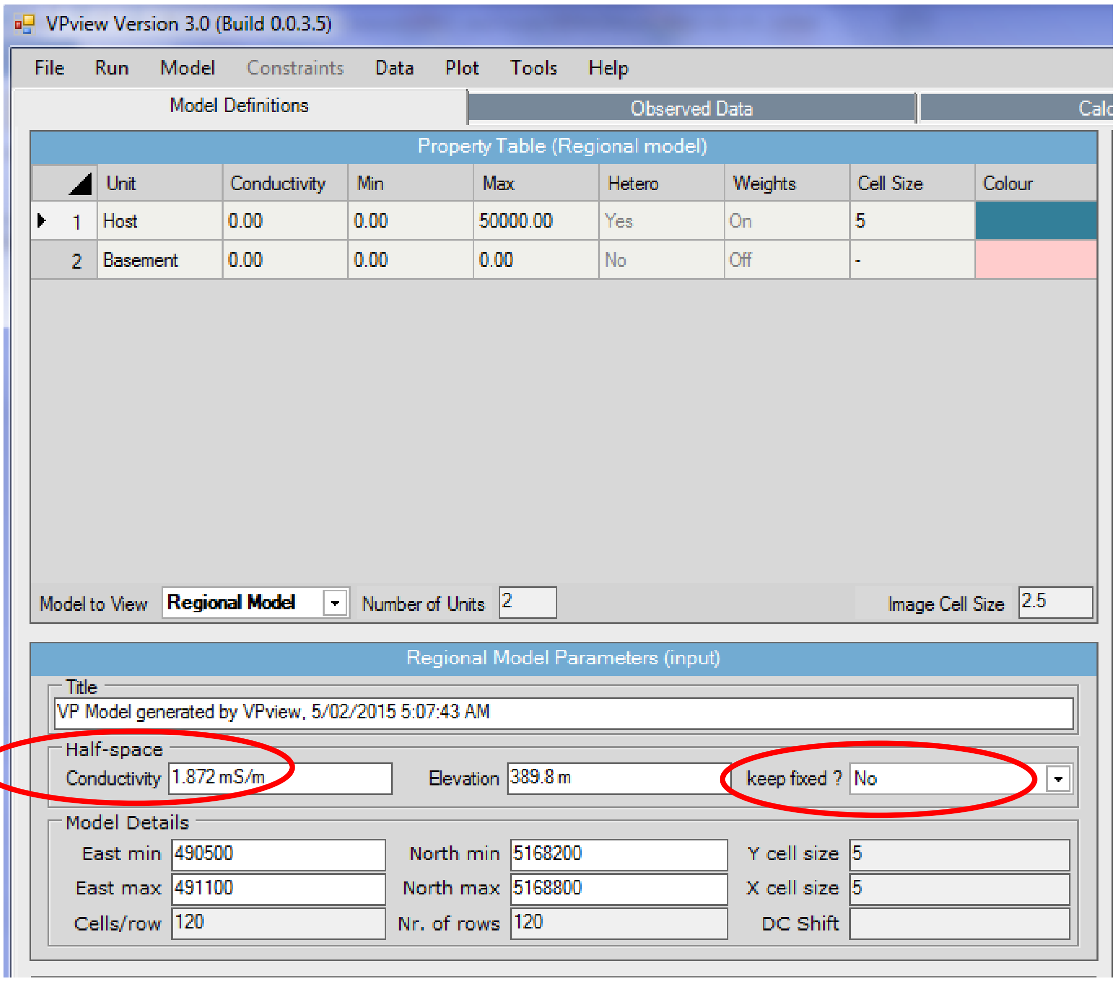


Figure 5.1: The effect of a homogeneous host can be accounted for by setting the *Half-space conductivity* to a non-zero value. The *Half-space conductivity* can either be fixed, or allowed to vary.

- 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 2.11 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 2.14 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 1st order moment ("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.

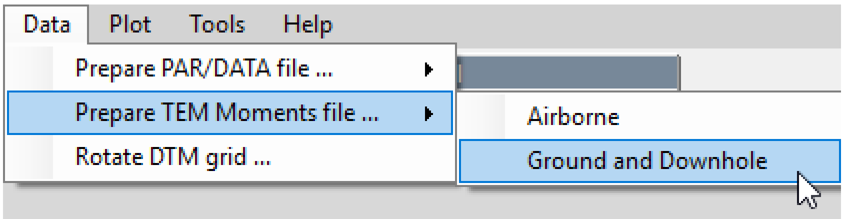


Figure 5.2: Accessing TEM2Mom from VPview

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.

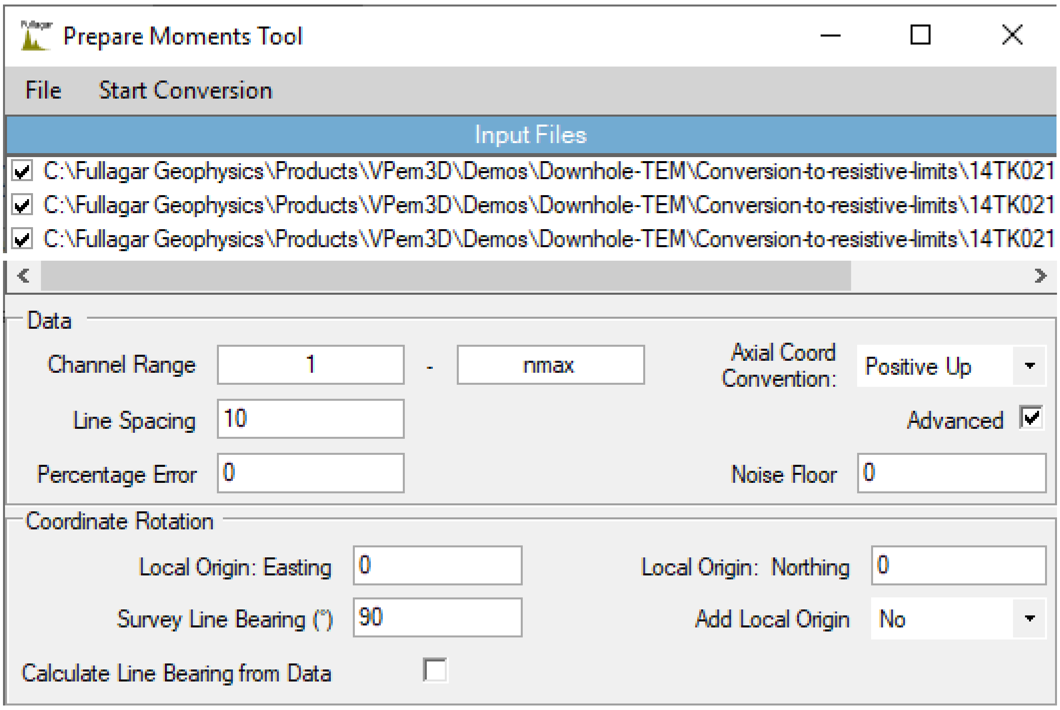


Figure 5.3: Selecting the TEM files to be processed by TEM2Mom, and the processing parameters.

The channel range (hence time interval for integration) and downhole TEM polarity convention (e.g. 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 TEM moment 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 10µs.

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.]

Coordinate rotation is not fully implemented for downhole TEM data. In particular, the rotation is applied to Tx and Rx locations only, not to the TEM components.

The user can define a percentage error, PCERR, and a noise floor, SDMIN, by checking the “Advanced” box. The noise floor is in original TEM data units, e.g. pT/A or nT/s. TEM2Mom computes the corresponding errors associated with the moment (“resistive limit”) data. **Care is required** if setting a percentage error, especially if the starting model has zero conductivity. In that case, if SDMIN is small, the normalised residuals (which drive the inversion) will assume a boxy form, alternating from approximately +V to approximately –V, where V = 100/PCERR, at the start of the inversion. This is very undesirable because (in the limit as SDMIN → 0) the smallest anomaly will have the same normalised amplitude as the largest anomaly. Assigning a realistic percentage error is not problematic if the starting model is non-zero in conductivity and/or if SDMIN is appreciable. If using a zero conductivity starting model (which is often convenient), percentage errors can be introduced after a few iterations, if desired.

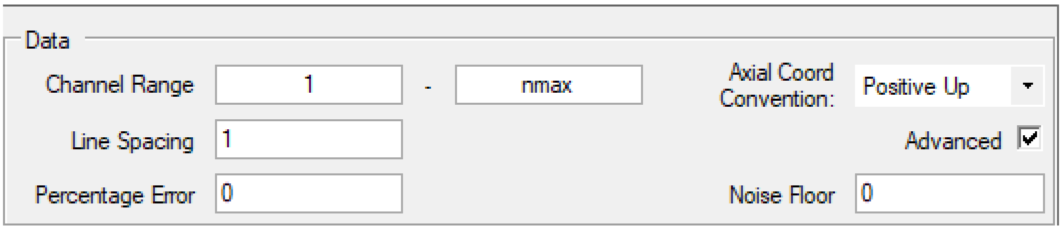


Figure 5.4: Error parameters can be defined by checking the "Advanced" box.

The *Line Spacing* is not meaningful for downhole TEM, and is ignored by TEM2Mom.

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 measured axial and transverse (AUV) components into the Earth frame coordinates using hole survey information (either dip and azimuth or direction cosines) included in the TEM file. The TEM moment ("resistive limit") data file created by TEM2Mom has extension XYZ.

The user can specify a coordinate rotation, if desired, but this is rarely appropriate for downhole TEM. The *Coordinate Rotation* parameters are defined in Figure 5.3. The *Survey Line Bearing* is the clockwise angle in degrees from north (as defined in the original coordinates) of the rotated x-axis (local east). Note that TEM2Mom will ***not*** rotate the horizontal "resistive limit" components into the local coordinate system.

If TEM2Mom is launched from VPview (as illustrated here), a VPem3D PAR file is created. The PAR file defines the format of the moment data (XYZ) file. The VPem3D PAR file format is described in Section 7.3. No PAR file is created if TEM2Mom is run from command line; see Section 7.3.4.

Examples of VPem3D PAR files for the #VPEM# and #VPEM2 moment data formats are shown in Figures 5.6 and 5.7 below. In the sample #VPEM# PAR file (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 #VPEM# variant of the PAR file format, the Tx loop is assumed to be rectangular. If #VPEM# format is specified, and 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, defined in Section 7.3.3. In a #VPEM2 PAR file (e.g. Figure 5.7), RLXE, RLYE, RLZE are the standard deviations for RLX, RLY, RLZ respectively. If the user enters PCERR and SDMIN values when running TEM2Mom, sds will be computed and recorded by TEM2Mom. Alternatively, the user can assign sds by editing the moment data file.

If the RLXE, RLYE, RLZE records are deleted from the PAR file, VPem3D will ignore the sds in the moment data file and assign the universal error defined in the control file to all data. The sds recorded in the moment data file will also be ignored if they are all zero, which is the default, i.e. when PCERR and SDMIN are not defined by the user.

```
#VPEM2
TEM2Mom_2019-04-04_0.mom
10
-3
4       RLX
5       RLY
6       RLZ
7       PROXYSTN
8       RLXE
9       RLYE
10      RLZE
```

Figure 5.7: VPem3D parameter (PAR) file for #VPEM2 format resistive limit data file generated by TEM2Mom.

5.3 Creating a starting model

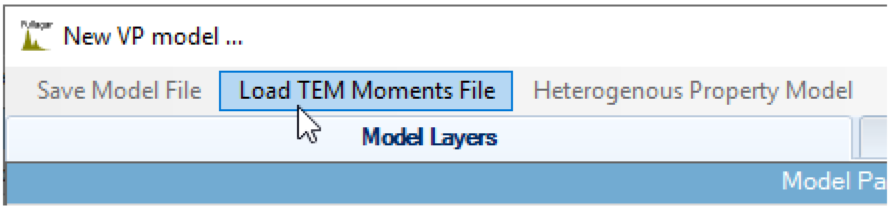
Simple layered starting models for VPem3D can be created using the *Create New Model* utility in the VPview/Model menu.

For unconstrained inversion, the starting model can consist of a single uniform conductivity host unit overlying VPem3D basement. The host unit 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 shallowest sub-cell 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.

If the user specifies the TEM moment ("resistive limit") data file when running the *Create New Model* utility, VPview inserts default model parameters into the Model Parameters table, based on information in the data file header. These defaults are suitable for unconstrained inversion, i.e. for a model comprised of a single host unit on basement. For further details, see Section 12.3 (if a DTM is available) or Section 13.4 (in the absence of a DTM).



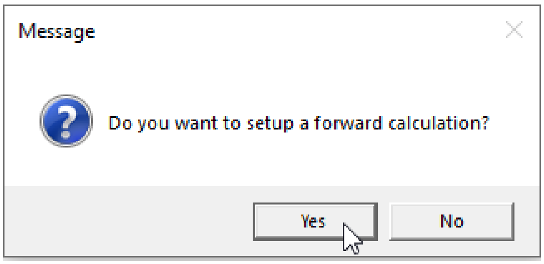
Impose constraints, if available. If intending to perform geometry inversion, flag model contacts as fixed, bounded, or free depending on their geometrical relationship to existing drill holes; see Section 2.3 above. The constraint flags are defined in Section 7.4 below. If intending to perform heterogeneous 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.

A global noise level (uncertainty) can be defined in the control file in moment data units [pTms/A]. Alternatively, individual sds can be defined in the moment file. The individual errors will be adopted by VPem3D if the VPem3D PAR file includes entries for RLXE, RLYE, and/or RLZE.

A control file is required for a forward calculation. VPview can create a control file at the end of a *Create New Model* process.



Alternatively, 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\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. Depth weights can be applied during model construction when using the Create New Model utility, as described in Section 12.3Application 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 *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.

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 2.15 above. Depth weighting, described in Section 2.12, 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 fixed loop 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 fixed loop ground TEM. Moving loop ground TEM and downhole TEM can be inverted simultaneously provided the Tx loop for the downhole data is rectangular.

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. TEM2Mom outputs the moment (“resistive limit”) data in a column ASCII format, as described in Section 7.2 below. The moment data file has extension XYZ. TEM2Mom also creates a VPem3D PAR file, which defines the fields in the XYZ file.

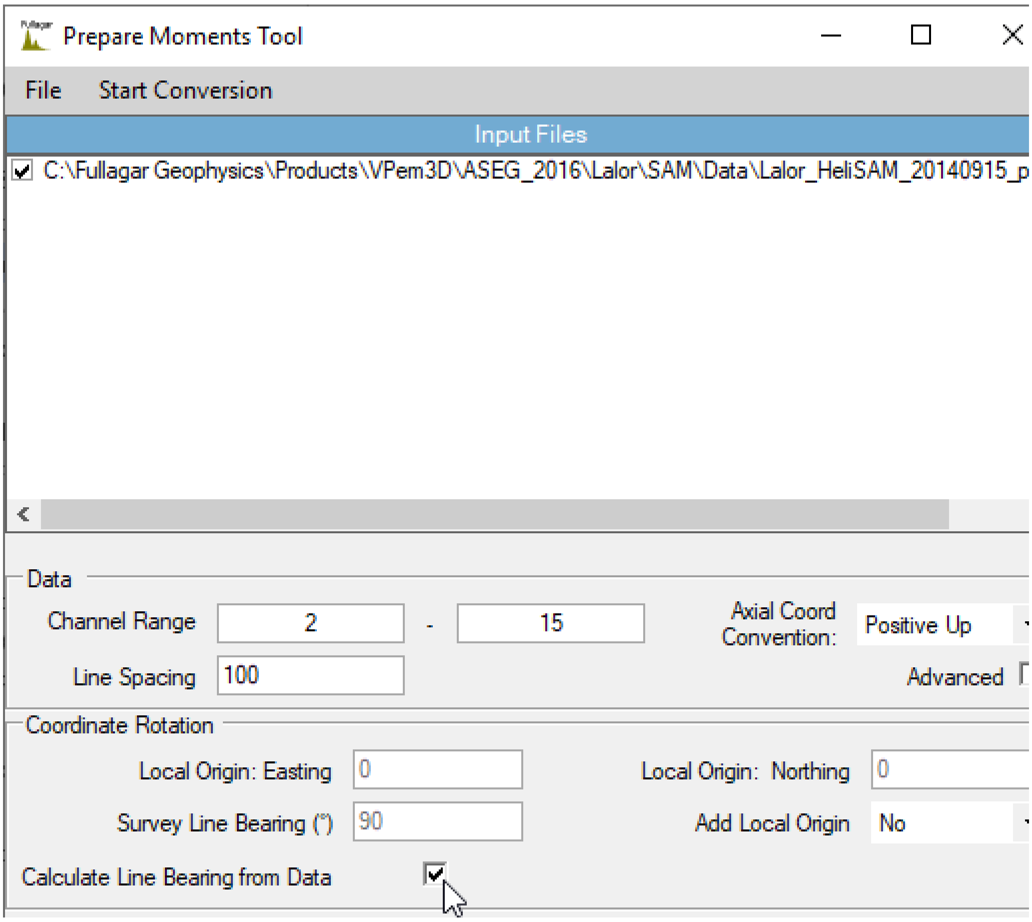
Care is required with component labels and polarity. There is no universal standard for ground TEM acquisition, but commonly the along-line survey component is labelled “x”. The polarity of the x-component may be positive in a nominated direction, e.g. northeast for a set of NE-SW survey lines, or polarity 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 east, north, and up respectively in the coordinate system adopted for the conductivity model. It is standard practice (but not essential) for the VPem3D x and y model axes to be oriented parallel and perpendicular respectively to survey lines. If the survey lines are oblique, i.e. neither N-S nor E-W in the contractor’s coordinate system, TEM2Mom can rotate the data. The *Coordinate Rotation* parameters can be entered using the form shown in Figure 5.3. The *Survey Line Bearing* is the clockwise angle in degrees from north (as defined in the contractor’s coordinates). The bearing defines the orientation of the rotated x-axis (local east). The default *Survey Line Bearing* is 90^o; no rotation is applied by TEM2Mom in that case.

It is often convenient to allow TEM2Mom to determine the *Survey Line Bearing* and local origin from the TEM data. To trigger this option, check the *Calculate Line Bearing from Data* box (see image below).

Whether the local coordinate system parameters are defined by the user or computed by TEM2Mom, only the Tx vertex and Rx locations are rotated; the TEM components delivered by the contractor are assumed to be oriented parallel and perpendicular respectively to survey lines. Thus the *Survey Line Bearing* defines the orientation of the positive x-component.

Model construction for unconstrained inversion can be expedited using default parameters computed by TEM2Mom and recorded in the moment data file header. The user can (optionally) nominate the moment data file when running the *Create New Model* utility. The line spacing has an important bearing on the default parameters, but cannot be reliably determined by TEM2Mom, even if the line spacing is uniform, because ground TEM data recorded along individual survey lines are often recorded in separate TEM files. Therefore the user is invited to enter the *Line Spacing* on the TEM2Mom form (see below).



TEM2Mom does not rotate the horizontal TEM components because the usual convention adopted by contractors is to define the "X" component along-line. Thus the VPem3D convention is compatible with the "standard" contractor's convention: in the rotated coordinate system, the VPem3D local east (RLX) moment will relate directly to the measured TEM X-component, though there might still be an issue with polarity. Likewise, the local north (RLY) moment will relate directly to the measured TEM Y-component (assuming the contractor's "Y" is across line), though care is required to ensure that the contractor's Y-component is positive in the rotated y-direction. 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 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 VPem3D PAR file and, if necessary, the moment data file (…MOM.XYZ) generated by TEM2Mom. The most convenient way to interchange RLX and RLY is to swap their respective column indices in the PAR file. The VPem3D 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 moment data 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 labelling and polarity conventions in order to ensure that the correct survey geometry is communicated to VPem3D.

TEM2Mom can compute standard deviations for the moment components. The user can define a percentage error, PCERR, and a noise floor, SDMIN, by checking the “Advanced” box (Figure 5.4). The noise floor is in original TEM data units, e.g. pT/A or nT/s. TEM2Mom computes the corresponding errors associated with the moment (“resistive limit”) data. **Care is required** if setting a percentage error, especially if the starting model has zero conductivity. In that case, if SDMIN is small, the normalised residuals (which drive the inversion) will assume a boxy form, alternating from approximately +V to approximately –V, where V = 100/PCERR, at the start of the inversion. This is very undesirable because the smallest anomaly will have the same normalised amplitude as the largest anomaly. Assigning a realistic percentage error is not problematic if the starting model is non-zero in conductivity. If using a zero conductivity starting model (which is often convenient), percentage errors can be introduced after a few iterations, if desired.

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, as described in Section 12.3.

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 for ground TEM. Such prism dimensions will capture the full resolution of the survey. Ideally, the model prism centres should coincide with data points.

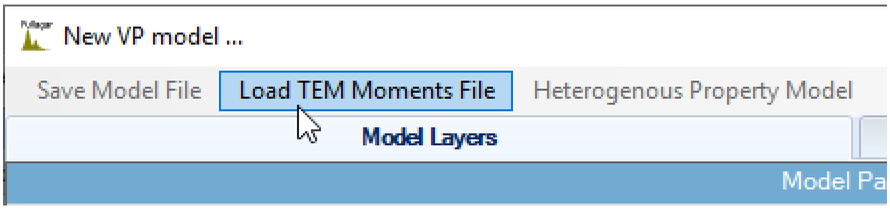
The *Create New Model* utility generates “homogeneous” layered models, with a single cell spanning the entire thickness of each layer. Thus each layer (geological unit) is uniform in conductivity initially. In order to permit conductivity variations within layers, they must be converted to heterogeneous 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 for more detail.

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, Exp Fac, can be applied to the thickness of successive cells during model construction. The expansion factor is entered as a percentage. For example, if Exp Fac is 10%, 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 the user specifies the TEM moment data file (output from TEM2Mom) when running the *Create New Model* utility, VPview adopts default model parameters based on information recorded in the data file header. These defaults define a model comprising a single host unit on basement, suitable for unconstrained inversion, for. For further details, see Section 12.3 (if a DTM is available) or Section 13.4 (in the absence of a DTM).



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

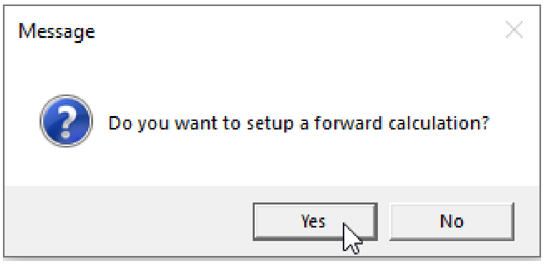
Depth weighting, briefly described in Section 2.12 above, is often applied prior to "unconstrained" heterogeneous unit inversion; the procedure is illustrated in Section 13.8. Conductivity weighting, which focusses changes in the conductive zones, is often beneficial if the starting model is based on 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.

A global noise level (uncertainty) can be defined in the control file in moment data units [pTms/A]. Alternatively, individual sds can be defined in the moment file. The individual errors will be adopted by VPem3D if the VPem3D PAR file includes entries for RLXE, RLYE, and/or RLZE.

A control file is required for a forward calculation. VPview can create a control file at the end of a *Create New Model* process.



Alternatively, 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\Run VPxx from file* option.

An initial forward calculation allows the interpreter to assess the contribution from a uniform host conductivity. 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**}**]		
pert	∆property	[User_ROI]			
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.

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 = 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.

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 ≥ 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 jth 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 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 jth 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.

pert or *BodyRad* If running geometry inversion (*ild*=2), *pert* is the maximum relative change in interface depth per iteration, *Δdepth*. For example, *pert* =0.1 permits a change of at most 10% of the depth during each iteration.

If running compact body inversion (*ild*=299), *BodyRad* is the maximum radius (m) of the conductive body introduced during a single iteration. For example, *BodyRad*=40 restricts all changes in conductivity during each iteration to a 40m radius sphere centred on the seed cell. If *BodyRad*=0, the restriction is removed and changes in conductivity are not necessarily localised around the seed cell.

Δproperty Maximum absolute change in density (g/cm^3), susceptibility (10^{-3} SI), conductivity (mS/m), or time constant (µs) per iteration (*ild*=0,1, -1 inversion).

User_ROI This parameter (referred to as W in Section 16) controls damping weights in a "neighbourhood of influence" around underground data points or around drill hole constraints (property or geometry). The *User_ROI* parameter usually defines the radius of influence (in metres). *User_ROI* is usually optional; if it is missing, the default "neighbourhood of influence" is used (2.5*diagonal cell size for property inversion, 1m for geometry inversion).

For underground data points, there are two types of proximity weights which can be applied during heterogeneous property inversion: function-based and derivative-based. For function-based weights, *User_ROI* ≥1 and 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. Additional details are provided in Section 16.1. For derivative-based data proximity weights, 0 < *User_ROI* < 1. Derivative based weights cannot be applied during compact body inversion. For additional details see Section 16.2.

If the *User_ROI* < 0 for heterogeneous inversion, the Tx loop, data proximity, and fixed cell weights are only computed if the starting model is "new", i.e. if *ibackg*=0 (where *ibackg* is defined in Section 7.4 below). If *ibackg*=0, the calculation of weights is governed by the absolute value, |*User_ROI*|, and the final weights (combining depth ± conductivity ± Tx loop ± data proximity ± fixed cell effects) are recorded at the end of the output model file. In subsequent VPem3D runs with *User_ROI* < 0, if the starting model is "old" (*ibackg*≠0), the weights read from the model file are treated as final weights, and are applied during inversion without modification. This is advantageous because (a) it saves some run time, and (b) it allows the final weights (not just depth +/- conductivity weights) to be displayed in VPview. However, recording final weights in the model file can cause confusion if different styles of inversion are run in succession: it is possible for VPem3D to modify existing weights in unintended ways if at some stage *ibackg* is re-set to zero. In addition, because of the model file format (defined in Section 7.4), the dynamic range of the recorded weights is only $1{:}10^4$.

observed.par File to define the name and format of the resistive limit data file, and the data components to be inverted. The par file rootname is arbitrary, but it must have extension ".par". The par file format is defined in Section 7.3 below.

calculated.out Model File containing inverted model plus observed and calculated data. The output model filename is arbitrary, but files with extensions ".con" or ".mod" are recognised as models by VPview.

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 #VPEM2 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,
(iv) the columns in the data file where the transmitter coordinates are recorded and, optionally,
(v) the columns in the data file where the standard deviations associated with the data components reside.

7.3.1 VPem3D parameter file format for airborne TEM

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. The format of the PAR file for airborne data is 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 for the "resistive limit" components are RLX, RLY, RLZ for the east, north, and vertical components respectively.

Then *3* records of the form $column_n$ Lid_n where

VDX colTxX or CDX colTxX

VDY colTxY or CDY colTxY

VDZ colTxZ or CDX colTxZ

Then 2 records

LINE colLINE

DEM colDEM

Then nch records of the form $column_n$ $chnum_n$ *defining the number of channels contributing to each moment component,* where

$column_n$ Column number for the channel count for the *n*th component.

$chnum_n$ NTGX, NTGY, or NTGZ as appropriate for the *n*th data channel.

Finally, nch records of the form $column_n$ sd_n *defining the standard deviation estimated for each moment component,* where

$column_n$ Column number for the sd for the *n*th component

sd_n RLXE, RLYE, or RLZE as appropriate for the *n*th data channel.

There are two variants of the PAR file format for large loop (ground and downhole) TEM, a moving loop format (#VPEM#) and a fixed loop format (#VPEM2).

7.3.2 VPem3D parameter file format for moving loop ground TEM

Rectangular loops are assumed for moving loop ground TEM. The details of the moving loop (#VPEM#) PAR file 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 can also be used for fixed loop surveys with quadrilateral Tx loops.

7.3.3 VPem3D parameter file format for fixed loop ground and downhole TEM

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 for resistive limit components are RLX, RLY, RLZ.

Then (optionally) *nch* records of the form $column_n$ $sdid_n$ where

$column_n$	Column number for the *n*th data channel.
$sdid_n$	4-character ID for the standard deviation of the *n*th data channel. The legal channel identifiers resistive limit component sds are RLXE, RLYE, RLZE.

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, either select "Positive Down" *Axial Coord Convention* in VPview or 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.

7.3.4 Command line conversion of ground and downhole TEM data

TEM2Mom can be launched from VPview or from command line. Examples of command line syntax are shown below:

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 15000000.
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}]		
$dlay_1$	$dmin_1$	$dmax_1$	[Q_1	dec_1	inc_1]	$label_1$	
$dlay_2$	$dmin_2$	$dmax_2$	[Q_2	dec_2	inc_2]	$label_2$	
…….							
$dlay_{nlay}$	$dmin_{nlay}$	$dmax_{nlay}$	[Q_{nlay}	dec_{nlay}	inc_{nlay}]	$label_{nlay}$	
elevback	densback		ehsfix				
ibackg	minel	imask	distmask [elmin]				
$east_1$	$north_1$	$elev_1$	$nlay_1$	$elev(1)_1$	$flag(1)_1$	…..$elev(nlay_1\text{-}1)_1$	$flag(nlay_1\text{-}1)_1$
$east_2$	$north_2$	$elev_2$	$nlay_2$	$elev(1)_2$	$flag(1)_2$	…..$elev(nlay_2\text{-}1)_2$	$flag(nlay_2\text{-}1)_2$
…….							
$east_n$	$north_n$	$elev_n$	$nlay_n$	$elev(1)_n$	$flag(1)_n$	…..$elev(nlay_n\ \text{-}1)_n$	$flag(nlay_n\ \text{-}1)_n$
Basement Block title							
$eastb_1$	$northb_1$	$elevb_1$	$propertyb_1$			[$baseb_1$]	
$eastb_2$	$northb_2$	$elevb_2$	$propertyb_2$			[$baseb_2$]	
…….							
$eastb_n$	$northb_n$	$elevb_n$	$propertyb_n$			[$baseb_n$]	
title3 for Heterogeneous Unit Block				nhetu	nhetc	ihu	
$eastc_1,northc_1,nheti_1,${$ihu(j)_1,zt(j)_1,zb(j)_1,nsc(j)_1,$j=1,$nheti_1$}{[$phet(k)_1,pflag(k)_1,$k=1,$nsc(j)_1$],j=1,$nheti_1$}							
$eastc_2,northc_2,nheti_2,${$ihu(j)_2,zt(j)_2,zb(j)_2,nsc(j)_2,$j=1,$nheti_2$}{[$phet(k)_2,pflag(k)_2,$k=1,$nsc(j)_2$], j=1,$nheti_2$}							
….							
$eastc_n,northc_n,nheti_n,${$ihu(j)_n,zt(j)_n,zb(j)_n,nsc(j)_n,$j=1,$nheti_n$}{[$phet(k)_n,pflag(k)_n,$k=1,$nsc(j)_n$], j=1,$nheti_n$}							
title4 for Responses Block							
$eastd_1$	$northd_1$	$elevd_1$	obs_1	$calc_1$	[Bx_1,By_1,Bz_1]		**$back_1$**
$eastd_2$	$northd_2$	$elevd_2$	obs_2	$calc_2$	[Bx_2,By_2,Bz_2]		**$back_2$**
….							
$eastd_n$	$northd_n$	$elevd_n$	obs_n	$calc_n$	[Bx_n,By_n,Bz_n]		**$back_n$**

[DC_SHIFT dc]
[DAT_NORM dnorm]

Extended VP model format for rotated models:

Prism centres defined in real world coordinates.
Changes to header:
MOD_3D# -> #VP_ROT#
XMIN & YMIN unchanged
XMAX -> local east model extent
YMAX -> local north model extent
THETA (bearing of local north, clockwise from real world north): extra parameter on the XMIN, XMAX, YMIN, YMAX record

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.
xmax	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". xmax is defined in the model coordinate system. It is the coordinate of the external wall of the most "easterly" boundary prism. It is xcell/2 greater than the most "easterly" prism centre.
ymin	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". ymin is defined in the model coordinate system. It is the coordinate of the external wall of the most "southerly" boundary prism. It is ycell/2 less than the most "southerly" prism centre.
ymax	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". ymax is defined in the model coordinate system. It is the coordinate of the external wall of the most "northerly" boundary prism. It is ycell/2 greater than the most "northerly" prism centre..
xcell	Dimensions of model cells in E-W direction (m).
ycell	Dimensions of model cells in N-S direction (m).
nlay	Total number of geological units, including basement, in model. *nlay*=1 for basement-only models, e.g. terrain models. If nlay < 0, some of the geological units are heterogeneous.
nhet	Number of heterogeneous units; required only when *nlay* < 0.
uindex(j)	Unit index for the jth heterogeneous unit; required only when *nlay* < 0. If *uindex(j)* < 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 *uindex(j)* > 0, the property weights from the Heterogeneous Unit block are ignored.
dzsc(j)	Notional sub-cell dimension (m) for the jth heterogeneous unit; required only when *nlay* < 0.
$dlay_n$	Density, susceptibility, or conductivity of unit n (g/cm^3, 10^{-3} SI, or mS/m respectively).

$dmin_n$	Lower limit of density, susceptibility, or conductivity in inversion for unit n (g/cm^3, milli SI, or mS/m). If *$dmin_n$=$dmax_n$*, the property of the nth layer is fixed, i.e. plays no part in inversion.
$dmax_n$	Upper limit of density, susceptibility, or conductivity in inversion for unit n (g/cm^3, milli SI, or mS/m). If *$dmin_n$=$dmax_n$*, the property of the nth layer is fixed, i.e. plays no part in inversion.
Q_n	When the linear algorithm is selected (*igrav* = -4), current flow for unit n is confined to planes with a preferred orientation (strike *dec_n* and dip *$dinc_n$*) if Q_n = -1. Only the primary field component orthogonal to these planes contributes to the magnetic dipole moments. No preferred orientation if $Q_n \geq 0$.
	When the non-linear algorithm is selected (*igrav* = 4), Q_n = Cmin in mS/m, where Cmin is the threshold conductivity for non-linear calculations. The response from cells with conductivity < Cmin is computed using the linear algorithm. If $Q_n \leq 0$ the default Cmin value is 999.9 mS/m.
dec_n	Preferred strike (clockwise angle in degrees from VP model north) of unit n applied during linear calculations (*igrav* = -4) if Q_n = -1. Ignored if $Q_n \geq 0$.
$dinc_n$	Preferred dip (angle in degrees, clockwise down when looking in the preferred strike direction) of unit n applied during linear calculations (*igrav* = -4) if Q_n = -1. Ignored if $Q_n \geq 0$.
$label_n$	Text description of geological unit n.
elevback	Background elevation for uniform half-space enclosing model (m). Read from regional model file if one exists; otherwise from local model.
densback	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.
ehsfix	*ehsfix = 1*: enclosing half-space property fixed during inversion
	ehsfix = 0: enclosing half-space property variable during inversion
	Read from regional model file if one exists; otherwise from local model.
ibackg	Background response calculation flag. Read from local model file if one exists; otherwise from regional model.
	ibackg = 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.
	ibackg = 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 (*ild=2*), setting *ibackg=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.
	ibackg = 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 *ibackg* is zero initially, *VPem3D* re-sets *ibackg* to 2 in the output file; in that sense *ibackg=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 *itmax* is large.
	ibackg = -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 *minel* = -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 *elmin* value specified for the *minel* = -1 run, i.e. top of EHS coincides with the base of the extra layer. In all other respects, *ibackg* = -1 is equivalent to *ibackg* = 0.
minel	Controls the basal elevation of model prisms, below which a uniform half space is assumed. If *minel = 0* then -25 km is adopted as the model base. If *minel = 1*, model base is at RL=0 (usually sea level); this is appropriate for terrain effect calculations.

	minel = 2 is a special test setting. *minel = 3* for the "irregular heterogeneous layer" option [section 2.11]. If *minel* = -1, the base of the model is arbitrary, i.e. in this case *elmin* 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, *elmin* is the RL of the seafloor. The top of the "enclosing half-space" is at elevation *elevback*, as usual. The *minel* = -1 option is used in combination with the *ibackg* = -1 option if a 2-layer "enclosing half-space" is required, e.g. for seafloor gravity.VPem3D adopts the *minel* value read from the active model, i.e. from the local model file if one exists or otherwise from the regional model.
imask	Allows the user to restrict inversion to model prisms which are within a certain range, *distmask*, of data points. If *imask = 0*, a default *distmask* value is adopted by VPem3D: only prisms within the default horizontal radius *distmask* of a data point will contribute to its derivatives. If *imask = 1*, the default *distmask* applies to derivative calculations (as for *imask = 0*) and all interfaces are fixed in prisms further than the default *distmask* radius from the nearest data point during geometry inversion. For property inversion ($ild \neq 2$), *imask = 1* is equivalent to *imask = 0*. If *imask = 2*, the *distmask* radius is specified by the user (see below). The effect of *imask = 2* is as for *imask = 1*, except that the horizontal "radius of influence" is prescribed by the user. VPem3D adopts the *imask* value from the local model file if one exists; otherwise from the regional model.
distmask	Radius of influence (in metres) for derivative calculations. See *imask* above. A value of *distmask* is required when *imask = 2*; otherwise the *distmask* parameter is dummy. Read from local model file if one exists; otherwise from the regional model.
[elmin]	Defines the basal elevation of model prisms, below which a uniform half space is assumed. *elmin* is used only in the special case when *minel* = -1. *elmin* is read from the active model file.

$east_n$	Easting of centre point of vertical prism n. [Geological units not defined if *nlay = 1*, i.e. basement only model. See Note 1 below]
$north_n$	Northing of centre point of vertical prism n. [Geological units not defined if *nlay = 1*, i.e. basement only model. See Note 1 below]
$elev_n$	Surface elevation of top of vertical prism n. [Geological units not defined if *nlay = 1*, i.e. basement only model. See Note 1 below]
$nlay_n$	Number of cells or interfaces in prism n, including the basement.
$elev(j)_n$	Elevation of interface at base of cell j within vertical prism n.
$flag(j)_n$	Flag controlling whether the interface at $elev(j)_n$ 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

$$FLAG(j,n) = IFLAG(j,n) + \mathrm{sgn}\{IFLAG(j,n)\} * \frac{INDD(j-1,n)}{100}$$

where *IFLAG(j,n)* denotes the 2D format integer interfacial flag, and where *INDD(j-1,n)* is the index for the geological unit assigned to the cell immediatel;y above the interface. [Note that interface j is at the base of the (j-1)th cell.]

$iflag(j)_n$ *= 0* : free interface (bounded above by the ground surface)

$iflag(j)_n$ *= 1* : 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.

$iflag(j)_n$ *= 2* : fixed interface, constrained by the operator or by VPem3D, e.g. if *imask=1*. A contact flagged with 2 will not affect parameter weighting during geometry inversion. Use 2 flags to fix contacts which are not drilled.

$iflag(j)_n$ *= -1* : fixed "artificial" interface, to restrict movement of a free interface during inversion. Imposed owing to a near-miss by drill hole(s)

$iflag(j)_n$ *= -2* : fixed "artificial" interface, to restrict movement of a free interface during inversion. Imposed operator.

$iflag(j)_n$ *= -3* : fixed "artificial" interface between sub-cells in a heterogeneous unit.

title2	Basement section title. Must begin with the word "Basement", starting in first column.
$eastb_n$	Easting of centre point of vertical prism n.
$northb_n$	Northing of centre point of vertical prism n.
$elevb_n$	Elevation of top of basement within vertical prism n.
$propertyb_n$	Basement density (g/cm^3), susceptibility (10^{-3}SI), or conductivity (mS/m) within vertical prism n.
$baseb_n$	Elevation of base of heterogeneous layer in vertical prism n. Only required for the special heterogeneous layer option. See section 2.11

title3	Title for Heterogeneous Unit block. Must begin with the word "Heterogn", starting in first column.
nhetu	Number of heterogeneous units defined in this block. *nhetu=1*.
nhetc	Number of sub-cells in the heterogeneous unit #ihu.
ihu	Index (unit number) for the heterogeneous unit defined in this data block.
$eastb_n$	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.
$northb_n$	Northing of centre point of vertical prism n.
$nheti_n$	Number of intervals of heterogeneous units within vertical prism n. There may be more than one interval of a particular heterogeneous unit.
$ihu(j)_n$	Unit index identifying the jth interval of a heterogeneous unit within vertical prism n; j increases downwards.
$zt(j)_n$	Elevation of top of the jth interval of a heterogeneous unit in vertical prism n.
$zb(j)_n$	Elevation of bottom of the jth interval of a heterogeneous unit in vertical prism n.
$nsc(j)_n$	Number of cells which comprise the jth 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 kth cell within the jth 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 kth cell within the jth 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. Note that if v=0.nnnn is the *pflag* value recorded in the model file, the weight actually applied to the parameter derivatives during inversion is 1-v.

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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9 USER SUPPORT

Peter Fullagar
Fullagar Geophysics Pty Ltd
Vancouver
Canada
GMT -8 hours (GMT -7 hours in northern summer)
peter@fullagargeophysics.com
phone: +61 3 6229 5631
mobile: +1 778 847 3428

James Reid
Mira Geoscience Asia Pacific Pty Ltd
Perth
Australia
GMT +8 hours
jamesr@mirageoscience.com
phone: +61 8 9429 8838

Phil Muir
Fullagar Geophysics Pty Ltd
Hobart
Australia
GMT +10 hours (GMT +11 hours in southern summer)
phil@fullagargeophysics.com
phone: +61 3 6229 5631

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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. The same format is used for the VPem1D long form PAR file.

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.

4	**ILINE, IX, IY, IALT, IDATI, IDATF, ITXRL, IOFFX, IOFFZ, ItxCrnt, [IDEM, IRALT, IDATI2, IDATF2, IDATI3, IDATF3]**

ILINE	column number containing flightline or line number; ILINE can be zero if data file is in Geosoft XYZ format (with line block identifiers)
IX	column number containing eastings.
IY	column number containing northings.
IALT	column number containing transmitter altitude (metres above ground surface).
IDATI	column number containing first TEM window to be processed; if X & Z components are inverted simultaneously, IDATI refers to the along-line (X) component.
IDATF	column number containing last TEM window to be processed; if X & Z components are inverted simultaneously, IDATI refers to the along-line (X) component.
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).
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.
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.
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.
IDEM	column number containing digital elevation of ground surface
IRALT	column number containing receiver altitude (metres above ground surface).
IDATI2	Not required for inversion of single component; leave blank in that case. If X & Z components are processed simultaneously, IDATI2 is column number containing first TEM window for the vertical (Z) component. If X, Y, & Z components are processed simultaneously, IDATI2 is column number containing the first TEM window for the transverse (Y) component.
IDATF2	Not required for inversion of single component; leave blank in that case. If X & Z components are processed simultaneously, IDATF2 is column number containing last TEM window for the vertical (Z) component. If X, Y, & Z components are processed simultaneously, IDATF2 is column number containing the last TEM window for the transverse (Y) component.
IDATI3	Not required unless processing 3 components. If X, Y, & Z components are processed simultaneously, IDATI3 is column number containing first TEM window for the vertical (Z) component.
IDATF3	Not required unless processing 3 components. If X, Y, & Z components are processed simultaneously, IDATF3 is column number containing last TEM window for the vertical (Z) component.

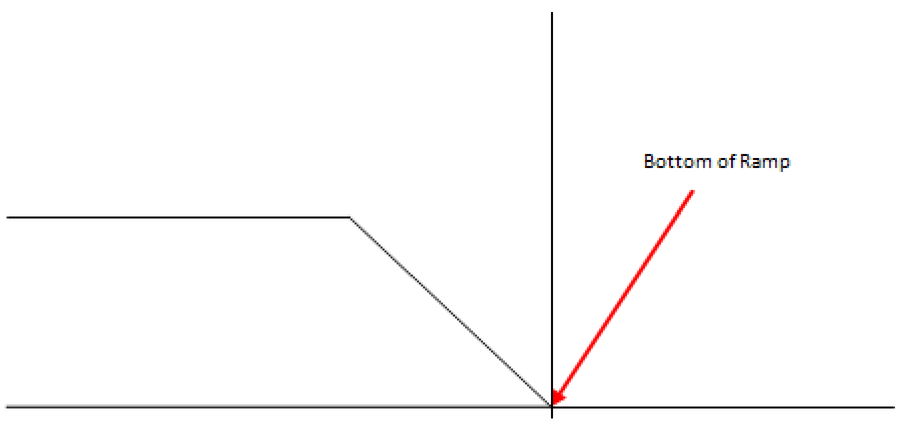
The TEM data columns are assumed sorted in order of increasing delay time.

Data files with up to 100 columns can be read.

IDEM, IRALT, IDATI2, IDATF2, IDATI3, IDATF3 are optional.

5	**LMIN, LMAX** 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.
6	**XMIN, XMAX, YMIN, YMAX** 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.
7	**IDAT, ConversionFactor** 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). Data can be multiplied by **ConversionFactor** to convert them to VPem3D "standard units"; see **data unit** column in Tables 11.1 and 11.2.
8	**NSKIP, POSLAG** NSKIP stations skipped between each station processed. Set NSKIP = 0 to process decays at all stations. 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 *If POSLAG = 1 or -1, coords are altered to Tx-Rx midpoint.* *If POSLAG = 0, coords are not altered.*
9	**TXFREQ, TXMOM, RXAREA** TXFREQ is the transmitter "fundamental" operating frequency (Hz), e.g. 0.125Hz (for 2 sec bi-polar square wave TEM data) 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. RXAREA is the effective area of the receiver (turn.m^2). For B-field data, (|IDAT|=2), RXAREA is arbitrary. Normally set it to 1.

10	**PULSE, ISTEP** PULSE is the duration of maximum Tx current, in microseconds. Dummy parameter for AEM2Mom. ISTEP = 0 for slingram configuration, with arbitrary waveform. Use this option for GEOTEM, with appropriate half-sine waveform defined in a WVF file*. ISTEP = 1 for 100% duty cycle waveform, slingram configuration (TEMPEST, SPECTREM) 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. ISTEP = -4 for SkyTEM, with waveform defined in a WVF file*. ISTEP = -5 for VTEM, with waveform defined in a WVF file*. *AEM2Mom processing is independent of waveform at present
11	**MODE** MODE = 1 for horizontal-axis receiver (normalized w.r.t. primary horizontal component if data is in ppm, i.e. IDAT>0) MODE = 12 for horizontal-axis receiver (normalized w.r.t. primary vertical component if IDAT>0) MODE = 10 for horizontal-axis receiver (normalized w.r.t. total primary field if IDAT>0) MODE = 2 for vertical-axis receiver (normalized w.r.t. primary horizontal component if data is in ppm, i.e. IDAT>0) MODE = 22 for vertical-axis receiver (normalized w.r.t. primary vertical component if IDAT>0) MODE = 20 for vertical-axis receiver (normalized w.r.t. total primary field if IDAT>0) MODE = 3 for simultaneous processing of both along-line and Z-components (normalised w.r.t. their respective primary components if IDAT>0). MODE = 32 for simultaneous processing of both X- and Z-components (normalised w.r.t. the primary vertical component if IDAT>0).
12	**R, DEL0, ALT0** 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. DEL0 is the notional (survey spec) vertical Tx-Rx separation (metres). DEL0 > 0 if the Tx is above the Tx; DEL0 < 0 if the Tx is below the Rx. ALT0 is the horizontal offset of the Rx from the centre of the Tx for SkyTEM (ISTEP=-4) and VTEM (ISTEP=-5) systems. Otherwise, ALT0 is the notional (survey spec) Tx altitude (metres) . *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) .* *The “actual” Tx altitude (from radar altimeter) at each station is normally read from the TEM data file.*

13	**T, CHW, PCERR, SDMIN** 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. ***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.* *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.*  *A zero channel width, corresponding to instantaneous recorded voltages, is not valid in this version.* *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).*
13 + NCH	**ITMAX, PERT, TOL, IPRINT** **4 dummy parameters for AEM2Mom** ITMAX is the maximum number of iterations allowed for determination of apparent conductivity for one time window. *Usually 10.* PERT is the maximum fractional change in the conductivity at each iteration. *Usually 0.5.* 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. *Usually 0.01.* IPRINT controls the written output. If IPRINT = 0, the written output is minimal.
14 + NCH	**IINT** **Dummy parameter for AEM2Mom** 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. IINT is a dummy parameter for step-current systems (ISTEP = 1, -1).

15 + NCH	**SIG1, SIG1MAX** **2 dummy parameters for AEM2Mom** SIG1 is the initial conductivity estimate (S/m) for the *first channel* at the *first station*. 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). 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.
16 + NCH	**PCERR0, SDMIN0** The standard deviation of the nth TEM channel value Vn is estimated as SDn = PCERR0*|Vn|/100 + |SDMIN0| 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). |SDMIN0| is the minimum allowable standard deviation, or noise floor, (in TEM data units) unless a specific SDMIN value has been defined for the TEM Channel (see above). Express as ppm or in dimensional units according to the value of IDAT. SDs based on percentage error alone can become unreasonably small at late times, as the signals decay. |SDMIN0| is an absolute error, which can be regarded as the noise floor. If SDMIN0 > 0, TEM channels within the specified range (columns IDATI to IDATF, and IDATI2 to IDATF2 and IDATI3 to IDATF3 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 SDMIN0 < 0, TEM channels within the specified column 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 or three components are being processed, the same SDMIN0 is applied to all. If the resistive limit is based on fewer than 1/3 of the number of selected channels, it will be rejected.

17 + NCH	**ISHARP, ITSHEET, OutputFmt** **3 dummy parameters for AEM2Mom** **ISHARP** = 0 : no "sharpening" is applied. ISHARP = 1 : the original apparent conductivities are treated like conductances, and are differentiated to produce a final "sharpened" apparent conductivity versus depth profile. ISHARP = 2 : the original apparent conductivities are treated like inner products of the true conductivity with the linear sensitivity functions of Christensen (*Geophysics, 2002, 67, 438-447*). 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. **ITSHEET** = 0 : homogeneous halfspace model for conductivity calculation (NORMAL USE). ITSHEET = 1 : thin sheet model for conductivity calculation (*only for Hoistem*, IF DESIRED). **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; option A, flag = 1 : standard "CDI" format. option B, flag = 2 : Geosoft XYZ format – with Line headers; one output file per flightline. option C, flag = 4 : Geosoft XYZ format – with flightline column but *no* Line headers. option D, flag = 8 : Geosoft XYZ format – suitable for array channel import to Oasis Montaj. Set OutputFmt equal to the *sum of the flags* 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**. *A maximum value of 10 S/m is enforced if sharpening is applied, i.e. if ISHARP = 1 or 2.*
18 + NCH	**IHC** **Dummy parameter for AEM2Mom** 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. IHC = 0 : no height-corrected data output. IHC = 1 : yes, height-corrected data output. IHC = -1 : yes, height-corrected data output : written in Hoistem binary BDB format. *Output data units are always those defined by IDAT.* *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.* **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.***
19 + NCH	**RON, ROFF** **2 dummy parameters for AEM2Mom** RON is the Tx ramp turn-on time (microseconds) ROFF is the Tx ramp turn-off time (microseconds) 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.

20 + NCH	**#WAVEFORM# <filename>** <filename> is the name of a WVF file containing an arbitrarily defined waveform. ***THIS RECORD IS OPTIONAL – waveform is not used by AEM2Mom*** *If it is present then the standard waveform defined above by ISTEP, RON, ROFF will be ignored and the arbitrary waveform used instead.* A waveform file is not required for Hoistem & Aerotem (ISTEP=-1) or for Tempest & Spectrem (ISTEP=1). The file should contain two columns separated by spaces or a comma; Time (seconds) and Current (normalised to 1 maximum). 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.
21 + NCH	**#ROTATE# DEC XREF YREF IADD or #ROTATE# -999** ***This record is only required if flight line coordinates are adopted*** DEC is the bearing of flight lines in degrees clockwise from survey north. XREF is the survey easting of the origin of the local coordinate system. YREF is the survey northing of the origin of the local coordinate system. IADD = 1 if XREF is added to local eastings and YREF is added to local northings; otherwise IADD = 0 AEM2Mom computes default rotation parameters if #ROTATE# -999 is entered.

Table 11.1: AEM2Mom parameter combinations for dB/dt systems

dB/dt system	data unit	IDAT	ISTEP	MODE	ConversionFactor	Tx Moment (Am^2)	RxArea (m^2)
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 (μs), and PULSE=0 (see Section 2.3 below)

Table 11.2: AEM2Mom parameter combinations for B-field systems

B-field system	data unit	IDAT	ISTEP	MODE	Conversio n 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

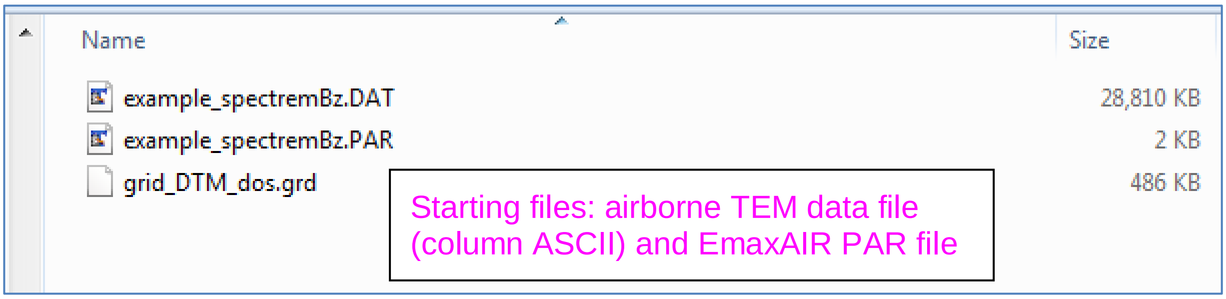
12 APPENDIX B: Example Airborne TEM Inversion

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.

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.

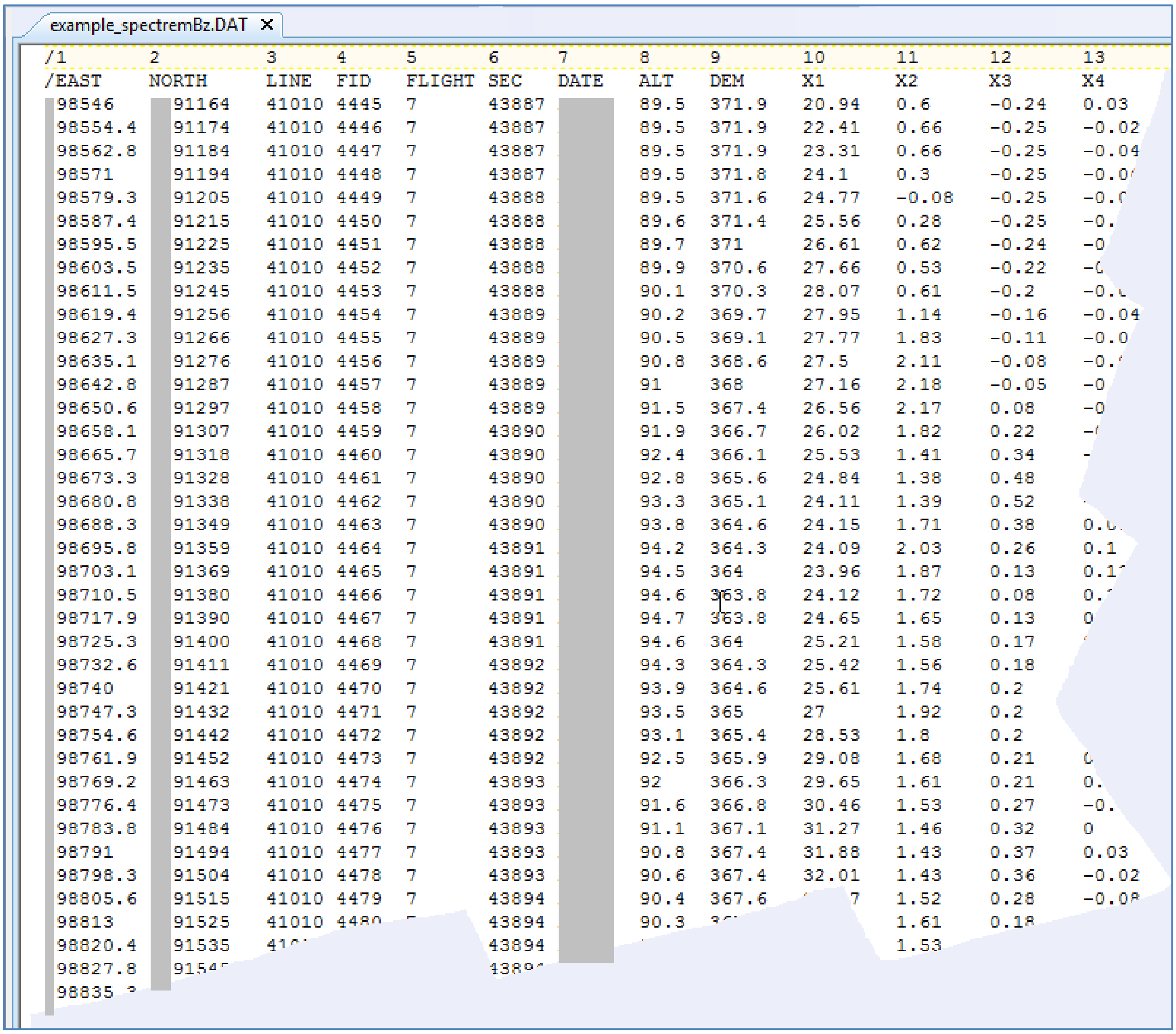
12.2 Computing resistive limit data



The files required to compute AEM resistive limits are;

- a data file in ASCII columnar format (*.DAT example is shown below).
- a parameter file for AEM2Mom (*.PAR example is shown below).

The *.DAT and *.PAR files are the same files that are used for EmaxAIR and VPem1D. The only difference is that some parameters are not used by AEM2Mom and VPem1D.



example_spectremBz.DAT

/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	-0.0
98579.3	91205	41010	4449	7	43888		89.5	371.6	24.77	-0.08	-0.25	-0.0
98587.4	91215	41010	4450	7	43888		89.6	371.4	25.56	0.28	-0.25	-0.
98595.5	91225	41010	4451	7	43888		89.7	371	26.61	0.62	-0.24	-0
98603.5	91235	41010	4452	7	43888		89.9	370.6	27.66	0.53	-0.22	-
98611.5	91245	41010	4453	7	43888		90.1	370.3	28.07	0.61	-0.2	-0.
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	-0.0
98635.1	91276	41010	4456	7	43889		90.8	368.6	27.5	2.11	-0.08	-0.
98642.8	91287	41010	4457	7	43889		91	368	27.16	2.18	-0.05	-0
98650.6	91297	41010	4458	7	43889		91.5	367.4	26.56	2.17	0.08	-0
98658.1	91307	41010	4459	7	43890		91.9	366.7	26.02	1.82	0.22	-
98665.7	91318	41010	4460	7	43890		92.4	366.1	25.53	1.41	0.34	-
98673.3	91328	41010	4461	7	43890		92.8	365.6	24.84	1.38	0.48	
98680.8	91338	41010	4462	7	43890		93.3	365.1	24.11	1.39	0.52	
98688.3	91349	41010	4463	7	43890		93.8	364.6	24.15	1.71	0.38	0.0
98695.8	91359	41010	4464	7	43891		94.2	364.3	24.09	2.03	0.26	0.1
98703.1	91369	41010	4465	7	43891		94.5	364	23.96	1.87	0.13	0.1
98710.5	91380	41010	4466	7	43891		94.6	363.8	24.12	1.72	0.08	0.
98717.9	91390	41010	4467	7	43891		94.7	363.8	24.65	1.65	0.13	0
98725.3	91400	41010	4468	7	43891		94.6	364	25.21	1.58	0.17	
98732.6	91411	41010	4469	7	43892		94.3	364.3	25.42	1.56	0.18	
98740	91421	41010	4470	7	43892		93.9	364.6	25.61	1.74	0.2	
98747.3	91432	41010	4471	7	43892		93.5	365	27	1.92	0.2	
98754.6	91442	41010	4472	7	43892		93.1	365.4	28.53	1.8	0.2	
98761.9	91452	41010	4473	7	43892		92.5	365.9	29.08	1.68	0.21	0
98769.2	91463	41010	4474	7	43893		92	366.3	29.65	1.61	0.21	0.
98776.4	91473	41010	4475	7	43893		91.6	366.8	30.46	1.53	0.27	-0.
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	7	1.52	0.28	-0.08
98813	91525	41010	4480		43894		90.3	36		1.61	0.18	
98820.4	91535	410			43894					1.53		
98827.8	9154				4389							
98835												

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

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

```
#VPEM#
This is an EmaxAIR parameter file, with additional parameters (column numbers a
example_air_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,   :
0 42000                                !LMIN, LMAX
-100000 10000000 -10000000 10000000 !XMIN, XMAX, YMIN, YMAX
2  1000                                   !IDAT (=1 for dB/dt [2 for B] in ppm; -1
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)  (=2
122.9  36.6  91                        !Y0, DEL0, ALT0 (notional configuration geo
    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    0.01                              !PCERR, SDMIN (units as per IDAT)
0    0   15                            !ISHARP, ITSHEET, OutputFormats
0                                      !IHC
800  40                                !RON, ROFF
#ROTATE# -999                          !Define coordinate rotation: specify the Fl
```

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

Example of an EmaxAIR-format *.PAR parameter file. The format is defined in Appendix A.

