The Influence of Geomagnetic Storms on Calculating Magnetotelluric Impedance

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The influence of geomagnetic storms on calculating magnetotelluric impedance

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Key point:
(1) The positive effects of a geomagnetic storm on the MT data quality are shown by three case studies. Moreover, a case study shows that using the data observed during the geomagnetic storm can overcome the locale noise and bring a reliable impedance from a survey line contaminated by the strong noise.
(2) A variety of parameters are used to discuss the influence of geomagnetic storms on the MT data quality.

Abstract: Magnetotelluric (MT) field data contain natural electromagnetic signals and artificial noise sources (instrumental, anthropogenic, etc.). Not all available time-series data contain usable information about the electrical conductivity distribution at depth, particularly when the signal-to-
noise ratio (SNR) is low. Geomagnetic storms represent temporary disturbances of the Earth's magnetosphere caused by solar wind-shock wave interacts with Earth's magnetic field. The variation of the electromagnetic signal increases dramatically in the presence of a strong geomagnetic storm. Using the data observed during a strong geomagnetic storm may overcome the locale noise and bring a reliable MT impedance at contaminated sites. Three case studies are presented to show the positive effect of geomagnetic storms on MT field data. A more reliable and interpretable impedance calculated from a survey line contaminated by strong noise is obtained using the data observed during a strong geomagnetic storm.

Keywords: geomagnetic storm, impedance tensor, magnetotelluric method

1 INTRODUCTION

The magnetotelluric 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). The natural MT sources from the Earth's magnetosphere and ionosphere or global lighting are far enough from the observation site. Therefore, we can treat the EM signals as plane waves. Many works have focused on the Earth's EM environment (Constable, 2016; Constable and Constable, 2004; McPherron, 2005). Generally, the low-frequency signals (< 1 Hz) originate from the interaction between solar winds and the Earth's magnetosphere and ionosphere. In comparison, high-frequency signals (> 1 Hz) originate from worldwide thunderstorm activity. Constable (2016) reviewed EM sources in high frequencies band (> 1 Hz). McPherron (2005) reviewed the ultralow frequency (ULF) band EM source. Garcia (2002) used MT data to research the characteristics of EM signals in the high-frequency band. The MT field data include natural EM signals and noise. Szarka (1988) and Junge (1996) summarized the active and passive noise sources observed in MT measurements. Not all MT time series include
usable information about the electrical conductivity distribution at depth, particularly when the
signal-to-noise ratio is low. 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 to estimate the frequency-domain impedance
tensor from the measured time-series data. All MT data interpretations are based on the MT
impedance. Therefore, it is very important to obtain a reliable impedance. The low signal-to-
noise ratio 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).

The effect of lightning and geomagnetic storms on MT data is well understood. From the
perspective of the signal-to-noise ratio (SNR), Hennessy and Macnae (2018) reduced the
impedance bias by stitching the highest amplitude audio-frequency MT (AMT) time-series data,
which corresponds to lightnings. 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. Noise can be neglected under
this condition. The noisy data segment is converted to high signal-to-noise ratio data, depending
on the strength of the geomagnetic storm and the noise. However, the plane-wave assumption of
the MT is violated at high magnetic latitudes because the source field is nonuniform during
gеомеgаnеtnіс stоrnеs (Mаrеsсhаl, 1981; Віlжаnеn еt аl., 1993; Gаrcіа еt аl., 1997; Lеzаеtа еt аl.,
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).
The plane wave assumption is generally acceptable at midlatitudes (Lezaeta et al., 2007;
Віlжаnеn еt аl., 1993). This paper used three field datasets at mid-latitudes to research the
influence of geomagnetic storms on MT data.

In this paper, a statistical analysis of geomagnetic storm was performed first in section 2.
Section 3 introduces the parameters and the impedance estimator used in the research. Section 4
shows three case studies influenced by geomagnetic storms.

In the practical MT surveys, we may meet the noisy sites occasionally that can't obtain a reliable impedance by the current method. When we redo the MT surveys at noisy sites, we may acquire MT data during strong geomagnetic storms. Although strong geomagnetic storms do not occur frequently, we could predict strong geomagnetic storms using space weather forecasts and acquire MT data during intense geomagnetic storms. Using the data observed during the intense storm period may bring a reliable result from the site contaminated with continuous noise.

2 GEOMAGNETIC STORM

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 a profile in the frequency domain.

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. Geomagnetic storms start when the enhanced energy of the solar wind transfer into the magnetosphere. 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 of the geomagnetic field during a storm day and a non-storm day at the Kakioka (KAK) station in Japan. 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 intensity of the magnetic field observed during the storm day can be almost two orders stronger than during the non-storm day.

The disturbance storm time (Dst) index is a negative index of geomagnetic activity used to estimate the averaged change of the horizontal component of the Earth's magnetic field based on measurements from a few magnetometer stations. It is derived from hourly scalings of low-latitude horizontal magnetic variation and expressed in nanoteslas. When the Dst index is less than -50 nT, it is categorized as a geomagnetic storm. When the Dst index is less than -100 nT, it is categorized as a strong geomagnetic storm. 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 (Dst <= -50 nT), and the light blue line denotes the boundary of the strong geomagnetic storm (Dst <= -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 statistical analysis of each strong geomagnetic storm event by the hour. The upper figure shows the number of strong geomagnetic storm events versus the strong storm event's length by the hour. The horizontal axis denotes the length of the strong storm event, and the y-axis denotes the number. The lower figure shows the cumulative distribution of the upper figure. It shows that about 46% of strong geomagnetic events lasted more than 4 hours, and 8% of the strong geomagnetic event lasted more than one day. The longest strong geomagnetic event lasted 55 hours. There are 688 strong geomagnetic storms from 1957 to 2020; one year had about ten strong geomagnetic events, and about five events lasted more than 4 hours on average.

Fig. 4 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. 5 shows the yearly count of geomagnetic storms that occurred in each year. Fig. 6 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.

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

Fig. 3 The statistical analysis of each strong geomagnetic storm event. The upper figure shows the
number of each strong geomagnetic storm event in a different storm event length. The lower figure shows the cumulative distribution of the upper figure.

