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The influence of geomagnetic storms on the quality of magnetotelluric impedance

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Abstract: Magnetotelluric field data contain natural electromagnetic signals and artificial noise sources (instrumental, anthropogenic, etc.). Not all available time-series data contain usable information of the electrical conductivity distribution at depth with a low signal-to-noise ratio. The variation of the natural electromagnetic signal increases dramatically in a strong geomagnetic storm, and the signal-to-noise ratio increases. A more reliable impedance may be obtained using the storm data in a noisy environment. Three field data observed at mid-latitude were used to investigate the effect of geomagnetic storms on MT impedance quality. We mainly combined the coherence between the electric and magnetic fields and the result of MT impedance to evaluate the MT impedance quality; we also used the polarization direction, linear coherence and amplitude ratio between the local and remote magnetic field to evaluate the data quality in the noisy environments. The case studies showed that the utilization of the data observed during the geomagnetic storm could overcome the local noise and bring a reliable impedance.

Keywords: geomagnetic storm, impedance tensor, magnetotelluric method

1 INTRODUCTION

The magnetotelluric (MT) method is a passive electromagnetic (EM) method used to infer the subsurface electrical conductivity from the natural geomagnetic and geoelectric fields observed at Earth's surface. It was first proposed by Rikitake (1948), Cagniard (1953) and Tikhonov (1950). Many works have focused on the Earth's EM environment (Constable, 2016; Constable and Constable, 2004; Garcia and Jones, 2002; Hennessy and Macnae, 2018; Mareschal, 1986; McPherron, 2005). Generally, the high-frequency signals (> 1 Hz) originate from worldwide thunderstorm activity. In comparison, the low-frequency signals (< 1 Hz) originate from the interaction between solar winds and the Earth's magnetosphere and ionosphere. The MT method assumes that the EM source is located at a large distance to the measurement area, and the signal propagates as plane waves. This condition is also known as the far-field assumption (Oettinger et al., 2001; Zonge and Hughes, 1987) and is dependent on the target period. The natural EM signal from the Earth's magnetosphere and ionosphere or global lighting is far from the observation site and can be treated as plane waves. On the contrary, the local anthropogenic sources violate the plane wave assumption and are regarded as noise in the MT method. Szarka (1988) and Junge (1996) summarized the active and passive noise sources observed in MT measurements.

Not all MT time-series data include usable information of the electrical conductivity distribution at depth with a low signal-to-noise ratio (SNR). It can occur when the natural signal level is comparable to or below the instrument noise level or in the presence of some types of cultural noise (Chave and Jones, 2012). The first step in MT data processing is estimating the frequency-domain impedance tensor from the measured time-series data. All MT data interpretations are based on the impedance. Therefore, it is very important to obtain a reliable impedance. The low SNR data can be regarded as noisy data. Robust procedures can only obtain reliable impedance from a reasonable proportion of noisy data, i.e., typically no more than 40-50%

(Smirnov, 2003). When a large amount of noise contaminates the data, it isn't easy to get a reliable impedance from the current technology.

The geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by the solar wind's shock wave interacts with the Earth's magnetic field. Geomagnetic storms start when the enhanced energy of the solar wind transfer into the magnetosphere (Chave and Jones, 2012; Tsurutani et al., 2006). It has been known that the horizontal geomagnetic field is depressed during the geomagnetic storm and recover to its average level gradually. The disturbance storm time (Dst) is an index of magnetic activity derived from the four low-latitude horizontal magnetic fields and is defined as follows (see the homepage of WDC Kyoto Observatory):

$$Dst(T) = \sum_{i=1}^4 \frac{D_i(T)}{\cos(\varphi_i)}, \quad (1)$$

where φ is the dipole latitudes of the observatory, T denotes the time in hours. $D(T)$ is the disturbance variation for each observatory and is defined by :

$$D(T) = \Delta H(T) - S_q(T), \quad (2)$$

where $\Delta H(T)$ denotes the deviations from the baseline for each observatory, and $S_q(T)$ denotes the solar quiet daily variation. Dst can indicate the occurrences of magnetic storms and their severity when they occur. When the Dst is less than -50 nT, it is categorized as a geomagnetic storm. When the Dst is less than -100 nT, it is categorized as a strong geomagnetic storm. During a strong geomagnetic storm, the variation in the natural EM signal increases substantially. Sometimes, the amplitude of EM signals during the strong storm can be 100 times greater than during the non-storm period (see Fig. 1 in the supplementary document). Noise can be neglected under this condition. The high SNR data can be obtained even with artificial noise, depending on the strength of the geomagnetic storm and the noise.

It is well known in MT communities that the natural EM signal increases significantly during a strong geomagnetic storm. However, the examples of evaluating the effects of the geomagnetic

storm on the MT impedance quality are rare. On the other hand, the plane wave assumption is generally acceptable at midlatitudes (Lezaeta et al., 2007; Viljanen et al., 1993). However, it is violated at high magnetic latitudes because the source field is nonuniform during geomagnetic storms (Mareschal, 1981; Viljanen et al., 1993; Garcia et al., 1997; Lezaeta et al., 2007). Possible biases in the MT transfer function due to the source effect are considered only at long periods (> 1000 s) and near the auroral or equatorial electrojets (Murphy and Egbert, 2018).

Our hypothesis for the influence of the geomagnetic storm on the MT impedance quality is shown in Table 1. The storms are beneficial to MT impedance quality in a noisy environment. This paper tried to investigate the hypothesis and compared the MT impedance quality during the storm and non-storm days using three field data observed at mid-latitude.

Table 1 The MT impedance quality during the storm and non-storm days.