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 should exclude tie lines.

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

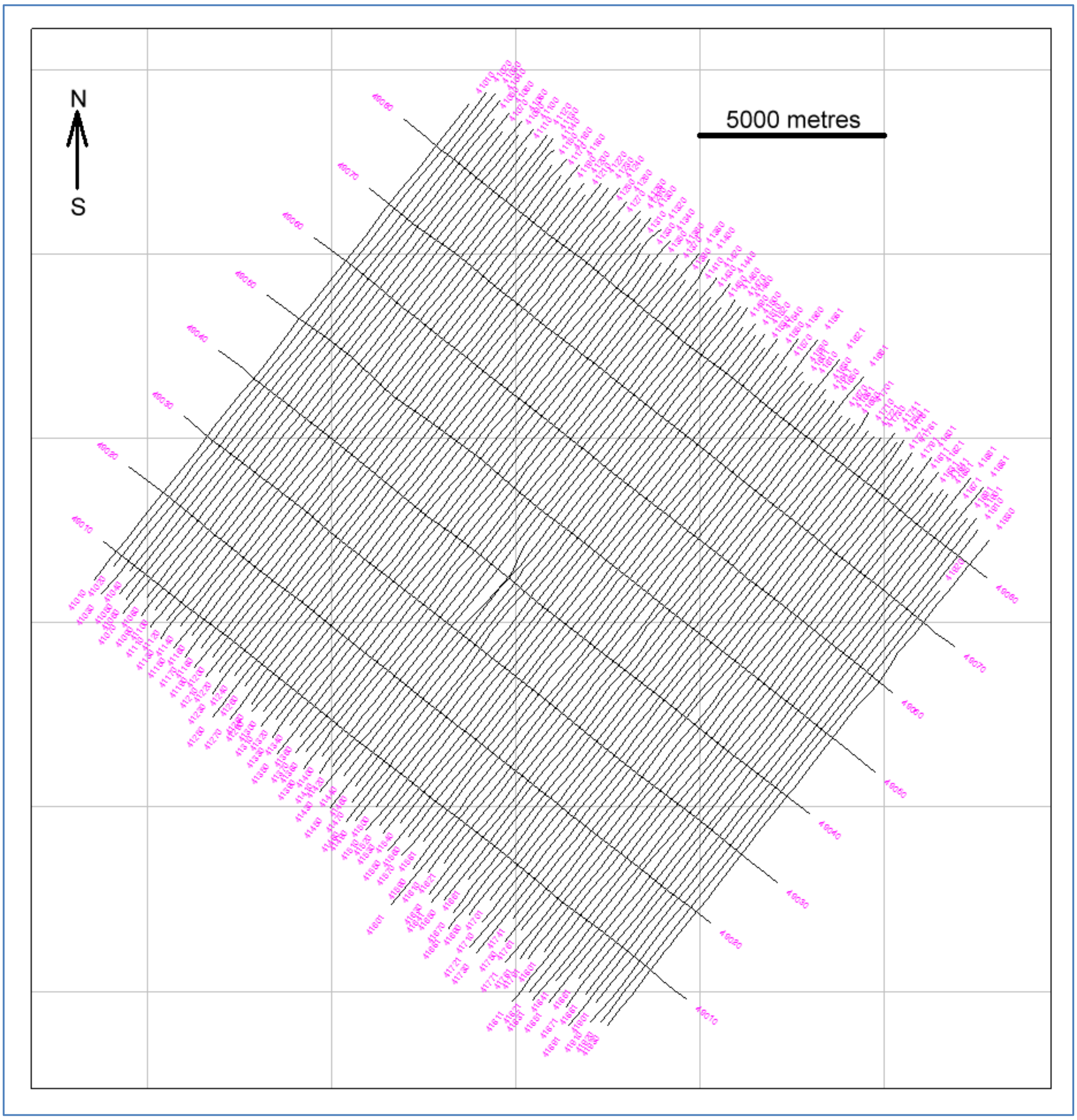
The order for the column numbers defining data quantities on record 5 is described in Appendix A. For example the 3 column numbers (0 9 0) circled above define the columns in the data file containing Tx_current, DEM, and Rx_altitude values. The zeros indicate that Tx_current and Rx_altitude are not actually present on the *.DAT file.

Y0 DEL0 ALT0 define the system geometry. Y0 is the loop radius for central loop systems (ISTEP < 0) or the Tx-Rx horizontal offset for slingram systems. DEL0 is the vertical Tx-Rx separation. If the Tx is above the Rx, DEL0 > 0; if the Rx is above the Tx, then DEL0 is negative. ALT0 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 no rotation will be applied, and the inversion will be performed using the survey coordinates as recorded in the data file. The model cells will be defined in a rectangular grid oriented N-S and E-W in the survey coordinates in that case.

For oblique flight lines, i.e. oriented neither N-S nor E-W, rotation into flight line coordinates is recommended because, ideally, the model cells should be oriented parallel and perpendicular to flight lines, with flight lines tracking across the model prism centres. Working in flight line coordinates also circumvents the need to rotate the horizontal TEM components into survey coordinates. Four parameters are required to specify the rotated coordinates: the flight line BEARING in degrees clockwise from survey north; XREF, YREF (in survey coordinates) defining the origin of the flight line coordinates; and an integer, IADD. If IADD=1, XREF (YREF) are added to the flight line eastings (northings). IADD=0 otherwise, which is the recommended setting. Choose (XREF, YREF) on a flight line.

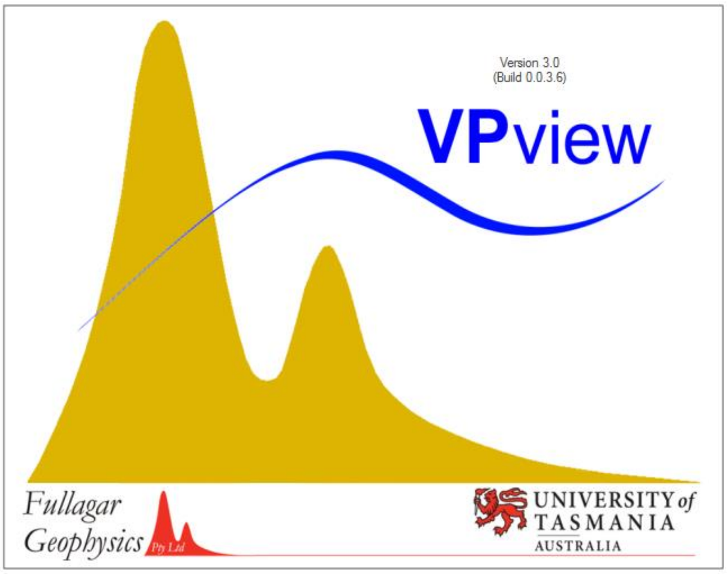
Default rotation parameters are computed by AEM2Mom if the PAR file includes a #ROTATE# -999 record. The derived rotation parameters, as well as default model prism dimensions, are recorded in the header of the moment data file outputted by AEM2Mom. The header is read by VPview if the user specifies the moment data file when running the *Create New Model* utility. This expedites creation of simple host-over-basement starting models for unconstrained inversion (see Section 12.3 below).



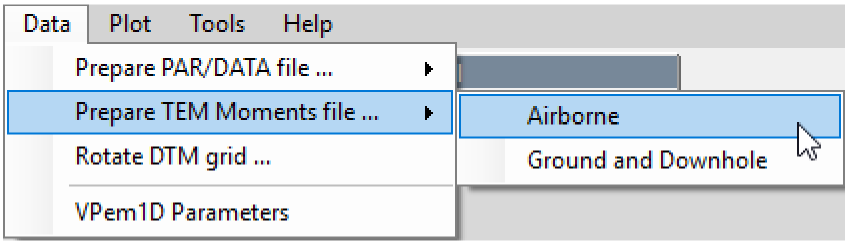
Flight line plot of the example survey.

Due to the flight line bearing of 038 degrees the *.PAR file requires a #ROTATE# record, either with explicit parameter values or with -999 for defaults derived by AEM2Mom. A #ROTATE# -999 record is included in the parameter file here (see above).

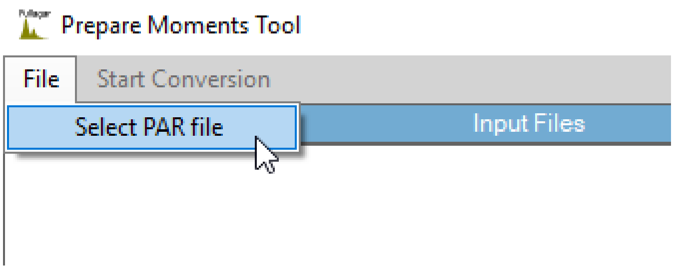
Start VPview from either the Desktop icon, or from the Windows Start → Programs menu.



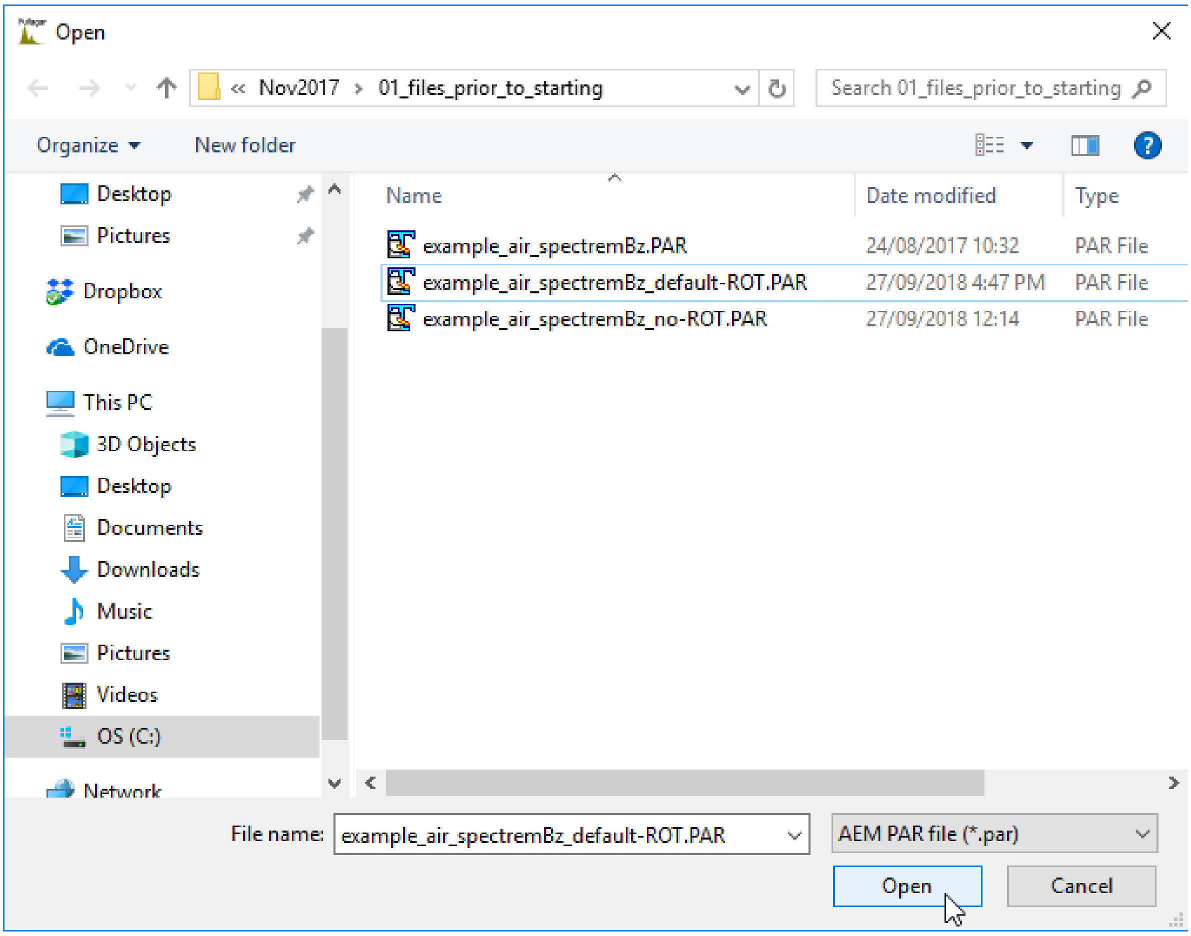
VPview splash screen



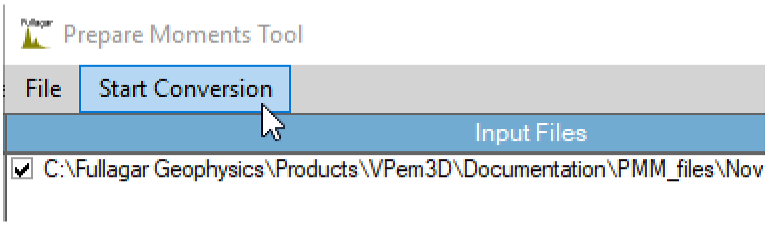
Convert the AEM decays (in the *.DAT file) into a resistive limits (TEM moments) using the Data\Prepare TEM Moments\Airborne option.



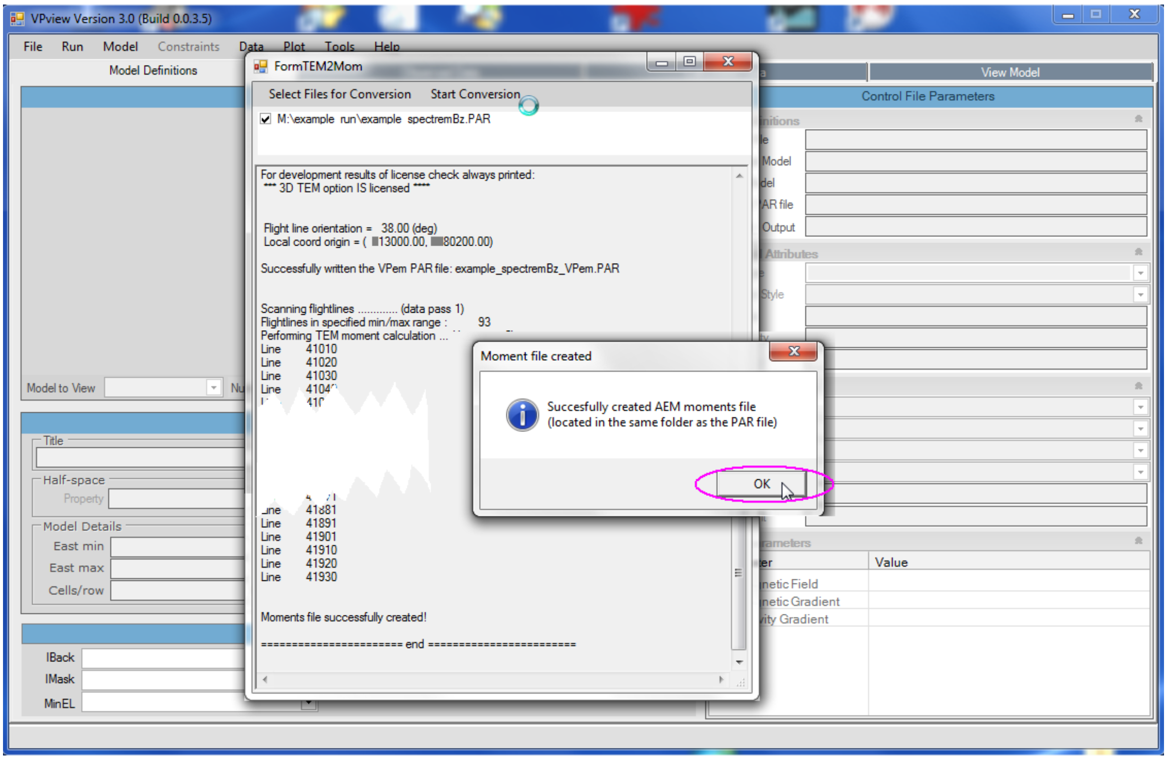
For airborne data select the desired AEM2Mom PAR file.



Select the *.PAR file (EmaxAIR format file).



Start the conversion.
This will launch the conversion program, AEM2Mom.



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

example_air_spectremBz_default-ROT.LOG	27/09/2018 10:07	Text Document
example_air_spectremBz_default-ROT.PAR	27/09/2018 4:47 PM	PAR File
example_air_spectremBz_default-ROT_MOM.XYZ	27/09/2018 10:07	XYZ File
example_air_spectremBz_default-ROT_VPem.PAR	27/09/2018 10:07	PAR File

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 *VPem.PAR files will be the input for VPem3D.

```
/Processed from AEM sources
/C:\Fullagar Geophysics\Products\VPem3D\Documentation\PMM_files\Nov2017\01_files_prior_to_starting\example_air_spectremBz.DAT
/!!IntegrationTimeWindow #max#  (start-end time in ms):    0.0109     2.7669
/TXradius(m) TXmoment(Am2):  0.00  0.400000E+06
/Tx-Rx horizontal offset(m)  Tx-Rx vertical offset(m):  122.9   36.60
/AEM2Mom : version = v3.0.5  build date = Sep 27 2018  build time = 16:33:14  lic_var = 1(mlm)
/Flight line orientation:   38.15 (deg)
/Local coord origin: (   98546.00,    91164.00)
/Add local origin: N
/Data easting min & max:   -1991.86    17270.44   Data northing min & max:  -18414.13        0.00
/>>> N.B.: coordinates are rotated, with local east along bearing   38.15 (deg) <<<
/Estimated line spacing:   200  (m)   Flight lines accepted:  93
/System altitude estimate:   83.09  (m)   Number of stations accepted: 120306
/Across-line prism dimension:  200.0  (m)   Along-line prism dimension:  51.0
/Model easting min & max:   -2524.50    17824.50   Model northing min & max:  -18900.00      500.00
/>>> N.B.: coordinates are rotated, with local east along bearing   38.15 (deg) <<<
RXX RXY RXZ RLZ VDX VDY VDZ LINE DEM NTGZ RLZE
Line 41010>
      -61.42         2.01        424.80  0.236169E+02        61.42        -2.01        461.40    41010    371.90    6  0.223130E+00
      -48.36         1.59        424.80  0.238253E+02        74.47        -2.44        461.40    41010    371.90    6  0.223433E+00
      -35.31         1.16        424.80  0.255827E+02        87.52        -2.87        461.40    41010    371.90    7  0.309969E+00
      -22.40         0.16        424.70  0.264661E+02       100.47        -2.41        461.30    41010    371.80    [illegible]  0.313198E+00
       -8.63        -2.06        424.50  0.264879E+02       114.25         0.34        461.10    41010    371.60    7  0.314361E+00
        4.24        -0.13        424.40  0.267647E+02       127.12        -1.97        461.00    41010    371.40    7  0.314775E+00
       17.10        -0.33        424.10  0.264568E+02       139.99        -2.16        460.70    41010    371.00    7  0.312894E+00
       29.91        -0.81        423.90  0.266216E+02       152.80        -1.90        460.50    41010    370.60    7  0.310976E+00
       42.71        -0.92        423.80  0.269637E+02       165.61        -2.01        460.40    41010    370.30    7  0.311458E+00
       56.30        -3.53        423.30  0.263666E+02       179.08         1.76        459.90    41010    369.70    7  0.310047E+00
       68.98        -0.75        423.00  0.268113E+02       191.88        -1.09        459.60    41010    369.10    7  0.312096E+00
       81.67        -1.09        422.80  0.265656E+02       204.57        -0.66        459.40    41010    368.60    7  0.312124E+00
       95.17        -3.52        422.40  0.269327E+02       217.88         3.25        459.00    41010    368.00    7  0.315016E+00
      107.75        -0.30        422.30  0.278253E+02       230.65         0.12        458.90    41010    367.40    7  0.320060E+00
      120.27        -1.19        422.00  0.287522E+02       243.14         1.57        458.60    41010    366.70    7  0.324811E+00
```

Start of the *.XYZ moments data file created by AEM2Mom.

The header records the rotation parameters computed by AEM2Mom:
Bearing = 38.15^{o}, XREF = 98546.0, YREF = 91164.0

The receiver coordinates (RXX, RXY) and transmitter coordinates (TXX, TXY) are recorded in rotated (flight line) coordinates.

The header also contains default model prism dimensions derived from the data file:
Across-line dimension = 200m and along-line dimension = 51m.

A suffix has been added to the line numbers to indicate direction of advance: '>' for lines flown in the local east direction, and '<' for lines flown in the local west direction. Direction of advance is needed in order to assign correct polarity to the horizontal TEM components: contractors refer polarity to the direction of advance whereas VPem3D refers to a fixed frame of reference.

AEM2Mom creates a *VPem.PAR file, which defines the format of the moment file.

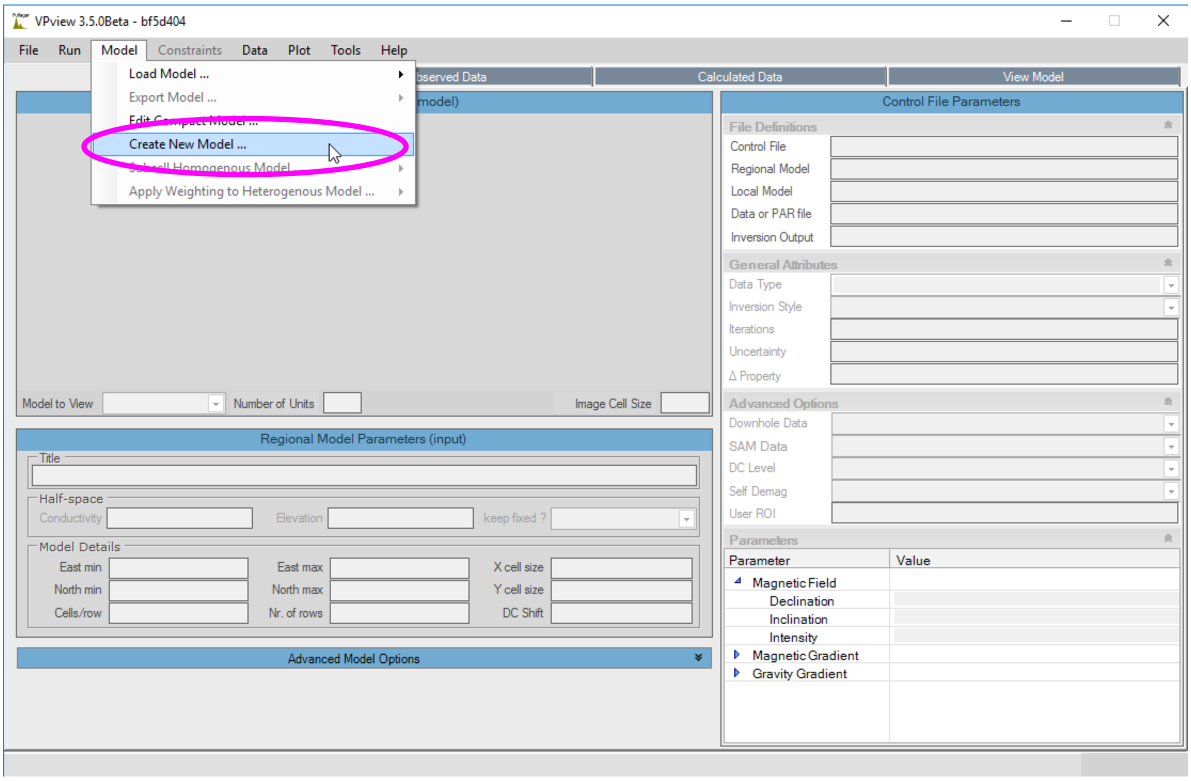
```
#VPEM#
 example_air_spectremBz_default-ROT_MOM.XYZ
 11    ! NVAR
-1    ! NCH
 4 RLZ
 5 VDX
 6 VDY
 7 VDZ
 8 LINE
11 RLZE
```

VPem.PAR parameter file generated for the example data set. This PAR file defines the format of the moments (.XYZ) file for VPem3D. Normally it will not be necessary to edit the VPem3D PAR file.

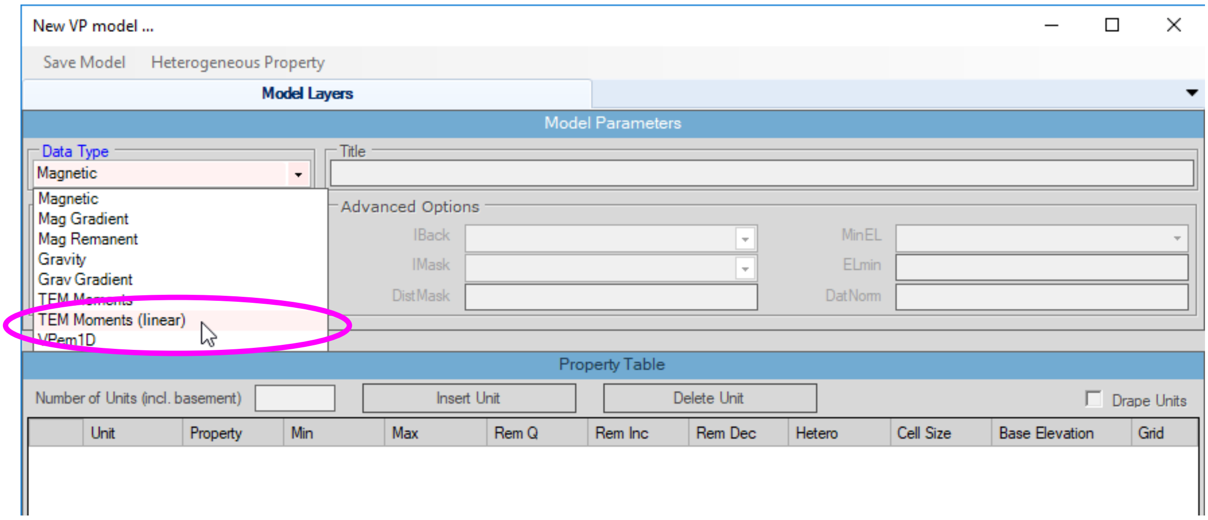
In this case the vertical resistive limit, RLZ, is in column 4, and its standard deviation, RLZE, is in column 11. The coordinates of the transmitter centre, (VDX,VDY,VDZ), are located in columns 5, 6, and 7 respectively.

12.3 Create a starting model (DTM grid available)

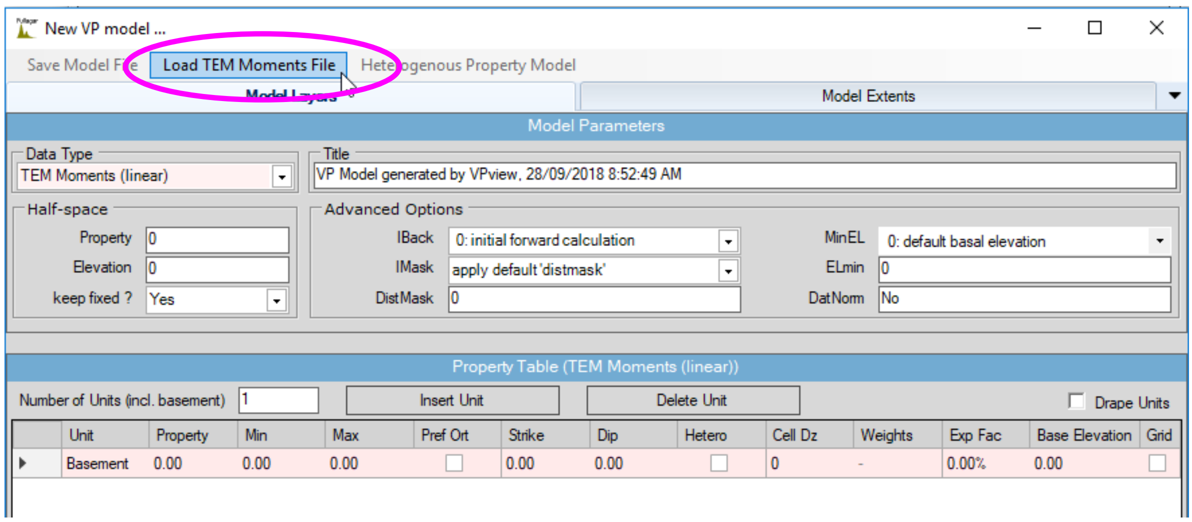
VPview includes a *Create New Model* utility under the Model menu for constructing layered models. The layers span the entire model area, but layer thickness can reduce to zero, allowing discrete bodies to be represented.



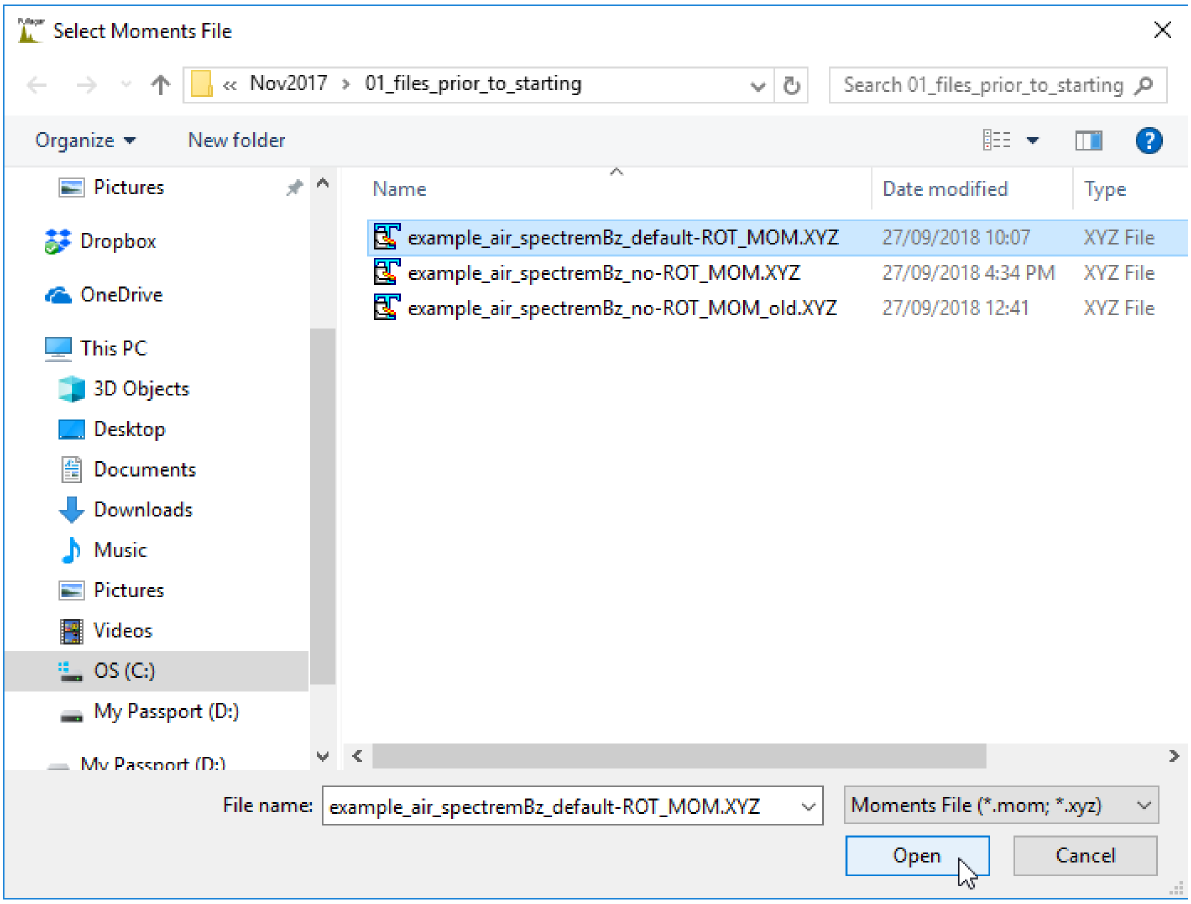
Create a layered model as a starting point for inversion.



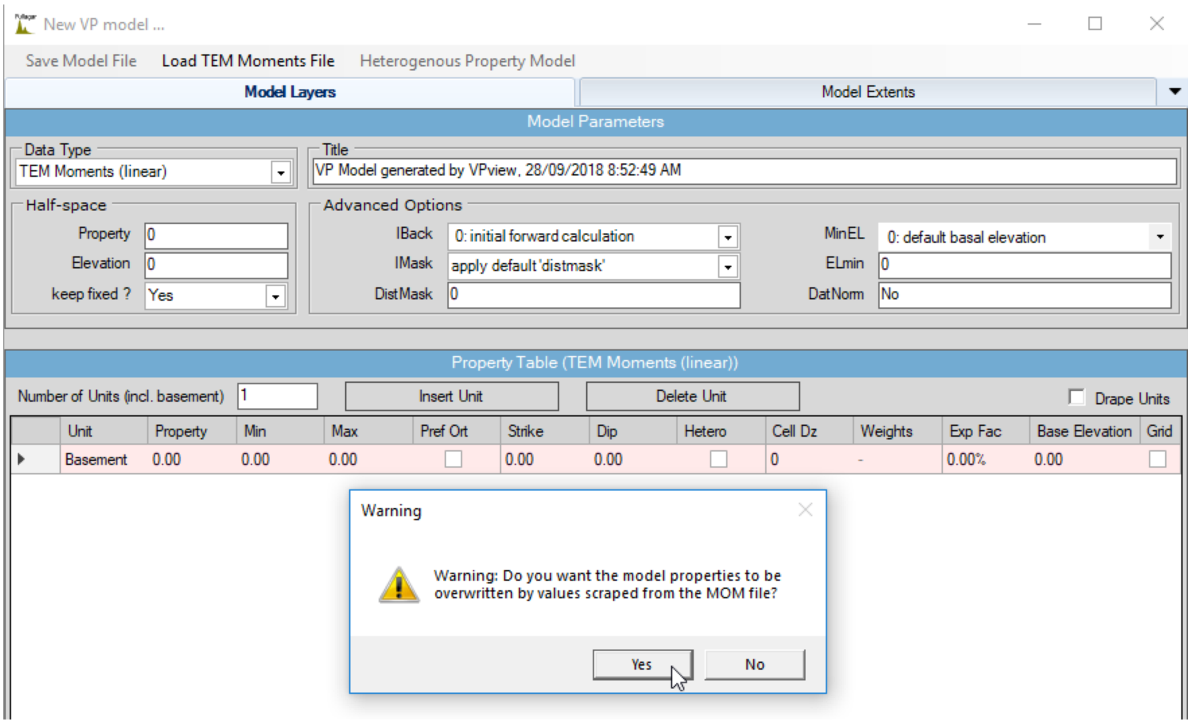
On the *Model Definitions* form, select data type “TEM Moments”.



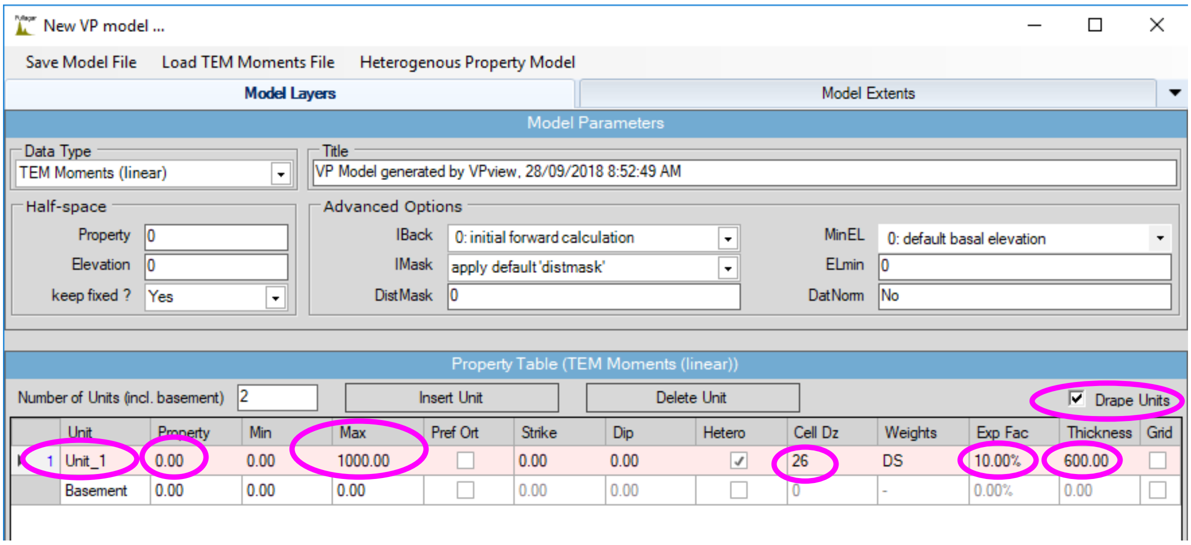
The simplest VPem3D model consists of a single layer above basement, which is suitable for unconstrained inversion. AEM2Mom records default model parameters for a simple host-over-basement model, as well as rotation parameters, in the moment file header. Model file creation for unconstrained inversion can be expedited by loading the moments file.



Specify the required moments file



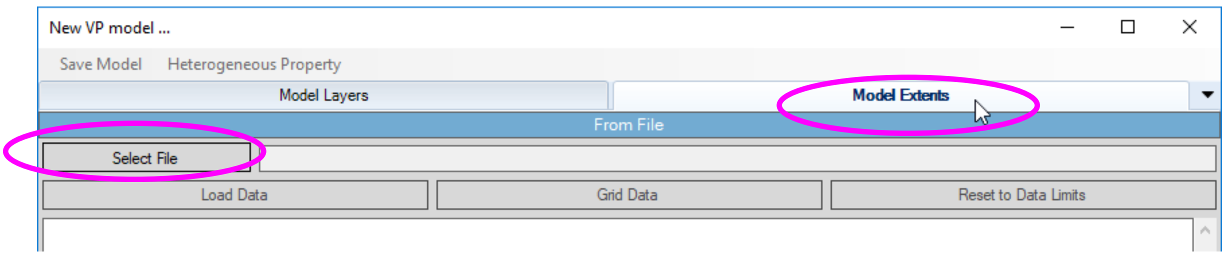
Just a warning, in case you've spent time entering parameters for an elaborate set of layers. Usually safe to ignore.



VPview has entered defaults which the user can edit if desired. For example, the user could

(a) change the name of the host unit, called Unit_1 by default
(b) change the starting conductivity of the host unit; default is zero
(c) re-set the maximum conductivity for the host; default is 1000 mS/m
(d) change the minimum vertical dimension of model cells; the default calculated by AEM2Mom is 26m in this case.
(e) alter the expansion factor; the default is 10%, which means that the thickness of successively deeper cells will increase by a factor of 1.1
(f) uncheck the *Drape Units* box, and define the elevation of the (horizontal) base of the host unit; the default is to drape the base of the host below the topography
(g) change the thickness of the host unit; the default is 600m

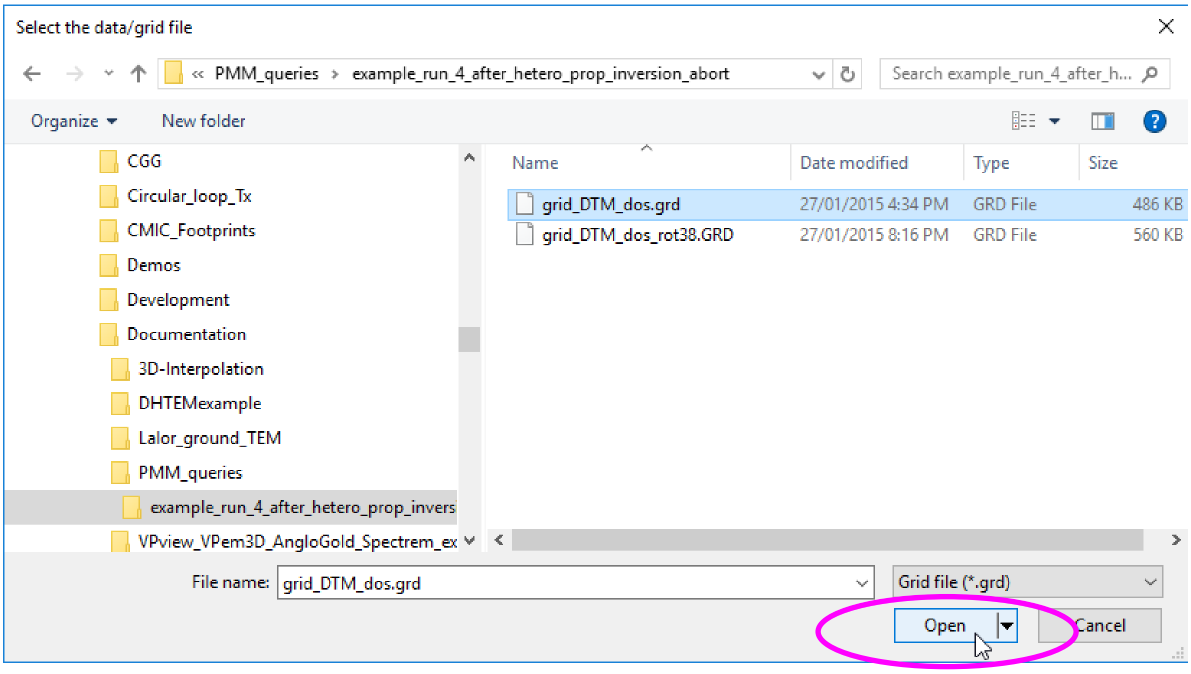
The shallowest model cells are most sensitive to the AEM data. Therefore, VPem3D will preferentially introduce near-surface conductivity changes during inversion unless surficial conductivity is penalised. Development of shallow conductive zones is usually damped using depth weights (see Section 13.8). "DS" depth weighting (referenced to system elevation) is recommended for heterogeneous unit inversion of AEM.



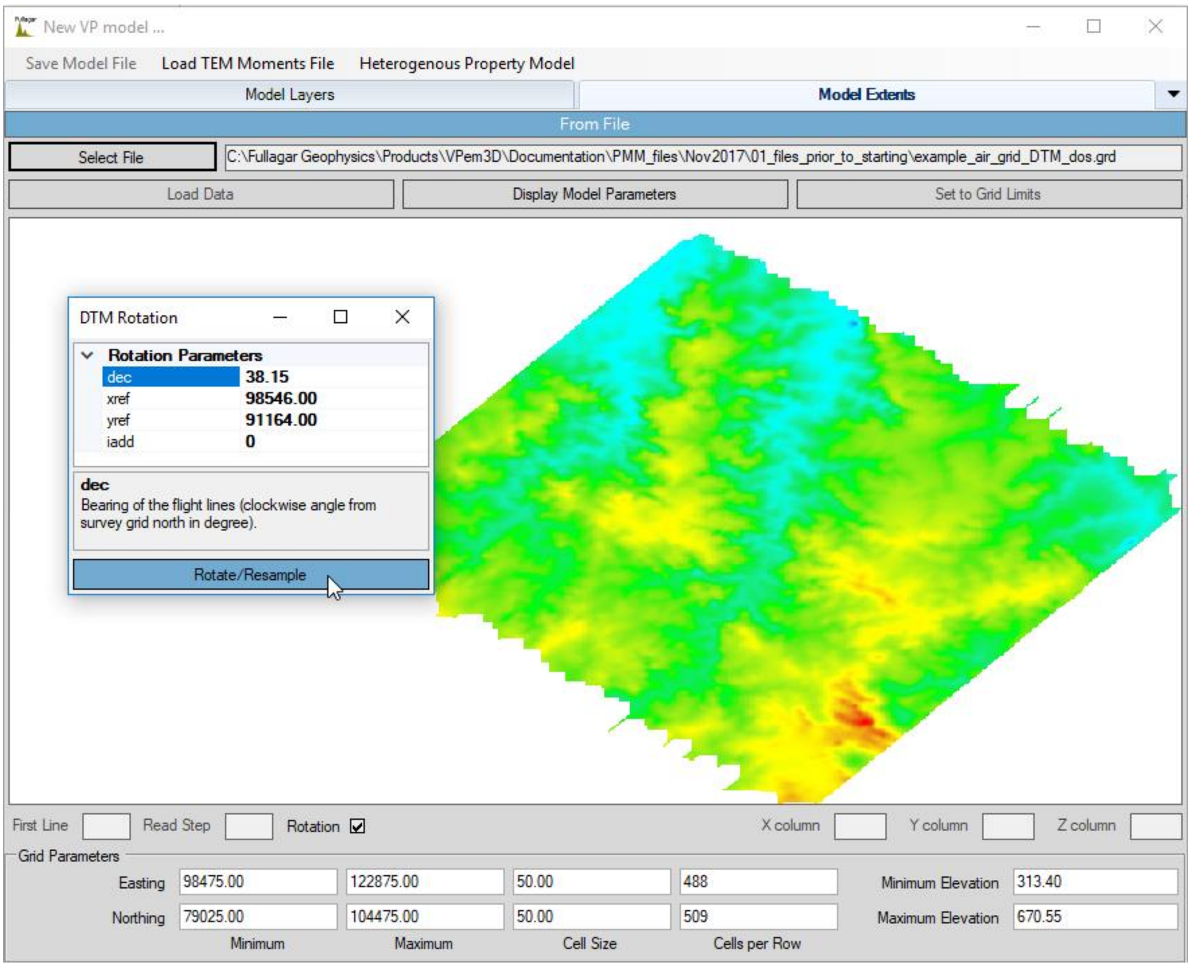
In VPem3D models, the model top coincides with the ground surface. Therefore VPview uses a DTM grid, if available, to define the model top during starting model construction. The format of the DTM grid must be Geosoft "DOS", i.e. uncompressed GRD.

To import the DTM topography grid file, open the *Model Extents* form and click on *Select File*.

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

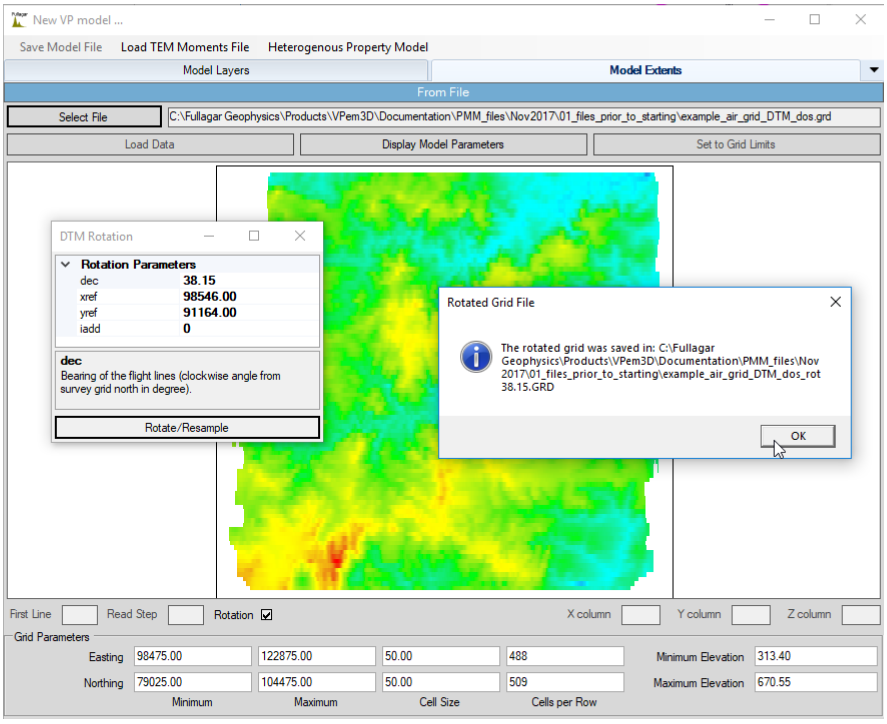


Open the DTM grid file.

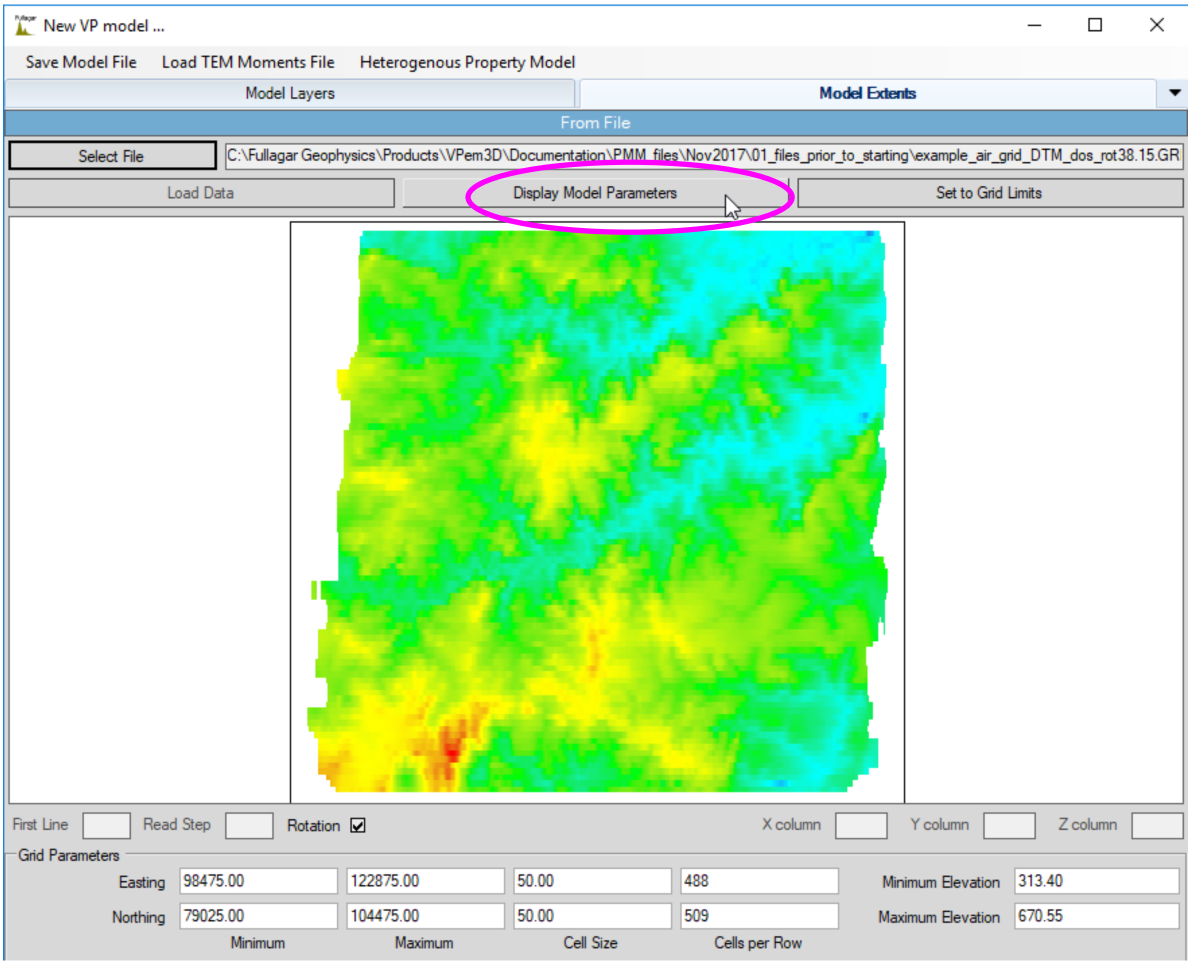


The rotation parameters have been read from the moment file header.

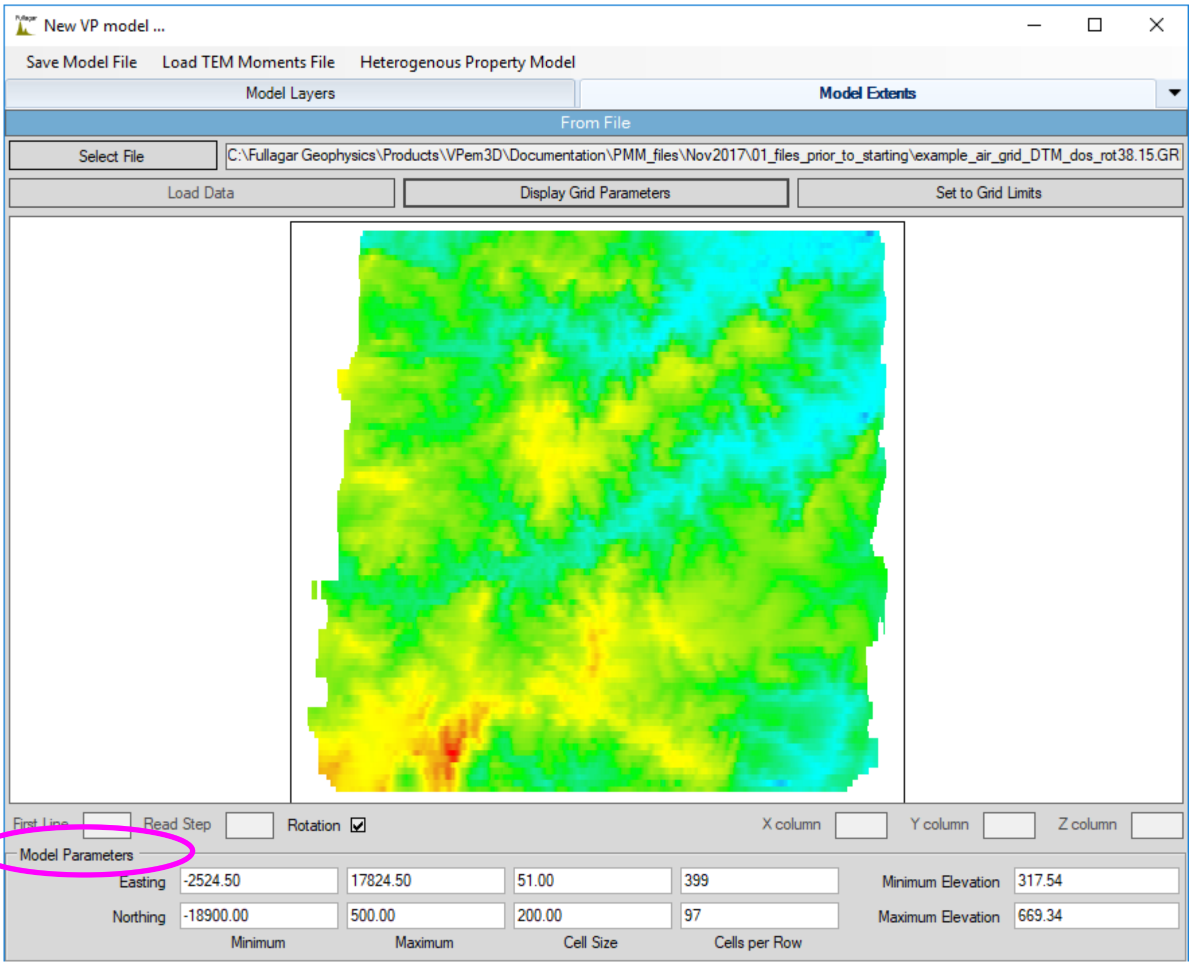
Click on *Rotate/Resample* to rotate the DTM and re-grid to a pixel size which conforms with the default prism dimensions calculated by AEM2Mom.



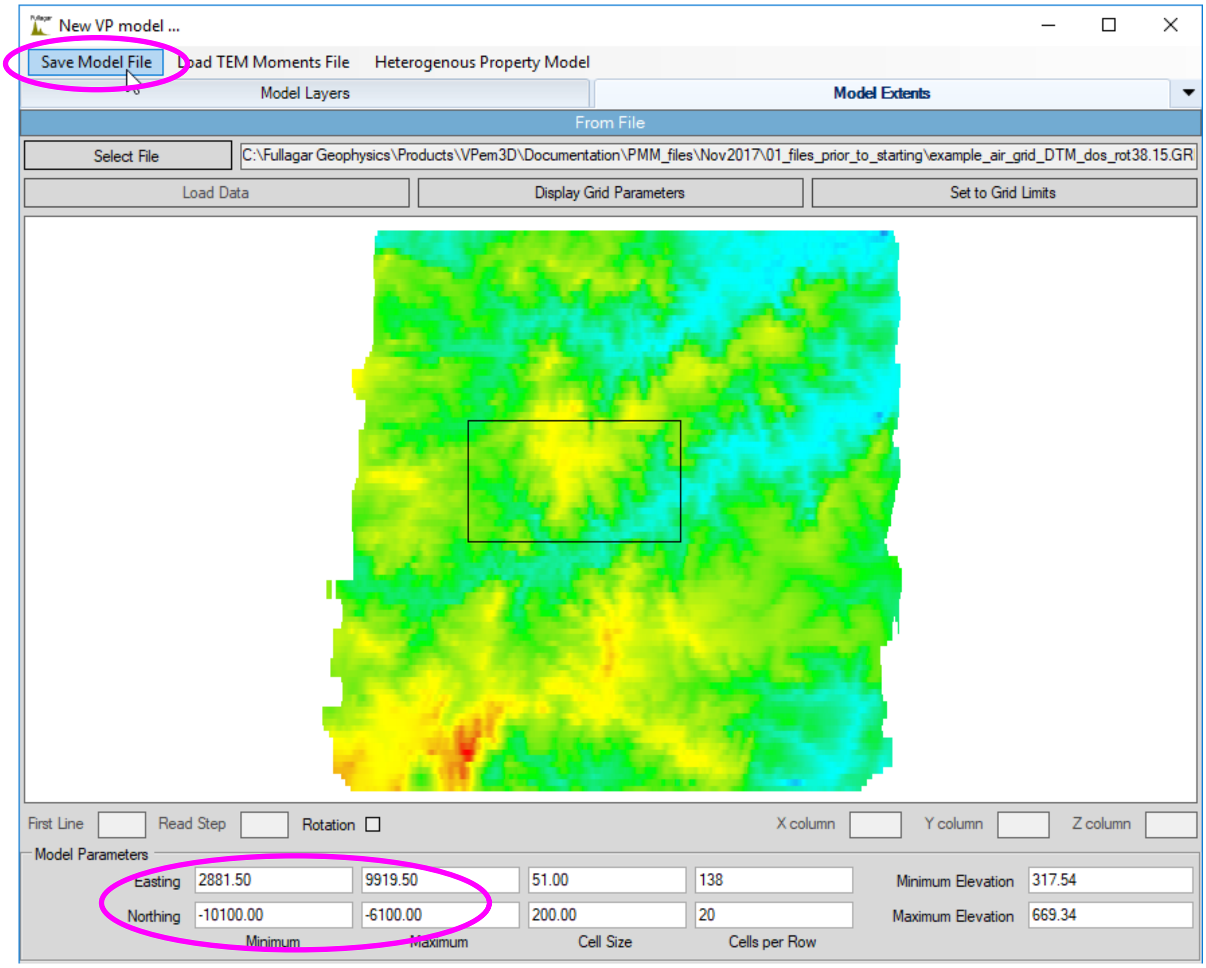
A rotated DTM grid is saved to disk. It could be re-used later if required, e.g. to define a different starting model. Click on OK to clear the message window.



