Multiple-band electric field responding to the geomagnetic storm on 4 November 2021

Jie Zheng¹, Jianping Huang¹, Zhong Li², Jing Wen Li¹, Ying Han³, and hengxin lu¹

¹National Institute of Natural Hazards, Ministry of Emergency Management of China
²School of Emergency Management, Institute of Disaster Prevention
³Institute of Disaster Prevention

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Abstract

In this paper, based on the electric field data (EFD) of the China Seismo-Electromagnetic Satellite (CSES), which is divided into 4 frequency bands (ULF, ELF, VLF, HF) from DC to 3.5 MHz, we study the impact characteristics of the 4 November 2021 magnetic storm activity in different frequency bands. It was found that the electric field anomalies caused by magnetic storms were mainly concentrated below 18 kHz, and above 18 kHz the effects were weak and gradually diminished to negligible. In the ULF band, excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, with the most influential frequency point being 3.4 Hz. In the ELF band, the more obvious anomalies appear at 300 Hz – 900 Hz and above 1.8 kHz, with the most significant anomalies in the 300 Hz – 900 Hz band around 780 Hz. In the VLF band, electric field anomalies are concentrated in 2.5 - 10 kHz. Magnetic storms had essentially no effect on the HF band. Magnetic storms at low and middle latitudes have a weak effect on the ELF and VLF bands and are more pronounced in the ULF band. During the main phase of the magnetic storm, the absolute magnitude of variance change in the ELF and VLF bands is greater than that in the ULF band as a whole, but the relative magnitude of variance change in the ULF band is 10% greater than that in the ELF and VLF bands.

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Multiple-band electric field responding to the geomagnetic storm on 4 November 2021

Jie Zheng¹,², Jianping Huang²*, Zhong Li³, Wenjing Li², Ying Han³, Hengxin Lu²

¹University of Chinese Academy of Sciences, Beijing 101408, China.
²National Institute of Natural Hazards, Ministry of Emergency Management of China, Beijing 100085, China.
³Institute of Intelligent Emergency Information Processing, Institute of Disaster Prevention, Langfang 065201, China.
*Corresponding author (email: jianpinghuang@ninhm.ac.cn)

Keypoints:
- Presentation of the electric field response of the 4 November 2021 strong magnetic storm to different frequency bands
- The frequencies and bands most affected by magnetic storms were found
- A significant anomaly at 3.4 Hz in the ULF band was demonstrated during the magnetic storms.

Abstract  In this paper, based on the electric field data (EFD) of the China Seismo-Electromagnetic Satellite (CSES), which is divided into 4 frequency bands (ULF, ELF, VLF, HF) from DC to 3.5 MHz, we study the impact characteristics of the 4 November 2021 magnetic storm activity in different frequency bands. It was found that the electric field anomalies caused by magnetic storms were mainly concentrated below 18 kHz, and above 18 kHz the effects were weak and gradually diminished to negligible. In the ULF band, excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, with the most influential frequency point being 3.4 Hz. In the ELF band, the more obvious anomalies appear at 300 Hz – 900 Hz and above 1.8 kHz, with the most significant anomalies in the 300 Hz – 900 Hz band around 780 Hz. In the VLF band, electric field anomalies are concentrated in 2.5 - 10 kHz. Magnetic storms had essentially no effect on the HF band. Magnetic storms at low and middle latitudes have a weak effect on the ELF and VLF bands and are more pronounced in the ULF band. During the main phase of the magnetic storm, the absolute magnitude of variance change in the ELF and VLF bands is greater than that in the ULF band as a whole, but the relative magnitude of variance change in the ULF band is 10% greater than that in the ELF and VLF bands.

Plain Language Summary
In this paper, the anomalous frequency points and bands affected by strong magnetic storms are found by using CSES-1 satellite data, using methods such as satellite data processing and wavelet coherence. We find that magnetic storms have a significant effect on ULF, ELF, and VLF bands, and a negligible effect on HF bands, and that the
electric field anomalies caused by magnetic storms are mainly below 18 kHz, and the
effect is weak and decreases gradually to negligible beyond 18 kHz. In the ULF band,
Schumann waves affect different frequencies in different hemispheres, mainly 7 - 8
Hz Schumann waves in the southern hemisphere and 13 - 14 Hz Schumann waves in
the northern hemisphere, and magnetic storms enhance the influence of Schumann
waves. Excluding the influence of Schumann waves, the electric field anomalies
cau
sed by magnetic storms are mainly below 5 Hz, and the frequency point with the
greatest influence is 3.4 Hz.

1. Introduction

Magnetic storms, also known as solar storms or magnetic storms, are phenomena
in which energetic particles and magnetic fields in the solar wind interact with the
Earth's magnetic field. Such interactions can lead to violent disturbances of the
magnetic field in the Earth's magnetosphere, causing sharp changes in the Earth's
magnetic field (Blagoveshchenskii, 2013a; Piddington, 1964). Geomagnetic storms are
usually caused by interplanetary disturbances and are accompanied by a long-duration
southward interplanetary magnetic field. These events release large amounts of energy
and charged particles, which are propagated through space by the solar wind (Gonzalez
et al., 1994, 2007; Zong et al., 2010). When these charged particles interact with the
Earth's magnetic field, they can trigger a complex set of phenomena. In extreme cases,
magnetic storms can have serious effects on the Earth's communication systems,
navigation systems, etc. (G. S. Lakhina et al., 2012; Gurbax S. Lakhina & Tsurutani,
2016; Rama Rao et al., 2009; Roodman, 2015). In addition to this, geomagnetically
induced currents caused by magnetic storms can cause abnormalities in transportation,
and in the operation of signaling, centralization, and blocking systems of the power
system (Eroshenko et al., 2010; Lanzerotti, 2017; Pulkkinen et al., 2017). If we can find
the specific frequency points and frequency bands affected by magnetic storms, it will
not only be helpful for the in-depth study of magnetic storms, but also be of great
significance for the anti-jamming design of spacecraft and communication equipment.

The data used to study magnetic storms studied mainly include interplanetary
characterization data (Tripathi & Mishra, 2006, 2006; Yermolaev et al., 2010),
ionospheric magnetospheric data, and geomagnetic disturbance indices. However,
interplanetary signature data or geomagnetic disturbance indices do not identify
specific frequency points and bands affected by magnetic storms, and it is the use of
electric and magnetic field data that allows for an in-depth study of this topic.

The use of satellite electric and magnetic field data to study the frequency points
with large perturbations caused by anomalous space phenomena has been partially
investigated by previous researchers. In 2002, (Witasse & Zender, n.d.) analyzed
electric field data in the frequency range of 10 Hz to 300 Hz during magnetic storms,
including the Schumann resonance frequency, and concluded that the peaks of the
perturbation signals were concentrated in the range of 10 to 200 HZ. (Parkhomov et al.,
2017) observed short bursts of geomagnetic pulsations in the frequency range of 0.2 to
5 Hz during magnetic storms, with a global maximum at a frequency of 2.78 ± 0.38 Hz.
Although a preliminary range of anomalous frequencies is available in the ULF band,
the most significant specific frequencies for the effects of magnetic storms have not been found so far.

In the ULF band, the discussion of Pc waves accounts for an important part of the study of ULF waves. As early as 1993, (Fraser-Smith, 1993) conducted electromagnetic monitoring of ULF waves and found that ELF/VLF waves are much less affected than ULF when a magnetic storm is approaching. It has been demonstrated that the response of ULF waves during magnetic storms is closely related to geomagnetic activity and solar parameters (Ahmad et al., 2015). ULF wave power is linearly correlated with the absolute value of the SYM-H index during the main phase of the storm and exponentially correlated with the absolute value of the SYM-H index during the recovery phase (Li et al., 2023). The intensity of geomagnetic pulsations with a frequency of 27 mHz during the initial phase of the magnetic storm is maximum in the morning and night segments at polar and auroral latitudes, respectively. Daytime Pc5 wave pulsations are strongest during the main phase of the magnetic storm, not the recovery phase as previously thought (Kozyreva & Kleimenova, 2008, 2009). Different interplanetary sources cause different pulsation strengths. the higher latitude position of the Pc5 pulsation intensity maximum in CIR storms points to larger dimensions of the daytime magnetosphere during CIR storms as compared to CME storms. (Kozyreva & Kleimenova, 2010).

In the ELF and VLF bands, (Tatsuta et al., 2015) Based on two years of nightly data from the VLF/LF observation network in Japan, it was found that high latitudes are less affected by geomagnetic activity and mid-latitude and low-mid-latitude paths are less affected by geomagnetic activity. During the strong magnetic storm from 8 to 10 November 2004, intense electromagnetic harmonic emissions between 500 and 2000 Hz were detected at midlatitudes, and similar emissions were also observed on 21–22 January 2005 and on 15 May 2005 during two magnetic storms of lower intensity (Parrot et al., 2006). (Pinto & Gonzalez, 1989) suggests that the enhancement of these waves during geomagnetic storms and substorms is characterized by a peak at 550 Hz and that their intensity is very dependent on magnetic activity. (Zhima et al., 2014, 2021) by studying the ELF/VLF waves, it was found that very low-frequency waves below 3 kHz were significantly enhanced throughout the magnetic storm, whereas high-frequency waves above 3 kHz were significantly enhanced in the later part of the main phase and the earlier part of the recovery phase.

In the study on the HF band, (Blagoveshchenskii, 2013b) analyzes the manifestation of the so-called main ionospheric effect in the propagation properties of ten-meter waves during geomagnetic storms. Specifically, these parameters increase before the disturbance active phase, decrease during the active phase, and increase again after this phase. Since the response of magnetic storms in the HF band is not as good as that of ULF/ELF/VLF, fewer studies have been conducted on magnetic storms using the HF band.

Even though there is a consensus that magnetic storms affect different frequency points and bands differently, there are no conclusions on the detailed frequency points and bands. In this paper, we will use the EFD spectrum data from the CSES-1 to study the spectral characteristics of the frequency points and bands of the strong perturbation
in different regions during the magnetic storm activity (Dst<-100nT) of 4 November 2021, which will fill in the gaps of research in this area.

2. Data and Method

The main scientific objective of the CSES-1 is to monitor ionospheric perturbations associated with natural hazards in the quest for possible anomaly forecasting (Zhima et al., 2021). The CSES-1 completes 15.2 orbits around Earth per day, with an orbital period of ~94.6 min and a five-day recursive period over the same geographic area with the ascending/descending node local time of 02 a.m./02 p.m., respectively. Eight payloads are assembled on CSES-1, that is, high-precision magnetometer (HPM), search coil magnetometer (SCM), electric field detector (EFD), Langmuir probe (LA), plasma analyzer (PAP), high-energy particle detector (HEPD), GNSS occultation receiver (GOR), and tri-band beacon (TBB). The entire star is capable of acquiring 17.6 hours of scientific exploration data per day and has the capability of continuous exploration within the latitude of 65° north and south at all hours of the day (Yuan et al., 2018). The electric field is detected by an electric field detector (EFD), which consists of four spherical sensors mounted at the near-end part of four booms (4.5 m long), measuring the electric field in four frequency channels: ULF (DC to 16 Hz), ELF (from 6 Hz to 2.2 kHz), VLF (1.8 to 20 kHz), and HF (from 18 kHz to 3.5 MHz), with sampling rates of 128 Hz, 5 kHz, 50 kHz, and 10 MHz, respectively.