	Non-storm period	Storm period
Quiet site	good	good
Noisy site	bad	good

2 PARAMETERS TO EVALUATE MT IMPEDANCE QUALITY

The coherence (Egbert and Livelybrooks, 1996; Fontes et al., 1988; Weckmann et al., 2005; Jones and Jödicke, 1984) is an important parameter for analyzing data quality. In general, we can combine the performance of impedance and coherence to estimate the MT impedance quality; we also used the polarization (Weckmann et al., 2005), the linear coherence and amplitude ratio between local and remote magnetic fields to examine the data quality when the data is contaminated by noise.

2.1 Impedance Tensor

In the MT method, the magnetic field (**H**) and the electric field (**E**) have a linear relationship in the frequency domain. The impedance tensor at a specific frequency can be calculated in the

frequency domain as follows:

$$\begin{pmatrix} \mathbf{E}_x(\omega) \\ \mathbf{E}_y(\omega) \end{pmatrix} = \begin{pmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{pmatrix} \begin{pmatrix} \mathbf{H}_x(\omega) \\ \mathbf{H}_y(\omega) \end{pmatrix}, \quad (3)$$

where $\mathbf{E}$ and $\mathbf{H}$ are the horizontal electric and magnetic fields at a specific frequency, respectively, ω denotes the angular frequency, and Z means the MT impedance. The suffix x denotes the north-south direction, and y denotes the east-west direction.

In a certain geological situation, the impedance tensor is shown in Table 2. In the 1-D case, the impedance of the diagonal elements is zero. In the 2-D case, when the observation axes coincide with the geoelectrical strike, the diagonal elements' impedance is zero, and the off-diagonal elements are unequal. In the 3-D case, all Z values are nonzero. When the 1-D/2-D model can explain the data, we show the off-diagonal element of the impedance. When the data is a 3-D case, we should show all elements of impedance.

Table 2 The impedance tensor characteristics in certain geological situations.

1-D structure	2-D structure	3-D structure
$\begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix}$	$\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$
$Z_{xy} = -Z_{yx}$	$Z_{xy} \neq Z_{yx}$	all Z values are nonzero

Bound Influence Remote Reference Processing (BIRRP; Chave and Thomson, 2004) is a typical conventional robust estimator to calculate the impedance tensor based on windowed FFT. In this paper, we used the BIRRP code to calculate the impedance.

The impedance result is the most important parameter to discuss the MT impedance quality. The MT sounding curves should be smooth according to the forward modeling. However, in the presence of strong local noise, the impedance phase is close to 0° or 180° , and the apparent resistivity increases as a line in the log scale (Zonge and Hughes, 1987). Therefore, the sounding curves should be smooth, and the impedance phase is not close to 0° or 180° in a quiet EM environment.

125

126 2.2 Coherence between the Electric Field and Magnetic Field

127 The MT time-series data are observed simultaneously in several channels; each channel is divided
128 into N segments, and we can obtain N spectra by applying the Fourier transform to each segment.

129 In polar coordinates, the cross-power spectra are expressed as follows:

$$130 A_i \bar{B}_i = |A_i| \cdot |B_i| e^{j(\varphi_{A_i} - \varphi_{B_i})}, \quad (4)$$

131 where j denotes the imaginary unit, i (=1,2,..., N) is the number of spectra; A_i and B_i are the
132 spectra calculated from the i^{th} segment in the different channel; and φ_{A_i} and φ_{B_i} denote the
133 phases of A_i and B_i , respectively. The overline denotes the complex conjugate. The amplitude of
134 the cross-power spectra equal the product of $|A_i|$ and $|B_i|$, and the phase equals the phase difference
135 between A_i and B_i . The auto-power spectra are calculated as follows:

$$136 A_i \bar{A}_i = |A_i|^2, B_i \bar{B}_i = |B_i|^2. \quad (5)$$

137 Coherence between two vectors is defined as the ratio between cross-power spectra density and
138 the root of auto-power spectra density. It is defined as follows:

$$139 \text{Coh}(\mathbf{A}, \mathbf{B}) = \frac{|\langle \mathbf{A} \bar{\mathbf{B}} \rangle|}{\sqrt{\langle \mathbf{A} \bar{\mathbf{A}} \rangle \langle \mathbf{B} \bar{\mathbf{B}} \rangle}}, \quad (6)$$

140 where the brackets represent the averages of N individual auto-power spectra and cross-power
141 spectra. For instance, the inner product of $\mathbf{A}$ and $\bar{\mathbf{B}}$ can be expressed as follows:

$$142 \langle \mathbf{A} \bar{\mathbf{B}} \rangle = \frac{1}{N} \sum_{i=1}^N A_i \bar{B}_i. \quad (7)$$

143 As shown in Table 2, the diagonal element of impedance is zero in the 1-D or 2-D models (when
144 the observation axes coincide with the geoelectrical strike). That means the orthogonal electric
145 and magnetic fields should be coherent, and the coherence value should be one. In the MT
146 campaign, some random noise may exist, and the observation axes are not in the geoelectrical
147 strike; therefore, the coherence value between the orthogonal electric and magnetic fields is not
148 one but should be high in the 1-D or 2-D structure.

149 In specific geologic environments, the phenomenon of the phase rolling out of the quadrant

(PROQ) may appear (Chouteau and Tournerie, 2000; Weckmann et al., 2003; Yu et al., 2018.). The current channeling caused by complex 3-D isotropic media can explain the PROQ phenomenon. The characteristic of PROQ is that the coherence value between the parallel electric and magnetic fields is high, while the coherence between the orthogonal component is relatively low.

According to the definition of coherence, it lies in the range from zero to one. We suggest that the coherence value higher than 0.7 can be regarded as high-coherence. A coherence value lower than 0.5 can be regarded as low-coherence. On the other hand, time-series data with coherent and incoherent noise may have high and low coherence values. Therefore, we should combine the performance of the impedance result with the coherence to decide the specific situation.

