

USE OF THE MAGNETOTELLURIC METHOD IN BRAZIL AND FUTURE CHALLENGES

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ABSTRACT. The magnetotelluric (MT) method is based on measurements of natural electric and magnetic fields at the Earth's surface to probe the subsurface electrical resistivity structure. It is presented summary of the use of the method in Brazil, emphasizing on the initial theoretical and experimental developments for its implementation. The expansion of the method in recent years is related to academic studies on the tectonic evolution of geological provinces and contracted surveys mainly restricted to supporting oil exploration. Two major challenges are proposed to increase the contribution of the method in the following years. One is the planning and installing an extensive experimental program to obtain long-period data from stations installed in a 3D grid. It can contribute to improving the knowledge of the tectonic evolution of the Brazilian shield and also to locating new areas with potential for exploration of mineral resources. Coupled with this expansion of field measurements, another challenge is the need to formulate new data processing techniques. The main objective will be to minimize the effects of coherent and intermittent electromagnetic method (EM) noise related to the installation in the country of electric power transmission networks using high voltage direct currents (HVDC).

Keywords: MT method, historical development, 3D grid, EM noise.

INTRODUCTION

Electrical resistivity ρ (conductivity σ) is an important parameter of Earth materials that is sensitive to the presence of small amounts of fluids, melts or electrically conductive minerals in the host rock matrix. However, these minor constituents of the host rock are often key parameters for defining the rheology and tectonics of the crust and upper mantle. Knowledge of the variation of electrical conductivity within the Earth can thus provide complementary information to bulk property physical parameters determined by other geophysical methods, such as seismic and potential field data.

Magnetotellurics (MT) is a passive electromagnetic (EM) geophysical prospecting technique that provides information on the three-dimensional electrical conductivity distribution within the Earth. It is based on the simultaneous measurement of natural time variations in the geomagnetic field components (H_x , H_y and H_z) and in the orthogonal horizontal components of the induced electric field (E_x and E_y)

at the Earth's surface. At high frequencies (1 Hz to typically 20 kHz, or periods from 0.0005 to 1 s), natural external sources are geomagnetic field variations that propagate in the Earth-ionosphere waveguide and are associated with worldwide lightning activity. Low frequency geomagnetic variations (0.1 mHz to 1 Hz, periods from 1 to 10,000 s) are due to interactions between the solar wind and the Earth's magnetosphere. The versatility of the MT method allows the investigation of conductivity variations from shallow depths (a few meters) to great depths (hundreds of kilometers), depending on the frequency of the analyzed signal and the electrical conductivity of the medium. This ability to probe different depths with small variations in the instrumentation used is attributed to the diffusive dissipation of EM energy on Earth (Simpson and Bahr, 2005; Chave and Jones, 2012).

This article presents a personal view of the historical use of the MT method in Brazil and discusses some challenges to be faced in coming years. Traditionally, the method has been used by the Brazilian aca-

demic community for structural studies of the South American platform in order to understand the evolution of different tectonic provinces. More recently, the potential of the method as a valuable tool for mapping deep sedimentary basins for oil exploration has been recognized. A more systematic MT data acquisition in large projects became operative, supported by the National Agency of Petroleum, Natural Gas and Biofuels (ANP) and oil companies, and concentrated mainly on unexplored or little-known onshore basins aiming at a possible reduction of exploratory risk. Another potential use of the method in the prospection of mineral resources at shallow depths is still very incipient, despite the growing demand from the mining industry. However, greater emphasis will be given here to works developed with an academic focus due to the greater ease of accessing articles published in specialized scientific journals.

MAGNETOTELLURIC METHOD

The MT method was proposed in the early 1950s with a brief description of how the frequency-dependent relationship between the orthogonal components of the electric and magnetic fields at the surface could be used to measure the resistivity structure of the Earth (Tikhonov, 1950). More specifically, it has been shown that there is a proportionality and a phase shift between the perpendicular components of the horizontal EM fields at the surface. Independently, Cagniard (1953) published the theoretical basis of the MT method in more detail. Starting from Maxwell's equations that describe the propagation and attenuation of EM fields in a conductive medium, he obtained expressions that relate the ratio between the electromagnetic fields measured at the surface (defined as the electromagnetic impedance, Z) with the electrical resistivity in the subsurface. For a homogeneous half-space, this resistivity would equal the actual subsurface resistivity. However, over a nonuniform Earth this estimate is more correctly referred to as an apparent resistivity (ρ_a), defined as:

$$\rho_a = \frac{1}{\omega\mu} |Z|^2, \quad (1)$$

where ω is the frequency and μ the magnetic permeability. In the case of a noninsulating medium with finite conductivity σ , the propagation constant of an EM wave is complex and there is a phase shift between the electric and magnetic components given by

$$\phi = \arg Z = \tan^{-1} \left(\frac{\Im Z}{\Re Z} \right), \quad (2)$$

where $\Im Z$ and $\Re Z$ are the imaginary and real parts of the complex impedance Z , respectively. For a half-space of constant resistivity, the phase is 45° . The phase is sensitive to changes in resistivity with depth:

as the resistivity increases, the phase becomes less than 45° , and as the resistivity decreases, the phase becomes more than 45° .

