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# A new methodology for the acquisition and processing of audio-magnetotelluric (AMT) data in the AMT dead band

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## ABSTRACT

Distant lightning activity, the natural energy source for the audio-magnetotelluric (AMT) method, has a signal minimum between 1 and 5 kHz, the so-called AMT dead band. The energy in this band exhibits both diurnal and annual variation; magnetic-field amplitudes during the daytime are often well below the noise levels of existing sensors (coil magnetometers), thus reducing the effectiveness of the method for quantitative high-resolution studies of near-surface targets. To overcome this deficiency, we propose a hybrid acquisition and processing methodology based on combining the telluric-telluric (T-T) and telluric-magnetotelluric (T-MT) methods in this frequency range. Our method records the telluric channels at several sites and at base and remote reference stations during the day and records the full magnetotelluric (MT) components at the base and remote stations only during the night. Applying a tensor multiplicative relationship between these responses, we obtain the T-MT AMT transfer functions for the sites; these transfer functions can represent a reasonable approximation of the real AMT impedance tensors. To test the approach, a T-MT experiment was carried out in Sudbury, northern Ontario, during summer 2000. We compare the processed daytime data using the conventional MT approach to those obtained from our T-MT approach. The results demonstrate that our method can determine high-quality estimates in the dead band, although the estimates can be severely affected by noise.

## INTRODUCTION

Our study of lightning activity (Garcia and Jones, 2002) confirms the diurnal and seasonal variation of the amplitude of electromagnetic (EM) signals at audio-magnetotelluric (AMT) frequencies and demonstrates the problems of acquiring data at AMT dead-band frequencies of 1 to 5 kHz. The daily variation in the amplitude of the EM fields, with a significant decrease during daytime hours, is a result of absorption in the photo-ionized atmosphere. The seasonal variation corresponds to a minimum of source (lightning) activity during winter months for the northern hemisphere. In particular, we show that during the daytime, the AMT dead-band magnetic signals are typically one to two orders of magnitude below sensor noise levels of the best magnetometer coils currently available. This is a severe problem because deep mineralized targets, lying 500 to 1000 m deep within a resistive host such as the Canadian Shield, are first sensed at AMT dead-band frequencies. Thus, for optimum resolution one needs to obtain high-quality AMT responses at those frequencies. As a consequence, we conclude that dead-band AMT data must be acquired during the night. However, this requirement comes at a high logistical cost and, therefore, a high per-site cost, along with concomitant safety concerns about operating during the night.

To address this high cost, we proposed in Garcia and Jones (2002) a novel method of AMT data acquisition with daytime acquisition of telluric channels at local, base, and remote stations along with conventional nighttime acquisition of magnetic and telluric data at base and remote stations. The quasi-magnetotelluric transfer function at each telluric station is then obtained from tensor multiplication of the transfer functions between the daytime telluric channels and the nighttime conventional magnetotelluric (MT) base estimates. This transfer function represents the ratio of the local telluric to base magnetic fields, rather than the conventional local telluric to local magnetic relationship used in MT. The methodology is, in principle, identical to the telluric-magnetotelluric (T-MT) method proposed by Hermance and Thayer (1975), with the exception that the telluric transfer functions are derived at different times from the MT transfer functions. In addition, we require at least two base stations so that we can undertake remote-reference processing of both the telluric-telluric (T-T) and the MT transfer functions. Our hybrid approach has

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a distinct logistical advantage: Recording crews can record a large number of telluric channels during the daytime, while at night, two or three stations can be set to automatic data acquisition and be used as base and remote stations. This adds little logistical cost to acquisition; in fact, time is saved because magnetic fields are not acquired during the daytime. In addition, safety is preserved because crews are not installing equipment during nighttime hours. However, we do not advocate recording telluric data only, as it is always preferable to record as many components as possible at each site (e.g., Jones and McNeice, 2002). Indeed, one can usually acquire good-quality AMT data from 800 to 10 Hz during the daytime.

During summer 2000, a test of this approach with T-MT measurements was undertaken in Norman Township, Sudbury, northern Ontario, Canada. The stations were divided into site (daytime telluric), base (both daytime telluric and nighttime MT), and remote (both daytime telluric and righttime MT). The survey consisted of four profiles, of which only the data from the northernmost profile are analyzed for this T-MT study. This northernmost profile consists of five site stations (solid circles in Figure 1) and a base station (X in Figure 1) plus a remote station (RR in Figure 1) some 450 m west-southwest from the base station. The results suggest that the T-MT method can be used routinely to determine interpretable quasi-MT responses in the AMT dead band. The main problem is still the presence of noise, but now it is on the electric field rather than on the magnetic field. Because the quasi-AMT transfer function of every site is estimated from the product from two transfer functions, the propagation of errors can become important.