2.3 Polarization Directions

Weckmann et al. (2005) showed the effectiveness of using the polarization directions to estimate the background noise. The polarization directions for the electric field (α_E) and magnetic field (α_H) at a specific frequency (Fowler et al., 1967) are defined as:

$$\alpha_{E_i} = \tan^{-1} \frac{2\text{Re}(E_{x_i}\bar{E}_{y_i})}{|E_{x_i}|^2 - |E_{y_i}|^2}, \quad (8)$$

$$\alpha_{H_i} = \tan^{-1} \frac{2\text{Re}(H_{x_i}\bar{H}_{y_i})}{|H_{x_i}|^2 - |H_{y_i}|^2}. \quad (9)$$

We can rewrite the polarization directions (α) as follows:

$$\alpha = \tan^{-1} \frac{2\text{Re}(A_i\bar{B}_i)}{|A_i|^2 - |B_i|^2} = \tan^{-1} \frac{2\frac{|B_i|}{|A_i|}\cos(\theta_i)}{1 - \left(\frac{|B_i|}{|A_i|}\right)^2}, \quad (10)$$

where $i(=1,2,\dots, N)$ is the number of each component; A_i and B_i are the spectra calculated from the i^{th} segment in the different channel; A_i and B_i denote H_{x_i} and H_{y_i} or E_{x_i} and E_{y_i} , respectively. The polarization direction is related to the phase difference (PD) and amplitude ratio (AR) between the two orthogonal fields. A variety of sources generate natural magnetic signals. These sources generate magnetic fields that vary in their incident directions and amplitude. The

PD and AR between the two orthogonal magnetic fields vary with time; thus, the magnetic field has no preferred polarization direction. However, according to a given conductivity distribution in the subsurface, a preferred polarization direction may exist for the induced electric field (Weckmann et al., 2005).

2.4 The Linear Coherence and Amplitude Ratio between the Local and Remote Magnetic Fields

The PD between two spectra is calculated as follows:

$$\theta_i = \varphi_{A_i} - \varphi_{B_i} = \arg(e^{j(\varphi_{A_i} - \varphi_{B_i})}) = \arg\left(\frac{A_i \bar{B}_i}{|A_i||B_i|}\right), \quad (11)$$

where θ_i denotes the angle of the PD between the two spectra at a specific frequency.

The linear coherence (Lcoh) is proposed as the cosine of the PD as follows:

$$\cos(\theta_i) = \text{Re}(e^{j(\varphi_{A_i} - \varphi_{B_i})}) = \text{Re}\left(\frac{A_i \bar{B}_i}{|A_i||B_i|}\right), \quad (12)$$

where Re denotes the real part of the complex number. The Lcoh lies in the range from -1 to 1. When the PD is close to 0° , the Lcoh value is close to 1. According to Euler's formula, Lcoh is also equal to the real part of $e^{j(\varphi_{A_i} - \varphi_{B_i})}$.

If there is a remote site available, for the north-south direction, the linear coherence between the remote and local magnetic fields (RLcoh) is defined as follows:

$$\text{RLcoh} = \text{Re}\left(\frac{H_{x_i} \bar{H}_{xr_i}}{|H_{x_i}||H_{xr_i}|}\right), \quad (13)$$

where H_{x_i} and H_{xr_i} are the local and remote magnetic field spectra at a specific frequency calculated from the i^{th} segment.

The field MT data include natural EM signals and noise coming from the local environment. We can rewrite the magnetic field $\mathbf{H}$ as follows:

$$\mathbf{H} = \mathbf{H}^{\text{MT}} + \mathbf{H}^{\text{N}}, \quad (14)$$

where N denotes the locale noise, and MT denotes the natural EM signals from the

magnetosphere and ionosphere. The portion of the natural magnetic signals in the local ($\mathbf{H}^{\text{MT}}$) and remote sites ($\mathbf{H}_r^{\text{MT}}$) comes from the same source. The $\mathbf{H}^{\text{MT}}$ and $\mathbf{H}_r^{\text{MT}}$ values should be similar to each other, indicating that the amplitudes and phases of the spectra should be comparable.

Suppose the SNR is high at local and remote sites, the PD between the local and remote magnetic fields should be close to 0° , and the RLcoh value is close to one. The amplitude ratio (AR) between the local and remote magnetic fields (R_{AR}) is approximated as follows:

$$R_{\text{AR}} = \frac{|\mathbf{H}^{\text{MT}}|}{|\mathbf{H}_r^{\text{MT}}|}. \quad (15)$$

The R_{AR} value should be low and close to one.

RLcoh and R_{AR} are parameters to measure the similarity between the remote and local magnetic fields. Suppose there is a quiet remote reference site; we could use RLcoh and R_{AR} to measure the similarity between the local and remote magnetic fields to evaluate the data quality at the local site changing with time.

3 CASE STUDIES AT THREE MT FIELDS

Three field datasets are used to evaluate the influence of geomagnetic storms on the MT impedance. Fig. 1 shows the location map of the three field datasets (KAP03, USArray, Sawauchi). The first field dataset used the long-period 5-component MT time-series data observed at Kaapvaal 2003 (KAP03). The sampling period of this survey is a 5-second. The data were recorded for almost a month at each site using GSC LIMS systems in 2003 as a part of the SAMTEX project. The 26 long-period sites distributed in a NE-SW profile are shown in the right corner of Fig. 1. Data for the sites in the middle of the profile (site 127- site 145 of KAP03) were heavily contaminated by DC signals from the DC train line running between Kimberley and Johannesburg (MTNET, see the website in references). The second field dataset was observed at site TNV48 from the USArray project. The third field dataset was observed at Sawauchi station,

Japan. All of the filed data include geomagnetic storms.