A transfer function is also defined from the complex ratio of vertical to horizontal magnetic fields in the frequency domain. It is called tipper (or vertical magnetic transfer function) and is generally presented in the form of induction vectors that are indicative of lateral conductivity contrasts and also used as a support in defining the dimensionality of subsurface structures.

The skin depth δ is another fundamental parameter of the MT method, which gives a measure of the distance that EM fields diffuse in a conducting medium, such as the Earth. It is defined as the depth at which the amplitude of the EM fields observed at the surface is reduced by a factor of $1/e$, expressed as

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{\rho T}{\pi\mu}}, \quad (3)$$

where T is the period. Consequently, EM waves penetrate deeper for longer periods in a resistive medium. On the other hand, both the period reduction and the decrease in resistivity decrease the skin depth. Skin depth relates resistivity to subsurface depth via signal period (or equivalently frequency). It is this property that allows the MT method to sample different depths within the Earth, simply by using different periods of the measured EM signal.

The amplitude and phase relationships between the ratios of the horizontal orthogonal electric and magnetic fields at the Earth's surface are represented by the electromagnetic impedance which is defined as

$$\mathbf{E} = \mathbf{Z}\mathbf{H}. \quad (4)$$

Impedance is a transfer function because it describes the frequency-dependent connection between the input (magnetic field) and output (electric field) of a linear, time-invariant system. In general, impedance represents a tensor quantity and is expressed as

$$\begin{pmatrix} \mathbf{E}_x \\ \mathbf{E}_y \end{pmatrix} = \begin{pmatrix} \mathbf{Z}_{xx} & \mathbf{Z}_{xy} \\ \mathbf{Z}_{yx} & \mathbf{Z}_{yy} \end{pmatrix} \begin{pmatrix} \mathbf{H}_x \\ \mathbf{H}_y \end{pmatrix}, \quad (5)$$

where x and y represent two orthogonal directions. The impedance tensor contains information about the geoelectrical direction, dimensionality and conductivity of the Earth.

In an MT field survey, the temporal variations of the three orthogonal components of the magnetic field and the two horizontal components of the electric field are measured simultaneously at a given site under which the electrical resistivity distribution is to be known. As these signals are generally of low amplitude, it is necessary to have sensors with an excellent signal-to-noise ratio and high amplification capacity. In general, the electric field is measured in-

directly by recording the temporal variation of the potential difference between pairs of electric sensors (electrodes) separated by at least one hundred meters. This separation is necessary so that the measured voltage is much greater than the noise generated by the sensors themselves, which are generally non-polarizable porous electrodes. These electrodes consist of ceramic-based pots filled with solutions, usually lead-lead chloride, and kept in direct contact with the ground. To measure the temporal variations of the magnetic field, magnetometers with high sensitivity and low intrinsic noise are used in the frequency intervals of interest. At low frequencies (less than about 0.1 Hz; periods greater than 10 s) fluxgate magnetometers are used. At higher frequencies (periods less than 10 s), however, the natural variations of the geomagnetic field have very low amplitudes, lower than the noise level intrinsic to these magnetometers. At these frequencies, induction coil magnetometers are used to measure geomagnetic variations.

MT data processing involves estimating a small number of continuous and smooth transfer functions in the frequency domain from fairly large time series of the measured EM fields. These characteristics of smoothness and continuity of the Earth's response to EM wave propagation are theoretically consistent with the various MT transfer functions generated by different Earth models, including those where significant lateral and depth variations in electrical resistivity occur (Simpson and Bahr, 2005; Chave and Jones, 2012). This is due to the fact that the propagation of the EM wave, and consequently the process of electromagnetic induction inside the Earth, is diffusive and thus sensitive only to the spatial average of the conductivity. Therefore, if large variations in transfer functions are observed between contiguous frequencies, it can be inferred that these functions were erroneously estimated. Several mathematical methods have been developed and applied to the estimation of MT impedance tensor elements and include robust and remote reference techniques (see review in Chave, 2017).

Transfer functions derived from surface MT soundings can be transformed into Earth resistivity models by inversion methods. Inversion theory deals with estimating model parameters (in this case electrical resistivity) to approximate subsurface electrical structures from geophysical data measured at the surface. The inversion problem is not unique, as for any set of observations there is a range of different models that can reproduce the observations with the same degree of precision. This is even more complicated as geophysical observations are always contaminated by noise and MT data are often sparsely distributed and only available at the Earth's surface. Additional independent information from other geophysical, geochemical or geological studies is commonly used to constrain the resistivity model derived from inversion of MT data.

MT IN BRAZIL

The original quantitative description of the MT response (Cagniard, 1953) established a scalar relationship between a magnetic field and its associated orthogonal electric field for an Earth model composed of stratified horizontal layers (1D approximation). This representation was not sufficient to describe geological situations of lateral variation in conductivity frequently found in experimental studies. During his doctoral thesis at MIT, the Portuguese-born Antonio de Sousa Neves was the first to recognize and propose a tensor relationship between electric and magnetic fields for the Earth's interior (NEVES, 1957). He also presented a finite difference algorithm to solve the MT forward problem and calculate 2D apparent resistivities over vertical and dipping interfaces between media of different conductivities. Subsequently, Sousa Neves emigrated to Brazil and actively worked for several decades in academic institutions and geophysical companies located in the city of Rio de Janeiro.

