Tensor IP Data Processing
Program TIP v2.00

December 18, 2006

Introduction

Program TIP processes sets of two-component (Ex,Ey) data generated by one to four transmitter-antenna orientations and produces tensor and vector apparent resistivity and IP phase. Data sets with only one transmitter orientation are processed for vector results only. TIP's apparent resistivity calculations will include the effects of down-hole transmitter electrodes, but are currently limited to ground surface receiver locations. TIP assumes a flat, uniform resistivity half-space to calculate apparent resistivities. TIP reads *.mde, *.avg , *.stn and *.txc files and writes *.log, *_cmp.csv, *_vt?.csv and *_tip.csv files. *.log files hold a copy of screen output, so that TIP.exe can be run from a batch file with later review of the *.log file to see how things went. Electric field components are saved in *_cmp.csv files. One *_vt?.csv file is produced for each transmitter bipole. A *_tip.csv file will be written if there are data for two or more transmitters. Sample files tipdemo1.* are distributed with TIP for verification of correct program operation and to provide file-format examples.

Input Files

Processing control, *.mde files:

TIP looks for an optional *.mde file with the same file-name stem as the *.avg file. *.mde files can include comment lines flagged by a ", !, / or | in the first column. Lines with processing control keywords start with a $ and have the general form "$program_name:keyword=keyword_value". Although the "program_name:" section is optional, including it names the program which should use that keyword setting. TIP.exe reads keywords that are not preceded by a program name and colon or that are preceded by "TIP:" and it ignores keywords preceded by program names other than "TIP".

*.mde file keywords recognized by TIP include:
Line.Name = text string line name or number (up to 16 characters)
Auto = yes for batch file operation without stops for interactive verification of parameters.
= no for normal operation with TIP asking questions about parameter values (default).
PhzFlip = yes if SHRED was run with default settings or with /p+ (default).
= no if SHRED was run with the command-line argument /p-.
IPFreq0 = selects values at a single frequency directly from *.avg file. using IPFreq0=0 selects the *.avg file's three-point magnitude and phase values. IPFreq1, IPFreq2, IPFreq3 = if IPFreq0 is not present, IPFreq1, IPFreq2 & IPFreq3 specify frequencies to use for quadratic extrapolation of Ex and Ey to 0 hertz (default=0.125,0.375,0.625). If IPFreq0 is present, IPFreq1, IPFreq2 & IPFreq3 are not used.
ReIm3Pnt= if yes and IPFreq0 not present, TIP does 3-point extrapolation using Re(E) and Im(E)
= if no and IPFreq0 not present, TIP does 3-point extrapolation using |E| and phase(E)
IPAvg = Arithmetic for arithmetic average of tensor IP phase (default).
= Geometric for geometric average of tensor IP phase.
Unit.Length = length units (default=m, ft).
TxcFile = name of file holding Tx electrode coordinates (default= same file-name stem as *.avg).
StnFile = name of file holding station location coordinates (default= same file-name stem as *.avg).

TIP.exe updates the *.mde file with current TIP keyword records, so that after running TIP once in interactive mode to set processing parameters, you will get the same parameter values if the data are reprocessed. TIP processing control keywords in *.mde files are a written record of processing parameter values and with auto=yes, allows for batch-file control of data processing.

Vector and tensor field data, *.avg files:

Two-component Tensor IP data (Ex,Ey) are collected by the GDP CR program and processed with DATPRO SHRED and HEMAVG programs to generate *.avg files for TIP. Ex and Ey data should be collected with a consistent right-handed coordinate system with positive Ex 90 degrees clockwise of positive Ey in map view (z positive up). Receiver dipoles may be rotated relative to grid north from one station to the next. An optional fifth column in *.stn files specifies receiver Ey azimuths for each station.

Transmitters are identified by a numeric label in the GDP CR program. Use integer labels between 0 and 99 to identify transmitter antennas. TIP segregates vector IP data by transmitter number and stores VIP results in separate files named using the integer transmitter label.

SHRED reformats GDP files into a form suitable for Zonge data processing programs. By default SHRED multiplies IP phase values collected with the GDP CR program by -1, to get IP values consistent with IP sign conventions. If SHRED is run with the /p- command-line argument, phase values are not multiplied by -1. TIP looks for a "PhzFlip" keyword in the *.mde file. The default PhzFlip=yes is consistent with SHRED /p+. PhzFlip=no is consistent with SHRED /p-. If SHRED was used with the /p- command-line argument, set PhzFlip=no in the *.mde file.

Average data with using the HEMAVG mode CALC=Real/Imag so that measurements with phases near +/-pi are not averaged to a phase of 0. The HEMAVG mode CALC=Real/Imag averages data using Real and Imaginary components rather than Magnitude and Phase.

A HEMAVG v7.63 *.avg file includes the data columns titled: "Skp", "Tx", "Rx", "Freq", "Cmp", "Magnitude", "Phase", %Mag and SPhz. HEMAVG v7.65 replaced Magnitude values in volts/(amp*pi/4) with an Amplitude column (volts) and Current (amps*pi/4). A CRAVG *.avg file may be run through TIP by editing the "Resistivity" column title to "Magnitude". Refer to HEMAVG documentation for a detailed description of *.avg file formats.

All HEMAVG *.avg files require that file "Magnitude" or "Amplitude" values be normalized by dipole length to get electric field values in V/m. The *.avg file $ASPACE mode is used for normalization. $ASPACE mode values are assumed to be in metres, unless the line has a trailing "ft" to indicate a length in feet. TIP.exe will handle *.avg file mode lines like $ASPACE=500ft correctly.