Fig. 1 The location map of the three field data (KAP03, USArray, Sawauchi). The left map shows the detailed site location used in USArray, and the right map shows the survey line of KAP03.

3.1 Case Study 1: KAP03, South Africa

We use the first difference filter to remove the trends and means of the signal; the first difference filter to a signal $\mathbf{x}$ is expressed as follows:

$$\text{Diff}(x_i) = x_i - x_{i-1}, \quad (16)$$

where i denotes the number of the time-series data. The absolute value of $\text{Diff}(\mathbf{x})$ can represent the strength of the fluctuation. The $k = 1.5\sigma$ is used to detect the abnormally high value. Here σ is the standard deviation; a common approach is to take $\sigma = \text{MAD}/0.44845$, where MAD is defined as the median of the absolute deviations from the data's median and $\text{MAD} = \text{median}(|x_i - \text{median}(\mathbf{x})|)$. Fig 2 shows the time variations in the Hx component and Dst index. The red dash line denotes the k used to detect the abnormally high value in the lower figure. The high absolute value of $\text{Diff}(\text{Dst})$ corresponds to the $\text{Diff}(\text{Hx})$'s high variation and the storm. We could

use the $\text{Diff}(\text{Dst})$'s absolute value to detect the high variation data in the presence of a storm. This geomagnetic storm started at around 06:00 on October 29 and ended at around noon on October 31. We extracted the two-day data from 06:00 on October 29 to 06:00 on October 31 as the storm data.

Fig. 2 The time variations in the H_x component and Dst index. The first-row figure shows the variation in the H_x component. The red vertical lines show the data gaps because of the data collection. The second-row figure shows the first derivative of the H_x component. The third-row figure shows the variation in the Dst index. The fourth-row figure shows the first derivative of the Dst index's absolute value; the red dash line denotes 1.5σ (σ is the standard deviation). The horizontal axis denotes the time in UTC.

Fig. 3 shows the MT sounding curves and coherence distributions during the storm and non-storm days using the data observed at site 163 of KAP03. The non-storm data from 00:00 on November 1 to 00:00 on November 4 is used. The coherence values between the orthogonal electric and magnetic field, i.e., $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ and $\text{Coh}(\mathbf{E}_y, \mathbf{H}_x)$, increased and were close to one across all periods during the storm. Because the environment is quiet, the high SNR data's proportion is high enough to get a reliable impedance during the storm and non-storm days;

therefore, the MT impedance results calculated by storm and non-storm data are similar.

The results show that the data obtained during the geomagnetic storm also follows the plan-wave assumption in this area, and nonstationarity is not a problem for the method based on the FFT. Otherwise, the result calculated by the storm data should be biased.

Fig. 3 The MT sounding curves and coherence distributions during the storm and non-storm days using the data observed at site 163 of KAP03. The black color indicates the results calculated by the non-storm data; the red color indicates the storm day results. The upper figures show the apparent resistivity. The second-row figures show the impedance phase. The lower figures show the distribution of coherence. The horizontal axis denotes the period in seconds.

Fig. 4 shows the MT sounding curves and coherence distributions during the storm and non-storm days using the data observed at site 142 of KAP03. The non-storm data from 00:00 on October 26 to 00:00 on October 29 is used. The coherence is low during the non-storm days. It increased considerably and was close to one across all periods during the storm. The low coherence during the non-storm days may be attributed to the incoherent noise.

The storm result is smoother than the non-storm result, and the error bar is small. Moreover, The non-storm results using the remote reference data coincide with the storm results(see Fig. 6

in the supplementary document). It shows that the storm results are reliable, and the impedance may be biased during the non-storm days due to the incoherent noise. The data quality is improved during the storm, and we can get a reliable result using the storm data.

Fig. 4 The MT sounding curves and coherence distributions during the storm and non-storm days using the data observed at site 142 of KAP03. The color and marks are the same as Fig. 3.

Fig. 5 shows MT sounding curves and coherence distributions during the storm and non-storm days using the data observed at site 133 of KAP03. The non-storm data from 00:00 on October 26 to 00:00 on October 29 is used. The coherence values between the orthogonal electric and magnetic field $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ and $\text{Coh}(\mathbf{E}_y, \mathbf{H}_x)$ are high during the non-storm period. However, the XY phase calculated by non-storm data is close to 0° , and the apparent resistivity increases as a line in the log scale. That is the phenomenon of local noise (Zonge and Hughes, 1987). 180° or 0° would correspond to the train line. The impedance curve changed more reasonable than the non-storm result after using the storm data.

Fig. 5 The MT sounding curves and coherence distributions during the storm and non-storm days using the data observed at site 133 of KAP03. The color and marks are the same as Fig. 3.

We also used several parameters (polarization direction, RLcoh and R_AR) to analyze the data observed at site 133. Fig. 6 shows the time variations in the polarization direction at 84 seconds from October 26 to 31. The magnetic field polarization has a preferred direction of approximately -30° during non-storm days (October 26 to 29) and becomes scattered during storm days (October 29 to 31). On the other hand, the electric field polarization direction is scattered during non-storm days and has a preferred direction of approximately 60° during storms.

The polarization direction is a function of the amplitude ratio and PD. The local EM noise source usually has a constant location; the incident direction and the energy exhibit similar properties over time. On the contrary, various sources generate the natural EM signal, the incident direction and power change with time. If there is a preferred polarization direction for the magnetic field, we can consider that the local noise contaminates the data in that period. That coincides with the high coherence value in $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ and $\text{Coh}(\mathbf{E}_y, \mathbf{H}_x)$ during the non-storm period. The data are dominated by coherent noise during non-storm days.