Two decades later, Luiz Rijo presented a modular finite element algorithm to solve the 2D forward modeling problem during his doctoral thesis at the University of Utah (RIJO, 1977). This flexible code made it possible to calculate MT responses for different 2D models and was used globally to perform systematic studies to support MT modeling and interpretation. It was also used as the core of inversion algorithms as the routine that solves the forward 2D problem of computing MT transfer functions. Rijo was an active researcher at UFPA leading a research team dedicated to EM numerical modeling.

At the same time, Edson Sampaio was discussing analytical solutions to 2D problems for different types of geological structures (Sampaio, 1976). He remains an active researcher at UFBA, involved with theoretical solutions of different EM problems and leading projects for experimental geophysical studies.

The first published experimental measurements using the MT method in Brazil were carried out under the leadership of Nalin Trivedi of the INPE's Geomagnetism group (Trivedi et al., 1981). It was used in-house instrumentation built at INPE under the coordination of Trivedi and support of the French researcher Hugo Fournier. This MT instrument would be improved in the following years (DUTRA, 1984) and used in field campaigns carried out in different sedimentary basins throughout the 1980s. Antonio Padilha's doctoral thesis presented at the University of São Paulo summarizes some of these initial studies by INPE (PADILHA, 1989). It should be mentioned, however, that the first large-scale MT survey in Brazil was carried out in the early 1980s with hundreds of stations acquired by a US commercial contractor for a short-living oil company of the State of São Paulo (Paulipetro, 1982). The study was located in the north-central part of the Paraná Basin with the main goal of identifying areas favorable to the possible

exploration of oil deposits hidden under thick volcanic rocks. The data processed by the contractor were interpreted by USGS researchers with a focus on the stratigraphic features of the basin and regional tectonics of its basement (Stanley et al., 1985).

Simultaneously, Jandyr Travassos and Sergio Fontes of the Observatório Nacional (ON) were developing their doctoral theses with the MT method at the University of Edinburgh, Scotland (Travassos, 1987; Fontes, 1988). Upon returning to Brazil, they would implement the MT method at ON with the help of the researcher Jean Flexor. In the following decades, INPE and ON would develop intense field activity of MT data acquisition in different tectonic provinces of the country using state-of-the-art commercial MT systems; in the case of INPE under the coordination of Ícaro Vitorello. Figure 1 shows the location of the field surveys carried out by these two institutions in the last two decades.

The expansion in MT data acquisition in recent years seen in Figure 1 can largely be credited to the implementation of a geophysical equipment pool (PEGBr) to support research projects in geotectonic studies. Initially financed by Petrobras, this pool is installed at ON under the leadership of Sergio Fontes and, specifically for the MT method, dozens of broadband and long-period equipments are available. One of the consequences is the dissemination of research groups by different Brazilian research institutes and universities using the MT method as a support for their geophysical investigations. This can be proven by checking the academic articles published in the last five years in specialized journals and led by researchers from UFBA (Corrêa-Gomes et al., 2022), ON (Romero-Beltran et al., 2022), UFCE (Castelo Branco et al., 2021), UFRGS (Menezes et al., 2021), INPE (Padilha et al., 2021), UERJ (Correa and Menezes, 2021), USP (Dragone et al., 2021), UFPA (Nunes and Régis, 2020), UFRN (Garcia et al., 2019), and UnB (Pedrosa Junior et al., 2017).

FUTURE CHALLENGES

The significant increase in MT research discussed in the previous section still leaves open several gaps that need to be filled in order to optimize the use of this method in Brazil. Two activities that need to be scaled up are discussed here. One is linked to the experimental part, with the need to carry out surveys in grid format covering the national territory, and the other is related to theoretical development, with the need to develop data processing tools that minimize EM noise associated with the expansion of High Voltage Direct Current (HVDC) electric power transmission lines in the country.

3D MT

Until recently, MT investigations worldwide were limited to 2D interpretations of field surveys along profiles that were supposedly interpreted as being orthogonal to regional geological and geoelectrical directions. There are still many 2D surveys that persist today, largely due to the higher cost of acquiring gridded 3D data compared to acquiring 2D data along profiles. In addition, there are the high computational demands of 3D inverse modeling compared to 2D inversion. However, in recent years, these 2D surveys have increasingly given way to 3D meshes, in which MT stations are installed on nearly regular latitude and longitude grids. This transition from 2D to 3D MT surveys was made possible in part by the availability of noncommercial 3D MT inverse modeling codes developed to produce subsurface resistivity structure images from impedance tensor matrices (e.g., Egbert and Kelbert, 2012). The development of large MT projects, capable of operating dozens of long-period instruments simultaneously, has made it possible to collect large sets of gridded data needed for 3D interpretation. Examples are the ongoing nationwide EarthScope program in the United States (Schultz et al., 2006), SinoProbe in China (Dong et al., 2013) and AusLAMP in Australia (Robertson et al., 2016).

While there were some initial concerns that the spacing between stations in large 3D surveys would be too large to allow for meaningful local interpretations, the 3D coverage and large number of stations significantly compensates these potential limitations. The results already published show that the resolution of the 3D inversion models of these gridded MT soundings is comparable to the inversions of seismic tomography, with the difference that the sensitivity of the EM methods is superior in the resolution of factors such as the melting fraction, temperature and water content in the mantle (Selway, 2014). As an example, the ~ 70 km spacing between long-period EarthScope stations is suitable for delineating key structural features from the middle crust to the upper mantle of the United States (Bedrosian, 2016). On the other hand, with greater interest in shallower mineral resources, Australia's AusLAMP cluster employs ~ 55 km (half degree) station spacing with successful results in showing robust correlations between orogenic mineral deposits and electrical conductors at different lithospheric depths (see Kirby et al., 2022, and references therein). Critical zones in the upper crust identified from these regional scale 3D surveys have been detailed using broadband MT equipment with much smaller spacing between stations ($< 1 - 20$ km; Heinson et al., 2018).