Transmitter electrode coordinates, *.txc files:

Locations of transmitter antenna endpoints are stored as comma-separated values in *.txc files. The first *.txc file line should hold the column labels TxID, East+, North+, Depth+, East-, North-, and Depth-. Comment lines with a leading '\', '/', '"' or '!' character may be placed anywhere in the files and are ignored by TIP. Every line beginning with a numeric value is assumed to hold comma separated numeric data. Each *.txc-file numeric-data line describes one transmitter bipole with an integer label and six endpoint electrode coordinates. Numerical data are expected for TxID, East+, North+, Depth+, East-, North-, and Depth- values. Coordinates (East+,North+,Depth+) should be the positive end of the transmitter bipole and coordinates (East-, North-, Depth-) should locate the negative end. Coordinates should be in the same length units used for *.stn file coordinates, and specified in the *.mde file. Depths = 0 if transmitter electrodes are on the ground's surface and should have positive depth values if Tx electrodes are down-hole. Coordinates for up to four transmit bipoles may be included, each on a separate line. *.txc file TxID values are expected to correspond to *.avg file "Tx" values. TxID values do not have to be in order in a *.txc file. A four-line file could hold coordinates for TxID 1, 5, 3 and 9.

Note that Zonge data processing and modeling programs store station numbers and grid coordinates as single precision numbers with six to seven significant figures. Complete UTM coordinates can quite long and using all of the leading digits can cause truncation of important trailing digits within the computer programs. Subtract a constant from very large coordinate values so that locations can be represented precisely with six significant figures.

Apparent resistivity calculations are performed by converting transmitter bipole and station coordinates to metres with tip.exe, if required. Units of "m" or "ft" are read from the *.mde mode $units and verified in tip's interactive dialog. If no unit is given in mode $units, metres are assumed by default.

*.txc files should have the following columns:

1: TxID = numerical label for each transmitter, matching entries used in the GDP.
2: East+ = grid-east coordinate of positive Tx electrode (length units).
3: North+ = grid-north coordinate of positive Tx electrode (length units).
4: Depth+ = depth of positive Tx electrode (length units).
5: East - = grid-east coordinate of negative Tx electrode (length units).
6: North - = grid-north coordinate of negative Tx electrode (length units).
7: Depth - = depth of positive Tx electrode (length units).

Receiver station coordinates, *.stn files:

Each *.stn file line includes a label and coordinates for one station, with columns for station, grid-east, grid-north, elevation and receiver Ey-dipole azimuth. Lengths are scaled to metres within TIP to allow correct apparent resistivity calculations, but the original length units are restored in output files. The optional column of Ey-azimuth data is an extension to a standard *.stn file. Azimuths are given in degrees clockwise from grid north. Coordinates must be provided for EACH station.

The first *.stn and *.txc file line beginning with an alphabet character is interpreted as a column label line. Comment lines beginning with '\', '/', '"' or '!' character may be placed anywhere in the files and are skipped by TIP. Comment lines allow free-form annotation of data files.

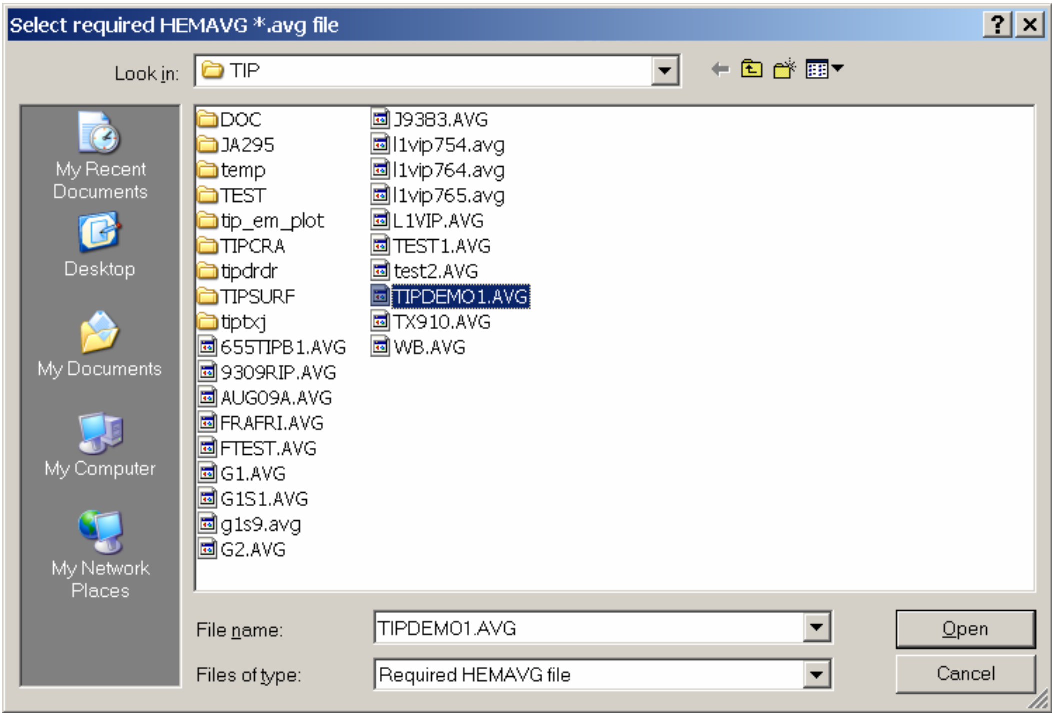
*.stn files should use the scaled and shifted client station numbers defined by modes Stn.GdpBeg, Stn.GdpInc, Stn.Beg & Stn.Inc (equivalent legacy keywords are STNLO, STNDELT, LBLFRST & LBLDELT). In the absence of Stn.Beg and Stn.Inc modes, client station numbers are the same as GDP station numbers.

