A review of the application of telluric and magnetotelluric methods in geophysical exploration

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Abstract
This study presents a review of the application of telluric and magnetotelluric field techniques in understanding the subsurface structures of the earth, which stems from the analytical solution of the Maxwell’s basic wave equations of electromagnetic theory. The work articulates the fundamentals of a magnetotelluric survey, showing how it is applied in the field, and an explanation of its use in solving geophysical problems. Case histories and the advantages and limitations of employing telluric and magnetotelluric field techniques are also discussed.

Keywords: Telluric, magnetotelluric, subsurface, geophysical exploration, geoelectrical

1. Introduction
The last few decades have witnessed increased use of natural-source geophysical techniques particularly for petroleum, gas and geothermal explorations, and geotechnical engineering problems. In addition to this, continuous monitoring of magnetotelluric (MT) signals to study the earthquake precursor phenomena is now a new initiative (Harinarayana, 2008).

Certain large-scale, low-frequency naturally alternating magnetic fields is described as MT fields, while the induced terrestrial current systems by the fields are known as telluric currents. The telluric current induced by geomagnetic storms generates secondary geoelectric storms (Xin and Xuebin, 2017). The MT method is a passive electromagnetic (EM) exploration method that measures orthogonal components of the electric and magnetic fields on the Earth’s surface. In MT method, the primary field is usually taken to be a plane wave vertical incident on the earth’s surface. This model permits easy calculation of a field in a horizontally homogeneous geoelectric medium (Zhdanov, 2009). The source field is naturally generated by variations in Earth’s magnetic field, which provide a wide and continuous spectrum of EM field waves. These fields induce currents into the Earth, which are measured at the surface and contain information about subsurface resistivity structures (Tamrat, 2010). Magnetotelluric can also be described as a geophysical method that measures naturally occurring, time-varying magnetic and electric fields from which it is possible to derive resistivity estimates of the subsurface from the very near to tens of thousands of feet (Christopherson, 1999).

Both telluric and MT methods apply natural earth currents and are referred to as natural-source electrical methods similar to self-potential. Anomalies are sought in the passage of the currents through the earth materials. Unlike controlled-source EM methods which may use an inductive loop as a source, the MT method relies on naturally-occurring EM fields. The type of natural source depends on the frequency of the EM field (Dobrin, 1988).

1.1 Origin and characteristics of telluric currents and magnetotelluric fields
The natural-field EM method has its source signal in naturally occurring fluctuations in the earth’s magnetic field. This source exists
at any place on earth, at practically any time and is applied over a wide range of frequencies. The use of natural variations of EM field of micro-pulsations that was limited in the frequency range, from 1 sec to few thousand seconds was later extended to audio frequencies and higher, a few Kilo-Hz, specifically, between 0.0001Hz and 10,000Hz (Dobrin, 1988; Harinarayana, 2008).

The origin of the source energy for the frequency range below 1Hz is accounted for by the micro-pulsations of the natural EM field resulting from disturbances in the ionosphere, caused primarily by the interaction of the solar wind with the Earth’s magnetic field. As solar storms emit streams of ions, this energy disturbs the Earth’s magnetic field and causes low frequency energy to penetrate the Earth’s surface (Christopherson, 1999). Micro-pulsations strength varies with the diurnal variations (rise and fall) of the ionosphere and is strongly dependent on the presence and magnitude of solar flares causing what is known as electron mass ejection (ems). This effect produces what is known as the magnestosphere (Fig. 1a). Variations in the density, velocity, and intensity of the solar wind produce time-varying EM fields. Together, these natural sources provide the primary EM fields to excite the Earth. The energy of the ionospheric source increases significantly as frequency decreases, and this accounts for the high penetrating power of natural-field source signals (Mosnier, 1985). The mechanism of inducing telluric current in the earth by ionospheric current is that of an electromagnetic field propagated with slight attenuation over large distances in the space between the ionosphere and earth surface (Tamrat, 2010).