In this paper, satellite electric field data and Dst data are used to study the abnormal frequency points and bands, where the electric field data are from CSES-1 (https://www.leos.ac.cn/) and the Dst data are from the website (https://wdc.kugi.kyoto-u.ac.jp/index.html).

2.1 Satellite data processing

We use the average degree of difference between electric field data and the background field data during magnetic storms which call D value as a criterion for determining the magnitude of the effect of magnetic storms. The background field data is set to be a revisited orbit in a quiet period within one month before the current orbit. The power spectrum of the satellite electric field with background noise removed for the selected latitude width is

\[ P = \left| P_{n(storm)} - P_{n(background)} \right| \]

The average degree of difference of frequency point j is

\[ D_j = \frac{\sum_{i=1}^{n} P_{ij}^2}{n} \]

The relative degree of variation is

\[ r_j = \frac{D_j}{D_{background}} \]

where \( n \) is the selected latitude width. \( P_n \) is the satellite electric field power spectrum for the selected latitude width.
2.2 Wavelet Coherence (WTC) analysis

This work uses wavelet coherence (WTC) to analyze the correlation between electric field power sequences and Dst values at different frequency points. Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT) are the two types of WT. Because of its appropriate time and frequency localization, the Morlet wavelet (dimensionless frequency, $\omega_0 = 6$) is an ideal option for extracting features (Grinsted et al., 2004). The WTC spectrum quantifies the degree to which two-time series co-vary as a function of time and frequency. The XWT spectrum exposes large shared power areas and relative phases between two-time series in time frequency space (Giri et al., 2023; Xiang et al., 2019). The XWT of two-time series $X(t)$ and $Y(t)$ is defined as:

$$ W_{t}^{XY}(s) = W_{t}^{X}(s)W_{y}^{Y^{*}}(s) $$

The CWT coefficients of sequences $X(t)$ and $Y(t)$ at frequency scale $s$ are denoted by $W_{t}^{X}(s)$, and $W_{y}^{Y^{*}}(s)$ respectively and $^{*}$ denotes the complex conjugate.

The square of the wavelet coherence factor is defined as

$$ R_t^2(s) = \frac{|S[s^{-1}W_{t}^{XY}(s)]|^2}{S[s^{-1}W_{t}^{X}(s)][s^{-1}W_{t}^{Y}(s)]} $$

S is the smoothing operator, $s$ is the scale. WTC values around 1 indicate a higher degree of resemblance across time series, whilst coherence values near 0 indicate no correlation.

This paper focuses on the analysis of the magnetic storm on January 4, 2021, and the data from three days before and three days after the occurrence of this magnetic storm were selected to observe the initial phase, the main phase, and the restoration phase of the magnetic storm. Drawing the geomagnetic latitude of 65°N - 65°S, 22°N - 65°S, and 22°N - 22°S regions of D value spectrograms, comparative analysis shows the magnitude of the effect of magnetic storms on different frequency bands different hemispheres. Because the electric field triplicates $Ex$, $Ey$, and $Ez$ removed background noise have more outliers, we can use the median absolute difference (MAD) method to remove the anomaly outliers. Then use the sliding averages method (Smith, 2003) to smooth the signal, which can reduce random noise and maintain the trend of the original signal at the same time. Finally, WTC is used to look at the correlation between the electric field power spectra and the Dst values at different frequency points to find the frequency points that have the highest correlation with magnetic storms.

3. Observations

3.1 ULF band’ D value analysis

Figure 1 shows the Dst values, the ULF band spectra (with background noise removed), and the average degree of different (D value) hemispheric and latitudinal
sub-bands from 1 November 2021 to 7 November 2021. It can be seen that the Dst index decreases sharply on 4 days in the presence of magnetic storms, and the spectrum of the ULF band as well as the D value also shows significant changes. (Sanfui et al., 2016) gave the conclusion that the maximum values of the SR mode frequencies of the first, second, and third orders of the Schumann resonance are 8.51 Hz, 14.71 Hz, and 21.22 Hz, respectively, and the presence of constant perturbed Schumann waves is also clearly seen in this case. For the total region of 65°N - 65°S, Schumann waves around 8 Hz and 13 Hz are present at a constant level and are significantly intensified by magnetic storms, with the intensification of the Schumann waves at 13 Hz more than that at 8 Hz. The enhancement of Schumann waves at 13 Hz is more significant than at 8 Hz. The occurrence of magnetic storms greatly affects the whole frequency band of ULF. For the southern hemisphere 22°S - 65°S, 8 Hz Schumann waves exist stably, and 13 Hz Schumann waves have no effect in the southern hemisphere, while the effect of magnetic storms on the ULF band in the southern hemisphere is more pronounced around 3 Hz, and also in the range 15 - 20 Hz, but has little effect in the 6 – 13 Hz frequency range. In the middle and low latitudes of 22°N - 22°S, the Schumann waves of 8 Hz and 13 Hz existed steadily and strengthened significantly during the onset of the storms. The strongest impact of the storms on this region was centered in the frequency range of 6 - 13 Hz. In the northern hemisphere 22°N - 65°N, the main Schumann wave is 13 Hz, which is slightly strengthened at the onset of the storm. However, in this hemisphere, the main impact of the storm is in the frequency band below 7 Hz and is concentrated at about 3 Hz. In addition, the time of the most significant effect of the magnetic storm on the northern and southern hemispheres was not the same, and the northern hemisphere was affected before the southern hemisphere in this magnetic storm.

Since the regions affected by magnetic storms are concentrated at the poles and high latitudes, the manifested electric fields from interplanetary origin can instantaneously penetrate to equatorial and low latitudes (Lissa et al., 2020) and particle movement, etc. In addition to this, the middle and low latitudes are subject to interference from Schumann waves and human communication equipment. Therefore, the frequency band anomalies at high latitudes are more representative of the electric field anomalies caused by magnetic storms. The analysis of the D value by subregion leads to the conclusion that magnetic storms affect the entire frequency band of the ULF band, with the most significant frequency point of the anomaly located around 3 Hz.

Combining the anomaly changes in each latitude band, it can be seen that the discrepancy degree becomes more than 1 at the beginning of a magnetic storm. Therefore, the ULF band discrepancy degree greater than 1 can be used as a sign of the beginning of a magnetic storm, which may become a new predictor of magnetic storms in the future.
Figure 1 7 day’s Dst index, ULF band spectrogram, and sub-band D value map. a) 65°N - 65°S, b) 22°S - 65°S, c) 22°N - 22°S, d) 22°N - 65°N

3.2 Full bands’ quantitative analysis of D value

Table 1 summarizes the magnitude of the anomaly differences in the frequency bands and frequency points of significant anomalies in the satellite-observed electric field during the occurrence of magnetic storms. It can be seen that the effect of magnetic storms in the ULF band is below 5 Hz for both the Southern Hemisphere and Northern Hemisphere high latitudes, with a consistent significant anomaly frequency of 3.4 Hz. This is consistent with (Parkhomov et al., 2017) observation of the 0.2 to 5 Hz frequency range during magnetic storm outbursts, which has a global maximum at a frequency of 2.78 ± 0.38 Hz. For middle and low latitudes, the anomalous difference in the electric field caused by Schumann waves on satellite observations during quiet periods averages at $2[mV/m/Hz^2]^{\frac{1}{2}}$ or so, but during magnetic storms the maximum D value reaches $3.4[mV/m/Hz^2]^{\frac{1}{2}}$, demonstrating that magnetic storms also have an enhancement effect on Schumann waves.

In the ELF band, the full-band impact is enhanced at the minimum Dst value over the full latitude range of 65° S - 65° N. More pronounced anomalies appear below 300 Hz, along with significant anomalies at 780 Hz, 1.5 kHz, and other frequency points. Comparison of the northern and southern hemispheres at high and mid-low latitudes reveals a clear difference in the anomalous enhancement of the electric field. The effects of magnetic storms in the ELF band are concentrated in the high latitudes of the Southern Hemisphere, while they have less impact in the high and middle-low latitudes of the Northern Hemisphere. The strongest electric field anomalies in the northern hemisphere do not occur at the same time, and the southern hemisphere electric field anomalies are mainly concentrated in the range of 300 Hz – 900 Hz and above 1.8 kHz, with a maximum D value of $4[mV/m/Hz^2]^{\frac{1}{2}}$ above,
suggesting that magnetic storms have a greater effect at high latitudes in the southern hemisphere, where the most significant anomalies are around 780 Hz in the band 300 Hz - 900 Hz. (Zhang et al., 2022) used satellite electric field data at 225 Hz, 725 Hz, 1125 Hz, 5000 Hz, 7500 Hz and 13500 Hz in his study of the electric field anomalies, and the results showed that the electric field anomalies were most pronounced at 725 Hz, which is in agreement with the conclusions of the analysis. The electric field anomalies in the middle and low latitudes are concentrated below 300 Hz, while there are no obvious anomalies in the higher frequency bands, and it can be assumed that the equatorial ionospheric anomalies caused by the penetration of the electric field from high latitudes to low latitudes are mainly concentrated at about 0 – 300 Hz. The effects of the ELF band on the northern hemisphere's high latitudes by the present storm are not obvious compared with those in the southern hemisphere's high latitudes.

In the VLF band, the electric field anomalies caused by magnetic storms are mainly concentrated at 2.5 - 10 kHz over the full latitude range of 65° S - 65° N. There is a constant electric field anomaly around 4 - 5 kHz, probably due to the constant interference frequency of the device itself. A constant electric field anomaly of 4 - 5 kHz exists at high latitudes in the southern hemisphere, with a tendency to be enhanced in comparison to the constant electric field anomaly at full latitude, and therefore constant disturbances are mainly present in the southern hemisphere, and the northern hemisphere is undisturbed. The electric field anomalies caused by high-latitude magnetic storms in the southern hemisphere are mainly concentrated at 3 – 10 kHz, with the strongest anomalies occurring around 6 kHz, and the maximum discrepancy reaches 4.54 \left(\frac{mV}{m/Hz^2}\right)^2. Although electric field anomalies are also enhanced at middle and low latitudes under the influence of magnetic storms, they are very weak and non-significant in the middle and low latitude regions compared to those at high latitudes in the northern and southern hemispheres. The electric field anomalies in the northern hemisphere are concentrated at 6-15kHz, with a maximum anomaly frequency around 9 kHz and a maximum discrepancy of 1.94 \left(\frac{mV}{m/Hz^2}\right)^2, which is less affected than higher latitudes in the southern hemisphere. The anomaly bands in the northern and southern hemispheres roughly overlap, so the anomalies caused by strong magnetic storms for the VLF band are mainly in the band 3 - 15 kHz. By analyzing the electric field anomalies at all latitudes, as well as in the equatorial regions of high and middle-low latitudes in the northern and southern hemispheres, the anomalies in the VLF frequency band have a smaller and diminishing effect above 18 kHz, and for the southern hemisphere the frequency of the affected frequency bands is lower than that for the northern hemisphere as a whole.

