Jurnal Natural
Vol.13, No. 1, 2013

IMPORTANCE OF LOCATING STRIKE IN 2D MAGNETOTELLURIC DATA MODELING

Nazli Ismail
Physics Department, Faculty of Mathematic and Natural Science
Syiah Kuala University, Darussalam, Banda Aceh, Indonesia

Abstract. 2D inversion is still believed as the fastest, cheapest, and most reliable method magnetotelluric data interpretation. Traditionally the magnetotelluric data are collected on 2D profile perpendicularly across an assumed geological strike. However there is no guarantee where the chosen strike is exactly or nearly same as true geoelectrical strike. For this purpose, 2D synthetic magnetotelluric impedance data of a simple 2D model were generated along a profile across the model. The data were inverted on various presumed strike in order to study how far the inverted model is deviated when the presumed strike is moved away to the true strike. By the aim, first the data were inverted as measured on 2D profile perpendicularly across true strike in order to see how the inversion works in the ideal case. The data were also inverted as measured on 2D profile perpendicularly across an assumed strike. The presumed strike deviated 60 degrees to the true strike was selected as an example of extreme case. The model inverted from the extreme presumed strike data is compared to the actual one. The inversions on determinant and combined TE and TM modes have been done as well for model resolution comparison.

Keywords: Magnetotelluric method, 2D modeling, strike

INTRODUCTION

Although 3D modeling codes have been introduced recently by many articles [1], 2D inversion is still preferred in magnetotelluric data interpretation. The 2D inversion is still believed as the fastest, cheapest, and most reliable method magnetotelluric data interpretation. In this way, the magnetotelluric data are collected on 2D profile perpendicularly across an assumed geoelectrical strike. The strike is typically chosen prior to data acquisition. There are many natural signatures can be used to choose the strike assumption. The strike can be based on the trend of coastline, known faults, or other regional structures [2]. Therefore, in practice, there is no guarantee the chosen strike is exactly or nearly same as true geoelectrical strike. Of course, there are some methods that can be used to check this presumed geoelectrical strike or dimensionality on the measured data, such as skew value [3] and real induction arrow plots [4]. However, the calculations are done after data collection and processing.

Choosing more realistic geoelectrical strike before data collection is important in 2D modeling of magnetotelluric data. Ideally, the more precision of the strike is chosen the more realistic model is resulted. Based on this argument, 2D synthetic magnetotelluric impedance data of simple 2D model were generated along profile across the model. The data were inverted on various presumed strike in order to study how far the inverted model is deviated when the presumed strike is moved away to the true strike. By the aim, first the data we inverted as measured on 2D profile perpendicularly across true strike in order to see how the inversion works in the ideal case. The data were also inverted as measured on 2D profile perpendicularly across an assumed strike. The presumed strike deviated 60 degrees to the true strike as an example of extreme case was selected. The model inverted from the extreme presumed strike data is compared to the actual one. The inversions on determinant and combined TE and TM modes have been done for comparable.

THEORY OF 2D PLANE-WAVE TRANSFER FUNCTIONS

Magnetotelluric method is done by measuring three magnetic and two horizontal electric components at certain station of studied area. The impedance tensor and tipper vector are estimated from the measuring data. Under plane-wave conditions there exits a unique linear transfer function (the impedance tensor **Z**) between the horizontal electric field (E_x, E_y) and horizontal magnetic field (H_x, H_y) for a given angular frequency (ω) as described by [5]

$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \begin{bmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{bmatrix} \begin{bmatrix} H_x(\omega) \\ H_y(\omega) \end{bmatrix}. \quad (1)$$

The subscript *x* and *y* denote north and east, respectively. The apparent resistivity (ρ_{jk}^{app}) and phase (ϕ_{jk}) of an impedance elements (Z_{jk}), where *jk* is *xy* or *yx*; the first subscript indicates the measurement direction of the electric field and the second subscript indicates the measurement direction of the magnetic field, can be determined with the formulae

$$\rho_{jk}^{app} = \frac{1}{\omega\mu_0}\left|Z_{jk}\right|^2, \quad (2)$$

μ_0 is the permeability of vacuum ($4\pi 10^{-7}$ Vs/Am) and

$$\phi_{jk} = \tan^{-1}\left(\frac{Z_{jk}^{i}}{Z_{jk}^{r}}\right). \quad (3)$$

The subscript *i* and *r* denote the imaginary and real part of the impedance element, respectively.