At frequencies higher than 1 Hz, most of the energy originates from electrical phenomena in the atmosphere, such as lightning during thunderstorms (Fig. 1c). A number of major storm centers could be found in the equatorial regions having an average of 100 stormy days per year (Gutro, 2020). The EM energy which has its source from distant lightning strokes travel in a guided-wave mode, with energy being reflected back and forth between the conductive surface of the Earth and the ionized layers of air in the ionosphere (Fig. 1b). The weak currents induced by these EM fields in the Earth subsurface is useful in telluric and magnetotelluric prospecting, particularly because they have amplitude peaks at several distinct frequencies (Telford et al., 1976).

Starting from the separate pioneering works of Tikhonov (1950) and Cagniard (1953), some significant attention has been given to both tellurics and magnetotellurics as natural-source EM methods by explorers. These two researchers, and many others generally accepted at least as a working principle that natural sources generate plane EM waves at the surface of the earth, and due to the large resistivity contrast between the more conductive earth and the air, these plane EM waves have the ability to penetrate to great depths vertically into the earth (Dobrin, 1988; Harinarayana, 2008). The assumption that the incoming natural-source EM has plane wave characteristic, makes it adaptable in telluric and MT works. The validity of the plane wave assumption was questioned by Wait (1954), but was resolved by Price (1962), and Madden and Nelson (1964) who showed that the assumption was acceptable for frequencies greater than $10^{-3}$ Hz in mid-latitudes (Harinarayana, 2008). In addition to this, Hermance and Peltier (1970), studied the effect of equatorial and auroral electrojet wind current and concluded that in generally conductive environments, the basic source assumptions still hold for frequencies
between $10^{-4}$ and 1 Hz. Banister (1969), also showed that for the high-frequency part of the spectrum, the plane-wave assumption was valid (Dobrin, 1988; Harinarayana, 2008).

Finally, study has shown that the magnetic induction field vector $\mathbf{H}$ generated by ionospheric and thunderstorm activities at a given spot on the Earth’s surface produces a plane wave that penetrates vertically into the geology.

![Fig. 1 (a)](Source: Geophyimages/mt_magn.png)

**Fig. 1 (a)**
Interaction between the solar wind and Earth’s magnetic field creates the magnetosphere, which is a natural source of EM fields below 1 Hz.

![Fig. 1 (b)](Source: Geophyimages/mt_magn.png)

**Fig. 1 (b)**
EM waves generated by lightning, bounce between the Earth’s surface and the highly conductive ionosphere, and travel as plane waves.

![Fig. 1 (c)](Source: Geophyimages/mt_magn.png)

**Fig. 1 (c)**
Lightning is one of the natural EM sources that allows MT be used.

2. **Theoretical background**

2.1 **Solution of Maxwell’s Electromagnetic Wave Equations**

Employing Maxwell’s work on electromagnetism, the four fundamental equations emanating from the well-known principles of Ampere’s and Faraday’s laws related to electrical and magnetic fields which solved the problem of EM waves propagating through a layered medium such as the Earth are stated as follows:

\[
\nabla \times \mathbf{E} = 0 \quad \text{(1)}
\]

\[
\nabla \times \mathbf{H} = -\mu \frac{\partial \mathbf{E}}{\partial t} \quad \text{(3)}
\]

\[
\nabla \cdot \mathbf{E} = 0 \quad \text{(2)}
\]

\[
\nabla \cdot \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \quad \text{(4)}
\]

Taking the curl of equation (3) gives (Halliday, 1978; Gupta, 1980; Griffiths, 2007; Erkan, 2008; Fitzpatrick, 2013):

\[
\nabla \times (\nabla \times \mathbf{E}) = \nabla (\nabla \cdot \mathbf{E}) - \nabla \mathbf{E} = -\nabla \times \left( \mu \frac{\partial \mathbf{H}}{\partial t} \right) = -\mu \sigma \frac{\partial \mathbf{E}}{\partial t} - \varepsilon \mu \frac{\partial^2 \mathbf{E}}{\partial t^2}, \quad \text{and since, } \nabla \cdot \mathbf{E} = 0,
\]

\[
\nabla^2 \mathbf{E} = \mu \sigma \frac{\partial \mathbf{E}}{\partial t} + \varepsilon \mu \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad \text{(5)}.
\]

Similarly,

\[
\nabla^2 \mathbf{H} = \mu \varepsilon \frac{\partial \mathbf{H}}{\partial t} + \varepsilon \mu \frac{\partial^2 \mathbf{H}}{\partial t^2} \quad \text{(6)}
\]

where $\mathbf{H} =$ magnetic field intensity, $\mathbf{E} =$ electric field intensity, $\mu =$ permeability, $\varepsilon =$ permittivity or dielectric constant and $\sigma =$ conductivity of medium.