Tensor IP *.stn files should have the following columns:

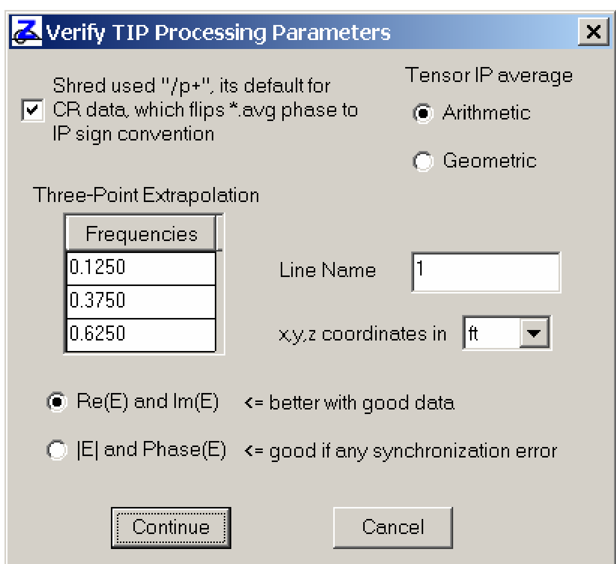
1: Station = numerical label for each station (client station numbers).
2: East = grid-east station coordinate (length units).
3: North = grid-north station coordinate (length units).
4: Elevation = elevation (length units).
5: EyAzimuth = rotation of receiver dipoles relative to grid coordinate system (deg cw from grid N).

General flow of the TIP program:

1) Get *.avg file name from command line or from an open file dialog.



2) Read processing control values from an optional *.mde file.



3) Verify processing control information if auto=no.

If CR data in a GDP *.raw file are processed by SHRED.exe using default settings, phase values are automatically flipped from the EM to the IP sign convention. If that is the case, mark the "Shred used '/p+'" check-box in the upper left corner of TIP's "Verify TIP Processing Parameters" dialog. If SHRED is run with the command-line argument "\p-", it will not flip CR data phase values to the IP sign convention and the "Shred used '/p+'" dialog check box should be unmarked.

You can select between Arithmetic" or "Geometric" averaging for average tensor IP phase in the upper right corner of the "Verify TIP Processing Parameters" dialog. Arithmetic averaging is the default, but geometric averaging may be appropriate if there are very large maximum tensor IP values.

Frequencies to use for E-field extrapolation to 0 hertz are specified in the field labeled "Three-Point Extrapolation". If only one frequency is entered, data for that single frequency will be used without extrapolation. Three frequencies are usually entered to reduce inductive EM effects with three-point extrapolation to 0 hertz. By default the first three harmonics of 1/8 hertz are used. If signals are weak, the field crew may collect data with 0.125, 0.25 and 1 hertz transmitter frequencies and 0.125, 0.25, 1.0 can be entered into the "Three-Point Extrapolation" field to use the least-noisy, fundamental-frequency data for extrapolation.

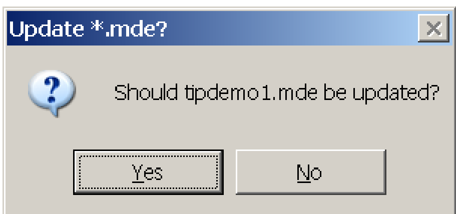
If you wish to used the existing decoupled values already in the input *.avg file, delete the values in rows two and three of the Three-Point Extrapolation field and enter 0.0 in row 1. TIP.exe will then use values from the frequency = 0 rows in the *.avg files "as is".

With clean data, extrapolating Real(E) and Imag(E) values to 0 hertz works slightly better than extrapolation of Magnitude(E) and Phase(E). If there is any synchronization error, extrapolating Magnitude(E) and Phase(E) is best as it corrects for synchronization error exactly.

"Verify TIP Processing Parameters" shows x,y,z coordinate length units, either m or ft. The same length units should be used to specify both transmitter electrode and receiver station positions.

After verifying parameter values, click on the **OK** button to process the data or select **Cancel** to stop tip.exe processing.

4) After processing parameters are verified, TIP will update the *.mde file with current parameter values. If a *.mde files does not exist, tip will create one. If a *.mde files does already exist, tip will request permission to update it.



Select Yes to update the *.mde file or No to skip the update.

5) Read transmitter coordinates from *.txc file.

6) Read electric-field values from a HEMAVG *.avg file.

7) Read receiver station coordinates from *.stn file.

8) Loop through stations.

Recover (x,y,z) station coordinates and Ey-azimuth. Rotate measured (Ex,Ey) from measurement to geographic components.

Calculate apparent resistivity and IP phase tensors using data from one to four transmitter bipoles.

Write rotated E-field component values to *_CMP.csv file.

Calculate minimum, maximum and average vector apparent resistivity and IP phase from tensors.

Calculate azimuth of Real(E) vectors associated with minimum and maximum apparent resistivity and Imag(E) vectors associated with minimum and maximum IP phase.

Estimate error in average vector apparent resistivity and IP phase by repeating calculations many times with gaussian errors added to measured electric-field values.