In 2D modeling, the magnetotelluric data are collected along profile perpendicularly across an assumed geoelectrical strike. 2D model of Earth conductivity distribution in MT method assumes there is a coordinate system in which the conductivity variation is negligible along one axis. This axis is defined as the strike direction. In the strike coordinate system or principal coordinate system, with the x-axis pointing in the strike direction, the horizontal components of the electric field are connected to horizontal components of magnetic field by impedance tensor (**Z**) in simple form

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 0 & Z_{\mathrm{TE}} \\ Z_{\mathrm{TM}} & 0 \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}. \quad (4)$$

We use the subscripts TE and TM instead of *xy* and *yx* as shown in equation (1) to represent transverse electric and transverse magnetic modes, respectively. In the TE mode, the electric fields component is in the strike direction causing the currents to flow in the x-directions. In the TM mode, the magnetic field is in the strike direction and the electric field is perpendicular to the strike. In this mode the current flow is in the y- and z-directions [6].

Beside TE and TM modes we also use determinant mode in the inversion. The determinant of the impedance tensor is rotationally invariant [7]. The determinant impedance for 2D model can be written as

$$\begin{aligned} Z_{DET} &= \left|Z_{DET}\right| \exp\left[i\phi_{DET}\right] = \sqrt{Z_{TE}\left(-Z_{TM}\right)} \\ &= \sqrt{\left|Z_{TE}\right|\left|Z_{TM}\right|}\exp\left[\tfrac{1}{2} i\left(\phi_{TE}+\phi_{TM}\right)\right] \end{aligned} \quad (5)$$

Where the TM phase is defined from the negative of TM impedance to get positive phases for a 1D environment. Transforming to logarithmic variable, i.e., the logarithm of apparent resistivity and the phase, directly gives

$$\log\rho_{DET}^{app} = \tfrac{1}{2}\left(\log\rho_{TE}^{app} + \log\rho_{TM}^{app}\right) \quad (6)$$

$$\phi_{DET} = \tfrac{1}{2}\left(\phi_{TE} + \phi_{TM}\right) \quad (7)$$

The determinant data can be considered as the arithmetic mean of TE and TM mode data.

The theories described above are used in the strike coordinate system (principal coordinate system). In practice the measurement are often performed in a coordinate system other than the strike coordinate system (Figure 1). Assume that φ is the angle between the horizontal axes of measuring system (*x', y'*) and the horizontal axes of the coordinate system (*x, y*). The measured electromagnetic field components (H_x', H_y', E_x', E_y') and the electromagnetic components (H_x, H_y, E_x, E_y) are related as

$$\begin{bmatrix} H_x' \\ H_y' \end{bmatrix} = \mathbf{R}\begin{bmatrix} H_x \\ H_y \end{bmatrix}, \quad (8)$$

$$\begin{bmatrix} E_x' \\ E_y' \end{bmatrix} = \mathbf{R}\begin{bmatrix} E_x \\ E_y \end{bmatrix}. \quad (9)$$

R is the rotation matrix defined by

$$\mathbf{R} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \quad (10)$$

In measuring coordinate system, the horizontal magnetic field components are related to electric field components by equation

$$\begin{bmatrix} E_x' \\ E_y' \end{bmatrix} = \mathbf{Z}' \begin{bmatrix} H_x \\ H_y \end{bmatrix} \qquad (11)$$

Then using equation (5) we find

$$\mathbf{Z} = \mathbf{R}^{\mathrm{T}} \mathbf{Z}' \mathbf{R} \qquad (12)$$

The subscript T denotes transposition. Using equation (12) it follows that the trace of the impedance tensor is invariant to rotation of the coordinate axes. Hence for 2D structure it follows that

$$Z_{xx} + Z_{yy} = Z_{xx}' + Z_{yy}' = 0 . \qquad (13)$$

This is what we have seen in equation (4).