Tikhonov (1950) and Cagniard (1953) further analyzed the equations and proposed a relation between the resistivity of a medium and electric-magnetic field variations giving birth to a new geophysical method, namely ‘the Magnetotellurics’ (Harinarayana, 2008).
In MT work, sinusoidal time-varying electromagnetic fields are generally chosen such that:

\[
E(t) = E_0 e^{i\omega t}, \quad H(t) = H_0 e^{i\omega t}; \quad \frac{\partial E}{\partial t} = j\omega E \quad \text{and} \quad \frac{\partial H}{\partial t} = j\omega H,
\]

where \( \omega = 2\pi f \) is the angular frequency of the field and \( j \) is the imaginary notation having a value of \( \sqrt{-1} \).

Equations (5) and (6) can then be simplified to:

\[
\nabla^2 E = j\omega \mu \sigma E \quad \text{and} \quad \nabla^2 H = j\omega \mu \sigma H - \omega^2 \varepsilon \mu H
\]

(7), (8)

The first and second terms on the right hand side of equations (7) and (8) represent the conduction and displacement currents respectively. These two equations are the electromagnetic equations for propagation of electric and magnetic field vectors in an isotropic homogeneous medium which has conductivity, \( \sigma \) relative permeability, \( \mu \) and dielectric permittivity, \( \varepsilon \) (Ramo, et al., 1965).

In the case of a conducting medium, the displacement current \( \frac{\partial D}{\partial t} \) is negligible in comparison with the conduction current, which implies that \( w \varepsilon \ll \sigma \) (Ramo, et al., 1965; Shunjiro, et al., 1996; Griffiths, 2007; Fitzpatrick, 2013). Thus, equations (7) and (8) is reduced to

\[
\nabla^2 E = j\omega \mu \sigma E \quad \text{(9)}
\]

And, \( \nabla^2 H = j\omega \mu \sigma H \quad \text{(10)} \)

while the equation for the current density \( \nabla^2 J = j\omega \mu J \quad \text{(11)} \)

Solving the differential equations (9), (10) and (11) requires imposing boundary condition of certain physical shapes of interest for practical conductors.

Consider for example, a plane conductor of infinite depth and with no field-variations along the width or length dimension. This case is frequently taken as that of a conductor filling the half space \( z > 0 \) in a rectangular coordinate system with the \( x-y \) plane coinciding with the conductor surface and then spoken of as a “semi-infinite solid” (Ramo, et al., 1995).

Assume the wave is propagating along the \( z \)-axis so that the \( xy \) plane is the plane of polarization. Equation (10) then becomes:

\[
H_y = \frac{\partial^2 H_y}{\partial z^2} = j\omega \mu \sigma H_y = \gamma^2 H_y
\]

(12), where \( \gamma^2 = j\omega \mu \sigma \) \( \quad \text{(13)} \)

Since the field is time-varying, we try a solution of the form

\[
H_y = H_0 e^{i\omega t - \gamma z}
\]

(14) in equation (12) to obtain

\[
\frac{\partial H_y}{\partial z} = \gamma H_0 e^{i\omega t - \gamma z} \quad \text{and} \quad \frac{\partial^2 H_y}{\partial z^2} = -\gamma^2 H_0 e^{i\omega t - \gamma z}
\]

and, \( \frac{\partial H_y}{\partial t} = j\omega H_0 e^{i\omega t - \gamma z} \) and \( \frac{\partial^2 H_y}{\partial t^2} = -\omega^2 H_0 e^{i\omega t - \gamma z} \)

Using equation (15) in (12), the result is

\[
H_0 e^{i\omega t - \gamma z} - j\omega \mu \sigma H_0 e^{i\omega t - \gamma z} \quad \text{or} \quad \gamma^2 = j\omega \mu \sigma
\]