Write tensor results for current station to *_TIP.csv file.

Loop through transmitter bipoles.

> Calculate vector apparent resistivity and IP phase.
>
> Calculate azimuth Real(E) and Imag(E).
>
> Estimate error in vector apparent resistivity and IP phase by repeating calculations many times with Gaussian errors added to measured electric-field values.
>
> Write vector results for current station and transmitter to *_VT?.csv file.

Output Files

TIP output is saved in tabular ASCII files with column labels and comma-separated values. Tensor data are written to a *_tip.csv file and vector data for one to four transmitters are saved in *_vt1.csv, ..., *_vt4.csv files. Station coordinates are given in the length units specified by the *.mde mode $ Unit.Lenth (default=m). Apparent resistivities are given in ohm-m, apparent resistivity relative error in percent, IP phase is given in mrad, phase error in mrad, and azimuths are given in degrees clockwise from grid north. Additional columns for use by the Surfer program save log10(apparent resistivity) in units of log10(ohm-m) and angles = -azimuth in degrees counterclockwise from grid north.

Vector IP data, *_vt?.csv files:

One *vt?.csv file is generated for each transmitter bipole orientation present in the data set, where "?" is replaced by the transmitter ID number. Vector apparent resistivities are calculated by dividing electric-field vector amplitude by calculated half-space-current vector amplitude. Electric-field and half-space-current vectors are not necessarily collinear, but their relative amplitude or lengths are controlled by the ground's resistivity and electrical structure. Vector IP phase is based on the relative amplitudes or lengths of the in-phase and out-of-phase electric field vectors. Again, in- and out-of-phase field vectors are usually not collinear. Vector apparent resistivities are associated with the azimuth of the in-phase electric field and vector IP phase are associated with the azimuth of the out-of-phase electric field in *vt?.csv files.

Vector IP data are written to *_vt?.csv files with the following columns:

Station	= numerical label for each station.
Line	= line number
Easting	= grid-east station coordinate (m, ft).
Northing	= grid-north station coordinate (m, ft).
Elevation	= elevation (m, ft).
VecRes	= vector apparent resistivity = |E|/|J| (ohm-m).
VecResErr	= estimate of apparent resistivity relative error (%).
VecResAz	= azimuth of Real(E) (degrees cw from grid N).
VecPhz	= vector IP phase = 1000*arctan(|Im(E)|/|Re(E)|) (mrad).
VecPhzErr	= estimate of vector IP phase error (mrad).
VecPhzAz	= azimuth of Imag(E) (degrees cw from grid N).
Log10VecRes	= log10(vector apparent resistivity) for contour gridding.
VecResAngle	= negative of Real(E) azimuth for rotating posted symbols (deg ccw from N).
VecPhzAngle	= negative of Imag(E) azimuth for rotating posted symbols (deg ccw from N).
TxJAngle	= negative of half-space current azimuth, included so that half-space current directions can be compared with Re(E) directions. The two vector sets should be nearly parallel if Tx and Rx polarities are consistent.

Tensor IP data, *_tip.csv files:

If data for two or more transmitters is present, TIP will produce a *.tip file. Tensor measurements allow the generalization of vector apparent resistivity and phase to include all possible transmitter dipole orientations. An apparent resistivity tensor is used internally within TIP to predict the minimum, maximum and geometric average vector apparent resistivities that would be produced by sweeping the source field through all possible orientations. Similarly, an apparent IP phase tensor is used internally to calculate the minimum, maximum and average vector phase produced with all possible in-phase electric-field orientations.

Tensor data are written to *.TIP files with the following columns:

Station	= numerical label for each station.
Line	= line number
Easting	= grid-east station coordinate (m, ft).
Northing	= grid-north station coordinate (m, ft).
Elevation	= elevation (m, ft).
AvgRes	= geometric average of minimum and maximum vector apparent resistivity = |E|/|J| (ohm-m).
AvgResErr	= estimate of average app. resistivity error (percent).
TxLinearity	= values greater than 100 indicate nearly parallel in-phase E-fields, which results in poor estimates of tensor resistivity and phase
AvgPhz	= arithmetic or geometric average of min and max vector IP phase (mrad).
AvgPhzErr	= estimate of average IP phase error (mrad).
MinRes	= minimum possible vector apparent resistivity (ohm-m).
MinResJAz	= currrent azimuth at minimum apparent resistivity (deg cw from grid N).
MinResEAz	= Real(E) azimuth at with minimum apparent resistivity (deg cw from grid N).
MaxRes	= maximum possible vector apparent resistivity (ohm-m).
MaxResJAz	= current azimuth at maximum apparent resistivity (deg cw from grid N).
MaxResEAz	= Real(E) azimuth at maximum apparent resistivity (deg cw from grid N).
RBeta	= beta angle from apparent resistivity tensor, equivalent to skew (degrees).
MinPhz	= minimum possible vector IP phase (mrad).
MinPReEAz	= Real(E) azimuth associated with minimum IP phase (deg cw from grid N).
MinPImEAz	= Imag(E) azimuth associated with minimum IP phase (deg cw from grid N).
MaxPhz	= maximum possible vector IP phase (mrad).
MaxPReEAz	= Real(E) azimuth associated with maximum IP phase (deg cw from grid N).
MaxPImEAz	= Imag(E) azimuth associated with maximum IP phase (deg cw from grid N).
PBeta	= beta angle from phase tensor, equivalent to skew (degrees).
Log10AvgRes	= log10(average app resistivity) used for contour gridding (log10(ohm-m).
Log10MinRes	= log10(average min resistivity) (log10(ohm-m).
Log10MaxRes	= log10(average max resistivity) (log10(ohm-m).
MinResJAngle	= negative of current azimuth at minimum vector apparent resistivity, used to rotate posted symbols in vector plots (degrees ccw from grid N).
MinResEAngle	= -Real(E) azimuth at minimum vector apparent resistivity (deg ccw from N).
MaxResJAngle	= -current azimuth at maximum apparent resistivity (deg ccw from grid N).
MaxResEAngle	= -Real(E) azimuth at maximum apparent resistivity (deg ccw from grid N).
MinPReEAngle	= -Real(E) azimuth at minimum IP phase (degrees ccw from grid N).
MinPImEAngle	= -Imag(E) azimuth at minimum IP phase (degrees ccw from grid N).
MaxPReEAngle	= -Real(E) azimuth at maximum IP phase (degrees ccw from grid N).
MaxPImEAngle	= -Imag(E) azimuth at maximum IP phase (degrees ccw from grid N).