Fig. 4 The monthly count of strong geomagnetic storms based on the Dst index.

Fig. 5 The yearly count of geomagnetic storms based on the Dst index from 1957 to 2020.

Fig. 6 The calculated periods by Fourier analysis using the yearly count of geomagnetic storms from 1957 to 2020.
3 METHOD

We introduce the method to estimate the influence of geomagnetic storms on the MT data in this section. At first, we introduce two MT impedance estimators. And then, introduce the linear coherency (RLcoh) and amplitude ratio (R_AR) between the local and remote magnetic field and polarization direction to discuss the data quality at the noisy site KAP03 133. Finally, We also investigate the influence of geomagnetic storms based on cross-power spectra and coherency distribution.

3.1 Impedance Tensor Estimator

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:

$$
\begin{pmatrix}
E_x(\omega) \\
E_y(\omega)
\end{pmatrix} =
\begin{pmatrix}
Z_{xx}(\omega) & Z_{xy}(\omega) \\
Z_{yx}(\omega) & Z_{yy}(\omega)
\end{pmatrix}
\begin{pmatrix}
H_x(\omega) \\
H_y(\omega)
\end{pmatrix},
$$

(1)

where $E$ and $H$ are the horizontal electric and magnetic field at a specific frequency, respectively, $\omega$ 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.

Bounded 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 mainly show the impedance calculated by BIRRP.

There is an issue that the natural EM signal may be nonstationary during the geomagnetic storm. It is not suitable for the basic requirements of conventional methods based on the Fourier transform and leads the impedance biased. In this research, we also used a nonstationary processing routine named EMT (Neukirch et al., 2014) to calculate the impedance at the quiet site Kap03-163. The biggest difference between EMT and BIRRP is that EMT transforms the time series into the frequency domain by the time-frequency transform technique Hilbert-Huang
Transform (HHT) and can estimate MT response functions even in the presence of nonstationary (NS) signal.

### 3.2 The Linear Coherency and Amplitude Ratio between the Local and Remote Magnetic field

More than four channels are observed simultaneously in MT fieldwork; the time series of each channel is divided into N segments, and N spectra can be obtained from these N segments by applying the Fourier transform to each channel.

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

\[ A_i \overline{B}_i = |A_i| |B_i| e^{(\varphi_{A_i} - \varphi_{B_i})}, \tag{2} \]

where \( j \) denotes the imaginary number unit, \( i = 1, 2, \ldots, N \); \( A_i \) and \( B_i \) are the spectra calculated from the \( i^{th} \) segment from the different channel; and \( \varphi_{A_i} \) and \( \varphi_{B_i} \) denote the phases of \( A_i \) and \( B_i \), respectively. The overline denotes the complex conjugate.

The amplitude of the cross-power spectra equal the product of \( |A_i| \) and \( |B_i| \), and the phase equals the phase difference (PD) between \( A_i \) and \( B_i \).

The auto-power spectra are calculated as follows:

\[ A_i \overline{A}_i = |A_i|^2, \quad B_i \overline{B}_i = |B_i|^2. \tag{3} \]

The PD is calculated as follows:

\[ \theta_i = \varphi_{A_i} - \varphi_{B_i} = \text{arg}(e^{j(\varphi_{A_i} - \varphi_{B_i})}) = \text{arg}\left(\frac{A_i \overline{B}_i}{\sqrt{|A_i| |B_i|}}\right), \tag{4} \]

where \( \theta_i \) denotes the angle of the PD between the two spectra at a specific frequency.

The linear coherency is proposed as the cosine of the PD as follows:

\[ \text{Lcoh} = \cos(\theta_i) = \text{Re}(e^{j(\varphi_{A_i} - \varphi_{B_i})}) = \text{Re}\left(\frac{A_i \overline{B}_i}{\sqrt{|A_i| |B_i|}}\right), \tag{5} \]

where \( \text{Lcoh} \) denotes the linear coherency and \( \text{Re} \) denotes the real part of the complex number.

The value of \( \text{Lcoh} \) lies in the range of \((-1,1)\). When the PD is close to \( 0^\circ \), the \( \text{Lcoh} \) value is high and close to 1. According to Euler’s formula, \( \text{Lcoh} \) 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 coherency between the remote and local magnetic fields (RLcoh) is defined as follows:

\[
\text{RLcoh} = \Re \left( \frac{H_{x,i} \overline{H_{xr,i}}}{\sqrt{(H_{x,i} \overline{H_{x,i}})(H_{xr,i} \overline{H_{xr,i}})}} \right),
\]

(6)

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 \(H\) as follows:

\[
H = H^{\text{MT}} + H^N,
\]

\[
H_r = H_r^{\text{MT}} + H_r^N,
\]

(7)

where \(N\) denotes the noise and \(MT\) denotes the natural EM signals coming from the magnetosphere and ionosphere.

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

When the signal-to-noise ratio (SNR) is high at both local and remote sites, the PD between the local and remote magnetic fields should be close to \(0^\circ\), and the RLcoh value should be close to one. The amplitude ratio (AR) between the local and remote magnetic fields (\(R_{\text{AR}}\)) is calculated as follows:

\[
R_{\text{AR}} = \frac{|H^{MT}|}{|H_r^{MT}|},
\]

(8)

the \(R_{\text{AR}}\) value should be low and close to one.

In contrast, in the presence of strong noise, the PD between the local and remote magnetic fields will be scattered; therefore, the RLcoh will be unstable; and the \(R_{\text{AR}}\) value will deviate from one.

RLcoh and \(R_{\text{AR}}\) are parameters to measure the similarity between the remote and local
magnetic fields. If there is a quiet remote reference site, we could use RLcoh and R_AR to evaluate the variation of SNR change with time at the local site.

