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Letter

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A B S T R A C T

Through a large number of magnetotelluric (MT) observations conducted in a study area, one can obtain regional one-dimensional (1-D) features of the subsurface electrical conductivity structure simply by taking the geometric average of determinant invariants of observed impedances. This method was proposed by Berdichevsky and coworkers, which is based on the expectation that distortion effects due to near-surface electrical heterogeneities will be statistically smoothed out. A good estimation of a regional mean 1-D model is useful, especially in recent years, to be used as *a priori* (or a starting) model in 3-D inversion. However, the original theory was derived before the establishment of the present knowledge on galvanic distortion. This paper, therefore, reexamines the meaning of the Berdichevsky average by using the conventional formulation of galvanic distortion. A simple derivation shows that the determinant invariant of distorted impedance and its Berdichevsky average is always downward biased by the distortion parameters of shear and splitting. This means that the regional mean 1-D model obtained from the Berdichevsky average tends to be more conductive. As an alternative rotational invariant, the sum of the squared elements (ssq) invariant is found to be less affected by bias from distortion parameters; thus, we conclude that its geometric average would be more suitable for estimating the regional structure. We find that the combination of determinant and ssq invariants provides parameters useful in dealing with a set of distorted MT impedances.

1. Introduction

The magnetotelluric (MT) method is one of the geophysical exploration methods for studying the electrical conductivity distribution within the Earth. This method estimates the MT impedance tensor, defined as a 2×2 complex-valued tensor relating the observed horizontal vectors of electric and magnetic field fluctuations, and then inverts a set of MT impedances into a conductivity model. Since the establishment of the basic theory (Cagniard, 1953), there has been considerable progress in the technology of inversion of MT impedances (e.g., Ogawa, 2002; Siripunvaraporn, 2012). Three-dimensional (3-D) inversion is now possible, at least to some extent, in complex and realistic situations where target anomalous bodies of various scales are distributed in the Earth, if a number of observations are made over a sufficiently wide area including the largest scale with a typical site spacing to resolve the target of smallest scale. However, in practice, because the number of possible observations is limited and the underground structure is unknown prior to exploration, it is often difficult to design an MT observation array so as to satisfy this ideal condition. In many cases, the site spacing has to be designed larger than the typical scale of near-surface lateral heterogeneities, especially in an area of complex surface geology (Fig. 1). This causes spatial aliasing in the sampling of spatially heterogeneous electromagnetic fields and thus of the MT impedance. We shall hereafter refer to aliasing of the MT impedance as "distortion" and the treatment of galvanic distortion in 3-D MT inversion is our main concern.

In theory, the distortion of the MT impedance may be both galvanic and inductive, but we can choose a proper frequency range so that near-surface lateral heterogeneities have only galvanic effects (Utada and Munekane, 2000). This paper treats such a case. Galvanic distortion is still a kind of spatial aliasing and hence must be removed independently before a reliable image of the underground structure can be obtained through the inversion of MT impedances (Simpson and Bahr, 2005). The removal of galvanic distortion is possible and practical assuming the regional structure is 2-D (Groom and Bailey, 1989); no generally practical method has yet been established for the 3-D case (Sasaki and Meju, 2006; Jones, 2011). The use of impedance properties unaffected by galvanic distortion such as the phase tensor (Caldwell

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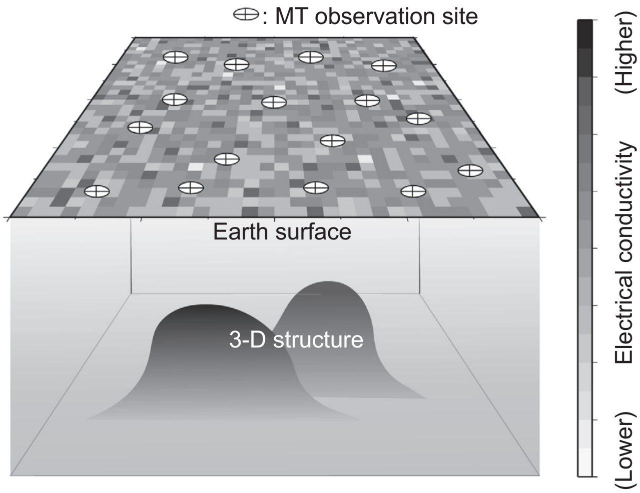

Fig. 1. A sketch of MT array study for 3-D electrical conductivity structure considered in this paper. Observation sites are located in a study region with complex surface geology. If near-surface heterogeneities with spatial scales smaller than the typical site spacing have significant galvanic effects, these effects are aliased to cause galvanic distortion.

et al., 2004) is another option to avoid the difficulty of removing galvanic distortion in the 3-D scenario. However, inversion of the phase tensor is more dependent on the starting model as a natural consequence of dealing with less information (Patro et al., 2013).