Hence, \( \gamma = \frac{\sqrt{1+i}}{\sqrt{2}} \sqrt{j\omega \mu \sigma} = \sqrt{i\omega \mu \sigma} \)

(16), but \( \sqrt{i} = \frac{\sqrt{2}}{\sqrt{2}} = \frac{\sqrt{1+2i+1}}{\sqrt{2}} = \frac{(1+i)^{1/2}}{\sqrt{2}} \)

From equation (16), \( \gamma = \frac{(1+i)}{\sqrt{2}} \sqrt{j\omega \mu \sigma} = (1+i) \frac{\sqrt{\omega \mu \sigma}}{\sqrt{2}} \), and equation (14) can be written as

\[
H_y = H_0 e^{i\omega t - (1+i) \frac{\sqrt{\omega \mu \sigma}}{\sqrt{2}} z} =
\]

\[
H_0 e^{i\omega t - \frac{\sqrt{\omega \mu \sigma}}{\sqrt{2}} z} |\frac{\omega \mu \sigma}{\sqrt{2}}|^2 \}
\]

The real amplitude \( H_0 e^{-\frac{\sqrt{\omega \mu \sigma}}{\sqrt{2}} z} \) is the dominant as the complex amplitude \( H_0 e^{i\omega t - \frac{\sqrt{\omega \mu \sigma}}{\sqrt{2}} z} \) has no physical significance. Thus, taking the real part as the required solution, we have
H_y = H_0 e^{-\left(\frac{\sqrt{\omega \mu \sigma}}{2} z\right)} \cos(\omega t - \frac{\sqrt{\omega \mu \sigma}}{2} z)

(18) (Jordan, 1968).

The second part of the expression in equation (18) represents simple harmonic with a phase shift while the exponential is the attenuation of the wave with propagation distance.

### 2.2 Attenuation of electromagnetic waves

Electromagnetic wave is attenuated in traveling through some media but not in free space. The exponential part of equation (18), that is $e^{-\left(\frac{\sqrt{\omega \mu \sigma}}{2} z\right)}$ is referred to as the attenuation factor. Using equation (18) and setting

$$\sqrt{\frac{\omega \mu \sigma}{2}} = \frac{1}{\delta}$$

(19),

And gives the complete solution of equation (12) as

$$H_y = H_0 e^{-z/\delta} \cos(\omega t - z/\delta)$$

(20),

$$E_x = E_0 e^{-z/\delta} \cos(\omega t - z/\delta)$$

(21), and

$$J_x = J_0 e^{-z/\delta} \cos(\omega t - z/\delta)$$

(22)

Where, $H_0$, $E_0$ and $J_0$ are respectively the magnitudes of the magnetic field, the electric field and the current density at the surface.

The symbol $\delta$ represents skin depth = distance traveled by the EM along the direction of propagation at which the signal is reduced by $1/e$ of its original value, that is to 37% of its original value at the surface (Ramo et al., 1965; Griffiths, 2007).

$z/\delta$ radians = phase angle of the current and fields as they lag behind their surface values at a depth $z$ into the conductor, implying that EM waves get attenuated exponentially.

From equation (19), skin depth $\delta = \sqrt{\frac{2}{\omega \mu \sigma}} = \sqrt{\frac{1}{\Pi \mu \sigma}}$

(23)

is a function of frequency of propagation for some common materials? It also depends on the conductivity, $\sigma$ of the medium, as well as its permeability $\mu$. Thus, $\delta \alpha \frac{1}{\sqrt{\mu \sigma}}$.

The physical interpretation of the functional expression for skin depth of EM waves is that, the high penetration of the electromagnetic waves into the earth. Lower frequencies decay more slowly with depth and penetrate deeper, according to the attenuation factor $e^{-\left(\frac{\sqrt{\omega \mu \sigma}}{2} z\right)}$ of the equation (18),

The attenuation term of equation (20) could be written as $|H_y| = e^{-\left(\frac{\sqrt{\omega \mu \sigma}}{2} z\right)}$.