Electric-Field Component data, *_cmp.csv files:

One *_cmp.csv file is generated for each input data set with data sorted by Tx number, station number, and frequency. Electric field magnitudes are given in nV/Am and phase is in mrad. Component data are written to a *_cmp.csv file with the following columns:

Station	= numerical label for each station.
Line	= line number
Easting	= grid-east station coordinate (m, ft).
Northing	= grid-north station coordinate (m, ft).
Elevation	= elevation (m, ft).
Tx	= Tx ID number
Frequency	= frequency, 0 = 3-point decoupled (hertz)
|Ex|	= Ex magnitude (nV/Am)
Phase(Ex)	= Ex phase (mrad)
Real(Ex)	= in-phase Ex (nV/Am)
Imag(Ex)	= out-of-phase Ex (nV/Am)
|Ey|	= Ey magnitude (nV/Am)
Phase(Ey)	= Ey phase (mrad)
Real(Ey)	= in-phase Ey (nV/Am)
Imag(Ey)	= out-of-phase Ey (nV/Am)
|Real(Evec)|	= $\mathrm{sqrt}(\mathrm{Real}(Ex)^2 + \mathrm{Real}(Ey)^2)$ (nV/Am)
|Imag(Evec)|	= $\mathrm{sqrt}(\mathrm{Imag}(Ex)^2 + \mathrm{Imag}(Ey)^2)$ (nV/Am)
|Evec|	= $\mathrm{sqrt}(\lvert\mathrm{Real}(Evec)\rvert^2 + \lvert\mathrm{Imag}(Evec)\rvert^2)$ (nV/Am)
Phase(Evec)	= 1000*atan(|Imag(Evec)|/ |Real(Evec)|) (mrad)

Tensor IP Theory

Tensor IP processing is derived from a paper by Bibby and Hohmann (1993). Bibby and Hohmann's paper describes tensor resistivity based on modeling and on exploration in New Zealand for geothermal sources. Our primary extension to the Bibby and Hohmann paper is to use tensor complex resistivities based on both magnitude and phase data, rather than tensor resistivities based only on magnitude values. Bibby and Hohmann's equations are used in TIP with magnitude and phase information represented as complex numbers.

Tensor resistivity and IP requires two or more sets of orthogonal electric-field measurements at each station, one set for each transmitter bipole orientation. In isotropic rocks, the electric-field vector, $\mathbf{E}$, and the source current, $\mathbf{J}$, are parallel, with complex apparent resistivities providing a convenient way to represent the magnitude and phase shift of the electric field. In general however, rocks are anisotropic and $\mathbf{E}$ is not parallel to $\mathbf{J}$, requiring a tensor apparent resistivity:

$$\mathbf{E} = \overset{=}{\rho} \cdot \mathbf{J} \quad \text{or} \quad \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \rho_{xx} & \rho_{xy} \\ \rho_{yx} & \rho_{yy} \end{bmatrix} \cdot \begin{bmatrix} J_x \\ J_y \end{bmatrix} \qquad \text{(after B\&H eqn 3)} \qquad (1)$$

where $\mathbf{E}$ is the complex electric field vector (v / m),

$\mathbf{J}$ is the assumed uniform - half - space current distribution (amp) and

$\overset{=}{\rho}$ is a complex apparent resistivity tensor (ohm - m).

The source-current vector, $\mathbf{J}$, is calculated using an equation for the current distribution around a transmitting bipole on the surface of an isotropic half-space:

$$J = \left(\frac{I}{2\pi}\right) \cdot \left(\frac{\mathbf{r}_a}{|\mathbf{r}_a|^3} - \frac{\mathbf{r}_b}{|\mathbf{r}_b|^3}\right) \qquad \text{(after B \& H eqn 1)} \qquad (2)$$

where $\mathbf{r}_a$ is the vector from the positive end of the transmitting dipole to the receiver site (m),

$\mathbf{r}_b$ is the vector from the negative end of the transmitting dipole to the receiver site (m) and

I is the transmitter current (amp).

Using a current vector based on magnetic field measurements rather than a theoretical isotropic-half-space vector would improve the accuracy of TIP apparent resistivity calculations. Normalizing electric field measurements by magnetic field values is equivalent to using low-frequency CSAMT measurements with a controlled-source apparent resistivity algorithm rather than Cagniard apparent resistivity.

