Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Magnetotelluric Method and Instrumentation for Geothermal Prospecting

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Keywords: Magnetotellurics, prospecting, instrumentation, remote reference, data processing.

ABSTRACT

Aquifers are usually characterized by low electrical resistivity due to conductive fluid presence in the interconnected pores. In geothermal regions this resistivity is still lower because the ions of dissolved minerals in the hot water possess higher mobility which increases the conductivity of solution. All inductive electromagnetic (EM) methods of geophysics reliably resolve highly conductive bodies or layers in the subsurface. Among other, the magnetotelluric (MT) one has several advantages. The most important one is that it is basically non destructive for environment, since it utilize the natural geomagnetic field variations as a source. MT allows recording of the EM field variations in a wide frequency (periods) band what directly relates to different depth of exploration. To this, with recent progress in instrumentation parameters and modern approaches development to data processing and interpretation the application of MT method became very useful and cost efficient for geothermal study.

It has to be stressed that the successful application of MT method greatly depends on the used instrumentation parameters. The wide band MT station (audio MT or AMT) may be considered as the most suitable instrument for the geothermal research. The frequency band from 0.001 to 10000 s allow us to study the subsurface conductivity distribution from a few hundred (sometimes even from a few tens) of meters to tens of kilometers. The most important parameters of corresponding MT instruments, their recent upgrade in modern wide band AMT instruments are presented and compared.

It is necessary also to mention that increasing data processing quality postulates, following from the recent practice of the MT results, the application of remote reference technique with simultaneous using as a minimum of two synchronously operating MT instruments. The details of such processing procedures with corresponding examples are discussed in our report also.

1. INTRODUCTION

Electrical resistivity is a primary physical property of the Earth crust strongly influenced by hydrothermal processes in geothermal reservoirs. Geothermal-water-rich rocks commonly have relatively lower resistivity than surrounding rocks, and the variation in the resistivity is related to the water abundance, temperature, and degree of mineralization. The rock matrix itself is an insulator and electric conduction occurs through an aqueous solution of common salts distributed throughout the pores of rocks, and through the alteration minerals, see Spichak and Manzella (2009). At moderate temperatures, 0-200°C, the resistivity of an aqueous solution decreases with increasing temperature. This is because of increasing mobility of the ions caused by a decrease in the viscosity of the electrolytic solution. But at higher temperatures, a decrease in dielectric permittivity (ε) of water results in a decrease in the number of dissociated ions in the solution. Above 300°C, this starts to increase the fluid resistivity. The effect of temperature variations is greatest at low temperatures (less than 200°C), but decreases at higher temperature when other factors, such as porosity, salinity and alteration mineralogy become dominant, see Manzella (2007). Thus, the geothermal structures are characterized by high electrical conductivity. Such high conductive anomalies have generally been the main target for the geophysical exploration of geothermal resources by MT method; see Simpson and Bahr (2005).

Several EM methods of prospecting geophysics which allow mapping the resistivity distribution of the subsurface are typically involved into the study of geothermal areas. The most common methods used for the geothermal exploration are the direct current (DC) soundings mostly such as Schlumberger sounding, the time domain or transient electromagnetic (TEM) soundings with the in-loop configuration as well as the magnetotelluric soundings, see Arnason (1989), Spichak and Manzella (2009), Cumming and Mackie (2010), Zhang et al. (2015). The EM methods utilize measurements of a variety of effects related to electrical current flow within the earth. The DC method employs measurements of an electrical potential distribution associated with the subsurface electrical current generated by a DC source. The TEM method allows imaging of the subsurface conductivity distributions by analyzing the non-stationary transient process of the EM field decay in the conductive medium due to the step current excitation described by the Heaviside function. The fluctuations of the natural magnetic field of the Earth and the induced electric field are measured with the MT method and their ratio is used to determine the apparent resistivity of the subsurface. Since the DC and TEM are the controlled source methods their prospecting depth is restricted to a few hundreds of meters in best case with the use of reasonable power. However, this is impractical in most in field cases.