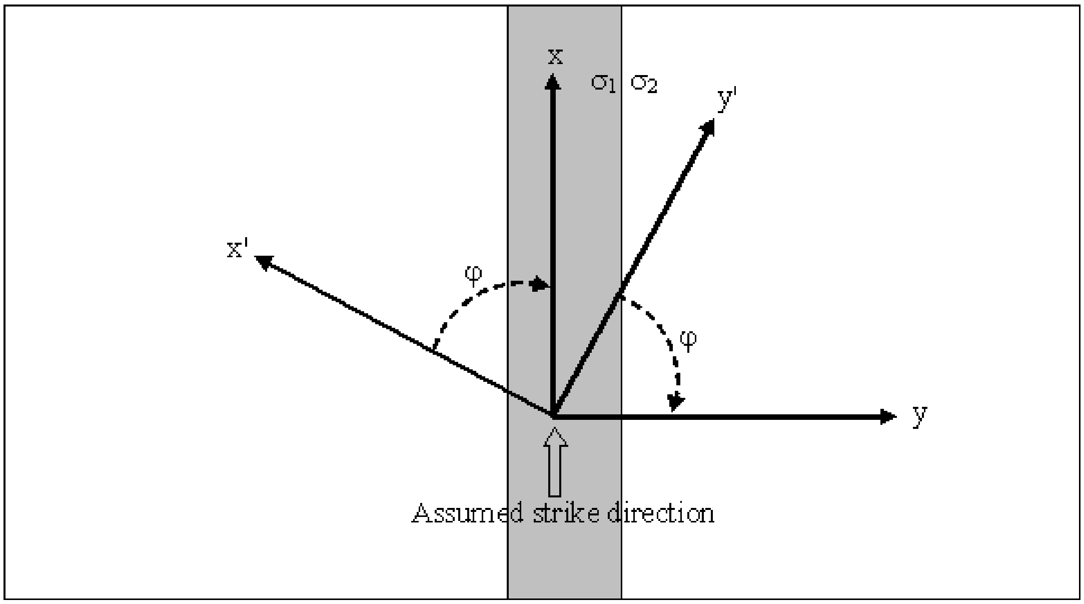

Figure 1. Geometrical representation of measuring and principal coordinate system.

2D MODELS OF DETERMINANT DATA

In order to examine how important choosing of strike direction in 2D inversion, we calculated MT determinant data from 2D synthetic model as shown in figure (2). The model has background 5000 Ωm with anomaly 100 Ωm. The anomaly has 40 m wide and 40 m depth extended along x-direction. The data were “collected” on y-axis across the true strike in x-direction. We use 12 frequencies from 4000 to 181019 Hz and 25 stations with a spacing 20 m. The data were inverted using REBOOC code [8]. The code was modified to allow inversion of determinant data [7] and 2% errors was applied on impedance data in the inversion. The inverted model of determinant data is shown in Figure 2 where 0.95 rms data fit was reached during the inversion. Distribution of “observed” and calculated data are shown in Figure 3.

The inverted model seemly agrees with the original model. Wide of the anomaly is almost same as the original model, but the inversion cannot resolve well the depth of anomaly. The conductor located at the shallow part of the model reduces penetration depth of the data to the deeper part. Therefore the depth of the inverted anomaly is deeper than the original model.

Resistivities of the “box” of the inverted model are generally higher than the original model. This is probably caused by effect of smoothing. The determinant data are also can be considered as average of TE and TM modes. The data provide a model that can be view as some mean of the TE and TM models. Usually, TE data are sensitive to conductor and TM data are sensitive to resistor. Therefore the determinant data can resolve well both conductor and resistor, but it does not as well as TE and TM data alone done for conductor and resistor, respectively.

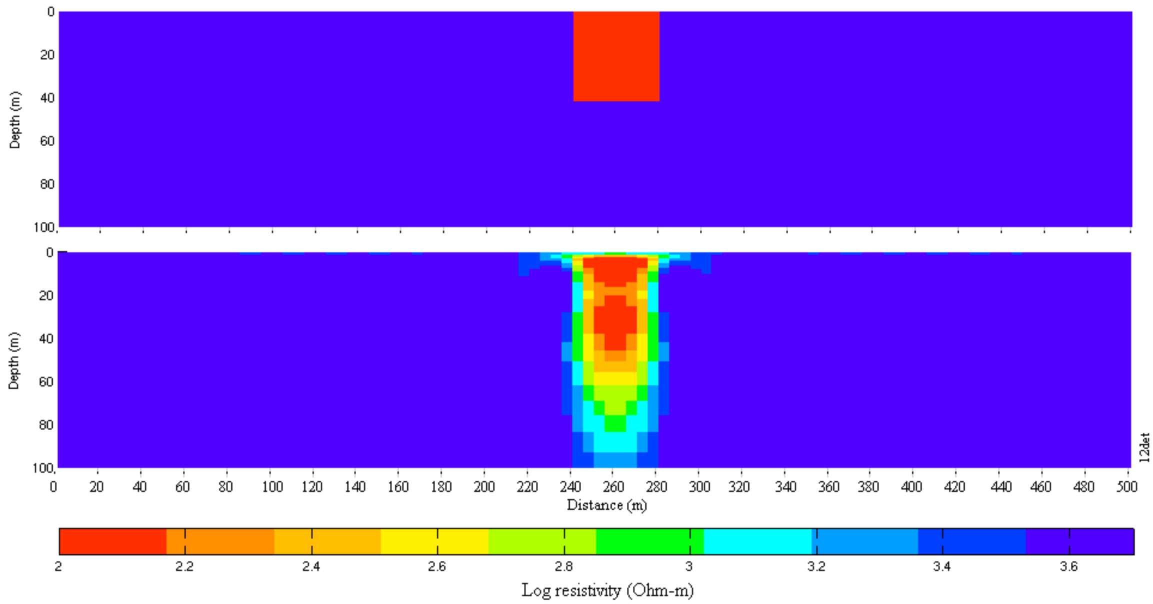

Figure 2 Synthetic model (above) and inverted model (below) of determinant data in ideal case.