## TELLURIC-MAGNETOTELLURIC METHODOLOGY

The tensor T-MT method was proposed initially by Hermance and Thayer (1975) and successfully applied to the reconnaissance of regional geothermal activity in Iceland (Hermance et al., 1976; Thayer et al., 1981). The T-MT method is based on combining the telluric method, used with some success mostly from the late 1930s to the early 1970s but also more recently (Schlumberger, 1939; Berdichevsky, 1965; Yungul, 1965; Slankis et al., 1972; Pham et al., 1995; Mlynarski and Zlotnicki, 2001), with Cagniard's (1953) MT method developed through the 1950s and 1960s. [See Vozoff (1986), for a collection of key papers]. Stodt et al. (1981) undertook numerical modeling studies of T-MT responses, but their approach has rarely been applied; the exceptions in the published literature are Adam et al. (1995), Nemesi et al. (1985), and Manzella et al. (1999).

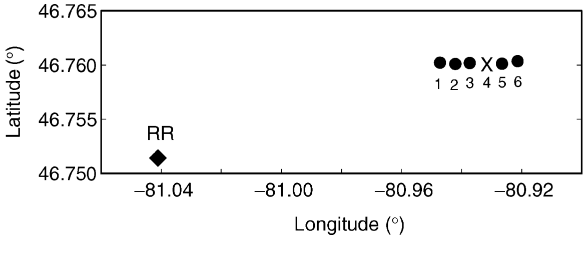

Figure 1. Location of the sites on the northern profiles from the Norman Township T-MT experiment. The filled circles are the sites, the cross is the base station, and the black diamond shows the relative location of the remote reference station.

Our version of T-MT differs from previous ones in that the telluric and MT data are not acquired at the same time. Daytime telluric data are acquired as orthogonal sets of electrodes located in sequence at a number of sites and two other orthogonal sets of electrodes, one at a base site and another at a clean remote-reference site. For these purposes, a clean site is one that has little noise contribution. During the night, conventional AMT data are acquired at the base and remote-reference sites.

The objective of this method is to compare measurements at the various local sites with simultaneous observations at the base site. The TT function $\mathbf{T}_i(\omega)$, between the parallel telluric pairs of the $i$th site and the base, is defined as a relation of the form

$$\mathbf{e}_i = \mathbf{T}_i \mathbf{e}_b \tag{1}$$

(dependence on frequency assumed), where $\mathbf{e}_i$ and $\mathbf{e}_b$ are vectors (of length two) comprising the two electric components at the $i$th local site $[e_x^i, e_y^i]$ and base $[e_x^b, e_y^b]$, respectively, and $\mathbf{T}_i$ is a $2 \times 2$ complex matrix relating the two vectors. The TT functions defined in this manner have been used to locate conducting structures (Slankis et al., 1972). We derive an estimate of $\mathbf{T}_i$, or $\mathbf{T}_i'$, that is unbiased in the presence of noncorrelating noise contributions by using the remote electric components $[e_x^r, e_y^r]$:

$$\mathbf{T}_i' = [\mathbf{e}_i \mathbf{e}_r][\mathbf{e}_b \mathbf{e}_r]^{-1}, \tag{2}$$

where the prime denotes an estimator. The value $[\mathbf{ab}]$ is the spectral density matrix for fields $\mathbf{a}$ and $\mathbf{b}$, defined by (Gamble et al., 1979b)

$$[\mathbf{ab}] = \begin{bmatrix} \langle a_x b_x^* \rangle & \langle a_x b_y^* \rangle \\ \langle a_y b_x^* \rangle & \langle a_y b_y^* \rangle \end{bmatrix} \tag{3}$$

where $\langle\,\rangle$ denotes ensemble averaging either by summation over neighboring frequencies or by averaging different estimates and the asterisk denotes the complex conjugate. The inverse of matrix $[\mathbf{ab}]$ is given by (Gamble et al., 1979b)

$$[\mathbf{ab}]^{-1} = \frac{\begin{bmatrix} \langle a_y b_y^* \rangle & -\langle a_x b_y^* \rangle \\ -\langle a_y b_x^* \rangle & \langle a_x b_x^* \rangle \end{bmatrix}}{\langle a_x b_x^* \rangle \langle a_y b_y^* \rangle - \langle a_y b_x^* \rangle \langle a_x b_y^* \rangle}. \tag{4}$$

In MT, this approach is called the remote-reference technique (Gamble et al., 1979a, b), and use of the remote reference avoids the well-known bias effects caused by noise in the autospectral estimates (Sims et al., 1971). The concept of avoiding autopower bias errors by using a remote reference was first introduced by Reiersøl in 1950 (discussed in Akaike, 1967) in econometric theory, where the remote reference field was termed the instrumental variable.