Fig. 6 The variation in polarization direction at 84 seconds using the data observed at site 133 of KAP03 from October 26 to 31. The upper figure shows the polarization directions for the electric field, and the lower figure shows the polarization directions for the magnetic field.

Fig. 7 shows the time variations in RLcoh and R_AR at 84 seconds. The data observed at site 151 are relatively quiet and are used as remote reference data. Because the natural signal is weak and easily influenced by local noise during non-storm days, RLcoh is scattered and low; R_AR is scattered and high during non-storm days (October 26 to 29). The natural magnetic signal increased drastically during the geomagnetic storm; the portion of the natural magnetic signal ($\mathbf{H}^{\text{MT}}$ and $\mathbf{H}_r^{\text{MT}}$) become high in the local and remote sites. Because the natural magnetic signal ($\mathbf{H}^{\text{MT}}$ and $\mathbf{H}_r^{\text{MT}}$) comes from the same source; the PD is close to 0° ; therefore, RLcoh becomes close to 1, and R_AR becomes stable and close to 1 during the geomagnetic storm (October 29 to October 31). This result indicates that the SNR is low during non-storm days and becomes high during storm days.

From the analysis above, we can conclude that this dataset is dominated by coherent noise during the non-storm day, and the SNR become high during the storm even with the coherent noise. As a result, we can get a reliable MT impedance during the magnetic storm.

Fig. 7 The time variations in RLcoh versus R_AR at 84 seconds using the data observed at site 133 of KAP03 from October 26 to 31. The blue and red line denotes the RLcoh. The blue color indicates a negative value, and the red color indicates a positive value. The black curve denotes the value of R_AR.

Fig. 8 shows the MT sounding curve and coherence distributions using the data observed during the storm and non-storm days at site 130. The non-storm data from November 6 to 10 is used. The coherence value in $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ and $\text{Coh}(\mathbf{E}_y, \mathbf{H}_x)$ are high between 10 and 200 seconds during the non-storm days; However, the XX and YX phases calculated by non-storm data are close to 0° , and the apparent resistivity increases as a line on the log scale between 10 and 200 seconds. That indicates that the data are dominated by strong coherent noise during non-storm days. On the other hand, the coherence value between the parallel electric and magnetic field $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ is high while the coherence value between the orthogonal electric and magnetic field $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ is relatively low during storm days. Moreover, for the north-south component, the result of Z_{xx} is stable while Z_{xy} is unstable. The storm result can be interpreted as the phenomenon of PROQ.

Fig. 8 The MT sounding curves and coherence distributions during the storm and non-storm days using the data observed at site 130 of KAP03. The black color indicates the results on the non-storm days; the red color indicates the storm day results. The upper figures show the apparent resistivity. The four figures at the middle layer show the impedance phase. The lower figures show the distributions of coherence. The horizontal axis denotes the period in seconds.

Fig. 9 shows the MT sounding curve and coherence distributions using the data observed during the storm and non-storm days at site 136 of KAP03. The non-storm data from October 26 to October 29 is used. The impedance curve is scattered, and the coherence is relatively low during the non-storm days. On the contrary, the coherence between the parallel component $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ is high, while the coherence between the orthogonal component $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ is low during the storm day. Moreover, for the north-south component, the result of Z_{xx} is stable while Z_{xy} is unstable. The storm result can be explained as the phenomenon of PROQ.

Fig. 9 The MT sounding curves and coherence distributions using the data observed during the storm and non-storm days at site 136 of KAP03. The color and marks are the same as Fig. 8.

3.2 Case Study 2: USArray, USA

The second field data used the long-period MT time-series data observed at TNV48 from the USArray project. The data sets were recorded with a 1-second sampling period for around two weeks in 2015. The geomagnetic storm started at around 18:00 on June 22 and ended at around 00:00 on June 24 (see Fig. 8 in the supplementary document).

Fig. 10 shows MT sounding curves and coherence distributions during the storm and non-storm days. The non-storm data from June 19 to June 21 and storm data from June 22 to June 24 are used. The coherence value increased obviously from 4 to 40-second and 400 to 2,000-second during the storm. The low coherence during the non-storm day may be attributed to the local random noise.

The non-storm result's apparent resistivity in the period from 8 to 30-second is severely down-biased, and the phase's error bar is bigger than that of the storm result. We think the incoherent noise makes the impedance severely down-biased between 8 to 30-second during the non-storm days. A more reliable impedance can be obtained using the storm data.

384

385 Fig. 10 The MT sounding curves and coherence distributions during the storm and non-storm
 386 days using the data observed at TNV48 from USArray. The color and marks are the same as Fig.
 387 3.

388

389 3.3 Case Study 3: Sawauchi, Japan

390 The Phoenix Geophysics system's broadband frequency 5-component MT time-series data were
 391 used in this case study. The data were observed from August 20 to August 28, 2018, at Sawauchi
 392 station, Japan. The geomagnetic storm occurred around August 26. The low-frequency data (15
 393 Hz) sampled continuously was used in the research.

394 We calculated the MT impedance using each day's data at first. Fig. 11 shows typical MT
 395 sounding curves and the coherence distributions using the data observed during the storm day
 396 (August 26) and non-storm day (August 23). In Fig. 11, the coherence value between parallel
 397 component $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ is much higher than the coherence value between orthogonal component
 398 $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$. Moreover, the impedance phase in the period over than 200-second rolls out of the
 399 quadrant. That is the phenomenon of PROQ. Because the environment is quiet, the high SNR
 400 data's proportion is high enough during the storm and non-storm days; therefore, the impedance
 401 results calculated by the storm and non-storm data are similar.