3.3 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 ($\alpha_E$) and magnetic field ($\alpha_H$) (Fowler et al., 1967) at a specific frequency are defined as:

$$\alpha_{E,i} = \tan^{-1} \frac{2 \text{Re}[E_{x,i} E_{y,i}]}{|E_{x,i} E_{x,i} - |E_{y,i} E_{y,i}|}$$  \hspace{1cm} (9)

$$\alpha_{H,i} = \tan^{-1} \frac{2 \text{Re}[H_{x,i} H_{y,i}]}{|H_{x,i} H_{x,i} - |H_{y,i} H_{y,i}|}$$  \hspace{1cm} (10)

We can rewrite the polarization directions as follows:

$$\tan^{-1} \frac{2 \text{Re}[A_i B_{i}]}{|A_i A_i| - |B_i B_i|} = \tan^{-1} \frac{2 |B_i| \cos(\theta_i)}{1 - (|B_i|/|A_i|)^2}.$$  \hspace{1cm} (11)

where $A_i$ and $B_i$ are $H_{x,i}$ and $H_{y,i}$ or $E_{x,i}$ and $E_{y,i}$, respectively. The polarization direction is related to the 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. The PD and amplitude ratio between the two orthogonal magnetic fields vary with time; thus, there is no preferred polarization direction for the magnetic field. 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).

3.4 Ordinary Coherency

The coherency is a quantitative measure of the phase difference (PD) consistency between the two channels. If two channels are coherent, their phases must be either the same or have a constant difference (Marple and Marino, 2004). Coherency is defined as the ratio between cross-power spectra density and the root of auto powers spectra density. For A and B spectrum at a
specific frequency, it is defined as:

$$\text{Coh}(A, B) = \frac{|<A\overline{B}>|}{\sqrt{<A\overline{A}> <B\overline{B}>}},$$

(12)

where the brackets represent the averages of \(N\) individual auto power spectra and cross-power spectra. For instance,

$$<A\overline{B}>=\frac{1}{N}\sum_{i=1}^{N} A_i\overline{B}_i.$$  

(13)

4 CASE STUDIES

Three case studies are shown to evaluate the influence of geomagnetic storms on the MT data. Fig. 7 shows the map of site locations in the three case studies (Sawauchi, USArray, KAP03). The left map shows a detailed map of the site location used in USArray, and the right map shows the detailed survey line of KAP03. All of the case studies include geomagnetic storm data.

Fig. 8 shows the spectrum calculated by the Hx component observed during storm and non-storm days in the three case studies. We used the moving median filter to smooth the spectra. The magnetic coils are used to observe the magnetic field at Sawauchi station, and we need to calibrate to the spectrum. The fluxgate magnetometer is used in the USArray and KAP03 project, and the calibration factor is 1. Because we have not calibrated the spectrum observed at the Sawauchi station, its intensity is smaller than that observed in the USArray and KAP03 projects.

During the storm day, the intensity is approximately five times stronger than that measured during the non-storm days between 10 and 1000 seconds at Sawauchi and USArray project. Moreover, the intensity is approximately 50 times stronger than that during non-storm days between 10 and 1000 seconds in KAP03.

Table 1 shows the name of each result and the corresponding data used to calculate the impedance in studies 2 and 3. The Quiet parameter was calculated using the data observed during the non-storm period, and QuietRR was calculated using the data observed during the non-storm period and using the remote reference technique. The Storm parameter was calculated using the
data observed during the storm. StormRR was calculated using the data observed during the storm period and using the remote reference technique. The period shows the month and day of the data. For example, 06.20-06.22 means the time from June 20 00:00:00 to June 22 00:00:00. The geomagnetic storm of USArray occurred in 2015. The geomagnetic storm of KAP occurred in 2003.

Fig. 7 The location map in the three case studies (KAP03, USArray, Sawauchi). The left map shows the detailed site location used in USArray, and the right map shows the survey line of KAP03.

Fig. 8 Comparison of the spectrum calculated by the Hx component observed during the storm and non-storm days. The black lines denote the non-storm day's data, and the red lines denote the storm day's data. The horizontal axis denotes the period. The vertical axis denotes the intensity.
Table 1: The classification of results and the corresponding data used to calculate MT impedances.

| Local Site | Quiet Period | Remote Site | QuietRR Period | Remote Site | Storm Period | Remote Site | StormRR Period |
|------------|--------------|-------------|----------------|-------------|--------------|-------------|----------------|
| TNV48      | 06.20-06.22  | ALW48       | 06.20-06.22    | ALW48       | 06.22-06.24  | ALW48       | 06.22-06.24    |
| KAP 130    | 11.06-11.10  | KAP 163     | 11.06-11.10    | 10.29-10.31 |
| KAP 133    | 10.26-10.28  | KAP 103     | 11.11-11.18    | 10.29-10.31 |
| KAP 136    | 11.06-11.10  | KAP 163     | 11.06-11.10    | 10.29-10.31 |
| KAP 139    | 11.06-11.10  | KAP 163     | 11.06-11.10    | 10.29-10.31 |
| KAP 142    | 10.25-10.27  | KAP 160     | 11.14-11.20    | 10.29-10.31 |
| KAP 145    | 11.06-11.10  | KAP 163     | 11.06-11.10    | 10.29-10.31 |
| KAP 163    | 11.01-11.04  |             |                |             |

4.1 Case Study 1: Sawauchi, Japan

The Phoenix geophysics system's broadband frequency 5-component MT time-series data were used in the first case study. The data were observed from August 20 to August 28, 2018, at Sawauchi station, Japan. The geomagnetic storm occurred on August 26. The MT time-series data were stored in three files. Two files sampled the high- and middle-frequency bands (2,400 and 150 Hz) intermittently; the other files continuously sampled the low-frequency data (15 Hz). The high-frequency band (2,400 Hz) was sampled for 1 second at intervals of 4 minutes from the beginning of the minute, and the middle-frequency band (150 Hz) was sampled for 16 seconds at intervals of 4 minutes from the beginning of the minute.

First, we analyzed the spectrum variation along with the Dst index. To obtain precise spectral information from these datasets, we first applied a set of Slepian tapers and then used the fast Fourier transform to the time series (Garcia and Jones, 2002). Fig. 9 shows the time-frequency distribution against the Dst index and the Hx component time-series data. The sampling rate is 15 Hz, and the upper figure shows the spectrum variation from August 20 to August 28. The color denotes the value of 10-log10 (amp.), and "amp" denotes the spectrum amplitude. The lower figure shows the Hx component time series along with the Dst index. This figure shows that the amplitude between approximately 1 second and 1,000 seconds increases dramatically and is
correlated with the geomagnetic storm around August 26. The high-frequency (< 1 Hz) amplitude
does not change correlated with the geomagnetic storm.