In the HF band, compared with the electric field anomalies in the ULF, ELF, VLF bands, the effects caused by magnetic storms in the HF band are almost negligible, with the maximum discrepancy basically below 0.52 \left(\frac{mV}{m/Hz^2}\right)^2. Comparison of the electric field anomalies in different regions of HF itself shows a
constant frequency interference around 1.88 MHz, which is strongest in the equatorial regions of the middle and lower latitudes, and weakest at high latitudes in the northern hemisphere. Combined with the conclusions in the VLF band, the effects of magnetic storms are progressively weaker above 18 kHz, and almost negligible up to the HF band.

In summary, the main frequency bands affected by magnetic storms are ULF, ELF and VLF bands, of which ELF and VLF bands have the strongest influence, especially at high latitudes in the southern hemisphere, and the frequency point with the greatest influence in the ULF band is 3.4 Hz, which is smaller than the frequency of the Schumann wave and is in the range of the frequency of the geomagnetic pulsation (the frequency of the geomagnetic pulsation, Pc1 - Pc5, is 0.2 – 5 Hz).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Frequency points and bands statistics of significant anomalies</th>
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<td><strong>Parameters</strong></td>
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<td>ULF</td>
<td>Anomalous Points/Bands</td>
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<td></td>
<td>Greatest D (([mV/m/Hz]^2))^2)</td>
</tr>
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4. Discussion
4.1 Analysis of relative changes

Figure 3 illustrates the relative change in the D value of the four frequency bands of the 1 to 7 November 2021 magnetic storms. It can be seen that the band with the largest relative change is the ULF band, which is generally above 0.2. The largest relative variations are found at the two Schumann wave frequencies and below 5 Hz. The band with the smallest relative change is the HF band, which is basically below 0.05. The ELF and VLF bands have the same relative change magnitude, which is around 0.1. Therefore, magnetic storms have the most drastic effect on the ULF band, and the effect is negligible in the HF band.

Figure 4 shows the relative difference curves corresponding to the tracks with the largest anomalies in the four frequency bands. The overall trend of the difference curves in the ULF band is decreasing, with an increase at the two Schumann wave frequencies, and the decreasing trend is weakened at 3.4 Hz. The relative difference is larger than 0.2 when it is lower than 15 Hz and larger than 0.1 when it is larger than 15 Hz and smaller than 20 Hz. In the ELF band, the relative difference stays around 0.09. In the VLF band, the relative variance tends to increase and then decrease. There is an extreme value around 6 kHz, at which the relative variability reaches 0.12. In the HF band, the relative variability is less than 0.015, with extreme values of 0.01 at 1.88 MHz and 2.5 MHz.

Figure 2 Relative change in the degree of variability of the four frequency bands of the magnetic storm on 4 November 2021. a) Dst values, b) ULF, c) ELF band, d) VLF, e) HF
4.2 Comparison of the three components of the electric field $E_x$, $E_y$ and $E_z$

Figure 5 illustrates the comparison of the electric field three-component for the 22°S-65°S and 22°N-65°N anomalous maximal orbit quadrature bands. Since the ELF and VLF bands have more signal outliers with background noise removed, the MAD method is used to remove the outlier anomalies before smoothing the signal with the sliding average method.

As can be seen from the figure, the trends of the curves of different electric field components $E_x$, $E_y$ and $E_z$ are the same basically, and only the magnitude of the energy amplitude is slightly different. In the southern hemisphere, the largest energy amplitude component in the ULF band is $E_y$, with a maximum value of 2. It is basically in the range of 1.5 - 2. The largest electric field component in the ELF band is $E_y$, and the energy amplitudes of the three components are basically in the range of 0 - 0.6, with an extreme value of 1.5 kHz. The maximum electric field component in the HF band is $E_y$, and the energy amplitudes are all below 0.2. There are extreme values around 1.88 MHz and 2.5 MHz.

The energy amplitude in the northern hemisphere is overall higher than that in the southern hemisphere. In the northern hemisphere, the ULF band has the largest electric field component, $E_z$, with a maximum magnitude of 2.5, and the overall magnitude is in the range of 1.5 - 2.5. The ELF band has the largest electric field component, $E_z$, with an overall magnitude of about 1.5, and the VLF band has the largest electric field component, $E_z$, with a maximum magnitude of 2, and there is an extreme value at about 9kHz.

Combining the three-component curves of the electric field in the ULF band for the Southern Hemisphere and the Northern Hemisphere, both are found to have an extreme value of around 3.4 Hz.
4.3 ULF anomaly point

To find out the most significant anomalies of magnetic storms in the ULF band and to generalize this frequency, we select three magnetic storms with Dst < -100 nT in the months of November 2021, February 2023, and November 2023 as the orbit of the Dst minimum, drawing the curve of D value of 22° - 65° in northern and southern hemispheres. The horizontal axis is the frequency and the vertical axis is the D value. Figure 2 shows that the three strong magnetic storms at 3.4 Hz, around 8 Hz, and around 13 Hz all have great values in the southern hemisphere. In the northern hemisphere, there are great values at 3.4 Hz and 13 Hz, but the great value at 8 Hz is not obvious. Ruling out the influence of the Schumann waves, it can be concluded that 3.4 Hz is the most significant frequency point for the effect of magnetic storms in the ULF band.

**Figure 4** Three-component comparison of the anomalous maximal orbital quad band on 4 November 2021. a) ULF, b) ELF, c) VLF, d) HF

**Figure 5** The curve of the D value of the orbit where the Dst minimum. a) 22°S -
65°S, b) 22°N - 65°N. The black dotted line shows the location of the most anomalous frequency point 3.4 Hz.

4.4 Wavelet Coherence (WTC) analysis

Figure 6 shows that among the frequency points 3.4 Hz, 7.8 Hz, 9.8 Hz and 13.6 Hz, the highest correlation with Dst is at the frequency point of 3.4 Hz. In all four frequency sequences, the wavelet coherent high-energy region occurs around November 4, with a total of periods around 4 and 8. The frequency sequence at 3.4 Hz has a strong wavelet coherence spectrum at a common period of about 20, although the other three frequencies also show up at a common period of 20, but do not reach the significance level. In the future the 3.4 Hz electric field power spectrum sequence may become a new indicator for recording magnetic storms.
Figure 6 Wavelet coherence spectra of Dst with different frequency points in the high latitudes of the northern and southern hemispheres

5. Conclusion

Through the analysis in this paper, we find that magnetic storms have a significant effect on ULF, ELF, and VLF bands, and a negligible effect on HF bands, and that the electric field anomalies caused by magnetic storms are mainly below 18 kHz, and the effect is weak and decreases gradually to negligible beyond 18 kHz. In the ULF band, Schumann waves affect different frequencies in different hemispheres, mainly 7 - 8 Hz Schumann waves in the southern hemisphere and 13 - 14 Hz Schumann waves in the northern hemisphere, and magnetic storms enhance the influence of Schumann waves. Excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, and the frequency point with the greatest influence is 3.4 Hz. In the ELF band, the impact of magnetic storms in the southern hemisphere is larger than that in the northern hemisphere, and the electric field anomalies in the southern hemisphere are mainly concentrated in the range of 300 Hz - 900 Hz and above 1.8 kHz, with the anomalies at about 780 Hz being the most significant in the 300 Hz – 900 Hz band. In the VLF band, the impact of magnetic storms in the southern hemisphere is also larger than that in the northern hemisphere, and the electric field anomalies are mainly concentrated in the range of 2.5 - 10 kHz, and the impacts are smaller and diminishing in the range of 18 kHz and above. Magnetic storms are weaker at low and middle latitudes for the ELF and VLF bands, and more pronounced for the ULF band. The timing of the maximum electric field anomaly is not consistent for different hemispheres. During the main phase of the magnetic storm, the absolute magnitude of changes in the ELF and VLF bands is greater than that in the ULF band, but the relative magnitude of changes in the ULF band is greater than that in the ELF and VLF bands.

Acknowledgments

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Multiple-band electric field responding to the geomagnetic storm on 4 November 2021

Jie Zheng\textsuperscript{1,2}, Jianping Huang\textsuperscript{2*}, Zhong Li\textsuperscript{3}, Wenjing Li\textsuperscript{2}, Ying Han\textsuperscript{3}, Hengxin Lu\textsuperscript{2}

\textsuperscript{1}University of Chinese Academy of Sciences, Beijing 101408, China.
\textsuperscript{2}National Institute of Natural Hazards, Ministry of Emergency Management of China, Beijing 100085, China.
\textsuperscript{3}Institute of Intelligent Emergency Information Processing, Institute of Disaster Prevention, Langfang 065201, China.
\*Corresponding author (email: jianpinghuang@ninhm.ac.cn)

Keypoints:
\begin{itemize}
  \item Presentation of the electric field response of the 4 November 2021 strong magnetic storm to different frequency bands
  \item The frequencies and bands most affected by magnetic storms were found
  \item A significant anomaly at 3.4 Hz in the ULF band was demonstrated during the magnetic storms.
\end{itemize}

Abstract In this paper, based on the electric field data (EFD) of the China Seismo-Electromagnetic Satellite (CSES), which is divided into 4 frequency bands (ULF, ELF, VLF, HF) from DC to 3.5 MHz, we study the impact characteristics of the 4 November 2021 magnetic storm activity in different frequency bands. It was found that the electric field anomalies caused by magnetic storms were mainly concentrated below 18 kHz, and above 18 kHz the effects were weak and gradually diminished to negligible. In the ULF band, excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, with the most influential frequency point being 3.4 Hz. In the ELF band, the more obvious anomalies appear at 300 Hz – 900 Hz and above 1.8 kHz, with the most significant anomalies in the 300 Hz – 900 Hz band around 780 Hz. In the VLF band, electric field anomalies are concentrated in 2.5 - 10 kHz. Magnetic storms had essentially no effect on the HF band. Magnetic storms at low and middle latitudes have a weak effect on the ELF and VLF bands and are more pronounced in the ULF band. During the main phase of the magnetic storm, the absolute magnitude of variance change in the ELF and VLF bands is greater than that in the ULF band as a whole, but the relative magnitude of variance change in the ULF band is 10% greater than that in the ELF and VLF bands.