The base station has a nighttime transfer function given by the form

$$\mathbf{e}_b = \mathbf{Z}_b \mathbf{h}_b, \tag{5}$$

where $\mathbf{Z}_b$ is the conventional Cagniard MT impedance tensor. Its unbiased estimate $\mathbf{Z}_b'$, using the remote magnetic fields $\mathbf{h}_r$, i.e., $[h_x^r, h_y^r]$, is given by (Gamble et al., 1979a, b)

$$\mathbf{Z}_b' = [\mathbf{e}_b\mathbf{h}_r][\mathbf{h}_b\mathbf{h}_r]^{-1}. \tag{6}$$

More correctly, Cagniard defines a scalar relationship between one magnetic field and its orthogonal collocated electric field. Sims et al. (1971) report that the first definition of a tensor relationship between **e** and **h** was in an unpublished dissertation by Neves (MIT, 1957), entitled "The Magnetotelluric Method in Two-Dimensional Structures."

Multiplying unbiased estimators 2 and 6 together, we thus obtain a noise-unbiased estimate of the quasi-MT transfer function at the local site $Z_i'$ from the expression

$$\mathbf{Z}_i' = \mathbf{T}_i'\mathbf{Z}_b' = [\mathbf{e}_i\mathbf{e}_r][\mathbf{e}_b\mathbf{e}_r]^{-1}[\mathbf{e}_b\mathbf{h}_r][\mathbf{h}_b\mathbf{h}_r]^{-1}, \tag{7}$$

which requires matrix multiplication of two $2 \times 2$ complex matrices.

If the anomalous magnetic field at the site is small, then the magnetic field at the site is approximately the same as at the base, $\mathbf{h}_i \cong \mathbf{h}_b$, and the quasi-MT transfer function defined in equation 7 will be the true single-site Cagniard MT impedance. However, this is a limitation only if one undertakes 1D modeling of the impedance. When undertaking 2D or 3D modeling, the measurement locations for the electric and magnetic components can be set differently for each site and not necessarily be at the same location (discussed below). This approach, with electric-field sensors at different locations from the magnetic-field sensors, is used in the EMAP profiling method of Torres-Verdin and Bostick (1992) and in the distributed-array MT systems of Mount Isa Mines' MIMDAS system and Quantec Ltd.'s Titan system.

Given error propagation arguments, it is essential that the estimates of the base MT transfer function $\mathbf{Z}_b'$ be as accurate and precise as possible. This can be achieved through robust processing [see, e.g., Jones et al. (1989)] and by observations over a number of nights for the same base station. The errors are calculated by a chain rule expansion of $\mathbf{Z}_i'$, namely,

$$\delta\mathbf{Z}_i' = \delta\mathbf{T}_i'(\mathbf{Z}_b') + (\mathbf{T}_i')\delta\mathbf{Z}_b'. \tag{8}$$

If the local magnetic fields are very different from those at the base station, then the T-MT responses can be modeled by modifying the 2D or 3D forward codes to account for the locations of the electric and magnetic sensors. This is done in two dimensions by Stodt et al. (1981) and recently in three dimensions by R. Mackie (2003, personal communication).

## EXPERIMENT

To test the above methodology, during July 2000 a T-MT experiment was carried out in the Norman Township of Sudbury, northern Ontario, Canada. This particular survey was undertaken in the summer; therefore, signal-strength conditions were as optimal as possible for daytime recording because the magnetic signal was at its seasonal peak in the AMT dead band (see Figures 3 and 4 in Garcia and Jones, 2002). AMT data were acquired at 18 stations on four profiles and at a continuous remote reference station. One station on each profile was left recording overnight and became the base station for that profile. Here, we show results from the northern profile only.

As stated in the Introduction, the northern profile consisted of six AMT stations: five of these we treated as daytime telluric sites (solid circles in Figure 1) and the sixth as the base station (site 4, X, in Figure 1). In addition, we had a remote-reference station (RR in Figure 1) some 450 m away. The daytime AMT estimates from the sites were used to test the veracity of our method.

The time-series processing was undertaken using the controlled-leverage robust remote-reference code of Chave (Chave and Thomson, 2003; based on Chave et al., 1987). Prior to processing, the data were notch filtered to remove 60 Hz and its even and odd order harmonics up to 10 kHz. Because of the instability of the powerline signal in the region, caused by variations in the transmission frequency with load, we adopted a cascaded, recursive approach. The filtering comprised cascaded two-pole, 6-dB/octave Butterworth recursion filters [see Shanks (1967) for a review of recursion filters] with notches at 60.0, 60.1, 60.2, and 60.3 Hz, and all even- and odd-order harmonics to 10 kHz (even-order harmonics were required because the power-supply system was not balanced). Such a procedure required far less computational effort than other schemes, requiring only single-precision arithmetic and only ten operations (five multiplications, four additions, and one division) per frequency per data point.