We calculated the impedance using each day's data. Fig. 10 shows typical MT sounding curves
and the coherency distribution using the data observed during the storm day (August 26) and non-
storm day (August 23). The sounding curves calculated using the storm data was more stable than
the result using the non-storm data between 300 and 1,000 seconds in the $Z_{xy}$ and $Z_{yy}$
components. The sounding curves of $Z_{xx}$ and $Z_{yx}$ are almost the same. In this result, the phases of
the XY component are out of the quadrant. The phenomenon that the phases of off-diagonal
impedance tensors exceed the normal quadrants is referred to as phase rolling out of quadrant
(PROQ). PROQ can appear in specific geologic environments (Chouteau and Tournerie, 2000;
Weckmann et al., 2003; Yu et al., 2018.). The current channeling caused by complex three-
dimensional (3-D) isotropic media is one explanation for the PROQ phenomenon. The
characteristic of PROQ is that the ordinary coherency between the parallel electric and magnetic
field is high, while the coherency between the orthogonal component is low. In Fig. 10, the
$\text{Coh}(E_x, H_x)$ value is much higher than the $\text{Coh}(E_x, H_y)$ value. Moreover, the value of $\text{Coh}(E_x, H_x)$
increased during the storm period between 4 and 30 seconds. That may have been caused by the
increasing intensity of the natural MT signal.
Fig. 9 The time-frequency distribution against the Dst index variation and the sampling rate is 15 Hz. The upper figure shows the time-frequency distribution from August 20 to 29. The color denotes the value of 10-log10 (amp.). The lower figure shows the time variations of the Hx component along with the Dst index. The unit of Hx is nT. The horizontal axis denotes the date.

Fig. 10 MT sounding curves and coherency distribution during storm days (August 26) and non-storm days (August 23). 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 distribution of coherency. The horizontal axis denotes the period in seconds.

Fig. 11 shows the amplitude variation at 16, 8, 4 and 1 second periods along with the Dst index. The upper figure shows the amplitude variation from August 20 to August 28. The lower figure shows the time variation of the Hx component along with the Dst index. The amplitude increased at the 16, 8, and 4 seconds correlated with the geomagnetic storm. In the variation of 1 second, there was no increase correlated with the storm. This result agrees that the interaction between the solar wind and the magnetosphere does not contribute to the MT high-frequency signal. The
signal strength at periods larger than 4 seconds increased dramatically along with the geomagnetic storm. Because the natural EM signal strength between the dead band (0.1-10 seconds) is low, and local noise can easily influence it. The enhancement of the natural EM signal may produce a more reliable impedance result. Next, we will investigate the change in impedance value during storm and non-storm days at 10 seconds.

Fig. 12 shows the XY component of the impedance value calculated by each day's data at a period of 10 seconds. Usually, the impedance corresponds to the underground resistivity structure and does not change with time. However, in the presence of local noise, the result may be biased and deviate from the true value. In Fig. 12, the red line is the impedance value calculated using the data observed from August 20 to August 28. The longer the data use, the more reliable the result will be. The results calculated using the data observed on August 22, 23, 24, and 25 deviate from the red line.

Moreover, Fig. 13 shows the variation in the XY component of the impedance curve calculated by each hour's data at a period of 10 seconds. We use one-hour time-series data to calculate each result. The impedance curve becomes more stable and correlated with the geomagnetic storm event.

Fig. 11 to Fig. 13 show that the enhancement of the natural EM signal produces a more stable and reliable impedance value.
Fig. 11 The amplitude variation in periods of 16, 8, 4 and 1 seconds against the Dst index. The upper figure shows the amplitude variation from August 20 to August 28. The lowest figure shows the time variation of the Hx component along with the Dst index variation. The unit of Hx is nT. The horizontal axis denotes the time.

Fig. 12 The XY component of the impedance curve was calculated by each day's data at a period of 10 seconds. The horizontal axis denotes the date. The upper figures show the apparent resistivity, and the lower figures show the impedance phase. The red lines show the apparent resistivity and phase calculated by the data from August 20 to August 28.

Fig. 13 The time variation of the impedance curves calculated using each hour's time-series data at a period of 10 seconds. The horizontal axis denotes the time. One result was calculated using one-hour data. The unit of Hx is nT.
Fig. 14 shows the time-frequency distribution against the Dst index. The sampling rate is 150 Hz, and the content is the same, as shown in Fig. 9. There were no obvious changes in the intensity that were correlated with the storms in this figure. The signal strength is extremely low at 50 Hz, as it is filtered out when fieldwork is carried out. On the other hand, distinct peaks appeared at approximately 7.83, 14.3, 20.8 and 27.3 Hz. These frequencies correspond to the frequencies of Schumann's resonances (SRs). SR is a set of spectrum peaks in the extremely low frequency (ELF) of the Earth's EM field spectrum. Lightning discharges generate global EM resonances in the cavity formed by the Earth's surface and the ionosphere.

4.2 Case Study 2: USArray, USA

In the second case study, long-period 5-component MT time-series data observed at two sites (ALW48 and TNV48) were used. The data sets were recorded with a 1-second sampling period for around two weeks in 2015 from the USArray project. The geomagnetic storm occurred between June 22 and June 24.

Fig. 15 shows the distribution of coherency in different periods and cross-power spectra at 16-
second during the storm and non-storm days. The ordinary coherency increased from 4 to 40-second and 400 to 2,000-second during the geomagnetic storm. The low coherency during the non-storm day may be attributed to the local random noise. We can see the signal strength increased dramatically from the distribution of cross-power spectra. The preferred direction of PD between the orthogonal electric and magnetic field becomes more obvious at 16-second.

Fig. 15 compared four results calculated using the data observed at site TNV48 and using ALW48 as the remote reference site. The apparent resistivity of Quiet in the period from 8 to 30-second is severely down-biased. And the phase of Quiet is scattered from 8 to 30-second and 400 to 2,000-second. The result calculated using the storm data is much stable than the result calculated using the non-storm data. After comparing all results, the StormRR is the most reliable, and we regard it as the true model here. The Storm result is closer to the true model than the Quiet result between 4 to 30-second. We can see from the case study that the signal strength increased during the geomagnetic storms, and a more reliable impedance is obtained using the storm data.