At first the DTM grid limits displayed below the image are in survey coordinates. Click on *Display Model Parameters* to view the model limits and prism dimensions in rotated coordinates.

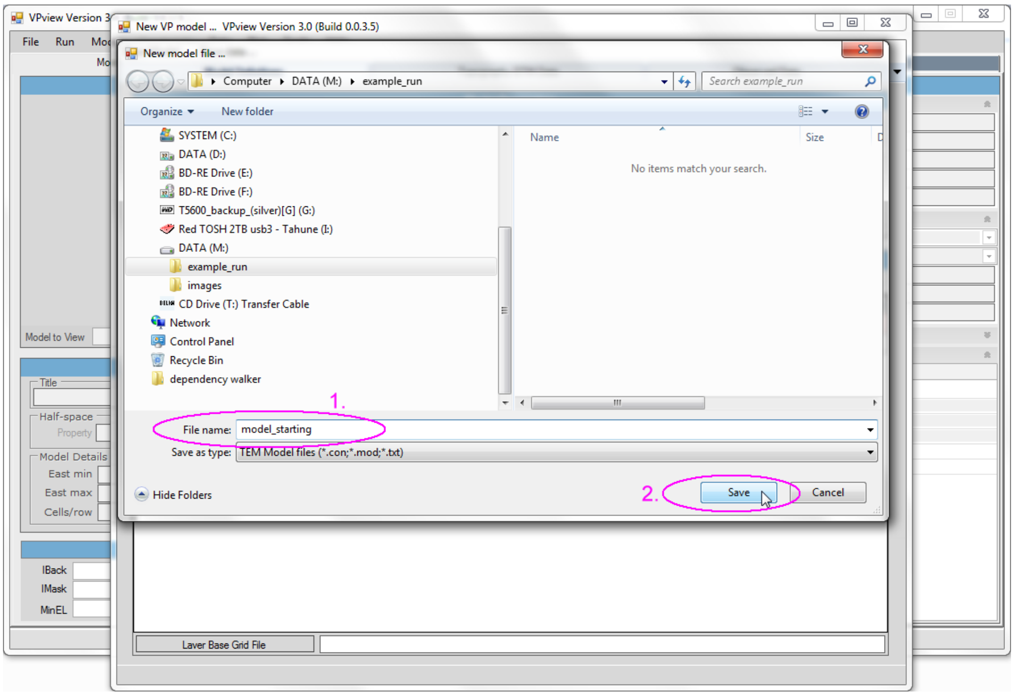


Model limits computed by AEM2Mom are displayed in rotated coordinates below the DTM image, and are traced in black on the image. Evidently the data coverage extends beyond the DTM in this case.

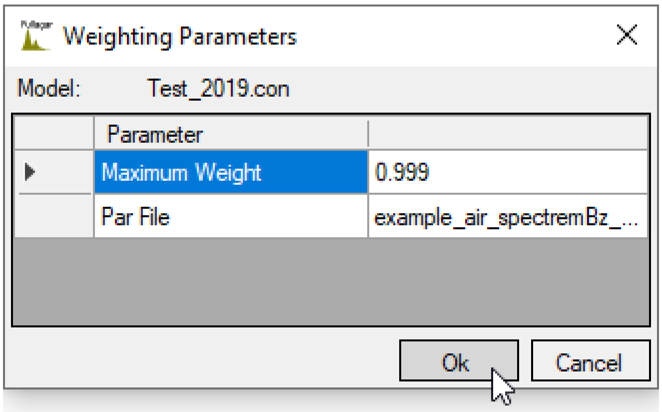


If necessary, edit the easting and northing limits (local coordinates) to define the desired model area for inversion. The model area is traced in black on the image. The minimum and maximum values must differ by an integral multiple of corresponding prism dimension (*Cell Size*).

When satisfied, save the model.



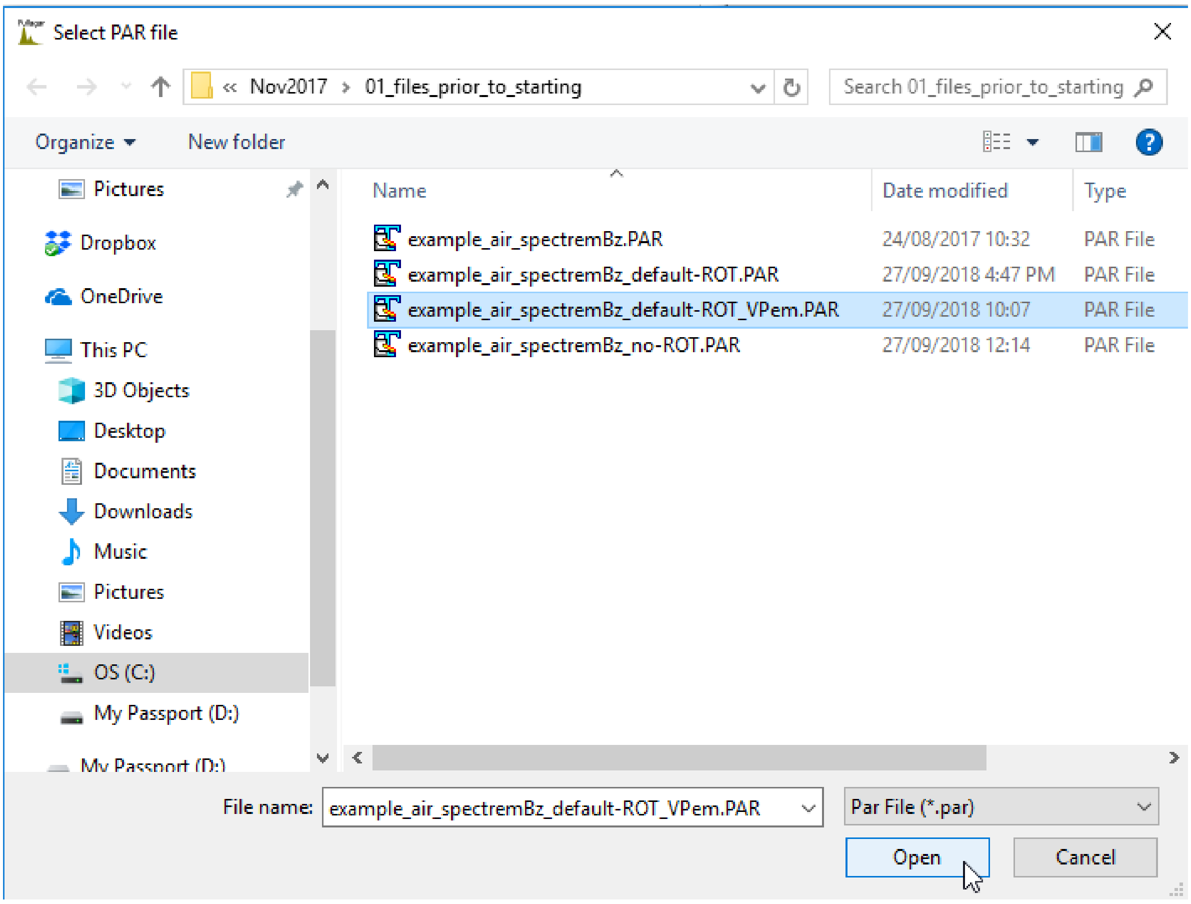
Choose a suitable file name.



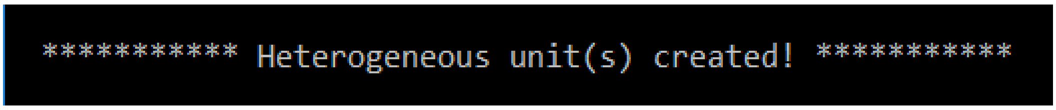
If depth weighting has been selected, the Weighting Parameters dialogue will appear. The user can alter the Maximum Weight (wmax) value and, if system height based ("DS") is required, select the VPem3D PAR file.

The weighting is stronger, i.e. model changes near-surface are more strongly suppressed, as wmax increases. The maximum value is 0.9999.

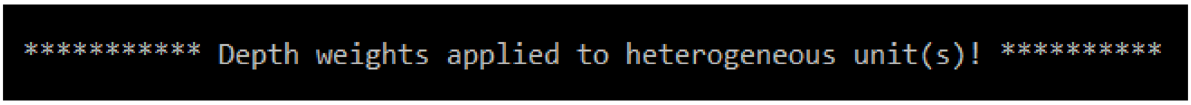
By default, VPview will select the PAR file with the same rootname as the moment (.XYZ) file specified by the user.



Select the appropriate *MOM.PAR file.

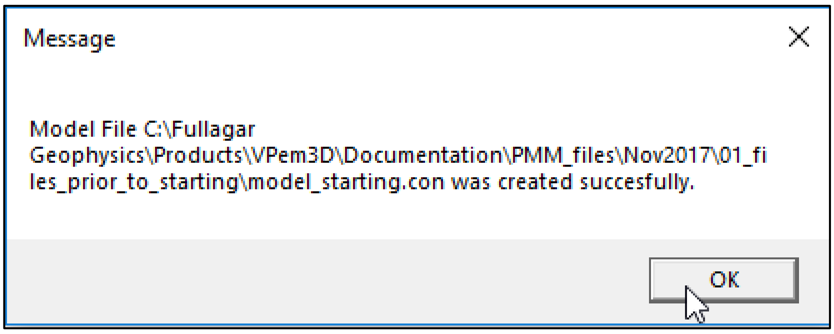


Initially VPview creates a homogeneous model with cells extending from the ground surface to the base of the host layer. VPem3D is then launched in a DOS command window to sub-divide the long model cells in accordance with the parameters specified on the Model Layers form above. In this example the first cell is 26m thick, and the thickness of successive underlying cells increases by a factor of 1.1.



Finally VPem3D computes depth weights and records them in the sub-celled model file.

The Command Window can be closed once sub-celling and depth weighting have completed.



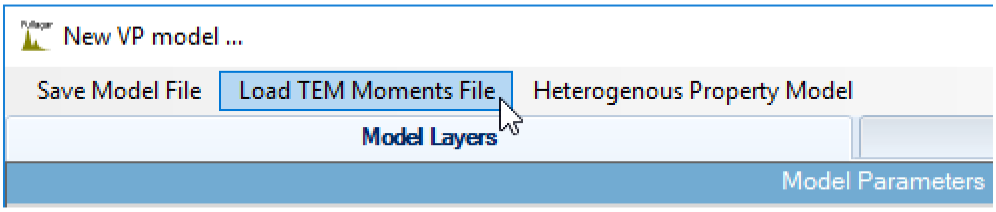
Click OK to complete the model creation process.

12.4 Create a starting model (no DTM grid available)

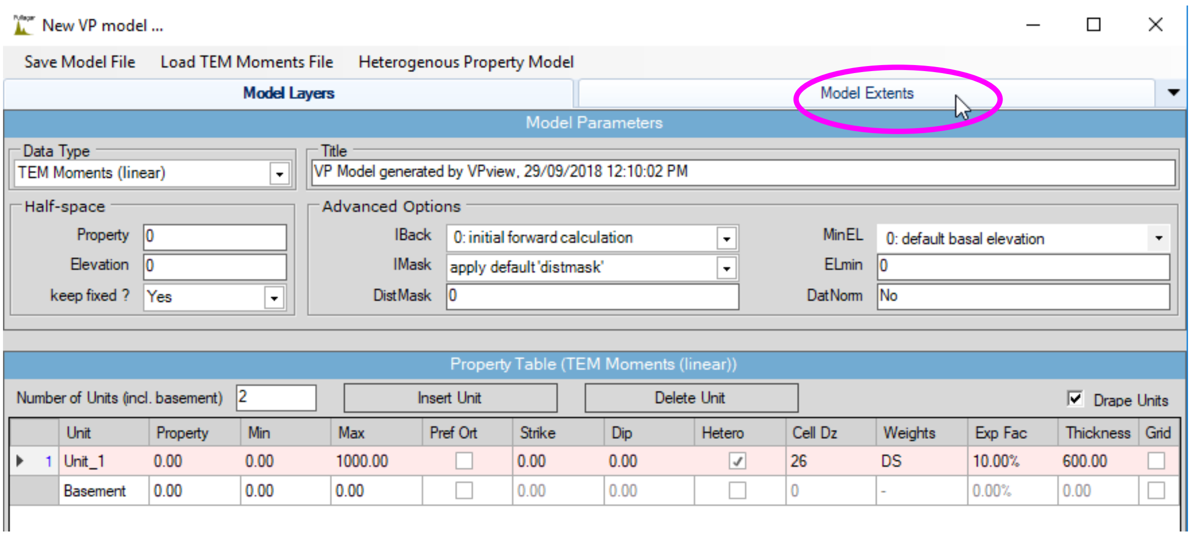
When no DTM grid is available, VPview can create a model with a horizontal upper surface. In this case it is usually most convenient to assign zero elevation to the AEM model top and to treat the receiver and transmitter altitudes above ground as their "elevations". So for the sample data set considered here, AEM2Mom would be run with radar altimeter treated as Tx elevation, i.e. with record 5 of the PAR file changed to 3 1 2 8 17 23 8 0 0 0 0 0. With that change, the first few lines of the moment data file are as follows:

```
/Processed from AEM sources
/C:\Fullagar Geophysics\Products\VPem3D\Documentation\PMM_files\Nov2017\01_files_prior_to_starting\examp
/!!IntegrationTimeWindow #max#  (start-end time in ms):    0.0109     2.7669
/TXradius(m) TXmoment(Am2):  0.00  0.400000E+06
/Tx-Rx horizontal offset(m)  Tx-Rx vertical offset(m):  122.9    36.60
/AEM2Mom : version = v3.0.5  build date = Sep 27 2018  build time = 16:33:14  lic_var = 1(mlm)
/Flight line orientation:   38.15 (deg)
/Local coord origin: (   98546.00,    91164.00)
/Add local origin: N
/Data easting min & max:   -1991.86    17270.44   Data northing min & max:  -18414.13       0.00
/>>> N.B.: coordinates are rotated, with local east along bearing   38.15 (deg) <<<
/Estimated line spacing:   200 (m)   Flight lines accepted:  93
/System altitude estimate:   83.09 (m)   Number of stations accepted: 120306
/Across-line prism dimension:  200.0 (m)   Along-line prism dimension:  51.0
/Model easting min & max:   -2524.50    17824.50   Model northing min & max:  -18900.00      500.00
/>>> N.B.: coordinates are rotated, with local east along bearing   38.15 (deg) <<<
RXX RXY RXZ RLZ VDX VDY VDZ LINE DEM NTGZ RLZE
Line 41010>
      -61.42         2.01         52.90  0.236169E+02       61.42        -2.01        89.50   41010
      -48.36         1.59         52.90  0.238253E+02       74.47        -2.44        89.50   41010
      -35.31         1.16         52.90  0.255827E+02       87.52        -2.87        89.50   41010
      -22.40         0.16         52.90  0.264661E+02      100.47        -2.41        89.50   41010
       -8.63        -2.06         52.90  0.264879E+02      114.25         0.34        89.50   41010
        4.24        -0.13         53.00  0.267647E+02      127.12        -1.97        89.60   41010
       17.10        -0.33         53.10  0.264568E+02      139.99        -2.16        89.70   41010
       29.91        -0.81         53.30  0.266216E+02      152.80        -1.90        89.90   41010
       42.71        -0.92         53.50  0.269637E+02      165.61        -2.01        90.10   41010
       56.30        -3.53         53.60  0.263666E+02      179.08         1.76        90.20   41010
       68.98        -0.75         53.90  0.268113E+02      191.88        -1.09        90.50   41010
       81.67        -1.09         54.20  0.265656E+02      204.57        -0.66        90.80   41010
```

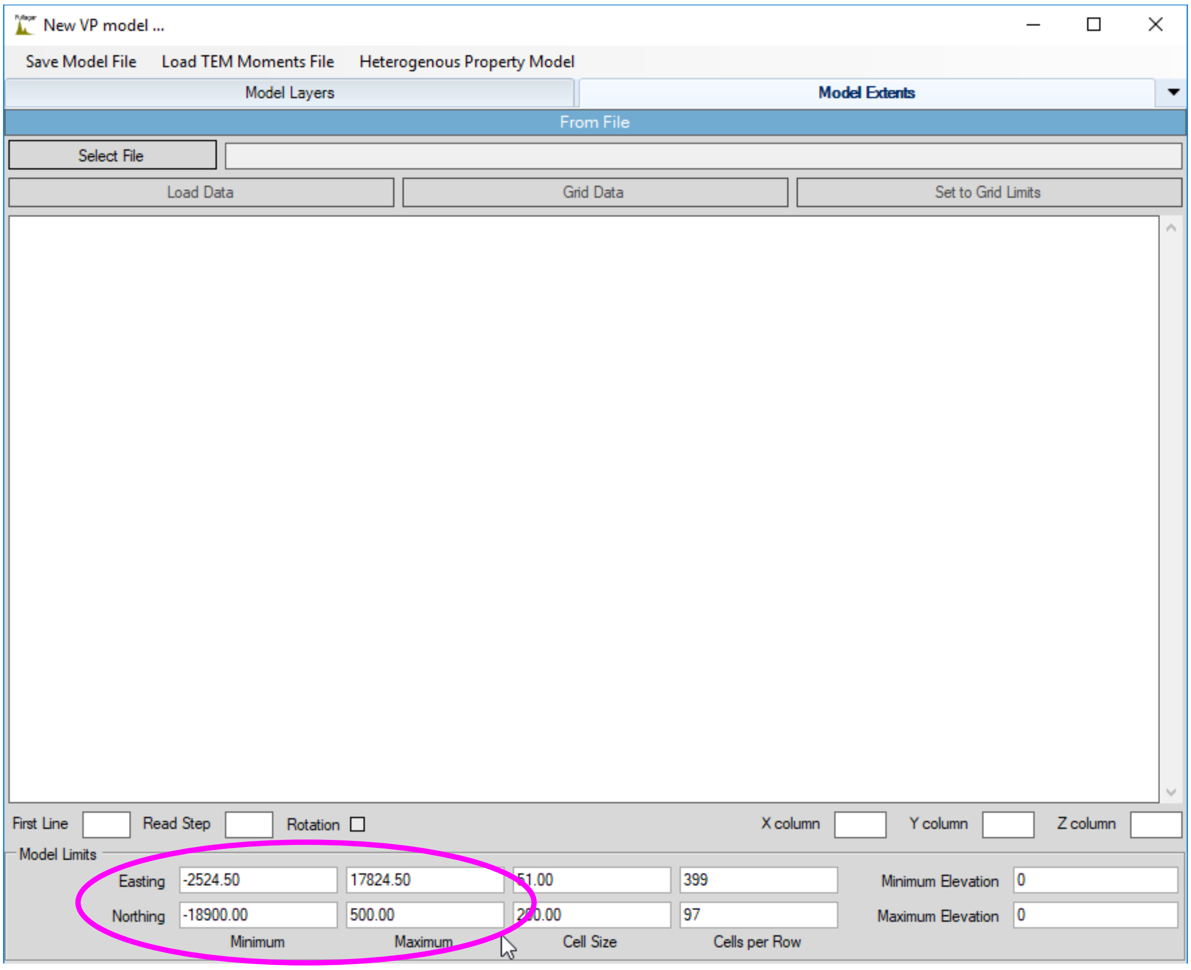
The Rx elevations (3rd column from left) are now actually altitudes above ground. [This re-processing has been performed purely for illustration; a DTM is of course available for this data set.]



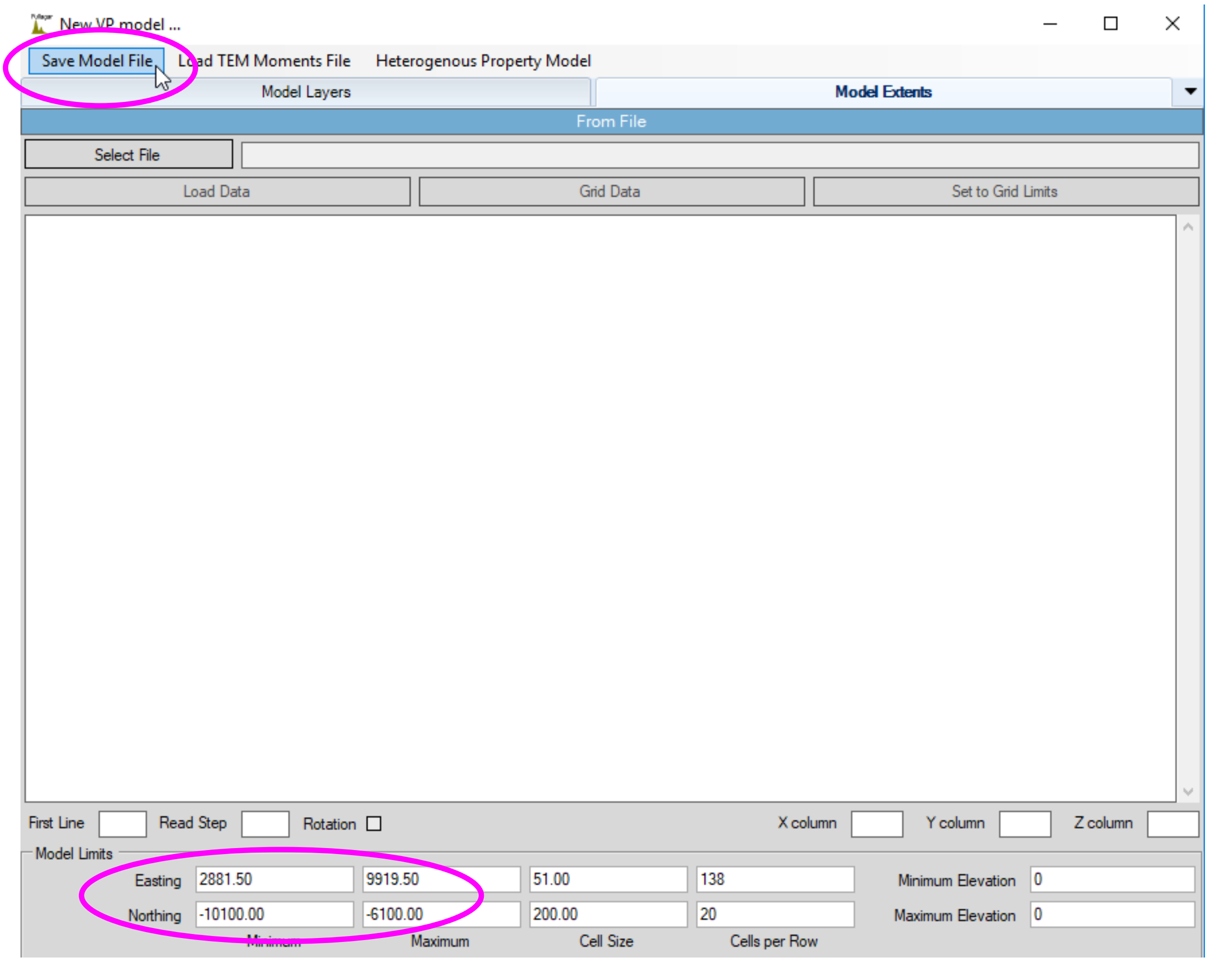
To create a model, launch the VPview *Create New Model* utility (in the *Model* menu) and, as described in Section 12.3, click on the *Load TEM Moments File* button to select the appropriate moment data file produced by AEM2Mom.



Once satisfied with the parameters on the *Model Layers* form (edit the AEM2Mom default settings if necessary), open the *Model Extents* form.



The default model limits calculated by AEM2Mom span the entire data coverage. These can be edited, if necessary.



Enter the desired model limits (in rotated coordinates) into the text boxes at the bottom of the form, and then save the model.

Sometimes it is more convenient to read the model extents and model top elevation from a dummy data file. Three records will suffice to define the corners of the model area. For example the model extents file could be of the form shown below:

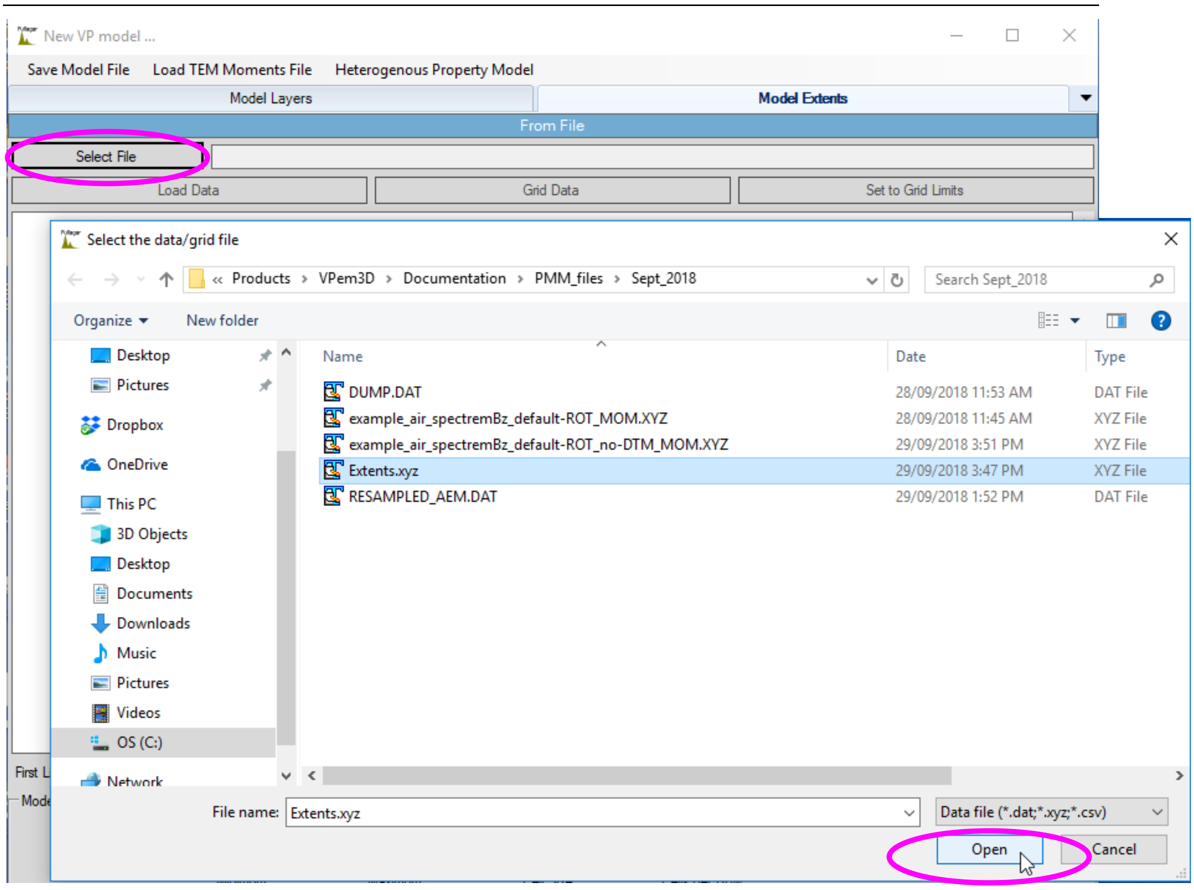
EAST NORTH ELEVATION READING

XMIN, YMIN, RL1, DATA1

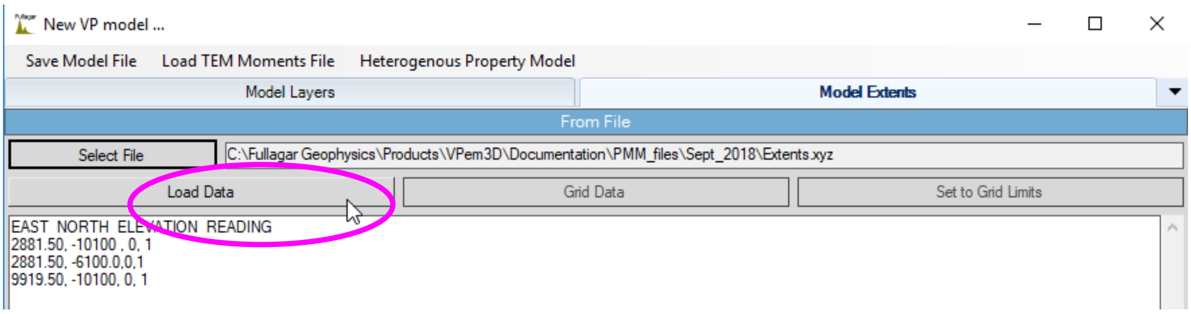
XMAX, YMIN, RL2, DATA2

XMAX, YMAX, RL3, DATA3

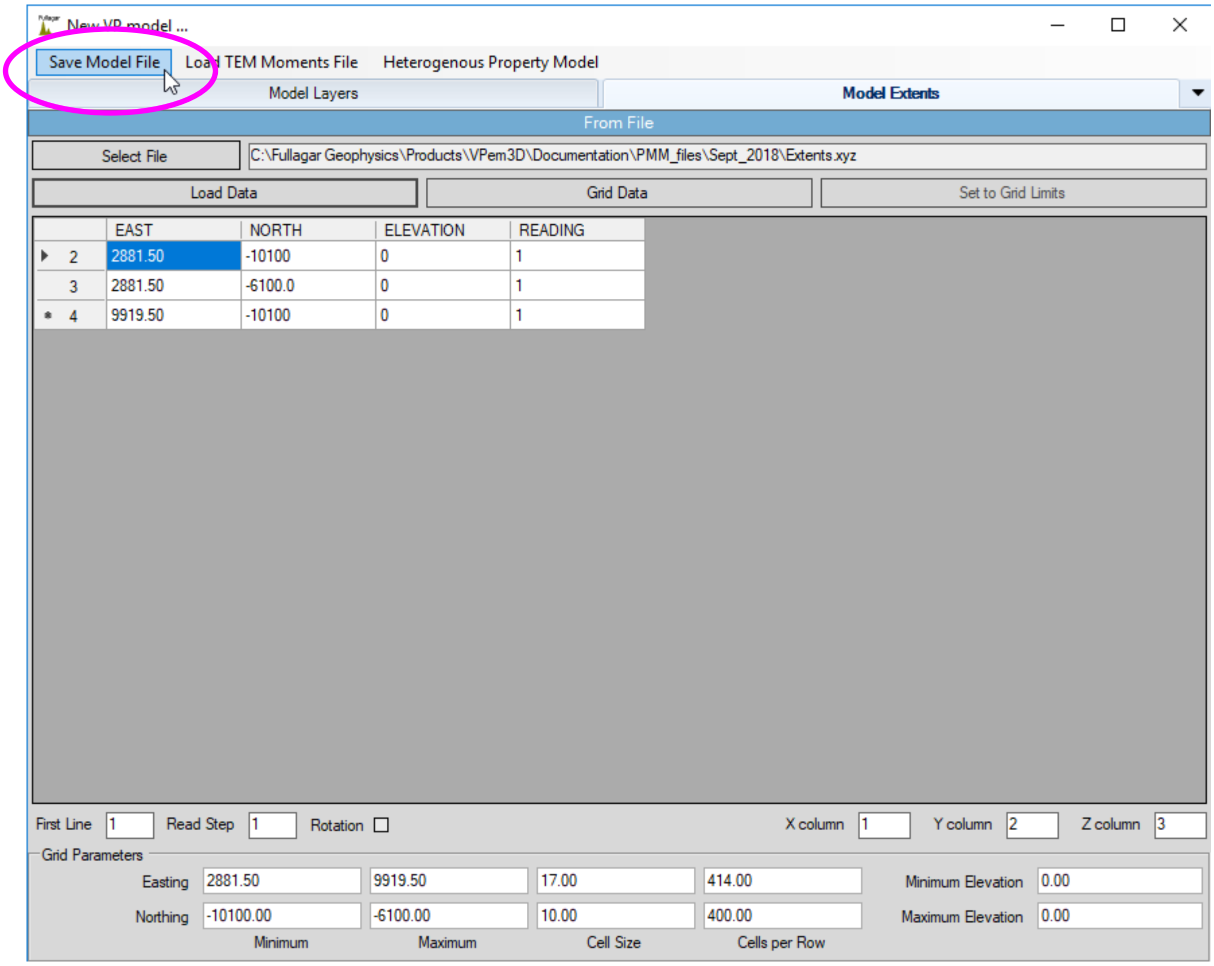
The first record here is an optional header line. If the corner elevations, RLn, are not identical the model top elevation will be their average value.



Select the dummy data file containing model limits.



Load the model extents by clicking on the *Load Data* button.

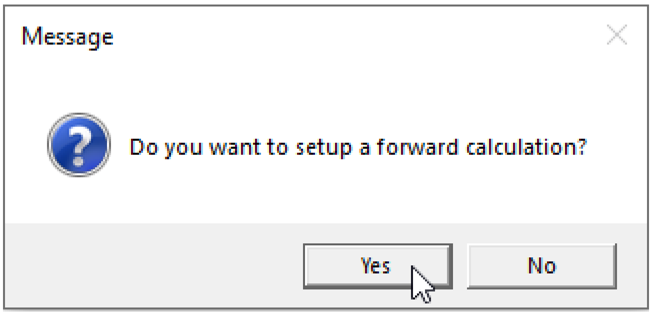


Save the model to disk. Sub-cells and depth weights will be introduced by VPem3D, as described in Section 12.3.

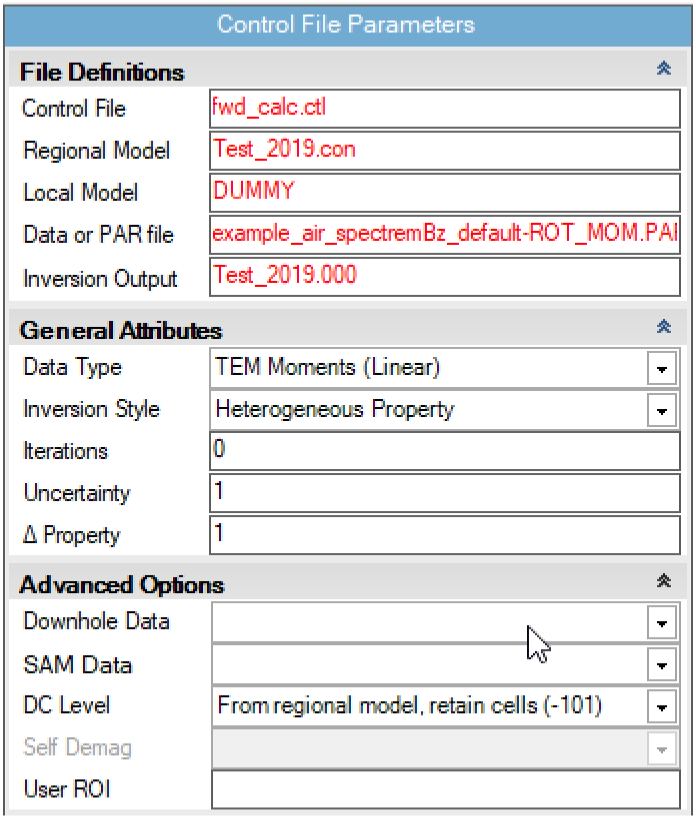
12.5 Create a control file for a forward calculation

A control file is required in order to run VPem3D, for either forward modelling or inversion.

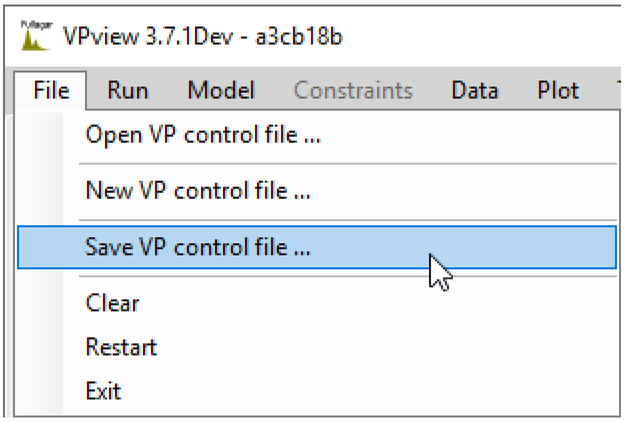
If a starting model has just been created using the *Create New Model* utility, the user will be prompted to prepare for a forward calculation.



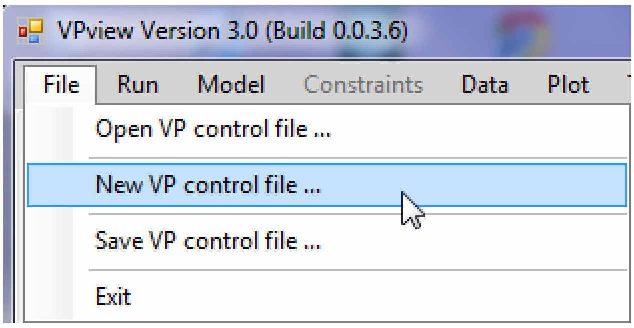
If the user clicks “Yes”, VPview creates a draft control file:



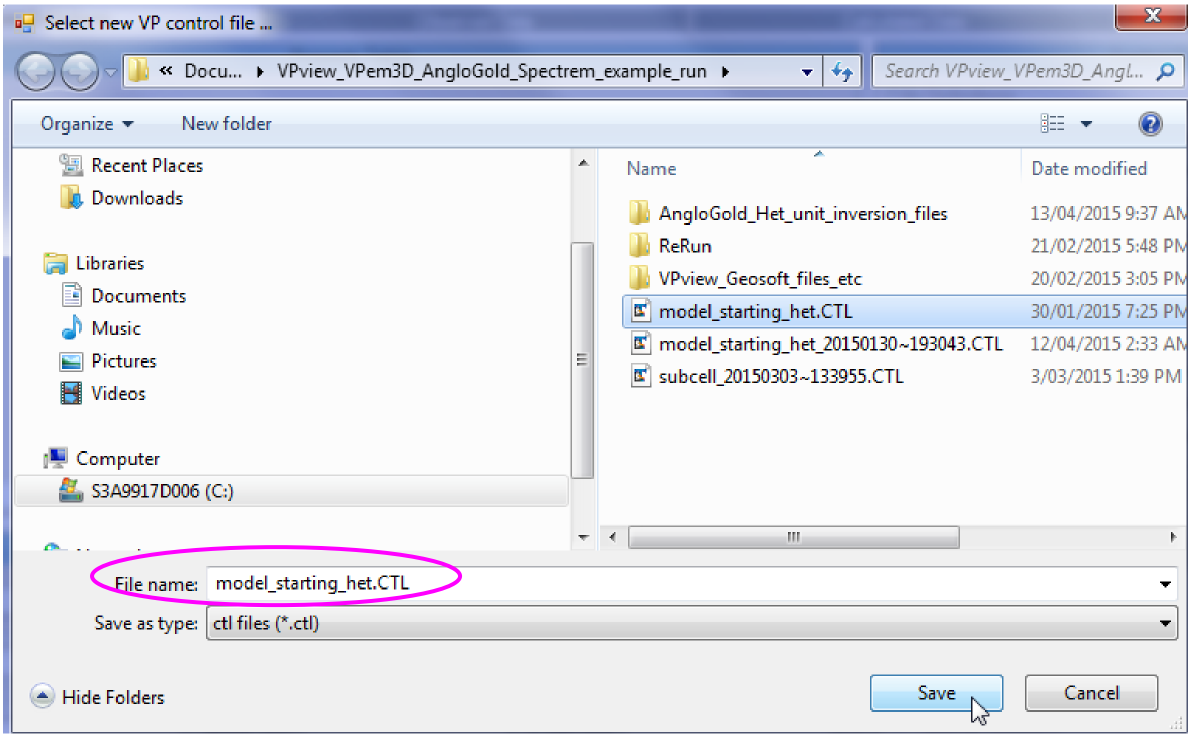
For a control file for an AEM forward calculation, the user need only specify *Downhole Data* = *No* and *SAM Data* = *No*, and then save the file.



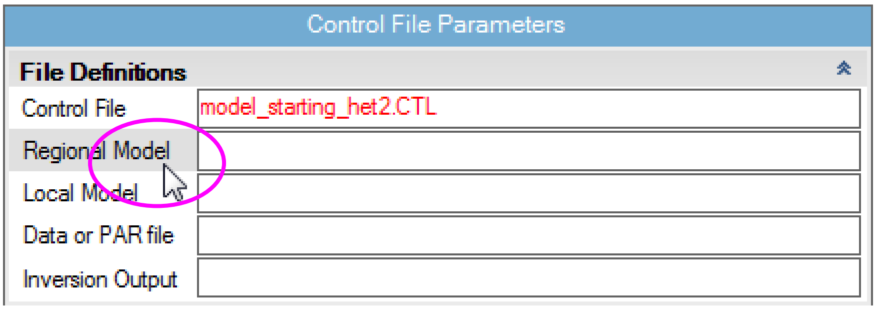
More generally, control files can be created using the *New VP control file* utility under the File menu.



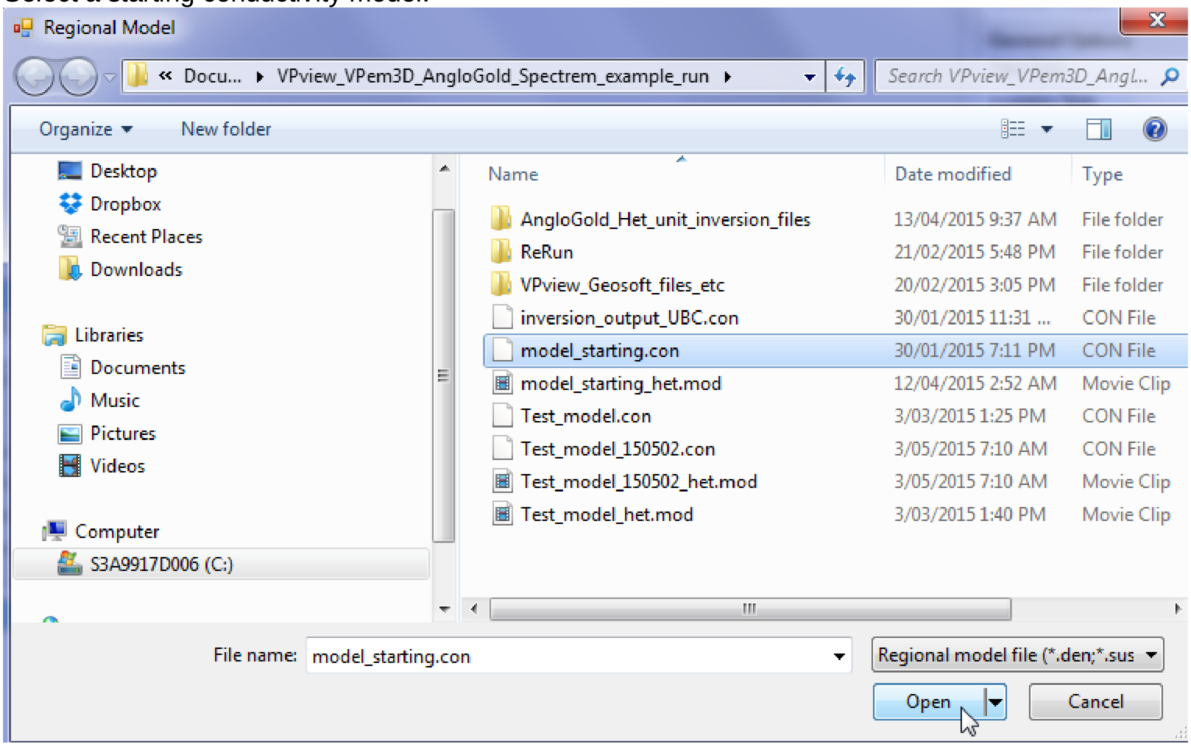
First select the project directory and choose a name for the control file. The control file has extension is CTL. In the illustration the control file already exists.



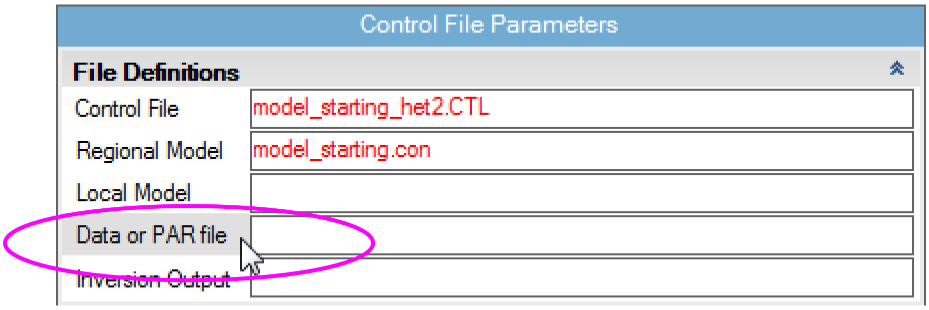
Click on a model file label to open a browse window.



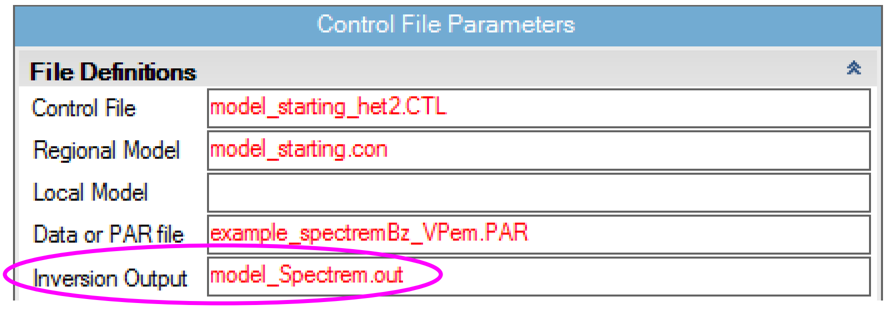
Select a starting conductivity model.



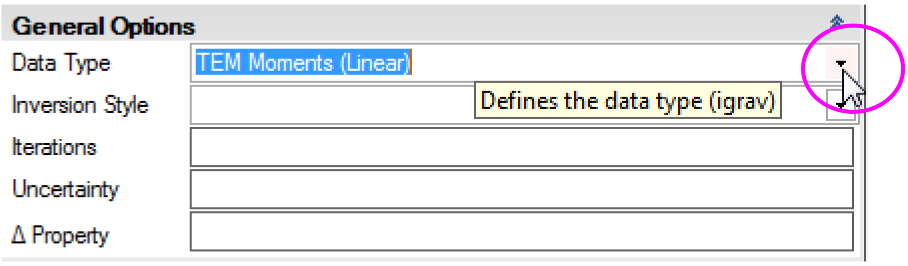
The starting model can be either regional or local. The text box for the other model can be left blank. Select a PAR file in the same fashion: click on the label to open a browse window.



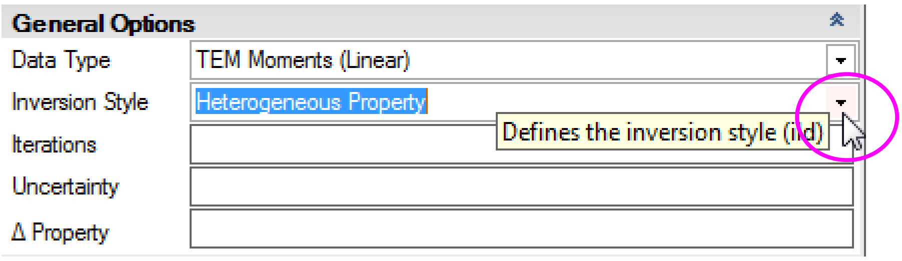
The output model file will usually not already exist. Type in a name for the output file. The extension is arbitrary, but VPview recognises *.CON files as conductivity models.



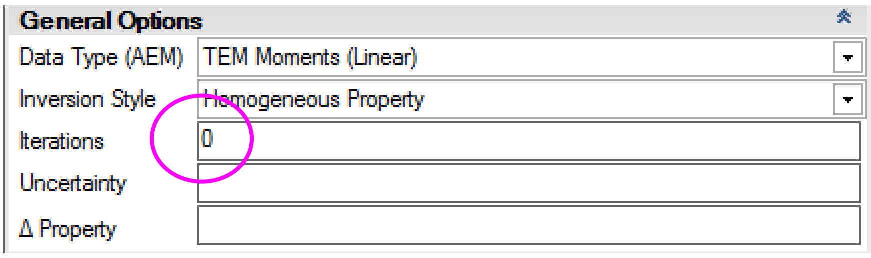
Now define ***General Options*** settings. Use the drop down menu to select *Data Type*. TEM Moments (Linear) is the appropriate *Data Type* for airborne TEM.



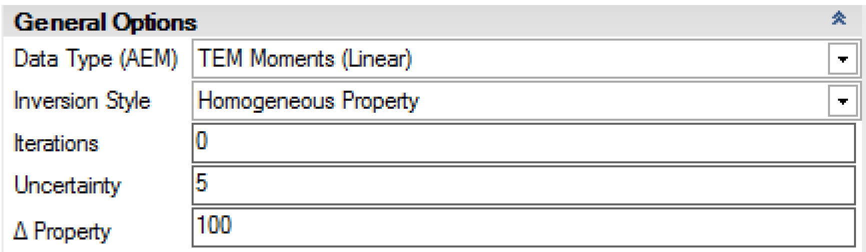
Use the drop down menu to select *Inversion Style*. Heterogeneous Property is the appropriate *Inversion Style* for the simple host-on-basement model created above, when the aim is to adjust the conductivity of individual model cells.



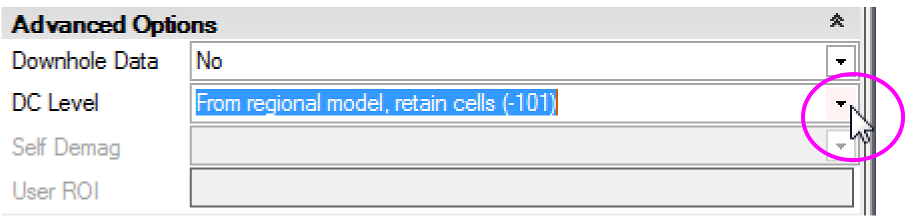
Set Iterations to zero for an initial forward calculation.



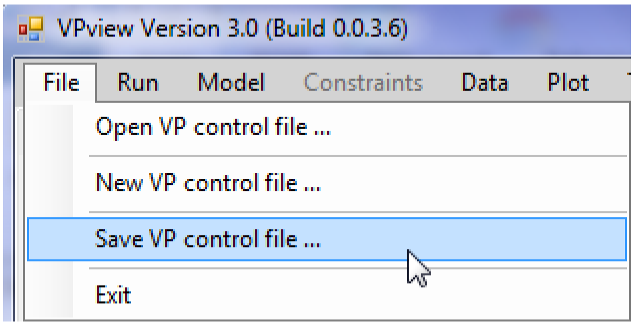
Define values for the *Uncertainty* (in data units) and the *Δ Property* (maximum conductivity change per iteration, in mS/m).



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.]

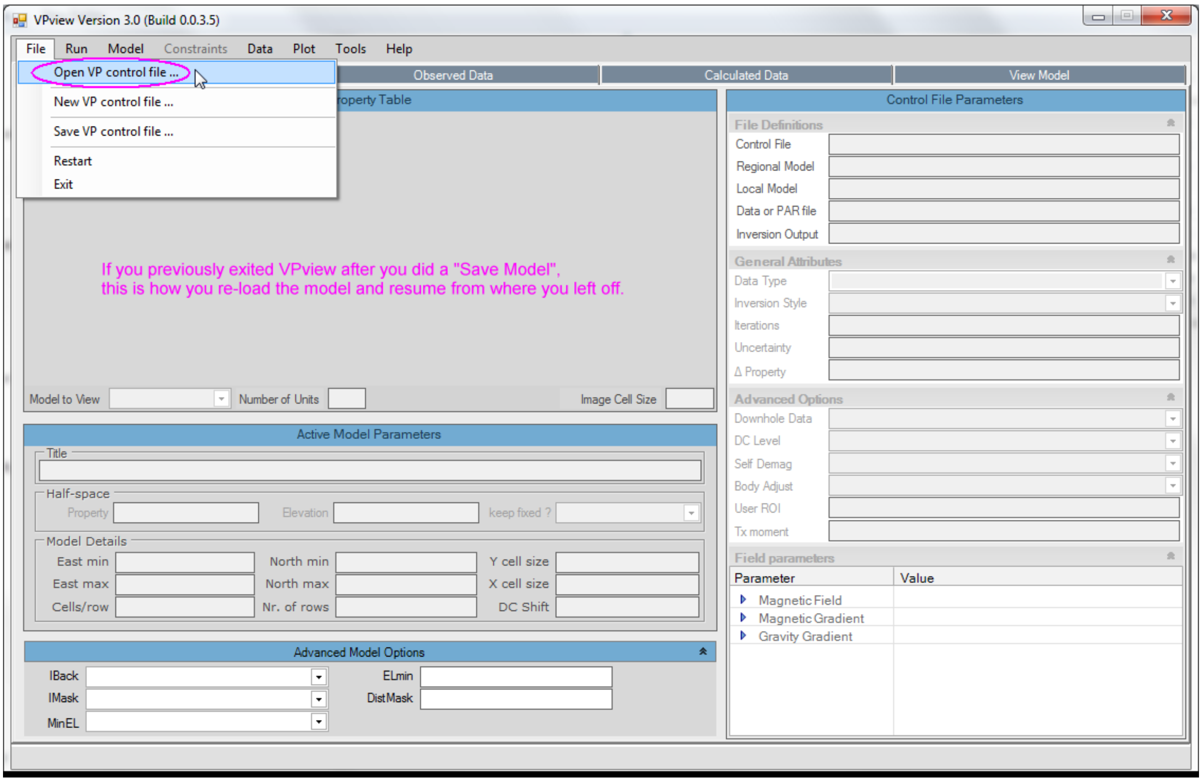


When all fields have been populated, save the new control file using the option under *File*.

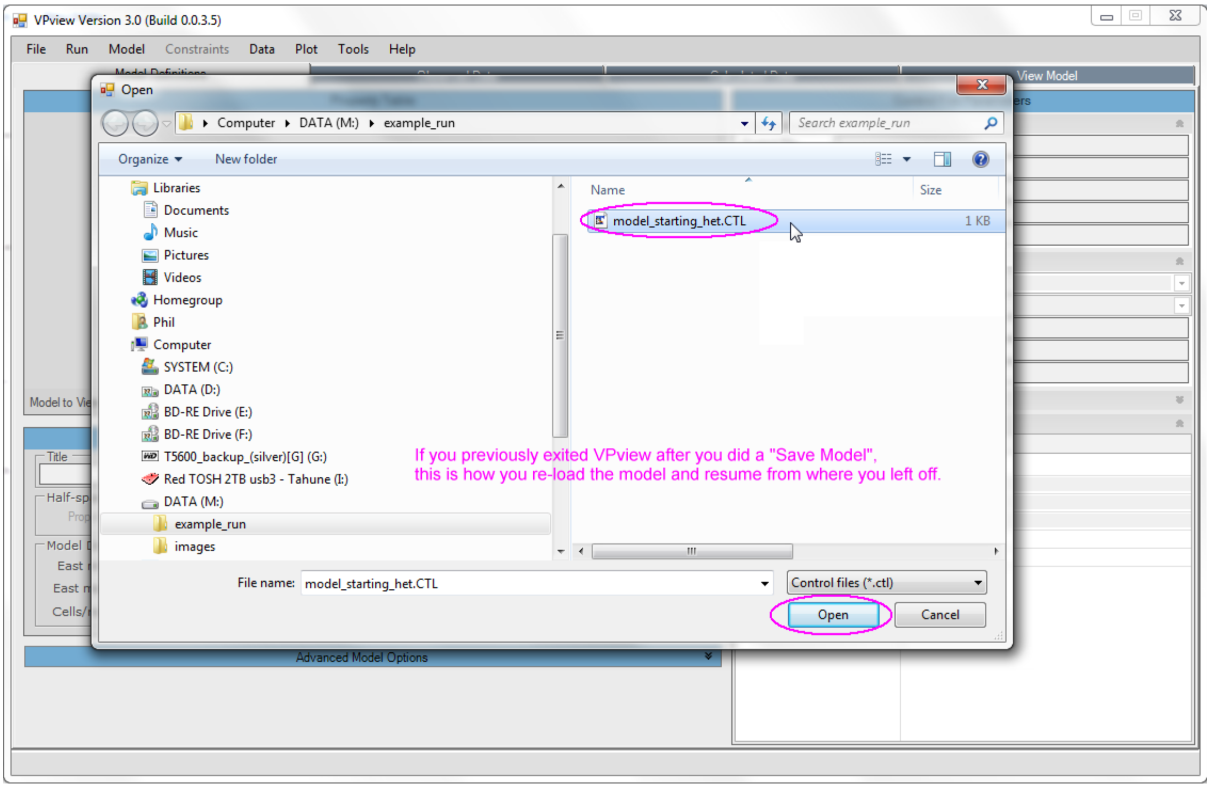


12.6 Performing a forward calculation

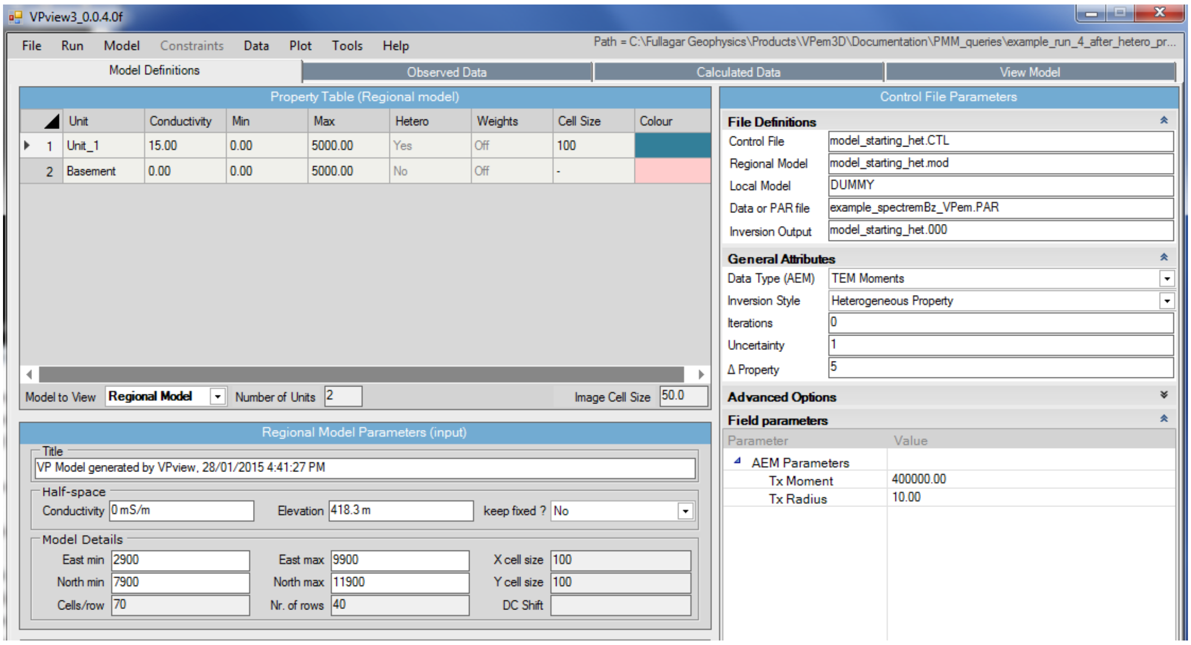
Select the “Open VP control file” option under the *File* menu.