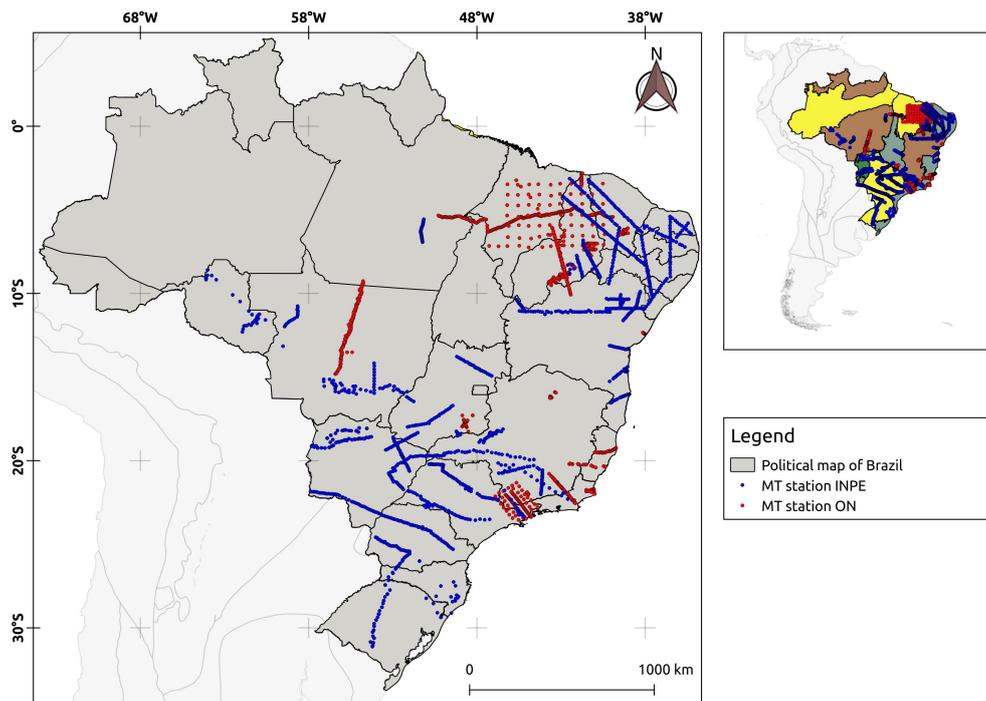


Figure 1: Political map of Brazil with the location of the MT soundings acquired in the last two decades by INPE (blue dots) and ON (red dots). Inset shows a simplified map of the main tectonic provinces of Brazil with the MT soundings.

As can be seen in Figure 1, grid surveys in Brazil are still scarce. In view of the results already obtained in the aforementioned large 3D surveys, it is urgent to make a transition from 2D surveys located on known structures on the surface to large-scale regional 3D surveys that can contribute to the expansion of knowledge of major tectonic provinces and provide targets for detailed surveys in areas still unexplored. The availability of modern broadband and long-period MT instrumentation at the ON's PEGBr, specialized technical personnel for field surveys especially at the ON and INPE, robust computational complexes in these two institutions for 3D inversion of large volumes of data and a team of researchers with great experience in processing and interpretation of MT data, and their integration with other geophysical and geological information in different research institutes and universities in Brazil makes this possibility viable. Its completion will provide unprecedented potential for dramatic improvements in regional 3D electrical conductivity models and, consequently, in the delineation of lithospheric structures linked to the geotectonic evolution of the South American platform and in the identification of new targets for mineral exploration.

HVDC noise

To show the distortional effect of HVDC lines on the MT data, we will present two examples of MT stations measured in the Paraná Basin. The MT transfer functions at a measurement site are usually presented as Cartesian graphs, with the period in seconds on a logarithmic scale on the abscissa axis and the trans-

fer function on the ordinate axis. In general, only the apparent resistivity and phase are shown for the two off-diagonal elements of the impedance tensor (ρ_{xy} , ρ_{yx} , ϕ_{xy} , and ϕ_{yx}), as these are the commonly used functions for data interpretation. For apparent resistivity plots, the ordinate axis is the logarithm of the apparent resistivity (in Ωm), while for phase the ordinate axis is linear (in units of degrees). Impedance values are rarely presented due to their large variation with period. To facilitate the visualization of these transfer functions and the consequent discussion of the noise effects, a scaled variation of the impedance function (divided by the square root of the frequency and magnetic permeability) will be presented in the following graphs.

Figure 2 shows an example of typical MT curve responses. This sounding was acquired in the western region of the state of São Paulo as part of an E-W profile (HORVATH, 2017). The data were processed using a robust regression code (Egbert and Booker, 1986) and are of good quality based on the criteria of smoothness and continuity of the various transfer functions at the target frequencies. The Z_{yx} , Z_{yy} and tipper components have only one anomalous outlier, identified by red ellipses in all transfer functions. It is associated with alternating current from local electrical transmission lines operating at 60 Hz. Noise is significant to affect the signal at its original frequency, but not high enough to produce harmonics and sub-harmonics at other frequencies. Its effect can be minimized in the interpretation by excluding this frequency from the analyses.