Solving for the four unknown elements of a tensor ρ requires two or more measurements of $\mathbf{E}$, with a different orientation of $\mathbf{J}$ for each set. Combining these measurements yields four or more equations and four unknowns, which can be solved for elements of ρ:

$$E_{x1} = \rho_{xx} \cdot J_{x1} + \rho_{xy} \cdot J_{y1}$$
$$E_{x2} = \rho_{xx} \cdot J_{x2} + \rho_{xy} \cdot J_{y2} \quad (3)$$
$$E_{y1} = \rho_{yx} \cdot J_{x1} + \rho_{yy} \cdot J_{y1}$$
$$E_{y2} = \rho_{yx} \cdot J_{x2} + \rho_{yy} \cdot J_{y2}$$

therefore

$$\rho_{xx} = \left(E_{x1} \cdot J_{y2} - E_{x2} \cdot J_{y1}\right) / \left(J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1}\right)$$
$$\rho_{xy} = \left(J_{x1} \cdot E_{x2} - J_{x2} \cdot E_{x1}\right) / \left(J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1}\right) \quad (4)$$
$$\rho_{yx} = \left(E_{y1} \cdot J_{y2} - E_{y2} \cdot J_{y1}\right) / \left(J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1}\right)$$
$$\rho_{yy} = \left(J_{x1} \cdot E_{y2} - J_{x2} \cdot E_{y1}\right) / \left(J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1}\right)$$

Tensor ρ predicts how the electric field will be rotated and scaled for any given orientation of the source current, **J**. For any given source current orientation, **J**(θ), an electric field vector, **E**(θ), can be predicted by **E**(θ) = ρ·**J**(θ), and a resultant scalar apparent resistivity can be calculated:

$$\rho(\theta) = \frac{|E(\theta)|}{|J(\theta)|} \quad \text{(after B\&H eqn 9)} \quad (5)$$

A maximum scalar apparent resistivity, $\rho_{max}(\theta)$, and a minimum scalar apparent resistivity, $\rho_{min}(\theta)$, can be calculated from tensor ρ:

$$\theta = (\alpha - \beta) + \frac{n\pi}{2}, \quad n = 0,1,... \quad (6)$$

$$\text{where } \tan(2\alpha) = \frac{(\rho_{xy} + \rho_{yx})}{(\rho_{xx} - \rho_{yy})} \quad \text{(B\&H eqn 10)}$$

$$\tan(2\beta) = \frac{(\rho_{yx} - \rho_{xy})}{(\rho_{xx} + \rho_{yy})} \quad \text{(B\&H eqn 11)}$$

β reflects the difference in orientation between the **E** and **J** vectors, and is analogous to the skew parameter in MT theory.

Values for ρ_{max} and ρ_{min} are saved in *.TIP files. Azimuths associated with ρ_{max} and ρ_{min} in *.TIP files represent the orientation of the vector **E**(θ), not the source current. Source currents for ρ_{max} and ρ_{min} are perpendicular to each other, but the resultant electric field vectors may not be.

The ratio of maximum and minimum apparent resistivities, ρ_{max}/ρ_{min}, indicates how anisotropic the geology is. An isotropic response will give $\rho_{max}/\rho_{min} = 1$. A geometric average of ρ_{max} and ρ_{min} can be obtained by taking the determinant of the apparent resistivity tensor:

$$\rho_{det} = \sqrt{\rho_{max} \cdot \rho_{min}} = \sqrt{\rho_{xx} \cdot \rho_{yy} - \rho_{yx} \cdot \rho_{xy}} \quad \text{(after B\&H eqn 7)} \quad (7)$$

Determinant apparent resistivities are independent of the choice of transmitter or receiver dipole orientation.

An analogous approach is taken to determine tensor IP results, starting with the relationship

$$\mathrm{Im}(\mathbf{E}) = \overline{\overline{\mathbf{Tphz}}} \cdot \mathrm{Re}(\mathbf{E}) \quad \text{or} \quad \begin{bmatrix} \mathrm{Im}(E_x) \\ \mathrm{Im}(E_y) \end{bmatrix} = \begin{bmatrix} \mathrm{Tphz}_{xx} & \mathrm{Tphz}_{xy} \\ \mathrm{Tphz}_{yx} & \mathrm{Tphz}_{yy} \end{bmatrix} \cdot \begin{bmatrix} \mathrm{Re}(E_x) \\ \mathrm{Re}(E_y) \end{bmatrix} \tag{8}$$

where $\mathrm{Im}(\mathbf{E})$ is the out-of-phase component of the complex electric field vector (v/m),
$\mathrm{Re}(\mathbf{E})$ is the in-phase component of the complex electric field vector (v/m) and
$\overline{\overline{\mathrm{Tphz}}}$ is a tan(IP phase) tensor which relates in- to out-of-phase eletric field components.

For any given orientation of the primary electric field $\mathrm{Re}(\mathbf{E}(\theta))$, an out-of-phase electric field vector, $\mathrm{Im}(\mathbf{E}(\theta))$, can be predicted using the tensor $\mathbf{Tphz}$. The in-phase and out-of-phase electric field vectors are usually not parallel. In-phase electric field values are dominated by the source field (with possible current channeling and distortion by anisotropic rock properties) while out-of-phase values are generated by chargeable rock units, which may have restricted extent.

By convention, the relative amplitudes of in- to out-of-phase electric field measurements are represented as an angle in milliradians, IP phase = ϕ = $1000 \cdot \mathrm{atan}(|\mathrm{Im}(\mathbf{E}(\theta))|/|\mathrm{Re}(\mathbf{E}(\theta))|)$. TIP.exe calculates maximum, minimum and average IP phase values and writes the results to *.TIP files along with the orientation of the out-of-phase electric field associated with maximum and minimum IP values.