Plain Language Summary
In this paper, the anomalous frequency points and bands affected by strong magnetic storms are found by using CSES-1 satellite data, using methods such as satellite data processing and wavelet coherence. we find that magnetic storms have a significant effect on ULF, ELF, and VLF bands, and a negligible effect on HF bands, and that the
Electric field anomalies caused by magnetic storms are mainly below 18 kHz, and the effect is weak and decreases gradually to negligible beyond 18 kHz. In the ULF band, Schumann waves affect different frequencies in different hemispheres, mainly 7 - 8 Hz Schumann waves in the southern hemisphere and 13 - 14 Hz Schumann waves in the northern hemisphere, and magnetic storms enhance the influence of Schumann waves. Excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, and the frequency point with the greatest influence is 3.4 Hz.

1. Introduction

Magnetic storms, also known as solar storms or magnetic storms, are phenomena in which energetic particles and magnetic fields in the solar wind interact with the Earth's magnetic field. Such interactions can lead to violent disturbances of the magnetic field in the Earth's magnetosphere, causing sharp changes in the Earth's magnetic field (Blagoveshchenskii, 2013a; Piddington, 1964). Geomagnetic storms are usually caused by interplanetary disturbances and are accompanied by a long-duration southward interplanetary magnetic field. These events release large amounts of energy and charged particles, which are propagated through space by the solar wind (Gonzalez et al., 1994, 2007; Zong et al., 2010). When these charged particles interact with the Earth's magnetic field, they can trigger a complex set of phenomena. In extreme cases, magnetic storms can have serious effects on the Earth's communication systems, navigation systems, etc. (G. S. Lakhina et al., 2012; Gurbax S. Lakhina & Tsurutani, 2016; Rama Rao et al., 2009; Roodman, 2015). In addition to this, geomagnetically induced currents caused by magnetic storms can cause abnormalities in transportation, and in the operation of signaling, centralization, and blocking systems of the power system (Eroshenko et al., 2010; Lanzerotti, 2017; Pulkkinen et al., 2017). If we can find the specific frequency points and frequency bands affected by magnetic storms, it will not only be helpful for the in-depth study of magnetic storms, but also be of great significance for the anti-jamming design of spacecraft and communication equipment.

The data used to study magnetic storms studied mainly include interplanetary characterization data (Tripathi & Mishra, 2006, 2006; Yermolaev et al., 2010), ionospheric magnetospheric data, and geomagnetic disturbance indices. However, interplanetary signature data or geomagnetic disturbance indices do not identify specific frequency points and bands affected by magnetic storms, and it is the use of electric and magnetic field data that allows for an in-depth study of this topic.

The use of satellite electric and magnetic field data to study the frequency points with large perturbations caused by anomalous space phenomena has been partially investigated by previous researchers. In 2002, (Witasse & Zender, n.d.) analyzed electric field data in the frequency range of 10 Hz to 300 Hz during magnetic storms, including the Schumann resonance frequency, and concluded that the peaks of the perturbation signals were concentrated in the range of 10 to 200 HZ. (Parkhomov et al., 2017) observed short bursts of geomagnetic pulsations in the frequency range of 0.2 to 5 Hz during magnetic storms, with a global maximum at a frequency of 2.78 ± 0.38 Hz. Although a preliminary range of anomalous frequencies is available in the ULF band,
the most significant specific frequencies for the effects of magnetic storms have not been found so far.

In the ULF band, the discussion of Pc waves accounts for an important part of the study of ULF waves. As early as 1993, (Fraser-Smith, 1993) conducted electromagnetic monitoring of ULF waves and found that ELF/VLF waves are much less affected than ULF when a magnetic storm is approaching. It has been demonstrated that the response of ULF waves during magnetic storms is closely related to geomagnetic activity and solar parameters (Ahmad et al., 2015). ULF wave power is linearly correlated with the absolute value of the SYM-H index during the main phase of the storm and exponentially correlated with the absolute value of the SYM-H index during the recovery phase (Li et al., 2023). The intensity of geomagnetic pulsations with a frequency of 27 mHz during the initial phase of the magnetic storm is maximum in the morning and night segments at polar and auroral latitudes, respectively. Daytime Pc5 wave pulsations are strongest during the main phase of the magnetic storm, not the recovery phase as previously thought (Kozyreva & Kleimenova, 2008, 2009). Different interplanetary sources cause different pulsation strengths. The higher latitude position of the Pc5 pulsation intensity maximum in CIR storms points to larger dimensions of the daytime magnetosphere during CIR storms as compared to CME storms. (Kozyreva & Kleimenova, 2010). In the ELF and VLF bands, (Tatsuta et al., 2015) Based on two years of nightly data from the VLF/LF observation network in Japan, it was found that high latitudes are less affected by geomagnetic activity and mid-latitude and low-mid-latitude paths are less affected by geomagnetic activity. During the strong magnetic storm from 8 to 10 November 2004, intense electromagnetic harmonic emissions between 500 and 2000 Hz were detected at midlatitudes, and similar emissions were also observed on 21–22 January 2005 and on 15 May 2005 during two magnetic storms of lower intensity (Parrot et al., 2006). (Pinto & Gonzalez, 1989) suggests that the enhancement of these waves during geomagnetic storms and substorms is characterized by a peak at 550 Hz and that their intensity is very dependent on magnetic activity. (Zhima et al., 2014, 2021) by studying the ELF/VLF waves, it was found that very low-frequency waves below 3 kHz were significantly enhanced throughout the magnetic storm, whereas high-frequency waves above 3 kHz were significantly enhanced in the later part of the main phase and the earlier part of the recovery phase.

In the study on the HF band, (Blagoveshchenskii, 2013b) analyzes the manifestation of the so-called main ionospheric effect in the propagation properties of ten-meter waves during geomagnetic storms. Specifically, these parameters increase before the disturbance active phase, decrease during the active phase, and increase again after this phase. Since the response of magnetic storms in the HF band is not as good as that of ULF/ELF/VLF, fewer studies have been conducted on magnetic storms using the HF band.

Even though there is a consensus that magnetic storms affect different frequency points and bands differently, there are no conclusions on the detailed frequency points and bands. In this paper, we will use the EFD spectrum data from the CSES-1 to study the spectral characteristics of the frequency points and bands of the strong perturbation
in different regions during the magnetic storm activity (Dst<-100nT) of 4 November 2021, which will fill in the gaps of research in this area.

2. Data and Method

The main scientific objective of the CSES-1 is to monitor ionospheric perturbations associated with natural hazards in the quest for possible anomaly forecasting (Zhima et al., 2021). The CSES-1 completes 15.2 orbits around Earth per day, with an orbital period of ~94.6 min and a five-day recursive period over the same geographic area with the ascending/descending node local time of 02 a.m./02 p.m., respectively. Eight payloads are assembled on CSES-1, that is, high-precision magnetometer (HPM), search coil magnetometer (SCM), electric field detector (EFD), Langmuir probe (LA), plasma analyzer (PAP), high-energy particle detector (HEPD), GNSS occultation receiver (GOR), and tri-band beacon (TBB). The entire star is capable of acquiring 17.6 hours of scientific exploration data per day and has the capability of continuous exploration within the latitude of 65° north and south at all hours of the day (Yuan et al., 2018). The electric field is detected by an electric field detector (EFD), which consists of four spherical sensors mounted at the near-end part of four booms (4.5 m long), measuring the electric field in four frequency channels: ULF (DC to 16 Hz), ELF (from 6 Hz to 2.2 kHz), VLF (1.8 to 20 kHz), and HF (from 18 kHz to 3.5 MHz), with sampling rates of 128 Hz, 5 kHz, 50 kHz, and 10 MHz, respectively.

In this paper, satellite electric field data and Dst data are used to study the abnormal frequency points and bands, where the electric field data are from CSES-1 ([https://www.leos.ac.cn/](https://www.leos.ac.cn/)) and the Dst data are from the website ([https://wdc.kugi.kyoto-u.ac.jp/index.html](https://wdc.kugi.kyoto-u.ac.jp/index.html)).

2.1 Satellite data processing

We use the average degree of difference between electric field data and the background field data during magnetic storms which call D value as a criterion for determining the magnitude of the effect of magnetic storms. The background field data is set to be a revisited orbit in a quiet period within one month before the current orbit. The power spectrum of the satellite electric field with background noise removed for the selected latitude width is

\[ P = |P_n^{(storm)} - P_n^{(background)}| \]

The average degree of difference of frequency point j is

\[ D_j = \frac{\sum_{i=1}^{n} P_{ij}^2}{n} \]

The relative degree of variation is

\[ r_j = \frac{D_j}{D_{background}} \]

n is the selected latitude width. \( P_n \) is the satellite electric field power spectrum for the selected latitude width.
2.2 Wavelet Coherence (WTC) analysis

This work uses wavelet coherence (WTC) to analyze the correlation between electric field power sequences and Dst values at different frequency points. Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT) are the two types of WT. Because of its appropriate time and frequency localization, the Morlet wavelet (dimensionless frequency, \( \omega_0 = 6 \)) is an ideal option for extracting features (Grinsted et al., 2004). The WTC spectrum quantifies the degree to which two-time series co-vary as a function of time and frequency. The XWT spectrum exposes large shared power areas and relative phases between two-time series in time frequency space (Giri et al., 2023; Xiang et al., 2019). The XWT of two-time series \( X(t) \) and \( Y(t) \) is defined as:

\[
W_{tX}^{XY}(s) = W_{tX}(s)W_{tY}^{*}(s)
\]

The CWT coefficients of sequences \( X(t) \) and \( Y(t) \) at frequency scale \( s \) are denoted by \( W_{tX}(s) \), and \( W_{tY}^{*}(s) \) respectively and \( * \) denotes the complex conjugate.

The square of the wavelet coherence factor is defined as

\[
R_t^2(s) = \frac{|S[s^{-1}W_{tX}^{XY}(s)]|^2}{S[s^{-1}W_{tX}^X(s)][s^{-1}W_{tY}^Y(s)]}
\]

S is the smoothing operator, \( s \) is the scale. WTC values around 1 indicate a higher degree of resemblance across time series, whilst coherence values near 0 indicate no correlation.