The natural EM field variations contain a very wide spectrum of frequencies - from the very low frequencies generated by ionospheric and magnetospheric currents that arise when plasma emitted from the Sun interacts with the Earth's magnetic field till the higher frequencies caused mainly by thunderstorms in low latitudes. These variations in turn induce eddy currents in the conductive Earth. At the same time, the depth of diffusion is proportional to the period of variation or opposite to the frequency. The frequency range of these variations used for applied MT prospecting covers the band from ~10^{-4} till ~10^{4} Hz. Using these fluctuations, the MT method alone can supply the information about conductivity distribution in subsurface from few hundreds of meters to tens of kilometers which in most cases are the depths of interest at geothermal research. This method was proposed still last century, see Tikhonov (1950), Cagniard (1953). As far as MT method utilizes the natural geomagnetic field variations as a source, it is basically non destructive for environment. Besides to be the environmental friendly, it is very compact one and there are numerous examples of its successful use in lonely and mountain area. To this, the MT method is typically the most cost-effective one so MT is often the default geophysics method applied for geothermal exploration.

This explains its wide application to the geothermal areas study worldwide, few examples may be given. The area over 300 km^2 at the Glass Mountain known geothermal resource area in northern California was covered by approximately 200 MT soundings sites, see Cumming and Mackie (2010). In December 2014, 33 MT stations were deployed to cover the 6×8 km area of interest surrounding the Fang Hot Springs in Thailand, see Amatyakul et al. (2016). To delineate the geoelectrical structure and provide geophysical evidence for the exploitation and evaluation of geothermal resources in the area next to Hailin, Mudanjiang, northeastern China, the MT investigation was conducted involving measurements at 18 sites distributed along three parallel profiles, see Zhang et al. (2015). And there are several cases of using MT in the Iceland, see for example Hersir at al. (2015).

2. MT METHOD AND ITS APPLICATION

The experimental MT data are time series of horizontal electric (*Ex, Ey*) and magnetic (*Hx, Hy*) orthogonal field components recorded with the help of a MT station placed at the Earth's surface at site of interest. Such components in the frequency domain are coupled by the following relationship:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix}, \tag{1}$$

where Z_{ij} are the components of the complex impedance tensor, x and y are field components in North and East directions, respectively.

The simplest approach to find the tensor elements is by minimizing the sum of squares of the electric field residuals $r_{x1...N}$ and $r_{y1...N}$ from the overdetermined system of equations based on the Fourier coefficients at a single frequency which are typically based on the Welch overlapped section averaging approach, see Marple (1987):

$$\begin{pmatrix} E_{x1} & E_{y1} \\ \vdots & \vdots \\ E_{xN} & E_{yN} \end{pmatrix} = \begin{pmatrix} B_{x1} & B_{y1} \\ \vdots & \vdots \\ B_{xN} & B_{yN} \end{pmatrix} \begin{pmatrix} Z_{xx} & Z_{yx} \\ Z_{xy} & Z_{yy} \end{pmatrix} + \begin{pmatrix} r_{x1} & r_{y1} \\ \vdots & \vdots \\ r_{xN} & r_{yN} \end{pmatrix}. \tag{2}$$

In a matrix notation, it can be resumed by: $E = BZ + r$, which is yielding.

$$Z = (B^H B)^{-1} (B^H E), \tag{3}$$

where $(B^H B)$and $(B^H E)$ are the averaged auto-power and cross-power spectra respectively based on the total available data, the superscript H denotes the conjugate transpose of complex matrix.