### Base

In Figure 2, the AMT apparent resistivities and phases for the base station for all four components of the MT tensor, derived from nighttime data, are displayed. Special care, including visual inspection of data and choice of parameters, was applied in processing the data from this station because

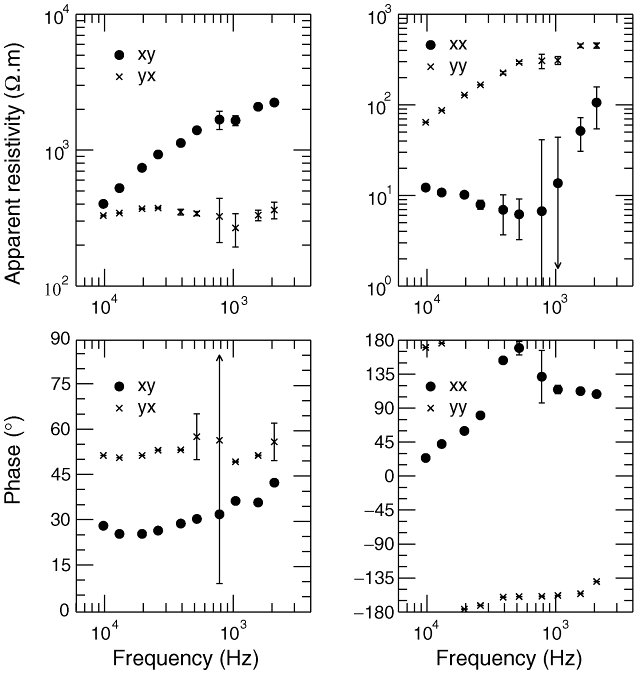

Figure 2. Night MT responses (apparent resistivity and phase) for base station 4. The filled circles are the *xy* (left column) and *xx* (right column) estimates, whereas the crosses are the *yx* (left column) and *yy* (right column) estimates.

of its importance for further calculations of the site T-MT responses. The responses are reasonably smooth but do exhibit large error bars and noise effects toward the low frequencies of the AMT dead band, around 1 to 2 kHz. These large error bars and noise can be explained by the low signal at these frequencies, even during the night and during the highest lightning activity time of the year. Because of the tensor relationships (equations 1 and 5), all of the elements of the MT tensor will contribute to the T-MT final responses, and the noise effects displayed in the *xx* component (filled circles in right-hand column on Figure 2) will be important when multiplied by the TT tensor.

### Sites

Figure 3 shows a typical example of TT tensor responses; these are between site 6 and the base station. In the case of a pure 1D earth without any lateral conductivity discontinuities or galvanic distortion and for a uniform (plane-wave) source field, these transfer functions should be equal to the real identity matrix; diagonal elements are real with a value of unity, and the off-diagonal elements are zero. The plane-wave assumption is safe to make at these high frequencies; nonplane-wave events will be too energetic and will be rejected by appropriate discrimination methods. For our data, the deviation from 1D behavior at even the highest frequencies suggests the presence of galvanic distortion by near-surface scatterers (e.g., Groom and Bailey, 1989). The observed scatter over the dead band in the T$xy'$ component is caused by noise not eliminated by the filtering routine and the processing scheme. The same is true for the scatter observed on the other components. The presence of noise is most likely because of the lack of signal; therefore, the noisy signals are predominant in this band. These responses could be improved with a larger amount of data.

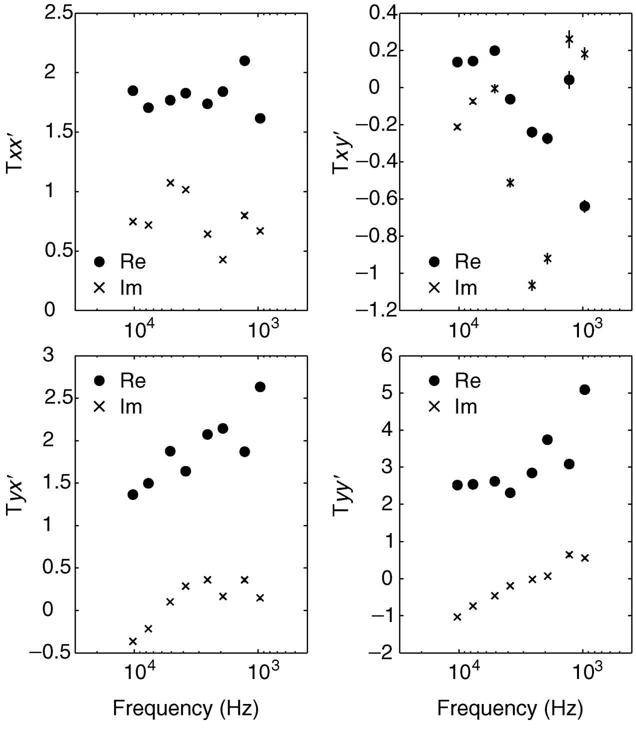

Figure 3. TT responses for station 6. The filled circles are the real parts of the transfer functions; the crosses are the imaginary parts.