This paper focuses on the analysis of the magnetic storm on January 4, 2021, and the data from three days before and three days after the occurrence of this magnetic storm were selected to observe the initial phase, the main phase, and the restoration phase of the magnetic storm. Drawing the geomagnetic latitude of 65°N - 65°S, 22°N - 22°S regions of D value spectrograms, comparative analysis shows the magnitude of the effect of magnetic storms on different frequency bands different hemispheres. Because the electric field triplicates Ex, Ey, and Ez removed background noise have more outliers, we can use the median absolute difference (MAD) method to remove the anomaly outliers. Then use the sliding averages method (Smith, 2003) to smooth the signal, which can reduce random noise and maintain the trend of the original signal at the same time. Finally, WTC is used to look at the correlation between the electric field power spectra and the Dst values at different frequency points to find the frequency points that have the highest correlation with magnetic storms.

3. Observations

3.1 ULF band’ D value analysis

Figure 1 shows the Dst values, the ULF band spectra (with background noise removed), and the average degree of different (D value) hemispheric and latitudinal
sub-bands from 1 November 2021 to 7 November 2021. It can be seen that the Dst index decreases sharply on 4 days in the presence of magnetic storms, and the spectrum of the ULF band as well as the D value also shows significant changes. (Sanfui et al., 2016) gave the conclusion that the maximum values of the SR mode frequencies of the first, second, and third orders of the Schumann resonance are 8.51 Hz, 14.71 Hz, and 21.22 Hz, respectively, and the presence of constant perturbed Schumann waves is also clearly seen in this case. For the total region of 65°N - 65°S, Schumann waves around 8 Hz and 13 Hz are present at a constant level and are significantly intensified by magnetic storms, with the intensification of the Schumann waves at 13 Hz more than that at 8 Hz. The enhancement of Schumann waves at 13 Hz is more significant than at 8 Hz. The occurrence of magnetic storms greatly affects the whole frequency band of ULF. For the southern hemisphere 22°S - 65°S, 8 Hz Schumann waves exist stably, and 13 Hz Schumann waves have no effect in the southern hemisphere, while the effect of magnetic storms on the ULF band in the southern hemisphere is more pronounced around 3 Hz, and also in the range 15 - 20 Hz, but has little effect in the 6 – 13 Hz frequency range. In the middle and low latitudes of 22°N - 22°S, the Schumann waves of 8 Hz and 13 Hz existed steadily and strengthened significantly during the onset of the storms. The strongest impact of the storms on this region was centered in the frequency range of 6 - 13 Hz. In the northern hemisphere 22°N - 65°N, the main Schumann wave is 13 Hz, which is slightly strengthened at the onset of the storm. However, in this hemisphere, the main impact of the storm is in the frequency band below 7 Hz and is concentrated at about 3 Hz. In addition, the time of the most significant effect of the magnetic storm on the northern and southern hemispheres was not the same, and the northern hemisphere was affected before the southern hemisphere in this magnetic storm.

Since the regions affected by magnetic storms are concentrated at the poles and high latitudes, the manifested electric fields from interplanetary origin can instantaneously penetrate to equatorial and low latitudes (Lissa et al., 2020) and particle movement, etc. In addition to this, the middle and low latitudes are subject to interference from Schumann waves and human communication equipment. Therefore, the frequency band anomalies at high latitudes are more representative of the electric field anomalies caused by magnetic storms. The analysis of the D value by subregion leads to the conclusion that magnetic storms affect the entire frequency band of the ULF band, with the most significant frequency point of the anomaly located around 3 Hz.

Combining the anomaly changes in each latitude band, it can be seen that the discrepancy degree becomes more than 1 at the beginning of a magnetic storm. Therefore, the ULF band discrepancy degree greater than 1 can be used as a sign of the beginning of a magnetic storm, which may become a new predictor of magnetic storms in the future.
3.2 Full bands’ quantitative analysis of D value

Table 1 summarizes the magnitude of the anomaly differences in the frequency bands and frequency points of significant anomalies in the satellite-observed electric field during the occurrence of magnetic storms. It can be seen that the effect of magnetic storms in the ULF band is below 5 Hz for both the Southern Hemisphere and Northern Hemisphere high latitudes, with a consistent significant anomaly frequency of 3.4 Hz. This is consistent with Parkhomov et al., (2017) observation of the 0.2 to 5 Hz frequency range during magnetic storm outbursts, which has a global maximum at a frequency of 2.78 ± 0.38 Hz. For middle and low latitudes, the anomalous difference in the electric field caused by Schumann waves on satellite observations during quiet periods averages at $2[mV/m/(Hz^{1/2})]^2$ or so, but during magnetic storms the maximum D value reaches $3.4[mV/m/(Hz^{1/2})]^2$, demonstrating that magnetic storms also have an enhancement effect on Schumann waves.

In the ELF band, the full-band impact is enhanced at the minimum Dst value over the full latitude range of 65° S - 65° N. More pronounced anomalies appear below 300 Hz, along with significant anomalies at 780 Hz, 1.5 kHz, and other frequency points. Comparison of the northern and southern hemispheres at high and mid-low latitudes reveals a clear difference in the anomalous enhancement of the electric field. The effects of magnetic storms in the ELF band are concentrated in the high latitudes of the Southern Hemisphere, while they have less impact in the high and middle-low latitudes of the Northern Hemisphere. The strongest electric field anomalies in the northern hemisphere do not occur at the same time, and the southern hemisphere electric field anomalies are mainly concentrated in the range of 300 Hz – 900 Hz and above 1.8 kHz, with a maximum D value of $4[mV/m/(Hz^{1/2})]^2$ above.
suggesting that magnetic storms have a greater effect at high latitudes in the southern hemisphere, where the most significant anomalies are around 780 Hz in the band 300 Hz - 900 Hz. (Zhang et al., 2022) used satellite electric field data at 225 Hz, 725 Hz, 1125 Hz, 5000 Hz, 7500 Hz and 13500 Hz in his study of the electric field anomalies, and the results showed that the electric field anomalies were most pronounced at 725 Hz, which is in agreement with the conclusions of the analysis. The electric field anomalies in the middle and low latitudes are concentrated below 300 Hz, while there are no obvious anomalies in the higher frequency bands, and it can be assumed that the equatorial ionospheric anomalies caused by the penetration of the electric field from high latitudes to low latitudes are mainly concentrated at about 0 – 300 Hz. The effects of the ELF band on the northern hemisphere's high latitudes by the present storm are not obvious compared with those in the southern hemisphere's high latitudes.

In the VLF band, the electric field anomalies caused by magnetic storms are mainly concentrated at 2.5 - 10 kHz over the full latitude range of 65° S - 65° N. There is a constant electric field anomaly around 4 - 5 kHz, probably due to the constant interference frequency of the device itself. A constant electric field anomaly of 4 - 5 kHz exists at high latitudes in the southern hemisphere, with a tendency to be enhanced in comparison to the constant electric field anomaly at full latitude, and therefore constant disturbances are mainly present in the southern hemisphere, and the northern hemisphere is undisturbed. The electric field anomalies caused by high-latitude magnetic storms in the southern hemisphere are mainly concentrated at 3 – 10 kHz, with the strongest anomalies occurring around 6 kHz, and the maximum discrepancy reaches 4.54\(\frac{mV}{m/Hz^2}\). Although electric field anomalies are also enhanced at middle and low latitudes under the influence of magnetic storms, they are very weak and non-significant in the middle and low latitude regions compared to those at high latitudes in the northern and southern hemispheres. The electric field anomalies in the northern hemisphere are concentrated at 6-15kHz, with a maximum anomaly frequency around 9 kHz and a maximum discrepancy of 1.94\(\frac{mV}{m/Hz^2}\), which is less affected than higher latitudes in the southern hemisphere. The anomaly bands in the northern and southern hemispheres roughly overlap, so the anomalies caused by strong magnetic storms for the VLF band are mainly in the band 3 - 15 kHz. By analyzing the electric field anomalies at all latitudes, as well as in the equatorial regions of high and middle-low latitudes in the northern and southern hemispheres, the anomalies in the VLF frequency band have a smaller and diminishing effect above 18 kHz, and for the southern hemisphere the frequency of the affected frequency bands is lower than that for the northern hemisphere as a whole.

In the HF band, compared with the electric field anomalies in the ULF, ELF, VLF bands, the effects caused by magnetic storms in the HF band are almost negligible, with the maximum discrepancy basically below 0.52\(\frac{mV}{m/Hz^2}\). Comparison of the electric field anomalies in different regions of HF itself shows a
constant frequency interference around 1.88 MHz, which is strongest in the equatorial regions of the middle and lower latitudes, and weakest at high latitudes in the northern hemisphere. Combined with the conclusions in the VLF band, the effects of magnetic storms are progressively weaker above 18 kHz, and almost negligible up to the HF band.

In summary, the main frequency bands affected by magnetic storms are ULF, ELF and VLF bands, of which ELF and VLF bands have the strongest influence, especially at high latitudes in the southern hemisphere, and the frequency point with the greatest influence in the ULF band is 3.4 Hz, which is smaller than the frequency of the Schumann wave and is in the range of the frequency of the geomagnetic pulsation (the frequency of the geomagnetic pulsation, Pc1 - Pc5, is 0.2 – 5 Hz).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Frequency points and bands statistics of significant anomalies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>Parameters</td>
</tr>
<tr>
<td>ULF</td>
<td></td>
</tr>
<tr>
<td>Anomalous Points/Bands</td>
<td>0 - 5 Hz</td>
</tr>
<tr>
<td>(3.4 Hz)</td>
<td></td>
</tr>
<tr>
<td>Greatest D</td>
<td>$([mV/m/(Hz^2)]^2)$</td>
</tr>
<tr>
<td>ELF</td>
<td></td>
</tr>
<tr>
<td>Anomalous Points/Bands</td>
<td>300 Hz - 900 Hz</td>
</tr>
<tr>
<td>(Around 780 Hz)</td>
<td>Above 1.8 kHz</td>
</tr>
<tr>
<td>Greatest D</td>
<td>$([mV/m/(Hz^2)]^2)$</td>
</tr>
<tr>
<td>VLF</td>
<td></td>
</tr>
<tr>
<td>Anomalous Points/Bands</td>
<td>3 - 10 kHz</td>
</tr>
<tr>
<td>(Around 6 kHz)</td>
<td>(Around 9 kHz)</td>
</tr>
<tr>
<td>Greatest D</td>
<td>$([mV/m/(Hz^2)]^2)$</td>
</tr>
<tr>
<td>HF</td>
<td></td>
</tr>
<tr>
<td>Anomalous Points/Bands</td>
<td>Around 1.88 MHz</td>
</tr>
<tr>
<td>Greatest D</td>
<td>$([mV/m/(Hz^2)]^2)$</td>
</tr>
</tbody>
</table>

4. Discussion
4.1 Analysis of relative changes

Figure 3 illustrates the relative change in the D value of the four frequency bands of the 1 to 7 November 2021 magnetic storms. It can be seen that the band with the largest relative change is the ULF band, which is generally above 0.2. The largest relative variations are found at the two Schumann wave frequencies and below 5 Hz. The band with the smallest relative change is the HF band, which is basically below 0.05. The ELF and VLF bands have the same relative change magnitude, which is around 0.1. Therefore, magnetic storms have the most drastic effect on the ULF band, and the effect is negligible in the HF band.