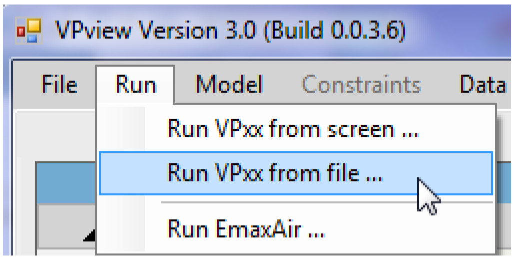
Select the desired VP control file.



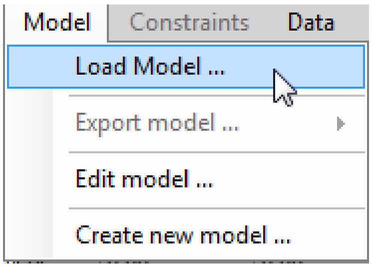
VPview displays the control file settings saved earlier.



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.



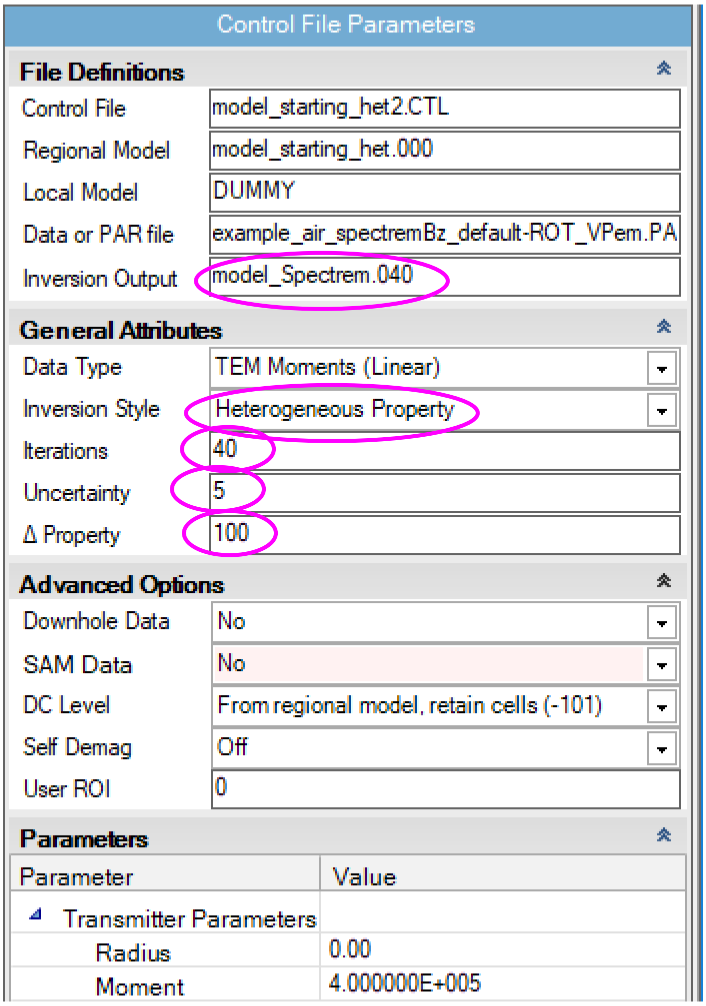
When the forward calculation has completed, display the starting model, and the observed and calculated data, using the “Load Model” option under the *Model* menu.



12.7 Running an AEM inversion

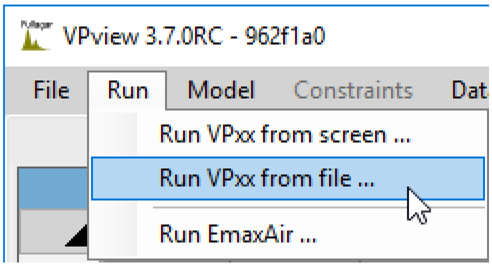
Once satisfied with the forward calculation, prepare to run an inversion.

The output model file, *model_starting_het.000*, 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.



Set remaining parameters in prepare for running the inversion:

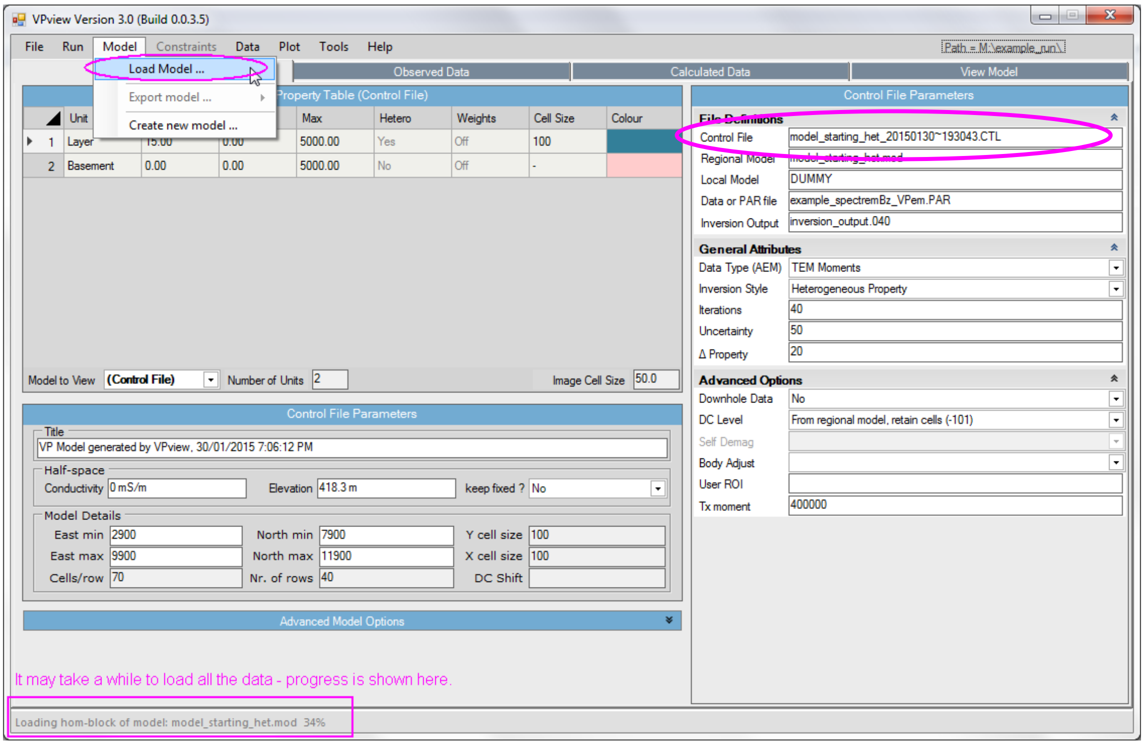
- Enter a file name for the inversion output.
- Set the inversion style.
- Set the number of iterations to perform.
- Set the uncertainty level in the data (data units).
- Set the maximum permitted change in property value per iteration (mS/m).



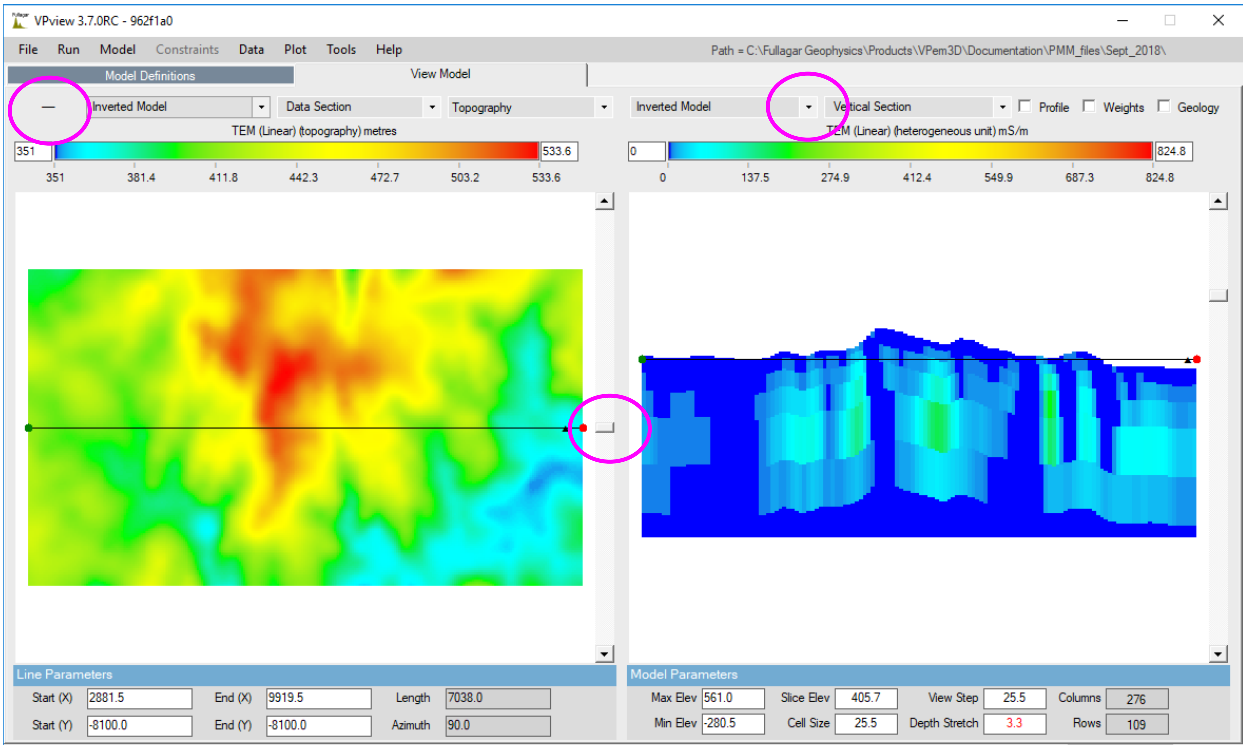
If any fields in the control file have been edited, select “Run VPxx from screen” to start the VPem3D inversion. A new Control File is created in this case, with date and time are appended to the original control file name in this case.

Otherwise, launch VPem3D via “Run VPxx from file” to use the parameters previously saved in the *.CTL file.

VPem3D inversion progress is displayed in a Command Window.



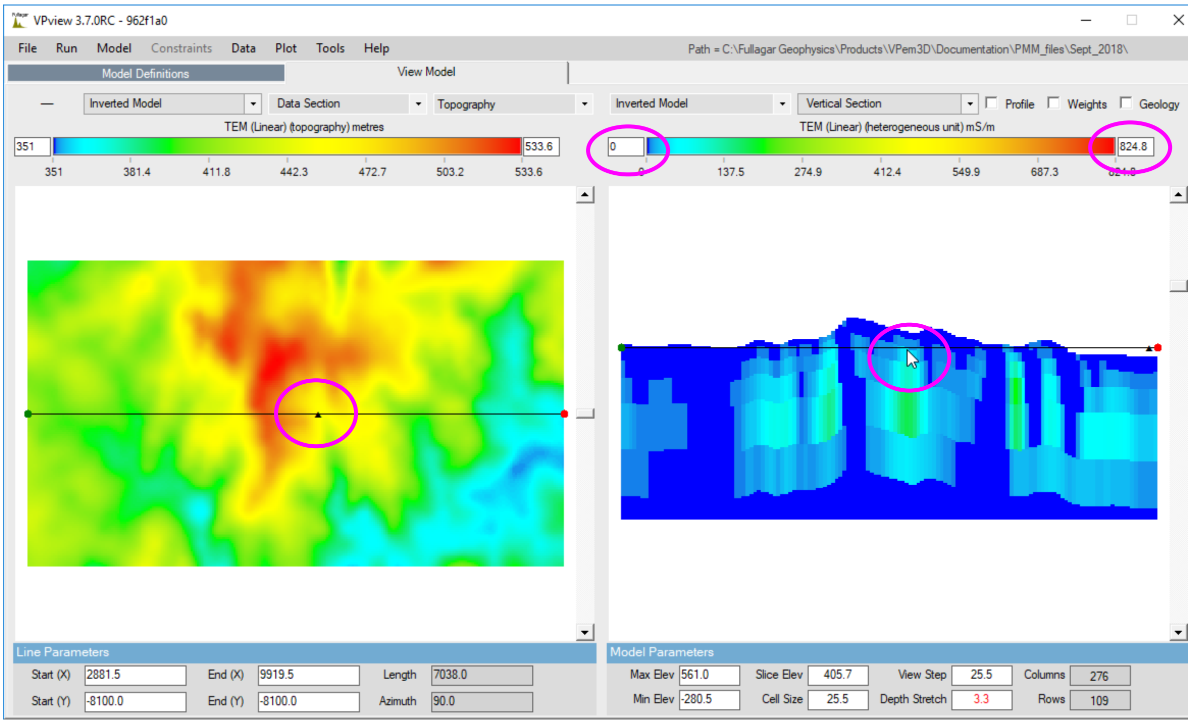
Once inversion has finished, load the model into memory.
The progress of various data load stages is shown in the bottom LH corner of the VPview window.



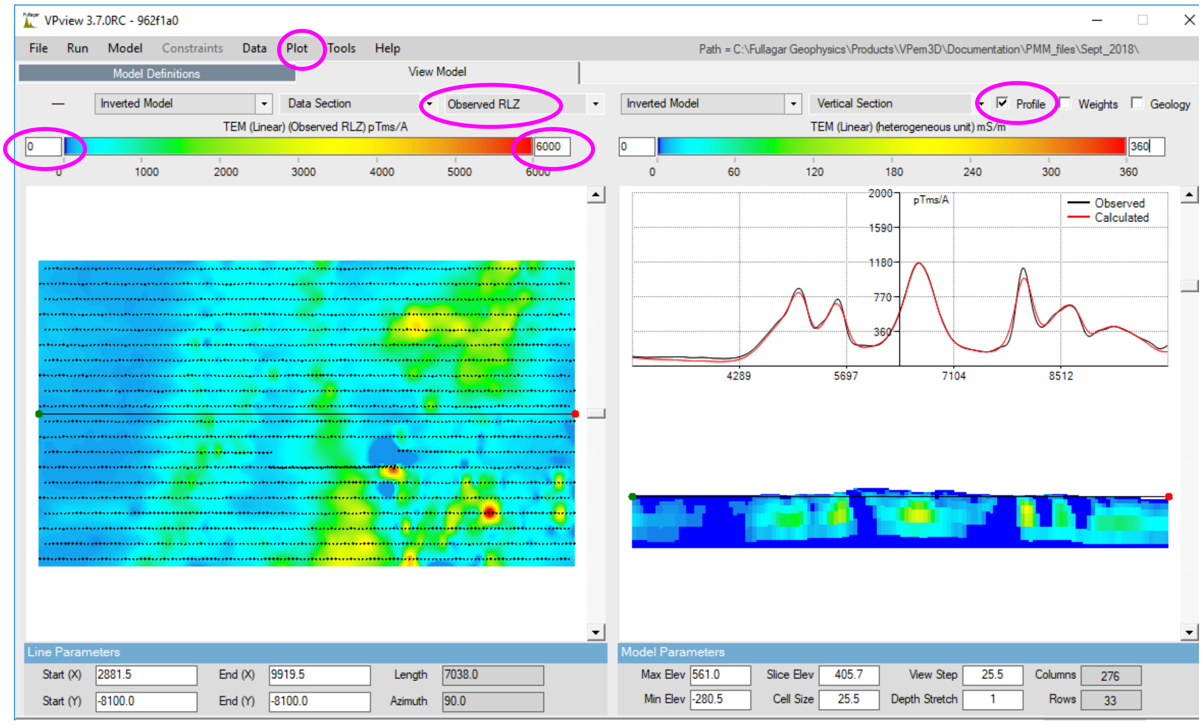
When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the inverted model is displayed in the right panel. The user can toggle between section views of the starting (Initial) and output (Inverted) models using the drop-down menu above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

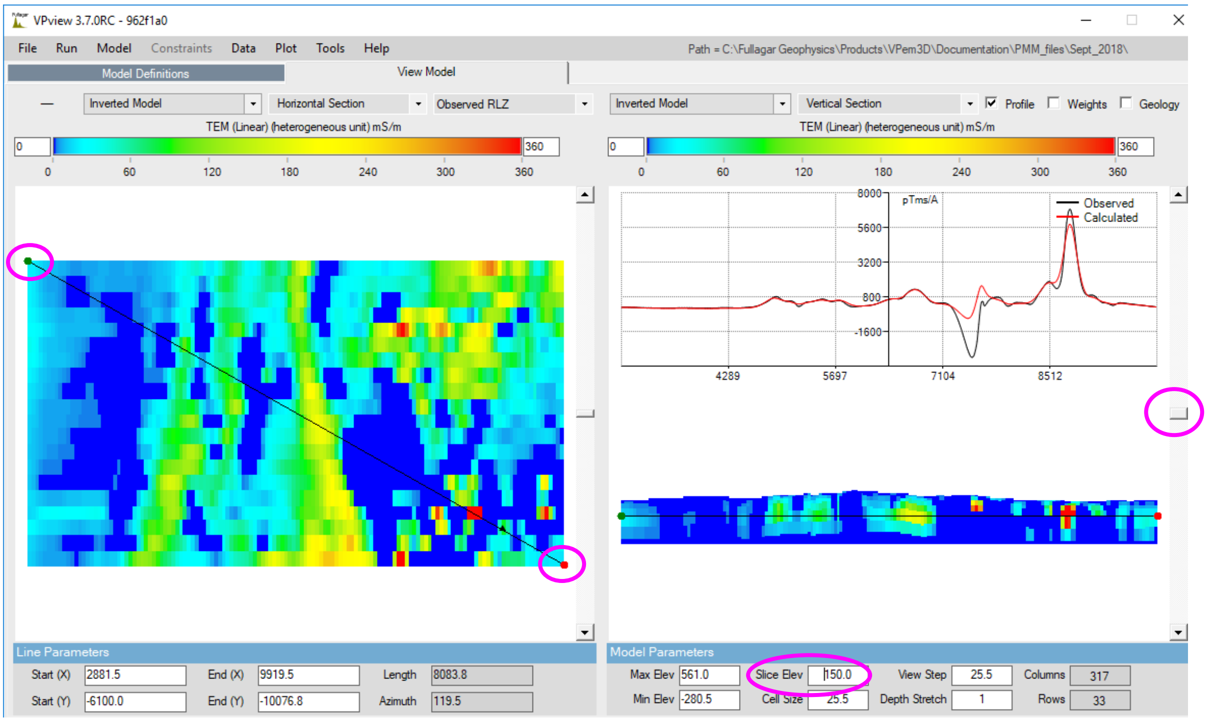
The model, data, and topography are displayed in LOCAL rotated (flight line) coordinates. The flight line direction is local east.



The cursor positions on left and right display panels shadow each other. If the 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.



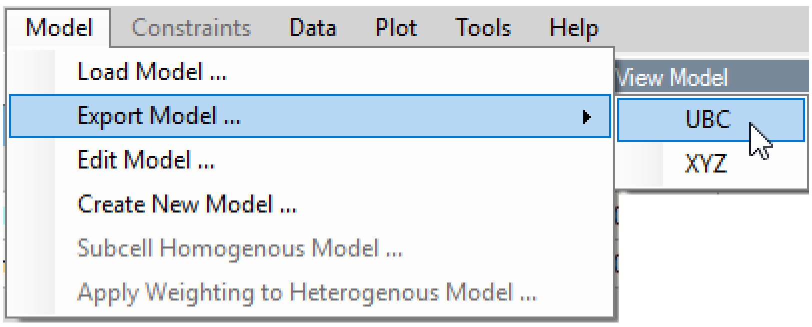
Here the left panel display has been changed from DTM to Observed Data by selecting “Observed RLZ” from the pull-down list. The colour stretch has also been reset to 0 – 6000 mS/m. A plot of observed (black) and calculated (red) data profiles appears above the vertical section when the Profile box is checked. Vertical exaggeration has been eliminated by setting Depth Stretch to 1. Flight line tracks have been plotted using the *Plot\Stations in Plan* option.

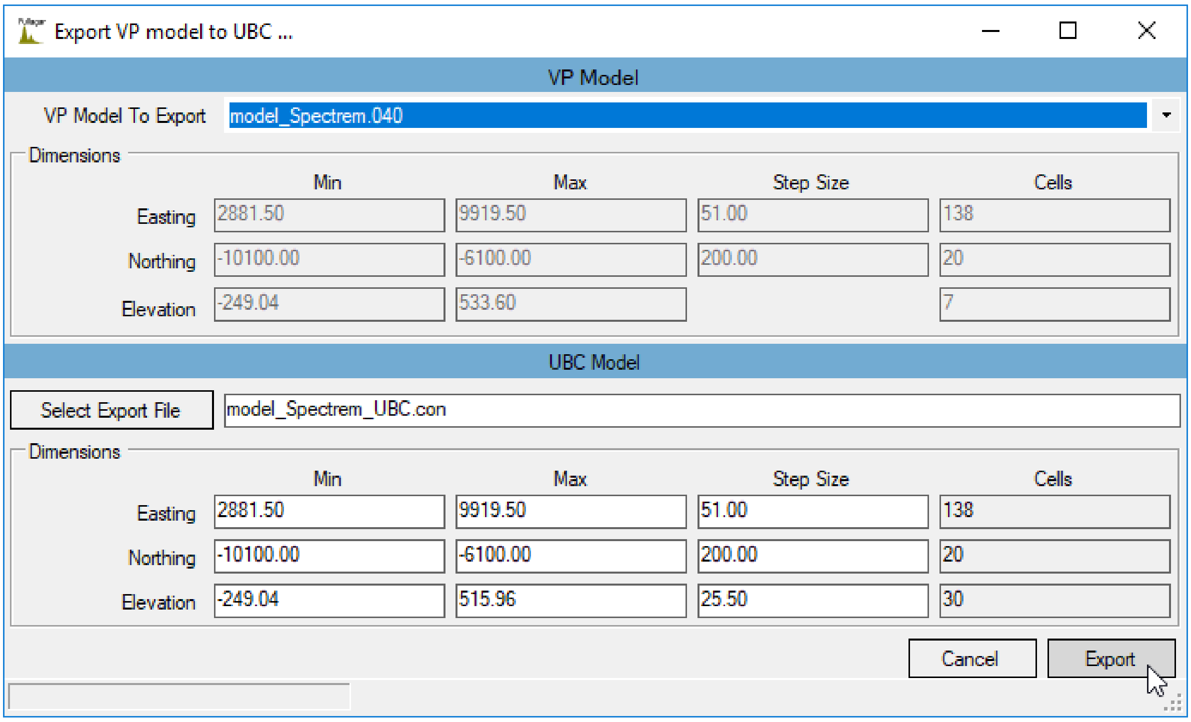


The position and orientation of the displayed section can be changed by dragging the ends of the black line on the plan view (left). The cursor positions on left and right still shadow each other. A horizontal section through the model is displayed in the LH panel if the scroll bar at right is adjusted. The black line in the RH panel indicates the elevation of the horizontal section. The slice elevation is displayed in the *Slice Elev* box, and can be altered by editing the value in the box.

12.8 Exporting the inverted model

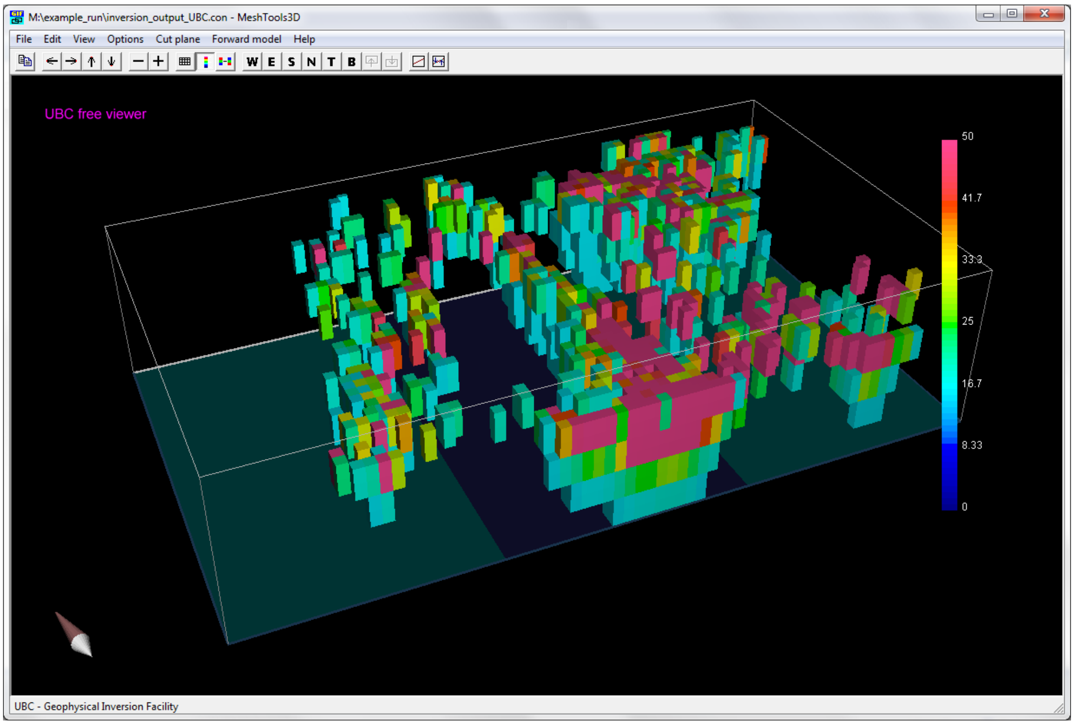
The inverted VPem3D model can be exported into a UBC model file or a column ASCII XYZ file. Both formats are available via the Model\Export Model option.





Window for export to UBC model format. Choose a cell size suitable for 3D display.

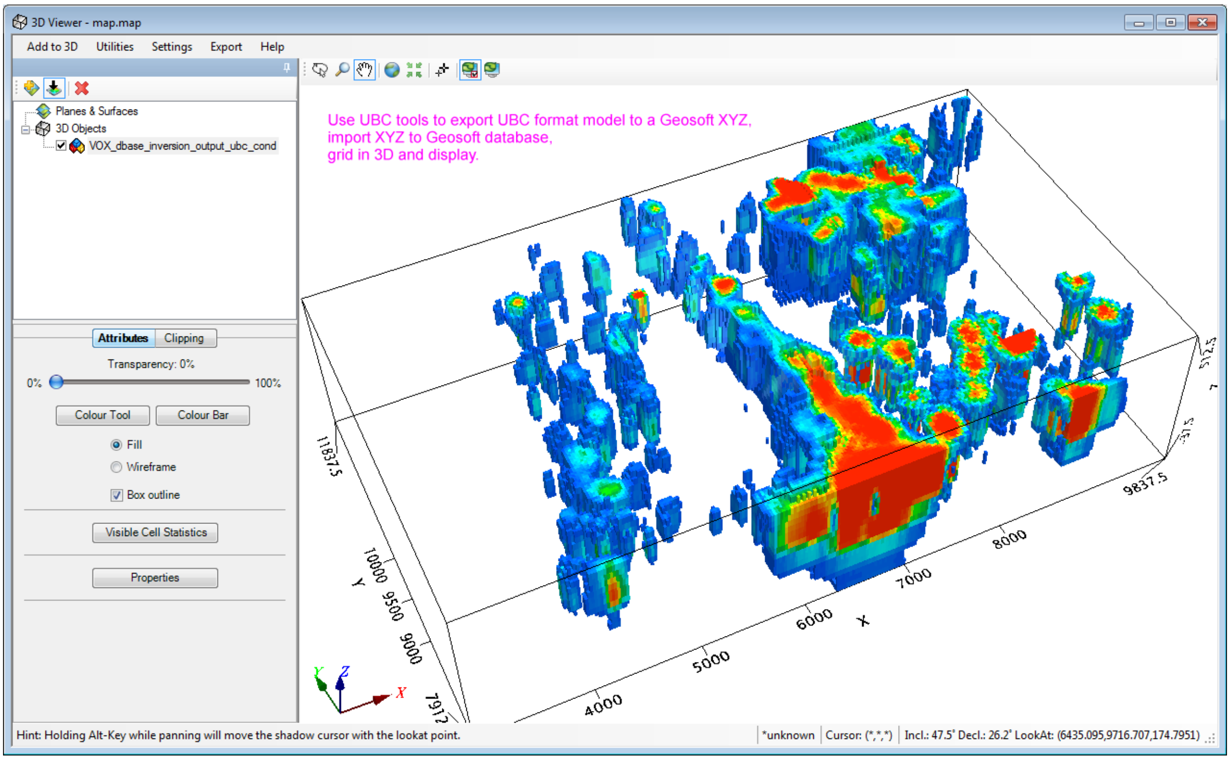
Two files, with extensions .CON and .MSH, will be created. UBC model files can be imported by a number of programs, including *Geoscience Analyst* which is a free viewer available from Mira Geoscience (www.mirageoscience.com).



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:

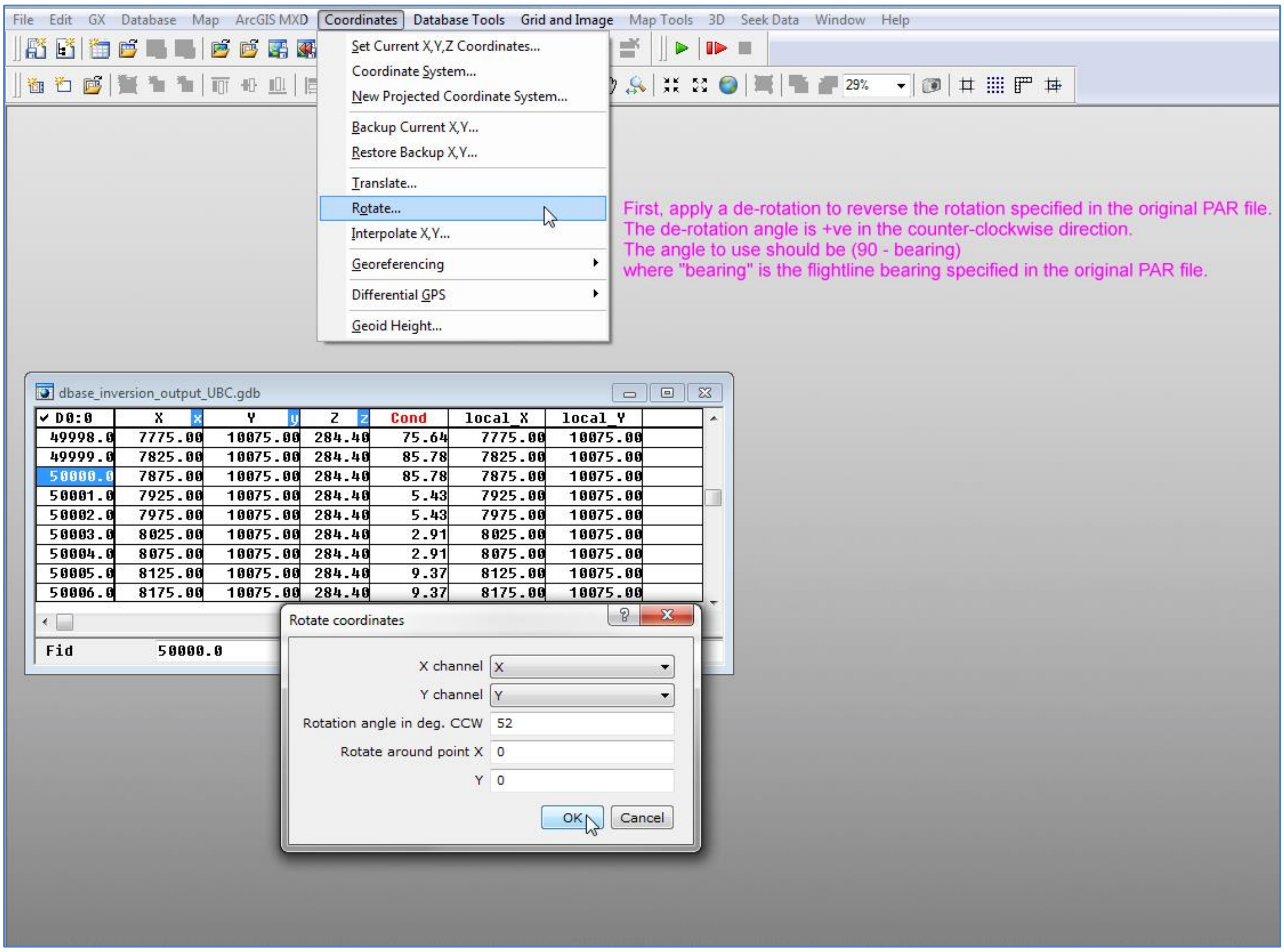
(a) A direct import of the UBC model to a Geosoft voxel. This runs IMPUBCVOX.GX, or can be accessed through the Geosoft menu 3D → Voxel_Conversions → UBC_to_voxel. [Some versions of Geosoft, for example 7.2.1, give an error when this import is attempted. The alternative import method described next can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

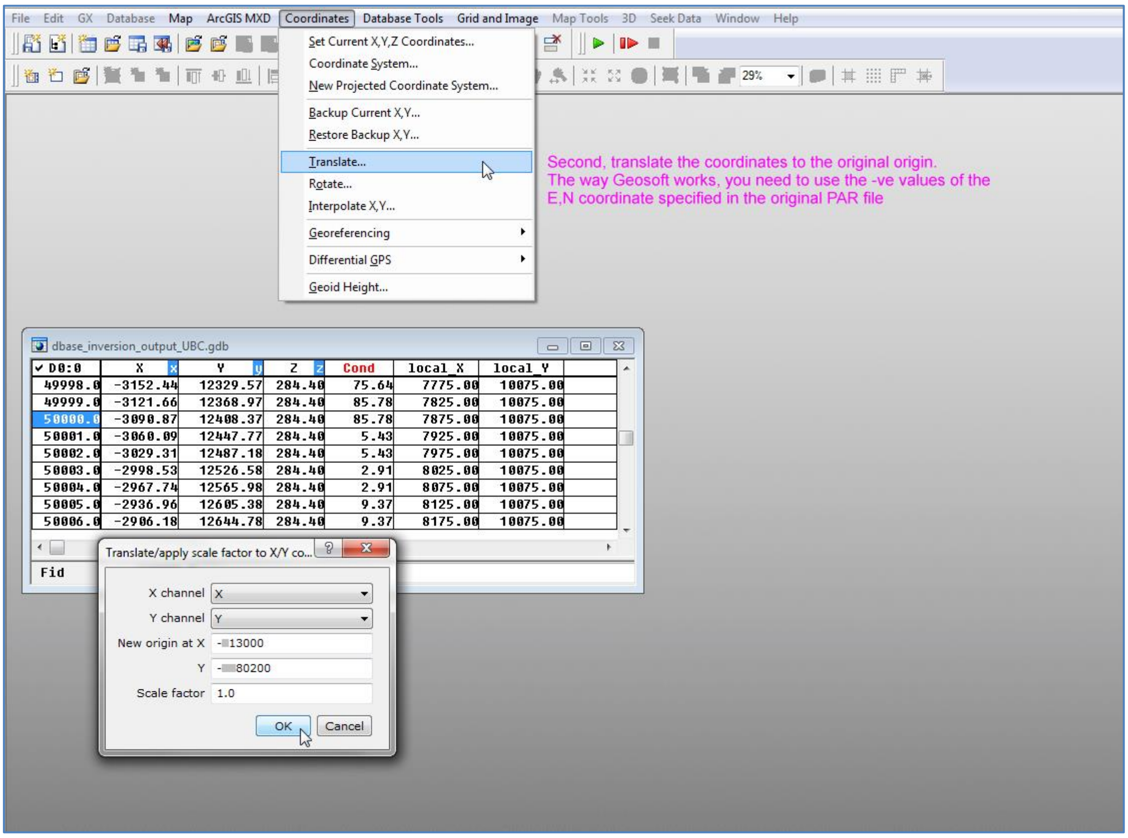


Once the XYZ file is imported into a Geosoft database, “de-rotate” the coordinates in two stages. First, reverse the angular rotation.

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.

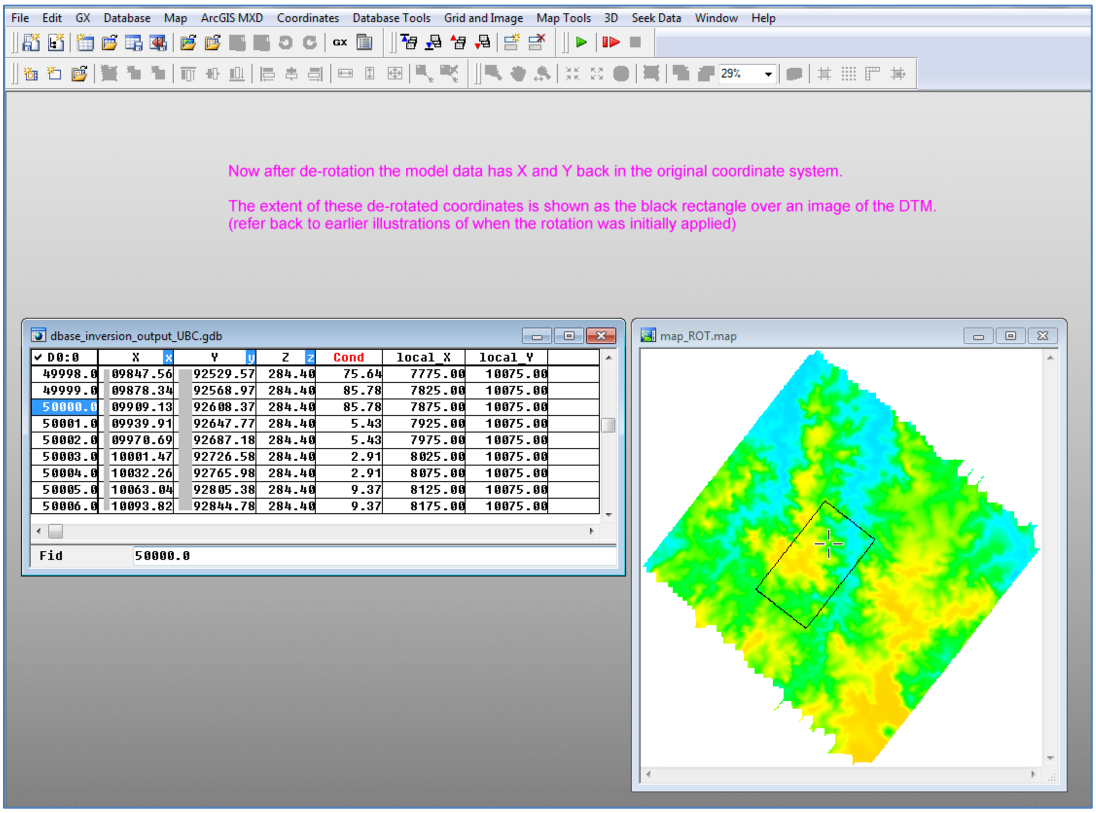
At this stage the Geosoft rotation should be done around point X=0, Y=0.

[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].



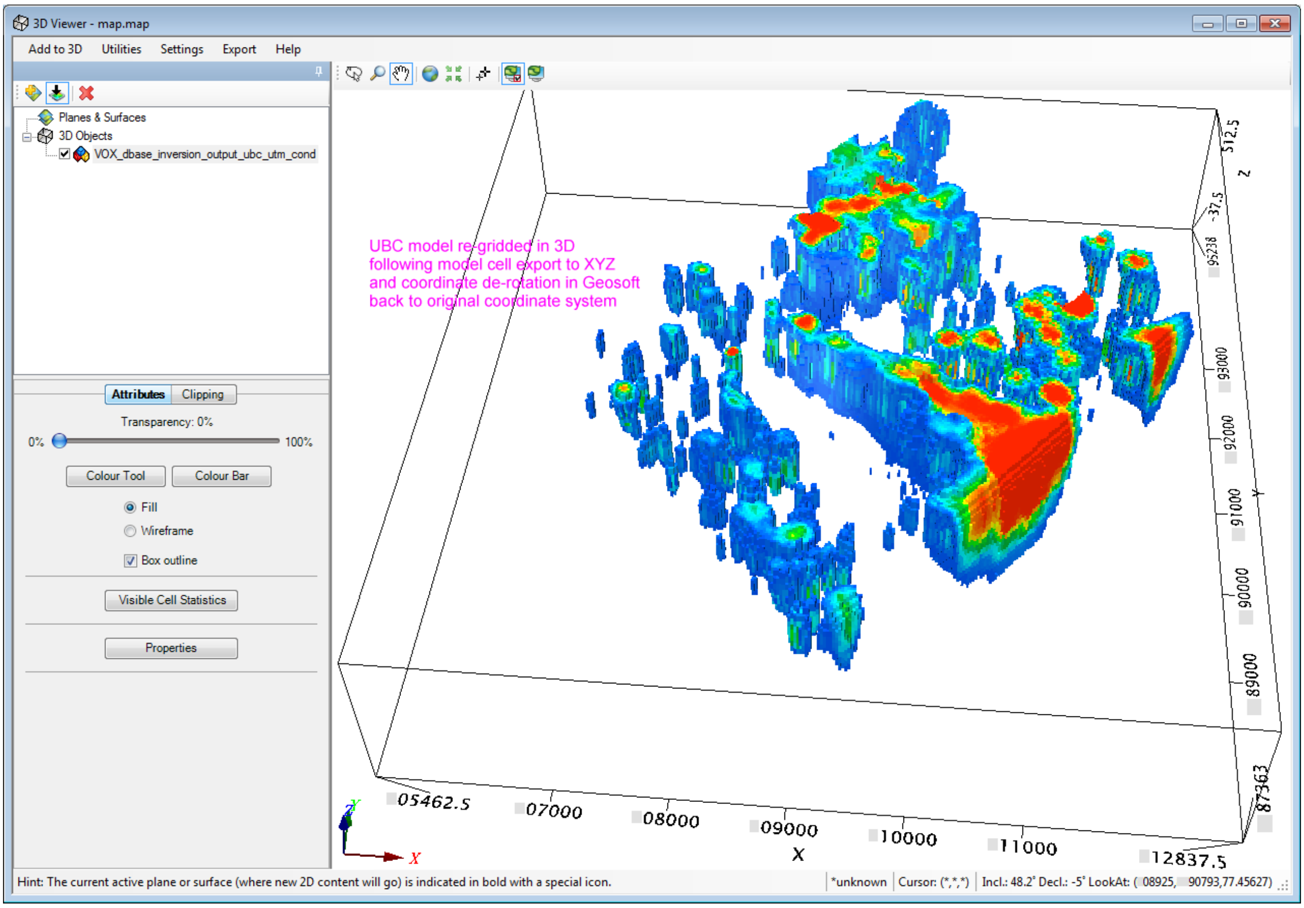
Second, move the de-rotated coordinates back to the correct origin.

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 to an example dataset is illustrated step-by-step 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.

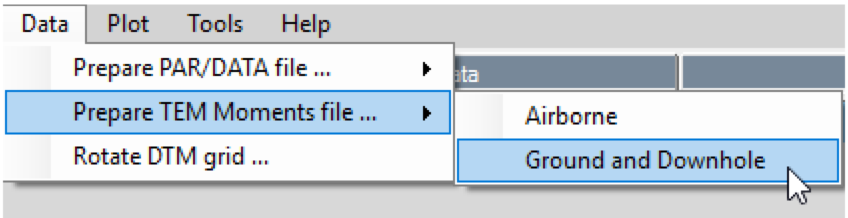
There are various ways to set up and run VPem3D inversion on downhole TEM data. The example used here illustrates conventional (smooth) heterogeneous unit inversion for data from two holes, excited by two Tx loops. The starting model comprises a zero conductivity uniform half-space.

13.2 Computing resistive limit data

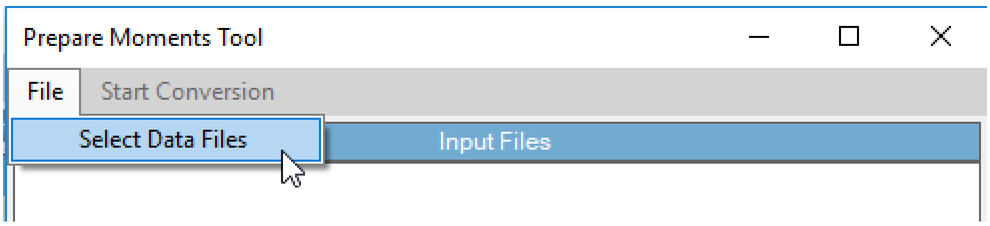
VPem3D operates on TEM resistive limit data. Therefore time decays must be integrated prior to VPem3D modelling and inversion. Downhole TEM data is expected in TEM format as exported from Maxwell.

```
TEM File Created by MAXWELL
LINE:East_116_3pntBoxDecayStn INSTRUMENT:CRONE DATATYPE:TEM CONFIG:DOWNHOLE UNITS:(nV/Am2) BFREQ:5.000 CURRENT:15.000 TXAREA:192000.000 LSIDE:438.178 OFFTIME:50.000 &
ONTIME:50.000 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 TXMOMENT: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 &
LV1X: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(ms)=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(ms)=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 12.435231
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 37.72474 36.29140 27.81587 18.343891 10.394093 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 37.644858 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 43.809169 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         1003.555 838.064448 671.571772 509.056479 370.68851 261.30697 177.77411 115.7842 72.099524 42.81024 23.907839 12.264973
```

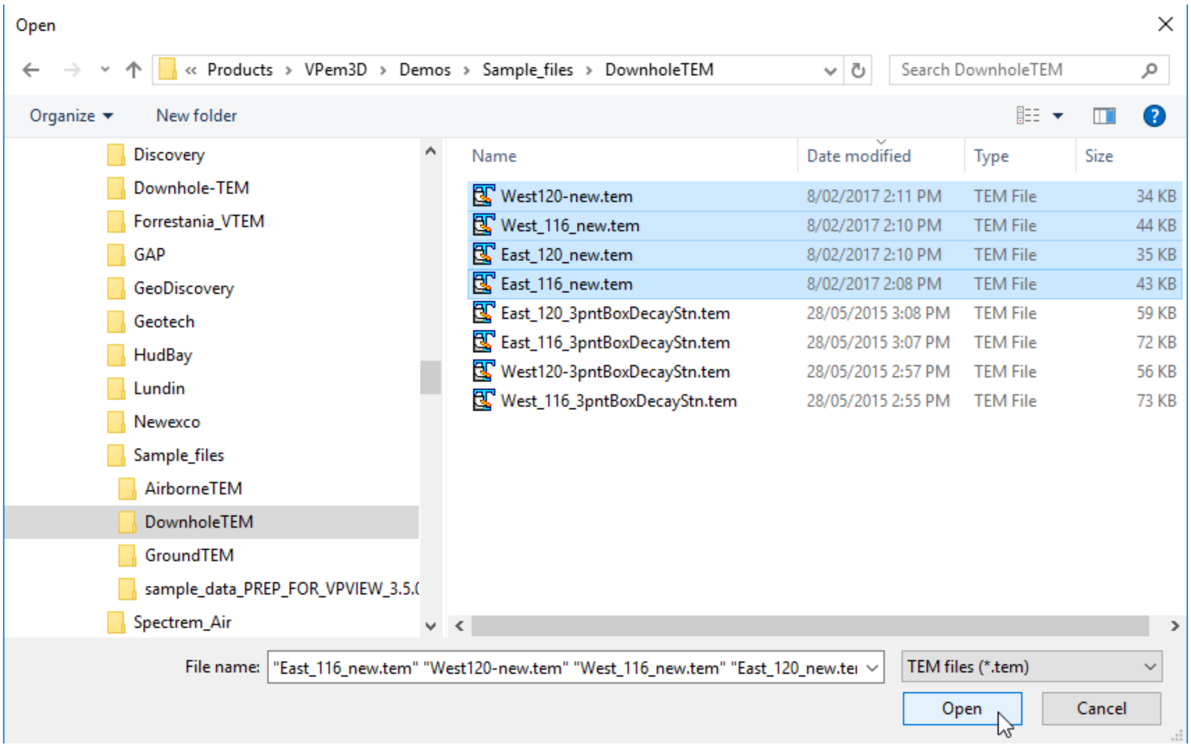
First few lines of a downhole TEM file generated by Maxwell. Tx loop vertices (LVnX, LVnY, LVnZ) are included in the header. Drill hole trajectory is defined by the DIP and AZIMUTH fields.



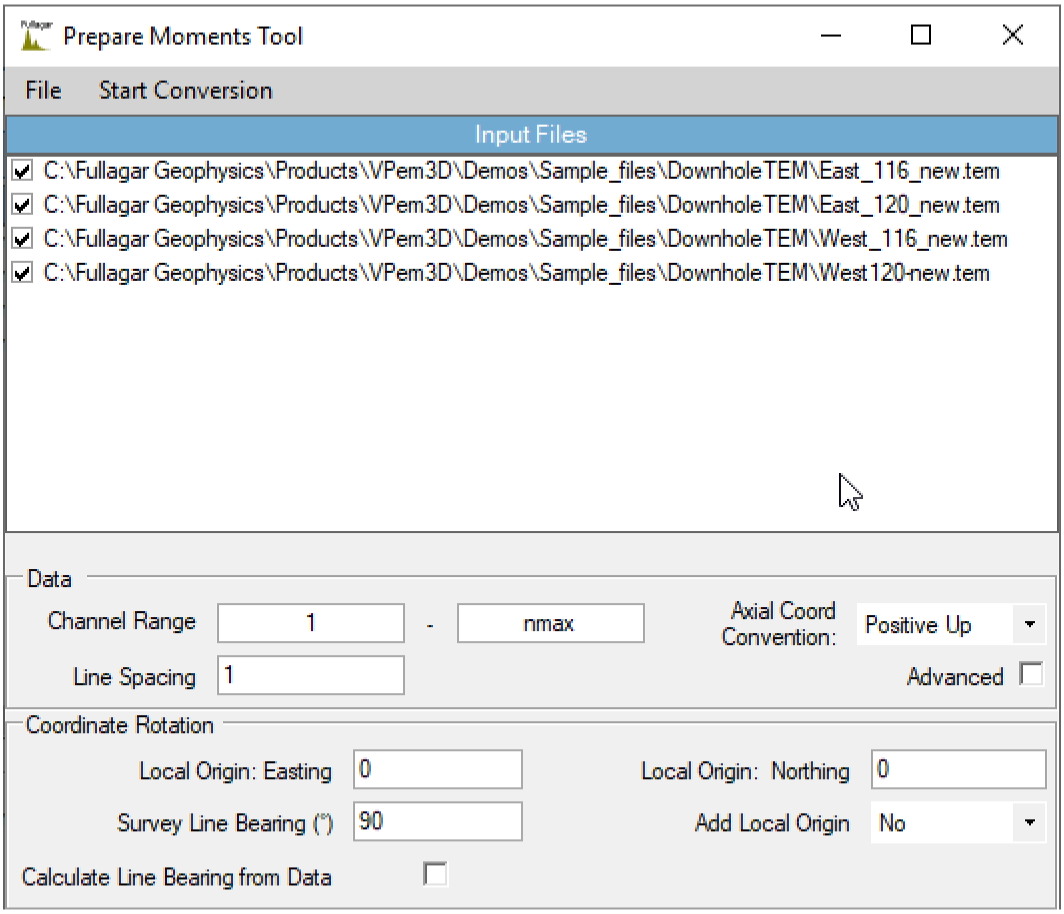
Accessing the data conversion programs under the VPview *Data* menu.



Browse for TEM data files.



Select the required downhole TEM files.



Select the channel range to be processed. 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. The time ranges are recorded in the header of the output file containing the resistive limit data.

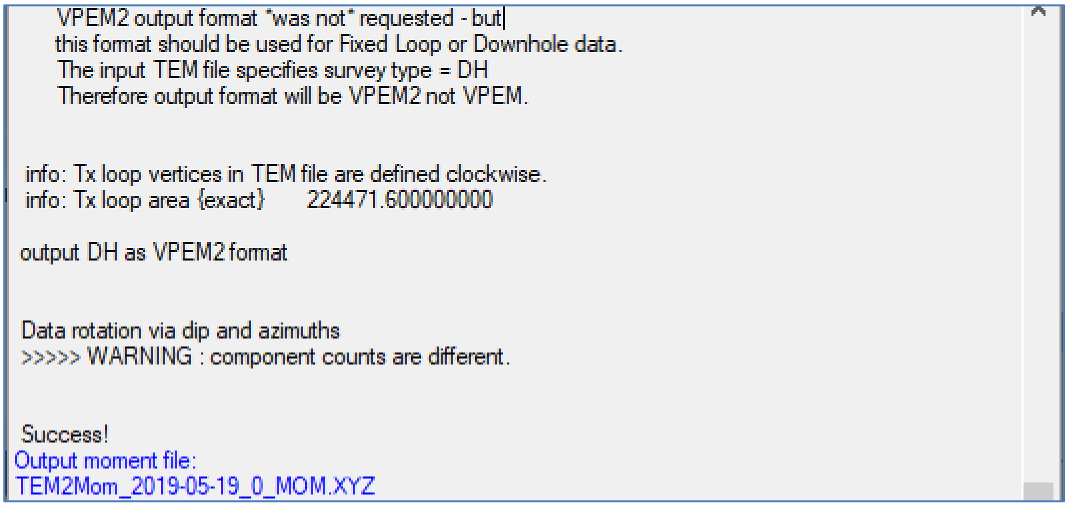
Select appropriate coordinate convention, either “Positive Up” (X=east, Y=north, Z=up) or “Positive Down” (X=north, Y=east, Z=down). Crone downhole TEM, for example, is usually recorded in the “Positive Up” system (aka ENU), whereas most UTEM downhole data is recorded in the “Positive Down” system (aka NED).

The user can define a percentage error, PCERR, and a noise floor, SDMIN, by checking the “Advanced” box. The noise floor is in original TEM data units, e.g. pT/A or nT/s. TEM2Mom computes the corresponding errors associated with the moment (“resistive limit”) data. As explained in Section 5.2, **care is required** if setting a percentage error, especially if the starting model has zero conductivity. The default (if the “Advanced” box is unchecked) is to assign a uniform error to all components; the uniform error default has been adopted in this example.

Line Spacing plays no role in the downhole TEM case, so can be left as 1.

Coordinate rotation is rarely applied to downhole TEM data. Note that TEM2Mom rotates the coordinates of the receiver stations and loop vertices, but does not rotate the RLX, RLY, RLZ moment components.

When satisfied with the parameter settings, launch TEM2Mom by clicking on *Start Conversion*.



Check the text output from TEM2Mom for any error or warning messages.

```
/ C:\Fullagar Geophysics\Products\VPem3D\Demos\Sample_files\DownholeTEM\West120-new.tem
/!!IntegrationTimeWindow #VPEM2  (start-end time in milliseconds):     0.0480     47.7000
/TEM2Mom : version = v3.7.13-dev  build date = May 19 2019  build time = 12:22:36  lic_var = 1(mlm)
/DataType = dB/dt: 1
/ConfigurationType = DH
/Across-line prism dimension:   16.0 (m)   Along-line prism dimension:  16.0 (m)
/Data elevation min :  -274.6 (m)
/Loop dimension     :   473.8 (m)
/Data easting  min & max:     818.70      898.95   Data northing  min & max:    1294.42     1305.76
/Model easting min & max:     760.00      952.00   Model northing min & max:    1256.00     1352.00
LOOP_DEF  EAST  4
1310.00       1112.00       390.78
1310.00       1607.00       390.78
890.50       1607.00       390.78
890.50       1112.00       390.78
LOOP_DEF  WEST  4
908.70       1117.50       390.47
908.70       1640.50       390.47
479.50       1640.50       390.47
479.50       1117.50       390.47
RXX                RXY                RXZ                RLX                RLY                RLZ
LINE EAST_116_3PNTBOXDECAYSTN  LOOP=EAST  DCX=1120.45  DCY=1279.89  DCZ=388.52
1107.072         1273.139          309.936          13.420884          10.039142          65.42788
1103.793         1271.452          290.279           6.101123          -3.264228          62.77828
1100.527         1269.860          270.612           7.865032         -12.954224          61.87106
1097.321         1268.278          250.934           6.836717         -23.139239          60.97919
1094.040         1266.848          231.257          25.039059         -21.198240          52.16039
1090.918         1265.307          211.562          18.574389         -17.588803          47.15021
1087.775         1263.831          191.866           2.046325           3.391432          43.27470
1084.659         1262.360          172.165          -7.090372          10.442652          44.41224
1081.625         1260.908          152.450         -13.720312          13.345246          47.24273
1078.556         1259.502          132.737          -8.074937           2.421567          58.19685
```

The last few lines of the header and the first few records of TEM moment ("resistive limit") data from the concatenated TEM2Mom output file are shown above. This file is in #VPEM2 format, as defined in Section 7.2, which is the default format for fixed loop TEM. The #VPEM# format is also legal for downhole TEM, provide the Tx loops are quadrilaterals.

Integration time ranges are recorded in the header, but commented out by default. In order for the integration time to be recognised by VPem3D when calculating a uniform half-space response, delete "!!" immediately before "IntegrationTimeWindow".

The header also includes default model parameters computed by TEM2Mom; these can be used by the *Create New Model* utility to expedite model construction (see below).

Tx loop geometry is defined in LOOP_DEF blocks. The downhole data are labelled with the drill hole ID, the Tx loop ID, and the drill collar coordinates.

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

```
#VPEM2
TEM2Mom_2019-05-19_0_MOM.XYZ
10
-3
4       RLX
5       RLY
6       RLZ
7       PROXYSTN
8       RLXE
9       RLYE
10      RLZE
```

The PAR file defines the TEM moment data file name and its format. The PAR file format is defined in Section 7.3. In this PAR file all three resistive limit components are identified, therefore modelling and inversion will be applied to 3 components. Columns 8-10 of the moment data file contain standard deviations for the "resistive limit" components. The sds are all zero in this case, and will be ignored by VPem3D.

13.3 Create a starting model (DTM grid available)

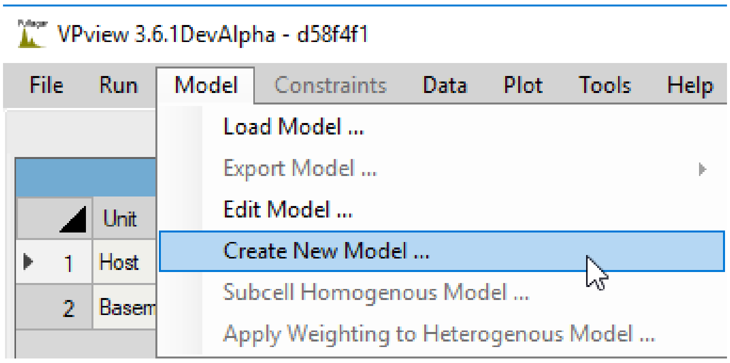
In VPem3D models, the model top coincides with the ground surface. Therefore VPview uses the DTM grid, if available, to define the model top during starting model construction. The format of the DTM grid must be Geosoft "DOS", i.e. uncompressed GRD.