It is well known that even a small amount of spikes in residuals, which not obey to the Gaussian distribution, might have a strong influence to the final estimate. This leads to applying different kinds of robust schemes including coherency threshold criteria, see Semenov (1998), Smirnov (2003) which are often based on the regression M-estimate, see Huber (1981). The algorithm, similarly to the least squares method, minimizes a norm of the scaled residuals:

$$min\left\{\sum_i w_i \, |r_i|^2\right\}$$

and is usually based on the weighted least squares method applied iteratively to the overdetermined system of equations (2), see Eisel and Egbert (2001), Chave and Thomson (2004). Thus:

$$Z = (B^H w B)^{-1} (B^H w E), \tag{4}$$

where w is a diagonal matrix of weights w_i which are computed based on the residuals r_i and some robust estimate of the error scale which are usually derived from median absolute deviation of residuals obtained from a previous iteration. Thus, starting from the standard least square estimation (3) the iterative algorithm is repeated until some convergence threshold in residuals.

When a single MT station is used the inverse auto-spectra $(B^H B)^{-1}$ are appeared in the equations (3) and (4) which leads to impedance values biased downward by noises in the horizontal magnetic components. The remote reference method, see Gamble et al. (1979), Clarke et al. (1983), exploits supplementary data, usually the horizontal magnetic components from a simultaneously operating remote site for reducing the influence of local noise. The minimization of the residuals magnitude, see Chave and Tomson (1989), allows generalizing the robust algorithm to this remote reference case:

$$Z = (B_R^H w B)^{-1} (B_R^H w E), \tag{5}$$

where B_R is the horizontal magnetic field at the remote site. Equation (5) shows that the remote reference estimates will not be biased downward by noise in the local magnetic field if the noise is not correlated between the two sites.

Thus modern requirements to the reliability of MT results oblige the simultaneous data recording by at least two separated MT stations. The corresponding MT data processing algorithm was realized in the specially developed LEMIGRAPH software. A more detailed description of the mathematical background involved into this algorithm may be found in Ladanivskyy et al. (2018).

Similar approach may also be applied to the geomagnetic depth sounding data since the vertical magnetic component *Bz* is usually recorded simultaneously with horizontal ones by any MT station what allows obtaining magneto-variation transfer functions also known as tippers or induction arrows. Unlike MT impedance, the tippers are related to the gradients of conductivity in the subsurface, see Parkinson (1983).

Near-surface resistivity inhomogeneities can distort the electrical field, since the field is not continuous across a resistivity boundary. It shifts the MT apparent resistivity sounding curves by some constant scale factor downward or upward that, if this effect is not properly dealt with, may lead to wrong and misleading interpretation of the data. This galvanic distortion effect is known as static shift and is a potential source of distortion shared by most resistivity methods that use electrodes. EM methods, which only measure magnetic fields, do not have the static shift problems that affect MT soundings (Simpson and Bahr, 2005). The most common approach to correcting MT static shift used in the geothermal industry in the last decades uses the TEM method to provide supplementary data (Cumming and Mackie 2010), which in case of the in-loop configuration is not subject to static distortion. Since at the in-loop (also known as central loop) TEM sounding no current has to be injected into the ground directly the results are less sensitive to the galvanic distortions due to local resistivity inhomogeneities, see Booker (2014), Ruthsatz et al. (2018).

In the central loop configuration the magnetic field is created by transmitting a current of known magnitude through a loop of wire (source loop) placed on the Earth's surface and when the current is abruptly turned off, the magnetic field starts to decay with time which causes the electric current in the conductive medium. As time passes this current will weaken and diffuse deeper into the ground. The measured by a wire loop (receiver loop) or an induction coil decaying signal contains information about the resistivity of the subsurface.

Thus the observed data from the central loop design can be used to correct the static shift of MT data. The correction is in such a way that the MT sounding curve is shifted vertically in such a way that the high-frequency part of the MT curve agrees with the TEM curve and consequently, the low frequency MT curve provides an undistorted picture of the deeper resistivity section.