Figure 4 shows the relative difference curves corresponding to the tracks with the largest anomalies in the four frequency bands. The overall trend of the difference curves in the ULF band is decreasing, with an increase at the two Schumann wave frequencies, and the decreasing trend is weakened at 3.4 Hz. The relative difference is larger than 0.2 when it is lower than 15 Hz and larger than 0.1 when it is larger than 15 Hz and smaller than 20 Hz. In the ELF band, the relative difference stays around 0.09. In the VLF band, the relative variance tends to increase and then decrease. There is an extreme value around 6 kHz, at which the relative variability reaches 0.12. In the HF band, the relative variability is less than 0.015, with extreme values of 0.01 at 1.88 MHz and 2.5 MHz.

![Figure 2](image)

Figure 2 Relative change in the degree of variability of the four frequency bands of the magnetic storm on 4 November 2021. a) Dst values, b) ULF, c) ELF band, d) VLF, e) HF
Figure 3 Relative discrepancy curves corresponding to the largest orbit of the magnetic storm anomaly on 4 November 2021. a) ULF, b) ELF, c) VLF, d) HF

4.2 Comparison of the three components of the electric field $E_x$, $E_y$ and $E_z$

Figure 5 illustrates the comparison of the electric field three-component for the 22°S-65°S and 22°N-65°N anomalous maximal orbit quadrature bands. Since the ELF and VLF bands have more signal outliers with background noise removed, the MAD method is used to remove the outlier anomalies before smoothing the signal with the sliding average method.

As can be seen from the figure, the trends of the curves of different electric field components $E_x$, $E_y$ and $E_z$ are the same basically, and only the magnitude of the energy amplitude is slightly different. In the southern hemisphere, the largest energy amplitude component in the ULF band is $E_y$, with a maximum value of 2. It is basically in the range of 1.5 - 2. The largest electric field component in the ELF band is $E_y$, and the energy amplitudes of the three components are basically in the range of 0 - 0.6, with an extreme value of 1.5 kHz. The maximum electric field component in the HF band is $E_y$, and the energy amplitudes are all below 0.2. There are extreme values around 1.88 MHz and 2.5 MHz.

The energy amplitude in the northern hemisphere is overall higher than that in the southern hemisphere. In the northern hemisphere, the ULF band has the largest electric field component, $E_z$, with a maximum magnitude of 2.5, and the overall magnitude is in the range of 1.5 - 2.5. The ELF band has the largest electric field component, $E_z$, with an overall magnitude of about 1.5, and the VLF band has the largest electric field component, $E_z$, with a maximum magnitude of 2, and there is an extreme value at about 9 kHz.

Combining the three-component curves of the electric field in the ULF band for the Southern Hemisphere and the Northern Hemisphere, both are found to have an extreme value of around 3.4 Hz.
4.3 ULF anomaly point

To find out the most significant anomalies of magnetic storms in the ULF band and to generalize this frequency, we select three magnetic storms with Dst < -100 nT in the months of November 2021, February 2023, and November 2023 as the orbit of the Dst minimum, drawing the curve of D value of 22° - 65° in northern and southern hemispheres. The horizontal axis is the frequency and the vertical axis is the D value. Figure 2 shows that the three strong magnetic storms at 3.4 Hz, around 8 Hz, and around 13 Hz all have great values in the southern hemisphere. In the northern hemisphere, there are great values at 3.4 Hz and 13 Hz, but the great value at 8 Hz is not obvious. Ruling out the influence of the Schumann waves, it can be concluded that 3.4 Hz is the most significant frequency point for the effect of magnetic storms in the ULF band.

Figure 4 Three-component comparison of the anomalous maximal orbital quad band on 4 November 2021. a) ULF, b) ELF, c) VLF, d) HF

Figure 5 The curve of the D value of the orbit where the Dst minimum. a) 22°S -
65°S, b) 22°N - 65°N. The black dotted line shows the location of the most anomalous frequency point 3.4 Hz.

4.4 Wavelet Coherence (WTC) analysis

Figure 6 shows that among the frequency points 3.4 Hz, 7.8 Hz, 9.8 Hz and 13.6 Hz, the highest correlation with Dst is at the frequency point of 3.4 Hz. In all four frequency sequences, the wavelet coherent high-energy region occurs around November 4, with a total of periods around 4 and 8. The frequency sequence at 3.4 Hz has a strong wavelet coherence spectrum at a common period of about 20, although the other three frequencies also show up at a common period of 20, but do not reach the significance level. In the future the 3.4 Hz electric field power spectrum sequence may become a new indicator for recording magnetic storms.
Figure 6 Wavelet coherence spectra of Dst with different frequency points in the high latitudes of the northern and southern hemispheres

5. Conclusion

Through the analysis in this paper, we find that magnetic storms have a significant effect on ULF, ELF, and VLF bands, and a negligible effect on HF bands, and that the electric field anomalies caused by magnetic storms are mainly below 18 kHz, and the effect is weak and decreases gradually to negligible beyond 18 kHz. In the ULF band, Schumann waves affect different frequencies in different hemispheres, mainly 7 - 8 Hz Schumann waves in the southern hemisphere and 13 - 14 Hz Schumann waves in the northern hemisphere, and magnetic storms enhance the influence of Schumann waves. Excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, and the frequency point with the greatest influence is 3.4 Hz. In the ELF band, the impact of magnetic storms in the southern hemisphere is larger than that in the northern hemisphere, and the electric field anomalies in the southern hemisphere are mainly concentrated in the range of 300 Hz - 900 Hz and above 1.8 kHz, with the anomalies at about 780 Hz being the most significant in the 300 Hz – 900 Hz band. In the VLF band, the impact of magnetic storms in the southern hemisphere is also larger than that in the northern hemisphere, and the electric field anomalies are mainly concentrated in the range of 2.5 - 10 kHz, and the impacts are smaller and diminishing in the range of 18 kHz and above. Magnetic storms are weaker at low and middle latitudes for the ELF and VLF bands, and more pronounced for the ULF band. The timing of the maximum electric field anomaly is not consistent for different hemispheres. During the main phase of the magnetic storm, the absolute magnitude of changes in the ELF and VLF bands is greater than that in the ULF band, but the relative magnitude of changes in the ULF band is greater than that in the ELF and VLF bands.

Acknowledgments

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Multiple-band electric field responding to the geomagnetic storm on 4 November 2021

Jie Zheng¹,², Jianping Huang²*, Zhong Li³, Wenjing Li², Ying Han³, Hengxin Lu²

¹University of Chinese Academy of Sciences, Beijing 101408, China.
²National Institute of Natural Hazards, Ministry of Emergency Management of China, Beijing 100085, China.
³Institute of Intelligent Emergency Information Processing, Institute of Disaster Prevention, Langfang 065201, China.
*Corresponding author (email: jianpinghuang@ninhm.ac.cn)

Keypoints:
● Presentation of the electric field response of the 4 November 2021 strong magnetic storm to different frequency bands
● The frequencies and bands most affected by magnetic storms were found
● A significant anomaly at 3.4 Hz in the ULF band was demonstrated during the magnetic storms.

Abstract In this paper, based on the electric field data (EFD) of the China Seismo-Electromagnetic Satellite (CSES), which is divided into 4 frequency bands (ULF, ELF, VLF, HF) from DC to 3.5 MHz, we study the impact characteristics of the 4 November 2021 magnetic storm activity in different frequency bands. It was found that the electric field anomalies caused by magnetic storms were mainly concentrated below 18 kHz, and above 18 kHz the effects were weak and gradually diminished to negligible. In the ULF band, excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, with the most influential frequency point being 3.4 Hz. In the ELF band, the more obvious anomalies appear at 300 Hz – 900 Hz and above 1.8 kHz, with the most significant anomalies in the 300 Hz – 900 Hz band around 780 Hz. In the VLF band, electric field anomalies are concentrated in 2.5 - 10 kHz. Magnetic storms had essentially no effect on the HF band. Magnetic storms at low and middle latitudes have a weak effect on the ELF and VLF bands and are more pronounced in the ULF band. During the main phase of the magnetic storm, the absolute magnitude of variance change in the ELF and VLF bands is greater than that in the ULF band as a whole, but the relative magnitude of variance change in the ULF band is 10% greater than that in the ELF and VLF bands.

Plain Language Summary
In this paper, the anomalous frequency points and bands affected by strong magnetic storms are found by using CSES-1 satellite data, using methods such as satellite data processing and wavelet coherence. We find that magnetic storms have a significant effect on ULF, ELF, and VLF bands, and a negligible effect on HF bands, and that the
electric field anomalies caused by magnetic storms are mainly below 18 kHz, and the effect is weak and decreases gradually to negligible beyond 18 kHz. In the ULF band, Schumann waves affect different frequencies in different hemispheres, mainly 7 - 8 Hz Schumann waves in the southern hemisphere and 13 - 14 Hz Schumann waves in the northern hemisphere, and magnetic storms enhance the influence of Schumann waves. Excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, and the frequency point with the greatest influence is 3.4 Hz.

1. Introduction

Magnetic storms, also known as solar storms or magnetic storms, are phenomena in which energetic particles and magnetic fields in the solar wind interact with the Earth's magnetic field. Such interactions can lead to violent disturbances of the magnetic field in the Earth's magnetosphere, causing sharp changes in the Earth's magnetic field (Blagoveshchenskii, 2013a; Piddington, 1964). Geomagnetic storms are usually caused by interplanetary disturbances and are accompanied by a long-duration southward interplanetary magnetic field. These events release large amounts of energy and charged particles, which are propagated through space by the solar wind (Gonzalez et al., 1994, 2007; Zong et al., 2010). When these charged particles interact with the Earth's magnetic field, they can trigger a complex set of phenomena. In extreme cases, magnetic storms can have serious effects on the Earth's communication systems, navigation systems, etc. (G. S. Lakhina et al., 2012; Gurbax S. Lakhina & Tsurutani, 2016; Rama Rao et al., 2009; Roodman, 2015). In addition to this, geomagnetically induced currents caused by magnetic storms can cause abnormalities in transportation, and in the operation of signaling, centralization, and blocking systems of the power system (Eroshenko et al., 2010; Lanzerotti, 2017; Pulkkinen et al., 2017). If we can find the specific frequency points and frequency bands affected by magnetic storms, it will not only be helpful for the in-depth study of magnetic storms, but also be of great significance for the anti-jamming design of spacecraft and communication equipment.