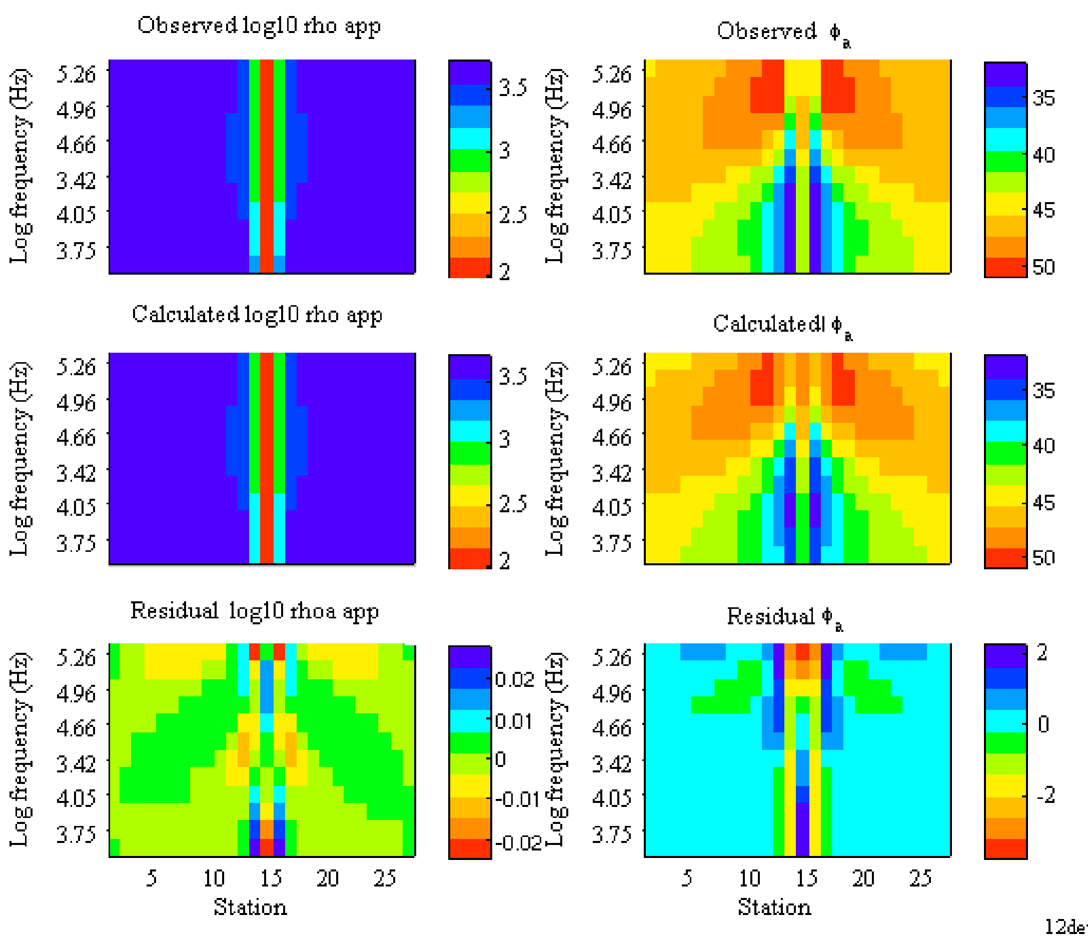

Figure 3 Distributions of observed and calculated residual of determinant data; apparent resistivity (left) and phase (right).

Now let we look what happen when the choosing of strike is deviated from the true strike. Figure 4 describes geometry of the studied model. The strike extends in x-direction. In this case we are supposed to measure data along y-direction, where the profile is perpendicular to the strike. However, let we say that we do not know exactly the strike direction at the area. In extreme case, for example, we turn around 60^o from the profile of the true strike. Therefore the data were collected along profile y'. Instead of collecting data along profile y', we also can project the data from the ideal profile to the presumed profile by expanding the distance between stations two times from the ideal measured profile, where $\Delta y' \cos 60^0 = \Delta y$ or $\Delta y' = 2\Delta y$. The 20 m of stations spacing in the ideal profile can be scaled to 40 m in presumed profile.

The same determinant data as in the ideal case, but with scaled spacing twice from the original stations, were used in this testing inversion. Figure 5 shows inverted model of determinant data collected across the strike which is deviated 60^0 from the ideal profile. About 1.02 rms data fit was reached during the inversion. Distribution of "observed" and calculated residual data are shown in Figure 6. As we expect before, the wide of inverted model is expanded twice from the actual model. But it does not give any significance change to the depth of the anomaly as we have already seen in the ideal case.

There are some unrealistic anomalies created at the left and the right sides of the anomaly. However resistivities of the unrealistic anomalies are much higher than resistivities of the true anomaly. The resistivities of unrealistic anomalies are above 1000 Ωm where the resistivity of true anomaly is 100 Ωm. In logarithmic scale, the resistivities of unrealistic anomalies, i.e. above 3, can be considered as resistivity of the background, i.e. about 3.7 or 5000 Ωm.