Berdichevsky et al. (1980) proposed a simple scheme to obtain the regional MT impedance by averaging the impedances measured at a number of stations in one study area via the equation

$$\log \bar{Z}_{det}(\omega) = \frac{1}{N}\sum_{i=1}^{N} \log Z_{det}(\mathbf{r}_i;\omega), \tag{1}$$

where $\mathbf{r}_i$ and ω are the location of the i-th site and angular frequency, respectively, and Z_{det} is what the authors called the effective impedance defined by the determinant of the impedance tensor.

$$Z_{det} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}}. \tag{2}$$

In this paper, we will call $Z_{\det}$ as the determinant impedance.

Berdichevsky et al. (1980) further assumed Z_{det} in Eq. (1) to be expressible as a product of normal (site-independent) impedance, Z_N, and local (site-dependent) distortion coefficient, K, at each observation site as

$$Z_{det}(\mathbf{r}_i;\omega) = K(\mathbf{r}_i)\cdot Z_N(\omega). \tag{3}$$

Using magnetotelluric results in the Baikal region, Berdichevsky et al. (1980) showed that the distribution of effective impedances can be approximated fairly accurately by the log-normal law. This suggests that the local galvanic effect, modeled using the coefficient K, is a random phenomenon, so that the right-hand side of Eq. (1) becomes

$$\log \bar{Z}_{det}(\omega) = \log Z_N(\omega) + \frac{1}{N}\sum_{i=1}^{N}\log K(\mathbf{r}_i) \approx \log Z_N(\omega). \tag{1'}$$

Similar procedures have been often employed, particularly by scientists in the former Soviet Union (e.g., Berdichevsky et al., 1989) and even in recent works to estimate the regional response and thus, we shall call the average of Eqs. (1) or (1′) the "Berdichevsky average".

Suppose a situation in which we try to study 3-D electrical conductivity distribution by inverting a set of MT impedances obtained by a given observation array and MT impedances include galvanic distortion (Fig. 1). We define a regional mean 1-D conductivity profile, $\sigma_R(z)$, by a surface integral in a area, ΔS, which the observation array occupies,

$$\sigma_R(z) = \frac{1}{\Delta S}\iint_{\Delta S}\sigma(x,y,z)dxdy, \tag{4}$$

where $\sigma(x,y,z)$ is 3-D electrical conductivity distribution in the Earth. In general, $\sigma(x,y,z)$ can be expressed by a sum of mean 1-D profile and the lateral heterogeneity or the conductivity anomaly, $\delta\sigma(x,y,z)$, as,

$$\sigma(x,y,z) = \sigma_R(z) + \delta\sigma(x,y,z). \tag{5}$$

These equations clearly show a merit of using $\sigma_R(z)$ as *a priori* (or a starting) model for 3-D inversion in a sense that it minimizes the variance of lateral heterogeneity, $\delta\sigma$. Alternatively, one can use logarithmic average,

$$log\sigma_R(z) = \frac{1}{\Delta S}\iint_{\Delta S}\log\sigma(x,y,z)dxdy, \tag{4'}$$

if the variance is to be minimized in log-scale. A further remaining question is how to obtain a good estimate of $\sigma_R(z)$ before conducting 3-D inversion from a set of MT impedances with galvanic distortion. The Berdichevsky average has been regarded as one of the most practical solutions (e.g. Tada et al., 2014; Avdeeva et al., 2015).

Although the distortion coefficient K in Eq. (1′) was treated as a real-valued scalar quantity without a clear definition except being a random quantity, present knowledge tells us that, in general, it should be derived from a 2×2 tensor quantity describing galvanic distortion acting on the regional impedance. In this paper, we examine the meaning of the Berdichevsky average given by Eq. (1′) by using the expression for galvanic distortion by Groom and Bailey (1989).

2. Determinant invariant of the MT impedance with galvanic distortion

We start from a general expression for the impedance tensor, $\mathbf{Z}$, with galvanic distortion at each observation site (Fig. 1), whose location is $\mathbf{r}_i$, distributed over our study area (Groom and Bailey, 1989; Utada and Munekane, 2000; Bibby et al., 2005):

$$\mathbf{Z}(\mathbf{r}_i;\omega) = \mathbf{C}(\mathbf{r}_i)\cdot\mathbf{Z}_R(\mathbf{r}_i;\omega), \tag{6}$$

where $\mathbf{C}$ is a 2×2 real-valued tensor describing galvanic distortion and $\mathbf{Z}_R$ is the so-called regional (undistorted) impedance, which reflects the induction effects due to the regional conductivity structure. Here, we treat a general 3-D regional structure so that $\mathbf{Z}_R$ is a 2×2 full complex-valued tensor.