Assuming $\mu = \mu_0 = 1.3 \times 10^{-6}$ H/m, and $\sigma = \frac{1}{\rho} = \frac{1}{\sqrt{\rho \sigma}}$, then $|H_y| = e^{-\left(\sqrt{2\Pi\tau\times1.3 \times 10^{-6}}\right)z}$

$$|H_x| = e^{-2\times10^{-3}\times z\sqrt{\tau/\rho}}$$

(24)

Since skin depth is distance traveled by the electromagnetic wave in which the signal ratio is reduced to $1/e$ of its original value, therefore, skin depth could be calculated from the expression: $|H_y| = e^{-z/\delta} = e^{-1}$, (where $z = \delta$)

(25)

Equating (24) to (25) gives $2 \times 10^{-3} \sqrt{\tau/\rho} = 1$, or skin depth $\delta = \frac{1}{2 \times 10^{-3} \sqrt{\tau/\rho}} = \frac{1000}{\sqrt{\rho \tau}}$, which implies that $\delta = 500 \left(\sqrt{\rho/\tau}\right) = 500 \left(\sqrt{\rho T}\right)$, where $T$ = period of the wave. Equation (24) shows resistivity dependence of frequency (Fitzpatrick, 2013).

### 2.3 Relevance of electromagnetic wave equations in solving telluric current and magnetotelluric field problems

In adapting the EM wave equations to tellurics and magnetotellurics, the following basic assumptions are to be made:
(i) Frequencies are considered so low that displacement currents are negligible,
(ii) For plane waves of this type, it is clear that horizontal variations E and H are small compared with vertical variations,
(iii) Since the fields are so erratic, only periodic frequency variations are considered (Telford et al., 1976).

By consistently taking the xy-plane as horizontal and z positive downward, it is possible to express these conditions mathematically in the form:

\[ \frac{\partial E}{\partial t} = 0, \quad \frac{\partial H}{\partial t} = 0, \quad \text{E } \propto e^{-j\omega t}, \text{H } \propto e^{-j\omega t}, \quad \frac{\partial}{\partial t} = -j\omega \]

Suppose the wave is polarized in the xy–plane and traveling in the z–direction, making the magnetic vector \( H_0 \) at an angle \( \theta \) to the x–axis so that the magnitudes of the magnetic components are:

\[ H_{x0} = H_0 \cos \theta, \quad H_{y0} = H_0 \sin \theta \]

(26)

It is possible to write

\[ H_x = (H_0 \cos \theta) e^{-z/\delta} \cos (\omega t - z/\delta) \]

(27)

Equation (4) produces

\[ E_x = \frac{1}{\sigma} \left( x \text{– component of } \nabla \times H \right) = \frac{1}{\sigma} \left[ -\frac{\partial H_y}{\partial z} \right] = \frac{1}{\sigma} \left( \frac{\partial}{\partial z} \right) H_y \]

\[ = -\frac{1}{\sigma} (H_0 \sin \theta) e^{-z/\delta} \left\{ -\frac{1}{\delta} \cos \left( \omega t - \frac{z}{\delta} \right) + \frac{1}{\delta} \sin \left( \omega t - \frac{z}{\delta} \right) \right\} \]

Ultimately,

\[ E_x = \sqrt{2} \frac{1}{\sigma \delta} (H_0 \sin \theta) e^{-z/\delta} \cos \left( \omega t - \frac{z}{\delta} + \frac{n}{4} \right) \]

(28)

Similarly,

\[ E_y = \sqrt{2} \frac{1}{\sigma \delta} (H_0 \cos \theta) e^{-z/\delta} \cos \left( \omega t - \frac{z}{\delta} + \frac{n}{4} \right) \]

(29)

Dividing (28) by (27) and (29) by (26), the following equations are obtained:

\[ \frac{E_x}{H_y} = \sqrt{2} \frac{1}{\sigma \delta} \frac{(H_0 \sin \theta)}{(H_0 \cos \theta)} e^{-z/\delta} \cos \left( \omega t - \frac{z}{\delta} + \frac{n}{4} \right) \]

\[ = \sqrt{2} \frac{1}{\sigma \delta} \cos \left( \frac{\omega t - z/\delta + n/4}{\delta} \right) \]