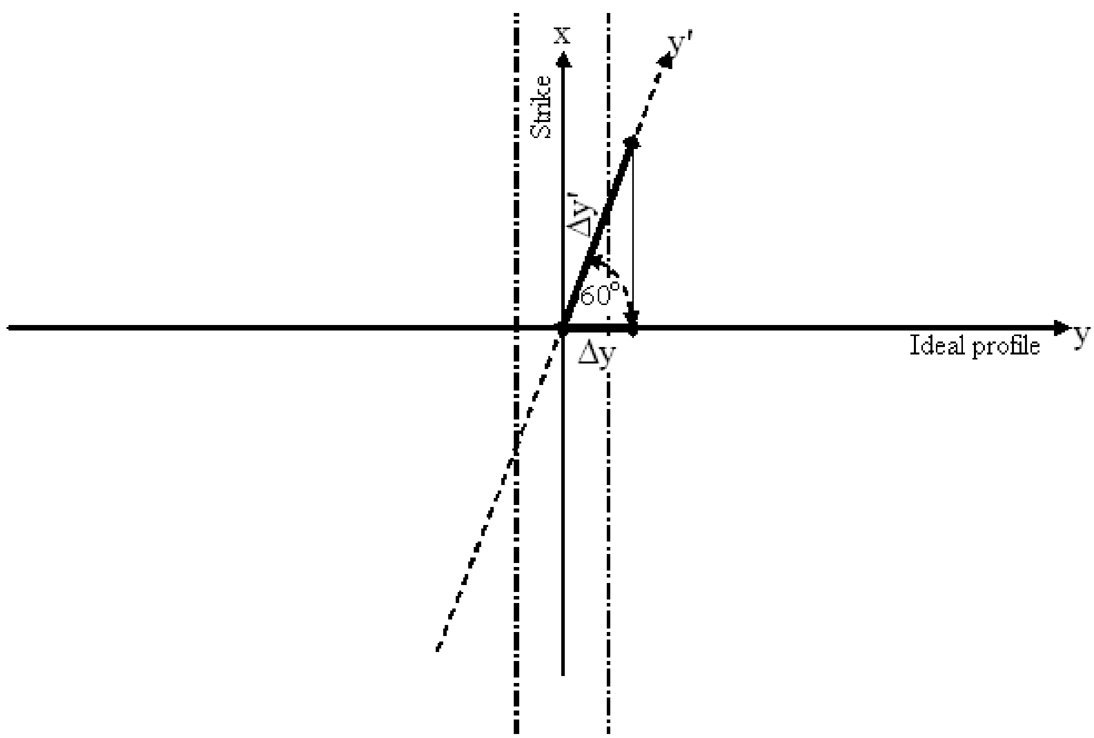

Figure 4. Geometry of strike model (x-direction), ideal profile (y-direction) and presumed profile (y'-direction).

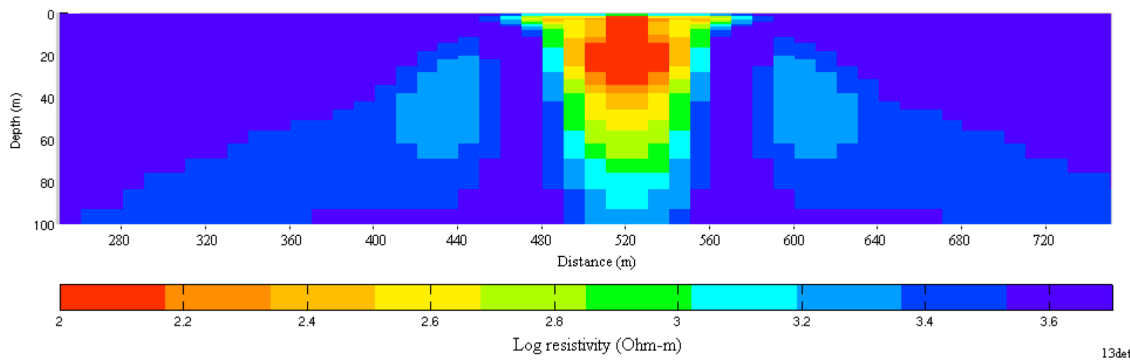

Figure 5 Inverted model of determinant data collected along profile y' where the profile is deviated 60^0 from the ideal profile.