TIP.exe estimates errors by repeated calculations of tensor resistivity and IP results using measured values perturbed with random errors. Data perturbations are given a Gaussian distribution with a zero mean and standard deviations based on field measurement repeats. Each run of TIP selects a different set of random perturbations, so error estimate values vary slightly from one run to the next.

Vector IP

Vector IP data processing is loosely based on equations presented in Kennecott (1972). The Kennecott in-house memorandum presents the concept of vector IP and uses terminology particular to Kennecott at that time. We have updated equations from their work and adapted their terminology to our equipment.

The magnitude of a measured electric-field vector normalized by a calculated isotropic half-space current amplitude gives a vector apparent resistivity:

$$\rho_{vec} = \frac{|\mathbf{E}(\theta)|}{|\mathbf{J}(\theta)|} \qquad \text{(after B\&H eqn 9)} \qquad (9)$$

The ratio of out-of-phase, electric-field-vector magnitude to in-phase, electric-field-vector magnitude produces a vector IP phase:

$$\phi_{vec} = 1000 \cdot \text{atan}\left(\frac{\sqrt{\text{Im}(E_x)^2 + \text{Im}(E_y)^2}}{\sqrt{\text{Re}(E_x)^2 + \text{Re}(E_y)^2}} \right) \qquad \text{(mrad)} \qquad (10)$$

The directions of in-phase and out-of-phase electric-field vectors are usually different. In-phase field measurements are dominated by the primary field, while out-of-phase values are generated by the IP response of chargeable rocks.

Point E-field calculation accuracy

Electric field component rotation and TIP's apparent resistivity calculations assume that data values represent electric field components measured with infinitesimally short receiver dipoles, even though VIP and TIP field data are usually collected with L-shaped Rx dipole arrays. The accuracy of point electric field calculations can be made by comparing VIP apparent resistivities using point E-field values with more complete calculations which include finite Rx dipole length and array shape.