Comparing the two impedance results detail, the coherence value in $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ increased during the storm between 4 and 30 seconds. That may be caused by the increased intensity of the natural EM signal. Because the natural EM signal strength is very low in the dead band (0.1-10 seconds), and local noise can easily influence it. The enhancement of the natural EM signal may produce a more reliable impedance result in that period. Next, we investigate the change in impedance result during storm and non-storm days at 10-second. Fig. 12 shows the time variations in the XY component calculated by each hour's data at the period of 10-second. The impedance curve becomes more stable and correlated with the geomagnetic storm event.

Fig. 11 The MT sounding curves and coherence distributions during storm days (August 26) and non-storm days (August 23). The color and marks are the same as Fig. 8.

Fig. 12 The time variation of the apparent resistivity and phase calculated using each hour's time-series data at the period of 10-second. One result was calculated using one-hour data. The upper figures show the apparent resistivity. The second-row figures show the impedance phase. The lower figure shows the absolute value of Diff(Dst); The horizontal axis denotes the time in UTC.

4 DISCUSSION

At first, we discuss the relationship between impedance and coherence. According to least-squares theory (Sims et al., 1971); for the north-south direction, Z_{xy} can be calculated as follows:

$$Z_{xy} = \frac{\langle E_x \bar{H}_y \rangle \langle H_x \bar{H}_x \rangle - \langle E_x \bar{H}_x \rangle \langle H_x \bar{H}_y \rangle}{\langle H_y \bar{H}_y \rangle \langle H_x \bar{H}_x \rangle - \langle H_y \bar{H}_x \rangle \langle H_x \bar{H}_y \rangle} = \frac{C - D}{E - F}, \quad (17)$$

For the numerator of Eq. 17, there is a relationship with the coherence as follows:

$$|C| = |\langle E_x \bar{H}_y \rangle \langle H_x \bar{H}_x \rangle| = \text{coh}(E_x, H_y) \sqrt{\langle E_x \bar{E}_x \rangle \langle H_y \bar{H}_y \rangle} \sqrt{\langle H_x \bar{H}_x \rangle}, \quad (18)$$

$$|D| = |\langle E_x \bar{H}_x \rangle \langle H_x \bar{H}_y \rangle| = \text{coh}(E_x, H_x) \sqrt{\langle E_x \bar{E}_x \rangle \langle H_x \bar{H}_x \rangle} \text{coh}(H_x, H_y) \sqrt{\langle H_x \bar{H}_x \rangle \langle H_y \bar{H}_y \rangle}, \quad (19)$$

$$\frac{|C|}{|D|} = \frac{|\langle E_x \bar{H}_y \rangle \langle H_x \bar{H}_x \rangle|}{|\langle E_x \bar{H}_x \rangle \langle H_x \bar{H}_y \rangle|} = \frac{\text{coh}(E_x, H_y)}{\text{coh}(E_x, H_x) \text{coh}(H_x, H_y)}, \quad (20)$$

For the denominator of Eq. 17, there is a relationship with the coherence as follows:

$$|E| = |\langle H_x \bar{H}_x \rangle \langle H_y \bar{H}_y \rangle| \quad (21)$$

$$|F| = |\langle H_y \bar{H}_x \rangle \langle H_x \bar{H}_y \rangle| = \text{coh}^2(H_x, H_y) \sqrt{\langle H_x \bar{H}_x \rangle \langle H_y \bar{H}_y \rangle} \quad (22)$$

$$\frac{|E|}{|F|} = \frac{1}{\text{coh}^2(\mathbf{H}_x, \mathbf{H}_y)} \quad (23)$$

Because various sources generate natural magnetic signals, they generate magnetic fields that vary in their incident directions, which means $\mathbf{H}_x$ and $\mathbf{H}_y$ are not coherent, and $\text{Coh}(\mathbf{H}_x, \mathbf{H}_y)$ is a small value. In the condition that the coherence value between the orthogonal component $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ is relatively high while the coherence value between the parallel component $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ is small. The C part dominates the numerator of Eq. 17, and the E part dominates the denominator. Therefore, in the case that $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ is high while $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ is small, the Z_{xy} can be rewritten as follows:

$$Z_{xy} \approx \frac{C}{E} = \frac{\langle \mathbf{E}_x \bar{\mathbf{H}}_y \rangle}{\langle \mathbf{H}_y \bar{\mathbf{H}}_y \rangle}. \quad (24)$$

In this situation, Z_{xy} is determined by the orthogonal electric and magnetic fields. The field data can be explained as the 1-D or 2-D cases.

On the contrary, if the coherence between the orthogonal component $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y)$ is relatively low while the coherence between the parallel component $\text{Coh}(\mathbf{E}_x, \mathbf{H}_x)$ is high. There is no relationship of Eq. 24. In that case, the Z_{xy} is undetermined by the orthogonal electric and magnetic fields, and the phenomenon of PROQ may appear.

We tried to categorize the three field datasets into 4 data types according to the coherence and polarization direction, as shown in Table 3. In brief, type 1 and type 2 denote the good data, type 3 and type 4 denote the noisy data.

The characteristic of PROQ is high coherence between the parallel electric and magnetic fields and low coherence between the orthogonal component. On the contrary, the characteristic of the 1-D or 2-D models is low coherence between the parallel electric and magnetic fields is low and high coherence between the orthogonal component. Moreover, the time-series data contaminated by the coherent and incoherent noise also has a high and low coherence value. We suggest that the coherence value higher than 0.7 can be regarded as high-coherence, and lower than 0.5 can be

regarded as low-coherence.