The data used to study magnetic storms studied mainly include interplanetary characterization data (Tripathi & Mishra, 2006, 2006; Yermolaev et al., 2010), ionospheric magnetospheric data, and geomagnetic disturbance indices. However, interplanetary signature data or geomagnetic disturbance indices do not identify specific frequency points and bands affected by magnetic storms, and it is the use of electric and magnetic field data that allows for an in-depth study of this topic.

The use of satellite electric and magnetic field data to study the frequency points with large perturbations caused by anomalous space phenomena has been partially investigated by previous researchers. In 2002, (Witasse & Zender, n.d.) analyzed electric field data in the frequency range of 10 Hz to 300 Hz during magnetic storms, including the Schumann resonance frequency, and concluded that the peaks of the perturbation signals were concentrated in the range of 10 to 200 HZ. (Parkhomov et al., 2017) observed short bursts of geomagnetic pulsations in the frequency range of 0.2 to 5 Hz during magnetic storms, with a global maximum at a frequency of 2.78 ± 0.38 Hz. Although a preliminary range of anomalous frequencies is available in the ULF band,
the most significant specific frequencies for the effects of magnetic storms have not
been found so far.

In the ULF band, the discussion of Pc waves accounts for an important part of the
study of ULF waves. As early as 1993, (Fraser-Smith, 1993) conducted electromagnetic
monitoring of ULF waves and found that ELF/VLF waves are much less affected than
ULF when a magnetic storm is approaching. It has been demonstrated that the response
of ULF waves during magnetic storms is closely related to geomagnetic activity and
solar parameters (Ahmad et al., 2015). ULF wave power is linearly correlated with the
absolute value of the SYM-H index during the main phase of the storm and
exponentially correlated with the absolute value of the SYM-H index during the
recovery phase (Li et al., 2023). The intensity of geomagnetic pulsations with a
frequency of 27 mHz during the initial phase of the magnetic storm is maximum in the
morning and night segments at polar and auroral latitudes, respectively. Daytime Pc5
wave pulsations are strongest during the main phase of the magnetic storm, not the
recovery phase as previously thought (Kozyreva & Kleimenova, 2008, 2009). Different
interplanetary sources cause different pulsation strengths. the higher latitude position
of the Pc5 pulsation intensity maximum in CIR storms points to larger dimensions of
the daytime magnetosphere during CIR storms as compared to CME storms. (Kozyreva
& Kleimenova, 2010).

In the ELF and VLF bands, (Tatsuta et al., 2015) Based on two years of nightly
data from the VLF/LF observation network in Japan, it was found that high latitudes
are less affected by geomagnetic activity and mid-latitude and low-mid-latitude paths
are less affected by geomagnetic activity. During the strong magnetic storm from 8 to
10 November 2004, intense electromagnetic harmonic emissions between 500 and 2000
Hz were detected at midlatitudes, and similar emissions were also observed on 21–22
January 2005 and on 15 May 2005 during two magnetic storms of lower intensity
(Parrot et al., 2006). (Pinto & Gonzalez, 1989) suggests that the enhancement of these
waves during geomagnetic storms and substorms is characterized by a peak at 550 Hz
and that their intensity is very dependent on magnetic activity. (Zhima et al., 2014, 2021)
by studying the ELF/VLF waves, it was found that very low-frequency waves below 3
kHz were significantly enhanced throughout the magnetic storm, whereas high-
frequency waves above 3 kHz were significantly enhanced in the later part of the main
phase and the earlier part of the recovery phase.

In the study on the HF band, (Blagoveshchenskii, 2013b) analyzes the
manifestation of the so-called main ionospheric effect in the propagation properties of
ten-meter waves during geomagnetic storms. Specifically, these parameters increase
before the disturbance active phase, decrease during the active phase, and increase
again after this phase. Since the response of magnetic storms in the HF band is not as
good as that of ULF/ELF/VLF, fewer studies have been conducted on magnetic storms
using the HF band.

Even though there is a consensus that magnetic storms affect different frequency
points and bands differently, there are no conclusions on the detailed frequency points
and bands. In this paper, we will use the EFD spectrum data from the CSES-1 to study
the spectral characteristics of the frequency points and bands of the strong perturbation
in different regions during the magnetic storm activity (Dst<-100nT) of 4 November 2021, which will fill in the gaps of research in this area.

2. Data and Method

The main scientific objective of the CSES-1 is to monitor ionospheric perturbations associated with natural hazards in the quest for possible anomaly forecasting (Zhima et al., 2021). The CSES-1 completes 15.2 orbits around Earth per day, with an orbital period of ~94.6 min and a five-day recursive period over the same geographic area with the ascending/descending node local time of 02 a.m./02 p.m., respectively. Eight payloads are assembled on CSES-1, that is, high-precision magnetometer (HPM), search coil magnetometer (SCM), electric field detector (EFD), Langmuir probe (LA), plasma analyzer (PAP), high-energy particle detector (HEPD), GNSS occultation receiver (GOR), and tri-band beacon (TBB). The entire star is capable of acquiring 17.6 hours of scientific exploration data per day and has the capability of continuous exploration within the latitude of 65° north and south at all hours of the day (Yuan et al., 2018).

The electric field is detected by an electric field detector (EFD), which consists of four spherical sensors mounted at the near-end part of four booms (4.5 m long), measuring the electric field in four frequency channels: ULF (DC to 16 Hz), ELF (from 6 Hz to 2.2 kHz), VLF (1.8 to 20 kHz), and HF (from 18 kHz to 3.5 MHz), with sampling rates of 128 Hz, 5 kHz, 50 kHz, and 10 MHz, respectively.

In this paper, satellite electric field data and Dst data are used to study the abnormal frequency points and bands, where the electric field data are from CSES-1 (https://www.leos.ac.cn/) and the Dst data are from the website (https://wdc.kugi.kyoto-u.ac.jp/index.html).

2.1 Satellite data processing

We use the average degree of difference between electric field data and the background field data during magnetic storms which call D value as a criterion for determining the magnitude of the effect of magnetic storms. The background field data is set to be a revisited orbit in a quiet period within one month before the current orbit. The power spectrum of the satellite electric field with background noise removed for the selected latitude width is

\[ P = \left| P_{n(\text{storm})} - P_{n(\text{background})} \right| \]

The average degree of difference of frequency point j is

\[ D_j = \frac{\sum_{i=1}^{n} P_{ij}^2}{n} \]

The relative degree of variation is

\[ r_j = \frac{D_j}{D_{\text{background}}} \]

\( n \) is the selected latitude width. \( P_n \) is the satellite electric field power spectrum for the selected latitude width.
2.2 Wavelet Coherence (WTC) analysis

This work uses wavelet coherence (WTC) to analyze the correlation between electric field power sequences and Dst values at different frequency points. Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT) are the two types of WT. Because of its appropriate time and frequency localization, the Morlet wavelet (dimensionless frequency, \( \omega_0 = 6 \)) is an ideal option for extracting features (Grinsted et al., 2004). The WTC spectrum quantifies the degree to which two-time series co-vary as a function of time and frequency. The XWT spectrum exposes large shared power areas and relative phases between two-time series in time frequency space (Giri et al., 2023; Xiang et al., 2019). The XWT of two-time series X(t) and Y(t) is defined as:

\[
W_{t}^{XY}(s) = W_{t}^{X}(s)W_{y}^{*}(s)
\]

The CWT coefficients of sequences X(t) and Y(t) at frequency scale s are denoted by \( W_{t}^{X}(s) \), and \( W_{y}^{*}(s) \) respectively and \( * \) denotes the complex conjugate.

The square of the wavelet coherence factor is defined as

\[
R^{2}(s) = \frac{|S[s^{-1}W_{t}^{XY}(s)]|^{2}}{S[s^{-1}W_{t}^{X}(s)][s^{-1}W_{t}^{Y}(s)]}
\]

S is the smoothing operator, s is the scale. WTC values around 1 indicate a higher degree of resemblance across time series, whilst coherence values near 0 indicate no correlation.

This paper focuses on the analysis of the magnetic storm on January 4, 2021, and the data from three days before and three days after the occurrence of this magnetic storm were selected to observe the initial phase, the main phase, and the restoration phase of the magnetic storm. Drawing the geomagnetic latitude of 65°N - 65°S, 22°N - 65°N, S - 65°S, and 22°N - 22°S regions of D value spectrograms, comparative analysis shows the magnitude of the effect of magnetic storms on different frequency bands different hemispheres. Because the electric field triplicates Ex, Ey, and Ez removed background noise have more outliers, we can use the median absolute difference (MAD) method to remove the anomaly outliers. Then use the sliding averages method (Smith, 2003) to smooth the signal, which can reduce random noise and maintain the trend of the original signal at the same time. Finally, WTC is used to look at the correlation between the electric field power spectra and the Dst values at different frequency points to find the frequency points that have the highest correlation with magnetic storms.

3. Observations

3.1 ULF band’ D value analysis

Figure 1 shows the Dst values, the ULF band spectra (with background noise removed), and the average degree of different (D value) hemispheric and latitudinal
sub-bands from 1 November 2021 to 7 November 2021. It can be seen that the Dst index decreases sharply on 4 days in the presence of magnetic storms, and the spectrum of the ULF band as well as the D value also shows significant changes. (Sanfui et al., 2016) gave the conclusion that the maximum values of the SR mode frequencies of the first, second, and third orders of the Schumann resonance are 8.51 Hz, 14.71 Hz, and 21.22 Hz, respectively, and the presence of constant perturbed Schumann waves is also clearly seen in this case. For the total region of 65°N - 65°S, Schumann waves around 8 Hz and 13 Hz are present at a constant level and are significantly intensified by magnetic storms, with the intensification of the Schumann waves at 13 Hz more than that at 8 Hz. The enhancement of Schumann waves at 13 Hz is more significant than at 8 Hz. The occurrence of magnetic storms greatly affects the whole frequency band of ULF. For the southern hemisphere 22°S - 65°S, 8 Hz Schumann waves exist stably, and 13 Hz Schumann waves have no effect in the southern hemisphere, while the effect of magnetic storms on the ULF band in the southern hemisphere is more pronounced around 3 Hz, and also in the range 15 - 20 Hz, but has little effect in the 6 – 13 Hz frequency range. In the middle and low latitudes of 22°N - 22°S, the Schumann waves of 8 Hz and 13 Hz existed steadily and strengthened significantly during the onset of the storms. The strongest impact of the storms on this region was centered in the frequency range of 6 - 13 Hz. In the northern hemisphere 22°N - 65°N, the main Schumann wave is 13 Hz, which is slightly strengthened at the onset of the storm. However, in this hemisphere, the main impact of the storm is in the frequency band below 7 Hz and is concentrated at about 3 Hz. In addition, the time of the most significant effect of the magnetic storm on the northern and southern hemispheres was not the same, and the northern hemisphere was affected before the southern hemisphere in this magnetic storm.