Fig.15 The distribution of coherency in different periods and cross-power spectra at 16-second during the storm and non-storm days. The black color denotes the result using the non-storm data, and the red color denotes the result using the storm data.
Fig. 16 The MT sounding curves using the data observed during storm day and non-storm day. The Quiet result is drawn in black; the QuietRR result is drawn in blue; the Storm result is drawn in red; the StormRR result is drawn in purple.

4.3 Case Study 3: KAP03, South Africa

In the third case study, the long-period 5-component MT time-series data observed at Kaapvaal 2003 (KAP03) were used. The data were recorded with a 5-second sampling period 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. 7. Data for the sites located in the middle of the profile (KAP127-KAP145) were heavily contaminated by DC signals from the DC train line running between Kimberley and Johannesburg (MTNET, see the website in references).

Fig. 17 shows the time series at site 133. The sampling period is 5 seconds. In this dataset, there was a geomagnetic storm event that was captured during the observation periods. The storms lasted approximately two days, from October 29 to October 31, 2003. We used the different period time-series data of the KAP03 to analyze the geomagnetic storm's influence on the impedance tensor calculation. The result calculated using the data observed at quiet site 163 is shown first. Then, the data observed at noisy sites 142 and 133 are analyzed in detail. Finally, the
results calculated using the data observed at the other site contaminated by the heavy noise between sites 130 and 145 are shown.

Fig. 17 Time-series of MT field data at site 133. The red vertical lines show the data gaps, and the black lines show the 5-component MT data. The blue line shows the variation in the Dst index. The electric field unit is mV/km, and the unit of the magnetic field is nT. The horizontal axis denotes the time in UTC.

Fig. 18 shows the distribution of coherency in different periods and cross-power spectra at 84 seconds between storm days and non-storm days at site 163. The coherency values, i.e., $\text{Coh}(E_x, H_y)$ and $\text{Coh}(E_y, H_x)$, increased and were close to one across all periods. The preferred direction of the phase difference between the orthogonal electric and magnetic fields is almost the same at 84 seconds.

Fig. 19 shows the MT sounding curves calculated using the storm and non-storm days data at site 163. The results obtained below 20 seconds are not stable. To obtain an accurate complex coefficient from the time series. It is better to sample 4 points in one period. The sampling rate is 5 seconds. This instability may be caused by aliasing. The results calculated by EMT and BIRRP using the storm and non-storm days data coincide well. From the results, we can see 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. It will not bias the MT transfer function.

Fig. 18 The distribution of coherency in different periods and cross-power spectra at 84 seconds during the storm and non-storm days at site 163.

Fig. 19 The MT sounding curves calculated using the data observed during the storm and non-storm days at site 163. The triangles denote results calculated by the EMT code; the circles denote the results calculated by the BIRRP.
Fig. 20 shows the distribution of coherency in different periods and cross-power spectra at 84 seconds during the storm and non-storm days at site 142. There is no preferred direction of PD between the orthogonal electric and magnetic fields, and the coherency is low during the non-storm days. The intensity of the cross-power spectra increased almost two orders of magnitude during the storm days, and the coherency increased considerably and was close to one across all periods. The low coherency during the non-storm days may be attributed to the incoherent noise, as shown in this case.

Fig. 21 shows the MT sounding curves calculated using the data observed during the storm and non-storm days at site 142. The result calculated by the storm data is smoother than the Quiet and QuietRR results, and the error bar is small. The QuietRR results coincide with the Storm results, but the error is larger than that of the Storm results. On the other hand, the result of Quiet is quite different from the results of Storm and QuietRR. Noise biased the impedance during the non-storm days. During the storm, the enhancement of the natural EM signal overcame the noise and provided a reliable impedance. Comparing all the impedance results, Storm is the most reliable from 20 to 700 seconds.

Fig. 20 The distribution of coherency in different periods and cross-power spectra at 84 seconds during the storm and non-storm days at site 142. The red color denotes the result during storm
days. The black color denotes the result during non-storm days.

Fig. 21 MT sounding curves using the data observed during the storm and non-storm days at site 142. The Storm result is in red. The Quiet result is shown in black. The QuietRR result is shown in blue.

Fig. 22 shows the distribution of coherency across different periods and the cross-power spectra at 84 seconds during the storm and non-storm days at site 133. The values of $\text{Coh}(E_x H_y)$ and $\text{Coh}(E_y H_x)$ are high during the non-storm period. However, the preferred direction of PD is close to $0^\circ$ and $-180^\circ$. The coherent noise may have caused this phenomenon. Coherent noise often appears as a spike or convex-like noise occurring simultaneously in the time domain between different channels. The phase difference tends to $0^\circ$ and $-180^\circ$. The preferred direction of PD is changed during storm days.

Fig. 23 shows the MT sounding curve calculated using the data observed at site 133. The XY phase calculated by non-storm data is close to $0^\circ$, and the apparent resistivity increases as a line on the log scale. That is the phenomenon of local noise (Zonge and Hughes, 1987). $180^\circ$ or $0^\circ$ would correspond to a dipole electric source, which could be the train line. The impedance changed using geomagnetic storm data. This result coincides with the preferred direction of PD changed at 84 seconds in Fig. 22. The QuietRR result calculated using seven days of data (see
Table 1) coincides with the Storm result but is slightly different in the XY component between 20 and 40 seconds. The remote reference technique can only reduce the influence of local noise. From Fig. 8, the signal strength during this storm is almost 50 times stronger than that during the non-storm days. The noise can be neglected in this condition. We believe that the Storm result is more reliable.

Fig. 22 The distribution of coherency across different periods and cross-power spectra at 84 seconds during the storm and non-storm days at site 133. The contents have the same meaning as those in Fig. 20.