3. INSTRUMENTATION

As it was already mentioned upper, because of low level of the natural EM fields variations there are high requirements to the applied for MT survey instrumentation quality. A set of MT stations was developed in Ukraine and manufactured by the Laboratory for Electromagnetic Innovations (LEMI). The modern trends in the field instrumentation development for an MT study are, first of all, improvement of the sensors resolution and decrease of power consumption and weight to be convenient for long-term measurements. There is also a necessity to increase the distance between sensors and electronic units, what is especially necessary for long-term observations realization in populated places. This is possible to realize by the changes in the MT station internal structure, placing the analogue electronics providing proper operation mode of the sensor inside the housing of the latter. Using this idea a set of new MT stations was developed – LEMI-423 for wide band research (0.001-1000 Hz, shallow depths) and LEMI-424 for long-period EM field variations measurement (from ~ 100.000 and more to 2 sec, deep sounding). We present here more in details the MT station LEMI-424 (see figure 1) and the results obtained with this type of stations, as more convenient for efficiency of remote sensing survey demonstration. More detailed description of this and other stations parameters may be found at www.isr.lviv.ua.

Figure 1: General view of the LEMI-424 magnetotelluric station.

The MT station LEMI-424 is composed of two units - data logger (DL) and flux-gate three-component analog magnetometer (AM). DL (at the photo above) is intended for the analog signals received both from AM and from electric lines for telluric field measurements digitizing and storage. In order to realize the design of electric channels major attention was paid to thermal and temporal stability, high input impedance and low drift. High-pass filter-free technology of input stages was used in order to let super-long period signals (up to 100.000 second) to pass. The lightning protection unit (at the photo, to the right below) assures both the protection against nearby lightning discharges and easy connection of electric lines in the field. To provide high quality electric field measurements also environmental-friendly low noise non-polarized electrodes LEMI-701 were produced (at the photo left side), but any other electrodes type may be used. The vector AM allows precise measurement of Earth's magnetic field and its variations at land conditions as well as in geomagnetic observatory (at the photo, in center below). It is produced on the base of flux-gate sensor, all three components of which are implemented in the same body made from the material with extremely low thermal dilatation. The electronics is implemented as "black box" PCB with analog output connected to DL. Very low MT station power consumption is convenient for long-term autonomous measurements in field conditions, where power breaks may often occur. See the list of its main parameters in table 1.

In addition, the LEMIGRAPH program was created for data processing of MT and geomagnetic deep sounding (GDS) which is based on the mathematical background described above. With its help, it is also possible to process AMT data, as well as carry out data processing with a second remote station, from which synchronously recorded data are available, without additional utilities. Another feature of the LEMIGRAPH program is the possibility of manual selection for processing of several separate segments of time series. The output of the results is performed in graphic form and in the form of EDI files.

Table 1: Main parameters of LEMI-424 MT station.

Data Logger		3-component Analog Magnetometer	
Parameter	Value	Measured range at analog output	±65000 nT
Frequency band	DC-0.5 Hz DC-0.5 Hz	Frequency band for magnetometer	DC-10 Hz
Measuring range for electrometer	±2450 mV	Transformation factor of analog output	25 μV/nT
Resolution	2 nV	Noise level at 1 Hz	≤7 pT/√Hz
Sample rate	1 per s	Temperature drift	<0.3 nT/°C
SD card	32 GB	Components orthogonality error	<30 min of arc
Digital output and control	USB	Operating temperature range	minus 20 to + 55°C
GPS timing, coordinates and altitude determination		Power consumption	< 0.5 W
Operating temperature range	minus 20 to +60°C	Power supply	5 V ±0.1V
Power supply	<0.5 W	Weight: sensor with 20 m cable	~5 kg
Weight	1.2 kg		

The advantages of the new development are following (table 2).

Table 2: Advantages of new MT station.

Advantages	Disadvantages
Less wires in the cable, greater flexibility. Cable length can be up to 200 meters. Excitation circuit close to the sensor – less power consumption. Does not require magnetic field compensation.	Possible influence of electronic components magnetization.

In terms of computing power, the LEMIGRAPH program is almost equivalent to the best processing programs in the world. Its main difference is that in the LEMIGRAPH program all parameters are selected close to optimal and only four options are provided changing the calculation process. Together with the graphical interface, this feature allows the user to easily master the program, which makes it particularly attractive for industrial applications.