### Site 1

Figure 4a shows the T-MT 2 × 2 impedance responses for site 1 together with the conventional daytime MT responses from the same site. In contrast to the more scattered responses from the daytime, the T-MT responses are smoother. The nature of EM methods at AMT and lower frequencies is such that the response functions observed on the surface of the earth must be smoothly varying with frequency. This necessity has been used by a number of workers, e.g., Bailey's (1970) uniqueness theorem, Weidelt's (1972) Hilbert transformation relationships, Parker's (1980) existence of solutions derivations, and Larsen's (1989) robust processing methods.

Around 2 kHz there is still some scatter caused by the lack of signal at this frequency, even during the night (Figure 2). The T-MT and MT apparent resistivities and phases are displayed in Figure 5a. Based on a comparison of the two schemes, the T-MT method gives superior apparent-resistivity estimates at the higher frequencies (>2.5 kHz), while for the lower frequencies (<2.5 kHz) only polarization *xy* is superior to the daytime transfer function. For the phases, the situation is different. The *xy* polarization is severely distorted from the nighttime estimates because the imaginary component of TT$xx'$ component (not shown) is nonzero and close to the real part, possibly as a result of noise not eliminated by the notching and processing codes.

### Site 2

Figure 4b shows site 2 T-MT and MT responses. With the exception of the T-MT*xy* component, the other matrix elements show some scatter caused by noise — especially the *yx* component where the impedances increase as the frequency decreases instead of trending asymptotically to zero. The fact that most of the noise effects are shown around 1 to 2 kHz is probably caused by a lack of energy. Therefore, noisy signals predominate in this band.

The off-diagonal apparent resistivities shown in Figure 5b are shifted from the daytime AMT estimates by a frequency-independent multiplicative number. This is a manifestation of static shift (e.g., Jones, 1988; Sternberg et al., 1988) caused by compounding the static effects at the base site with those at the local site. The T-MT*xy* component is smoother than its MT counterpart. This is also evident in the phases (circles) because they are superior to the MT phases (solid line). The *xy* phases are well estimated, while the *yx* phases are poorly estimated, possibly from galvanic distortion at this site, evident from the different levels of the apparent-resistivity curves.

### Site 3

The T-MT transfer functions (Figure 4c) are smooth except for the low frequencies in the *yx* component. Figure 5c shows the T-MT and MT apparent resistivity and phases. The MT*xy* component (circles) depicts some scatter, whereas its T-MT counterpart is smooth. For the *yx* component the situation is the opposite, and the MT response is better than the T-MT