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

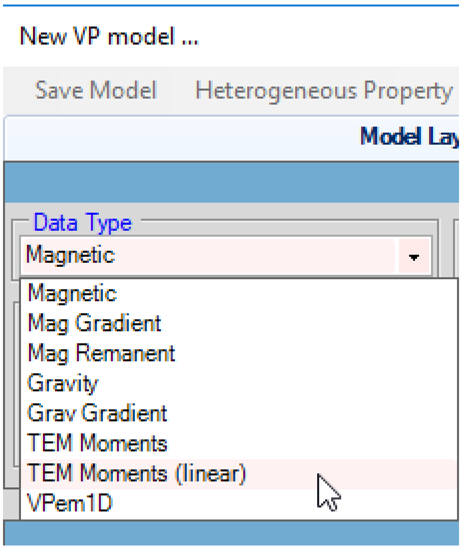
13.4 Create a starting model (no DTM grid available)

When no DTM grid is available, VPview creates a model with a horizontal upper surface. The procedure is outlined below.

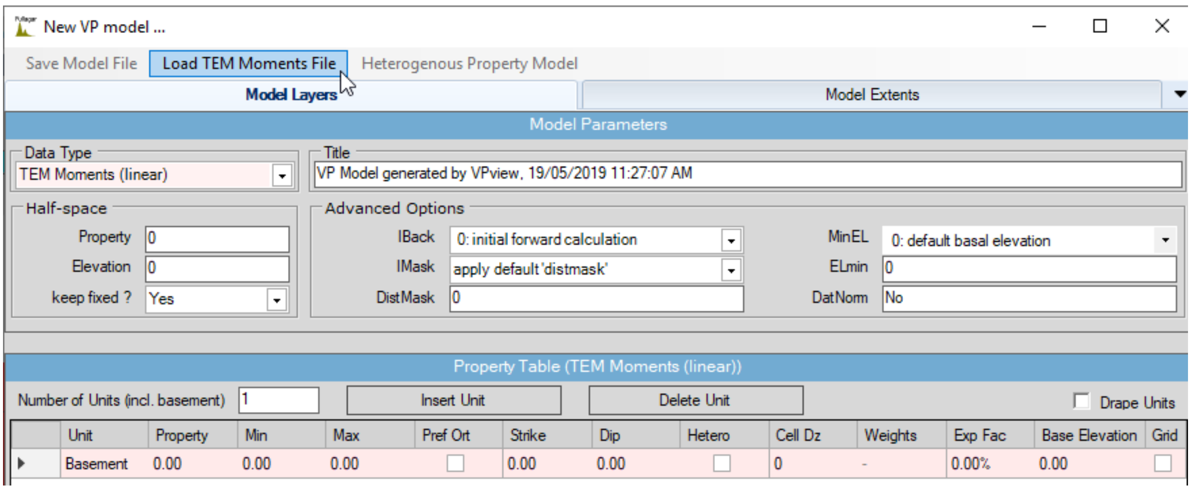
Launch the *Create New Model* utility:

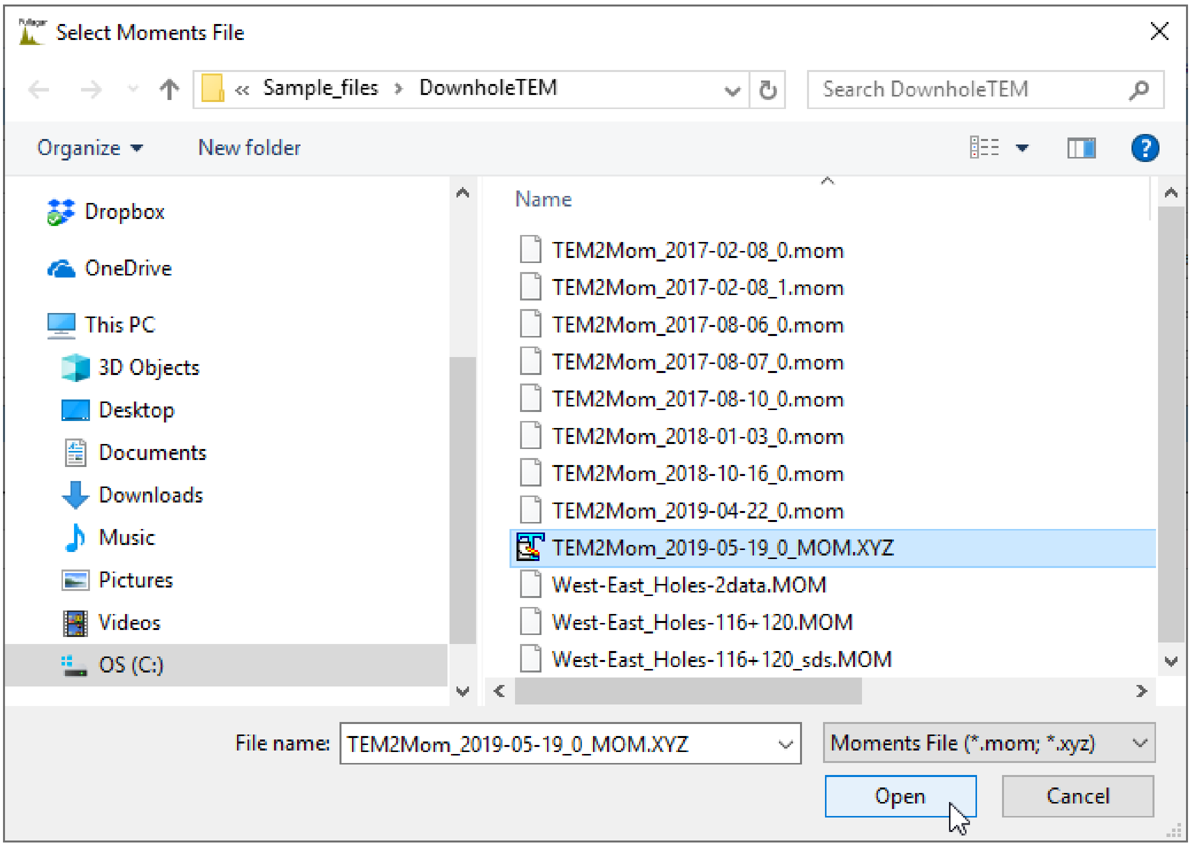


Select the TEM Moments (Linear) Data Type:

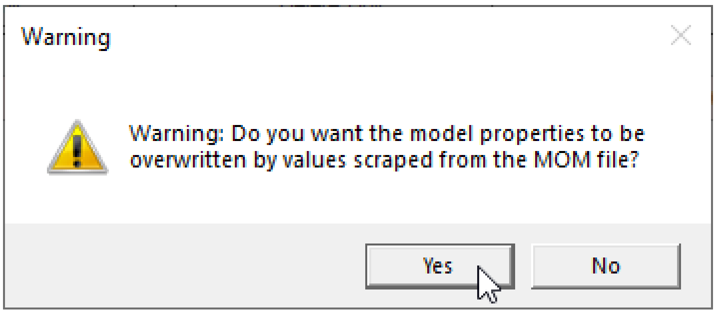


Load the TEM moments file, in order to read information from the header:



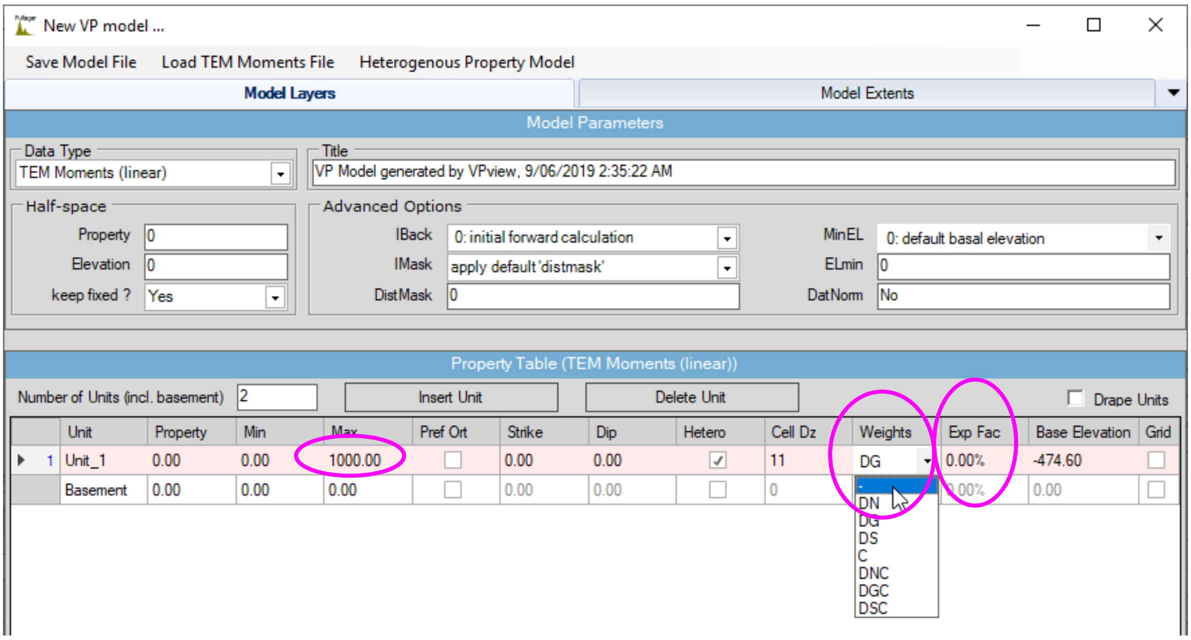


Ignore the warning unless you have loaded the Property Table with values which you wish to preserve.



VPview loads the Property Table with defaults based on information recorded in the TEM moment files header:

Edit the model parameters as desired:



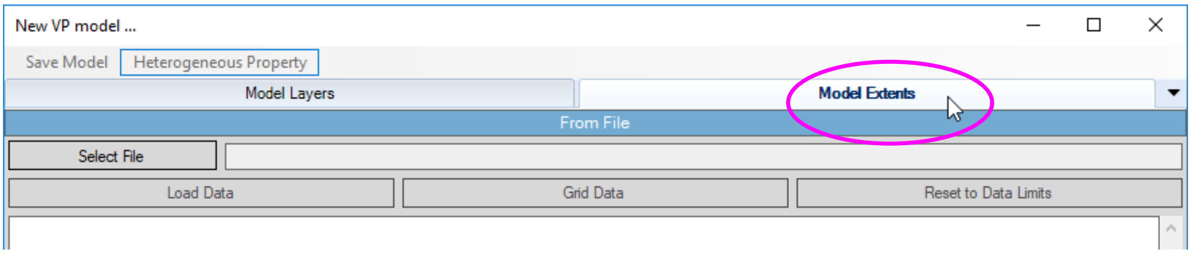
The default maximum conductivity of 1000 mS/m is often not high enough. It is usually desirable to enter a very high maximum conductivity value, e.g. 10^8 mS/m, if the intention is to run compact body inversion.

Depth weighting is often desirable for downhole TEM inversion, but in this example it has been disabled for illustration purposes; if introducing depth weights to an existing model, follow the procedure described in Section 13.8 below.

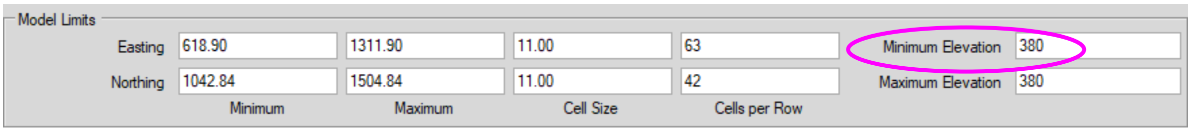
Cell Size refers to the vertical dimension, or thickness, of the shallowest model cell. The default thickness for downhole TEM modelling is equal to the lateral model prism dimension, which is (by default) the average downhole data spacing. Model cells are, by default, cubic for downhole TEM, so the expansion factor (Exp Fac) is set to zero.

By default, the base of the model is horizontal, at an elevation 200m below the lowest downhole TEM reading. In this case the model base is at an elevation of -474.6m.

The model limits, ground surface elevation, and prism dimensions are defined on the *Model Extents* form.

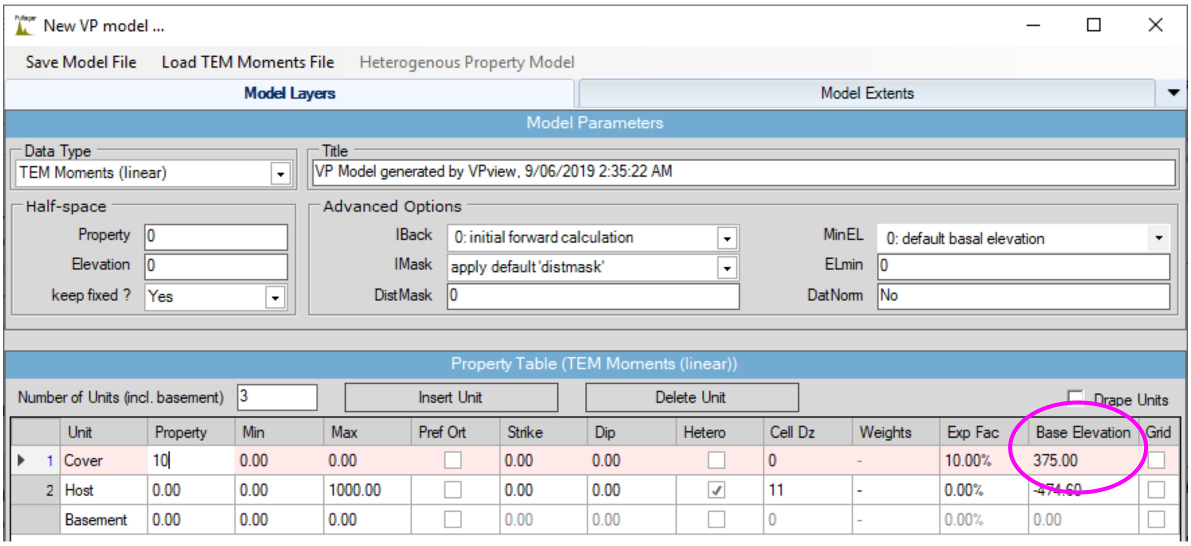


When no DTM (either grid or ASCII x,y,z file) is available, VPview creates a model with a horizontal upper surface. The default model extents and prism lateral dimensions (cell sizes) are displayed at the bottom of the *Model Extents* form:

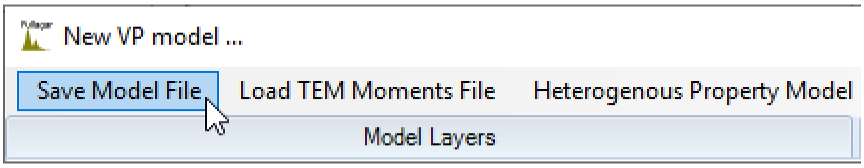


Enter the *Minimum Elevation* of the model top; VPview will assign an identical *Maximum Elevation*.

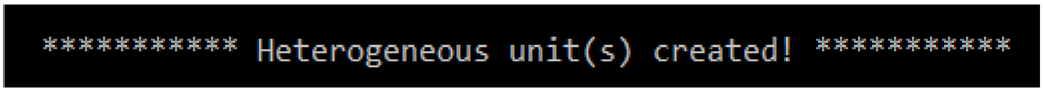
It is possible to enter additional model layers is desired. For example a 5m thick cover layer, with conductivity 10 mS/m, has been entered below:



When ready, save and name the model.

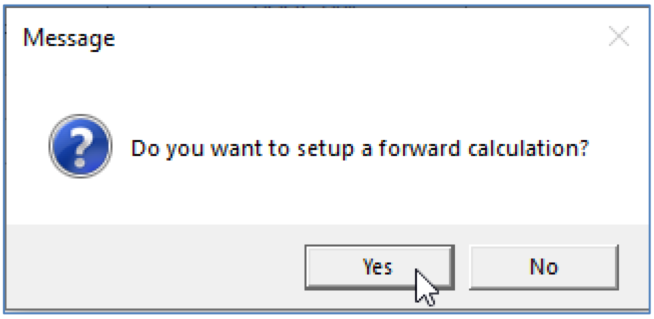


VPem3D (not VPview) is used to generate heterogeneous models. In this case the Host unit must be sub-celled. A command window opens for this reason after the original homogeneous model has been saved.

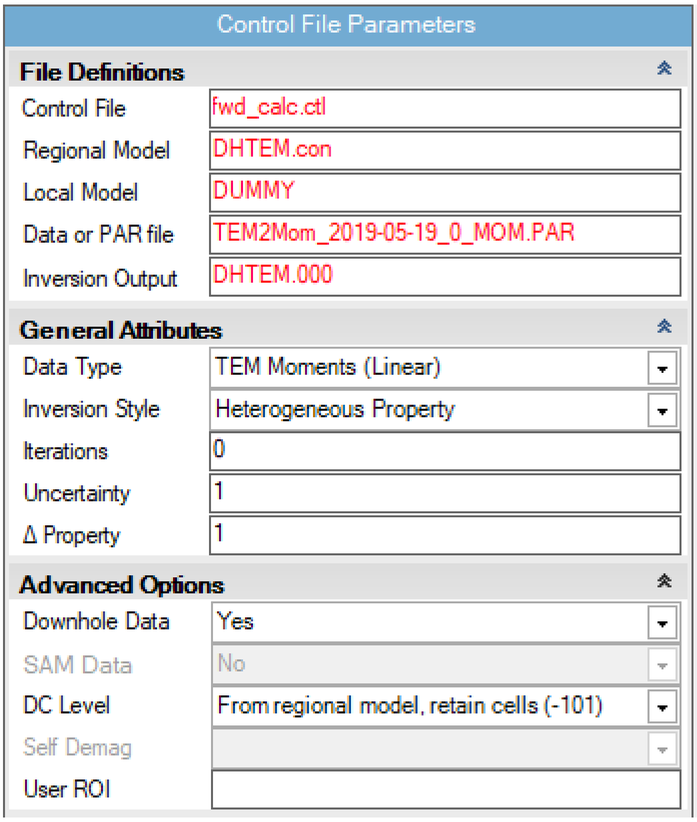


13.5 Create a control file

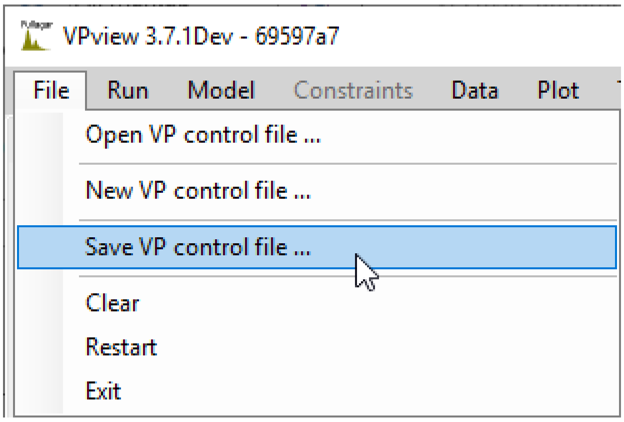
A control file is required in order to run VPem3D. If a starting model has just been created using the *Create New Model* utility, the user will be prompted to prepare for a forward calculation:



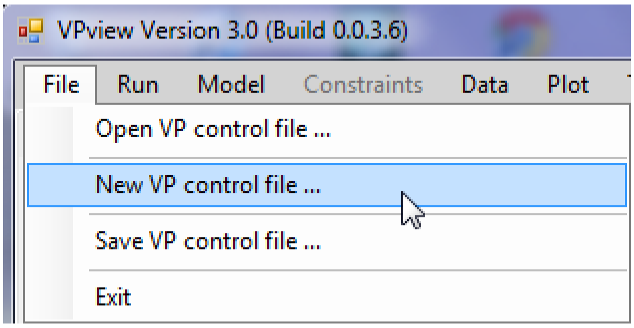
The default control file parameters are displayed in red:



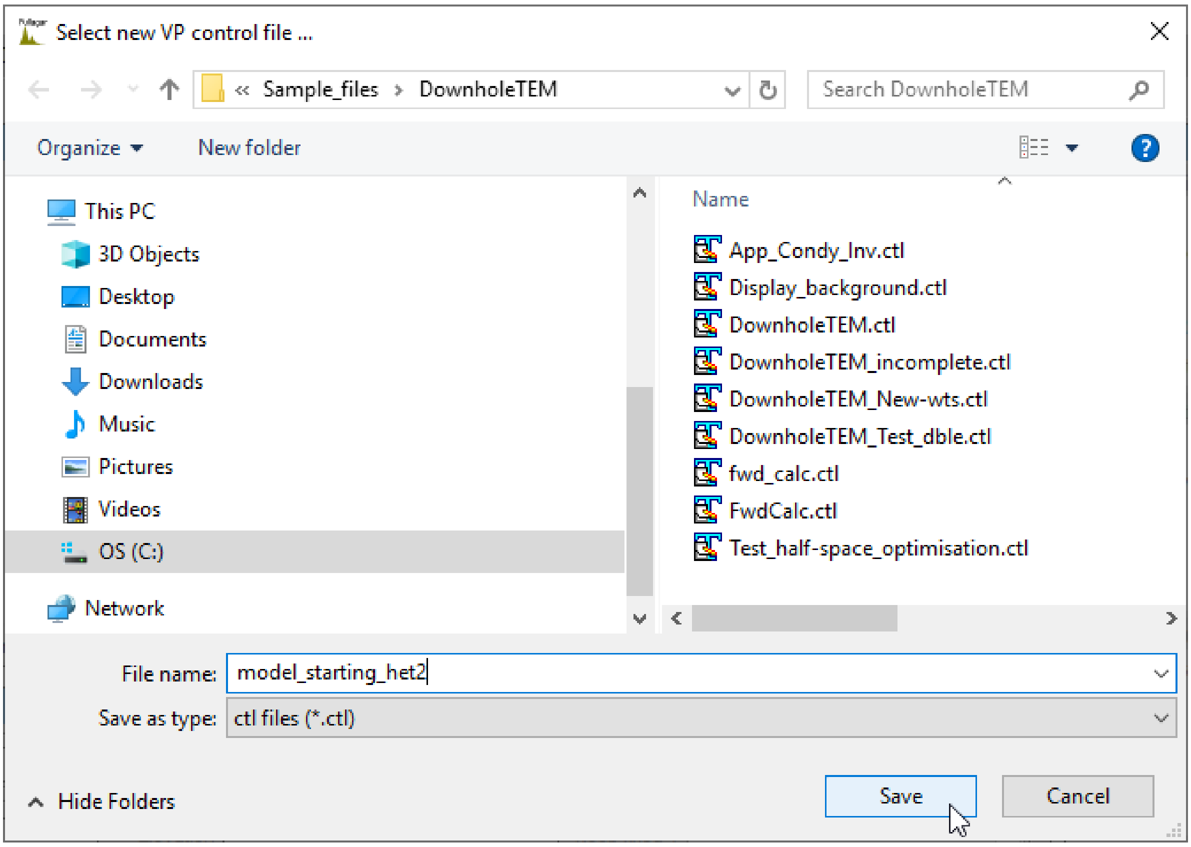
To accept the default settings, save the control file:



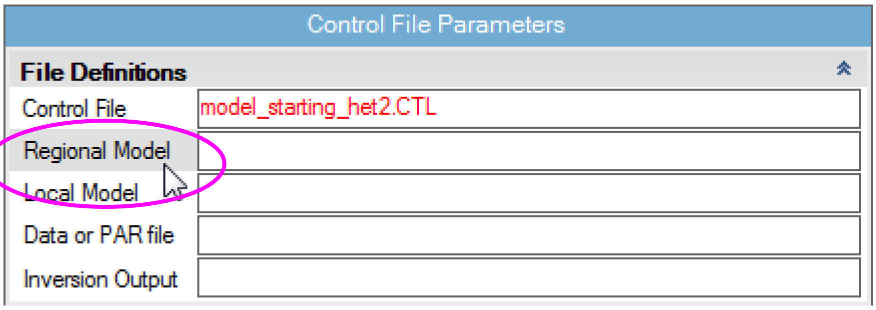
If not running a forward calculation immediately after creating a model, and if a suitable control file does not already exist, a CTL file can be created using the *New VP control file* utility under the File menu:



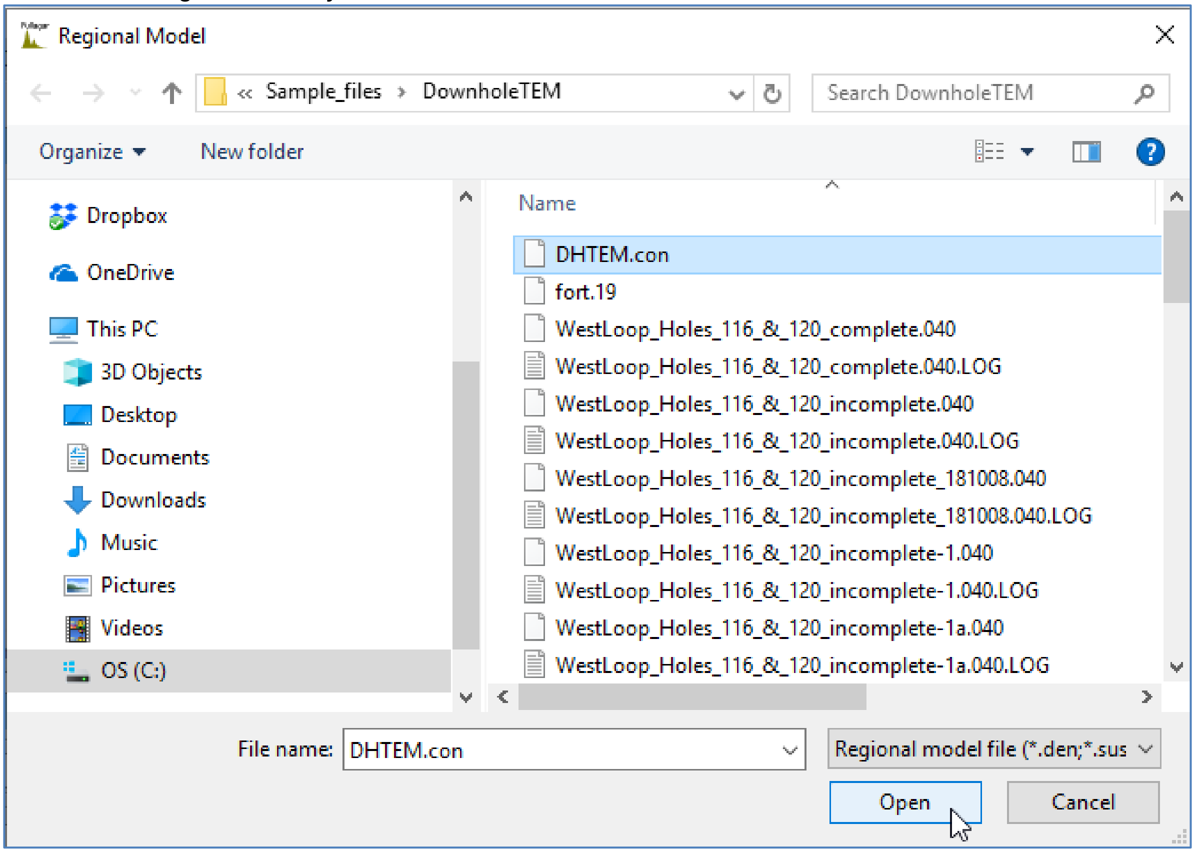
Browse to the project directory and enter a name for the control file:



VPview will display the control file name in red in the *Control File Parameters* table. To enter the model file, click on a model file label to open a browse window.

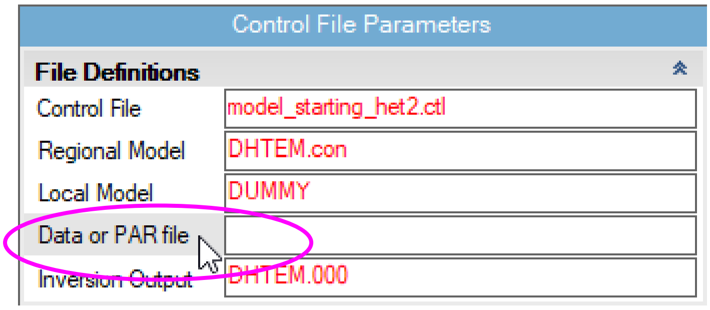


Select a starting conductivity model.

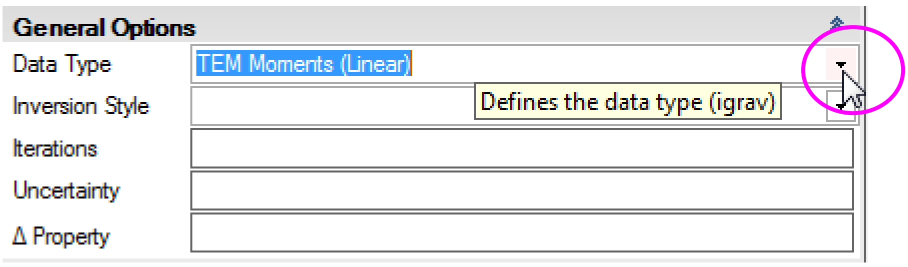


The starting model can be regarded as either regional or local. The text box for the other model can be left blank. VPview enters a default output model name; this can be altered by the user if desired.

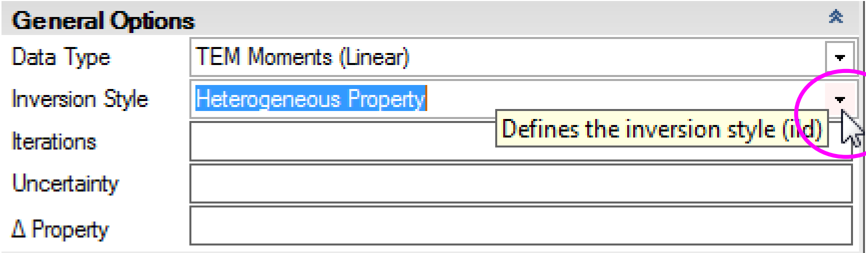
Select a PAR file in the same fashion: click on the label to open a browse window:



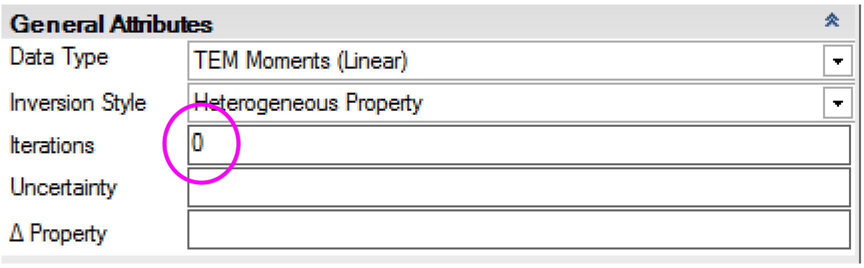
Now define ***General Options*** settings. Use the drop down menu to select *Data Type*. TEM Moments (Linear) is the appropriate *Data Type* for most downhole TEM inversion runs.



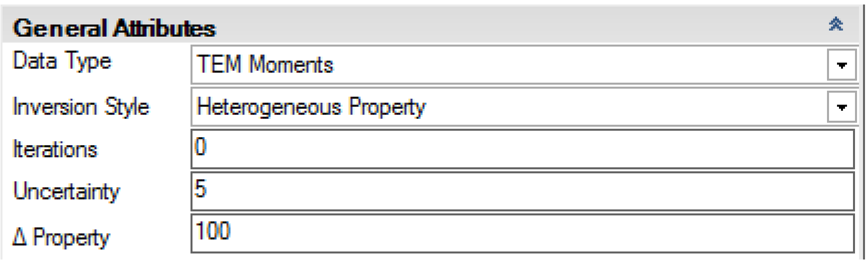
Use the drop down menu to select *Inversion Style*. Heterogeneous Property (either smooth or compact) is the most common *Inversion Style* for downhole TEM, since the aim is usually to adjust the conductivity of individual model cells.



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



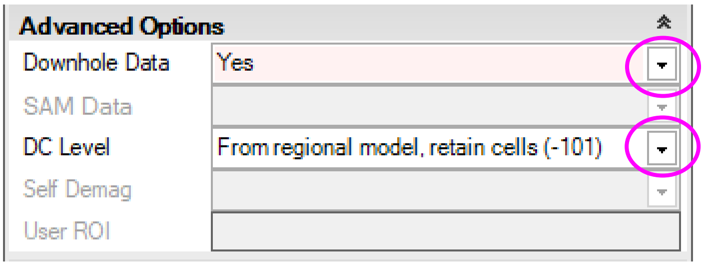
Define values for the *Uncertainty* (in pTms/A) and the *Δ Property* (maximum conductivity change per iteration, in mS/m). These parameters are arbitrary for a forward calculation.



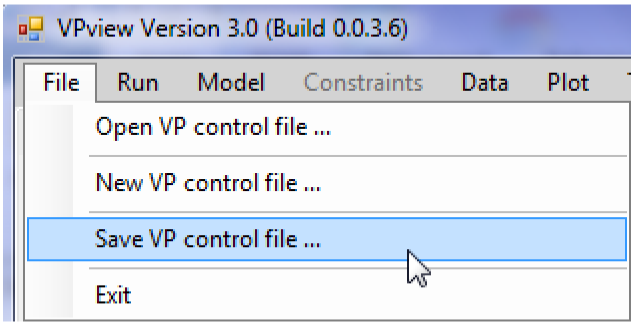
In the ***Advanced Options***, use the drop down menus to choose *Downhole Data* and *DC Level* settings. *Downhole Data* is “Yes” for downhole TEM data.

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.]

The *SAM Data*, *Self Demag*, and *User ROI* have no bearing on a forward calculation, and can be left blank.



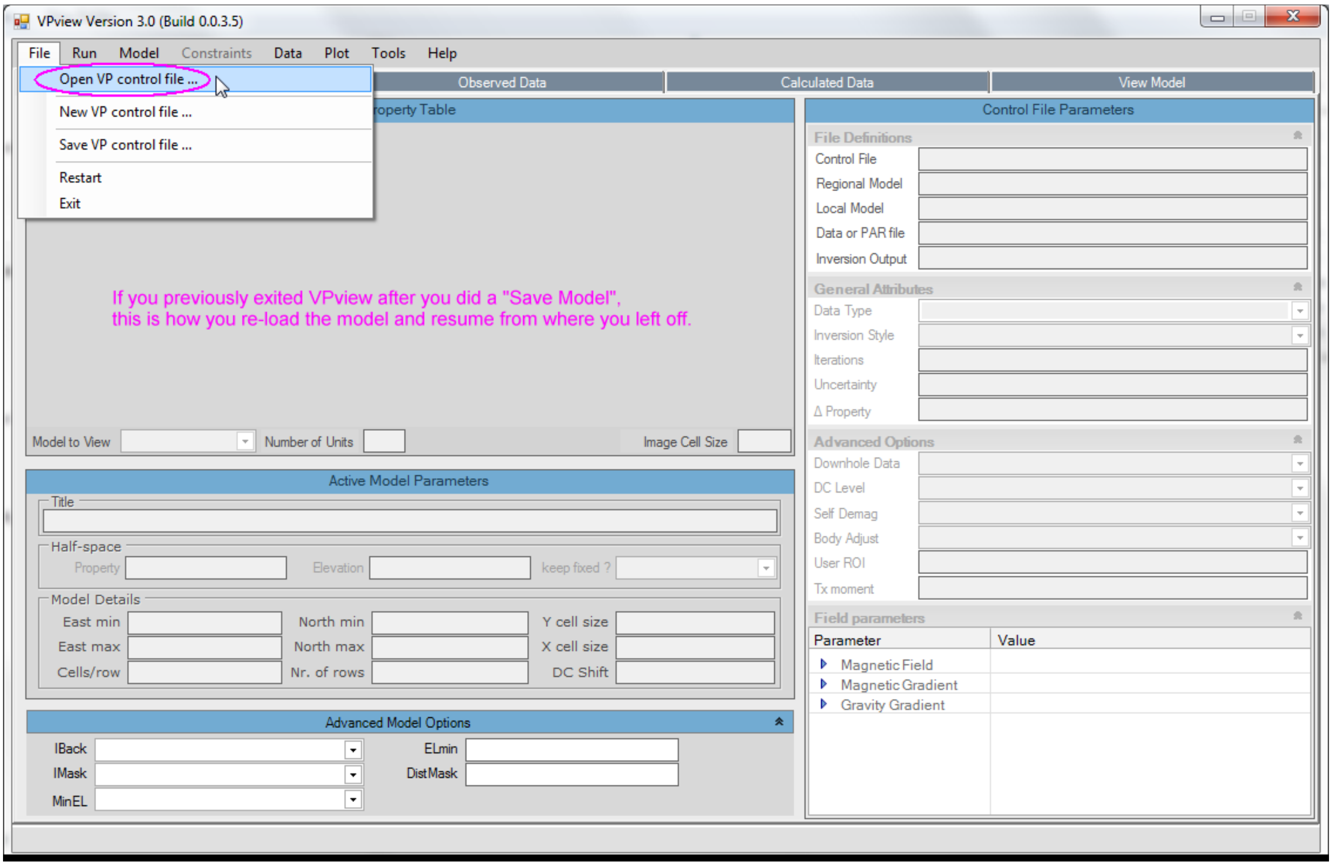
When all fields have been populated, save the new control file using the option under *File*:



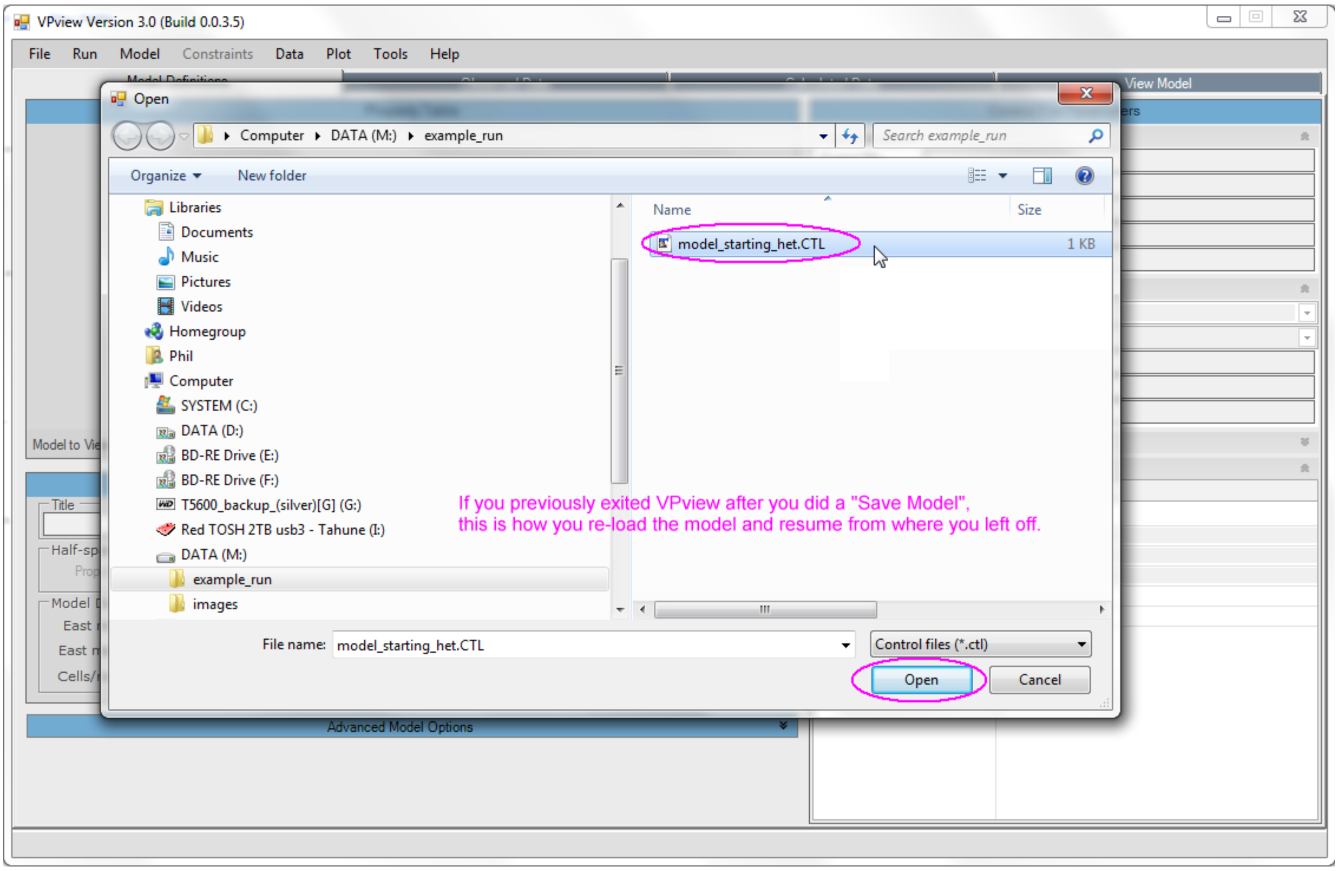
13.6 Performing a forward calculation

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.

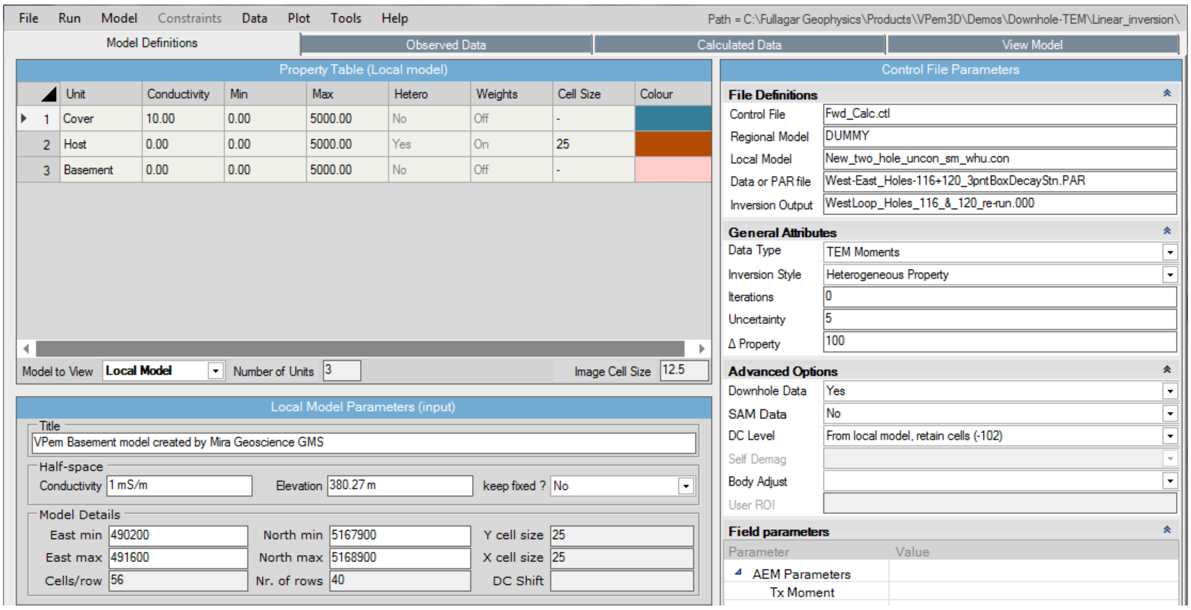
If you had exited, start VPview again and select the "*Open VP control file*" option under the *File* menu.



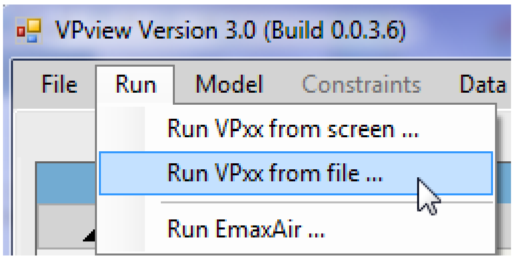
Choose the desired VP control file.



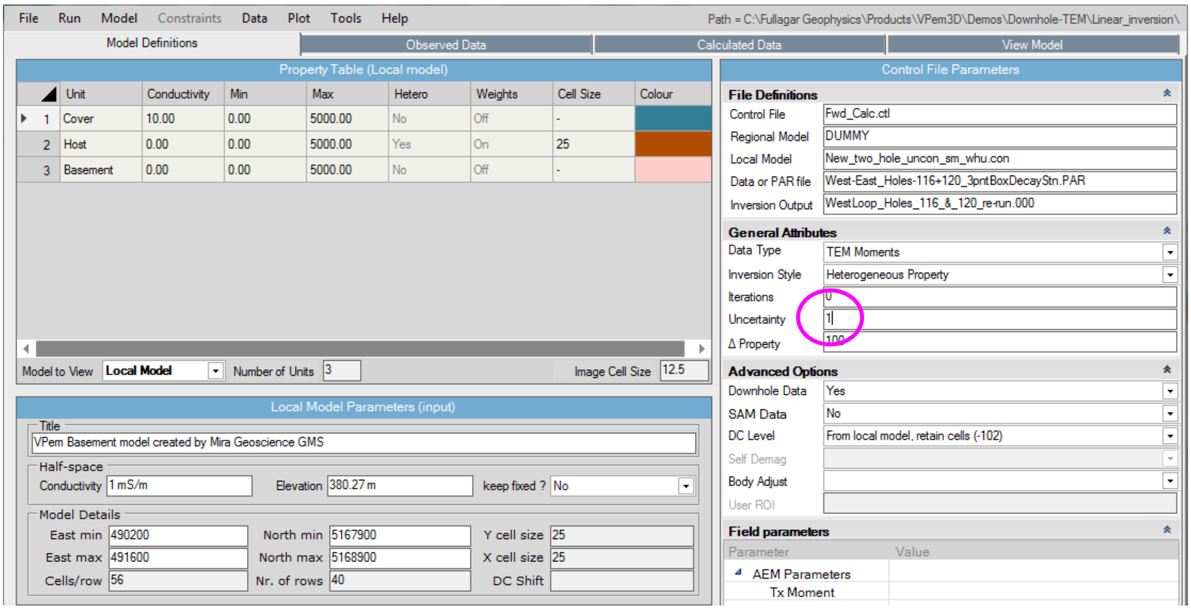
VPview displays the model file header information and control file settings.

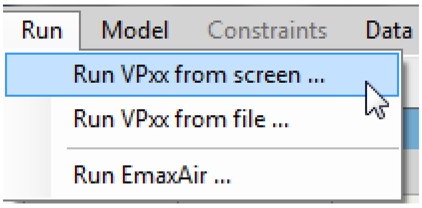


If the saved model parameter and control settings are all acceptable, launch VPem3D using the “Run VPxx from file” option under the *Run* menu:

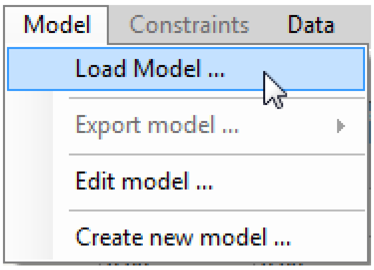


If some of the settings have been edited, but not saved, launch VPem3D using the “Run VPxx from screen” option. A new control file is created in that case, with the date and time appended to the original control file name. Here the Uncertainty has been changed, so VPem3D is run “from screen”.



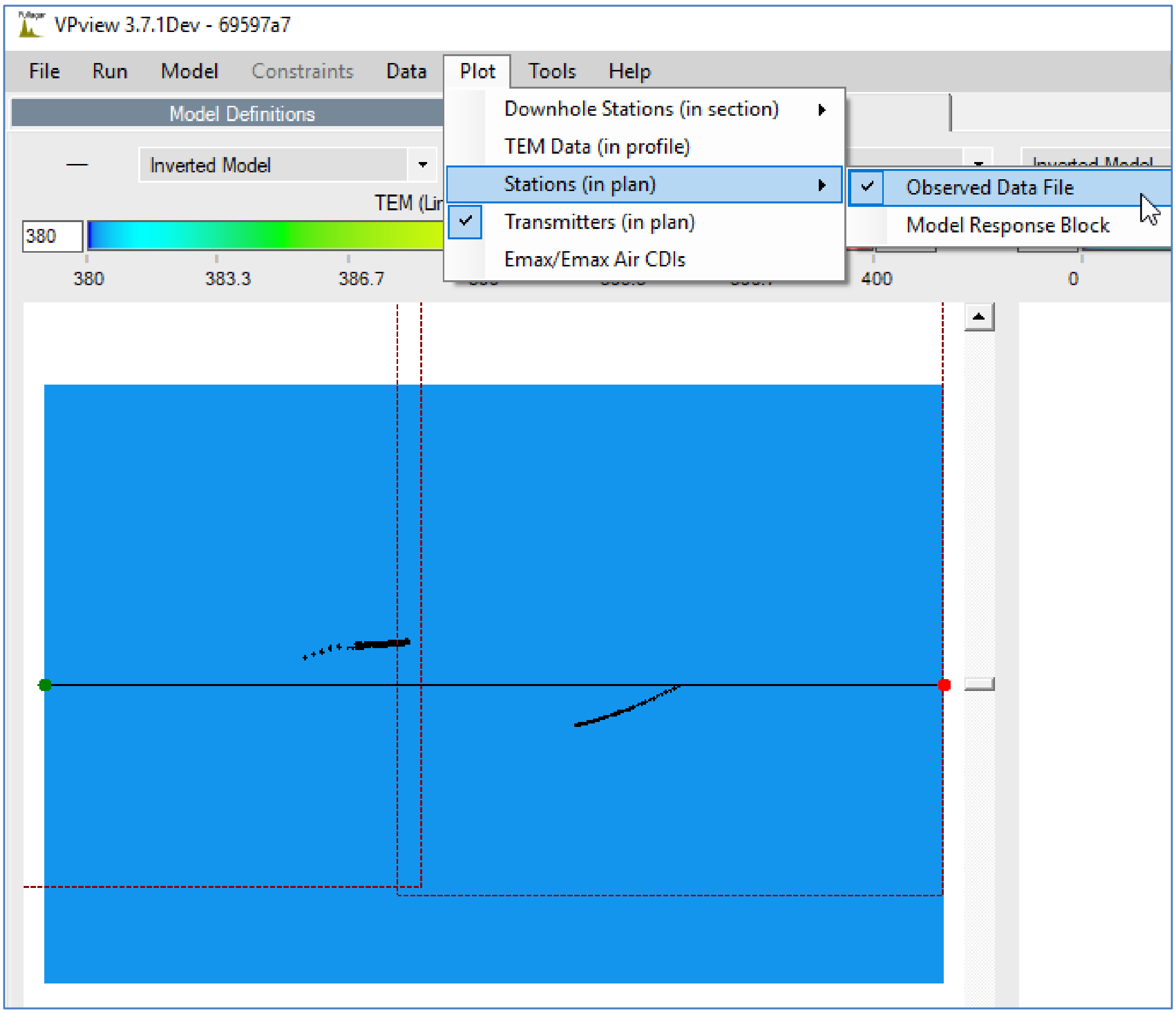


After the forward calculation has completed, load the model and data using the *Load Model* option under the Model menu, as shown.



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). In the image below the Tx loops extend well beyond the model limits, so are not visible in their entirety.



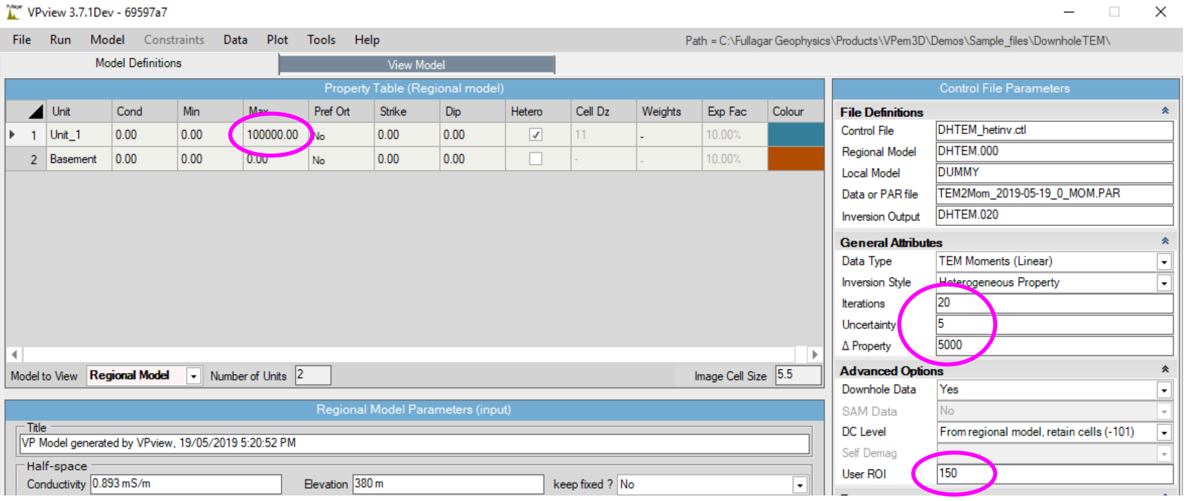
13.7 Running a Downhole TEM inversion

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. [For large data sets, skipping a forward calculation re-run can save appreciable time.]
- 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 1.E5 mS/m.

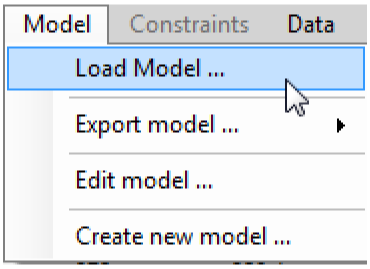
- check that the radius of influence around data points (*User ROI*) is suitable. *User ROI* options are described in Section 16 below. A *User ROI* of 150m was adopted in this example.

If any control file parameters 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.



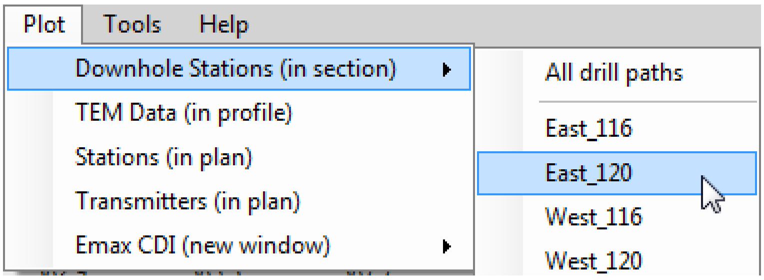
Details of the inversion, including data misfit, are displayed in a command window and recorded in a LOG file. The LOG file has the same name as the Inversion Output file, with extension .LOG.

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



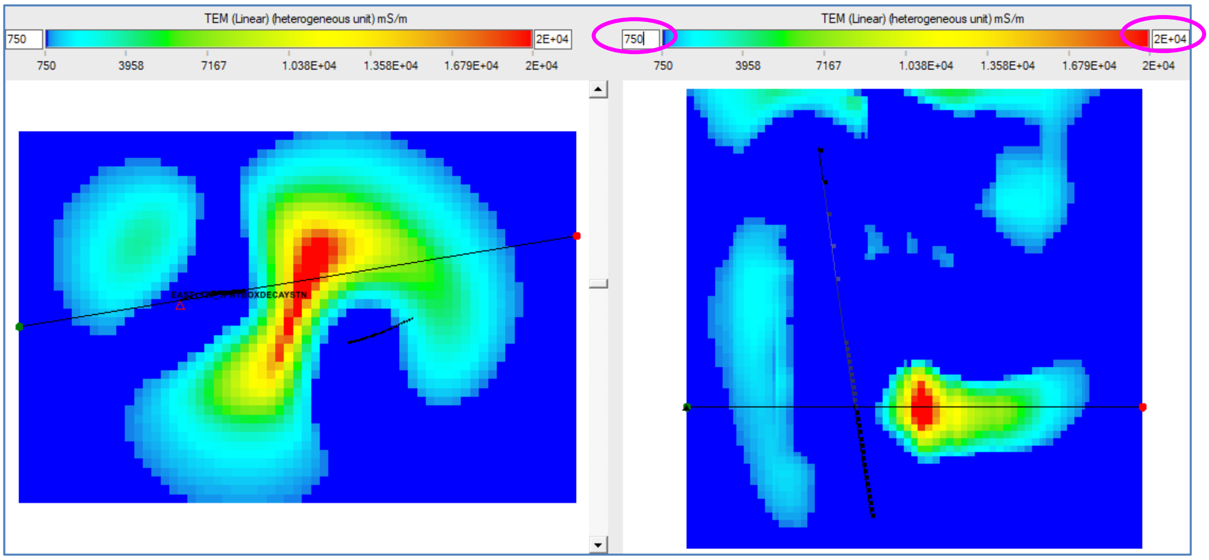
When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the inverted model is displayed in the right panel. The user can toggle between section views of the starting (Initial) and output (Inverted) models using the drop-down menu above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

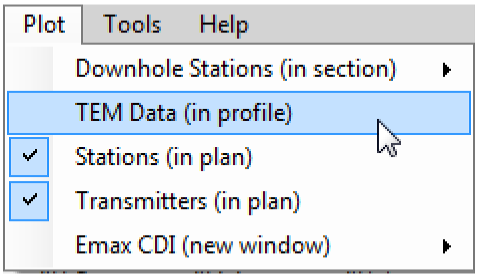


A horizontal section through the conductivity model is displayed below in the LH panel, at the elevation (-110m) defined by the horizontal black line through the vertical section in the RH panel.