Fig. 23 MT sounding curves using the data observed during the storm and non-storm days at site 133. The contents have the same meaning as those in Fig. 21.
In this section, three parameters (polarization direction, RLcoh and R_AR) are used to analyze the data observed at site 133. Fig. 24 shows the variation in the polarization direction at 84 seconds from October 26 to October 31. The magnetic field polarization has a preferred direction at approximately -30° during non-storm days (October 26 to October 29) and becomes scattered during geomagnetic storm days (October 29 to October 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 geomagnetic 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. Contrary to 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 environment contaminates the data in that period. That coincides with the high Coh(E_x, H_y) and Coh(E_y, H_x) and the preferred direction of PD is close to 0° and -180° during the non-storm period. The data are dominated by coherent noise during non-storm days.

Fig. 25 shows the variation in RLcoh and R_AR at 84 seconds. The data observed at site 151 are relatively quiet and are used as remote reference data. The blue and the red line denotes the RLcoh. The blue color denotes a negative value, and the red color denotes a positive value. The black curve denotes the log value of R_AR.

The natural magnetic signal (H^{MT} and H_r^{MT}) comes from the same source and should be similar. When the portion of the natural magnetic signal (H^{MT} and H_r^{MT}) is high in the local and remote sites; the PD will be close to 0°; therefore, RLcoh should be close to 1, and R_AR should be stable and close to 1. 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. The natural magnetic signal portion increased drastically during the geomagnetic storm, the
variation in RLcoh and R_AR became stable. This result indicates that the SNR is low during non-storm days and becomes high during storm days.

Fig. 24 The variation in polarization direction at 84 seconds using the data observed at site 133 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.

Fig. 25 The variation in RLcoh versus R_AR at 84 seconds using the data observed at site 133 from October 26 to October 31. The blue and the red line denotes the RLcoh. Blue indicates a negative value, and red indicates a positive value. The black curve denotes the log value of R_AR.

Fig. 26 shows the MT sounding curve and coherency distribution using the data observed during the storm and non-storm days at site 130. The Coh(E_x,H_x) and Coh(E_y,H_x) values are high between 10 and 200 seconds during the non-storm days; 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. A similar situation occurs at site 133. We consider that the data are dominated by strong coherent noise during non-storm days. The $\text{Coh}(E_x, H_x)$ value is high while the $\text{Coh}(E_y, H_y)$ value is low during storm days; this can be interpreted as the phenomenon of PROQ. The QuietRR result using four-day data (see Table 1) coincides with the Storm result; moreover, the Storm result is smoother, and the error bar is smaller than that of the QuietRR result.

Fig. 26 The MT sounding curves and coherency distributions obtained using the data observed during storm days and non-storm days at site 130. The storm result is shown in red. The quiet result is shown in black. The QuietRR result is shown in blue. For coherency, the red color denotes the result during storm days. The black color denotes the results obtained during non-storm days.

Fig. 27 shows the MT sounding curve and coherency distribution using the data observed during the storm and non-storm days at site 136. $\text{Coh}(E_x, H_y)$ is relatively high between 10 and 1000 seconds during the non-storm data; Fig. 28 shows the distribution of cross-power spectra of the $E_x H_x$ and $E_y H_y$ components at 168 seconds during the storm and non-storm days. The
preferred direction of PD between $E_x$ and $H_y$ is close to 0°. We consider that the strong coherent noise caused this phenomenon.

On the other hand, $\text{Coh}(E_x, H_x)$ is high, while $\text{Coh}(E_x, H_y)$ is low during the storm day. That can be explained as the phenomenon of PROQ. The QuietRR result using four days of data (see Table 1) partially coincides with the Storm result. Moreover, the Storm result is smoother, and the error bar is smaller.

Fig. 27 The MT sounding curves and coherency distribution using the data observed during the storm and non-storm days at site 136. The colors have the same meanings as those in Fig. 26.

Fig. 28 Distribution of cross-power spectra of $E_xH_x$ and $E_xH_y$ components at 168 seconds between
the storm day and non-storm day at site 136. The colors have the same meanings as those in Fig. 20.

Fig. 29 and Fig. 30 show the MT sounding curve and coherency distribution using the data observed during the storm and non-storm days at sites 139 and 145, respectively. Both the coherency between the orthogonal electric and magnetic fields increased during the storm days. The result calculated by the data observed on the storm day is smoother; the XY component of the QuietRR result has a similar trend to the Storm result. However, the YX component is very different between the QuietRR and Storm results at both sites. It is difficult to distinguish which represents the real conditions. From the perspective of SNR and based on the analysis in the previous case study, the storm has a positive effect on the MT data quality; we believe that the Storm result is more reliable.

Fig. 29 MT sounding curves and coherency distribution using the data observed during the storm and non-storm days at site 139. The colors have the same meanings as those in Fig. 26.
Fig. 30 MT sounding curves and coherency distribution using the data observed during the storm and non-storm days at site 145. The colors have the same meanings as those in Fig. 26.

5 DISCUSSION

In this section, we discuss how to use multiple parameters to estimate the data quality. Coherency is an important parameter to discuss the data quality. However, the characteristic of coherency is different in different situations. At first, we discuss the relationship between impedance and coherency. According to least-squares theory (Sims et al., 1971); $Z_{xy}$ can be calculated as follows:

$$Z_{xy} = \frac{<E_xH_y><H_xH_y> - <E_yH_y><H_yH_y>}{<H_yH_y><H_yH_y> - <H_xH_x><H_xH_x>} = \frac{C - D}{E - F}, \quad (14)$$

For the denominator, there is a relationship as follows:

$$|C| = |<E_xH_y><H_yH_y>| = \text{coh}(E_x, H_y) \sqrt{<E_xE_x><H_yH_y>}, \quad (15)$$

$$|D| = |<E_yH_y><H_yH_y>| = \text{coh}(E_y, H_y) \sqrt{<E_yE_y><H_yH_y>}, \quad (16)$$

$$\frac{|E|}{|D|} = \frac{|<E_yH_y><H_yH_y>|}{|<E_xH_y><H_xH_y>|} = \frac{\text{coh}(E_y, H_y)}{\text{coh}(E_x, H_x) \text{coh}(H_x, H_y)}, \quad (17)$$

For the denominator part of equation 14, there is a relationship as follows:

$$|E| = |<E_xH_x><H_xH_x>|$$

$$|F| = |<H_yH_y><H_yH_y>| = \text{coh}^2(H_x, H_y) <H_xH_x><H_yH_y>$$

$$<H_xH_x><H_yH_y>$$
Because various sources generate natural magnetic signals, they generate magnetic fields that vary in their incident directions, which means Hx and Hy are not coherent, and Coh(Hx, Hy) is a small value. In the condition that the Coh(Ex, Hy) is relatively high while the Coh(Ex, Hx) is small.