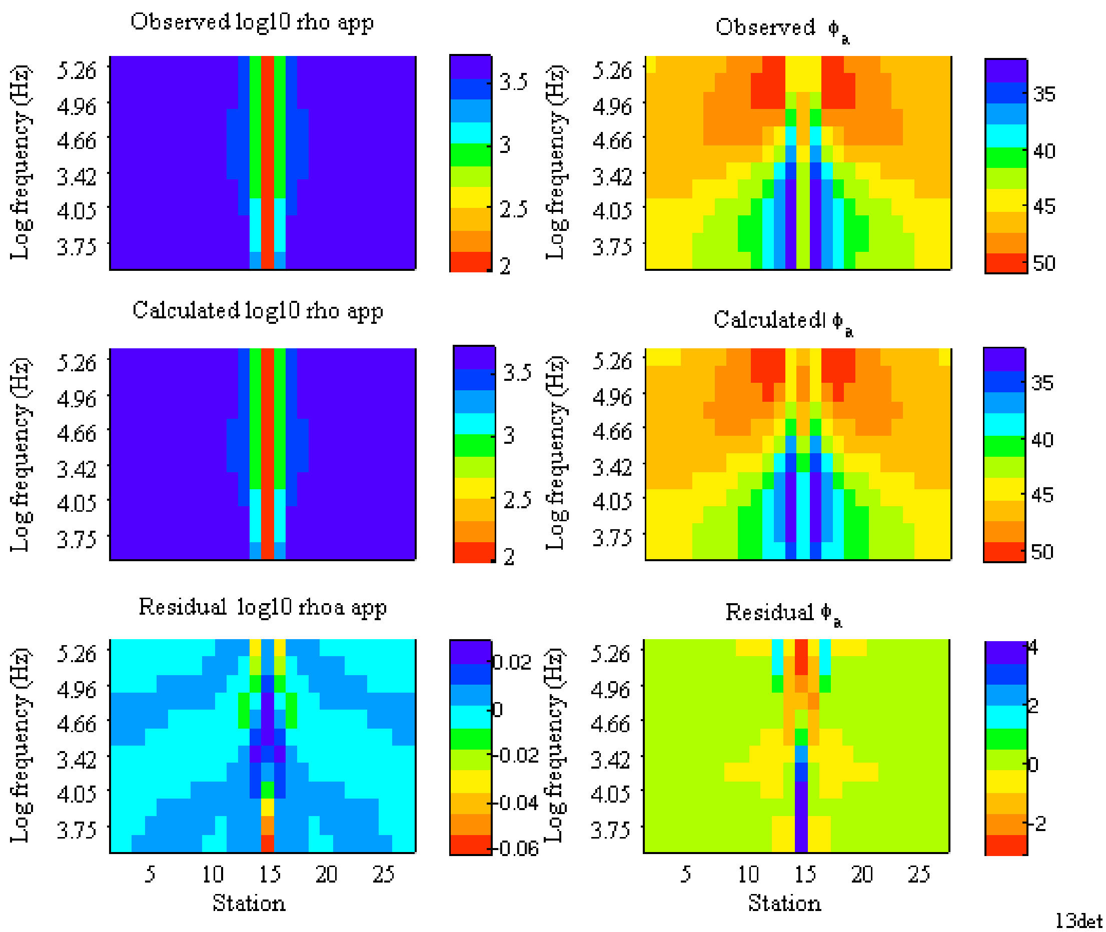

Figure 6 Distributions of observed and calculated residual of determinant data, apparent resistivity (left) and phase (right), collected along profile y'.

2D MODEL OF COMBINED TE AND TM MODES

TE and TM data were calculated from the same model as shown in figure 2. The calculation was done by using of X3D forward modeling code [9]. The area of model is 2000 m x 2000 m size with 20 m grid. The depth of anomaly is 40 m with 5 m grid. We collected data along two profiles at the center of the model. One data set was collected along the profile across perpendicularly to the true strike and the other data set was collected along the profile y', where the profile is deviated 60^o from the ideal profile.

As we did in the determinant data, first we invert the combined of TE and TM modes along actual profile for testing. The same procedure of inversion in determinant data was applied in this inversion. Figure 7 show the inverted model of combined TE and TM modes along the ideal profile y. The inversion reached around 1 rms data fit after 5 iterations. Distributions of observed and calculated residual data are shown in figure 8. Besides providing best rms data fit, the combined TE and TM modes inversion also show quite reliable model. Resistivity of the anomaly of combined TE and TM model is almost close to the original resistivity (100 Ωm), where it gives a better resolution model than determinant data does.