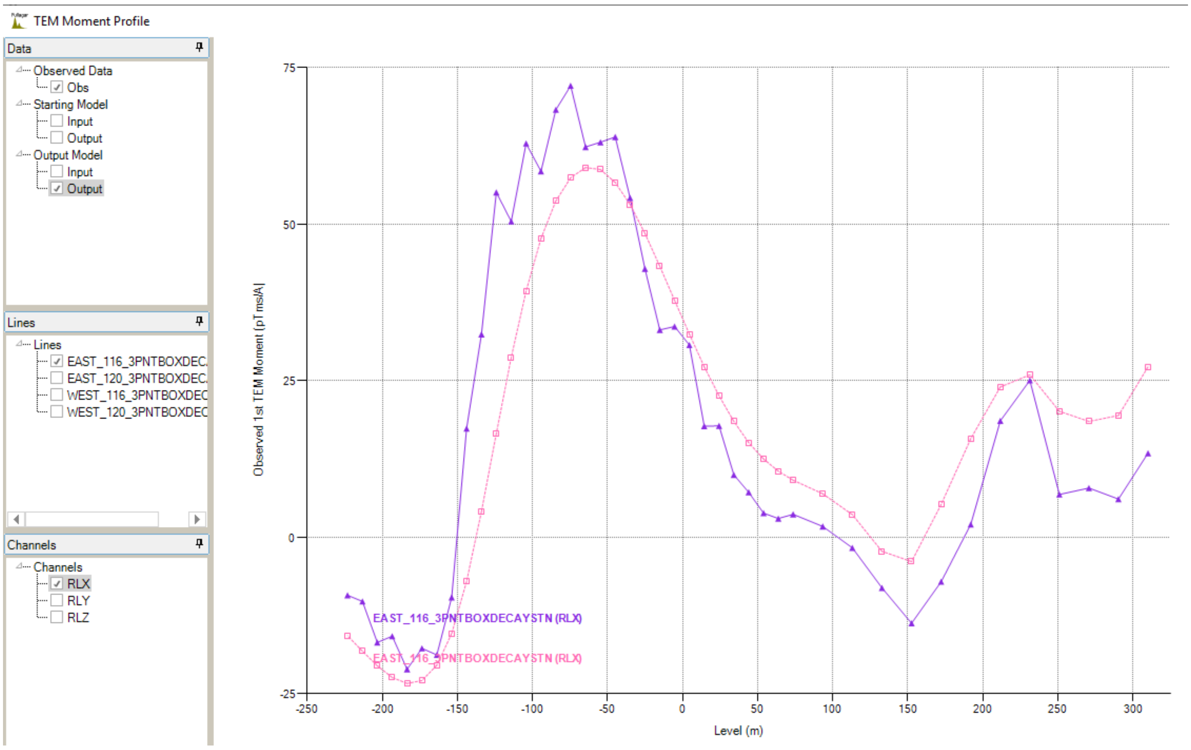
The vertical model section is in the plane which best captures hole East_120. Receiver positions in the RH panel are coloured black if located in the display section, grading to lighter shades of grey as their offset from the section increases. The colour stretch for the conductivity can be altered by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



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

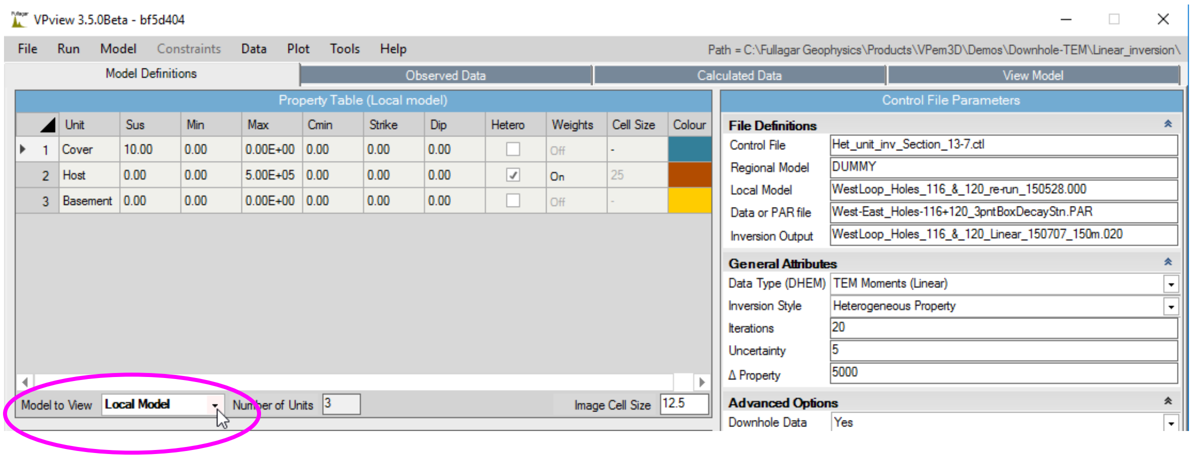


The profiles for the east component, RLX, after inversion are plotted below.

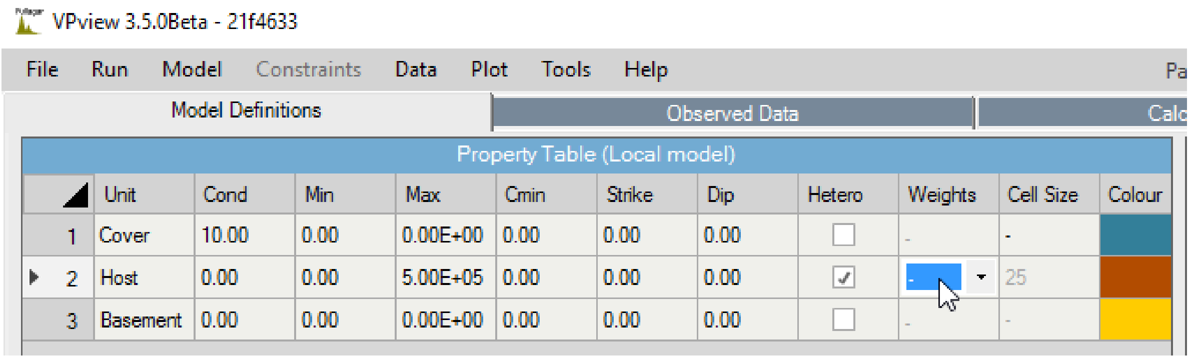


13.8 Applying Depth Weights

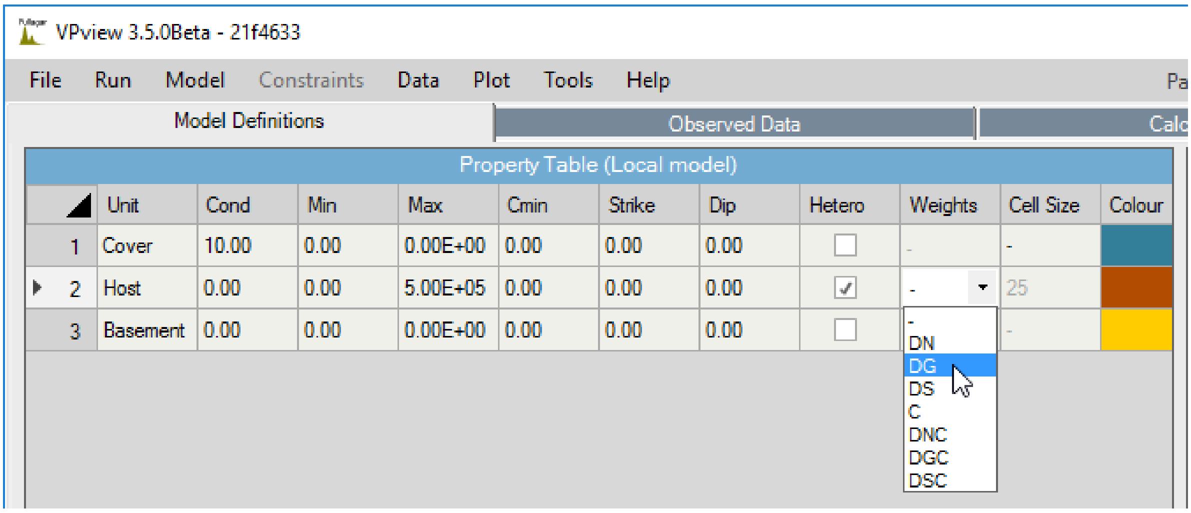
It is often beneficial to apply depth weighting prior to downhole TEM inversion, to suppress development of conductive zones close to loop wires on the ground surface. First select the model to be weighted, by choosing the *Model to View*. The Local Model is selected in this case.

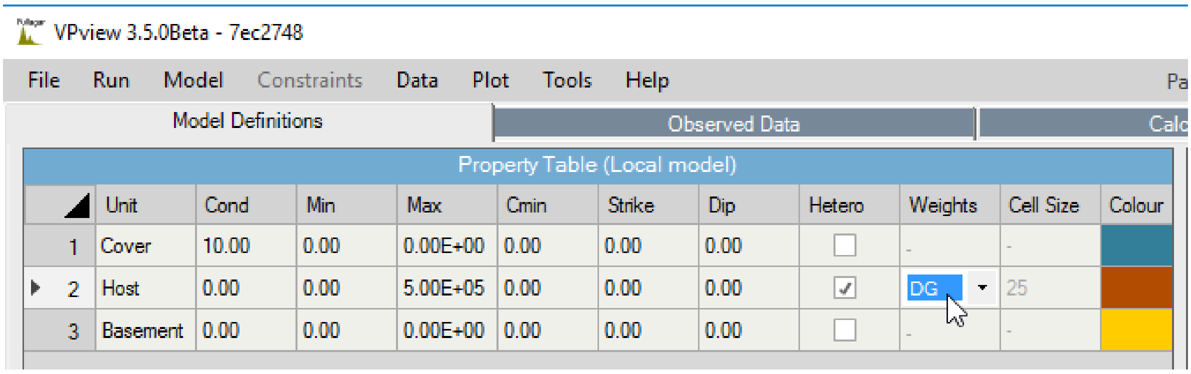


Click the Weights cell in the Property Table for the unit to be weighted; the Host unit has been selected in this case.

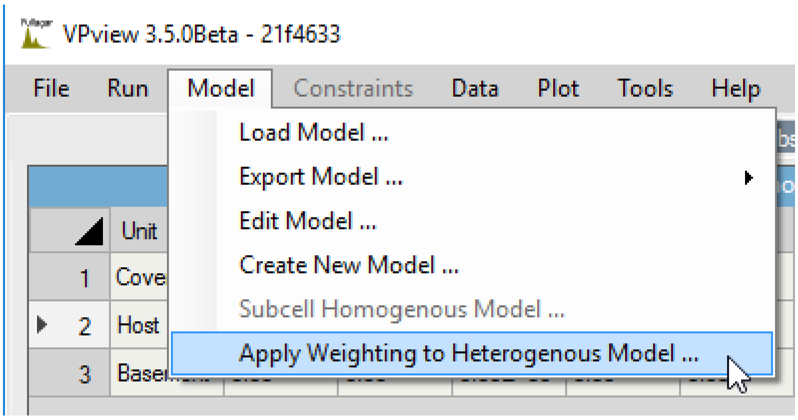


Choose the required weighting option; DG is selected here, i.e. depth weighting referenced to the ground, without cell size normalisation. This and other options are described in Section 7.1 (summarised in Table 7.1).

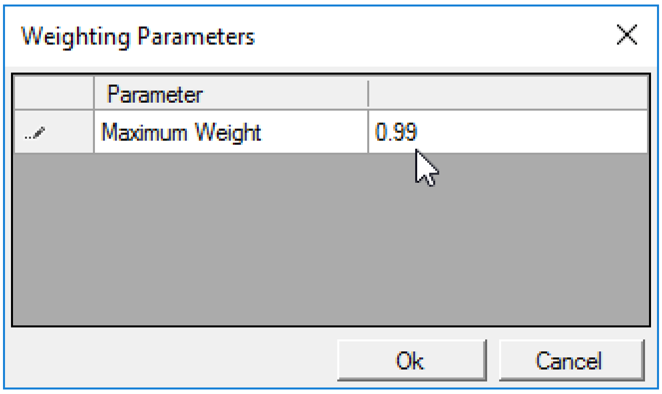




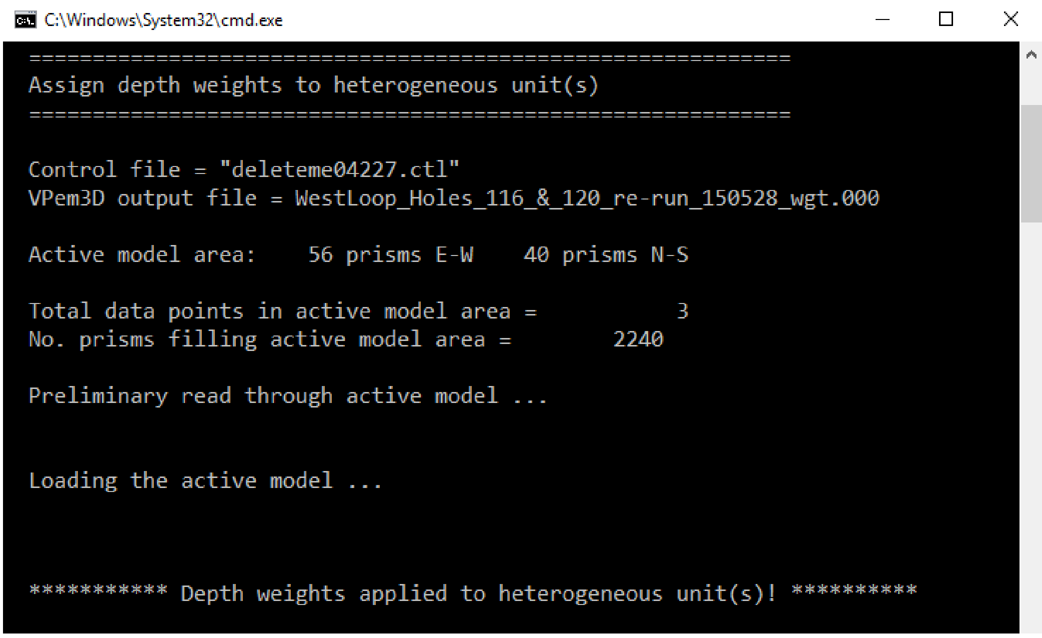
With the type of depth weighting defined, the *Apply Weighting to Heterogeneous Model* option becomes active under the *Model* menu.



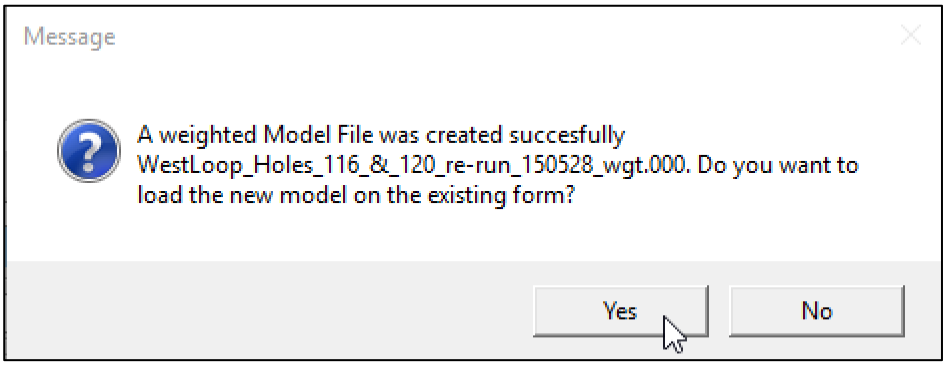
Now enter wmax, which controls the weights applied in the shallowest cells in the unit(s) being weighted. The wmax default value is 0.999. Click on OK when ready.



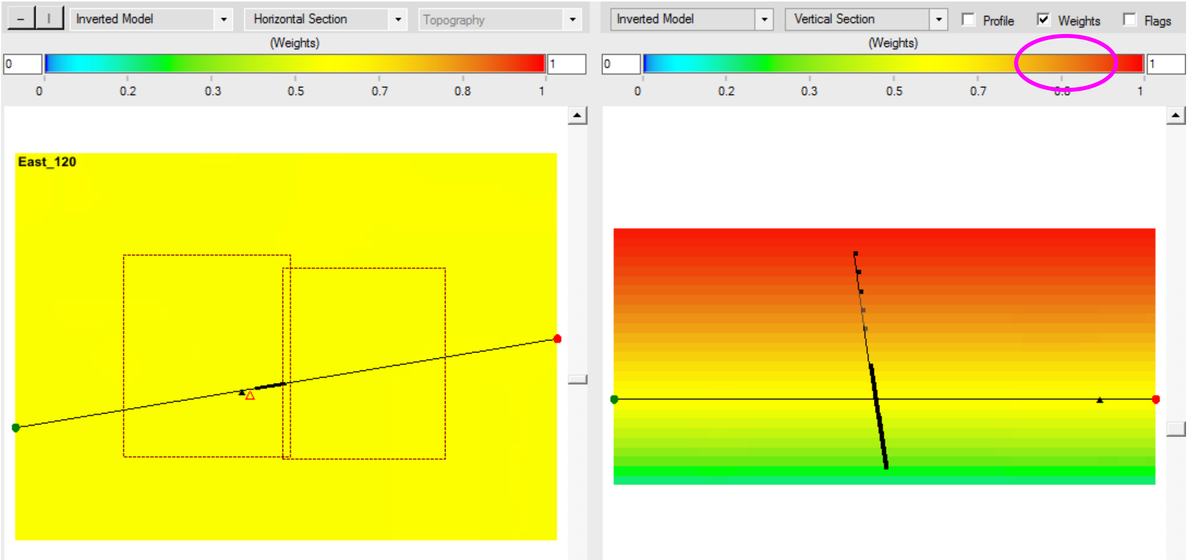
The depth weights are inserted in the model file by VPem3D. A command window displays some run details.



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.

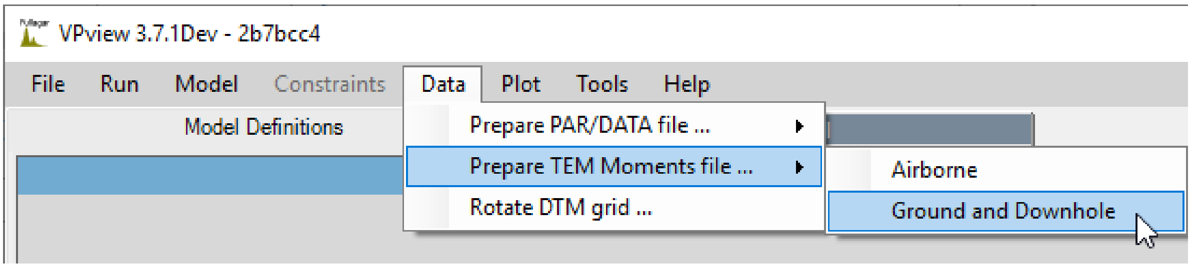
There are various ways to set up and run VPem3D inversion on ground TEM data. The example used here illustrates compact body (heterogeneous unit) inversion for fixed loop B-field (SQUID) data. The starting model was a zero conductivity uniform half-space.

14.2 Computing resistive limit data

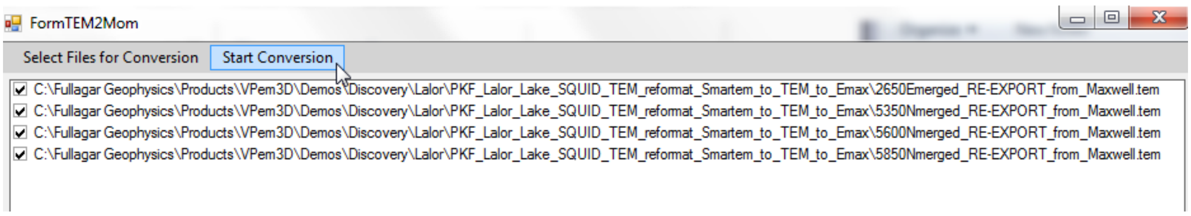
VPem3D operates on TEM resistive limit data. Therefore time decays must be integrated prior to VPem3D modelling and inversion. Ground TEM data are expected in TEM format as exported from Maxwell.

```
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 RXAREAZ:-1.000 RXAREAX:-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         CH1
   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           Y     20.000     32.000     28.000      0.040 5.768154e-02   -2.631100
   2650.000     4800.000       0.000       0.000     4800.000           X     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. Coordinates for the Tx loop vertices (LVnX, LVnY, LVnZ) are included in the header.



Accessing the data conversion program for ground TEM from the VPview *Data* menu.



Select TEM files to be processed.

By default, 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, or if the early time response (e.g. from conductive regolith) completely overwhelms the response from possible buried conductors. Channel range can be controlled via VPview, as described in Section 5.2.

It is standard practice (but not essential) for the VPem3D x and y model axes to be oriented parallel and perpendicular respectively to survey lines. If the survey lines are not N-S or E-W in the contractor's coordinate system, TEM2Mom can rotate the data. In this example no rotation is necessary.

A few records from the moment data (…MOM.XYZ) file written by TEM2Mom are shown below.

```
/RXX          RXY          RXZ          RLX          RLY          RLZ          LX1
LINE 2650Emerged_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 3 columns in the TEM moments ("resistive limits") file contain the receiver coordinates, RXX, RXY, RXZ. 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 the "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, along 2650E. 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	2650Emerged_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	54.48706	73.655603	201.096124	3060
2650	6200	0	72.826896	80.19751	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 [the record 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 is available, the procedure for model construction is the same for ground TEM as for airborne TEM. Therefore refer to Section 12.4 above. For the ground TEM data set considered here the ground surface was at an elevation of 300m.

In the absence of a DTM, the *Create New Model* utility creates a model with a horizontal upper surface. The model extents and ground elevation can be entered on the *Model Extents* form or read from a dummy data file. A 3 or 4 line dummy data file defining the corners of the model area will suffice, with records of the form shown below:

EAST NORTH RL DATA

XMIN, YMIN, RL1, DATA1

XMAX, YMIN, RL2, DATA2

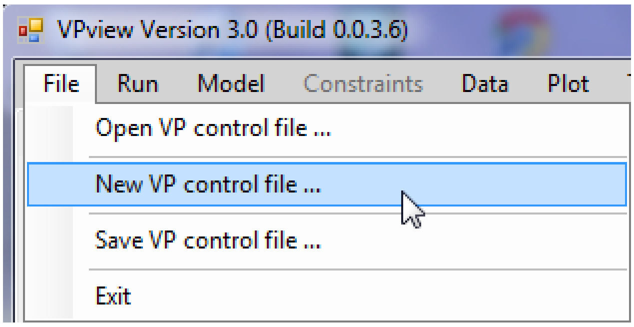
XMAX, YMAX, RL3, DATA3

The 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. This model resolution is 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.

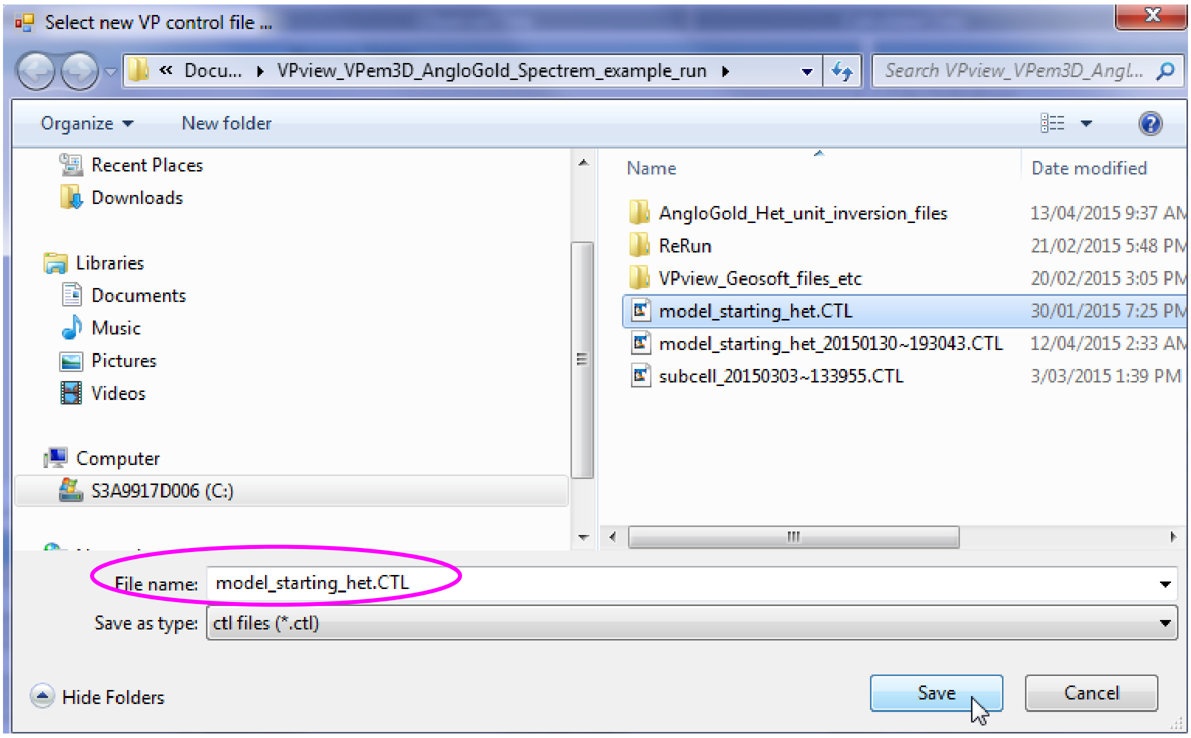
14.4 Create a control file

A control file is required in order to run VPem3D. If a starting model has just been created using the *Create New Model* utility, the user will be prompted to prepare for a forward calculation (see Section 13.5).

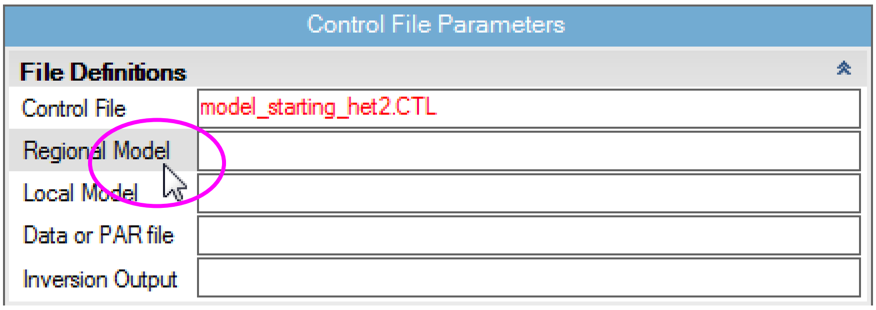
If not running a forward calculation immediately after creating a model, and if a suitable control file does not already exist, it can be created using the *New VP control file* utility under the File menu.



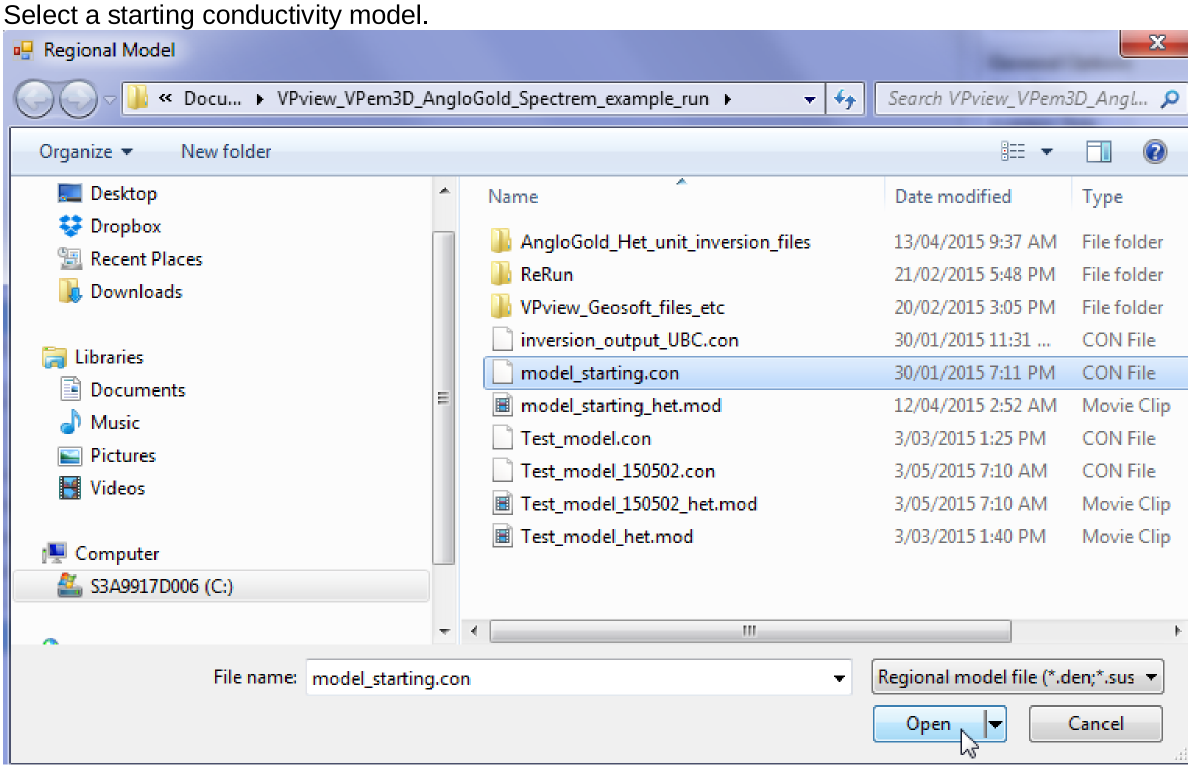
First select the project directory and choose a name for the control file. The control file has extension CTL. In the illustration the control file already exists.



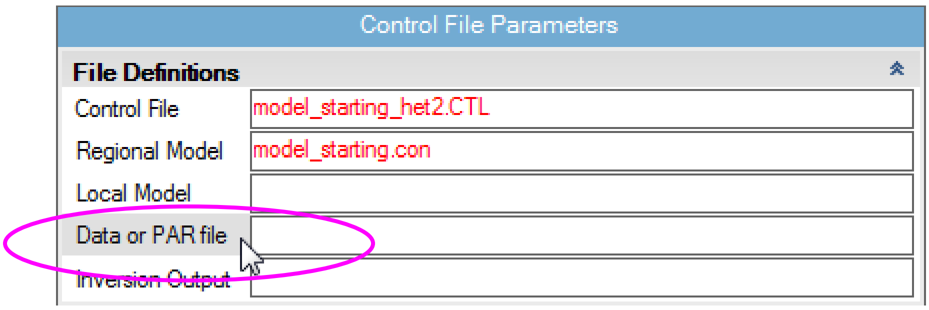
Click on a model file label to open a browse window.



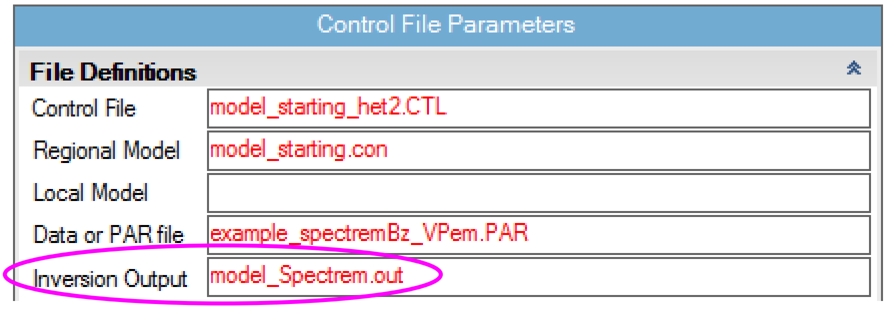
Select a starting conductivity model.



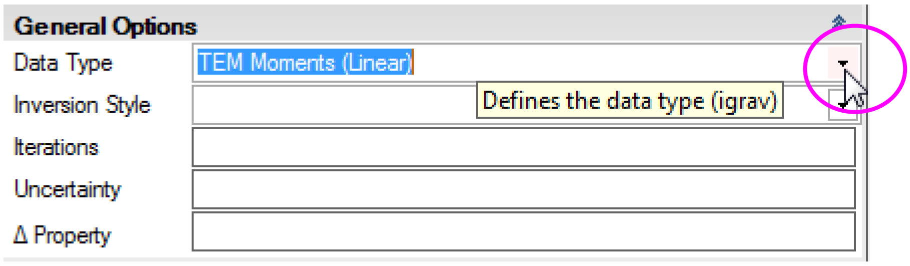
The starting model can be regarded as either regional or local. The text box for the other model can be left blank. Select a PAR file in the same fashion: click on the label to open a browse window.



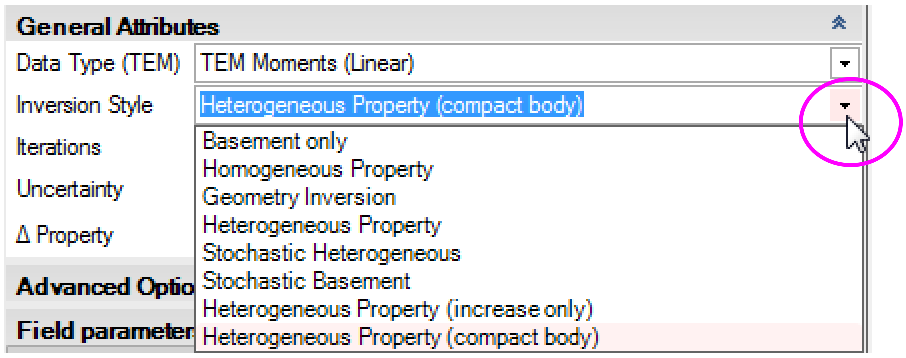
The output model file will usually not already exist. Type in a name for the output file. The extension is arbitrary, but VPview recognises *.CON files as conductivity models.



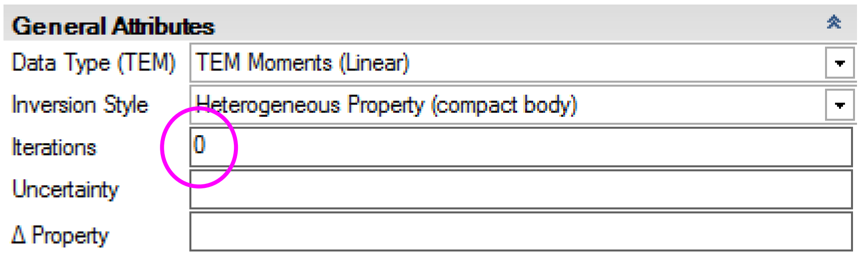
Now define ***General Options*** settings. Use the drop down menu to select *Data Type*. TEM Moments (Linear) is the appropriate *Data Type* for most downhole TEM inversion runs.



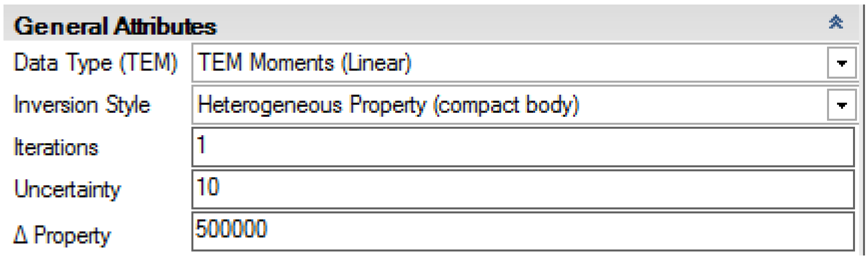
Use the drop down menu to select *Inversion Style*. Compact body inversion, which is a form of heterogeneous inversion, is selected here.



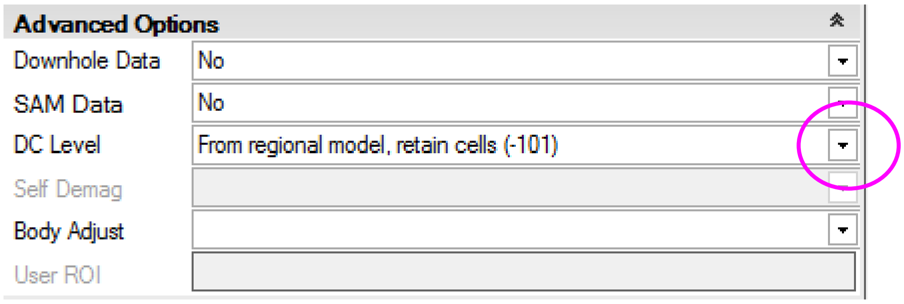
Set *Iterations* to zero for an initial forward calculation.



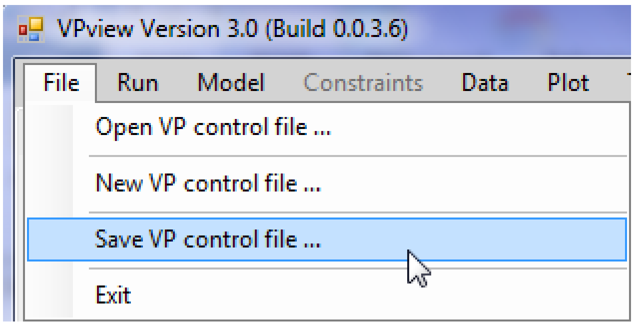
Define values for the *Uncertainty* (in pTms/A) and the *Δ Property* (maximum conductivity change per iteration, in mS/m). *Δ Property* is normally set very high for compact body inversion.



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.



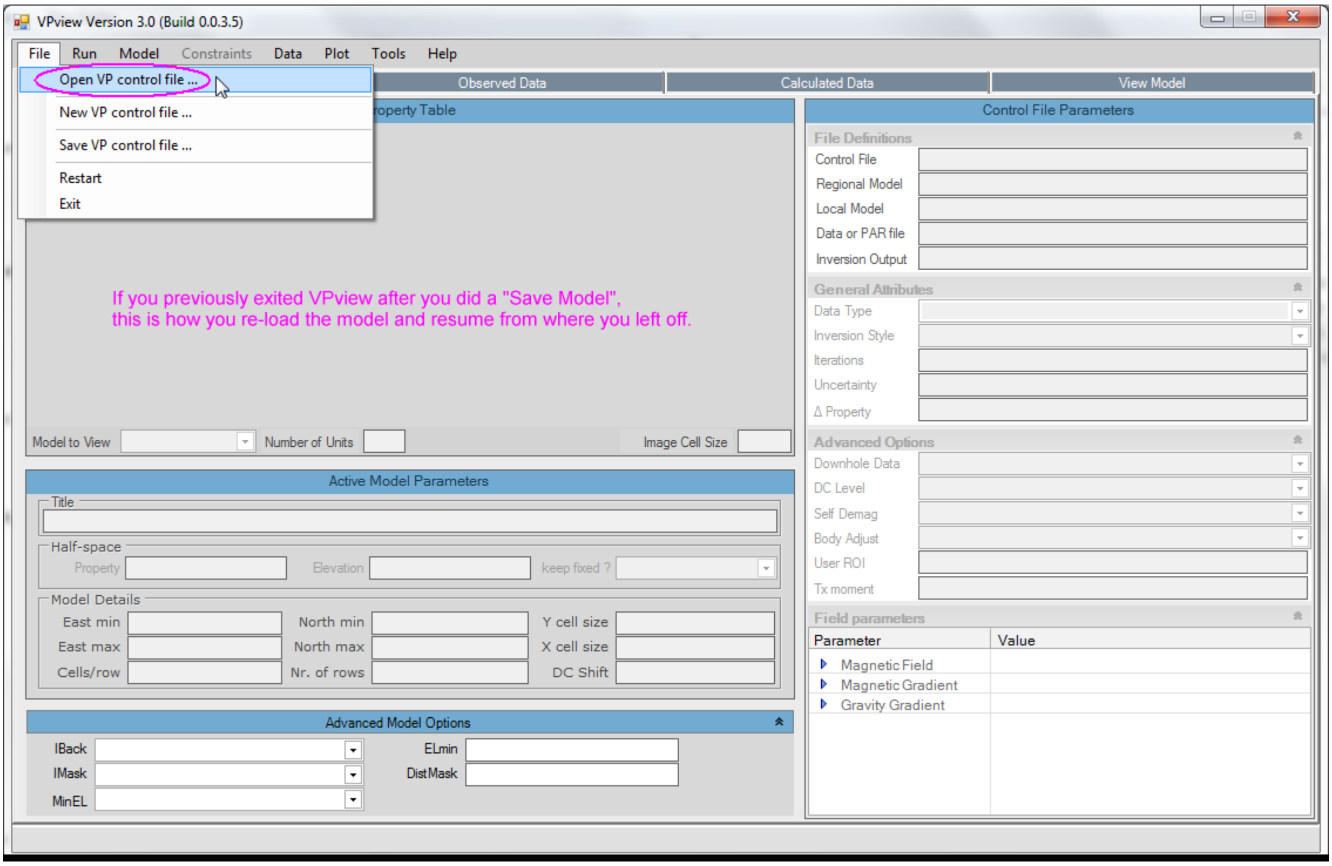
When all fields have been populated, save the new control file using the option under *File*.



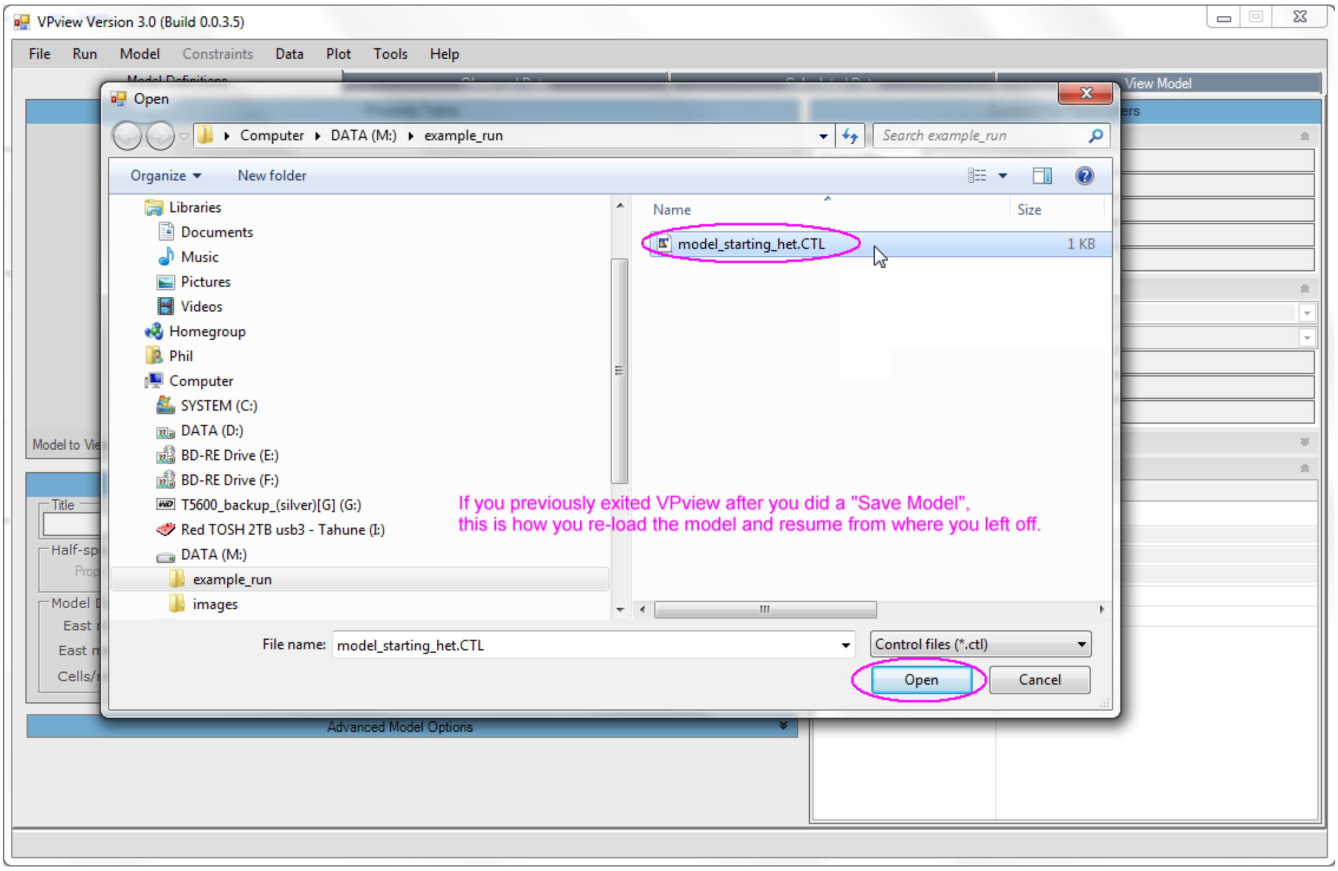
14.5 Performing a forward calculation

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.

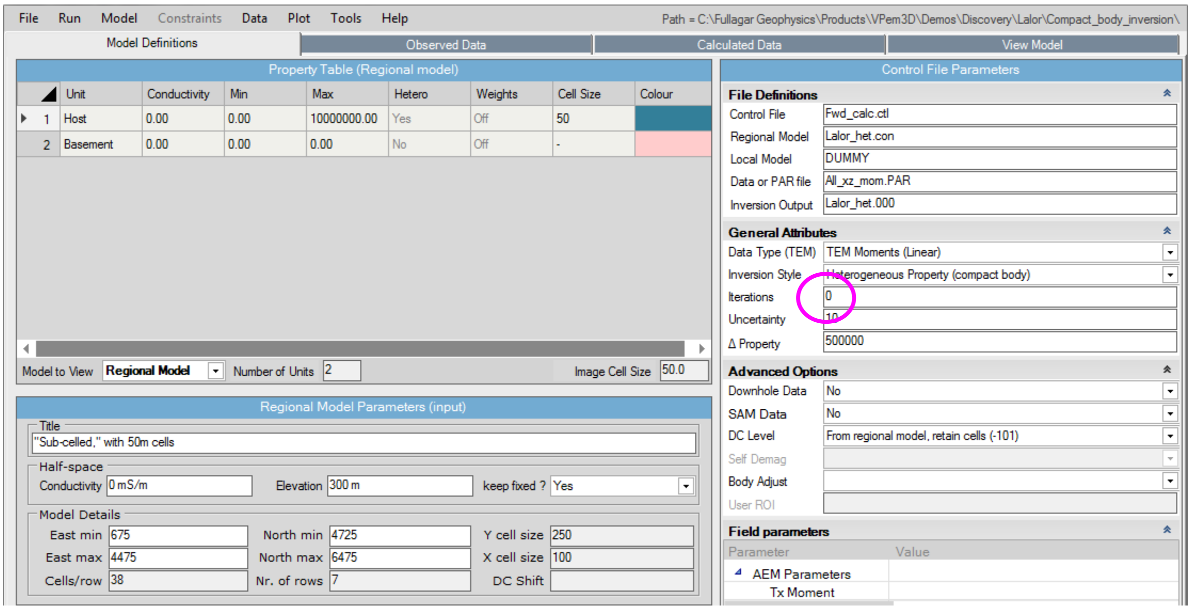
If you had exited, start VPview again and select the "Open VP control file" option under the *File* menu.



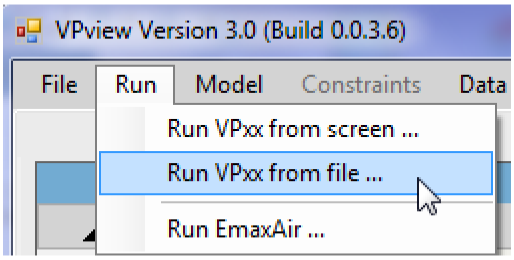
Choose the desired VP control file.



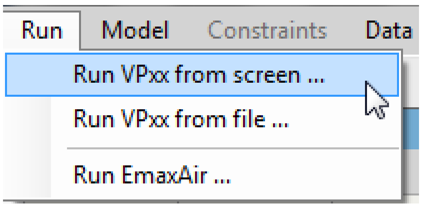
VPview displays the model file header information and control file settings. Cells in the Host unit are 100m E-W x 250m N-S x 50m vertically.



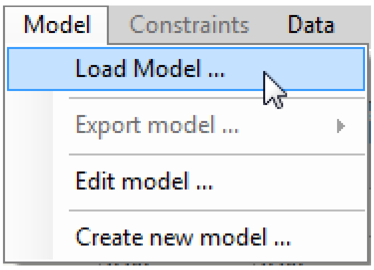
If the saved model parameter and control settings are all acceptable, launch VPem3D using the "Run VPxx from file" option under the *Run* menu. Iterations should be zero for a forward calculation.



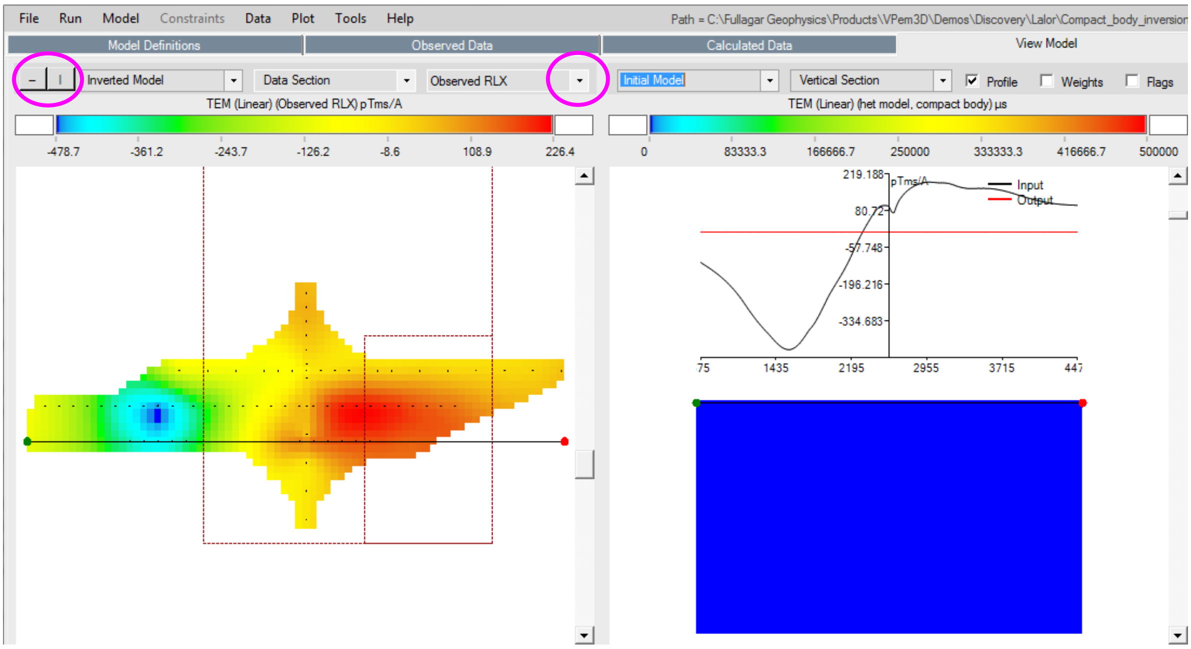
If some of the settings have been edited, but not saved, launch VPem3D using the "Run VPxx from screen" option.



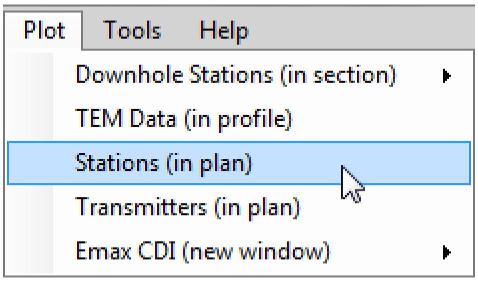
After the forward calculation has completed, load the model and data using the *Load Model* option under the Model menu, as shown.



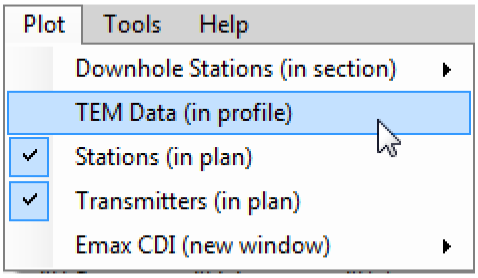
When the model first loads, the ground topography is displayed in the left panel; different quantities can be selected for display from the drop down menu above the LH panel. The observed east resistive limit component (RLX) is displayed below. The black line on the LH panel shows the position of the 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.



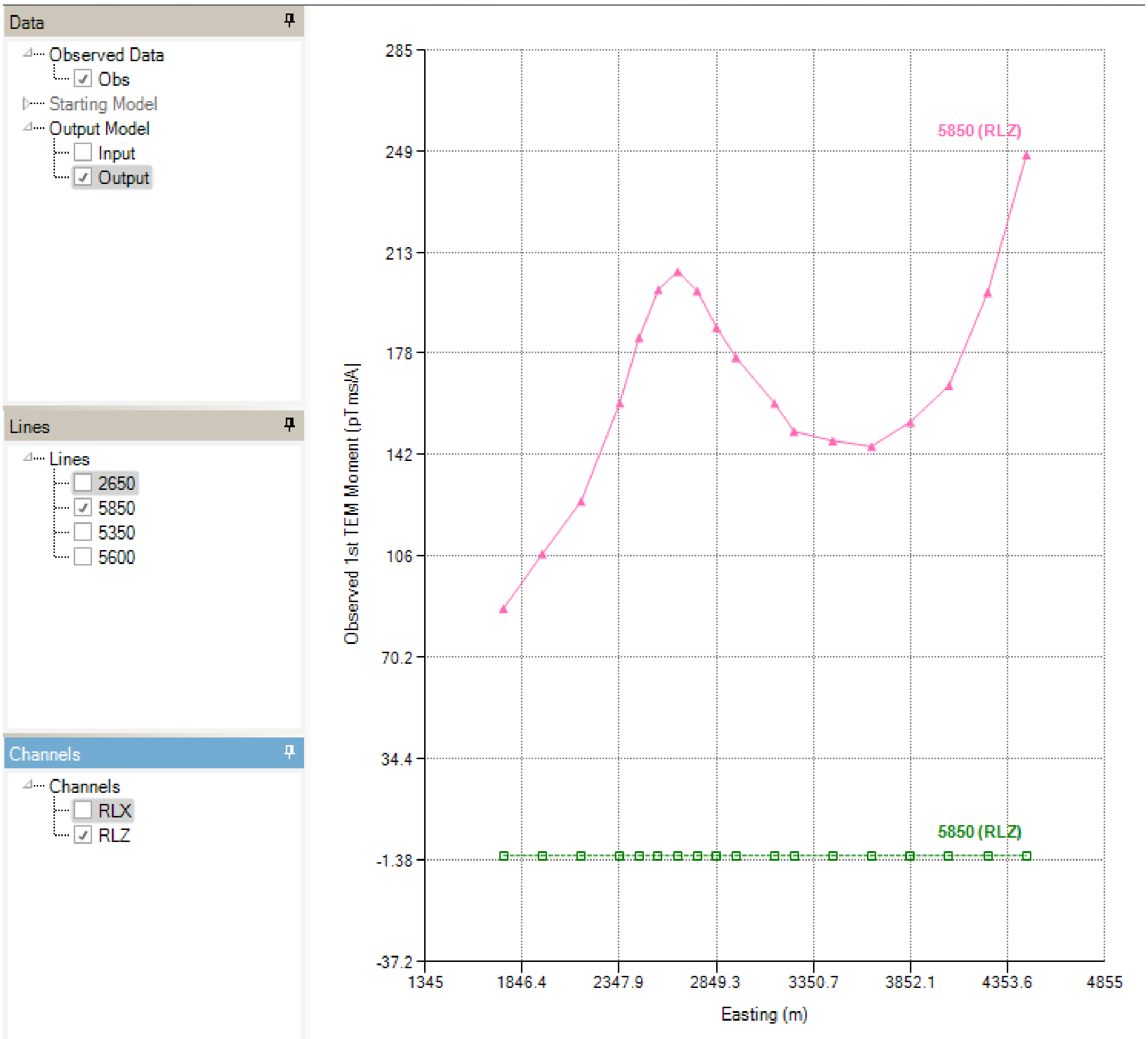
The black dots on the LH panel mark receiver locations; these are displayed using the *Stations (in plan)* option under the *Plot* menu. The red dashed lines trace the Tx loops; these are displayed using the *Transmitters (in plan)* option.



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

A 3 stage inversion is illustrated here:

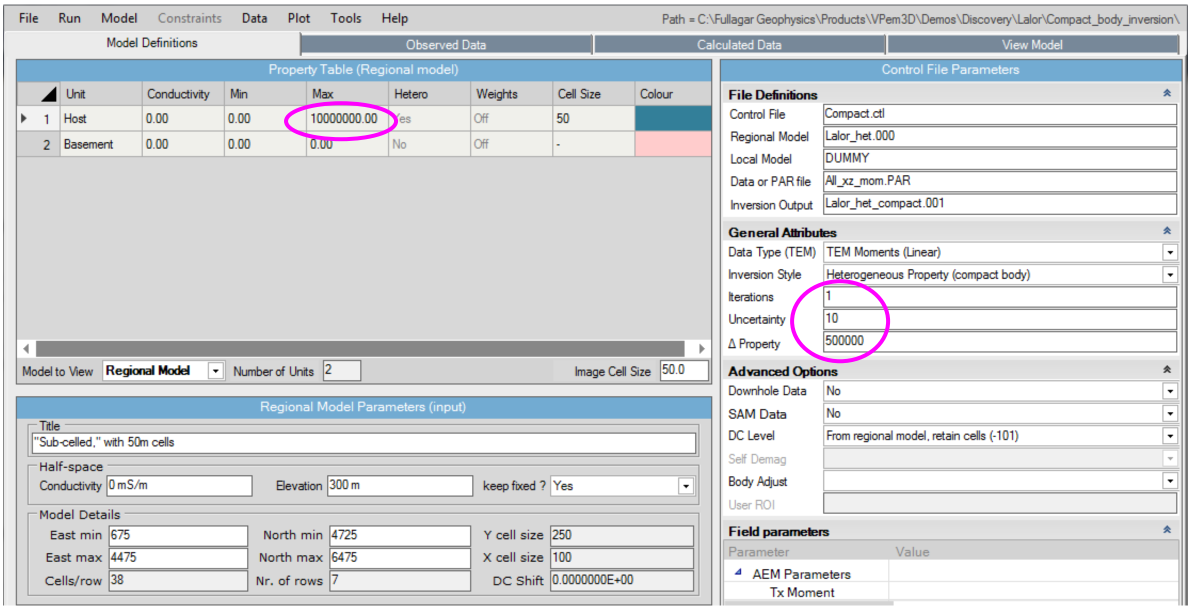
- An initial compact body inversion to delineate a volume of interest
- Editing of the volume of interest
- Homogeneous unit inversion to optimise the conductivity of the edited volume.

Once satisfied with the forward calculation, prepare to run compact body 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)

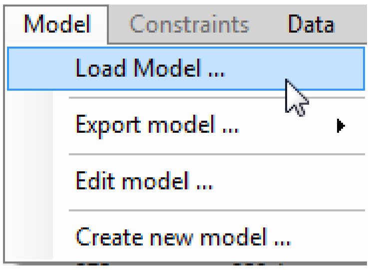
- set the maximum permitted change in property value per iteration (mS/m) to a very large for compact body inversion; here it is 5 x 10^5 mS/m.
- the maximum conductivity (upper bound) should be extremely large in the active unit for compact body inversion; here it is 10^7 mS/m.

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.

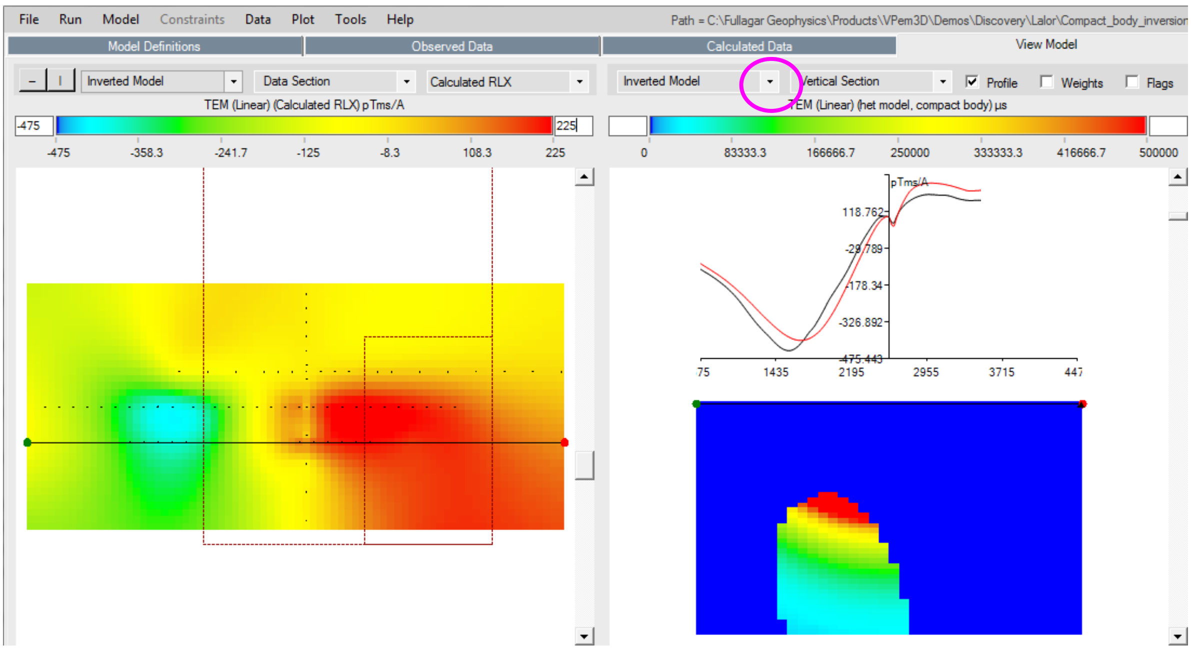


Details of the inversion, including data misfit, are displayed in a command window and recorded in a LOG file. The LOG file has the same name as the Inversion Output file, with extension .LOG.