4. CASE STUDY OF REMOTE REFERENCE PROCESSING

Today many successful examples of remote reference use in MT processing may be given, e.g., Ladanivskyy et al. (2018), Minami et al. (2018). We shall confine ourselves with a simple test that, from one side, demonstrates efficiency of remote sensing method and used algorithm, and from another side, confirms the high standard of the applied instrumentation.

Testing measurements have been carried out by two LEMI-424 instruments for two days on the surface of dried lake. In one site, animals dug out the flux-gate sensors unit after 10 hours of recording. However, at another site the MT station operated well for two days. The apparent resistivity and impedance phase curves obtained by single station algorithm on the base of two days data are shown in the figure 2. Appropriate tipper module and azimuth curves are presented in the figure 3. As can be seen the apparent resistivity values for periods shorter than 20 s are downward biased, which, obviously, is caused by noise in horizontal magnetic channels. For ten hours long time series we were able to apply the remote reference algorithm. So, we concatenated the remote reference response from 8 to 20 seconds with the single station one for periods over 20 seconds. Combined MT curves are shown in the figure 4 and GDS ones in the figure 5 respectively. The remote reference estimates look credibly and are not downward biased (see figure 4). Since two stations were placed at a distance of only 100 meters from each other, obviously, both of them recorded the similar magnetic signals and the downward biasing in single station estimates was caused by internal noise of sensors. Since remote reference estimates are not downward biased in our case we can expect that internal noise level of new sensors is even less than (or as minimum comparable with) the level of geomagnetic variations in so called “dead band”. Similar conclusion can be derived from GDS curves too (compare the figure 3 and the figure 5).

5. DISCUSSION AND CONCLUSIONS

As we showed it here, because of the specific sensitivity of MT survey to image the low resistivity layers in the Earth’s crust, it is commonly used to target geothermal wells and assess resource capacity. It is specified that MT survey acquisition include a supplementary time domain TEM survey for static shift correction, see Cumming and Mackie (2010). In addition, modern requirements to the reliability of MT results oblige the simultaneous data recording by at least two separated MT stations that allow applying the robust remote reference estimates.

We demonstrated here also the modern instrumentation as well as the processing software that can be successfully applied for studying the geothermal regions.

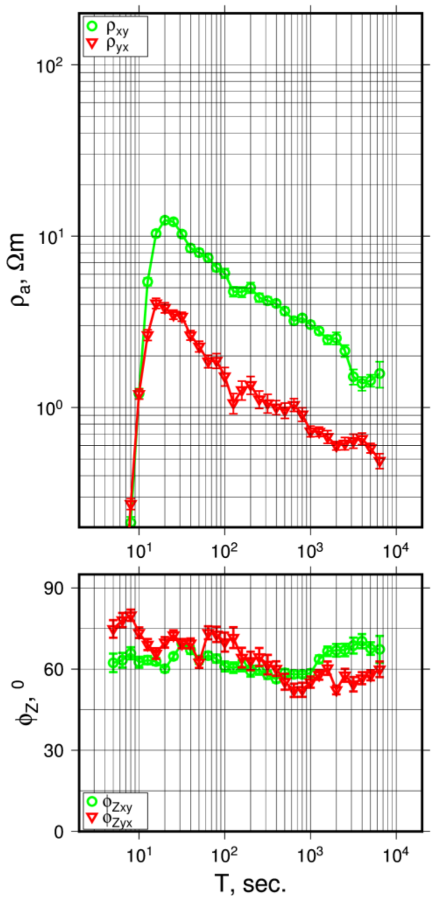

Figure 2: Apparent resistivity and impedance phase curves obtained by single station algorithm on the base of two days data.

