CSAMT Data Processing with Source Effect and Static Corrections, Application of Occam’s Inversion, and Its Application in Geothermal System

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Abstract. Controlled source audio-frequency magnetotellurics (CSAMT) is a frequency-domain electromagnetic sounding technique which uses a fixed grounded dipole as an artificial signal source. Measurement of CSAMT with finite distance between transmitter and receiver caused a complex wave. The shifted of the electric field due to the static effect caused elevated resistivity curve up or down and affects the result of measurement. The objective of this study was to obtain data that have been corrected for source and static effects as to have the same characteristic as MT data which are assumed to exhibit plane wave properties. Corrected CSAMT data were inverted to reveal subsurface resistivity model. Source effect correction method was applied to eliminate the effect of the signal source and static effect was corrected by using spatial filtering technique. Inversion method that used in this study is the Occam’s 2D Inversion. The results of inversion produces smooth models with a small misfit value, it means the model can describe subsurface conditions well. Based on the result of inversion was predicted measurement area is rock that has high permeability values with rich hot fluid.

1. Introduction

Controlled source audio-frequency magnetotellurics (CSAMT) is one of electromagnetic sounding method with frequency domain [1]. CSAMT is a frequency-domain electromagnetic sounding technique which uses a fixed grounded dipole as an artificial signal source. The differences between CSAMT technique with other techniques in electromagnetic methods such as magnetotelluric (MT) and audio-frequency magnetotelluric (AMT) is the use of an artificial signal source with a certain distance [2].

CSAMT using artificial signal source is injected in the form of an electric current. Near field, transitions, and far field are the zone in CSAMT based on measurement distance variation between the transmitter with receiver. The finite distance artificial source between the transmitter with the receiver cause plane wave assumption can not apply in the near field and the transition zone. It cause the modeling and interpretation of data CSAMT relatively more difficult than in MT [2].

The influence of the source should be corrected so that data can be interpreted properly. The source effect correction includes near field and transition zone. From the research that has been done Grandis (2000) by using a synthetic model of the classified area CSAMT measurement is based on the value of normalization frequency. From the normalized frequency data calculate near field coefficient (Kn) and the far field coefficient (Kf) to determine the resistivity values in areas near field and the transition to the actual data.

Static effects that occur must be minimized by carrying out static correction. The static correction is done by doing spatial filtering technique [2]. The static correction make data better so that in the
interpretation and modeling of the data may be easier and less complex. The data have been corrected by source effects and static correction can be inverted.

Inversion method performed by using Occam inversion. Occam inversion developed by Steven C. Constable. The basic principle of Occam is solve a problem by using the simplest of the many ways of solving the problems. Occam inversion been obtained model results more smooth so that a small change in the value resistivitas can be detected.

2. Experimental methods

2.1. Source effect correction

Based on the measurement distance variation the transmitter with receiver on CSAMT, there are three zones, near field, transition, and far field. In the far field zone the plane wave assumption already admitted so that the equation for calculating the value of the resistivity can be applied together with the MT method using Cagniard equation [3]. In the area of near field, source effects can still be captured directly by the receiver and the assumption of a plane wave can not be applied so that the data must be corrected. Correction data is also performed at the transition area.

The final equation for determining the resistivity values in areas near field and far field can be written in the form

\[ \rho'_s = \frac{K_s}{5f} \left( \frac{E_s}{H_s} \right) \Omega \cdot m \]  
\[ \rho''_s = K_s r \left( \frac{E_s}{H_s} \right) \Omega \cdot m \]  

Far field coefficient (Kf = 1) is used to calculate for the factors in the equation approaches the EM field in far field conditions, whereas (Kn = 0.65) for the coefficient in the region near field. In the transition field is used two regions approach between near field and far field. The value of Kf and Kn is required in terms of determining the transition field generally. Transition field can be determined by normalizing the frequency of measurement. The normalized frequency F can be expressed by the following equation

\[ F = f \left( \frac{E_s}{H_s} \right)^1 \]  