Following Groom and Bailey (1989), the galvanic distortion tensor, $\mathbf{C}$, is composed of two elements:

$$\mathbf{C}(\mathbf{r}_i) = g_i\cdot\mathbf{D}(\mathbf{r},t_i,e_i,s_i). \tag{7}$$

Here, g_i is a scalar parameter reflecting the impedance amplitude at each site due to local effect, and is thus referred to as static shift or site gain. $\mathbf{D}$ is a 2×2 real-valued tensor describing geometric distortion (twisting, shearing, and splitting) with respective scalar parameters t_i, e_i, and s_i at each site (Groom and Bailey, 1989).

The tensor $\mathbf{D}$ is normalized so that the Frobenius norm of $\mathbf{C}$ is equal to $\sqrt{2}g_i$ (Bibby et al., 2005), and therefore following Groom and Baily (1989)'s notation, we derive,

$$\mathbf{D}(\mathbf{r}_i,t_i,e_i,s_i) = N_i\begin{pmatrix}(1+s_i)(1-t_ie_i) & (1-s_i)(e_i-t_i)\\ (1+s_i)(e_i+t_i) & (1-s_i)(1+t_ie_i)\end{pmatrix}, \tag{8}$$

where

$$N_i = \frac{1}{\sqrt{1+t_i^2}\sqrt{1+e_i^2}\sqrt{1+s_i^2}}. \tag{9}$$

Defined in this way, changes in the electric field power with galvanic distortion can be parameterized only by the site gain. This expression also allows us to discuss the site gain and other distortion parameters separately.

Using Eq. (6), the determinant invariant of the distorted impedance at each site can be written as

$$\det(\mathbf{Z}(\mathbf{r}_i;\omega)) = \det(\mathbf{C}(\mathbf{r}_i)\cdot\mathbf{Z}_R(\mathbf{r}_i;\omega)) = \det(\mathbf{C}(\mathbf{r}_i))\cdot\det(\mathbf{Z}_R(\mathbf{r}_i;\omega)). \quad (10)$$

By using Eqs. (7)–(9), the determinant of the distortion tensor becomes

$$\det(\mathbf{C}(\mathbf{r}_i)) = g_i^2 N_i^2 (1-s_i^2)(1+t_i^2)(1-e_i^2) = g_i^2 \frac{(1-s_i^2)(1-e_i^2)}{(1+s_i^2)(1+e_i^2)}. \quad (11)$$

Instead of using Eq. (3), let us define the determinant impedance at each observation site in a more general case of distortion as

$$Z_{det}(\mathbf{r}_i;\omega) = \sqrt{\det(\mathbf{Z}(\mathbf{r}_i;\omega))} = g_i\sqrt{\frac{(1-s_i^2)(1-e_i^2)}{(1+s_i^2)(1+e_i^2)}}\cdot Z_{det}^R(\mathbf{r}_i;\omega), \quad (12)$$

where

$$Z_{det}^R(\mathbf{r}_i;\omega) = \sqrt{\det(\mathbf{Z}_R(\mathbf{r}_i;\omega))} \quad (13)$$

is obtained from determinant of the regional (undistorted) impedance tensor, $\mathbf{Z}_R$. Note that Gomez-Trevino et al. (2013) obtained a similar expression, in which related discussions were limited to the case in which the regional structure is 2-D. Comparing Eqs. (3) and (12), we find that the distortion coefficient K in Eqs. (3) and (1′) can be related to the distortion parameters in Groom and Bailey (1989) via

$$K(\mathbf{r}_i) = g_i\sqrt{\frac{(1-s_i^2)(1-e_i^2)}{(1+s_i^2)(1+e_i^2)}} \leqslant g_i. \quad (14)$$

This means that the determinant impedance is generally biased downward by the distortion parameters (shear and splitting). Even if the regional structure is 1-D, the Berdichevsky average given in Eq. (1) will yield the 1-D impedance with downward bias under the presence of galvanic distortion. In the case of on-land observation sites, especially where the surface geology is highly heterogeneous, MT impedances are usually affected by galvanic distortion. These results prompted us to seek another rotational invariant more appropriate for Berdichevsky averaging.