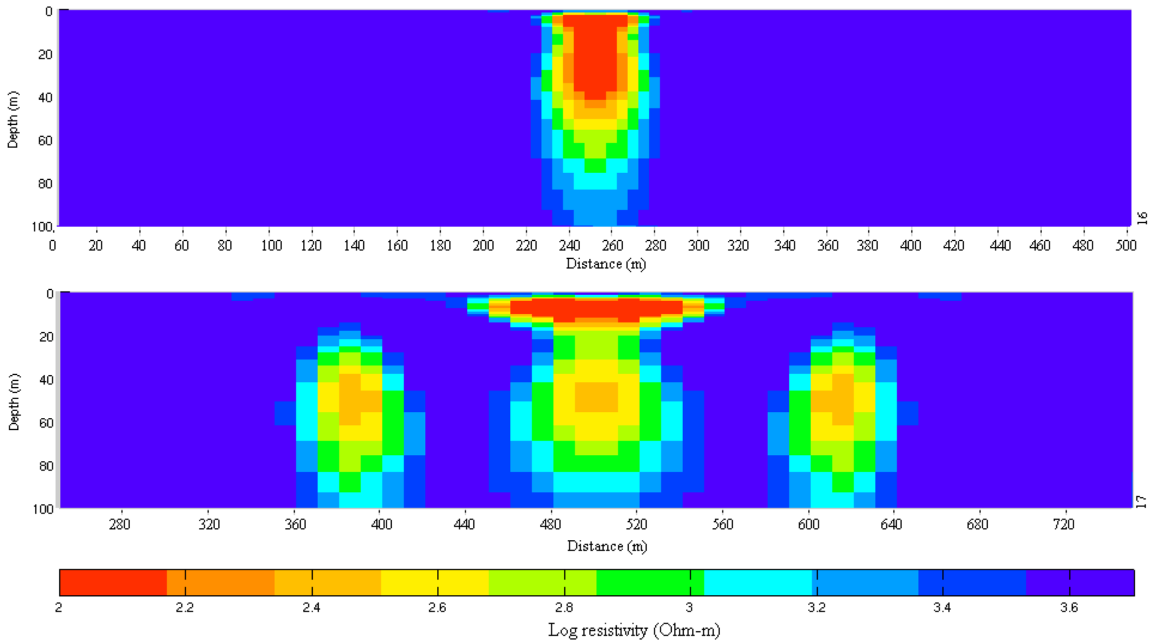

Figure 7. Inverted model of combined TE and TM modes collected (above) along the ideal profile, (below) along profile y' where the profile is deviated 60^0 from the ideal profile.

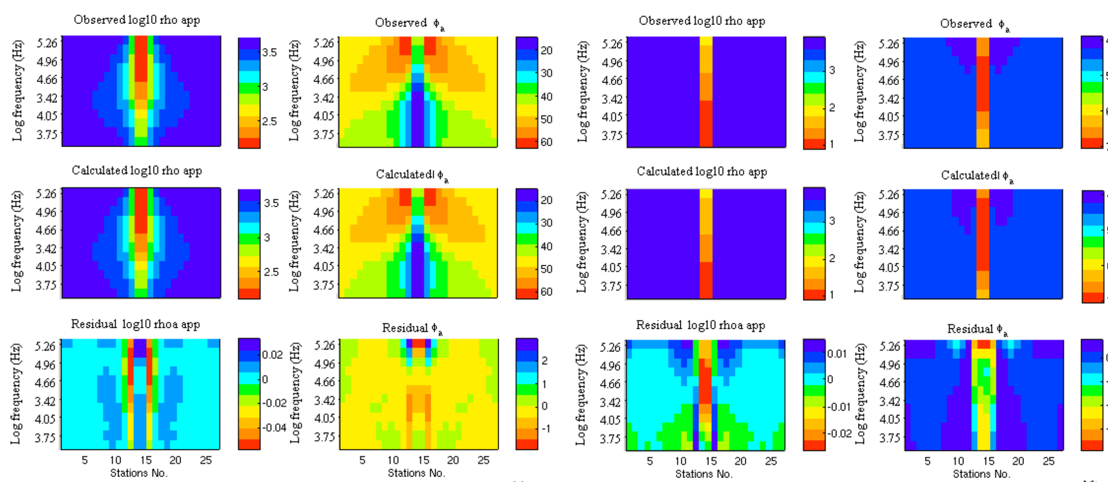

Figure 8. Distributions of observed and calculated residual of combined TE and TM modes data collected along profile ideal profile; (left) apparent resistivity and phase of TE mode and (right) apparent resistivity and phase of TM mode.

Conversely, this argument is not valid when we apply combined TE and TM modes inversion along profile y'. The data were not rotated to the presumed principal co-ordinate system. Figure 7 shows the inverted model of combined TE and TM modes along presumed profile y'. Around

5.46 rms data fit was reached during the inversion. The distributions of observed and calculated data are shown in figure 9. The rms data fit could be said fairly small. However the small rms data fit does not ensure a reliable model as we get in inverted model of determinant data. The shape of inverted anomaly is completely different from the original shape. It rather has circle-shaped than box-shaped.