Apparent resistivity for transition can be calculated using equation (1) or (2) by selecting one using Kf or Kn. Kf value or Kn is the result of interpolation of table 1

| No | F   | Kf  | Kn  | No | F   | Kf  | Kn  |
|----|-----|-----|-----|----|-----|-----|-----|
| 1  | 0.0003 | 0.0001 | 0.6479 | 16 | 1.3114 | 1 | 0.1600 |
| 2  | 0.0006 | 0.0021 | 0.6481 | 17 | 1.8102 | 1 | 0.1105 |
| 3  | 0.0011 | 0.0035 | 0.6483 | 18 | 2.5600 | 1 | 0.0781 |
| 4  | 0.0013 | 0.0042 | 0.6484 | 19 | 3.6204 | 1 | 0.0552 |
| 5  | 0.0026 | 0.0084 | 0.6488 | 20 | 5.1200 | 1 | 0.0391 |
| 6  | 0.0052 | 0.0169 | 0.6492 | 21 | 7.2408 | 1 | 0.0276 |
| 7  | 0.0104 | 0.0336 | 0.6485 | 22 | 8.9954 | 1 | 0.0247 |
| 8  | 0.0206 | 0.0663 | 0.6435 | 23 | 1.1449 | 1 | 0.0175 |
| 9  | 0.0401 | 0.1255 | 0.6263 | 24 | 1.6191 | 1 | 0.0124 |
| 10 | 0.0748 | 0.2188 | 0.5847 | 25 | 2.2897 | 1 | 0.0087 |
| 11 | 0.1314 | 0.3373 | 0.5133 | 26 | 2.5600 | 1 | 0.0078 |
| 12 | 0.2186 | 0.4666 | 0.4269 | 27 | 3.6204 | 1 | 0.0055 |
| 13 | 0.3549 | 0.6150 | 0.3466 | 28 | 5.1200 | 1 | 0.0039 |
| 14 | 0.5738 | 0.8039 | 0.2802 | 29 | 7.2408 | 1 | 0.0028 |
| 15 | 0.9078 | 1.0059 | 0.2216 |

2.2. Source effect correction

Static effects can be caused by factors of topography and changes in lateral resistivity values in shallow areas. Charge distribution on the surface of the resulting non-homogeneous electric field E be increased or decreased is not dependent on the frequency. The effect of the distribution of the charge made apparent resistivity values be shifted but did not affect the values of the phase [4]. The static effects could result for two values of resistivity which can cause large errors in depth estimation and
interpretation of the subsurface structure becomes complex. Static correction is done by averaging the resistivity curve in the measured region \cite{5}. Static correction can also be done by comparing the data obtained with the data TEM (Transient Electromagnetic) \cite{6}.

In general, static effects can not be avoided or can not be predicted so as to survey measurements using the electric field E required static correction. Zonge (1985) introduced a spatial filtering method that integrates data free static phase to find resistivity data corrected. Static correction is done through two stages of data processing. The first step, by integrating the data to determine the phase resistivity data for each measurement station. This integration is done with the equation

\[
\rho_\phi = \rho_n \exp\left[-\frac{4}{\pi} \int_{f_L}^{f_H} \frac{\phi - \pi/4}{4} d\ln f\right] \quad \text{(equation 4)}
\]

With:

- \( \rho_n \): Integration constant (normalized value)
- \( f_H \): The Highest Frequency
- \( f_L \): The Lowest Frequency
- \( \phi \): Phase difference between E and H Field

The value of \( \rho_n \) is estimated at the station did not experience the effects of static, by looking from Pseudosection or comparing the value and if the measurement is a vector measurement. The highest frequency data used in the measurement at 8192 Hz while the lowest value at 0.25 Hz.

The second step calculate the value of the resistivity results of static correction using the equation

\[
\rho_{stat} = \rho_n \frac{\rho_N}{\rho_{ref}} e^{(4/\pi)(\phi_r - \phi_s)} \quad \text{(equation 5)}
\]

Value \( \rho_a \) can be replaced with the value \( \rho_n \) obtained from equation (4). Phase reference value \( \phi_r \) obtained from the value of the phase at the reference station. The point of intersection between the two graphs serve as a value. Specific value of the phase is a phase value at each station at any frequency. The static resistivity values which will be modeled and made contours for further inversion.

2.3. Occam’s 2D Inversion

Occam method developed by Steven C. Constable. Occam name itself is taken from William Ockham a philosopher from England that said someone should not assume more than necessary. The basic principle of Occam method is if there are many explanations for a phenomenon, then choose the simplest version. In the form of Occam inversion under the earth’s surface model by making the grid in the form of squares where each element has a value of physical parameters respectively. Physical parameters for each element in the form of the resistivity values also show the value of conductivity.