The numerator of Eq. 14 will be dominant by the C part. The denominator is dominant by the E part.

The Zxy can be rewritten as follows:

\[
Z_{xy} = \frac{<E_x H_y^\dagger>}{<H_y H_y^\dagger>}
\]  

In this situation, Zxy is determined by the orthogonal component of the electric and magnetic field. A similar analysis to Zxx, Zxx is undeterminable. When Coh(Ex, Hy) is relatively high while Coh(Ex, Hx) is small; the field data can be explained as the 1-D and 2-D cases. Here we also need to quantify the coherency value in the different geological environments by doing some simulation. For example, rotate the observation axes in the 2-D case by the step of 5°, how high the coherency will be. We can see the example at TNV 48 from USArray, site 142 from KAP03.

The coherency between the orthogonal magnetic and electric components is relatively low during the non-storm day and increased dramatically during the strong storm. The low coherency can be attributed to the incoherent noise in this case.

On the contrary that the coherency between the orthogonal component Coh(Ex, Hy) is relatively low while the Coh(Ex, Hx) is high. The Zxy is undeterminable and Zxx is determinable. The phenomenon of PROQ appears. In this situation, we cannot explain the data by the 1-D or 2-D case. We can see the example at Sawauchi station, sites 130 and 136 from KAP03. Both site 130 and 136 is contaminated by coherent noise, and the Coh(Ex, Hy) become low while the Coh(Ex, Hx) become relatively high during the storm day.

The coherent noise may have a high coherency value and appear as the spike, or convex-like,
or other kinds of noise in the time domain at the different channel simultaneously. And the phase
difference between the two-channel tends to 0° or 180°. It is better to check the phase by plot the
distribution of the cross-power spectra. To estimate the data quality precisely, we would better
combine other parameters to discuss the situation.

The polarization direction is a function of PD and AR between the two orthogonal fields. The
local EM noise source usually has a constant location; the incident direction and the energy have
a similar property along with time. Contrary to the natural EM signal, the incident direction and
power are changed with time. 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. This situation can
be seen at site 133. But sometimes, the data is contaminated by incoherent noise. There is no
preferred polarization direction for the magnetic field. This situation appears in site 142 but is not
shown in this paper.

Suppose there is a quiet remote reference site. We also could use the RLcoh and R_AR to
measure the similarity between the local and remote sites to evaluate the influence of noise. This
example is shown in the data analysis at site 133.

Finally, the most important parameter to discuss the data quality is the result impedance. The
sounding curve should be smooth according to the forwarding modeling. On the other hand, in
the influence of strong locale noise, the phase will be close to 0° or 180°, and the apparent
resistivity increases as a line in the log scale (Zonge and Hughes, 1987); this phenomenon appear
during the non-storm day at site 130 and 133. Because the remote reference technique can
suppress the local noise, and the remote reference result can be used as a standard to evaluate the
data quality. The examples are shown in sites 130,136,139,145 from KAP03 and TNV48 from
USArray. Until now, we discussed how to use multiple parameters to estimate the geomagnetic
storm on the data quality. All examples of the method can be found in the case studies.

Finally, we will discuss the source effect and nonstationarity of the data observed during the
storm day. At mid-latitudes, geomagnetic pulsations (Pc's) in the Pc3-4 band (~10 - 100 s)
associated with field-line resonances can violate the fundamental assumption of the MT method over the resistive regions; where skin depths are large (Murphy and Egbert, 2018). In this case, the source effect is inevitable and is place-dependent. In this paper, from the perspective of SNR, we demonstrate the positive effect of a geomagnetic storm on the MT data quality, the impedance calculated using the data observed during the geomagnetic storm and the non-storm day at the quiet site 163 and Sawauchi station coincide well. It shows that the signal holds the plane-wave assumption, and the nonstationarity is not a problem for the method based on the FFT in this area. Otherwise, the result calculated by the storm period data should be biased. The sources effect may be considered near the auroral or equatorial electrojets. But the plane wave assumption is generally acceptable at midlatitudes.

6 CONCLUSIONS

It is well known that the signal strength will increase during a geomagnetic storm in the MT community. Still, the demonstration that shows the positive effects on the MT impedance by the field data is rare. This paper showed the positive influence of the geomagnetic storm on MT data quality by three case studies in mid-latitude. Using the data observed during a strong geomagnetic storm may overcome the influence of the local noise, depending on the strength of the geomagnetic storm and local noise. We obtained a more reliable and interpretable impedance using the data observed during the strong geomagnetic storm to calculate the impedance in the survey line from Kap03, which is contaminated by the strong noise.

MT field data include natural signal sources and noise. Along with urban constructions, artificial disturbances to EM observations are becoming more and more serious. The observation occasionally contains continuous noise, which is difficult to get a reliable result from the current technique. When we redo the MT campaign in the noisy site, we may get a reliable result using the data observed during geomagnetic storms. Sometimes, the variation during storm periods can be 100 times greater than in the non-storm period data. In that condition, the noise can be
neglected. However, a strong geomagnetic storm doesn't occur frequently. It is possible to predict
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 the strong geomagnetic storm may bring a
reliable result despite the site contaminated by continuous noise.

To get the accurate complex coefficient from the time series, we suggest that it is better to
contain at least four times longer than the expected period. For 1,000-second, a time-series
segment with 4,000 seconds is needed to get accurate spectra. The overlay rate is 50% to keep
each data's independence and get more sample data. By the continuous 4-hour time-series data,
we may get about eight samples to do the impedance estimation in the frequency domain by FFT.
If there is continuous 4-hour geomagnetic storm data, we may get a relatively reliable tensor until
1,000 seconds, depending on the geomagnetic storm's length. The longer the geomagnetic storm
last. A more stable result can be obtained. By the statistical analysis of the geomagnetic storm,
one year had about ten strong geomagnetic events, and about five events lasted more than 4 hours
on average. That is practical and meaningful for MT exploration.