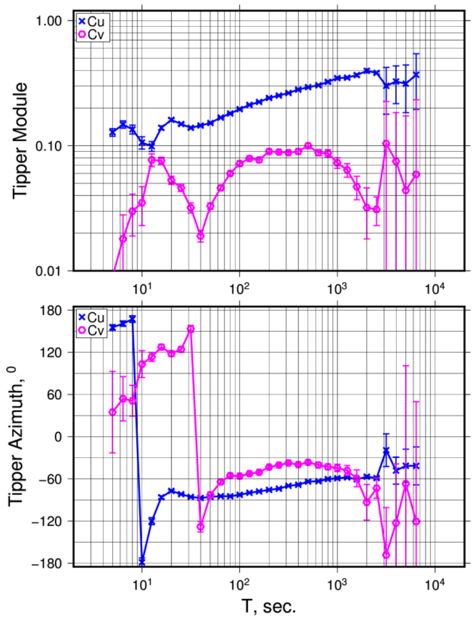

Figure 3: Real Cu and imaginary Cv tipper module and azimuth curves obtained by single station algorithm on the base of two days data.

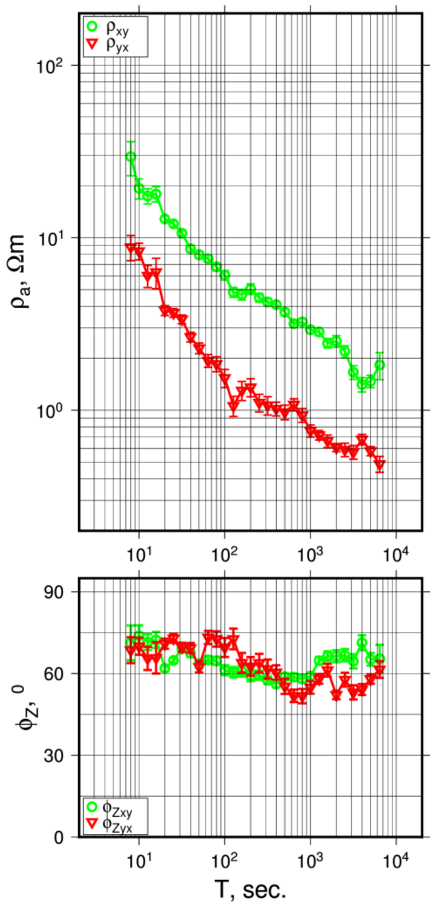

Figure 4: Concatenated apparent resistivity and impedance phase curves from 8 to 20 seconds obtained by remote reference algorithm and for periods over 20 seconds by single station one.

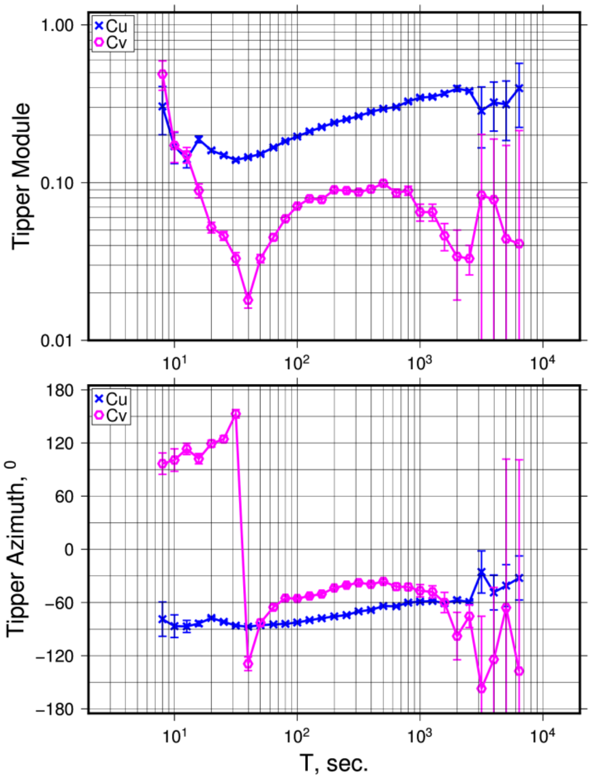

Figure 5: Real Cu and imaginary Cv tipper module and azimuth curves from 8 to 20 seconds obtained by remote reference algorithm and for periods over 20 seconds by single station one.

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