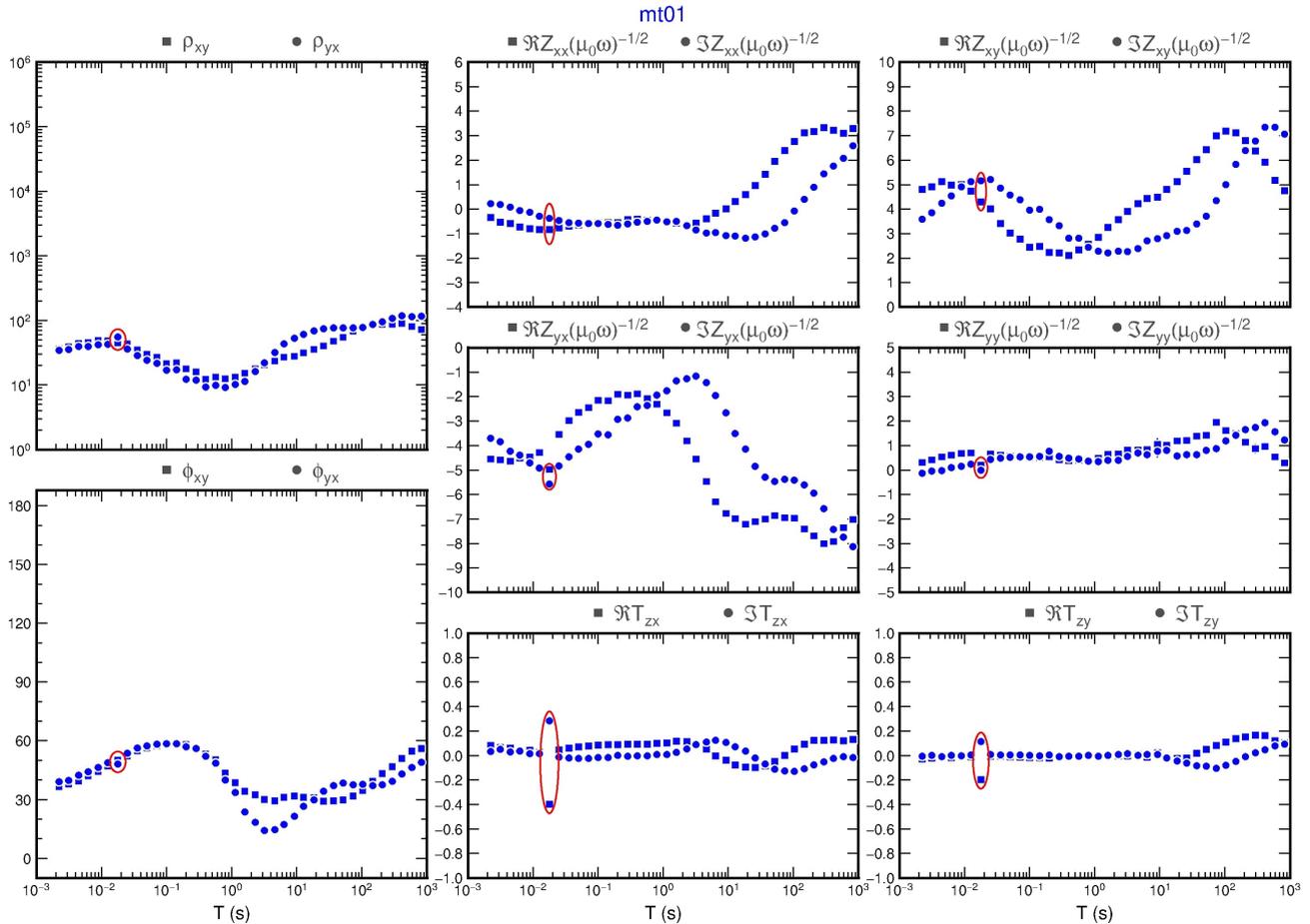


Figure 2: MT transfer functions for a station over the Paraná Basin obtained using robust processing (Egbert and Booker, 1986). It is shown Variations in apparent resistivity (ρ_{xy} and ρ_{yx}) in Ωm , phase (ϕ_{xy} and ϕ_{yx}) in degrees, real and imaginary components of a scaled function of the impedance tensor elements ($Z_{xx}/\sqrt{\mu_0\omega}$, $Z_{xy}/\sqrt{\mu_0\omega}$, $Z_{yx}/\sqrt{\mu_0\omega}$ and $Z_{yy}/\sqrt{\mu_0\omega}$) and real and imaginary components of adimensional vertical geomagnetic transfer functions (T_{zx} and T_{zy}) as a function of period. The red ellipses are discussed in the text.

Figure 3 shows the transfer functions of another station of the same MT profile, but located in its eastern part. Data were processed by the same robust algorithm as in the previous figure. The noise effect does not appear as an anomalous point located at a specific frequency, but over a wide range of frequencies (identified by red squares in all transfer functions). Visually, this noise completely affects the real part of all impedance tensor elements causing their amplitude to be hundreds of times greater than that observed in the imaginary part (compare the impedance amplitudes with those in Figure 2). As a consequence, the apparent resistivities and phases derived from the MT impedance are completely distorted (apparent resistivity increases with increasing period with an angle of 45° on the bilogarithmic scale and the phase concentrates close to 0°). This result completely masks the characteristics of the subsurface geoelectrical variation, being typical of MT soundings that suffer severe industrial interference (Qian and Pedersen, 1991).