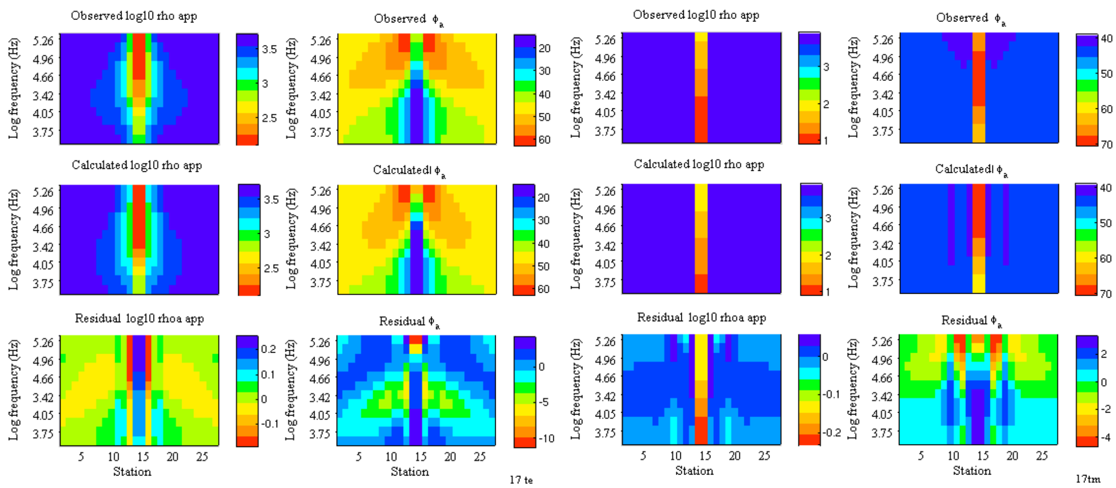

Figure 9 Distributions of observed and calculated residual of combined TE and TM modes data collected along profile y' where the profile is deviated 60^0 from the ideal profile; (left) apparent resistivity and phase of TE mode and (right) apparent resistivity and phase of TM mode

The inversion also creates some unrealistic anomalies in the inverted model. They appear symmetrically at the left and the right sides of the anomaly, which are not related to original model. Such unrealistic anomalies are also found in determinant data, but resistivities of the unrealistic anomalies of the un-rotated combined TE and TM modes are much lower than the resistivities of artificial anomalies created in the inverted model of determinant data. The values of the artificial anomalies are almost un-distinguishable with resistivity of the true anomaly, i.e. in logarithmic scale of 2.

Compare to the determinant data, 2D inversion of combined TE and TM modes actually can perform better resolution model. However the combined TE and TM modes purely depend on strike direction. Without rotating the data to the presumed principal co-ordinate system, the 2D modeling of combined TE and TM modes fails to model a realistic model. The inversion also introduces some unrealistic anomalies in the inverted model where that is not related to the original model.

CONCLUSIONS

Locating a realistic strike direction on 2D area before data collection is quite important in 2D magnetotelluric data inversion. Shape of model resulted from the inversion is depend assumed strike applied at the studied area.

In case when the strike direction can not be predicted accurately, using determinant data give more reliable model than using combined TE and TM modes in 2D modeling. The determinant impedance data depends less on the direction of the assumed strike direction.

REFFERENCES

1. Ledo, J., 2006, 2-D versus 3-D magnetotelluric data interpretation: *Survey in Geophysics*, **27**, 111-148.
2. Siripunvaraporn, W., G. Egbert, and M. Uyeshima, 2005, Interpretation of two-dimensional magnetotelluric profile data with three-dimensional inversion: Synthetic examples: *Geophys. J. Int.*, **160**, 804-814.
3. Swift, C. M., 1967, *A magnetotelluric investigation of an electrical conductivity anomaly in the southwestern United State*: Ph.D. thesis Massachusetts Institute of Technology.
4. Parkinson, W. D. 1962, The influence of continents and oceans on geomagnetic

variations: *Geophysical Journal of the Royal Astronomical Society*, **6**, 441-449.

5. Cantwell, T., 1960, Detection and analysis of low frequency magnetotelluric signal: Ph.D. thesis, Massachussetts Institute of Technology.
6. Zhang, P., R. G. Roberts, and L. B. Pedersen, 1987, Magnetotelluric strike rules: *Geophysics*, **52**, 267-278.
7. Pedersen, L. B., an M. Engels, 2005, Routine 2D inversion of magnetotelluric data using the determinant of the impedance tensor: *Geophysics*, **70**, G33-G41.
8. Siripunvaraporn, W., and G. Egbert, 2000, An efficient data-subspace inversion method for 2-D magnetotelluric data: *Geophysics*, **65**, 791-803.
9. Avdeev, D. B., A. V. Kuvshinov, O. V. Pankaratov, and G. A. Newman, 2002, Three dimensional induction logging problem problems, Part I: An integral equation solution and model comparisons: *Geophysics*, **67**, 413-426.