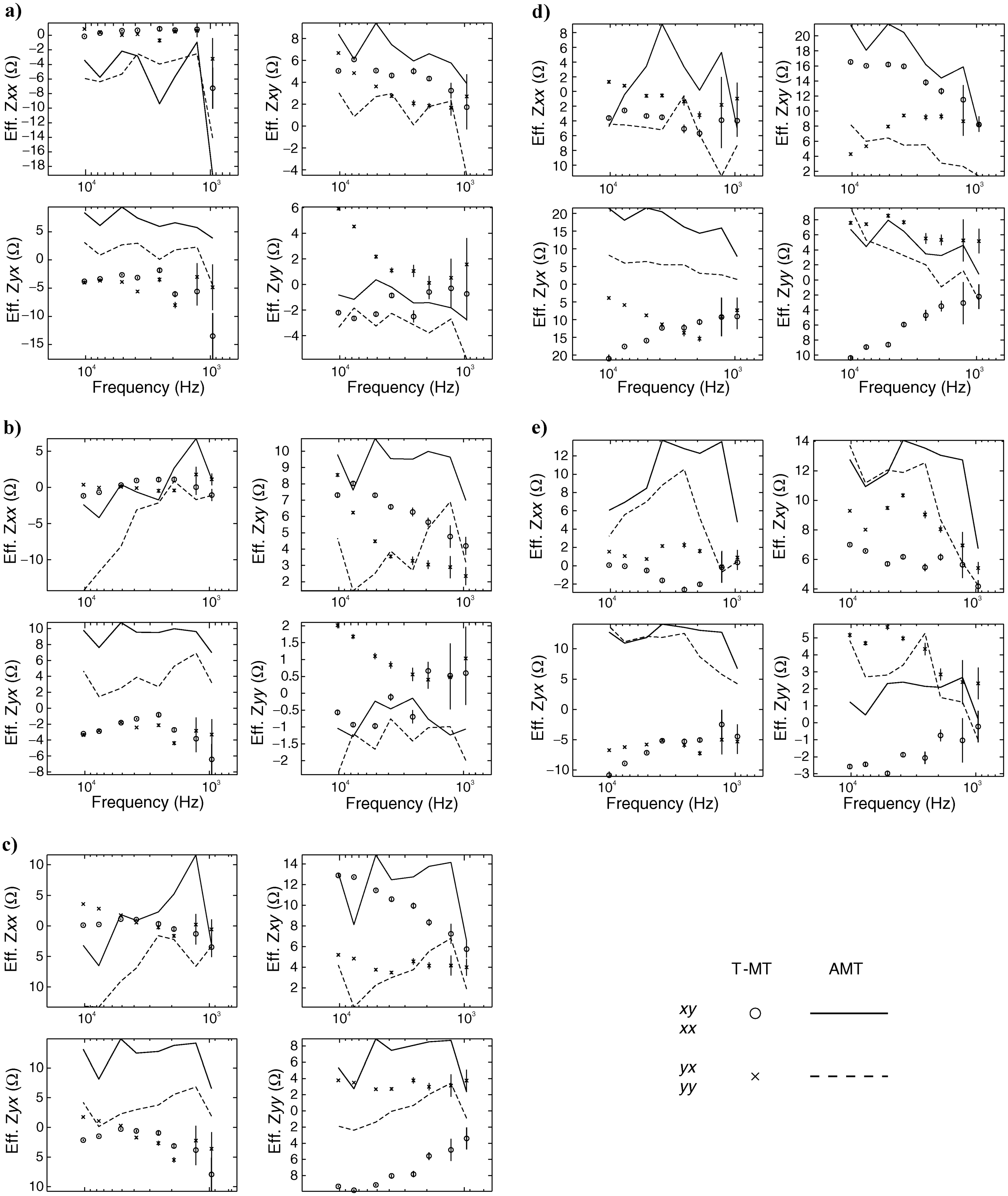

Figure 4. Effective impedances (T-MT) (*xy* and *xx* — dots; *yx* and *yy* — crosses) and daytime MT responses (*xy* and *xx* — solid lines; *yx* and *yy* — dashed lines) for all stations. The *xy* and *yx* estimates are shown in the left column for each site, and the *xx* and *yy* estimates are shown in the right column.