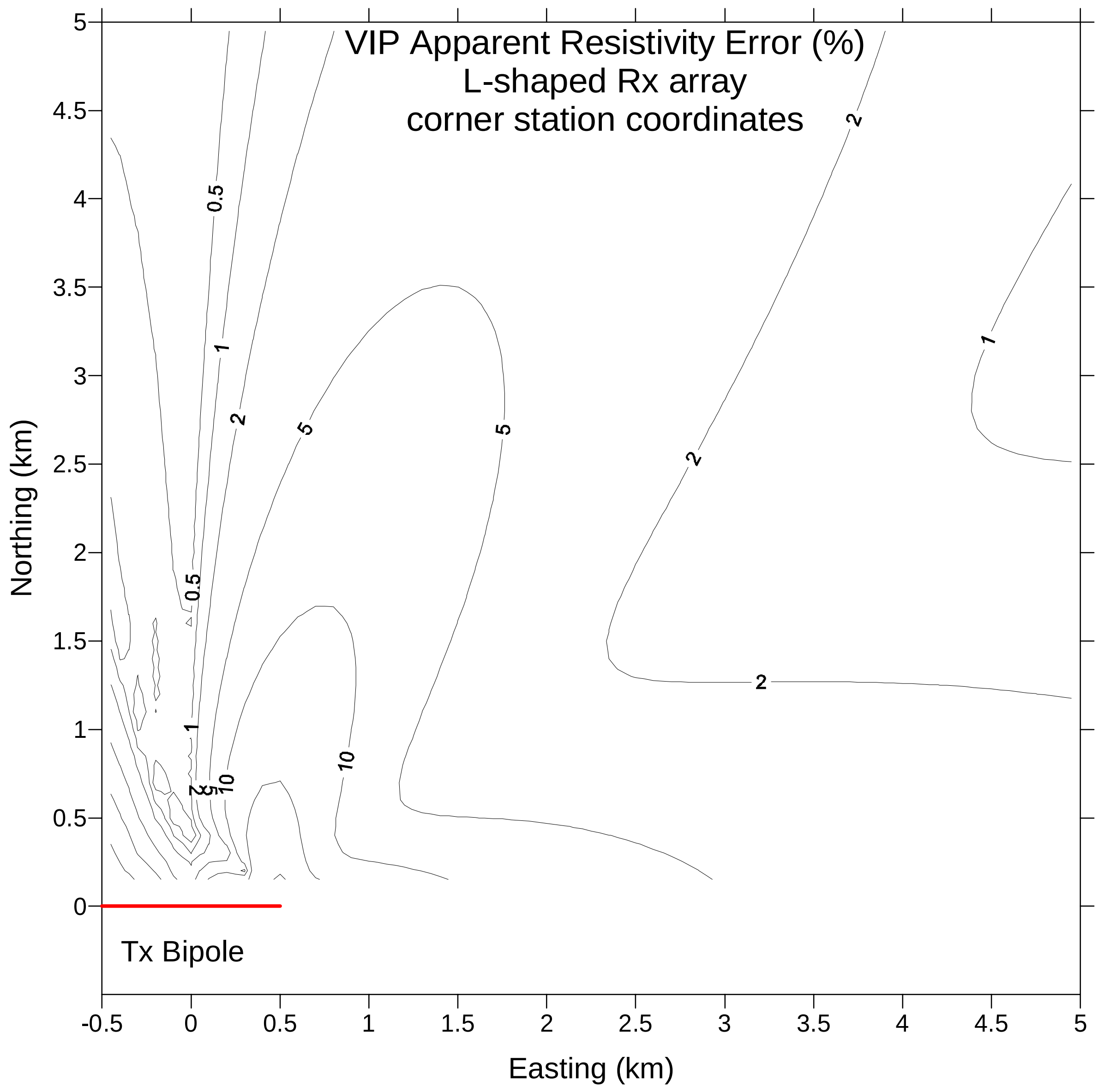


Figure 1: When data are collected with an L-shaped receiver dipole array (in this case 100 m dipoles) and apparent resistivities are calculated assuming point electric-field values at the corner of the L, some error is introduced. As might be expected, point-field apparent resistivity errors are highest close to the transmitter bipole. The median error for this map is 2.5 percent, but there are areas with higher error even for measurements 1 km away from the transmitter bipole. However, even an error of 10% is quite a bit smaller than variation introduced by geologic structure and/or steep topography.

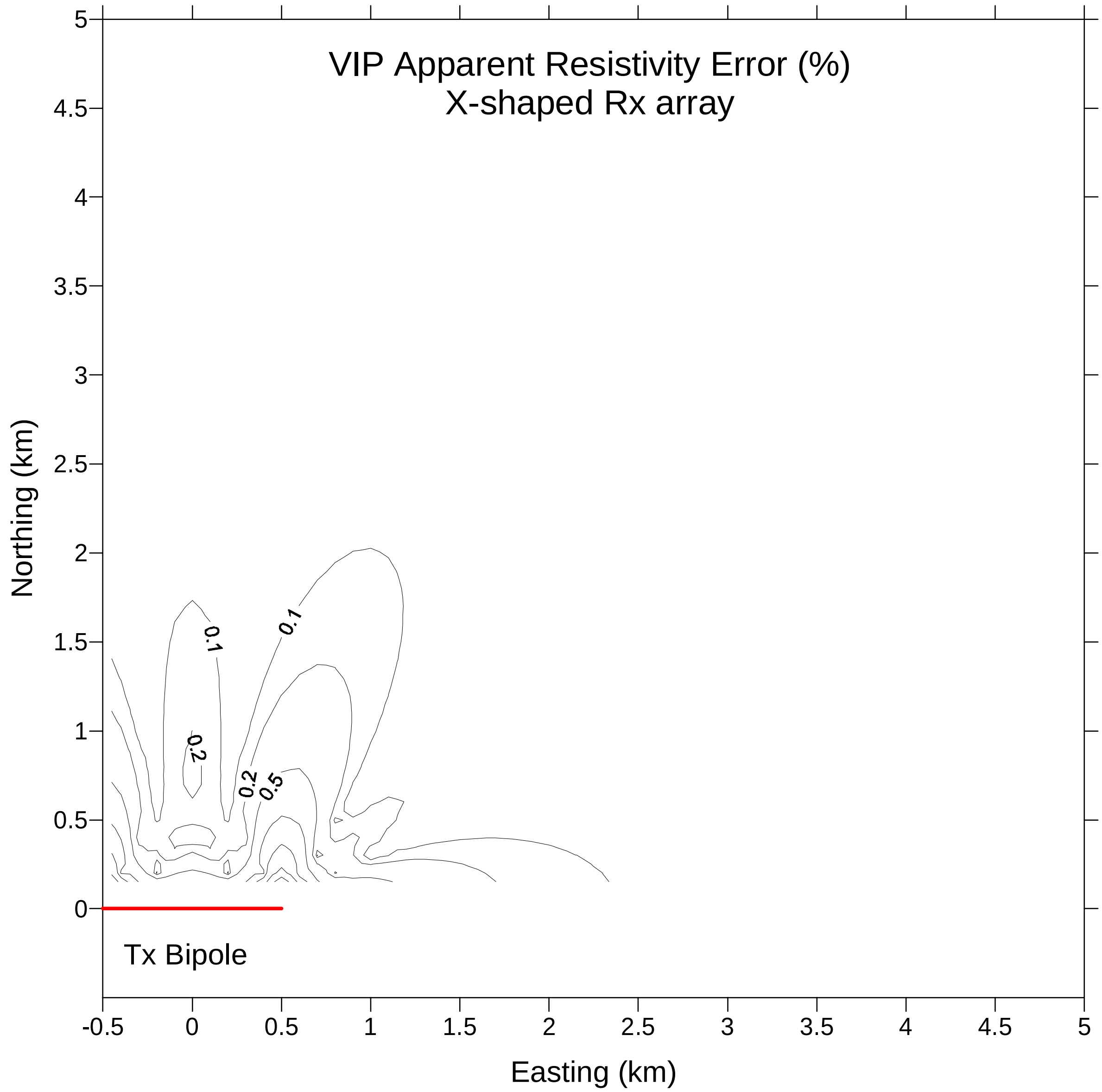


Figure 2: When measurements are made with crossed electric field dipoles, point field apparent resistivity error is reduced significantly. If accurate apparent resistivity information is important, VIP/TIP data can be efficiently supplemented by TEM soundings, resulting in a data set which includes information about resistivity changes versus depth at a relatively small incremental cost in acquisition effort. While the VIP/TIP data are being acquired with an L-shaped array, the crew can be pulling wire to complete a square loop for a coincident loop TEM sounding.

References

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Van Voorhis, G.D., Kennecott Internal Memo, Reconnaissance IP Data Reduction, September 13, 1972.