This EM noise is mostly associated with an HVDC power transmission line that connects the Itaipú power plant (Paraná state) to Ibiúna (São Paulo state). It consists of two ± 600 kV lines, approximately 820 km long, that transport energy to the region around the city of São Paulo, after conversion from direct current to alternating current (DC to AC) in Ibiúna. The use of this type of electrical energy transmission is justified because it is more economical than transmission in AC mode over long distances (transmission losses in the HVDC system are significantly lower). For surveys using natural EM signals, the presence of these HVDC lines represents a huge source of continuous and coherent EM noise that spreads over great distances (due to the high voltage used) and contaminates the entire frequency spectrum (through the DC level). The MT station to the west (Figure 2) is about 200 km away from the HVDC line and was the last of several stations in the profile, spaced about 30 km apart, in which the DC noise effect was not observed. On the other hand,

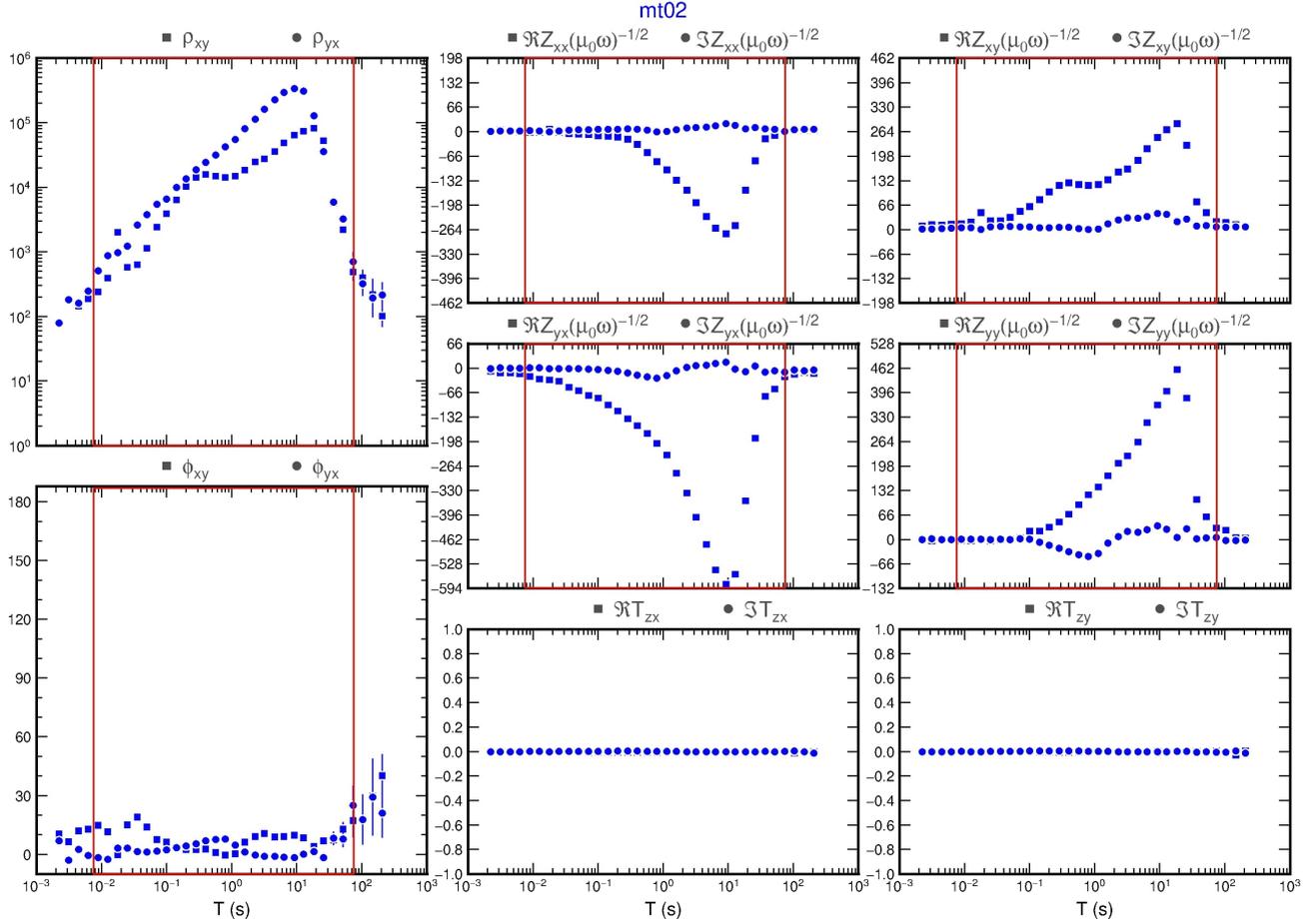


Figure 3: MT transfer functions for a station in the vicinity of an HVDC line cutting through the Paraná Basin. The functions shown are the same as in Figure 2 and the red squares are discussed in the text.

the station to the east (Figure 3) is located just over 40 km from the HVDC line and is severely contaminated by DC noise.

