

Tensor IP Data Processing

Program TIP v1.07

November 15, 1999

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 reads *.MDE, *.AVG, *.STN and *.TXC files and writes *.LOG, *.VT? and *.TIP. *.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. One *.VT? file is produced for each transmitter antenna. A *.TIP file will be written if there is data for two or more transmitters. Sample files TIPDEMO.* 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 have 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”. Including the optional “program_name:” section limits which programs will 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:

- Auto = yes for batch file operation without stops for interactive verification of parameter settings.
= 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 *.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 Ex and Ey to 0 hertz (default=0.125,0.375,0.625).
If IPFreq0 is present, IPFreq1, IPFreq2 & IPFreq3 are not used.
- Relm3Pnt= 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.
- Units = m, km, ft, kft, length units. TIP also reads units from the ASPACE value subscript in *.AVG file (default=m).
- TXCFile = name of file holding Tx electrode coordinates (default= same file-name stem as *.AVG).

TIP.EXE writes keyword records into the *.LOG file, so that after running TIP once in interactive mode to set processing parameters, you can cut the keyword block out of *.LOG and paste it into *.MDE files. Having TIP processing control keywords in *.MDE files provides a written record of processing parameters 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 using grid east for positive x and grid north for positive y. 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 *.AVG file includes the data columns titled: "Skp", "Tx", "Rx", "Freq", "Cmp", "Magnitude", "Phase", %Mag and SPhz. 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.

TIP will ask you to choose an IP phase frequency. Choosing the default 0 hertz will generate tensor results based on three-point 0 hertz data read directly from HEMAVG's *.AVG file. Choosing 0.125 hertz will generate results based on 0.125 hertz data read directly from HEMAVG's *.AVG file.

Transmitter electrode coordinates, *.TXC files:

Locations of transmitter antenna endpoints are stored in *.TXC files. Each *.TXC-file line describes one transmitter dipole with an integer label and four endpoint coordinates. On each line, data are expected for Tx#, XTx1, YTx1, XTx2 and YTx2 values. Coordinates for up to nine transmit bipoles may be included, each on a separate line. The *.AVG file "Tx" value is expected to correspond to a "Tx#" entry in the *.TXC file. Tx# values do not have to be in order. A four line file could hold coordinates for Tx# 1, 5, 3 and 9. Coordinates (XTx1,YTx1) should be the positive end of the transmitter bipole and coordinates (XTx2,YTx2) should locate the negative end.

Note that Zonge data processing and modeling programs store station numbers and grid coordinates as single precision numbers with about six 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, if required. Units of "m", "km", "ft", or "kft" are read from the *.AVG mode ASPACE. If no unit is given in mode ASPACE, metres are assumed by default.

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

- 1: Transmitter number = numerical label for each transmitter matching entries used in the GDP.
- 2: XTx1 = grid-east coordinate of positive Tx electrode (m, km, ft or kft).
- 3: YTx1 = grid-north coordinate of positive Tx electrode (m, km, ft or kft).
- 4: XTx2 = grid-east coordinate of negative Tx electrode (m, km, ft or kft).
- 5: YTx2 = grid-north coordinate of negative Tx electrode (m, km, ft or kft).

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 column of Ey-azimuth data is an extension of a standard *.STN file. Azimuths are given in degrees clockwise from grid north. Coordinates must be provided for EACH station.

*.STN and *.TXC files do not define header lines or titled columns. Comment lines that include a '\', '/', '" or '!' character in the first or second columns are skipped, so that free-form annotation may be included.

*.STN files should use the scaled and shifted client station numbers defined by modes STNLO, STNDELTA, LBLFRST, LBLDELTA. In the absence of LBLFRST and LBLDELTA 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: Grid_E = grid-east station coordinate (m, km, ft or kft).
- 3: Grid_N = grid-north station coordinate (m, km, ft or kft).
- 4: Elev = elevation (m, km, ft or kft).
- 5: RxEyAz = rotation of receiver dipoles relative to grid coordinate system (deg cw from grid N).