There is no preferred polarization direction for the magnetic field in a quiet EM environment. If there is a preferred polarization direction for the magnetic field, we can consider that the data is contaminated by coherent noise in that period. But sometimes, the data is contaminated by incoherent noise. The magnetic field has no preferred polarization direction (see Fig. 7 in the supplementary document).

RLcoh and R_AR are parameters to measure the similarity between the remote and local magnetic fields. Suppose there is a quiet remote reference site. We can use the RLcoh and R_AR to measure the similarity between the local and remote sites to evaluate the data quality. When the SNR is high at the locale site, RLcoh should be high and close to 1, and the R_AR should be low and close to 1.

The most important parameter to discuss the MT impedance quality is the smoothness of the MT sounding curve. The MT sounding curve should be smooth, and the impedance phase does not close to 0° or 180° in a quiet EM environment. To estimate the MT impedance quality precisely, we combined those parameters to discuss the specific situation. Table 4 summarises the data type of each site between the storm and non-storm days. It shows that no matter whether there is a storm, the MT impedance quality is good at a quiet site. However, the MT impedance quality is bad during the non-storm day at the noisy site and becomes good during the geomagnetic storm.

There is another issue that at mid-latitudes, geomagnetic pulsations (Pc's) in the Pc3-4 band ($\sim 10 - 100$ s) associated with field-line resonances can violate the fundamental assumption of the MT method over the resistive regions, where the skin depths are large (Egbert et al., 2000; Murphy and Egbert, 2018). In this case, the source effect is inevitable and is place-dependent. It may happen during non-storm and storm days. However, it is not the issue of this paper. And we have not found the obvious biases in the Pc3-4 band during the storm day in the case studies.

Table 3 The situation of the different parameters in the different data types. Type 1 and type 2 denote good data quality, type 3 and type 4 denote the noisy data quality. The normal polarization denotes no preferred direction for the magnetic field, and the abnormal polarization denotes that it violates that situation. The normal RLcoh and R_AR denote that RLcoh is high and close to 1, and the R_AR should be low and close to 1. The abnormal RLcoh and R_AR denote that they violate that situation. The normal impedance denotes the MT sounding curve should be smooth, and the impedance phase does not close to 0° or 180° , and the abnormal impedance denotes it violates that situation.

Classification	Coherence	Polarization	RLcoh & R_AR	Impedance
Type 1: PROQ	$\text{Coh}(\mathbf{E}_x, \mathbf{H}_x) > 0.7$ and $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y) < 0.5$	Normal	Normal	Normal
Type 2 : 1-D/2-D	$\text{Coh}(\mathbf{E}_x, \mathbf{H}_x) < 0.5$ and $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y) > 0.7$	Normal	Normal	Normal
Type 3: Incoherent noise	$\text{Coh}(\mathbf{E}_x, \mathbf{H}_x) < 0.5$ and $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y) < 0.5$	Normal	Abnormal	Abnormal
Type 4 : Coherent noise	$\text{Coh}(\mathbf{E}_x, \mathbf{H}_x) > 0.7$ or $\text{Coh}(\mathbf{E}_x, \mathbf{H}_y) > 0.7$	Abnormal	Abnormal	Abnormal

Table 4 The classification of data type for each site between the storm and non-storm day. Type 1 and type 2 denote good data quality, Type 3 and type 4 denote the noisy data quality.

Location	Non-storm period	Storm period
Site 163	Data Type 2 (1-D & 2-D)	Data Type 2 (1-D & 2-D)
Site 142	Data Type 3 (Incoherent noise)	Data Type 2 (1-D & 2-D)
Site 133	Data Type 4 (Coherent noise)	Data Type 2 (1-D & 2-D)
Site 130	Data Type 4 (Coherent noise)	Data Type 1 (PROQ)
Site 136	Data Type 3 (Incoherent noise)	Data Type 1 (PROQ)
TNV 48	Data Type 3 (Incoherent noise)	Data Type 2 (1-D & 2-D)
Sawauchi	Data Type 1 (PROQ)	Data Type 1 (PROQ)

5 CONCLUSIONS

We used the three field datasets observed at midlatitude to investigate the influence of a geomagnetic storm on the MT impedance from the perspective of SNR. The following is a summary of the finding from our case studies.

In a quiet EM environment, the high SNR data's proportion is high enough to get a reliable impedance during the storm and non-storm days; therefore, the impedance results calculated by the storm and non-storm data are similar. This situation is shown by the data observed at site Sawauchi and site 163 of KAP03. Moreover, the positive effect of the geomagnetic storm on the MT impedance quality is shown at 10-second around the dead band. Because the natural EM signal is relatively low, and the local noise can easily influence it. When there is a geomagnetic storm, the nature EM signal's strength increase and the SNR become higher, the impedance curve becomes more stable and reliable at 10-second.

In a noisy EM environment, the artificial noise dominates the data quality during non-storm days. In the presence of a geomagnetic storm, the high SNR data increases; the noisy data (data types 3 and 4) convert into good data (data types 1 and 2). Therefore, we can get a reliable impedance using the storm data. This situation is shown by the data observed at site TNV48 of USArray and sites 130, 133, 136, 142 of KAP03.

MT field data include natural EM signal and artificial EM noise. Especially in urban areas, artificial disturbances to EM observations are serious. The observation occasionally contains continuous noise, which is difficult to remove by the current technique. We recommend performing the MT campaign during the geomagnetic storm if we need to re-survey at such sites. The geomagnetic storm has a seasonal and 11-year solar cycle and doesn't frequently occur (see the statistical analysis of geomagnetic storm in the supplementary document). It is possible to get storm data by predicting the geomagnetic storm by the space weather forecast information. The Space Weather Prediction Center (SWPC; see the website in references) provides information about space weather in the coming three days. Utilizing the data observed during a strong geomagnetic storm may overcome the local noise's influence and obtain a more reliable and interpretable impedance, although the site is contaminated by continuous noise.