(30)

\[ \frac{E_y}{H_x} = \sqrt{2} \frac{1}{\sigma \delta} \frac{(H_0 \cos \theta)}{(H_0 \cos \theta)} e^{-z/\delta} \cos \left( \omega t - \frac{z}{\delta} - \frac{n}{4} \right) \]

\[ = \sqrt{2} \frac{1}{\sigma \delta} \cos \left( \frac{\omega t - z/\delta - n/4}{\delta} \right) \]

(31)

Squaring the ratios of the amplitudes in (30) and (31) we find that

\[ \left| \frac{E_x}{H_y} \right|^2 = \left| \frac{E_y}{H_x} \right|^2 = 2 \frac{1}{\sigma \delta} \frac{\cos^2 \left( \omega t - z/\delta + \frac{n}{4} \right)}{\cos^2 \left( \omega t - z/\delta \right)} \]

\[ = 2 \left( \frac{\omega \mu_0}{\sigma_0 \delta} \right)^2, \text{ by approximation} \]

\[ = 2 \left( \frac{\omega \mu_0}{\sigma_0 \delta} \right)^2 = \frac{\omega \mu_0}{\sigma_0 \delta} = \omega \mu \rho \]

(32)

Where, \( 1/(\text{skin depth}) \), \( \delta^{-2} = \frac{\omega \mu_0}{\sigma_0 \delta} \) and \( \rho = \text{resistivity} = \frac{1}{\sigma} \) (Shunjiro, et al.,1996; Fitzpatrick, 2013)

If \( \sigma \) is assumed to be the effective conductivity in a penetration depth \( z \), one can approximate values of \( z \) and \( \sigma \) by replacing \( \frac{1}{\sigma} \) by \( \frac{1}{z} \) in equation (28), where

\[ E_x = \frac{1}{\sigma} \left( -\frac{\partial H_y}{\partial z} \right) H_y \text{ or } E_x = -\frac{1}{\sigma} \frac{1}{z} H_y \text{ or } z \sim \frac{1}{\sigma} \frac{1}{z} H_y \]

Replacing \( \omega \) by \( \frac{2\pi}{T} \) and using equation (32),

\[ z \sim \frac{1}{\sigma} \frac{1}{z} \frac{H_y}{H_x} \sim \frac{1}{\sigma \sqrt{\omega \mu_0}} \sim \frac{1}{\omega \mu_0} \frac{\sqrt{\omega \mu_0}}{\mu_0} \]

\[ \therefore z = \frac{T}{2\pi\mu} \frac{E_x}{H_x} \]

(33)

and \( \rho = \frac{T}{2\pi\mu} \frac{|E_x|^2}{|H_x|^2} \)

(34)

Putting \( \mu \approx \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \) and making use of \( \text{mV/Km} \) for E, gamma for H,
Km for $z$, $z \sim \frac{T}{2\mu_0} \left(\omega \mu_0\right)^{1/2}$ or $z = \frac{1}{2\mu_0} \sqrt{\frac{5\rho T}{m}}$ (35)

and $\rho_a \sim 0.2T \text{ S} \Omega \text{m}$ (36) (Shunjiro, et al.,1996; Fitzpatrick, 2013)

These two equations reveal the possibility of measuring the amplitudes of orthogonal horizontal components of the electric and magnetic fields by applying natural earth currents for various frequencies and from that determine the variation of the apparent resistivity, $\rho_a$ of the subsurface body and depth of burial, $z$.

3. Results and discussion

3.1 Case histories of magnetotelluric field works

Successful MT geological surveys done by past researchers at designated locations across the globe are presented in this section. These relate to oil, gas and geothermal explorations, deep crustal studies and engineering problems. An example is the MT group at the National Geophysical Research India (NGRI) that conducted several MT investigations to tackle various geological problems beginning from the 70’s, published by Memoir Geological Society of India. No. 68, 2008, pp 337-356, shown in Figures 2(a-e).

