Comparison of 2D Inversion Concepts in Magnetotellurics

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Keywords

Magnetotellurics, Inversion Concepts, Comparison of the 2D Inversion Concepts.

Summary

Magnetotellurics is an electromagnetic geophysical method for inferring the earth's subsurface electrical conductivity from measurements of natural geomagnetic and geoelectric field variation at the earth's surface. Commercial uses include hydrocarbon (oil and gas) exploration, geothermal exploration, mining exploration, as well as hydrocarbon and groundwater monitoring. Research applications include experimentation to further develop the MT technique, long-period deep crustal exploration and earthquake precursor prediction research.

The data used for the study was a synthetic data. We generated 10 sites of TM-mode AND TE-mode data at 20 frequencies logarithmically spaced from 0.1Hz to 100Hz, from a simple layered 2D model, with layer boundaries. This paper brings the detailed analysis of 2-D modeling procedures and a comparison of 2D inversion concepts.

Introduction

Magnetotelluric (MT) technique is a passive electromagnetic (EM) method where the diffusion of the EM wave is monitored from surface measurements of the electric and magnetic fields. This is then used to obtain the geoelectric cross-section of the surface. Theoretical modeling techniques act as tools to improve the relationship between the MT response functions and the various sub-surface resistivity discontinuities that has generated them.

The quantitative interpretation of MT data is based on the mathematical inversion of resistivity versus frequency data into the resistivity versus depth form and based on improving the initial forward computer model. The use of computed models is especially important in areas of structural complexity, the effect of MT data of multiple, superimposed geologic structures strains the insight of even the most experienced interpreter. For modeling we used WINGLINK software, developed by Geosystem as a multi-disciplinary software program to process, interpret and integrate several geophysical disciplines in a unique interpretation model.

Theory and Methodology

MT uses, natural, low frequency electromagnetic (EM) waves to image the subsurface. These waves have frequencies in the band 1000 – 0.0001 Hz and originate in worldwide lightning activity and oscillations of the magnetosphere (Vozoff, 1991). These EM signals travel through the atmosphere as radio waves but diffuse into the earth and attenuate rapidly with depth. The penetration depth is called the skin-depth and surface measurement of electric and magnetic fields gives the average Resistivity from the surface to a Z equivalent of the skin-depth. The increases a frequency decreases, and thus a depth sounding of Resistivity can be achieved by recording a range of frequencies as illustrated in fig.1

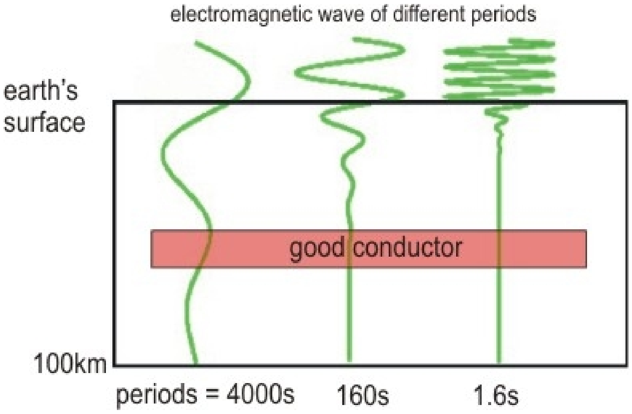

Figure 1: Long period electromagnetic waves penetrate deeper into the underground than short periods. So long term measurements must be accomplished in order to detect a good conductor at greater depths of the crust or upper mantle

At the highest frequencies (1000-300HZ), the apparent resistivity equals the true resistivity since only the apparent layer is sampled. At intermediate frequencies, the apparent resistivity drops as EM signals penetrate the second layer. Finally at the lowest frequencies, the resistive basement is detected.