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



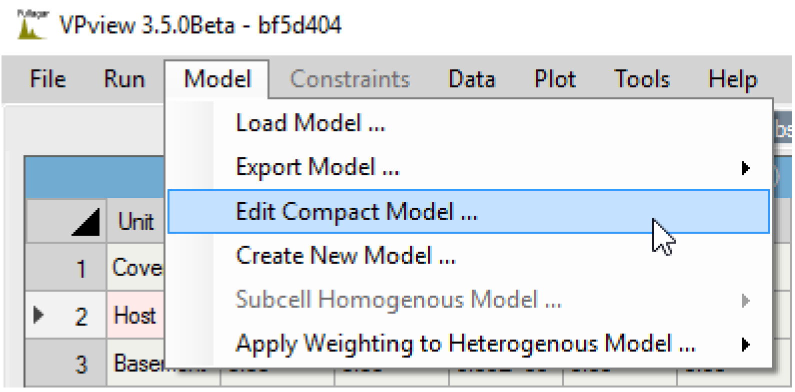
When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the inverted model is displayed in the right panel. The user can toggle between section views of the starting (Initial) and output (Inverted) models using the drop-down menu above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



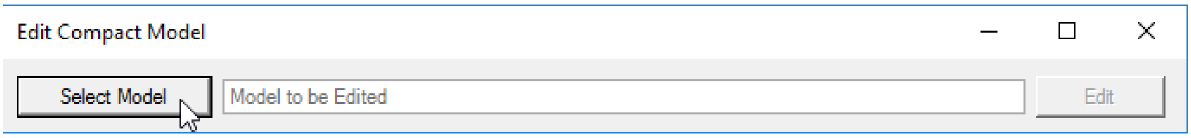
The compact inversion has defined what looks like an intrusive, with conductivity decreasing markedly with depth. Depending on the context and objectives, the user may wish to edit this conductive volume, e.g. to focus attention on the highly conductive, uppermost part. An utility is available under the Model menu 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 x 10^5 mS/m were retained.

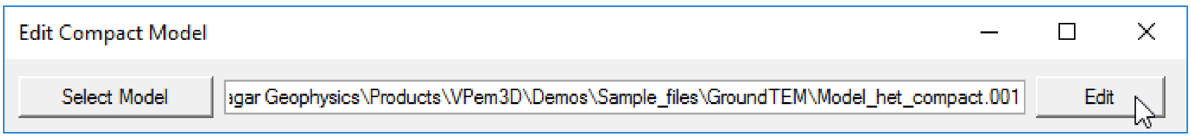
First, select the Edit Compact Model option.



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



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

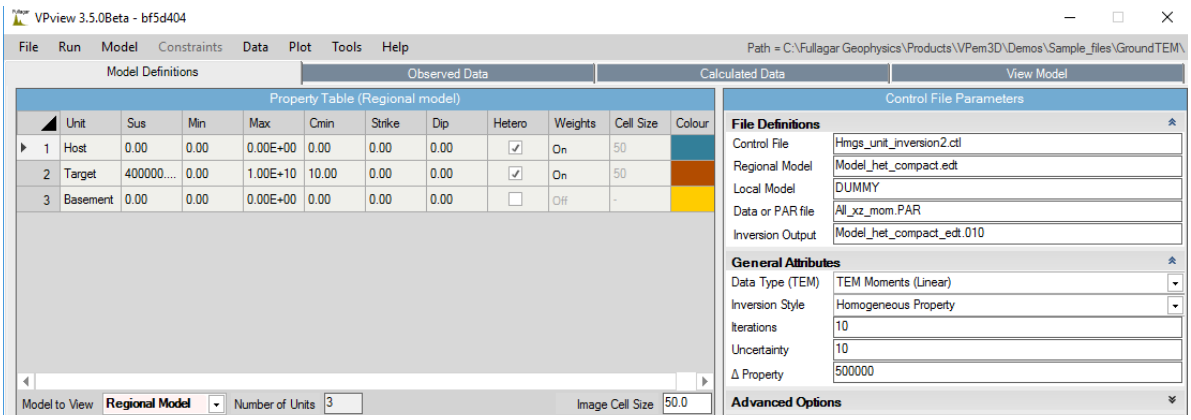


In this case a new model is created, consisting of two units: a zero conductivity host unit and a unit with uniform conductivity of PMIN = 4 x 10^5 mS/m comprised of all cells in the inverted model which originally had conductivity > 4 x 10^5 mS/m, i.e. the shallowest part of the volume of interest. 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.

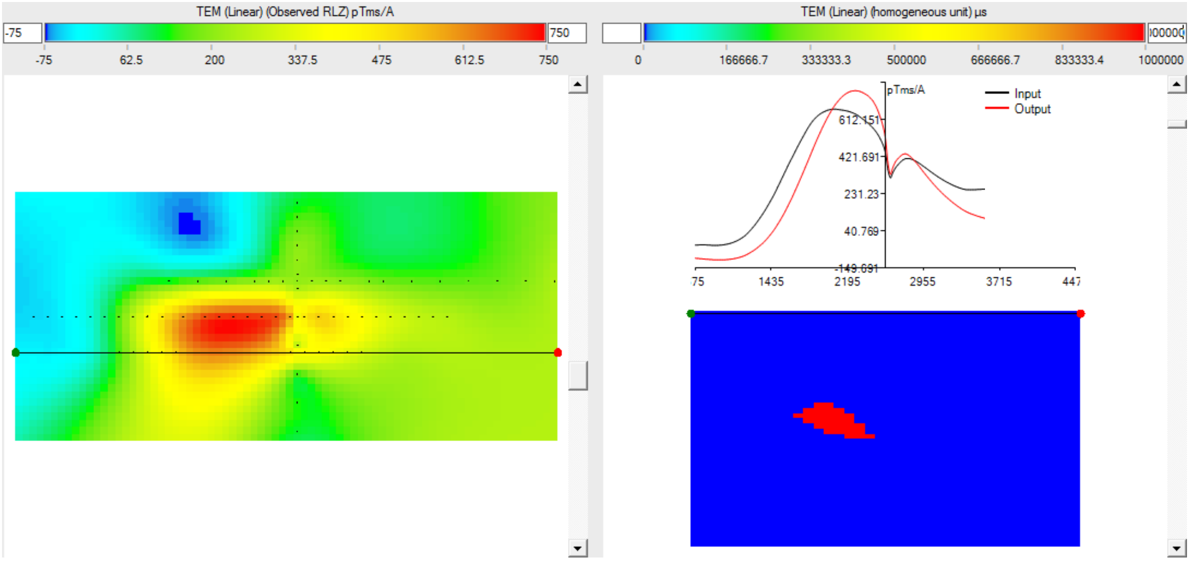
C:\Windows\System32\cmd.exe

```
 **** 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

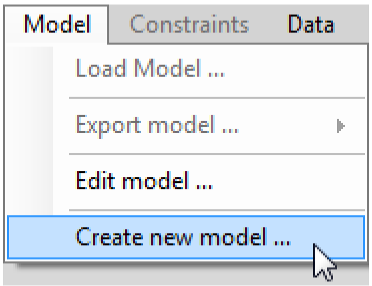
15.1 Introduction

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.

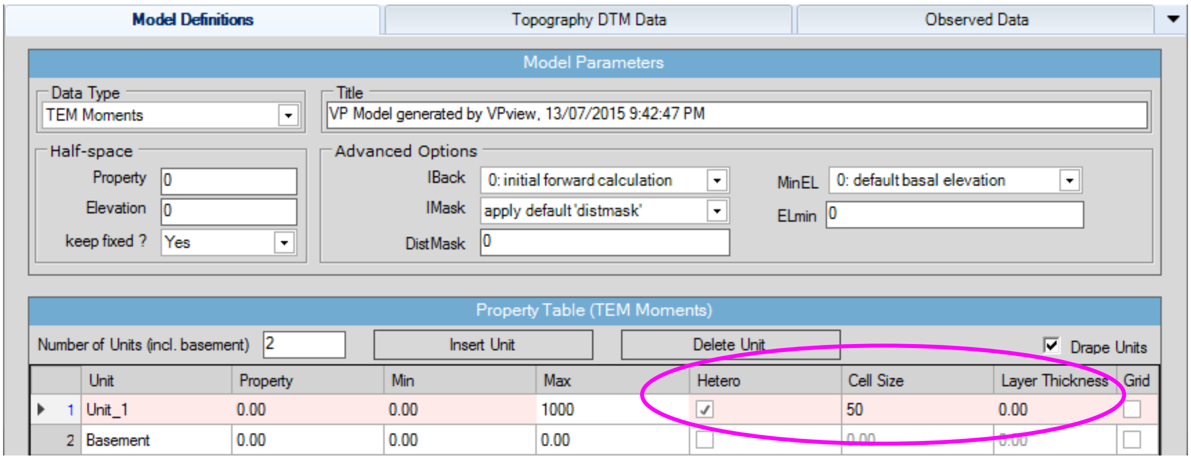
After construction of a starting model from CDIs or 1D inversions, it is usually desirable to apply calculated data normalisation (described in Section 2.17), in order to calibrate the VPem3D property (notionally time constant) against an independent conductivity. The application of calculated data normalisation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

15.2 3D Interpolation of EmaxAIR CDIs

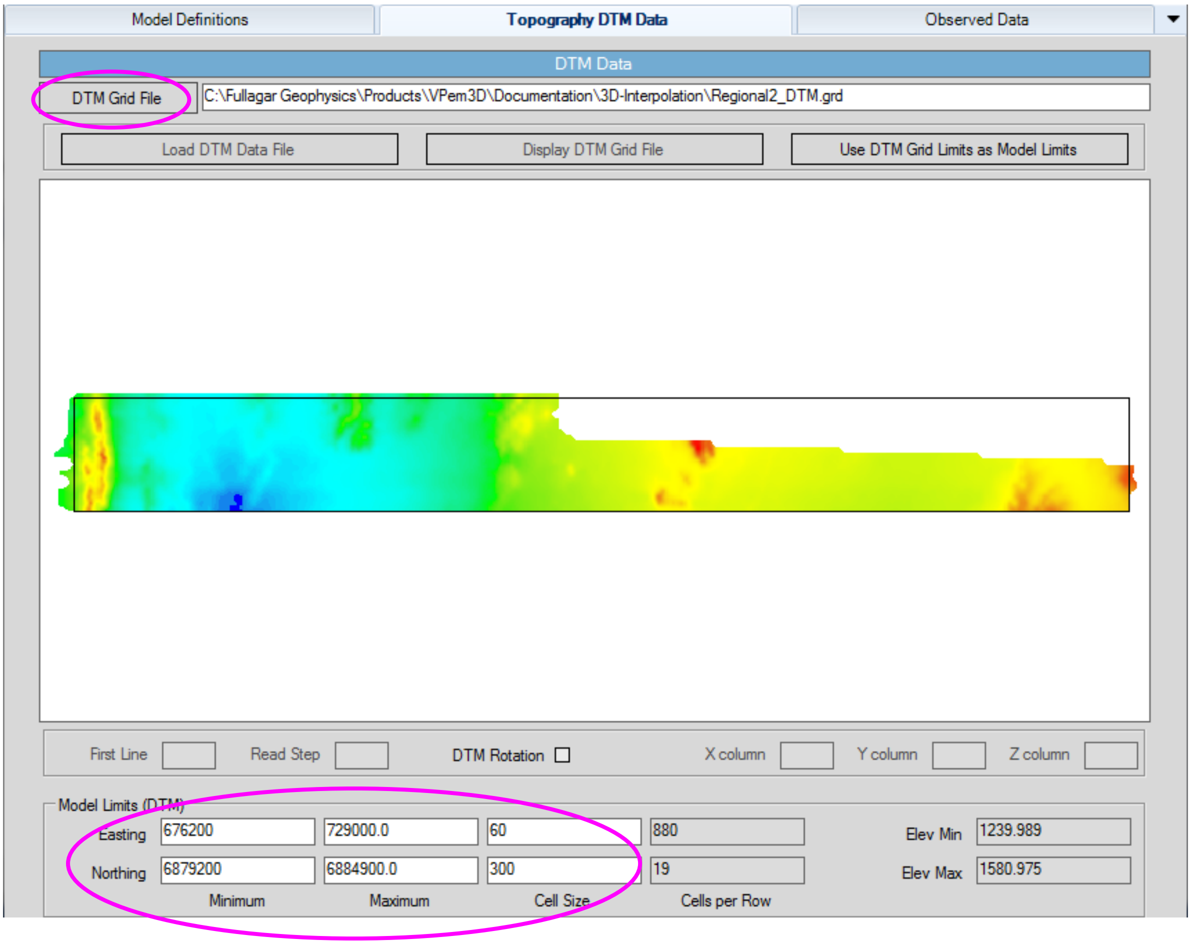


Select the *Create New Model* option from the Model menu.

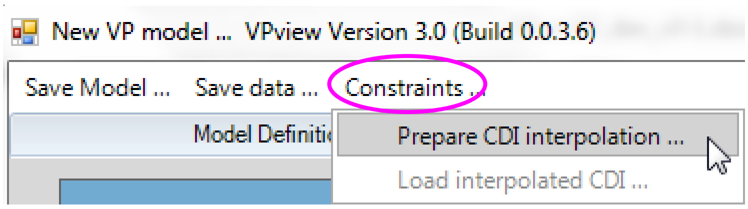
On the *Model Definitions* form define a single layer (host unit) on a basement. Click on the *Hetero* check box, and define the desired vertical cell dimension (*Cell Size*). The *Layer Thickness* can be left as zero initially.



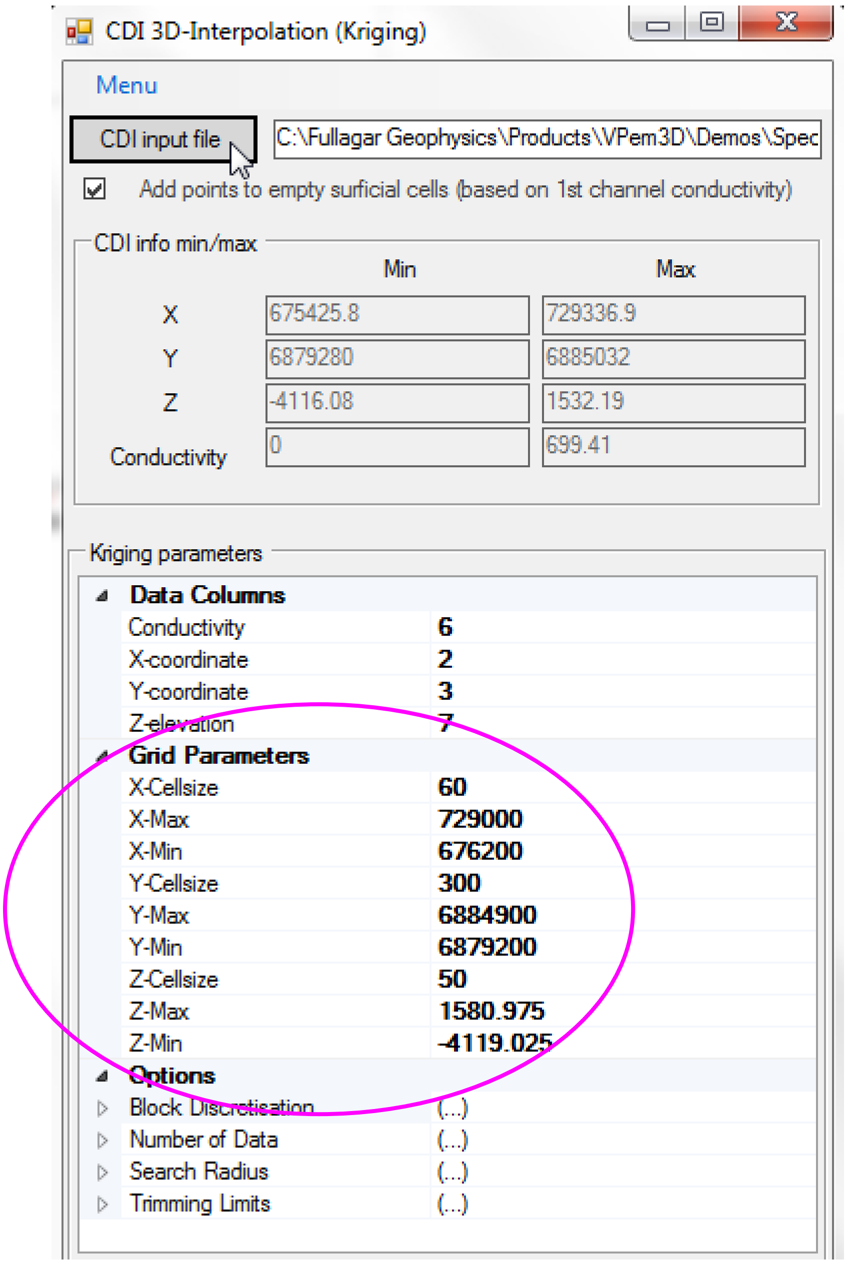
Select the *DTM Grid File* on the *Topography DTM Data* form. Edit the model limits and horizontal cell dimensions (east and north *Cell Size* values). The easting and northing extents must be exact multiples of the corresponding cell sizes.



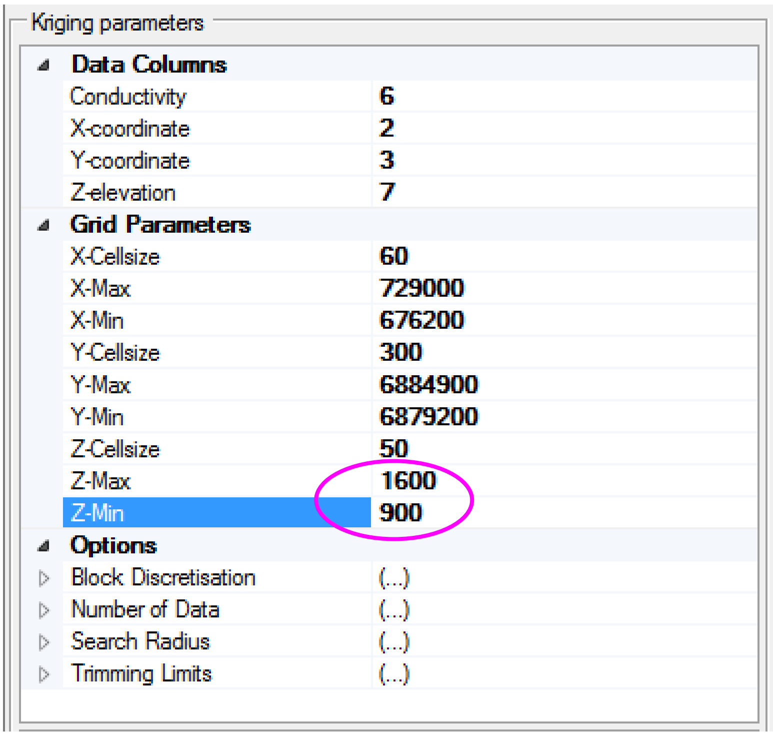
Now select the *Prepare CDI interpolation* option under the *Constraints* menu. The depths should increase monotonically with delay time; any "depth reversals" should be edited from the CDI file.



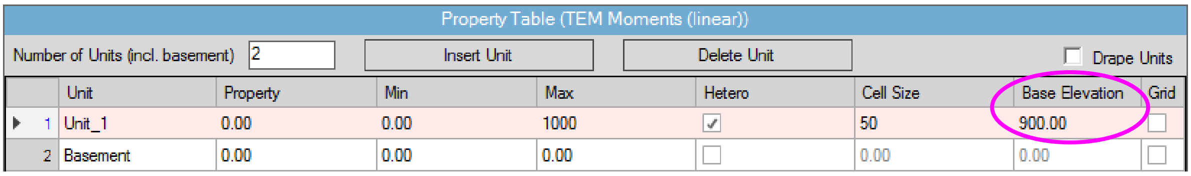
Select the EmaxAIR CDI input file; it usually has extension CDI. The model extents and prism dimensions (*Cellsize* values) are automatically passed from the *DTM Topography Data* form. The Z-Max value is the maximum elevation from the DTM file; the Z-Min value is the minimum elevation from the CDI file.



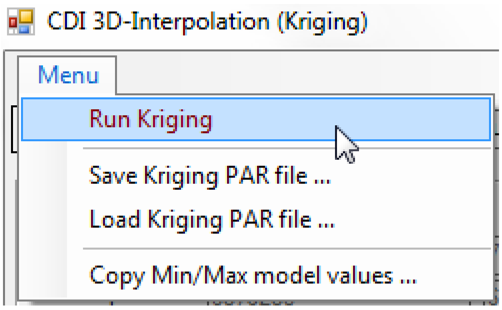
Define the vertical extent of the model grid. In particular, ensure that the Z-Min value is sensible; in this example the original Z-Min elevation is excessively low, i.e. well beyond the penetration of the TEM system. The Z-Min value defines the elevation of the base of the 3D model. The kriging is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



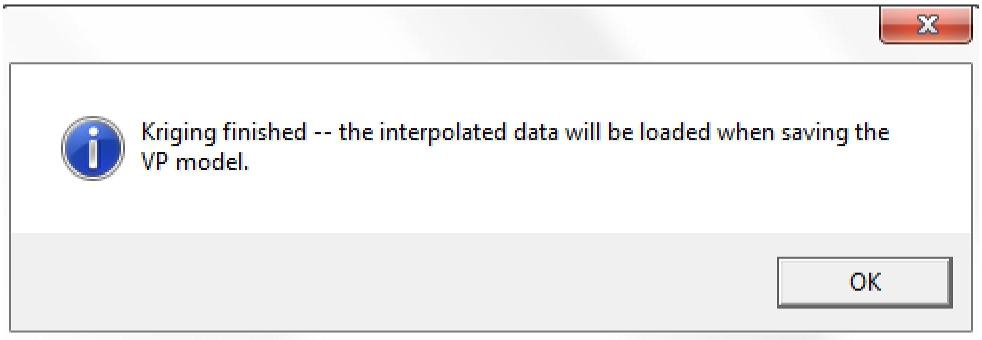
The basal elevation of the model (Z-Min value) is automatically transcribed to the Property Table on the Model Definitions form.



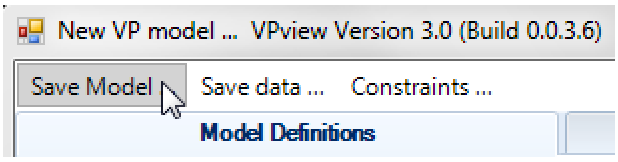
Now perform the kriging: click on *Run Kriging*. A DOS command window will open. The kriging may take a minute or two, depending on the model volume, cell dimensions, and spatial density of (conductivity,depth) points from the CDI file.



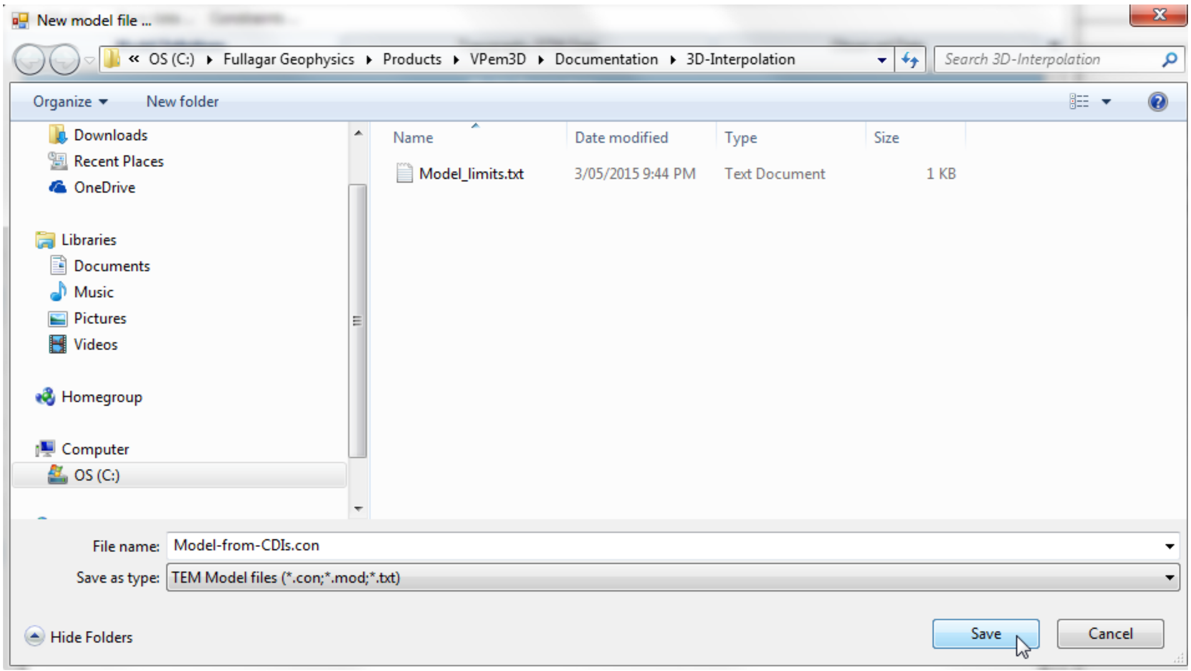
When the kriging has completed, this message is displayed:



Finally, save the model

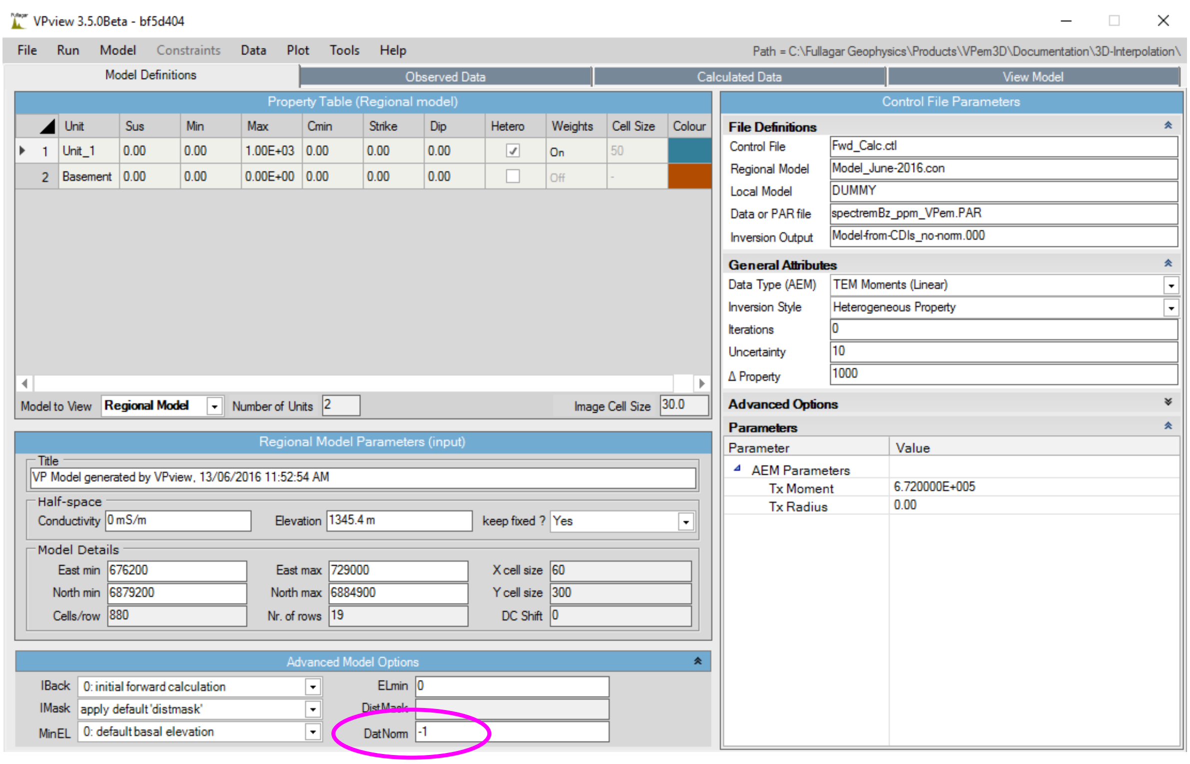


Choose a suitable model file name.

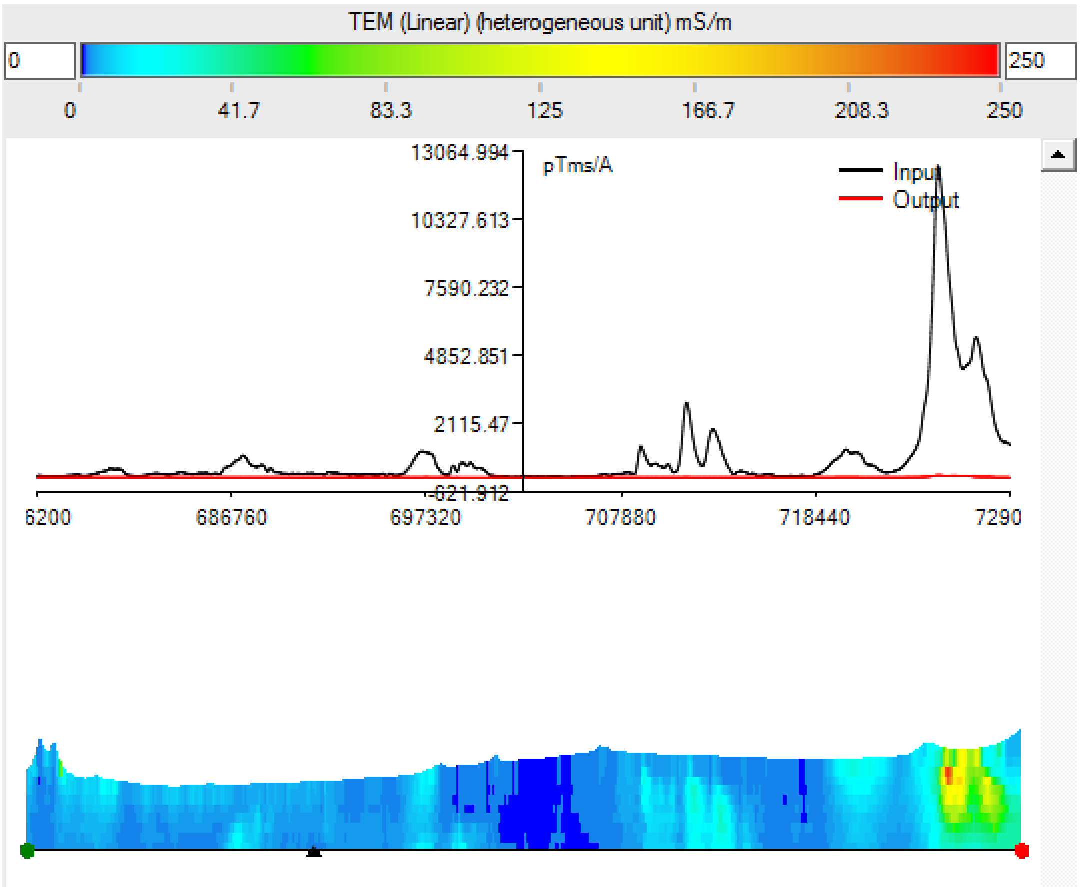


Given a starting model based on CDIs or 1D inversions, it is usually desirable to normalise the forward calculations so that the VPem3D model property is as close as possible to (apparent or inverted) conductivity. As explained in Section 2.16, the VPem3D model property is actually time constant, which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

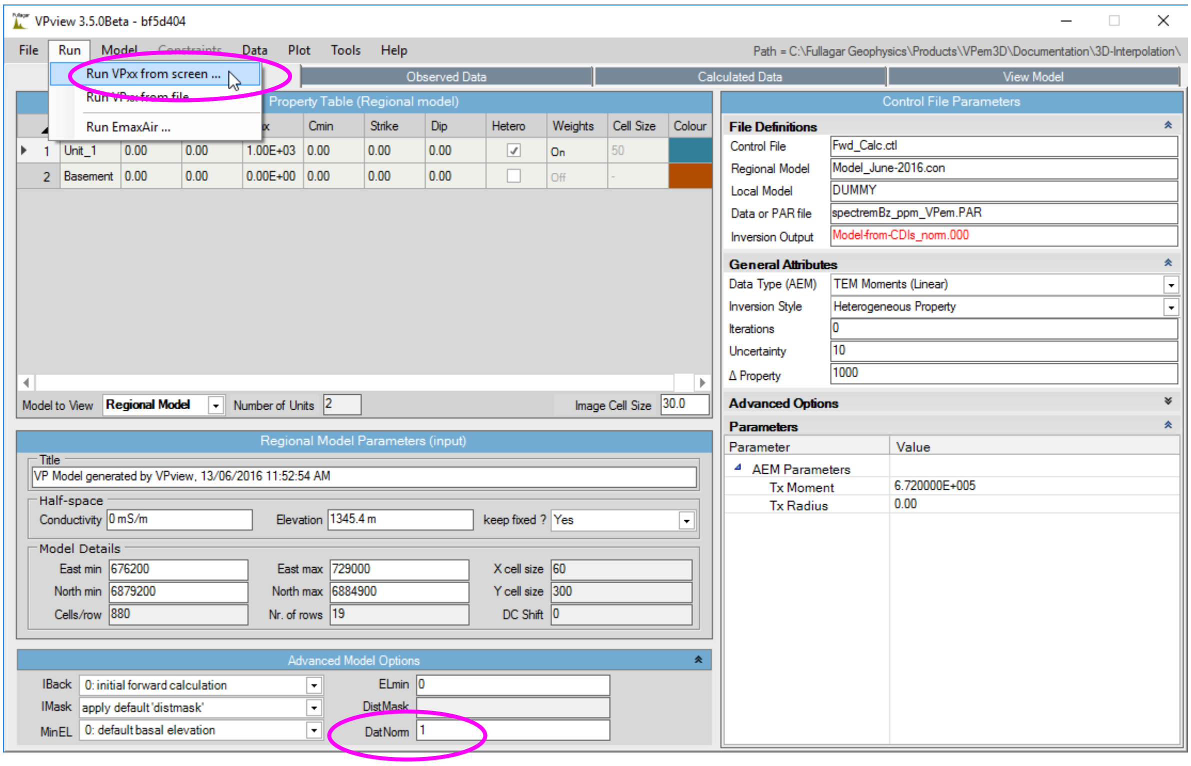
Calculated data normalisation is controlled by the *DatNorm* parameter, defined in the *Advanced Model Options* section of the VPview *Model Definitions* form (see below). Normalisation is not applied if *DatNorm* < 0. The default value of *DatNorm* is -1.



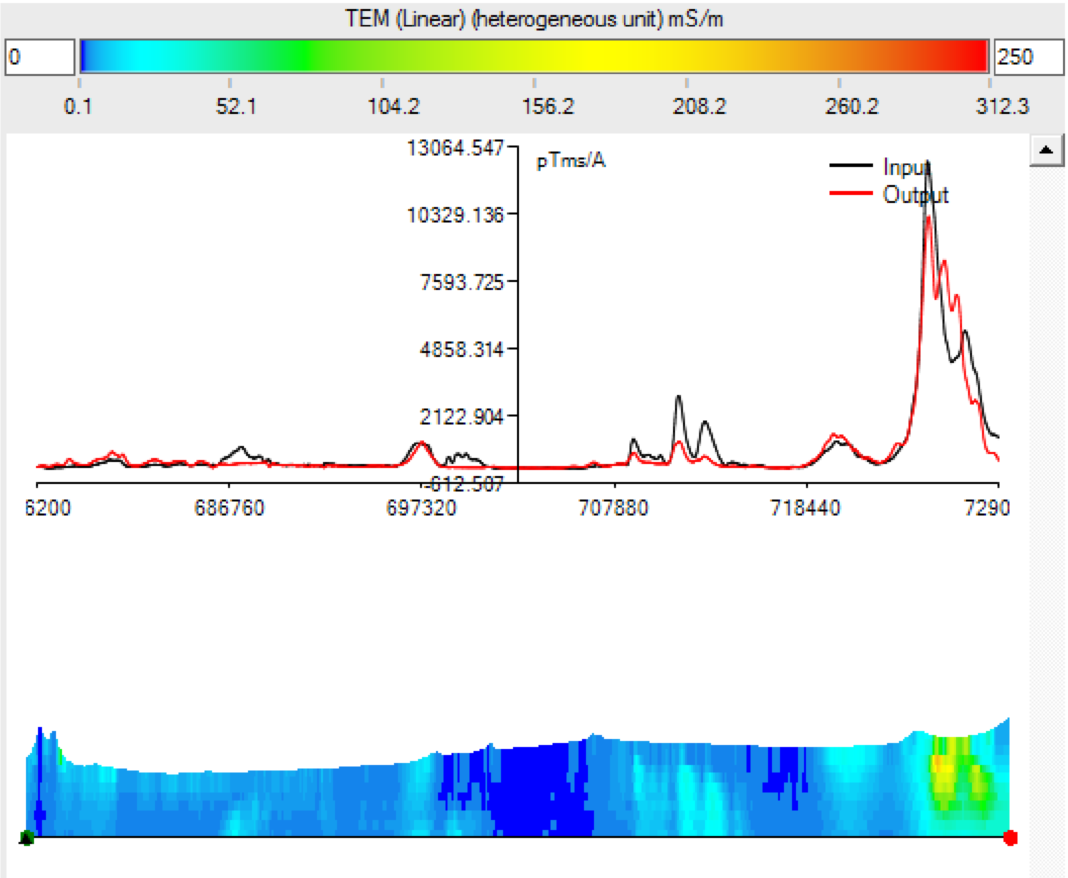
A section through the model after forward calculation without normalisation is shown below. The RMS misfit was 1340 pTms.



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. Cells which contain data points are termed “data cells” here. It is usually desirable to damp the conductivity derivatives of cells within a “radius of influence” around data cells; otherwise the inverted conductivity may be very localised at and near the data points. Therefore the user can impose data proximity weights during VPem3D heterogeneous unit inversion. Two types of data proximity weights are available: function-based weights and derivative-based weights. These are briefly described below.

Data proximity weights are computed for “new models” only, i.e. when *ibackg*=0 (Section 7.4). Data proximity weights are combined with depth, conductivity, Tx loop, and fixed cell weights and recorded in the output model file. When the starting model is “old”, i.e. when *ibackg*≠0, the final weights are read from the model file.

16.1 Function-based data proximity weights

Function-based damping is controlled by two parameters, namely the radius of influence, ROI, and the baseline weight, w0. These parameters are (optionally) specified in the control file, on the record containing the ∆depth and ∆property parameters which govern perturbation size (Section 7.1). The syntax is

∆depth ∆property W

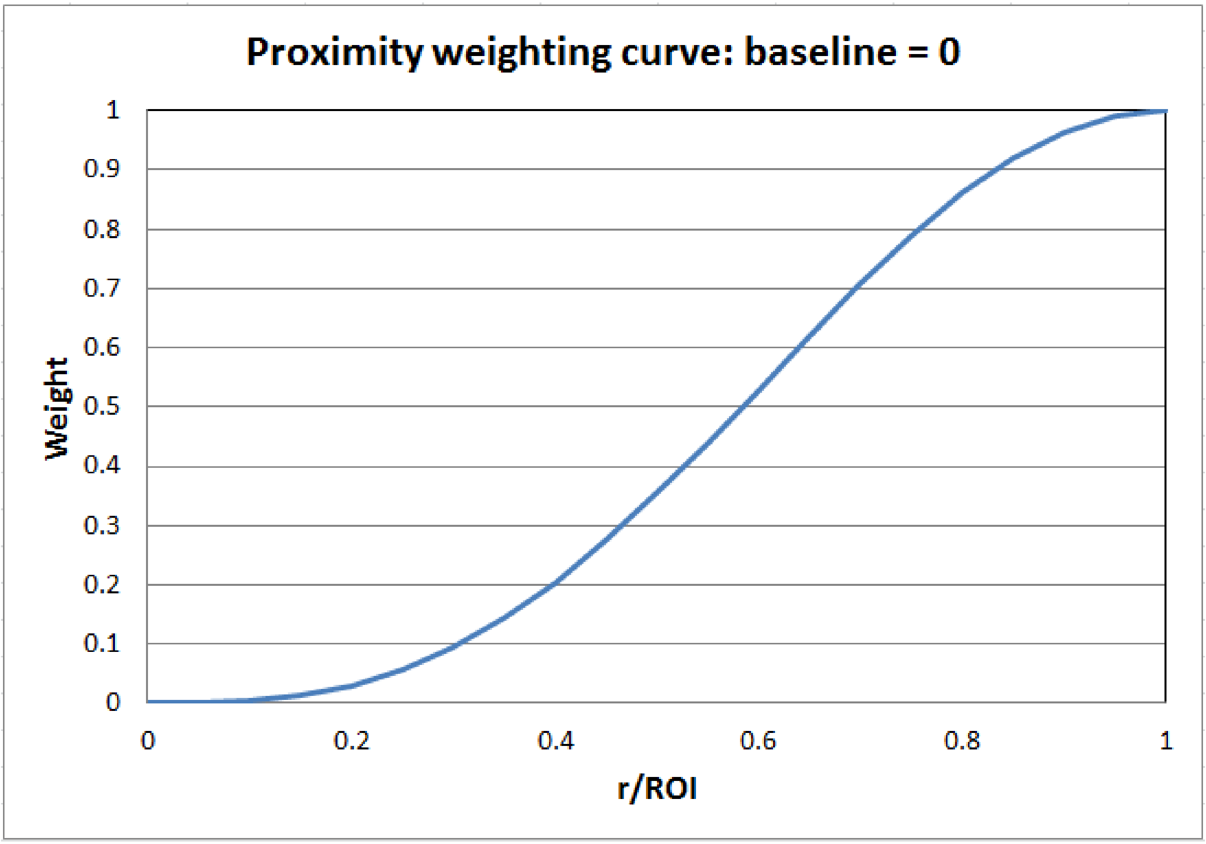
where W = ROI+w0

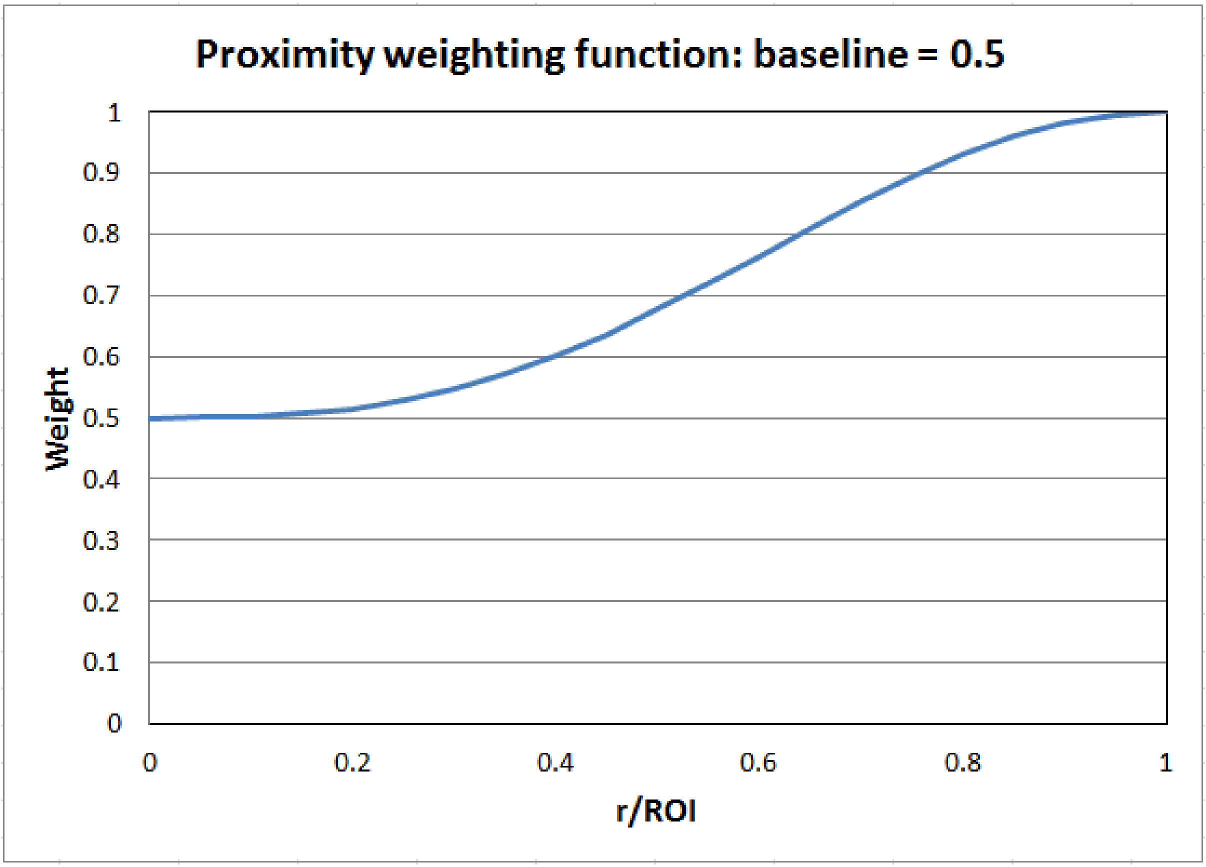
with ROI being the radius of influence in whole metres,

and w0 the baseline weight applied right at a data point (0 ≤ w0 < 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+w0 = 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 the centre of a cell containing one or more data points, i.e. data cell. If a cell lies within the ROI of more than one data cell, the smallest weight is adopted, i.e. the weight corresponding to the nearest data cell.

In the downhole TEM case, 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 baseline, 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 with distance (in accordance with the default proximity weighting curve below) from 0.05 at the data point to 1 at radius 150m.





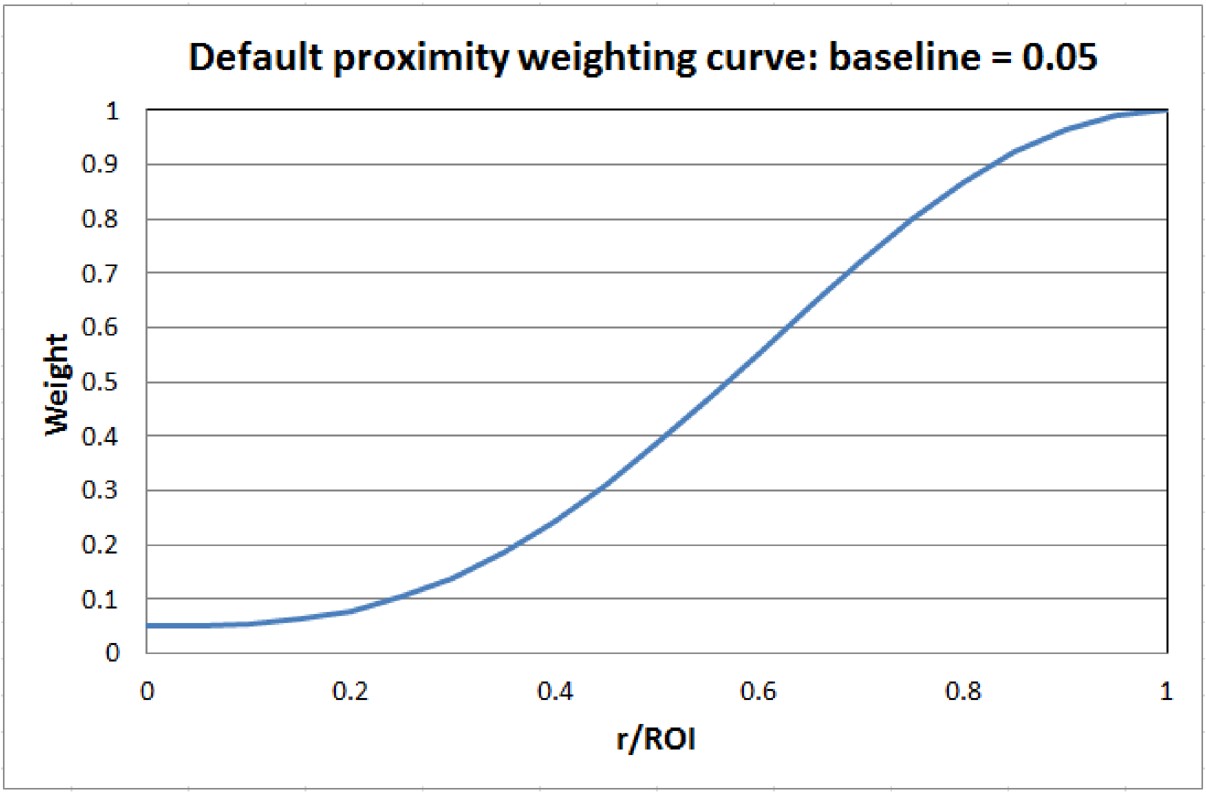
Special cases:

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 w0 = 0.99 for any ROI has virtually the same effect. Thus the weighting becomes more pronounced as w0 decreases.

   Setting ROI=0 also disables proximity weighting around fixed cells (Figure 2.11).

16.2 Derivative-based data proximity weights

Derivative-based damping of each model cell is controlled by its average sensitivity to the data, as described by Li & Oldenburg (2000). VPem3D can apply derivative-based proximity weights during heterogeneous inversions other than compact body inversions.

Derivative-based damping is triggered if the W parameter in the control file is between 0 and 1. The W parameter is specified on the record containing the Δdepth and Δproperty parameters (Section 7.1). The syntax is

Δdepth   Δproperty   W

The intensity of derivative-based damping is controlled by the value of W ($0 < W < 1$). The weights are inversely proportional to average sensitivity in cells with sensitivity > W*max{sensitivity}. A typical value for W in practice is 0.01. As W increases towards 1, the number of weighted model cells decreases and the effect of the weighting diminishes.

There is no default option for derivative-based proximity weights: if W is not specified, the default function-based weights defined above (Section 16.1) will be applied. Note also that function-based data proximity weights will be applied if W=1.0 (interpreted as ROI=1, w0=0), and no weights will be applied if W=0.

17 APPENDIX G: Example “Total Field” TEM Inversion

17.1 Introduction

This Appendix is intended as a guide for running VPem3D modelling and inversion of “total field” TEM data, as measured in sub-audio magnetic (SAM) surveys, using the VPview user interface. The application of VPem3D is illustrated step-by-step for 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.

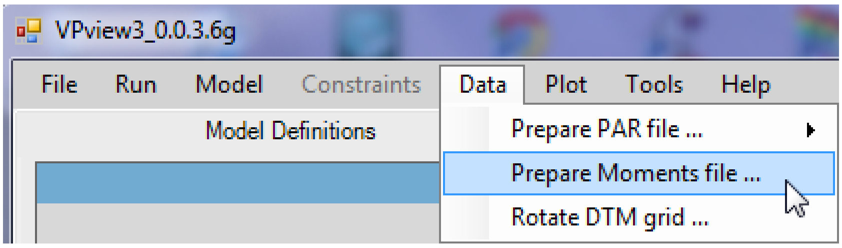
There are various ways to set up and run VPem3D inversion on “total field” TEM data. The example used here illustrates compact body (heterogeneous unit) inversion for fixed loop HeliSAM data. The starting model was a zero conductivity uniform half-space.

17.2 Computing resistive limit data

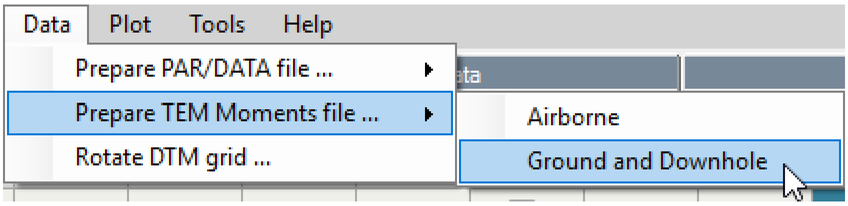
VPem3D operates on TEM resistive limit data. Therefore time decays must be integrated prior to VPem3D modelling and inversion. “Total field” TEM data are expected in TEM format as exported from Maxwell.

```
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 RXAREAZ:-1.000 RXAREAX:-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          CH1
  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           Y      20.000      32.000      28.000       0.040 5.768154e-02     -2.631100
  2650.000    4800.000      0.000       0.000    4800.000           X      20.000      32.000      28.000       0.040 2.496894e-01     -4.135500
```

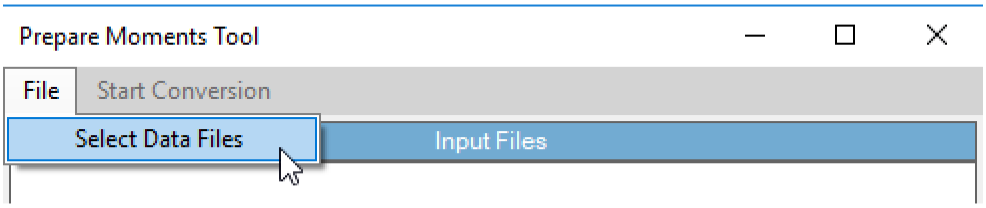
First few lines of a fixed loop TEM file generated by Maxwell. Tx loop vertices (LVnX, LVnY, LVnZ) are included in the header.

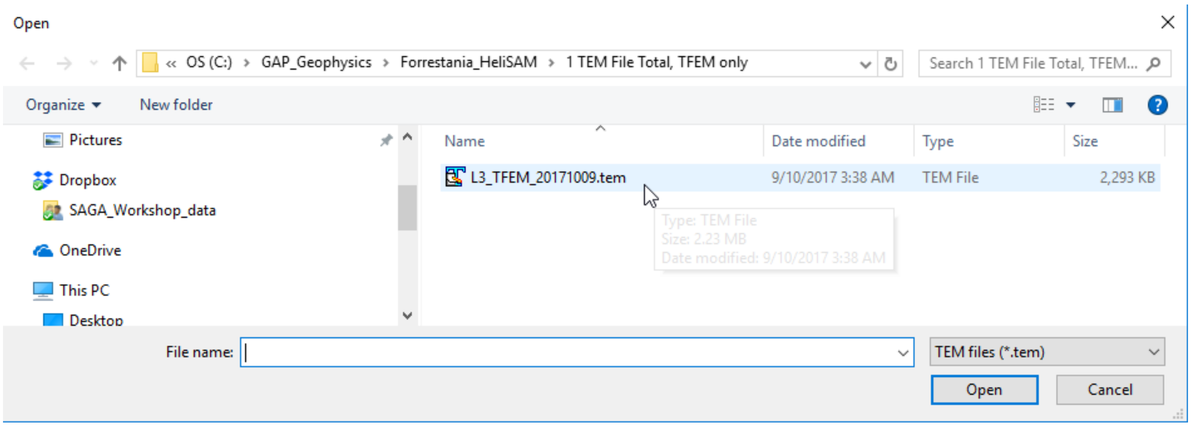


Accessing the data conversion programs under the VPview *Data* menu.

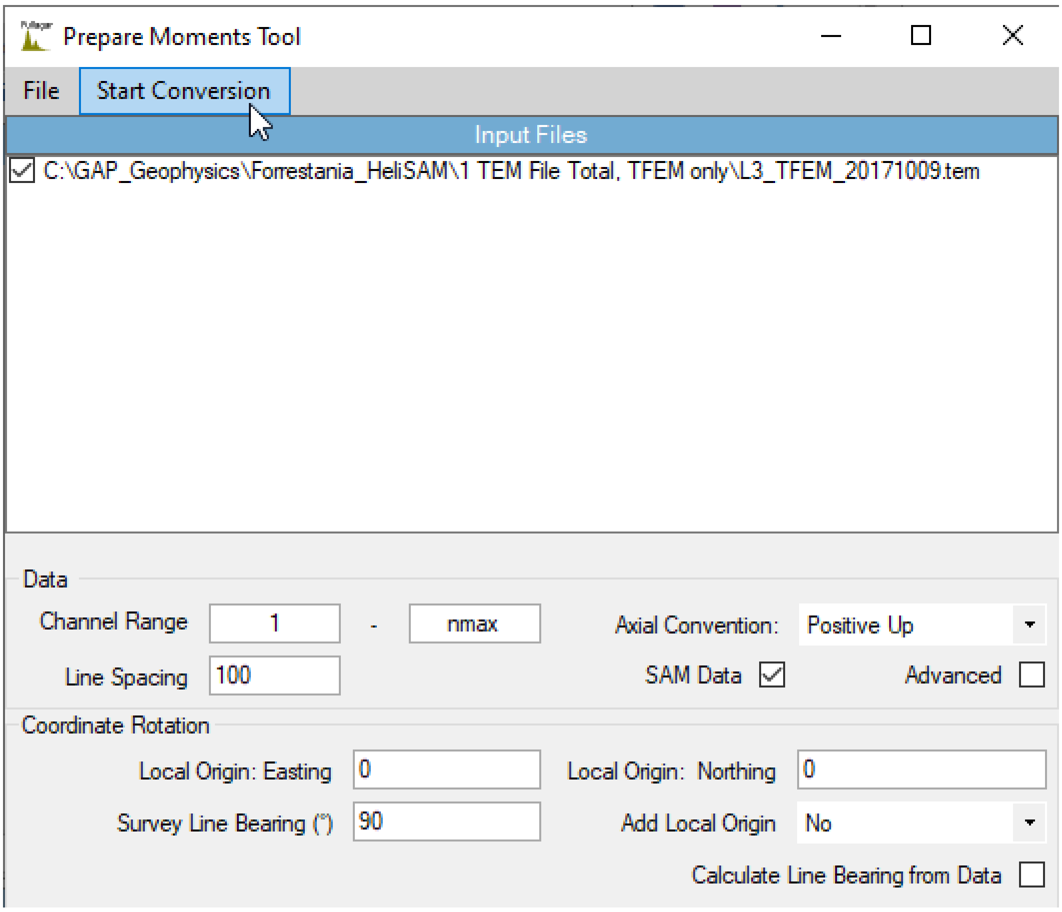


Because it employs a fixed transmitter (loop or dipole), HeliSAM is treated as a ground TEM data set.

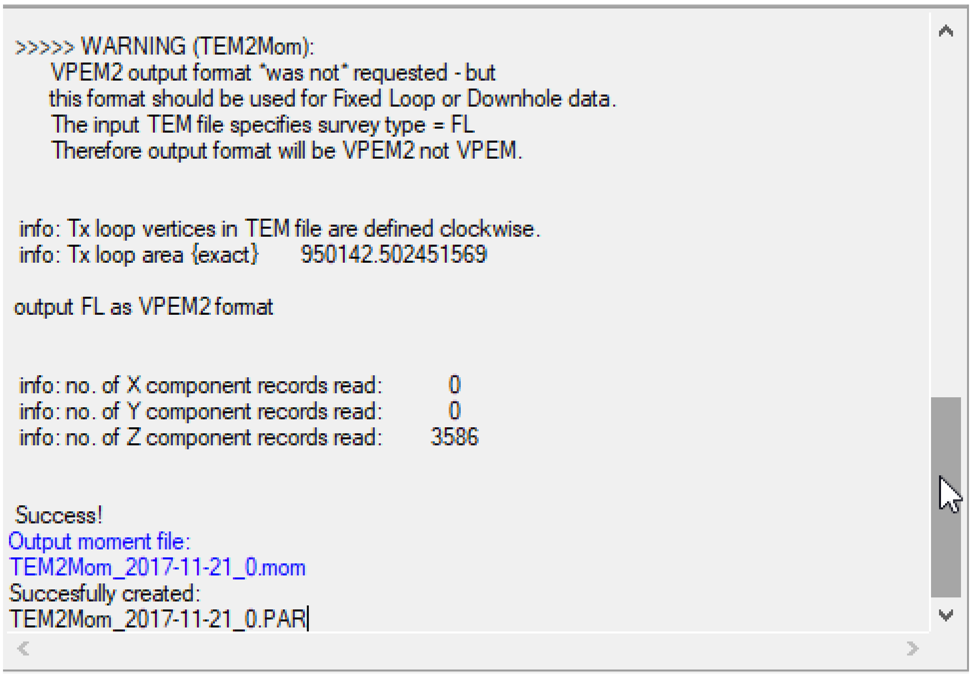




Select the appropriate TEM file for conversion.



Select the desired TEM channels for integration. Specify the line spacing and identify the data type as “SAM”, aka sub-audio magnetics aka “total field”. Lines were flown north-south for this survey, so no coordinate rotation is required. Launch TEM2Mom to convert the data to resistive limits.



Scroll through the messages, but generally the appearance of the word "Success!" is a good sign.

TEM2Mom writes a moment (.XYZ) file, containing resistive limit data, and VPview creates a parameter (.PAR) file defining the format of the moment file. The first few lines of the XYZ file are shown below. The time integration range is recorded in the moment file header. For fixed loop surveys, the Tx loop geometry is defined directly below the header.