![Fig. (a) Location of all MT stations occupied in different geological terrains distributed all over India. A total of about 2700 stations were occupied for the last 3 decades (1980-2008)](image1)

![Fig. (b) Anomalous high conductive zone is delineated near epicentral zone, which leads to interpretation for the presence of fluid field](image2)

![Fig. (c) Thick sediments towards EW direction of Saurashtra. A breakthrough result in India which has opened up a new scenario for the MT in India for oil exploration.](image3)

![Fig. (d) Geoelectric section from 2D modeling of the data in Puga showing anomalous conductive feature related to deep geothermal reservoir at a depth of about 1.5 km.](image4)

![Fig. (e) Thick sediments buried below 1.5 km thick trap cover is indicated towards NW quadrant of Saurashtra from MT study and other geophysical methods in the integrated studies](image5)

(Fig. 2a-e: Source: MT surveys performed by National Geophysical Research Institute India, 1980-2008), courtesy of Harinarayana Tirumalachetty (2008) in Applications of Magnetotelluric Studies in India (2008). Memoir Geological Society of India. No 68, pp337-356.)

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Magnetotelluric exploration field surveys were also carried out by Phoenix Geophysics Ltd. in China which was funded by New Energy Development Organization (NEDO) of Japan, involving 4-D or "time-lapse" MT shown in Figures 3 (a) and (b).

Fig. 3(a): Using MT to map subsurface resistivity changes in and around the 1 km-deep steam-producing zones at the Ogiri Geothermal Field in West Japan. (Source: Phoenix Geophysics Ltd. 2003).

Fig. 3(b): Groundwater Survey in China: showing pseudosection (top) and inversion (bottom) of ATM resistivity over a fracture zone in East China. Phoenix AMT equipment was used to explore for hot water that might be applied for hot spring resorts and for heating homes and greenhouses (Source: 5th Division, Phoenix Geophysics Ltd. 2000). In addition, Figures 4(a-c) represent reflections on the MT work done around the globe and published by the ‘EXPLORER’ in The Geophysical Corner, a publication of the American Association of Petroleum Geologists (AAPG).

Figure (a) – An example of MT apparent Resistivity curves (in ohm-meters) vs. frequency (in Hertz).  
Fig. (b) – An MT resistivity section in the Colombia Plateau.
3.2 Advantages of the natural-source EM geophysical techniques

Magnetotelluric method becomes the only practicable method in some cases where other geophysical methods such as seismic, gravity and electrical resistivity have failed, especially, in localities such as basalt-covered areas (Harinarayana 2008). MT is the only practical technique for sensing such deep resistivity changes, because it “sees” deeper than other EM techniques (Phoenix Geophysics Ltd., 2003). MT works best where seismic has problems, i.e. areas of high-velocity cover such as volcanic provinces (Christopherson, 1999). Due to power requirements, EM sounding has generally been limited to depth of a few kilometers or less, whereas natural-field methods can be used to sound through the crust and in the upper mantle (Manzella, et al., 2015).

For reconnaissance studies and deep soundings, controlled-source EM sounding may be more expensive than natura-source sounding (Manzella, et al., 2015). In contrast to direct-current (dc) methods, most EM methods are effective in resolving the parameters of conductive layers (Manzella, et al., 2015). Due to large resistivity contrast between volcanic rock and the buried sediments, MT is proved to be superior as compared to other geophysical methods as demonstrated in India and also at many locations around the world (Harinarayana 2008).

Geophysical exploration using natural field source signals enhances greater penetrating power into the geo-electrical medium (the earth) than most other geophysical exploration methods suffering little or no attenuation, if the lower range of the frequency spectrum is used (Tamrat, 2010). Apart from petroleum exploration, the sensitivity of natural-field EM techniques to conductive anomalies make them especially suitable for geothermal energy sources, giving it greater preference over other methods (Tamrat, 2010). MT costs less than controlled-source EM because MT requires no man-made energy source (Soupis and Kokinou, 2017). MT can be applied in lead of seismic to help determine the best placement of seismic lines (Christopherson, 1999).

The HSE impact of MT exploration is relatively low because of light-weight equipment, natural signal sources, and reduced hazards compared to other types of exploration, e.g. no drills, no explosives, and no high currents (Wikipedia, retrieved May 3, 2020). Source availability at all times and anywhere on the surface of the earth gives another preference to the natural-source EM methods (Xin, et al., 2017). The plane-wave characteristic of the natural EM source signal makes its study easier and peculiar (Cagniard, 1953; Harinarayana, 2008).