These mathematically can be represented as,

$$\text{Impedance } (Z) = E(x)/H(y)$$

For the Z measurements, we can determine the apparent resistivity of a homogenous half-space.

$$\rho = 0.2\, T\, |\, E(x) / H(y)\, |^2$$

Because of the skin depth effect, high frequency EM energy will penetrate only shallow depths whereas lower frequencies will penetrate deep. The skin depth is defined as the depth at which the EM fields have decayed in amplitude to 1/e of their values at the surface and is given by

$\delta = \sqrt{(2\rho/w\mu)}$ in meters
$= 0.5 \sqrt{(\rho\ t)}$ in kilometers for geophysical interpretation. The frequencies that are generally used in the MT method are from 10000HZ to 0.0001HZ.

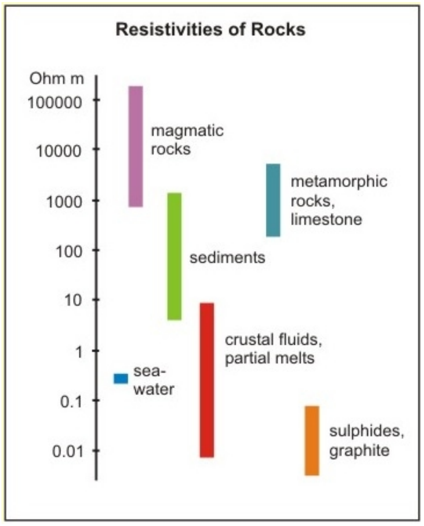

Fig 2. Electrical resistivities occurring in nature are very rock dependent and lower order of magnitudes.

Due to the well-known skin-depth phenomenon, namely greater penetration with decreasing frequency of signals, the impedance parameters computed over a range of frequencies provide the basic input of subsurface electrical conductivity as a function of depth. After a lot of theoretical and experimental work, the method was deployed for practical application. Versatility in MT improved with advances in instrumentation and electronics for wide band measurements, digital storage, online processing, modeling and inversion.

The basis for constructing models of electromagnetic field sources employed in deep geoelectric or Magnetotellurics include the electromagnetic properties of atmosphere, ionosphere, and magnetosphere by considering the origin of the main variations and pulsations, the effect of conductive excitation of the variations due to atmospheric vertical currents. The Magnetotellurics field is the time-varying portion of the earth's magnetic field. This induces eddy currents in the earth. These natural electromagnetic waves come from a variety of processes and from sources ranging from earth's core to distant galaxies. The signals from worldwide thunderstorm activity (sferics) is the main source of natural signal for frequency>1HZ. These two phenomena do not overlap in frequency and there exists "dead band" around 1HZ, with very low signal amplitude. We may define another dead band around 1KHZ as well. However, in magneto telluric context, the effect of first "dead band" refers to the low frequency band around 1HZ. The sharp peaks in the spectra between 10 to 1000 HZ are due to power line interference. This clearly shows how narrow band noise can override the natural signals.

The time variations of the natural electromagnetic field are of various types and offer a range of frequencies due to different sources includes: -

1. Secular variations
2. Diurnal variations
3. Geomagnetic Pulsations
4. Atmospherics

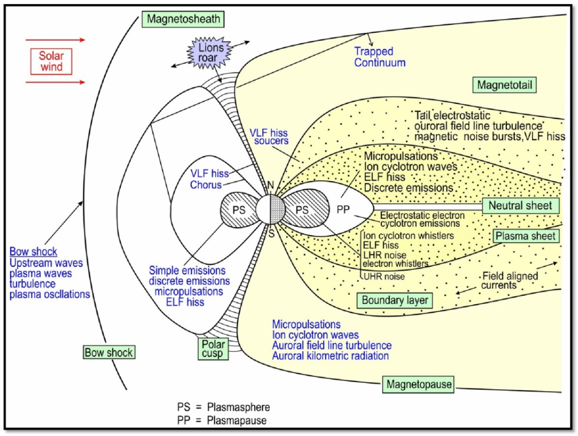

Fig 3: The source regions in the magnetosphere for the various types observed atmospherics.

As any modern geophysical survey, Magnetotelluric surveys are also planned before fieldwork starts. Though the survey must accommodate changes due certain unforeseen circumstances, the overall plan remains the same. Two major decisions to be made before start of survey are station spacing and minimum recording time. Minimum recording time depends on the depth of interest and the geological condition. Forward modeling of an assumed model can provide minimum safe recording time.