```
/ Processed from TEM sources: (9/11/2020 - 9:10 AM)
/ C:\GAP_Geophysics\Forrestania_HeliSAM\1 TEM File Total, TFEM only\L3_TFEM_20171009.tem
/!!IntegrationTimeWindow #VPEM2  (start-end time in milliseconds):    0.2080   116.8750
/TEM2Mom : version = v3.7.25 dev [3.0725]  build date = Sep 26 2020  build time = 10:14:00
lic_var = 1(mlm)
/DataType = SAM: 0
/ConfigurationType = FL
/Across-line prism dimension:  100.0 (m)   Along-line prism dimension:  19.0 (m)
/Data elevation min :   414.6 (m)
/Loop dimension     :   974.8 (m)
/Data easting  min & max:  747792.01   749727.09   Data northing  min & max: 6414803.42
6418192.26
/N-S survey lines without rotation: Yes
/Model easting min & max:  747550.00   749950.00   Model northing min & max: 6414542.50
6418456.50
LOOP_DEF  DEFAULTLOOP  44
749241.24   6416854.62     386.85
749247.59   6416892.55     387.21
749238.18   6416900.95     386.96
749036.62   6416901.23     382.69
749033.64   6416902.27     382.66
748987.24   6416893.37     382.06
748909.24   6416900.02     381.42
748788.19   6416896.11     378.54
748722.18   6416904.28     376.49
```

The resistive limits are recorded in the .XYZ file below the loop geometry. RXX, RXY, RXZ are the sensor coordinates.

```
749237.45    6416214.84       383.09
749239.69    6416277.94       383.16
749241.73    6416286.53       383.27
749244.41    6416316.33       383.44
749240.85    6416487.94       384.75
749240.91    6416488.46       384.75
RXX               RXY                    RXZ                  RLT           PROXYSTN      RLTE
LINE 9700   LOOP=DEFAULTLOOP
749713.911      6414811.777        441.593           78.697252        1.000       0.000000
749713.205      6414828.482        441.098           83.477269        2.000       0.000000
749712.097      6414845.671        440.633           76.761112        3.000       0.000000
749710.670      6414863.493        440.285           77.513168        4.000       0.000000
749709.473      6414881.557        439.476          111.813311        5.000       0.000000
749708.746      6414900.286        438.571           78.642543        6.000       0.000000
749708.568      6414919.639        437.756           61.941805        7.000       0.000000
749709.365      6414939.152        437.052           62.487086        8.000       0.000000
749710.927      6414959.091        436.826           66.687869        9.000       0.000000
749712.404      6414979.272        436.853           82.836927       10.000       0.000000
749713.364      6414998.671        437.058          103.821349       11.000       0.000000
749713.714      6415017.519        437.984           74.765676       12.000       0.000000
```

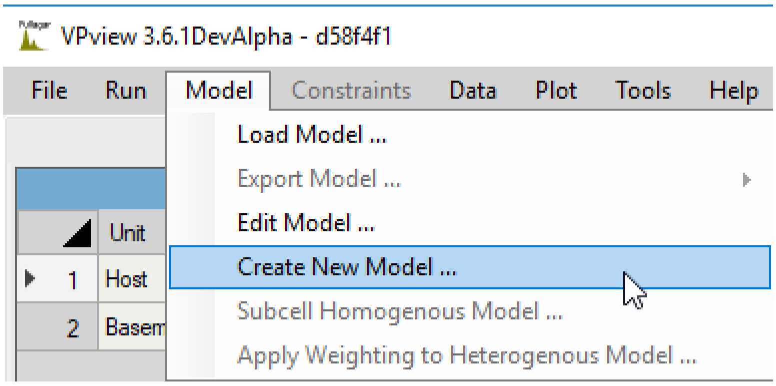
The "total field" resistive limit data are recorded in the column labelled RLT. This moment file is in #VPEM2 format. A different moment file format, denoted #VPEM#, is used for moving loop surveys, as described in Section 7.2.

The VPem3D parameter file is shown below. The error column is labelled RLTE. In this case the RLTE values are all zero because the standard deviation was not computed by TEM2Mom.

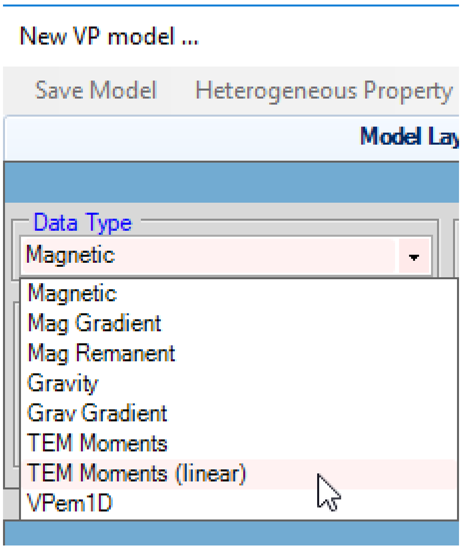
```
#VPEM2
TEM2Mom_2020-11-09_1_MOM.XYZ
6
-1
4        RLT
5        PROXYSTN
6        RLTE
```

17.3 Create a starting model (no DTM grid available)

Launch the Create New Model utility:

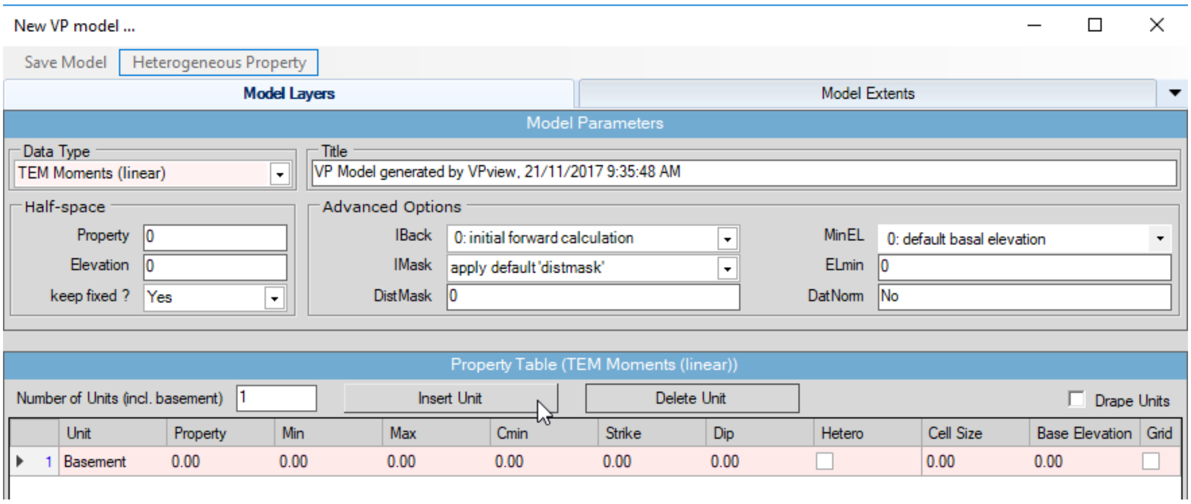


Select the TEM Moments (Linear) Data Type:

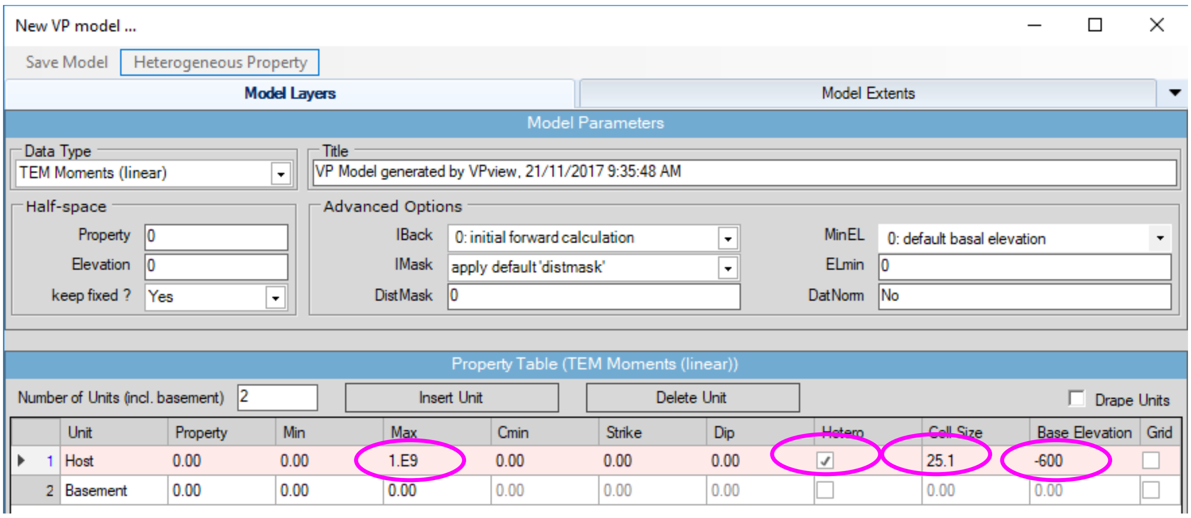


If intending to run an unconstrained inversion, starting model construction can be expedited using default parameters recorded in the moment data (.XYZ) file. However, fully "manual" model construction is illustrated here.

Basement is inert in VPem3D inversions, so insert an active unit overlying Basement:

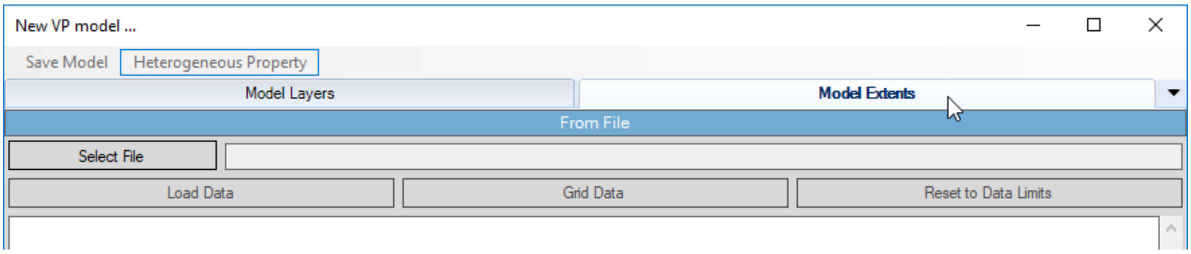


Define the active unit parameters:

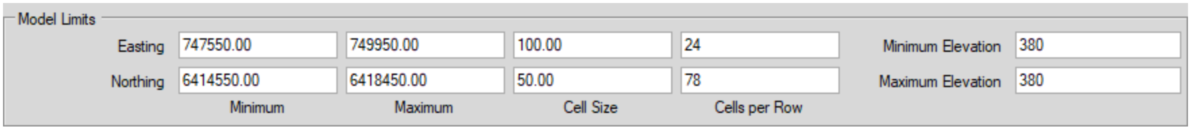


Choose a very high maximum conductivity when, as in this case, the intention is to run compact body inversion. Check the “Hetero” box in order to sub-cell the Host unit; otherwise the model cells will extend from the ground surface to the base of the model. Cell Size of 25.1 means that the shallowest cell will be 25m thick, and all underlying cells will increase successively in thickness by a factor of 1.1. The model base will be horizontal, at an elevation of -600m.

The model limits, ground surface (DTM), and prism dimensions are defined on the Model Extents form.

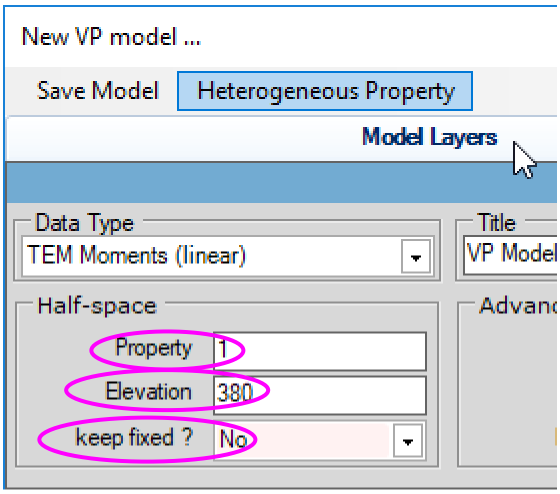


When no DTM (either grid or ASCII x,y,z file) is available, VPview creates a model with a horizontal upper surface. The model extents, prism dimensions (cell sizes), and ground surface elevation can be entered at the bottom of the Model Extents form:

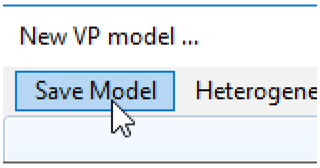


The HeliSAM survey lines were flown north-south at a spacing of 100m, with the sensor at a height of about 40m. Therefore, the across-line resolution (hence E-W Cell Size) is 100m. At a height of 40m, the anomaly produced by a dipole on the surface is about 100m wide, so along-line sampling at 50m intervals is adequate; hence the N-S Cell Size. If surficial conductors were of interest, then a smaller along-line Cell Size could be desirable. However, in this case the conductors of interest are buried to significant depth, so 50m along-line sampling is more than sufficient.

The (average) ground surface elevation is adopted as the elevation for the top of the homogeneous half-space which (optionally) contributes a background response. In this case a background response should be included, to account for conductive regolith. The half-space conductivity can be fixed or it can be optimised by VPem3D. When, as in this case, it is free to vary, the user need only provide a positive seed value. The unit is mS/m. If no background is required, set the Property to zero.



Finally, save and name the model.

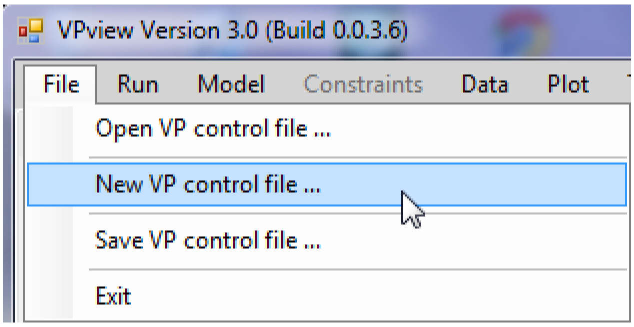


VPem3D is used to generate a heterogeneous model; a command window opens for this reason after *Save Model* has been selected.

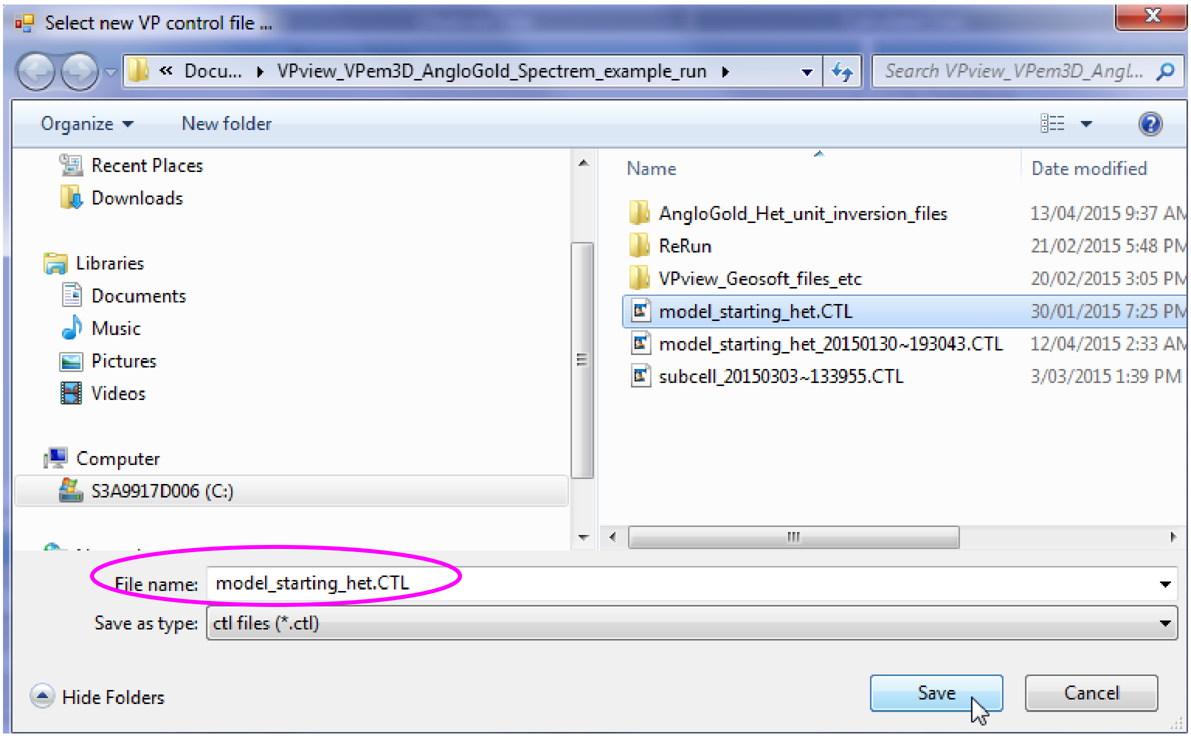
17.4 Create a control file

A control file is required in order to run VPem3D. The VPview *Create New Model* utility will optionally create a control file for a forward calculation after a starting model has been constructed.

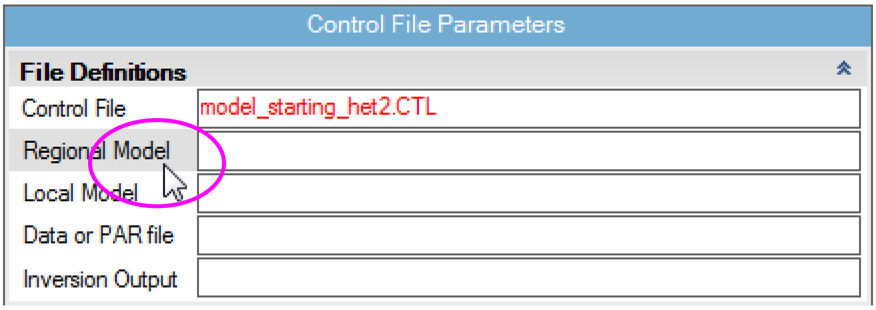
More generally, if a control file does not already exist, it can be created using the *New VP control file* utility under the File menu.



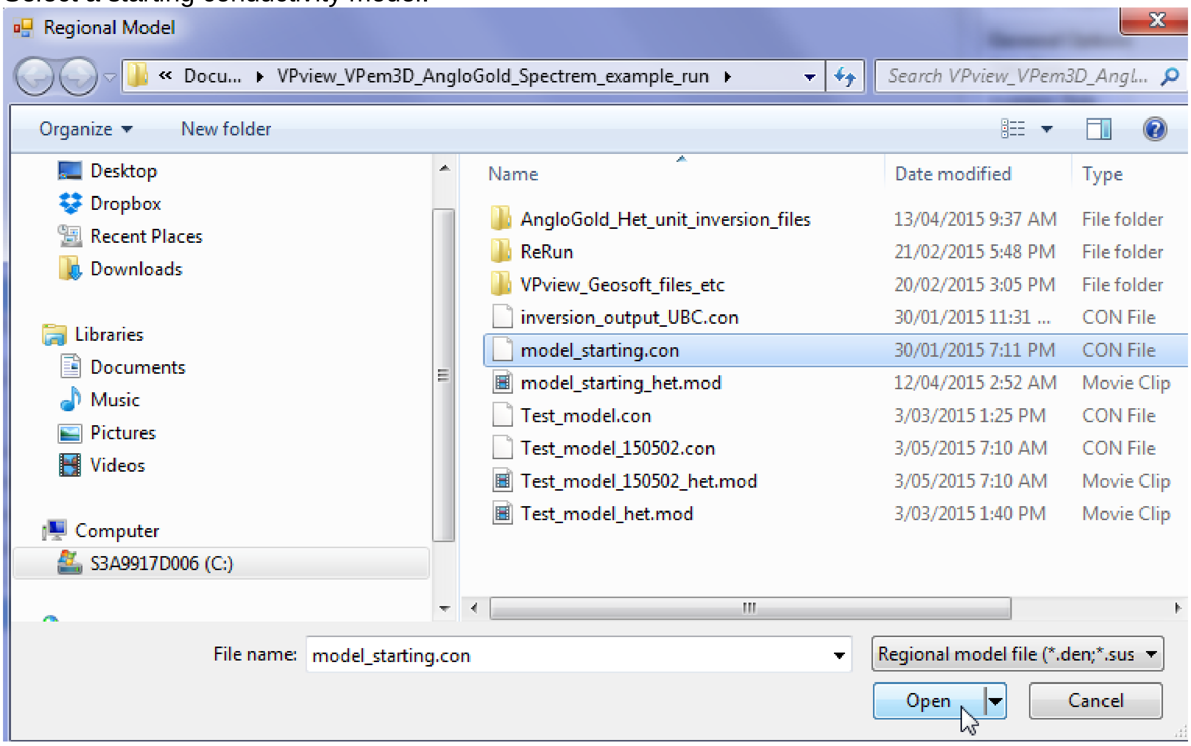
First select the project directory and choose a name for the control file. The control file extension is CTL. In the illustration the control file already exists.



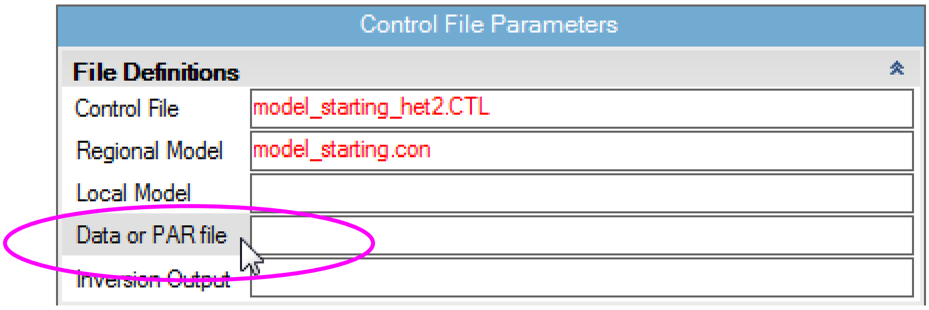
Click on a model file label to open a browse window.



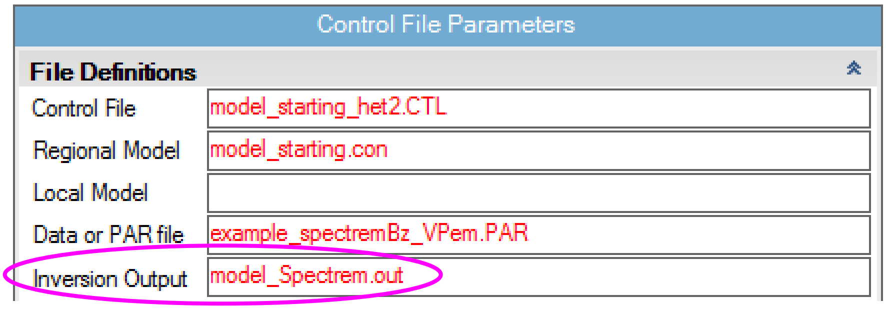
Select a starting conductivity model.



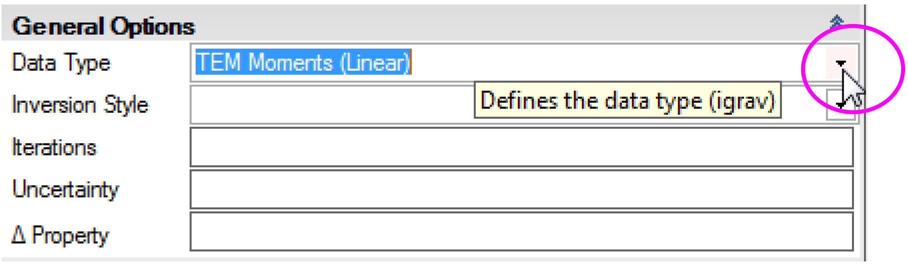
The starting model can be regarded as either regional or local. The text box for the other model can be left blank. Select the appropriate PAR file in the same fashion: click on the label to open a browse window.



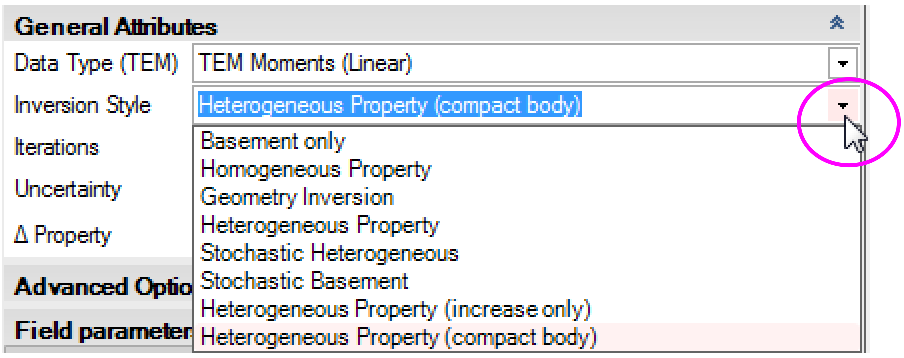
The output model file will usually not already exist. Type in a name for the output file. The extension is arbitrary, but VPview recognises *.CON files as conductivity models.



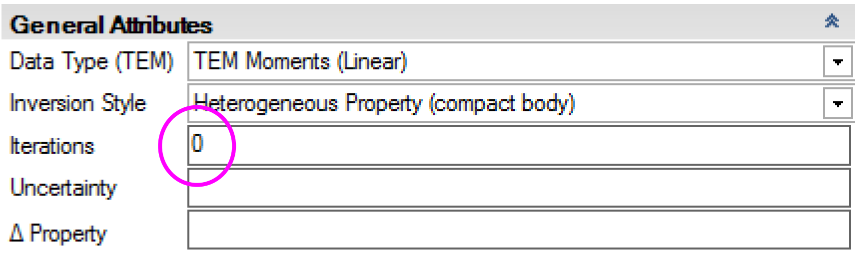
Now define ***General Options*** settings. Use the drop down menu to select *Data Type*. TEM Moments (Linear) is the appropriate *Data Type* for most downhole TEM inversion runs.



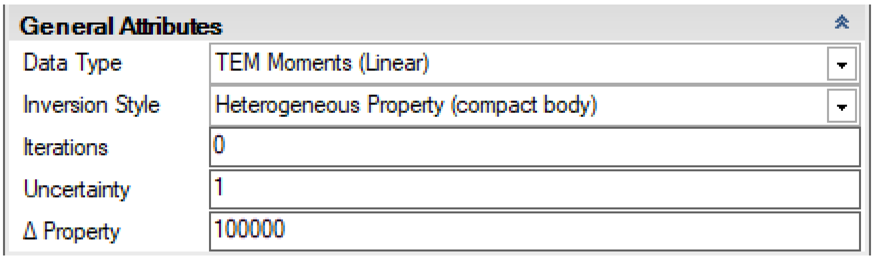
Use the drop down menu to select *Inversion Style*. Compact body inversion, which is a form of heterogeneous inversion, is selected here.



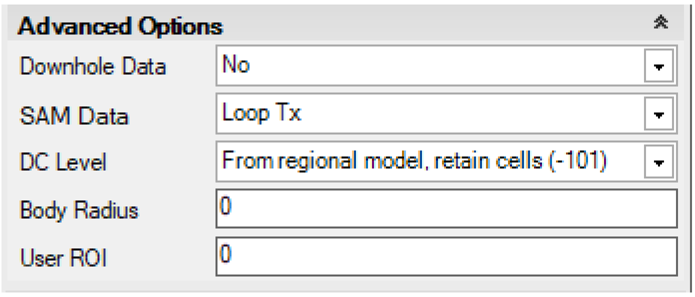
Set *Iterations* to zero for an initial forward calculation.



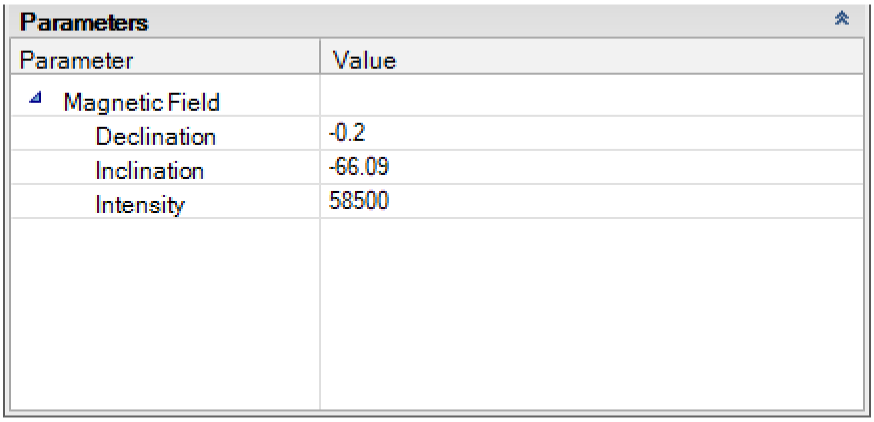
Define values for the *Uncertainty* (in pTms/A) and the *Δ Property* (maximum conductivity change per iteration, in mS/m). *Δ Property* is normally set very high for compact body inversion.



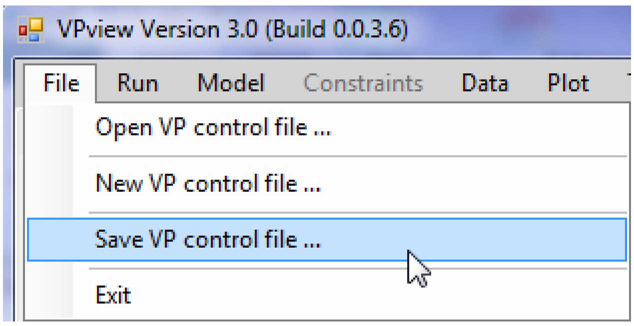
In the ***Advanced Options***, use the drop down menus to choose *Downhole Data*, *SAM Data*, and *DC Level* settings. A loop transmitter was used for the example HeliSAM data set. For regional models, -101 is the default setting for *DC Level*. This fixes the *DC Level*, which is added to all calculated data, to the value recorded at the end of the regional model file; it is almost always zero for TEM modelling. [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 Radius* (optional, for compact inversion) and *User ROI* (radius of influence of data, for calculation of weights) have no effect on forward modelling and so can be left blank.



Define the ambient geomagnetic field in the Parameters table:



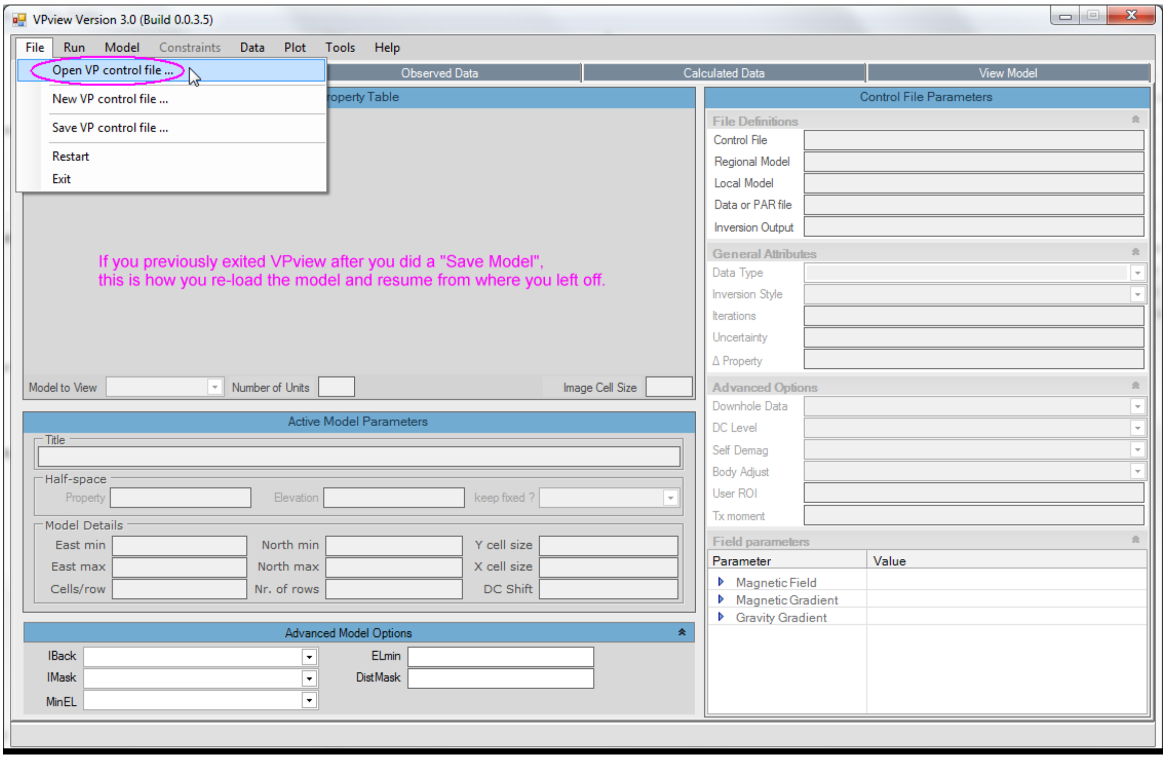
When all parameters have been entered, save the new control file using the option under *File*.



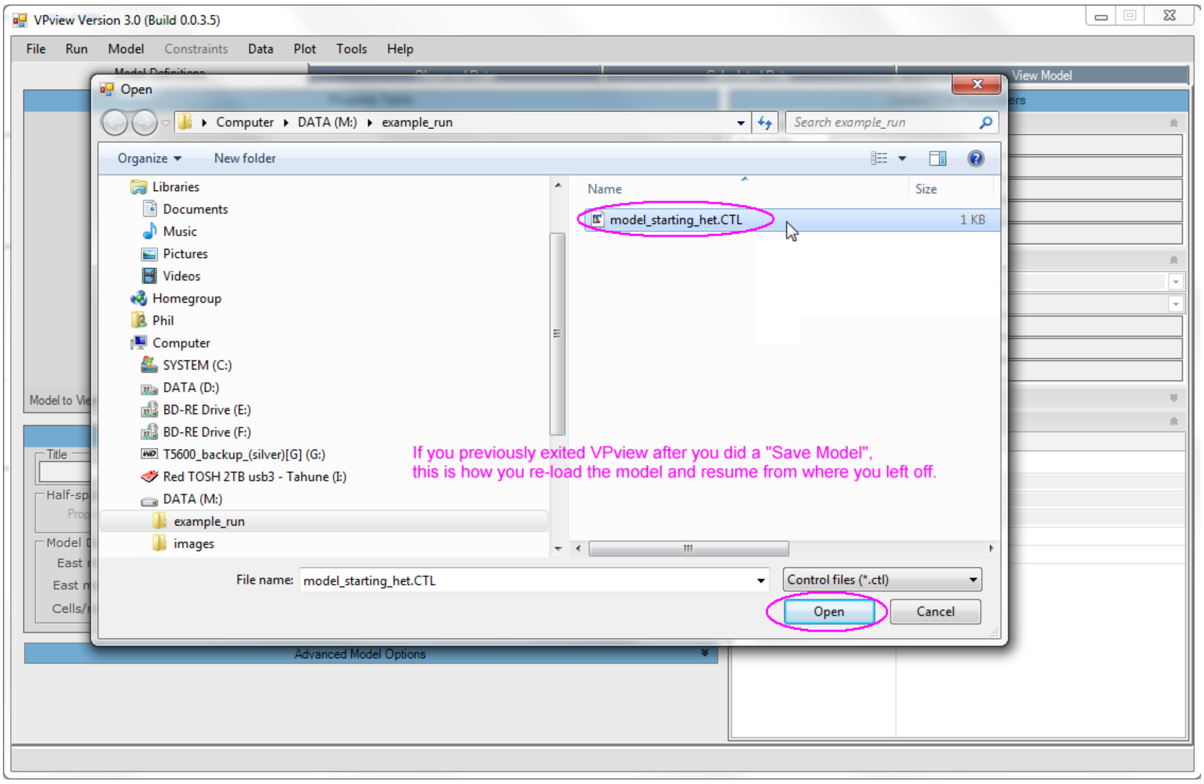
17.5 Performing a forward calculation

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. In cases when a background response is calculated, an initial forward calculation also allows the user to examine the background response if the starting model is uniformly zero.

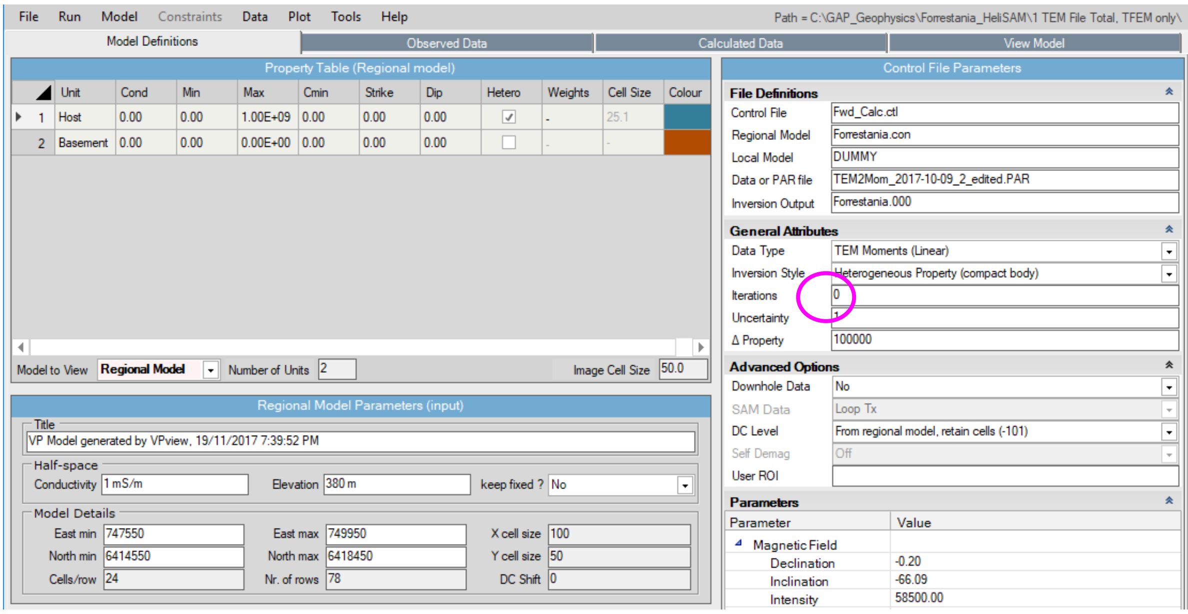
If you had exited, restart VPview and select the “Open VP control file” option under the *File* menu.



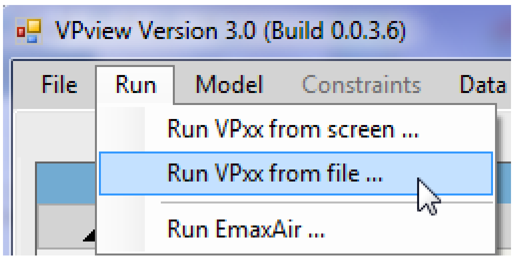
Choose the desired VP control file.



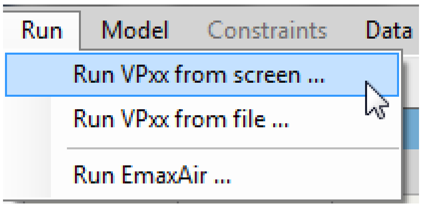
VPview displays the model file header information and control file settings. Cells in the Host unit are 100m E-W x 50m N-S.



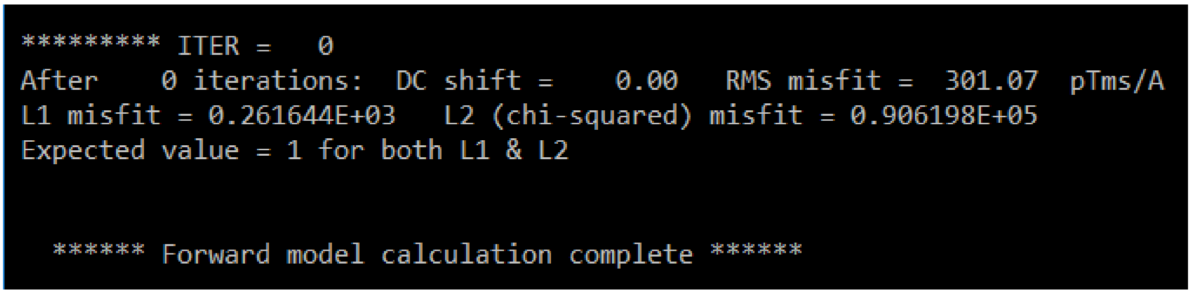
If the saved model parameter and control settings are all acceptable, launch VPem3D using the “Run VPxx from file” option under the *Run* menu. Iterations should be zero for a forward calculation.



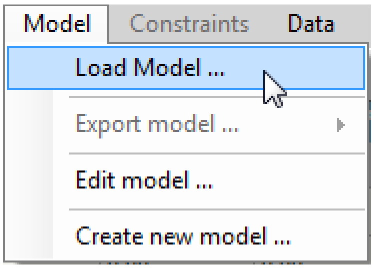
If some of the settings have been edited, but not saved, launch VPem3D using the “Run VPxx from screen” option.



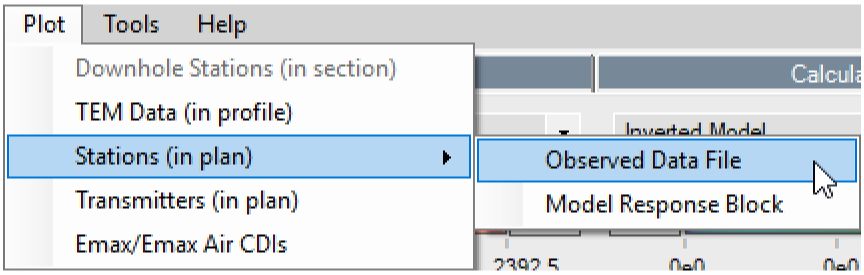
VPem3D will run in a command window.



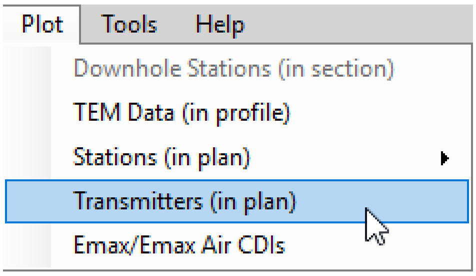
After the forward calculation has completed, load the model and data using the *Load Model* option under the Model menu, as shown.



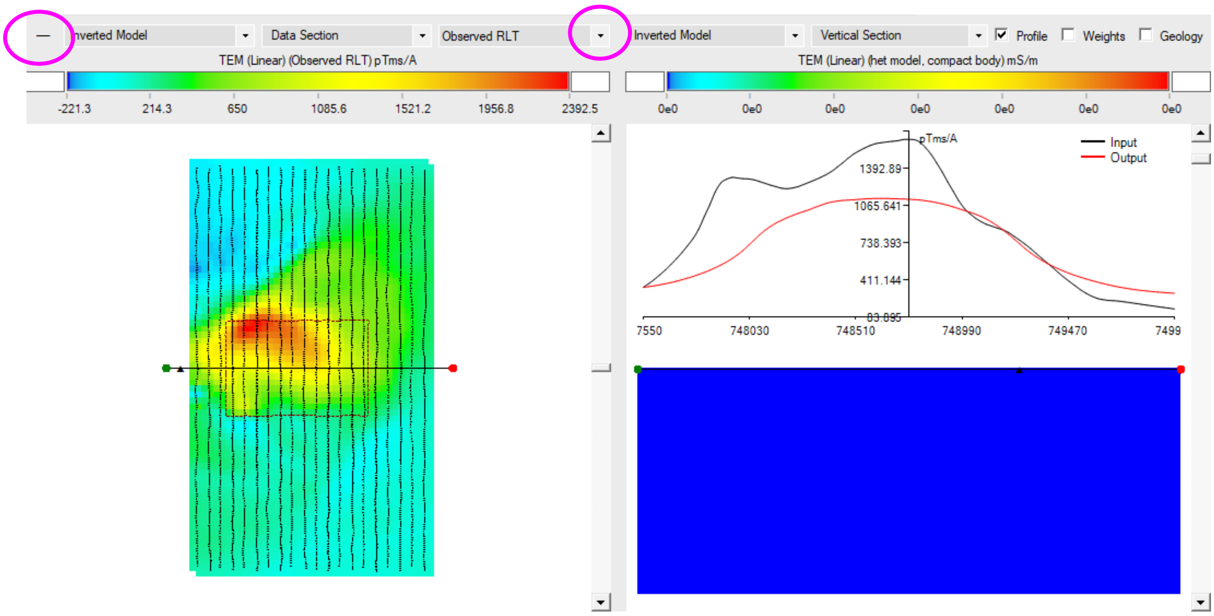
When the model first loads, the ground topography is displayed in the left panel; different quantities can be selected for display from the drop down menu above the LH panel. The observed “total field” resistive limit (RLT) is displayed below. Display the data locations using the *Plot/Stations (in plan)* option; these are represented as black dots on the LH panel.



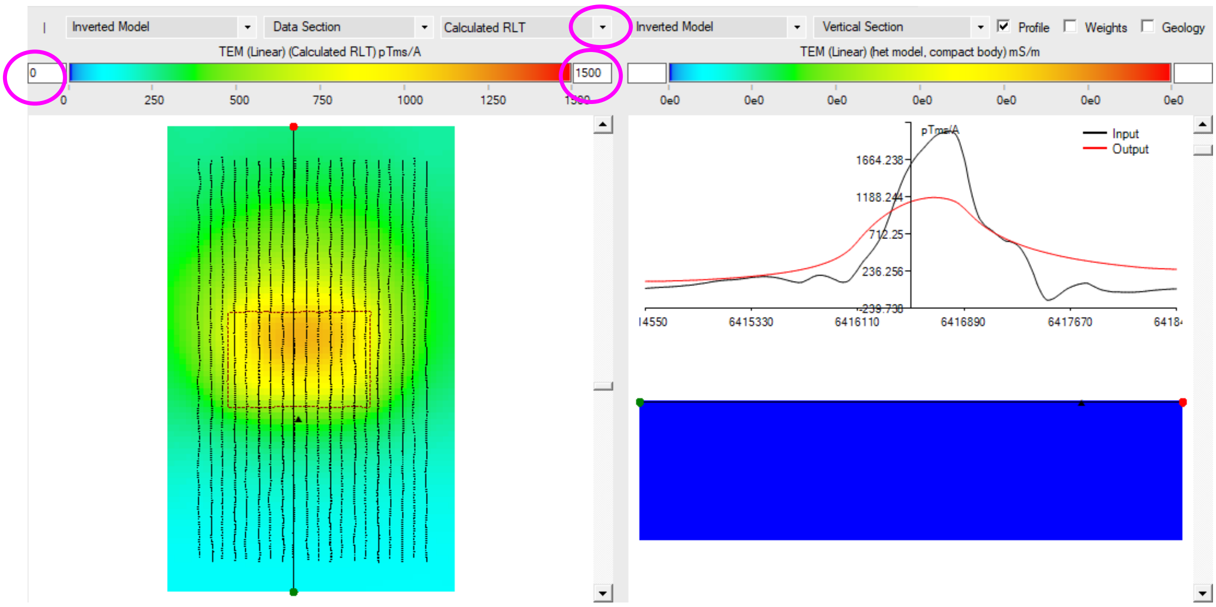
Display the Tx loop using the *Plot/Transmitters (in plan)* option; the loop is traced in red on the LH panel.



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 *Calculated RLT* can be selected for display via the drop down menu above the LH panel. In this case the calculated data is purely the background response from a homogeneous half-space. The colour assignment can be adjusted by editing the minimum and maximum values at the ends of the colour bar.



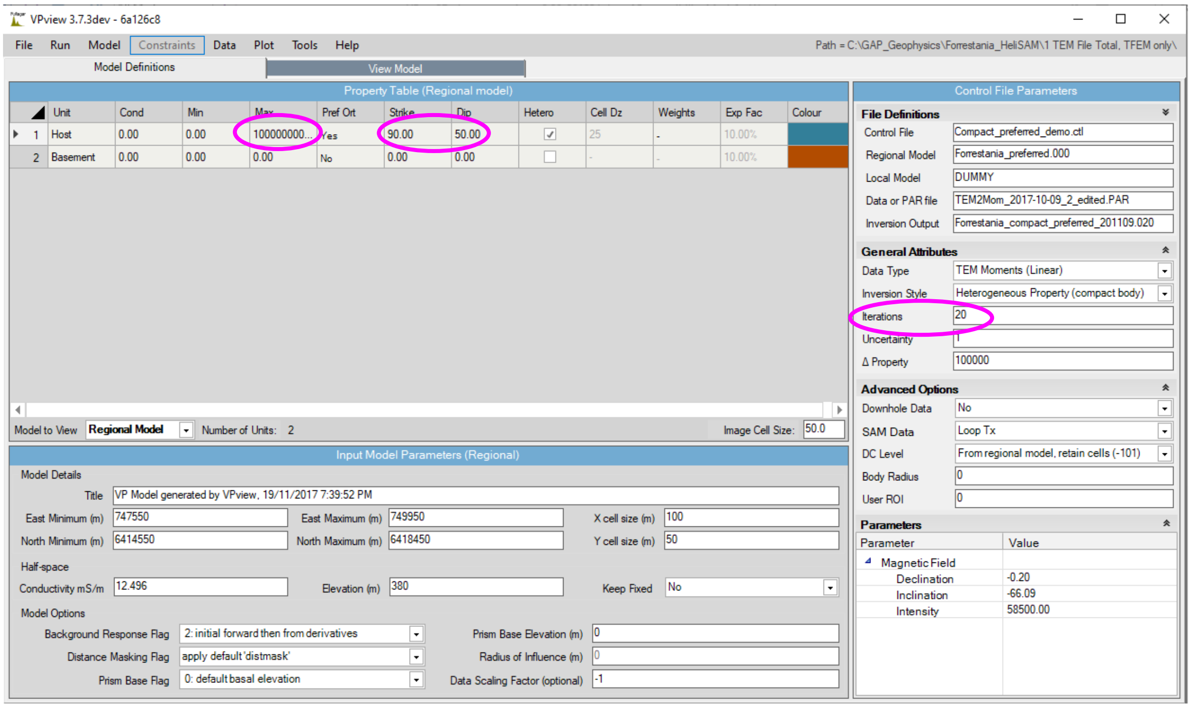
17.6 Running a "total field" TEM inversion

Once satisfied, in light of the forward calculation, that the data and model have been input correctly, prepare to run inversion:

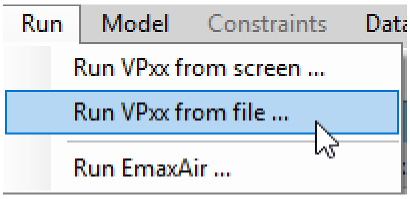
- the output model from the forward calculation becomes the input model for inversion; this obviates the need to re-run the forward calculation since the calculated data are recorded at the end of the model file. [For large models and large data sets, skipping a forward calculation re-run can save appreciable time.]
- 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; here a notional uniform value of 1 pTms/A is assumed.
- set the maximum permitted change in property value per iteration (mS/m). Δ Property is usually very large for compact body inversion; here it is 1 x 10^5 mS/m.
- likewise, the maximum conductivity (upper bound) is normally extremely large in the active unit for compact body inversion; here it is 10^9 mS/m.

From examination of the HeliSAM data, a south dip can be interpreted from the most intense part of the anomaly (in the NW corner of the loop). It is often advantageous to communicate prior knowledge of dip and strike by defining a preferred orientation. In effect VPem3D constrains induced current to flow in planes parallel to the preferred orientation. In this case the preferred strike and dip were defined as 90° and 50° respectively. The preferred strike and dip are read from the model file header (shown below); the values are ignored unless preceded by negative number (-1 in this case):

```
#VPEM3D#
VP Model generated by VPview, 19/11/2017 7:39:52 PM
   747550.000    749950.000    6414550.000    6418450.000
  100.00000     50.00000
          -2           1           1    25.10000
 0.000000E+00  0.000000E+00  0.100000E+10  -1   90   50 Host
 0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00  0.000000E+00 Basement
    380.00      12.496   0   0.124963E+02
  2   0   0       0.00
```



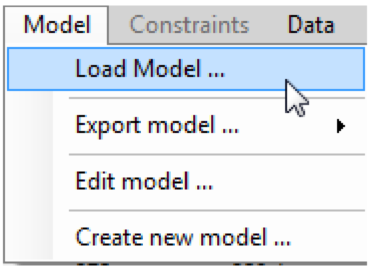
If any fields in the control file have been edited, select "Run VPxx from screen" to start the VPem3D inversion. Otherwise, launch VPem3D via "Run VPxx from file" to use the parameters saved in the *.CTL file.



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.

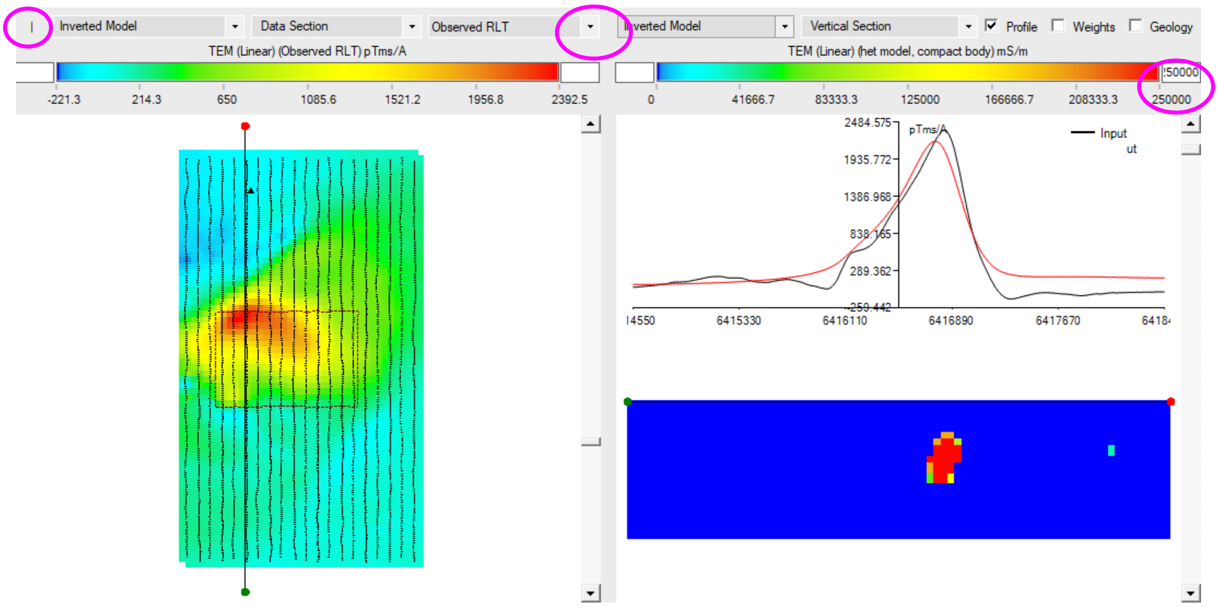
In this case the inversion stalls after 6 iterations. This is not unusual in general for VPem3D, and especially for compact body inversion which is sometimes used simply to define a "volume of interest".

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

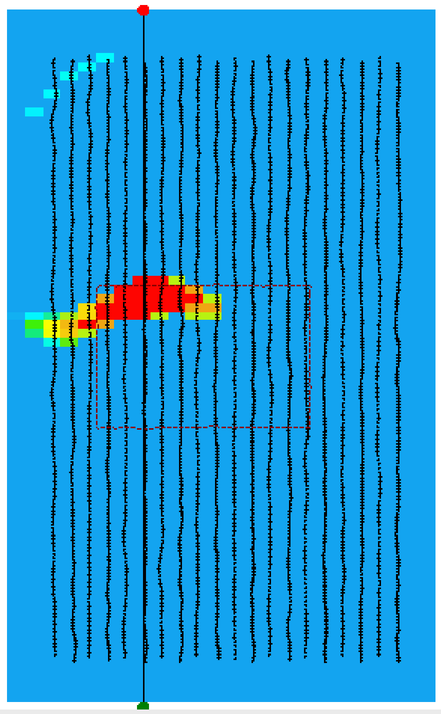


When the model first loads, the ground topography is displayed in the left panel and a vertical section through the centre of the inverted model is displayed in the right panel. The user can toggle between section views of the starting (Initial) and output (Inverted) models using the drop-down menu above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

VPview window toggles 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 on the LH panel.



The compact inversion has defined a steeply dipping conductor, striking approximately E-W, below the NW corner of the Tx loop. Its depth to top in the section displayed above is about 220m. The plan below is a slice through the model at an elevation of -57.5m; the ground surface is at RL ~380m.



Some details of the compact inversion are recorded in the CBN file, including the coordinates of the "seed" cell for each iteration.

#LIXCBN,	XSEED,	YSEED,	ZSEED,	RAD,	NKEEP,	IEDGE,	NCMAX,	ITER,	RMS,	CHI2
1088	748300.00	6416825.00	11.03	-999.00	56	0	125	1	0.301073D+03	0.906198D+05
1088	748300.00	6416825.00	-50.86	-999.00	72	0	125	2	0.263696D+03	0.695161D+05
1089	748400.00	6416825.00	-50.86	-999.00	105	0	125	3	0.229468D+03	0.526409D+05
1012	747900.00	6416675.00	11.03	-999.00	113	0	125	4	0.196584D+03	0.386346D+05
1614	748100.00	6417925.00	11.03	-999.00	51	0	125	5	0.180639D+03	0.326215D+05
1614	748100.00	6417925.00	11.03	-999.00	29	0	250	6	0.178124D+03	0.317194D+05