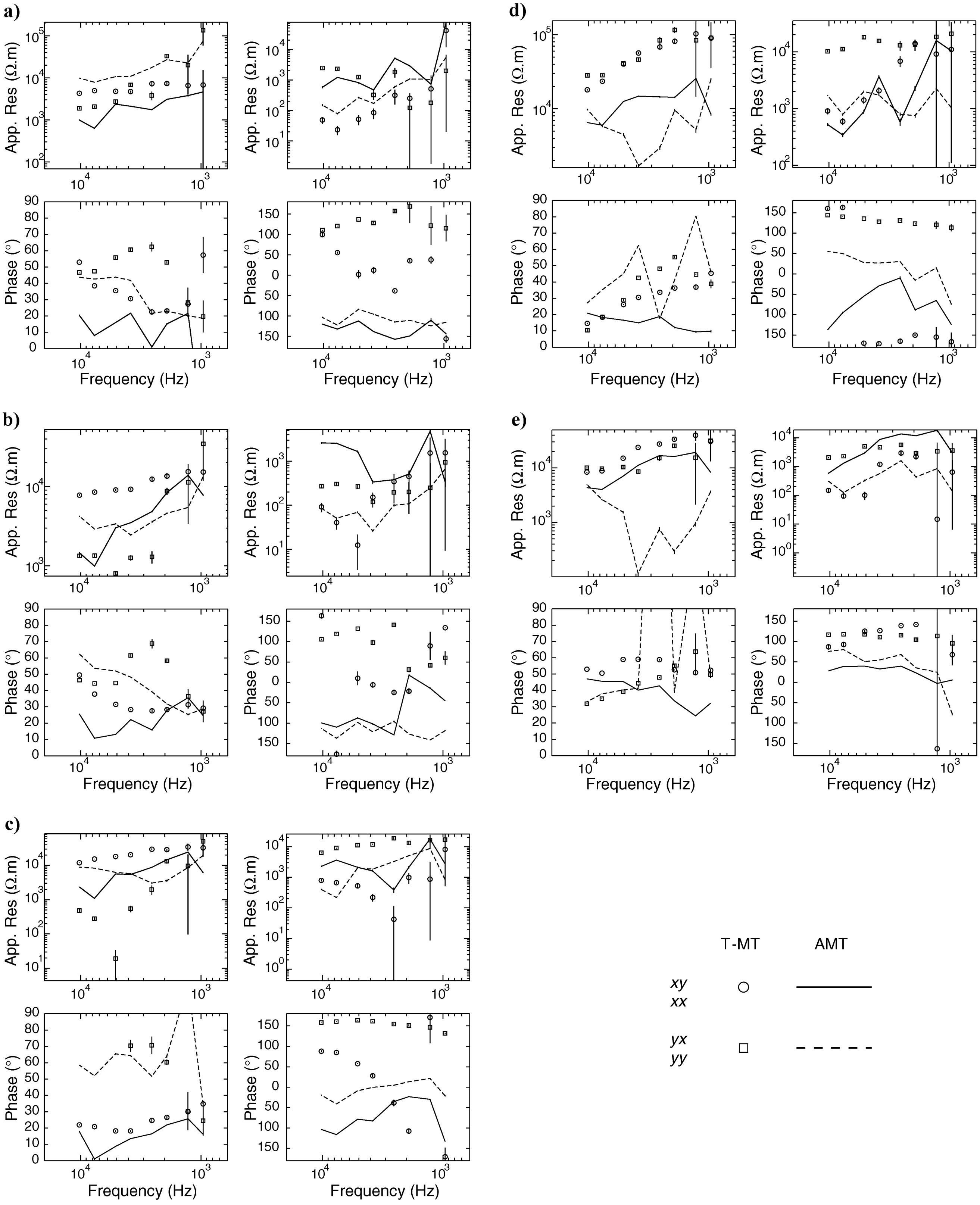

Figure 5. Effective apparent resistivities and phases (*xy* and *xx* mode — circles; *yx* and *yy* mode — squares) and daytime MT responses (*xy* and *xx* mode — solid lines; *yx* and *yy* mode — dashed lines) for all stations. The *xy* and *yx* estimates are shown in the left column for each site, and the *xx* and *yy* estimates are shown in the right column.

one, which displays downward-biased apparent resistivities at high frequencies and phases out of quadrant. The T-MT*xx* apparent resistivities display a downshift from the MT*xx* estimates, showing maximum downward biasing at around 3 kHz.

### Site 5

Figure 5d shows a particularly good example of how this method can be successful in situations where the conventional AMT estimates are poorly resolved. The solid and dashed lines are the robust AMT estimates from the AMT daytime data; the apparent resistivities are scattered with large error bars (not shown). Applying the T-MT method yields smooth and interpretable apparent resistivities and phases.

### Site 6

Figure 3 shows the scattered TT responses for this station. The T-MT transfer functions (Figure 4e) are not smooth as a consequence of noisy TT responses. In spite of this lack of smoothness, the apparent resistivities and phases (Figure 5e) show, as found at site 5, that the method gives much better estimates than the conventional one. The T-MT*xy* apparent resistivities are shifted up half a decade, caused by galvanic effects in the TT transfer functions. The MT*yx* polarization shows again a minimum around 3 kHz that is not present in the T-MT estimates. However, the phases reflect some of the noise effects on the T-MT transfer functions (Figure 4e).

## CONCLUSIONS

We have proposed a new methodology to derive quasi-AMT responses during the daytime using a telluric-magnetotelluric approach. The field tests demonstrate that the method can produce high-quality responses that are smoother than conventional daytime AMT responses. This method enhances the acquisition of AMT time series and overcomes some of the problems with low magnetic-field signal levels. The method comes with little logistical cost, as it requires only overnight recordings at base and remote stations. The method, however, is susceptible to the presence of noise because of error propagation. Such error propagation limits the applicability of the method. However, as shown in this work, even in the presence of noise, results can be improved and a quantitative interpretation undertaken. An additional challenge is caused by galvanic distortion: The distortion that affects the base station compounds the local distortion effects.

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## REFERENCES

Adam, A., L. Nemesi, and B. R. Arora, 1995, The role of telluric (TE) and magnetotelluric (MT) methods in the exploration of deep sedimentary basins: Journal of the Geological Society of India, **45**, 393–406.

Akaike, H., 1967, Some problems in the application of the cross-spectral method, *in* B. Harris, ed., Advanced seminar on spectral analysis of time series: John Wiley & Sons, 81–107.

Bailey, R. C., 1970, Inversion of the geomagnetic induction problem: Proceedings of the Royal Society of London, Series A, **315**, 185–194.

Berdichevsky, M. N., 1964, Electrical prospecting with the telluric current method: Colorado School of Mines Quarterly, **60**, 547–552.

Cagniard, L., 1953, Basic theory of the magneto-telluric method of geophysical prospecting: Geophysics, **18**, 605–635.

Chave, A. D., and D. J. Thomson, 2002, Bounded influence magnetotelluric response function estimation: Geophysical Journal International, **157**, 988–1006.

Chave, A. D., D. J. Thomson, and M. E. Ander, 1987, On the robust estimation of power spectra, coherences, and transfer functions: Journal of Geophysical Research, **92**, 633–648.

Gamble, T. D., W. M. Goubau, and J. Clarke, 1979a, Magnetotellurics with a remote reference: Geophysics, **44**, 53–68.