Survey design begins with the computation of the forward model to determine the required parameters and optimum site geometry. The model will also demonstrate the feasibility of applying the MT to the problem at hand. Survey design must also take into account topography and culture, and anticipated sources of noise and interference.

The geologist and geophysicist choose preliminary location on the analysis of available geological and geophysical information and survey objective. The instrumentation required detecting and record low frequency electromagnetic field variations must fulfill certain basic requirements. In common with other modern geophysical equipment, it must be maintain accuracy under field conditions. Finally, the instruments must be reliable and sufficiently portable for their transport in the field.

Additional requirements arise from the nature of the signals to be measured. GMS-05 and ADU-06 are the two variants of MT data acquisition system being used for data acquisition in NGRI, India.

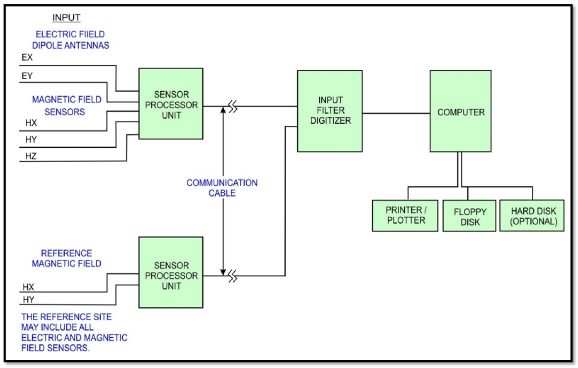

Fig: 4. Block diagram of a representative MT system

The objective of the data processing is to extract a smooth, repeatable function representing earth response from noise like signal to interpret conductivity structure. The data processing is done in frequency domain.

The governing equations involved in data reduction are those relating electric field components to the magnetic field components.

$E_x = Z_{xx}\ H_x + Z_{xy}\ H_y$

$E_x = Z_{yx}\ H_x + Z_{yy}\ H_y$

i.e. two complete equations in four complex unknown, the Z_{ij} . Equations are complex because all quantities have magnitude and phase. They can be solved because we can obtain many independent estimates of the E and H.

The processed data is represented in several ways. The computed functions, such as apparent resistivity, vertical magnetic field, skew etc are computed and presented as function of frequency. The value of apparent resistivity magnitude and phase are calculated at discrete frequencies and presented as individual points. These points are basic data. Steps involved in processing the MT data is shown in the flow chart Fig 5

Theoretical modeling techniques act as tools to improve the relationship between the MT response functions and the various sub-surface resistivity discontinuities that has generated them.

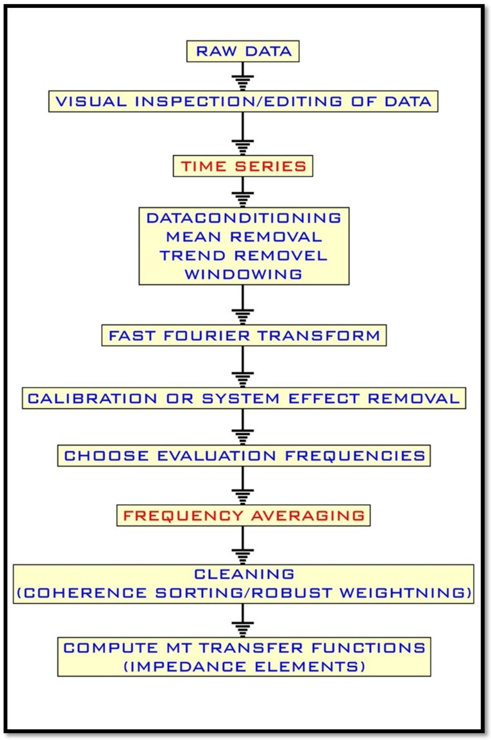

Fig 5. Processing steps for Magnetotellurics data

The quantitative interpretation of MT data is based on the mathematical inversion of resistivity versus frequency data into the resistivity versus depth form and based on improving the initial forward computer model. The use of computed models is especially important in areas of structural complexity, the effect of MT data of multiple, superimposed geologic structures strains the insight of even the most experienced interpreter. For modeling we used WINGLINK software, developed by Geosystem as a multi-disciplinary software program to process, interpret and integrate several geophysical disciplines in a unique interpretation model.