3. Properties of the ssq invariant of MT impedance with galvanic distortion

From the complete system of rotational invariants presented by Szarka and Menvielle (1997), here we select the sum of the squared elements (ssq) of the impedance, which is given by

$$\mathrm{ssq}(\mathbf{Z}(\mathbf{r}_i;\omega)) = Z_{xx}(\mathbf{r}_i;\omega)^2 + Z_{xy}(\mathbf{r}_i;\omega)^2 + Z_{yx}(\mathbf{r}_i;\omega)^2 + Z_{yy}(\mathbf{r}_i;\omega)^2. \quad (15)$$

We will also define the ssq impedance in analogy to the determinant impedance:

$$Z_{ssq} = \sqrt{\frac{\mathrm{ssq}(\mathbf{Z})}{2}}. \quad (16)$$

Considering that the distortion tensor includes a normalization factor, N_i, owing to its Frobenius norm and the apparent similarity between ssq and the Frobenius norm, we will examine the behavior of the ssq of distorted impedance tensor in what follows.

When the impedance is distorted as described in Eq. (6), its ssq becomes:

$$\begin{aligned}\mathrm{ssq}(\mathbf{Z}(\mathbf{r}_i;\omega)) = {} & g_i^2\,\mathrm{ssq}(\mathbf{Z}_R(\mathbf{r}_i;\omega)) - \frac{2g_i^2 s_i}{(1+s_i^2)}\Big[Z_{xx}^R(\mathbf{r}_i;\omega)^2 \\ & + Z_{xy}^R(\mathbf{r}_i;\omega)^2 - Z_{yx}^R(\mathbf{r}_i;\omega)^2 - Z_{yy}^R(\mathbf{r}_i;\omega)^2\Big] \\ & + \frac{4g_i^2 e_i(1-s_i^2)}{(1+e_i^2)(1+s_i^2)}\Big[Z_{xx}^R(\mathbf{r}_i;\omega)Z_{yx}^R(\mathbf{r}_i;\omega) \\ & + Z_{xy}^R(\mathbf{r}_i;\omega)Z_{yy}^R(\mathbf{r}_i;\omega)\Big].\end{aligned} \quad (17)$$

The second and third terms of the right-hand side of Eq. (17) will diminish if the regional structure is purely 1-D. In that case, Z_{ssq} will have a log-normal distribution with a mean equal to the 1-D impedance, Z_{1D}, so that we have:

$$\log\bar{Z}_{ssq}(\omega) = \frac{1}{N}\sum_{i=1}^{N}\log Z_{ssq}(\mathbf{r}_i;\omega) = \log Z_{1D}(\omega) + \frac{1}{N}\sum_{i=1}^{N}\log g_i. \quad (18)$$

On the basis of the central limit theorem, the second term of the right-hand side of Eq. (18) would be expected to approach zero, if we take the average for a large number of sites in a sufficiently large study area (deGroot-Hedlin, 1991; Ogawa and Uchida, 1996). In other words, the average of the distorted ssq impedances well approximates the average of the undistorted ssq impedances in the case of a regionally 1-D Earth structure.

When the regional structure is 2-D, the second term on the right-hand side of Eq. (17) remains finite, and both the second and third terms persist in the general case of a 3-D regional structure. However, if more resistive and more conductive anomalies have nearly equal induction effects in spatial distribution and intensity, we can reasonably assume that the contribution from the second and third terms in Eq. (17) will become negligibly small upon averaging over many sites in a wide study area. Thus, we have:

$$\begin{aligned}\log\bar{Z}_{ssq}(\omega) &= \frac{1}{N}\sum_{i=1}^{N}\log Z_{ssq}(\mathbf{r}_i;\omega) \\ &\approx \frac{1}{N}\sum_{i=1}^{N}\log Z_{ssq}^R(\mathbf{r}_i;\omega) + \frac{1}{N}\sum_{i=1}^{N}\log g_i.\end{aligned} \quad (19)$$

This property is what Berdichevsky et al. (1980) imposed in their averaging of Eqs. (1) and (1′).

4. Results

The results obtained here indicate that all properties of the Berdichevsky averaging are mostly applicable only if we redefine the effective impedance as Z_{ssq}. Moreover, the present derivation yields the following important properties in addition to the set of observed impedances:

(a) The apparent site gain:

Based on Eq. (19), we introduce a parameter that approximates the site gain at each site, which can be estimated from the observed impedances by

$$g_i^{ssq}(\omega) = \frac{Z_{ssq}(\mathbf{r}_i;\omega)}{\bar{Z}_{ssq}(\omega)}. \quad (20)$$

We call this parameter the apparent ssq site gain. It gives the true value of the site gain, if the regional structure is 1-D. Even in general cases where estimates of the apparent site gain given by Eq. (20) are complex-valued and frequency-dependent, its real part can still be assumed to be a good approximation of the actual site gain. We can also estimate an apparent site gain from the ratio of local to averaged determinant impedances as,

$$g_i^{det}(\omega) = \frac{Z_{det}(\mathbf{r}_i;\omega)}{\bar{Z}_{det}(\omega)}. \tag{21}$$

However in this case, the apparent determinant site gain includes effects of shear and splitting parameters so that it is supposed to be less accurate estimate than that from Eq. (20). Conversely, if static shift is the only significant galvanic effect in the given dataset, Eq. (21) will provide a better estimation of site gain than Eq. (20) because of the second and third-terms of the right hand side of Eq. (17).