Occam 2D inversion using a factor called the roughness factor. Roughness associated with smooth and rough shape models obtained when done inversion \cite{7}. The general equation for Occam inversion is

\[
U[m] = \|
\nabla_1 m
\|_2^2 + \|
\nabla_2 m
\|_2^2 + \mu^{-1} \left\|
Wd - WF(m)
\right\|^2 - X^2 \right) \quad \text{(equation 6)}
\]

The first term part is the part that states the model smoothness and the second term is the value of tolerance which is still acceptable. Functional U minimized to the point where the gradient of the model is zero. When the nonlinear functional data, functional U linearized and solved by iteration.

3. Results and discussion

3.1. Source effect correction

Source effect correction is made to the data source field in an area of measurement. In the area there are four line measurements with several measuring points. CSAMT data measurement using the five line is
line 04, line 05, line 06, and line C. Line 04, 05, and 06 stretches from the northwest towards the southeast. Line C stretches from the southwest toward the northeast.

By using MATLAB correction of measurement points are experiencing the effects of the source. Graph data correction to the effects of sources on one measurement point can be seen in the figure 1 that show the data on the C096 station. At the C096 station the data at low frequencies between 0125 Hz - 2 Hz was corrected by source effect correction characterized by the red line which is apparent resistivity corrected.

Figure 1. The difference between initial apparent resistivity and corrected apparent resistivity in C096 station

Comparison of baseline data and the data that has been corrected on each measurement station (line 05 YX serve as an example) can be seen in the following figure

Figure 2. The difference between initial apparent resistivity and corrected apparent resistivity in line 05

Pseudosection on line 05 YX sources that have been corrected by source effect correction shown in the figure below

Figure 3. Pseudosection Line 05 YX has been corrected of source effect
3.2. Static correction

Static correction is done by analyzing and selecting the station that affected resistivity value shift up or down. The corrected station is the station C091 and C041. Using equation (4) is determined value $\rho_\phi$.

From the value $\rho_\phi$ can be determined $\rho_{\text{Stat}}$ by using equation (5). The Results of static correction on line 05 can be seen in the following figure.

![Figure 4. Pseudosection Line 05YX has been corrected of source and static effect](image)

Figure 4. Pseudosection Line 05YX has been corrected of source and static effect

From the figure when compared with the previous image may be seen in the C091 station resistivity values at this station shifted rises at each frequency. On the C041 station resistivity values shifted slightly down following the trend resistivity values around stations.

Final data CSAMT results of static correction can already be said to be almost the same as the MT data. So that the inversion process can be done because it is free from the influence of the source and static effects that the result data can be said the same data with the data on MT.

3.3. The results of Occam 2D Inversion

The corrected CSAMT data was inverted by using Occam inversion method developed by Constable. There are four line was inverted and the inversion results of all line after merged can be seen in the following image.

![Figure 5. Inversion results for all line](image)

Figure 5. Inversion results for all line
Result of the merger of each line of measurement data that has been corrected and inverted using Occam method can be seen in the structure of the earth's subsurface. From the figure above is seen that in shallow areas and close to the soil surface resistivity value 10-100 Ohm meter and at some point have a high resistivity to 1000 and 10,000 Ohm meter. This indicates the area is not conductive, based on field geological data, there are several faults in this area. There is a possibility that high resistivity values caused by the fault which is resistive or unfilled non-conductive material.

At the depth of -200 m (200 meters below sea level) resistivity values dropped quite dramatically to the value of 1-10 Ohm meter that indicates this area is conductive. Increasingly down slightly increased resistivity values (shown on line 04,05, and C) although the change is not too large resistivity values. At this area is thought to be the area with a mixture of clay stamp, altered clay, or a combination of rock with high permeability values rich with hot fluid.

This result is also supported with geological data and surveys directly in the field. Referring to the survey directly visible in the field of geothermal manifestations found scattered in several places along the north and south which reinforce their geothermal potential in the area of this measurement.

4. Conclusion
Based on the results of research and discussion that has been done, there are some conclusions as follows:

1. The existence of source effect and static correction in CSAMT data makes the data more accurate. CSAMT data that have been corrected can already be considered as a response to the MT data that has been in the form of plane wave.

2. The results of the inversion CSAMT data using Occam inversion obtain a fairly accurate results. These results are marked with a small misfit value, so that it can obtain a good inversion models. The results of inversion indicates the measurement area there is a combination of rocks that have high permeability values that are rich with hot fluid.

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