Forward Modelling:

Usually, an equivalent geophysical model replaces earth structure. The process of computing its response mathematically is called forward modeling. Two-dimensional models are computed using finite element, finite difference and integral equation methods. For forward models the interpreter specifies the model geometry in terms of columns and rows of polygons and the resistivity of each block or unit. The MT response for the input model is then calculated and the results plotted in the form of apparent resistivity versus frequency for selected MT sites located on the surface or pseudo-sections. The input model is usually shown as cross section approximating the geologic model used.

Inversion:

Predicting the geophysical structure under the earth from the field measurements is called inversion. The 2D inversion module is used to perform smooth and sharp boundary inversions of MT data, using exact finite difference routines, developed by Dr. Randy Mackie. It provides a user-friendly interface for creating and editing 2d meshes and allows the user detailed control over the inversion parameters. To assist in the interpretation of the modeled data, the module includes options for outputting sensitivity maps, creating pseudo-sections and comparing observed and computed responses.

Recent inversions have been successful in finding smoothly varying two-dimensional models fitted to magnetotelluric data (e.g. deGroot-Hedlin and Constable 1990; Smith and Booker 1991). These inversions have been explicitly formulated to minimize some measure of the roughness of a conductivity model for some level of squared data misfit. For example, minimizing

$$\int \partial/\partial x \log \sigma))^2 + \partial/\partial z \log \sigma))^2 \, dx \, dz + \beta |r|^2,$$

where $\sigma(x,z)$ is the conductivity, $|r|^2$ is the squared data misfit and $\beta > 0$ is a trade-off parameter, results in a model which is smooth in both vertical and horizontal directions.

The MT 2D Inversion program contains two different routines for running inversions:

Synthetic Data:

We generated 10 sites of TM-mode AND TE-mode data at 20 frequencies logarithmically spaced from 0.1Hz to 100Hz, from a simple layered 2D model, with layer boundaries. The model consists of a surface layer of 51Ωm (e.g. basaltic trap) over a 13 Ωm layer (e.g. sediments) over a 6000 Ωm basement at 33km depth. The model response was calculated using the same forward modelling code (Randy Mackie) as used in forward modelling steps within our inversion. To simulate measurement errors, five percent Gaussian noise was added to apparent resistivities and impedance phases.

In inversion, the model was parameterized in terms of interface depths log (z_{ij})(j=1,10), (i=1,2), at nodes directly below the data sites, with layers and basement. One standard error rms misfit was chosen for inversion corresponding to the noise level in the input data, and this was achieved in the final iterations of the inversion. A comparison of rms values for the smooth inversion and sharp boundary inversion shows 1.0494 for smooth inversion and 0.8507 for sharp boundary inversion

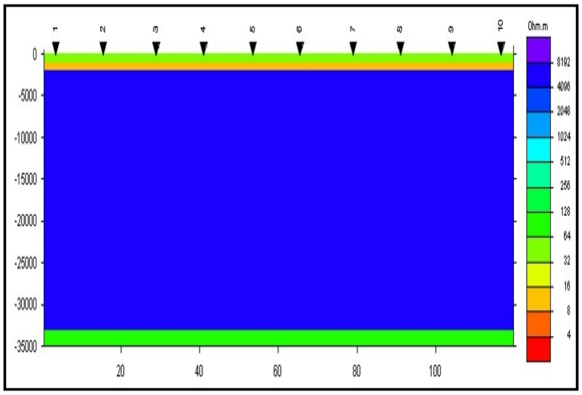

Fig: 6. Basic Model

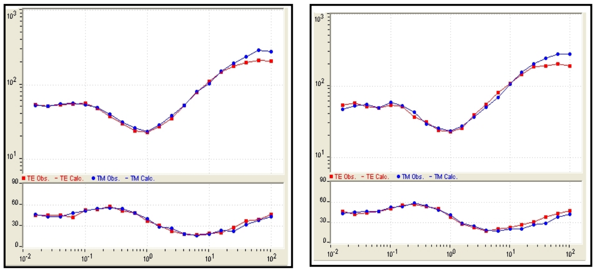

Fig: 7 Frequencies of the Basic Model

Sharp Boundary Inversion:

Sharp boundary inversion (SBI) results are shown in figure (8). Sharp boundary inversion was done for the discrete interfaces and the resistivities of the layers between those interfaces. These resistivities are described by a series of resistivity nodes, whose horizontal positions are fixed, but whose vertical positions can vary in the inversions. The interfaces are assumed to transect the entire model, i.e., there are no closed bodies. The interface varies linearly between each interface node. The resistivity of each layer is also described by a set of nodes at fixed horizontal positions within each layer. The resistivity is assumed to vary linearly between nodes. The interface and resistivity information is projected on to a finite difference mesh for computation, and the inversion calculates the best fitting interface node locations and resistivity nodal values in order to fit the observed data. According to the given data, Basalt resistivities (surface layer) are matched within four percent over the length of the profile. The base of this layer is matched to within 15-20m throughout the model. Sediment resistivities (second layer) are matched within four percent within the entire unit, and basement resistivities shows some difference. The particular result shown was started from a 1D model with uniform layer resistivities of 50, 13 and 6000 Ωm. Starting the SBI from other starting models has given almost identical results, giving some confidence that the algorithm has found a global minimum of the object function.

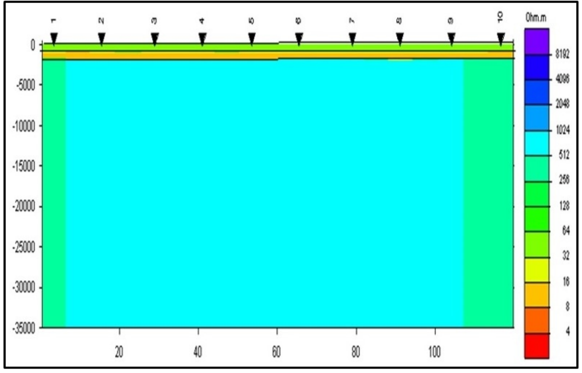

Fig:8. Sharp Boundary Model

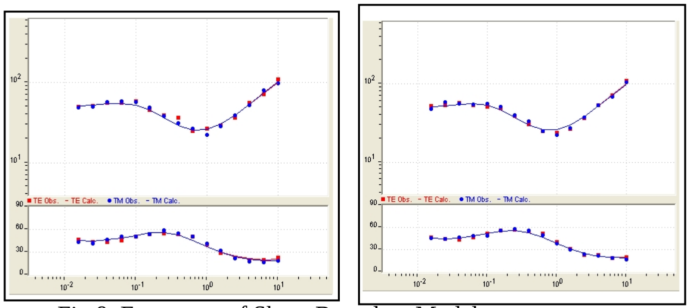

Fig:9. Frequency of Sharp Boundary Model

Smooth Inversion:

The same synthetic data have been inverted using a smoothly varying inversion algorithm (Mackie…..). There are some observations that can be made about smooth inversions of data from models with sharp boundaries, which are illustrated to varying degrees in fig. (9).