General flow of the TIP program:

- Read processing control values from an optional *.MDE file.
- Get processing control information if *.MDE file is not available or if auto=no.
 - 1) You are asked to choose between (1) using single-frequency values “as is” directly from the *.AVG file, (2) using *.AVG values at three frequencies to extrapolate $\text{Re}(E)$ and $\text{Im}(E)$ to 0 hertz or (3) using *.AVG values at three frequencies to extrapolate $|E|$ and $\text{phase}(E)$ to 0 hertz. You are then asked to specify frequency values. Responding to a question by pressing the Enter key selects the default.
 - 2) You are asked to select “Arithmetic” or “Geometric” averaging for average tensor IP phase. Arithmetic averaging is the default. Geometric averaging may be appropriate if there are very large maximum tensor IP values.
 - 3) You are asked if SHRED was run with the /p- command line argument. Press the Enter or N keys to select the default, no response. Press the E key to answer yes.
- Read electric-field values from a HEMAVG *.AVG file.
- Read transmitter coordinates from *.TXC file.
- Read receiver station coordinates from *.STN file.
- Loop through stations.
 - Recover (x,y,z) station coordinates and E_y -azimuth
 - Calculate apparent resistivity and IP phase tensors using data from one to four transmitter bipoles.
 - Calculate minimum, maximum and average vector apparent resistivity and IP phase from tensors.
 - Calculate azimuth of $\text{Real}(E)$ vectors associated with minimum and maximum apparent resistivity and $\text{Imag}(E)$ 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 file.
- Loop through transmitter bipoles.
 - Calculate vector apparent resistivity and IP phase.
 - Calculate azimuth $\text{Real}(E)$ and $\text{Imag}(E)$.
 - 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? file.

Output Files

TIP output is in tabular ASCII files with annotation labeling the content of each column. Tensor data are written to a *.TIP file and vector data for one to four transmitters are saved in *.VT1, ..., *.VT4 files. Station coordinates are given in the units specified by the *.AVG mode ASPACE (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 present $\log_{10}(\text{apparent resistivity})$ in units of $\log_{10}(\text{ohm-m})$ and -azimuth in degrees counterclockwise from grid north.

Vector IP data, *.VT? files:

One *.VT? file is generated for each transmitter bipole orientation present in the data set. “?” is replaced by the transmitter number. Files are given the extension *.V?? for two digit transmitter numbers. Vector apparent resistivities are derived from dividing the length of the measured electric-field vector by the length of the calculated half-space-current vector. Electric-field and half-space-current vectors are not necessarily collinear, but their relative lengths are controlled by the ground's resistivity. Vector IP phase is based on the relative 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? files.

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

- 1: Station = numerical label for each station.
- 2: Grid_E = grid-east station coordinate (m, km, ft or kft).
- 3: Grid_N = grid-north station coordinate (m, km, ft or kft).
- 4: Elev = elevation (m, km, ft or kft).
- 5: VecRes = vector apparent resistivity = $|E|/|J|$ (ohm-m).
- 6: VecResEr = estimate of apparent resistivity relative error (%).
- 7: VecResAz = azimuth of Real(E) (degrees cw from grid N).
- 8: VecPhz = vector IP phase = $1000 \cdot \arctan(|\text{Im}(E)|/|\text{Re}(E)|)$ (mrad).
- 9: VecPhzEr = estimate of vector IP phase error (mrad).
- 10: VecPhzAz = azimuth of Imag(E) (degrees cw from grid N).
- 11: LVecRes = $\log_{10}(\text{vector apparent resistivity})$ for contour gridding.
- 12: -VecResAz = negative of Real(E) azimuth for rotating posted symbols (degrees ccw from grid N).
- 13: -VecPhzAz = negative of Imag(E) azimuth for rotating posted symbols (degrees ccw from grid N).
- 14: -TxJAz = 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.

Tensor IP data, *.TIP 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:

- 1: Station = numerical label for each station.
- 2: Grid_E = grid-east station coordinate (m, km, ft or kft).
- 3: Grid_N = grid-north station coordinate (m, km, ft or kft).
- 4: Elev = elevation (m, km, ft or kft).
- 5: AvgRes = geometric average of minimum and maximum vector apparent resistivity = $|E|/|J|$ (ohm-m).
- 6: AvgResEr = estimate of average app. resistivity error (percent).
- 7: TxLinearity = values greater than 100 indicate nearly parallel in-phase E-fields, which results in poor estimates of tensor resistivity and phase
- 8: AvgPhz = arithmetic or geometric average of min and max vector IP phase (mrad).
- 9: AvgPhzEr = estimate of average IP phase error (mrad).
- 10: MinRes = minimum possible vector apparent resistivity (ohm-m).
- 11: MinResJAz = current azimuth at minimum apparent resistivity (deg cw from grid N).
- 12: MinResEAz = Real(E) azimuth at with minimum apparent resistivity (deg cw from grid N).
- 13: MaxRes = maximum possible vector apparent resistivity (ohm-m).
- 14: MaxResJAz = current azimuth at maximum apparent resistivity (deg cw from grid N).
- 15: MaxResEAz = Real(E) azimuth at maximum apparent resistivity (deg cw from grid N).
- 16: RBeta = beta angle from apparent resistivity tensor, equivalent to skew (degrees).
- 17: MinPhz = minimum possible vector IP phase (mrad).
- 18: MinPReEAz = Real(E) azimuth associated with minimum IP phase (deg cw from grid N).
- 19: MinPlmEAz = Imag(E) azimuth associated with minimum IP phase (deg cw from grid N).
- 20: MaxPhz = maximum possible vector IP phase (mrad).
- 21: MaxPReEAz = Real(E) azimuth associated with maximum IP phase (deg cw from grid N).
- 22: MaxPlmEAz = Imag(E) azimuth associated with maximum IP phase (deg cw from grid N).
- 23: PBeta = beta angle from phase tensor, equivalent to skew (degrees).
- 24: LAvgRes = \log_{10} (average app resistivity) used for contour gridding (\log_{10} (ohm-m)).
- 25: LMinRes = \log_{10} (average min resistivity) (\log_{10} (ohm-m)).
- 26: LMaxRes = \log_{10} (average max resistivity) (\log_{10} (ohm-m)).
- 27: -MinResJAz = negative of current azimuth at minimum vector apparent resistivity, used to rotated posted symbols in vector plots (degrees ccw from grid N).
- 28: -MinResEAz = -Real(E) azimuth at minimum vector apparent resistivity (deg ccw from grid N).
- 29: -MaxResJAz = -current azimuth at maximum apparent resistivity (deg ccw from grid N).
- 30: -MaxResEAz = -Real(E) azimuth at maximum apparent resistivity (deg ccw from grid N).
- 31: -MinPReEAz = -Real(E) azimuth at minimum IP phase (degrees ccw from grid N).
- 32: -MinPlmEAz = -Imag(E) azimuth at minimum IP phase (degrees ccw from grid N).
- 33: -MaxPReEAz = -Real(E) azimuth at maximum IP phase (degrees ccw from grid N).
- 34: -MaxPlmEAz = -Imag(E) azimuth at maximum IP phase (degrees ccw from grid N).

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:

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

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

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

$\underline{\underline{\rho}}$ 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:

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

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 $\underline{\underline{\rho}}$ 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 $\underline{\underline{\rho}}$:

$$\begin{aligned}
E_{x1} &= \rho_{xx} \cdot J_{x1} + \rho_{xy} \cdot J_{y1} \\
E_{x2} &= \rho_{xx} \cdot J_{x2} + \rho_{xy} \cdot J_{y2} \\
E_{y1} &= \rho_{yx} \cdot J_{x1} + \rho_{yy} \cdot J_{y1} \\
E_{y2} &= \rho_{yx} \cdot J_{x2} + \rho_{yy} \cdot J_{y2}
\end{aligned} \tag{3}$$

therefore

$$\begin{aligned}
\rho_{xx} &= (E_{x1} \cdot J_{y2} - E_{x2} \cdot J_{y1}) / (J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1}) \\
\rho_{xy} &= (J_{x1} \cdot E_{x2} - J_{x2} \cdot E_{x1}) / (J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1}) \\
\rho_{yx} &= (E_{y1} \cdot J_{y2} - E_{y2} \cdot J_{y1}) / (J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1}) \\
\rho_{yy} &= (J_{x1} \cdot E_{y2} - J_{x2} \cdot E_{y1}) / (J_{x1} \cdot J_{y2} - J_{x2} \cdot J_{y1})
\end{aligned} \tag{4}$$

Tensor ρ predicts how the electric field will be rotated and scaled for any given orientation of the source current, \mathbf{J} . For any given source current orientation, $\mathbf{J}(\theta)$, an electric field vector, $\mathbf{E}(\theta)$, can be predicted by $\mathbf{E}(\theta) = \rho \cdot \mathbf{J}(\theta)$, and a resultant scalar apparent resistivity can be calculated:

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

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

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

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

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

β reflects the difference in orientation between the \mathbf{E} and \mathbf{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 $\mathbf{E}(\theta)$, 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:

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

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

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

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

For any given orientation of the primary electric field $\text{Re}(\mathbf{E}(\theta))$, an out-of-phase electric field vector, $\text{Im}(\mathbf{E}(\theta))$, can be predicted using the tensor $\overline{\overline{\mathbf{Tphz}}}$. 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 = $\phi = 1000 \cdot \text{atan}(|\text{Im}(\mathbf{E}(\theta))|/|\text{Re}(\mathbf{E}(\theta))|)$. 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:

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

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

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

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.

References

Bibby, H. M. and G. W. Hohmann, Three-dimensional interpretation of multiple-source bipole-dipole resistivity data using the apparent resistivity tensor, *Geophysical Prospecting*, 1993, v41, pp 697-723.

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