Natural-source EM array techniques presents a significant improvement over older EM methods by using high redundancy, adequate spatial sampling, and proper array design, are capable of yielding high resolution and reducing the effects of the near surface on the resolution of deeper formations (Caldwell, 1993).

Unlike other geophysical methods such as gravity, seismics, magnetics, etc.,
which depend on the density, velocity, and susceptibility respectively, MT method depends mainly on a wide range of electrical resistivity ($10^4$ to $10^6$ Ohm. m) of the Earth (Erkan, 2008).

### 3.3 Limitations of the natural-source EM geophysical techniques

Adequate or not, whatever is provided from the natural-source is applied (Christopherson, 1999). The natural source can be very weak, especially in the middle-frequency range around 0.5 to 5Hz (Christopherson, 1999). Most EM methods are less effective in determining the resistivity of resistive layers (Manzella, et al, 2015). Natural-source EM fields vary in strength over hours, days, weeks and even over the sunspot cycle of about 11 years (Christopherson, 1999).

Natural-source EM methods measurements take hours at each station for good signal to ensure high quality data, especially when using low frequencies (Christopherson, 1999).

Most applications of natural-source EM methods have been reconnaissance of large relatively unexplored basins, generally used as a prelude or supplement to seismic exploration or as a substitute for seismic survey where surveys yield poor or no results (Unsworth, 2005). Many noise sources such as electrical generators, switching stations, underground pipelines with electrical corrosion protection, the seismic-electric effect from microseism, or even electrical fences, radio transmitters and microwave repeater stations can interfere with the natural-source information (Dobrin, 1988).

The origin of the natural-source EM signal has been traced to micropulsations of the natural EM field caused by disturbances in the ionosphere, as well as thunderstorm activities, both occurring at different frequency ranges. So also, the plane wave characteristic of the natural-source EM signal has been described. More importantly, the significance of the Maxwell’s electromagnetic wave equations to solving natural-source EM geophysical problems was explored. The time-varying electromagnetic fields were considered sinusoidal leading to the wave equations:

$$\nabla^2 \mathbf{E} = j\omega \mu \sigma \mathbf{E}$$

$$\nabla^2 \mathbf{H} = j\omega \mu \sigma \mathbf{H}$$

which were solved to give

$$H_y = H_0 e^{-z/\delta} \cos(\omega t - z/\delta)$$

and

$$E_x = E_0 e^{-z/\delta} \cos(\omega t - z/\delta)$$

where $H_y$ and $E_x$ are the horizontal components of the magnetic and electric fields respectively measured at the surface of the earth, while

$$z = \text{depth of penetration of wave},$$

$$\delta = \text{skin depth, having a value } \sqrt{\frac{2}{\omega \mu \sigma}}.$$  

Adapting EM equations to tellurics and magnetotellurics, the solutions of the equations resulted in the mathematical expressions:

$$z = \frac{1}{2\pi} \sqrt{5\rho T} \text{ Km,}$$

$$\rho_a = 0.2T \left| \frac{E_x}{H_y} \right|^2 \Omega \text{ m}$$

where $\rho_a = \text{apparent resistivity of the subsurface}$ and $T = \text{period of transmission of wave}.$

### Conclusion

In summarily, by applying the electromagnetic wave equations to telluric and magnetotelluric methods of geophysical explorations for various pre-determined frequencies, the apparent resistivity, $\rho_a$ with depth of penetration, $z$ could be determined precisely by measuring the orthogonal horizontal components of the electric and magnetic fields at the surface of the Earth.
As would be observed, the natural-source has increased energy in low frequencies and is generally sufficient to ensure significant penetration even in conductive materials, though sacrificing resolution. The MT survey requires detection of both magnetic fields and electric field components. In the telluric method, it is only necessary to measure the electric field associated with the earth currents. Thus, the latter technique is simpler and requires less equipment. However, the amount of information derived from tellurics is considerably less than that from MT work. Finally, the natural fields and currents have greater advantages over other methods of geophysical surveys. Typical MT geophysics surveys for diverse applications, which were conducted by researchers at different locations around the world were presented as case histories in this study.

References


Babarinde Boye Timothy and Nwankwo Levi I.: A review of the application of telluric and magnetotelluric methods in geophysical exploration

Geological Survey of Ethiopia (GSE).