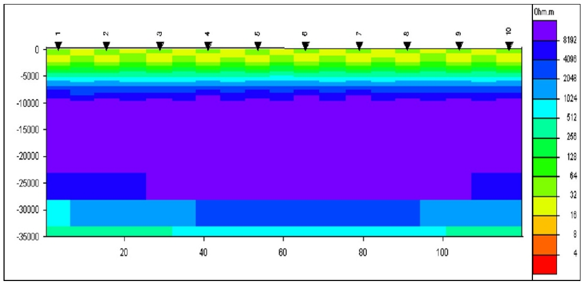

Fig:10. Smooth Boundary Inversion Model

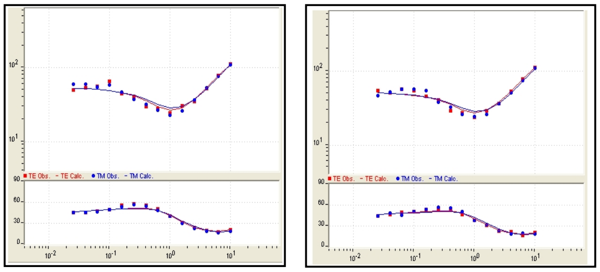

Fig:11 Frequencies of Smooth Boundary Inversion

Smooth inversion of data from models with sharp boundaries tends to overshoot resistivities on either side of a boundary. Smooth inversion results generally increased smoothing with increasing depth. The transition from sediment to basement resistivities is more spread out than the transition from basaltic trap to sediment resistivities in the smooth inversion results. The data by themselves are unable to resolve whether the transition to basement resistivities is smooth or abrupt. However, assuming that the transition is abrupt, the depth and resistivity of basement are quite accurately recovered.

Comparison of Sharp Boundary Inversion and Smooth Inversion Techniques:

The blurriness of the results of a minimum structure derived from smooth inversion give some ideas of resolution limits of a given data set. When it is suspected that the field area is made up of relatively homogeneous units, the positions of boundaries can be recovered more precisely using a sharp boundary inversion. Inverting directly for boundary positions in a sharp boundary inversion makes interpretation for structural geology.

A sharp boundary inversion provides MT interpreters with a tool specifically designed for structural interpretation. By parameterizing inverse models in terms of boundaries between units which may possess large contrasts in resistivity, conductivity, inversions which unambiguously locate such boundaries can be produced. In the case of petroleum exploration, where the base of a sequence of relatively uniform basalt, salt or carbonate is the goal of an MT survey, a sharp boundary inversion provides advantage over a smooth inverse model which leaves the interpreter with the need to inverse the model for the location of structural interfaces.

Conclusions

In order to understand the subsurface structure of the earth, one of the most effective geophysical techniques is Magnetotellurics. It is being used for solving various geological problems. Study of Magnetotelluric method was undertaken in this project. As a major part of project, an attempt has been made to study the detailed analysis of 2-D modeling procedures.

To understand the subsurface geoelectric structure, MT method measures apparent Resistivity and phase at any given site. To transform Resistivity curve in to appropriate geological structure, we have to do 1-D modeling and if necessary 2-D modeling. For that purpose Winglink software package was used.

A near-surface unit of high-resistivity and velocity (salt, basalt or carbonate) overlying prospective sediments is the most common case. In such cases, the geometry of the base of the resistive unit and the basement surface is primary interpretational goals. Present study focuses on delineating marked boundaries using Sharp Boundary Inversion technique.

The ambiguity of the results of a minimum structure based on smooth inversion gives some idea as to resolution limits of a given data set; whereas, the study of sharp boundary inversion provides MT interpreters with a tool specifically designed for structural interpretation. By parameterizing inverse models in terms of boundaries between units, which may possess large contrasts in conductivity, inversions, which unambiguously locate such boundaries, can be produced. In the case of petroleum exploration, where the sequence is uniform basalt, salt or carbonate underlain by sediments as the goal. In MT survey, a sharp boundary inversion provides advantages over a smooth inverse model as smooth inversion model leaves the interpreter to interpret the model for the location of structural interfaces.

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Acknowledgements

The authors express their gratitude and sincere thanks to Shri G.C.Katiyar, ED-Basin Manager –Western Offshore Basin, for giving giving permission to write this work.

Author thanks Dr.Prasanta K Patro, National Geophysical Research Institute, Hyderabad for his valuable guidance and support during the execution of work.

Author thanks to Dr.T.Harinarayana, National Geophysical Research Institute, Hyderabad for his support and guidance.

Author expresses gratitude to Head of the Department, Andhra University for giving an opportunity to complete the work and for their valuable advices.

N.B: The views expressed in the paper are solely of the authors and not necessarily of the organization in which they are working.