To qualitatively describe the characteristics of observed EM noise, the basic definition of electrical impedance can be used. It is a complex number (\mathbf{Z}) that has a real part (resistance - R) and an imaginary part (reactance - X), all given in ohms (Ω):

$$\mathbf{Z} = R + iX, \quad (6)$$

with

$$\begin{aligned} R &= \Delta V I \\ XL &= \omega L, \end{aligned} \quad (7)$$

where ΔV is the potential difference in Volts, I is the electric current in Amperes, XL is the inductive part of the reactance (the capacitive reactance is not being considered here), L is the inductance in Henrys and ω the angular frequency. A key difference between the two parts of impedance is that only the imaginary part is frequency dependent.

Three situations can be analyzed (DE PADUA, 2019):

- System powered only by direct current: the impedance will be a real value related to the amplitude of the injected direct current and independent of the frequency;
- System powered only by alternating current: The real part of the impedance will be related to the amplitude of the alternating current, and the imaginary part with the variation in frequency of this current;
- System powered simultaneously by direct and alternating current: the real part will be formed by the sum of the amplitudes of both currents, while the imaginary part will depend on the variation of the alternating current with frequency.

The MT station in Figure 2 is a typical example of a system powered only by alternating current, in which this current is related to the natural geomagnetic signal whose amplitude varies as a function of frequency. This natural signal is contaminated by an artificial signal source also in alternating current, but which affects a limited spectrum of frequencies. This is the ideal situation for an MT sounding. On the other hand, the MT station in Figure 3 fits the situ-

ation of the system fed by the two currents (AC and DC), in which the real part is contaminated by the direct current, while the imaginary part is apparently dominated mainly by the natural signal (alternating current).

The real part of the transfer functions in Figure 3 can be used to illustrate the DC noise effect on MT soundings as a function of signal frequency. Considering the noise source fixed and positioned at a certain distance from the MT station, its effect on the impedance tensor elements can be divided into near-field and far-field parts, depending on the relationship between the frequency of the considered signal and the skin depth for this frequency. At high frequencies ($> 100 \text{ Hz}$), the DC noise source is far enough away (more than 3 skin depths) so that the signals can be considered as far-field and therefore be detected as plane waves by the MT method (Sandberg and Hohmann, 1982). In this case, the result of the real part will approximate that of the imaginary part. For frequencies where the source distance is less than 3 skin depths, the magnetic field related to the DC source (EM noise) will be much greater than the magnetic field associated with the natural signal. This is the near-field situation, where MT responses will not be related to the impedance of the medium through which the EM waves propagate, but only to the geometry of the artificial signal source. In this situation, the plane wave assumption on which the MT method is based does not apply. Eventually, for much lower frequencies, the amplitude of the natural signal increases significantly and can overwhelm the artificial signal. The real part of the impedance then approximates the expected result for plane waves, approaching again the imaginary part in periods longer than 100 s.

In addition to the Itaipu-Ibiúna line (which runs mainly through the volcanic-sedimentary package of the Paraná Basin), there is another HVDC line operated at $\pm 600 \text{ kV}$ in the country. It is located between the Madeira River (Porto Velho, Rondônia) and Araraquara city (São Paulo state) with an extension of almost 2,400 km. It mainly crosses the Pantanal and Paraná basins and is also expected to be a significant source of coherent EM noise in the mid-west region of the country. In both cases, the effects of these lines are limited by the high conductance of the sedimentary basins they cross. Even so, the noise effects can reach distances of around 200 km, as observed for the Paraná Basin case study.

Figure 4 shows a simplified tectonic map of Brazil with the location of current and future HVDC lines. In addition to the two HVDC lines already mentioned, another two are coming into operation connecting Belo Monte (state of Pará) to Estreito (state of Minas Gerais) and Rio de Janeiro. These lines operate at $\pm 800 \text{ kV}$ and are located almost entirely on high resistivity terrain formed by Precambrian rocks from the São Francisco Craton and its marginal belts. Con-

sequently, EM noise is expected to be even more intense (due to higher voltage) and spread over several hundred kilometers (low damping by resistive rocks) covering much of the central part of the country.

The EM noise generated by HVDC lines in Brazil represents the most critical situation faced by MT data processing techniques. They are coherent, which affect both the electric and magnetic fields, persistent, by the continuous operation of the transmission lines, and can spread over great distances in regions of resistive crust. In such cases, currently available EM noise minimization techniques, based on remote reference and robust processing methods, cannot guarantee that reasonable results are obtained for the MT transfer functions. Furthermore, known attempts to deal with this type of problem have so far been unsuccessful for soundings in the vicinity of the lines, where significant noise appears simultaneously in the real and imaginary components of the impedance tensor (DE PADUA, 2019). The current distribution of these lines in the country and the possibility of their future expansion make it urgent to develop new methods capable of estimating the MT tensor in the presence of this HVDC-related EM noise.