(b) The local distortion indicator:

When the regional structure is 1-D, the determinant impedance will be biased by a factor incorporating shear and splitting parameters (Eq. (12)) but the ssq impedance will not. A similar relationship can be expected to hold for the case of the regional 3-D structure, so that the ratio

$$\gamma_i(\omega) = \frac{Z_{ssq}(\mathbf{r}_i;\omega)^2}{Z_{det}(\mathbf{r}_i;\omega)^2} \approx \frac{Z^R_{ssq}(\mathbf{r}_i;\omega)^2}{Z^R_{det}(\mathbf{r}_i;\omega)^2}\frac{(1+s_i^2)(1+e_i^2)}{(1-s_i^2)(1-e_i^2)}, \tag{22}$$

will serve as an indicator of the type of distortion at each site. In case the regional structure is 1-D, the regional (undistorted) impedance is independent of the site location and it is easy to show:

$$Z^R_{det}(\omega) = Z^R_{ssq}(\omega). \tag{23}$$

Therefore, if γ_i is almost real and frequency-independent, the regional structure can be assumed to be nearly 1-D. Note that if induction effects are intense, γ_i will be complex-valued and frequency-dependent. Further, a $|\gamma_i|$ value that is significantly greater than unity suggests the presence of strong galvanic distortion (shear and splitting). The local presence of galvanic distortion can be identified also by checking the consistency between spatial gradients of the impedance and the tipper at each site (Utada and Munekane, 2000). However, we should note that all distortion parameters including site gain contribute in this case, while γ_i is affected only by shear and splitting parameters. Therefore a combined use of this consistency and local distortion indicator will be useful to distinguish the type of distortion affecting the impedance at a particular site.

(c) The regional distortion indicator

Next, we construct a geometric mean of local distortion indicators in Eq. (22):

$$\gamma_R(\omega) = \left[\prod_{i=1}^{N}\gamma_i(\omega)\right]^{\frac{1}{N}} \approx \left[\prod_{i=1}^{N}\frac{(1+s_i^2)(1+e_i^2)}{(1-s_i^2)(1-e_i^2)}\right]^{\frac{1}{N}}\frac{\bar{Z}^R_{ssq}(\omega)^2}{\bar{Z}^R_{det}(\omega)^2}, \tag{24}$$

which can be referred to as the regional distortion indicator. The value of $|\gamma_R(\omega)|$ should approach unity if galvanic effect in the given dataset consists of only static shift. Only static shift correction is required for the inversion of such a dataset. The value of $|\gamma_R(\omega)|$, which is greater than unity, increases as the intensity of galvanic distortion (shear and splitting) at each site increases. It can thus serve as a regional indicator for the presence of galvanic distortion. This information will help to relieve unnecessary computational complexity (Avdeeva et al., 2015).

5. Conclusion

By combining the mathematical expressions for rotational invariants of the MT impedance tensor (Szarka and Menvielle, 1997) and for galvanic distortion (Groom and Bailey, 1989), the physical meaning of the Berdichevsky average was reexamined. It was found that the determinant invariant induces downward bias in the impedance amplitude (apparent resistivity) due to shear and splitting parameters when galvanic distortion is significant. This means that inversion of the Berdichevsky average provides a model that overestimates the conductivity of the regional structure. On the other hand, we found that the exact expression for the ssq (sum of squared elements) invariant of distorted impedance does not include a bias from the distortion parameters in the first order approximation. This result suggests that Berdichevsky averaging with ssq impedances is more suitable for estimating the regional mean 1-D profile that can be used for *a priori* (or starting) model in 3-D inversion. We also showed that some combinations of determinant and ssq invariants provide useful properties in dealing with a set of observed MT impedances, such as the apparent site gain and the local and regional distortion indicators. This paper presented an analysis scheme using two rotational invariants. To make the scheme applicable to real data, next we need to verify it by using a synthetic model, which will be done in our companion paper (Rung-Arunwan et al., 2016, under review).

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