DECLARATION

524

525 **Availability of data and materials**

526 Nittetsu Mining Consultants Co., Ltd. provided the broadband frequency MT time-series data
527 observed at Sawauchi, Japan. The SAMTEX team provided the time-series data of KAP03, and it
528 can be download from MTNET (see the reference). The USArray team provided the time-series
529 data of TNV48, and it can be download from IRIS (Incorporated Research Institutions for
530 Seismology). The Dst index data can be download from the WDC for Geomagnetism, Kyoto.
531 Alan Chave provided the BIRRP code.

532

533 **Competing interests**

534 We know of no conflicts of interest associated with this publication. We declare that this
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536 publication elsewhere.

537

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540

541 **Authors' contributions**

542 Hao Chen processed the time series data, created the result and wrote the paper. Hideki Mizunaga
543 reviewed the paper and contributed about 30%; Toshiaki Tanaka contributed about 10% to this
544 work. Hao Chen contributes about 60%.

545

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Supplementary document

1 The statistical analysis of geomagnetic storm

The geomagnetic storm is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock wave interacts with the Earth's magnetic field. A magnetic storm is seen as a rapid drop in the magnetic field strength at the Earth's surface. Fig.1 shows the X (N-S) component during a storm day and a non-storm day at Japan's Kakioka (KAK) station. In 1973, the KAK Magnetic Observatory was designated as one of four facilities to calculate the disturbance storm time (Dst) index, representing the strength of the equatorial ring current encircling the Earth. The magnetic field intensity observed during the storm day can be almost two orders stronger than during the non-storm day.

Fig. 1 The geomagnetic intensities along the N-S direction during a storm day and a non-storm day. The black lines denote the non-storm day's data, and the red lines denote the storm day's data. The left is a profile in the time domain, and the right is the spectrum in the frequency domain.

In this section, we analyzed the geomagnetic storm event statistically by the Dst index. Fig. 2 shows the distribution of the Dst index from 1957 to 2020; the orange line denotes the boundary of the geomagnetic storm ($\text{Dst} \leq -50$ nT), and the light blue line denotes the boundary of the strong geomagnetic storm ($\text{Dst} \leq -100$ nT). It shows that geomagnetic storms did not appear frequently. The probability of a strong storm is less than 1% per day.

Fig. 3 shows the monthly count of strong geomagnetic storms. One hour was recorded as one count in this figure. For example, a 3-hour storm is counted as three storms. The high probability of a strong geomagnetic storm occurred around April and October. Fig. 4 shows the yearly count of geomagnetic storms that occurred each year. Fig. 5 shows the FFT result of the yearly count of storms from 1957 to 2020. There is a 10.7-year peak, which corresponds to the 11-year solar cycle.

This section concludes that the geomagnetic storm has a seasonal and 11-year solar cycle. The strong geomagnetic storm doesn't happen frequently and causes significant EM field variations observed on the Earth's surface.

670

671 Fig. 2 The distribution of strong storms based on the Dst index between 1957 - 2020, the orange
 672 line denotes Dst (≤ -50 nT), and the light blue line denotes Dst (≤ -100 nT).

673

674

675 Fig. 3 The monthly cumulative count of strong geomagnetic storms based on the Dst index from
 676 1957 to 2020.

677

678

Fig. 4 The yearly cumulative count of geomagnetic storms based on the Dst index from 1957 to 2020.

Fig. 5 The calculated periods by Fourier analysis using the yearly count of geomagnetic storms from 1957 to 2020.

2 The supplementary information for site 142 of KAP03.

Fig. 6 compares the storm result without remote reference data and the non-storm result using remote reference data. The non-storm data from November 14 to November 20 is used. Site 142 of KAP03 is used as the remote site. The storm result is smoother than the non-storm result using the remote data. Overall, both result coincides well.

Fig. 7 shows the variation in the polarization direction at 84 seconds from October 26 to October 31. Both the electric and magnetic field polarization are scattered during the storm and non-storm days. There is no preferred polarization direction for the magnetic field when the incoherent noise contaminates the data.

Fig. 6 Comparison of the storm results without remote reference data and the non-storm result using remote reference data.

The variation in polarization direction at 84 seconds using the data observed at site 142 of KAP03 from October 26 to October 31. The upper figure shows the polarization directions for the electric field, and the lower figure shows the polarization directions for the magnetic field.

3 The supplementary information for TNV48.

Fig. 8 shows the variation in the Dst index. We can confirm that the geomagnetic storm started at around 18:00 on June 21 and ended at around 00:00 on June 24.

707

708

709 Fig. 8 The variation in the Dst index. The upper figure shows the variation in the Dst index. The
 710 lower figure shows the absolute value of Diff(Dst); the red dash line denotes 1.5σ (σ is the
 711 standard deviation). The horizontal axis denotes the time in UTC.

712

713 4 The supplementary information for site 133 of KAP03.

714 Fig. 9 shows the MT sounding curves using the data observed at site 133 of KAP03. The black
 715 curve was calculated using the data observed from October 21 to October 31, including storm and
 716 non-storm data. The red curve was calculated using the data during the storm days. The XY phase
 717 calculated by non-storm data is close to 0° , and the apparent resistivity increases as a line on the
 718 log scale. That is the phenomenon of local noise (Zonge and Hughes, 1987). Though we used
 719 long time-series data, including storm and non-storm data, we failed to get a reliable result. This
 720 result shows that it needs to choose the data period carefully in this situation.

721

Fig. 9 Compare the MT sounding curves calculated by the long data, including the storm and non-storm days and the storm result using the data observed at site 133 of KAP03.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [StormVSnon.jpg](#)