DECLARATION

Availability of data and materials
The magnetic time-series data observed at the KAK station is downloaded from the
INTERMAGNET (International Real-time Magnetic Observatory Network). The SAMTEX team
and USAArray team provided the long period time-series data to investigate. Kap03 data can be
download from MTNET (see the reference). USAArray data can be download from IRIS
(Incorporated Research Institutions for Seismology). Nittetsu Mining Consultants Co., Ltd.
provided the broadband frequency MT time-series data observed at Sawauchi, Japan. The Dst
index data can be download from the WDC for Geomagnetism, Kyoto. Alan Chave provided the
BIRRP code. Maik Neukirch provided the EMT code.

**Competing interests**

We know of no conflicts of interest associated with this publication. We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

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**Authors' contributions**

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

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Figures

Figure 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 a profile in the frequency domain.

Figure 2

The distribution of strong storms based on the Dst index between 1957 - 2020, the orange line denotes Dst (<= -50 nT), and the light blue line denotes Dst (<= -100 nT).
Figure 3

The statistical analysis of each strong geomagnetic storm event. The upper figure shows the number of each strong geomagnetic storm event in a different storm event length. The lower figure shows the cumulative distribution of the upper figure.

Figure 4

The monthly count of strong geomagnetic storms based on the Dst index.
Figure 5

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

Figure 6

The calculated periods by Fourier analysis using the yearly count of geomagnetic storms from 1957 to 2020.
Figure 7

The location map in the three case studies (KAP03, USArray, Sawauchi). The left map shows the detailed site location used in USArray, and the right map shows the survey line of KAP03. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 8

Comparison of the spectrum calculated by the Hx component observed during the storm and non-storm days. The black lines denote the non-storm day's data, and the red lines denote the storm day's data. The horizontal axis denotes the period. The vertical axis denotes the intensity.

Figure 9

The time-frequency distribution against the Dst index variation and the sampling rate is 15 Hz. The upper figure shows the time-frequency distribution from August 20 to 29. The color denotes the value of 10·log10 (amp.). The lower figure shows the time variations of the Hx component along with the Dst index. The unit of Hx is nT. The horizontal axis denotes the date.
Figure 10

MT sounding curves and coherency distribution during storm days (August 26) and non-storm days (August 23). 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 distribution of coherency. The horizontal axis denotes the period in seconds.

Figure 11

The amplitude variation in periods of 16, 8, 4 and 1 seconds against the Dst index. The upper figure shows the amplitude variation from August 20 to August 28. The lowest figure shows the time variation of the Hx component along with the Dst index variation. The unit of Hx is nT. The horizontal axis denotes the time.
Figure 12
The XY component of the impedance curve was calculated by each day's data at a period of 10 seconds. The horizontal axis denotes the date. The upper figures show the apparent resistivity, and the lower figures show the impedance phase. The red lines show the apparent resistivity and phase calculated by the data from August 20 to August 28.

Figure 13
The time variation of the impedance curves calculated using each hour's time-series data at a period of 10 seconds. The horizontal axis denotes the time. One result was calculated using one-hour data. The unit of Hx is nT.
Figure 14

The time-frequency distribution against the Dst index. The sampling rate is 150 Hz. The content is the same as Fig. 9.
Figure 15

The distribution of coherency in different periods and cross-power spectra at 16-second during the storm and non-storm days. The black color denotes the result using the non-storm data, and the red color denotes the result using the storm data.
Figure 16

The MT sounding curves using the data observed during storm day and non-storm day. The Quiet result is drawn in black; the QuietRR result is drawn in blue; the Storm result is drawn in red; the StormRR result is drawn in purple.

Figure 17

Time-series of MT field data at site 133. The red vertical lines show the data gaps, and the black lines show the 5-component MT data. The blue line shows the variation in the Dst index. The electric field unit is mV/km, and the unit of the magnetic field is nT. The horizontal axis denotes the time in UTC.
Figure 18

The distribution of coherency in different periods and cross-power spectra at 84 seconds during the storm and non-storm days at site 163.
Figure 19

The MT sounding curves calculated using the data observed during the storm and non-storm days at site 163. The triangles denote results calculated by the EMT code; the circles denote the results calculated by the BIRRP.
Figure 20

The distribution of coherency in different periods and cross-power spectra at 84 seconds during the storm and non-storm days at site 142. The red color denotes the result during storm days. The black color denotes the result during non-storm days.
Figure 21

MT sounding curves using the data observed during the storm and non-storm days at site 142. The Storm result is in red. The Quiet result is shown in black. The QuietRR result is shown in blue.

The distribution of coherency across different periods and cross-power spectra at 84 seconds during the storm and non-storm days at site 133. The contents have the same meaning as those in Fig. 20.
Figure 23

MT sounding curves using the data observed during the storm and non-storm days at site 133. The contents have the same meaning as those in Fig. 21.

Figure 24

The variation in polarization direction at 84 seconds using the data observed at site 133 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.
Figure 25

The variation in RLcoh versus R_AR at 84 seconds using the data observed at site 133 from October 26 to October 31. The blue and the red line denotes the RLcoh. Blue indicates a negative value, and red indicates a positive value. The black curve denotes the log value of R_AR.

Figure 26

The MT sounding curves and coherency distributions obtained using the data observed during storm days and non-storm days at site 130. The storm result is shown in red. The quiet result is shown in black. The QuietRR result is shown in blue. For coherency, the red color denotes the result during storm days. The black color denotes the results obtained during non-storm days.
Figure 27

The MT sounding curves and coherency distribution using the data observed during the storm and non-storm days at site 136. The colors have the same meanings as those in Fig. 26.
Figure 28

Distribution of cross-power spectra of ExHx and ExHy components at 168 seconds between the storm day and non-storm day at site 136. The colors have the same meanings as those in Fig. 20.
Figure 29

MT sounding curves and coherency distribution using the data observed during the storm and non-storm days at site 139. The colors have the same meanings as those in Fig. 26.

Figure 30

MT sounding curves and coherency distribution using the data observed during the storm and non-storm days at site 145. The colors have the same meanings as those in Fig. 26.

Supplementary Files
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- StormVSSnon.jpg