———, 1979b, Error analysis for remote reference magnetotellurics: Geophysics, **44**, 959–968.

Garcia, X., and A. G. Jones, 2002, Study of ionospheric sources for audio-magnetotelluric (AMT) sounding: Geophysics, **67**, 448–458.

Groom, R. W., and R. C. Bailey, 1989, Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion: Journal of Geophysical Research, **94**, 1913–1925.

Hermance, J. F., and R. E. Thayer, 1975, The telluric-magnetotelluric method: Geophysics, **40**, 664–668.

Hermance, J. F., R. E. Thayer, and A. Bjornsson, 1976, The telluric-magnetotelluric method in the regional assessment of geothermal potential: 2nd Symposium on the Development and Use of Geothermal Resources, United Nations, Proceedings, **2**, 1037–1048.

Jones, A. G., 1988, Static shift of magnetotelluric data and its removal in a sedimentary basin environment: Geophysics, **53**, 967–978.

Jones, A. G., and G. W. McNeice, 2002, Audio-magnetotellurics (AMT) for steeply dipping mineral targets: Importance of multicomponent measurements at each site: 77th Annual International Meeting, SEG, Expanded Abstracts, 496–499.

Jones, A. G., A. D. Chave, G. Egbert, D. Auld, and K. Bahr, 1989, A comparison of techniques for magnetotelluric response function estimation: Journal of Geophysical Research, **94**, 14201–14213.

Larsen, J. C., 1989, Transfer functions: Smooth robust estimates by least-squares and remote reference methods: Geophysical Journal International, **99**, 645–663.

Manzella, A., R. Mackie, and A. Fiordelisi, 1999, An MT survey in the Amiata volcanic area: A combined methodology for defining shallow and deep structures: Physics and Chemistry of the Earth, Part A (Solid Earth and Geodesy), **24**, 837–840.

Mlynarski, M., and J. Zlotnicki, 2001, Fluid circulation in the active emerged Asal rift (east Africa, Djibouti) inferred from self-potential and telluric-telluric prospecting: Tectonophysics, **339**, 455–472.

Nemesi, L., J. Hobot, and G. Varga, 1985, Telluric and magnetotelluric information about the geological structure of Transdanubia (Hungary): Acta Geodaetica, Geophysica, et Montanistica, Academy of Sciences Hungary, **20**, 135–150.

Parker, R. L., 1980, The inverse problem of electromagnetic induction: Existence and construction of solutions based on incomplete data: Journal of Geophysical Research, **85**, 4421–4425.

Pham, V. N., D. Boyer, X. C. Yuan, and S. C. Liu, 1995, Application of telluric-telluric profiling combined with magnetotelluric and self-potential methods to geothermal exploration in the Fujian Province, China: Journal of Volcanic and Geothermal Research, **65**, 227–236.

Reiersøl, O., 1950. Identifiability of a linear relation between variables which are subject to error: Econometrica, **18**, 375–389.

Schlumberger, M., 1939, The application of telluric currents to surface prospecting: Transactions of the American Geophysical Union, **3**, 271–277.

Shanks, J. L., 1967, Recursion filters for digital processing: Geophysics, **32**, 33–51.

Sims, W. E., F. X. Bostick, and H. W. Smith, 1971, The estimation of magnetotelluric tensor elements from measured data: Geophysics, **36**, 938–942.

Slankis, J. A., W. L. Telford, and A. Becker, 1972, 8 Hz telluric and magnetotelluric prospecting: Geophysics, **37**, 862–878.

Sternberg, B. K., J. C. Washburne, and L. Pellerin, 1988, Correction for the static shift in magnetotellurics using transient electromagnetic soundings: Geophysics, **53**, 1459–1468.

Stodt, J. A., G. W. Hohmann, and S. C. Ting, 1981, The telluric-magnetotelluric method in two- and three-dimensional environments: Geophysics, **46**, 1137–1147.

Thayer, R. E., A. Bjornsson, L. Alvarez, and J. F. Hermance, 1981, Magma genesis and crustal spreading in the northern neovolcanic zone of Iceland: Telluric-magnetotelluric constraints: Geophysical Journal of the Royal Astronomical Society, **65**, 423–442.

Torres-Verdin, C., and F. X. Bostick, 1992, Principles of spatial surface electric field filtering in magnetotellurics: Electromagnetic array profiling (EMAP): Geophysics, **57**, 603–622.

Vozoff, K., ed., 1986, Magnetotelluric methods: SEG Reprint Series **5**.

Weidelt, P., 1972, The inverse problem of geomagnetic induction: Zeitschrift für Geophysik, **38**, 257–289.

Yungul, S. H., 1966, Telluric sounding — A magnetotelluric method without magnetic measurements: Geophysics, **31**, 185–191.