CONCLUSION

The MT method is a valuable geophysical technique for exploring the Earth's interior at depths from a few meters to hundreds of kilometers. Its use in Brazil has experienced a significant increase in recent years, both in studies with an academic focus and those applied to the identification of oil-bearing structures in sedimentary basins. This is evidenced by the expansion of academic groups involved with this method in research institutes and universities focusing mainly on tectonic studies, and the recognition by the ANP and oil companies of its potential as one of the geophysical methods to be included in exploratory programs. Currently, there is an enviable situation to further expand the use of the method in the country due to the availability of a large number of instruments for academic studies, computational infrastructure for 3D inversion of large volumes of data, and technical-scientific personnel specialized in field surveys and data interpretation. This may allow increasing geotectonic knowledge about the different units that make up the Brazilian shield and also exploring the mineral potential in areas that are still little known.

However, serious challenges need to be faced to achieve this goal of increasing the use of the MT method in Brazil. Two of them are discussed in this work. The first is related to the establishment of a large program for the acquisition of grid data covering as much of the country as possible. Results already obtained in other countries show the immense benefits for tectonic studies and aid in mineral exploration by the availability of data over vast regions that can be

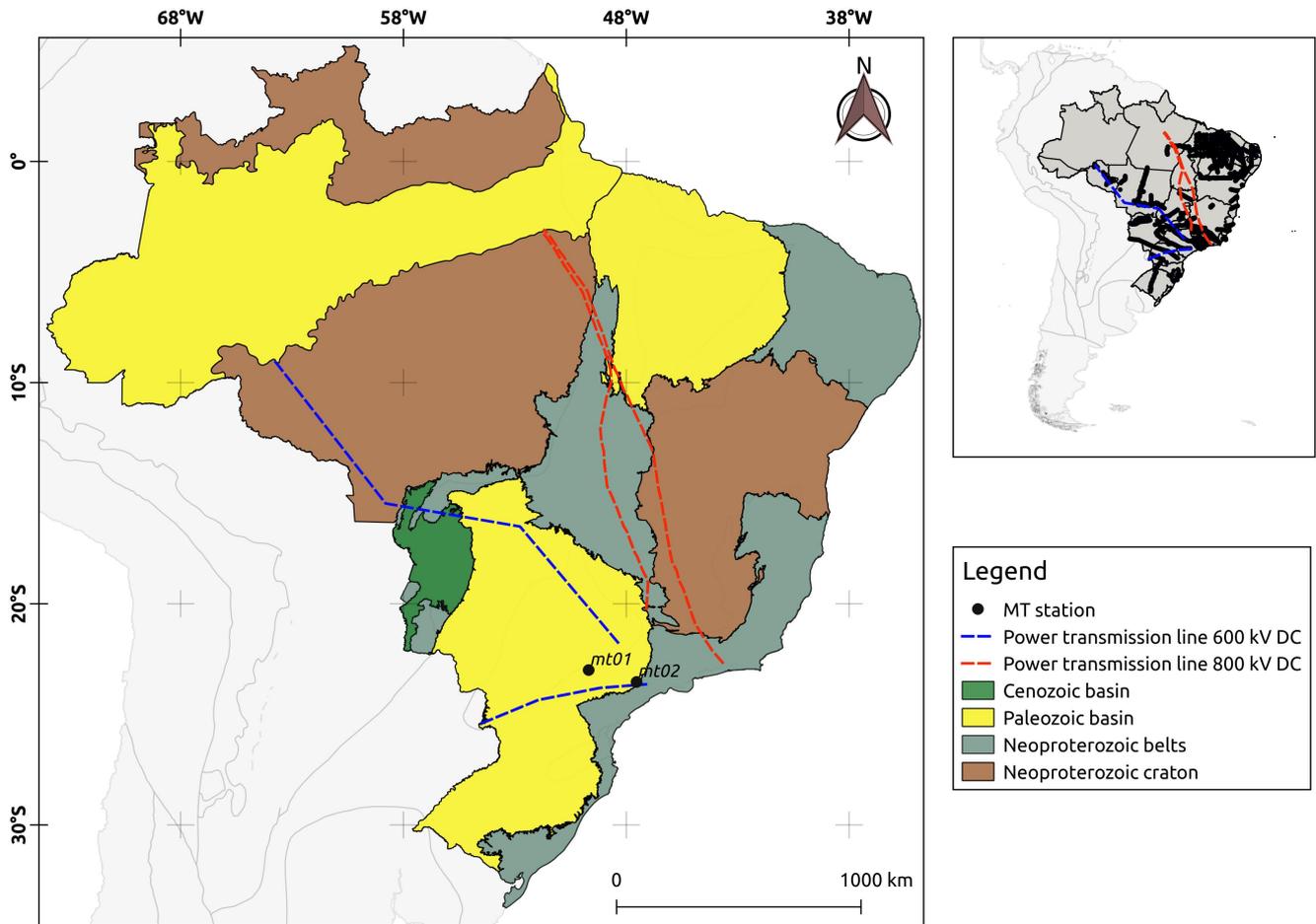


Figure 4: Simplified map of Brazil's main tectonic provinces with the HVDC lines currently in operation in the country. The location of the MT stations mt01 and mt02 discussed in Figures 3 and 4, respectively, is also shown. Inset presents the political map of Brazil with all MT soundings and the HVDC lines.

interpreted from 3D inversions. On the other hand, the continuous expansion of HVDC lines brings a huge problem of cultural EM noise that can affect the data collected in different areas. This type of coherent and intermittent noise can spread over great distances in resistive terrain and its effects cannot be minimized by currently available data processing techniques. An effort will be needed to develop new tools to deal with these EM noises and thus enable the expansion of the MT method in Brazil.

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