Since the regions affected by magnetic storms are concentrated at the poles and high latitudes, the manifested electric fields from interplanetary origin can instantaneously penetrate to equatorial and low latitudes (Lissa et al., 2020) and particle movement, etc. In addition to this, the middle and low latitudes are subject to interference from Schumann waves and human communication equipment. Therefore, the frequency band anomalies at high latitudes are more representative of the electric field anomalies caused by magnetic storms. The analysis of the D value by subregion leads to the conclusion that magnetic storms affect the entire frequency band of the ULF band, with the most significant frequency point of the anomaly located around 3 Hz.

Combining the anomaly changes in each latitude band, it can be seen that the discrepancy degree becomes more than 1 at the beginning of a magnetic storm. Therefore, the ULF band discrepancy degree greater than 1 can be used as a sign of the beginning of a magnetic storm, which may become a new predictor of magnetic storms in the future.
Figure 1 7 day’s Dst index, ULF band spectrogram, and sub-band D value map. a) 65°N - 65°S, b) 22°S - 65°S, c) 22°N - 22°S, d) 22°N - 65°N

3.2 Full bands’ quantitative analysis of D value

Table 1 summarizes the magnitude of the anomaly differences in the frequency bands and frequency points of significant anomalies in the satellite-observed electric field during the occurrence of magnetic storms. It can be seen that the effect of magnetic storms in the ULF band is below 5 Hz for both the Southern Hemisphere and Northern Hemisphere high latitudes, with a consistent significant anomaly frequency of 3.4 Hz. This is consistent with (Parkhomov et al., 2017) observation of the 0.2 to 5 Hz frequency range during magnetic storm outbursts, which has a global maximum at a frequency of 2.78 ± 0.38 Hz. For middle and low latitudes, the anomalous difference in the electric field caused by Schumann waves on satellite observations during quiet periods averages at $2[mV/m/Hz^2]^2$ or so, but during magnetic storms the maximum D value reaches $3.4[mV/m/Hz^2]^2$, demonstrating that magnetic storms also have an enhancement effect on Schumann waves.

In the ELF band, the full-band impact is enhanced at the minimum Dst value over the full latitude range of 65° S - 65° N. More pronounced anomalies appear below 300 Hz, along with significant anomalies at 780 Hz, 1.5 kHz, and other frequency points. Comparison of the northern and southern hemispheres at high and mid-low latitudes reveals a clear difference in the anomalous enhancement of the electric field. The effects of magnetic storms in the ELF band are concentrated in the high latitudes of the Southern Hemisphere, while they have less impact in the high and middle-low latitudes of the Northern Hemisphere. The strongest electric field anomalies in the northern hemisphere do not occur at the same time, and the southern hemisphere electric field anomalies are mainly concentrated in the range of 300 Hz – 900 Hz and above 1.8 kHz, with a maximum D value of $4[mV/m/Hz^2]^2$ above.
suggesting that magnetic storms have a greater effect at high latitudes in the southern hemisphere, where the most significant anomalies are around 780 Hz in the band 300 Hz - 900 Hz. (Zhang et al., 2022) used satellite electric field data at 225 Hz, 725 Hz, 1125 Hz, 5000 Hz, 7500 Hz and 13500 Hz in his study of the electric field anomalies, and the results showed that the electric field anomalies were most pronounced at 725 Hz, which is in agreement with the conclusions of the analysis. The electric field anomalies in the middle and low latitudes are concentrated below 300 Hz, while there are no obvious anomalies in the higher frequency bands, and it can be assumed that the equatorial ionospheric anomalies caused by the penetration of the electric field from high latitudes to low latitudes are mainly concentrated at about 0 – 300 Hz. The effects of the ELF band on the northern hemisphere's high latitudes by the present storm are not obvious compared with those in the southern hemisphere's high latitudes.

In the VLF band, the electric field anomalies caused by magnetic storms are mainly concentrated at 2.5 - 10 kHz over the full latitude range of 65° S - 65° N. There is a constant electric field anomaly around 4 - 5 kHz, probably due to the constant interference frequency of the device itself. A constant electric field anomaly of 4 - 5 kHz exists at high latitudes in the southern hemisphere, with a tendency to be enhanced in comparison to the constant electric field anomaly at full latitude, and therefore constant disturbances are mainly present in the southern hemisphere, and the northern hemisphere is undisturbed. The electric field anomalies caused by high-latitude magnetic storms in the southern hemisphere are mainly concentrated at 3 – 10 kHz, with the strongest anomalies occurring around 6 kHz, and the maximum discrepancy reaches \(4.54[\text{mV/m/Hz}^2]\)^2. Although electric field anomalies are also enhanced at middle and low latitudes under the influence of magnetic storms, they are very weak and non-significant in the middle and low latitude regions compared to those at high latitudes in the northern and southern hemispheres. The electric field anomalies in the northern hemisphere are concentrated at 6-15kHz, with a maximum anomaly frequency around 9 kHz and a maximum discrepancy of \(1.94[\text{mV/m/Hz}^2]\)^2, which is less affected than higher latitudes in the southern hemisphere. The anomaly bands in the northern and southern hemispheres roughly overlap, so the anomalies caused by strong magnetic storms for the VLF band are mainly in the band 3 - 15 kHz. By analyzing the electric field anomalies at all latitudes, as well as in the equatorial regions of high and middle-low latitudes in the northern and southern hemispheres, the anomalies in the VLF frequency band have a smaller and diminishing effect above 18 kHz, and for the southern hemisphere the frequency of the affected frequency bands is lower than that for the northern hemisphere as a whole.

In the HF band, compared with the electric field anomalies in the ULF, ELF, VLF bands, the effects caused by magnetic storms in the HF band are almost negligible, with the maximum discrepancy basically below \(0.52[\text{mV/m/Hz}^2]\)^2. Comparison of the electric field anomalies in different regions of HF itself shows a
constant frequency interference around 1.88 MHz, which is strongest in the equatorial regions of the middle and lower latitudes, and weakest at high latitudes in the northern hemisphere. Combined with the conclusions in the VLF band, the effects of magnetic storms are progressively weaker above 18 kHz, and almost negligible up to the HF band.

In summary, the main frequency bands affected by magnetic storms are ULF, ELF and VLF bands, of which ELF and VLF bands have the strongest influence, especially at high latitudes in the southern hemisphere, and the frequency point with the greatest influence in the ULF band is 3.4 Hz, which is smaller than the frequency of the Schumann wave and is in the range of the frequency of the geomagnetic pulsation (the frequency of the geomagnetic pulsation, Pc1 - Pc5, is 0.2 – 5 Hz).

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<th>Table 1 Frequency points and bands statistics of significant anomalies</th>
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4. Discussion
4.1 Analysis of relative changes

Figure 3 illustrates the relative change in the D value of the four frequency bands of the 1 to 7 November 2021 magnetic storms. It can be seen that the band with the largest relative change is the ULF band, which is generally above 0.2. The largest relative variations are found at the two Schumann wave frequencies and below 5 Hz. The band with the smallest relative change is the HF band, which is basically below 0.05. The ELF and VLF bands have the same relative change magnitude, which is around 0.1. Therefore, magnetic storms have the most drastic effect on the ULF band, and the effect is negligible in the HF band.

Figure 4 shows the relative difference curves corresponding to the tracks with the largest anomalies in the four frequency bands. The overall trend of the difference curves in the ULF band is decreasing, with an increase at the two Schumann wave frequencies, and the decreasing trend is weakened at 3.4 Hz. The relative difference is larger than 0.2 when it is lower than 15 Hz and larger than 0.1 when it is larger than 15 Hz and smaller than 20 Hz. In the ELF band, the relative difference stays around 0.09. In the VLF band, the relative variance tends to increase and then decrease. There is an extreme value around 6 kHz, at which the relative variability reaches 0.12. In the HF band, the relative variability is less than 0.015, with extreme values of 0.01 at 1.88 MHz and 2.5 MHz.

Figure 2 Relative change in the degree of variability of the four frequency bands of the magnetic storm on 4 November 2021. a) Dst values, b) ULF, c) ELF band, d) VLF, e) HF
Figure 3 Relative discrepancy curves corresponding to the largest orbit of the magnetic storm anomaly on 4 November 2021. a) ULF, b) ELF, c) VLF, d) HF

4.2 Comparison of the three components of the electric field $E_x$, $E_y$ and $E_z$

Figure 5 illustrates the comparison of the electric field three-component for the $22^\circ$S-65$^\circ$S and $22^\circ$N-65$^\circ$N anomalous maximal orbit quadrature bands. Since the ELF and VLF bands have more signal outliers with background noise removed, the MAD method is used to remove the outlier anomalies before smoothing the signal with the sliding average method.

As can be seen from the figure, the trends of the curves of different electric field components $E_x$, $E_y$ and $E_z$ are the same basically, and only the magnitude of the energy amplitude is slightly different. In the southern hemisphere, the largest energy amplitude component in the ULF band is $E_y$, with a maximum value of 2. It is basically in the range of 1.5 - 2. The largest electric field component in the ELF band is $E_y$, and the energy amplitudes of the three components are basically in the range of 0 - 0.6, with an extreme value of 1.5 kHz. The maximum electric field component in the HF band is $E_y$, and the energy amplitudes are all below 0.2. There are extreme values around 1.88 MHz and 2.5 MHz.

The energy amplitude in the northern hemisphere is overall higher than that in the southern hemisphere. In the northern hemisphere, the ULF band has the largest electric field component, $E_z$, with a maximum magnitude of 2.5, and the overall magnitude is in the range of 1.5 - 2.5. The ELF band has the largest electric field component, $E_z$, with an overall magnitude of about 1.5, and the VLF band has the largest electric field component, $E_z$, with a maximum magnitude of 2, and there is an extreme value at about 9kHz.

Combining the three-component curves of the electric field in the ULF band for the Southern Hemisphere and the Northern Hemisphere, both are found to have an extreme value of around 3.4 Hz.
4.3 ULF anomaly point

To find out the most significant anomalies of magnetic storms in the ULF band and to generalize this frequency, we select three magnetic storms with Dst < -100 nT in the months of November 2021, February 2023, and November 2023 as the orbit of the Dst minimum, drawing the curve of D value of 22° - 65° in northern and southern hemispheres. The horizontal axis is the frequency and the vertical axis is the D value. Figure 2 shows that the three strong magnetic storms at 3.4 Hz, around 8 Hz, and around 13 Hz all have great values in the southern hemisphere. In the northern hemisphere, there are great values at 3.4 Hz and 13 Hz, but the great value at 8 Hz is not obvious. Ruling out the influence of the Schumann waves, it can be concluded that 3.4 Hz is the most significant frequency point for the effect of magnetic storms in the ULF band.
65°S, b) 22°N - 65°N. The black dotted line shows the location of the most anomalous frequency point 3.4 Hz.

4.4 Wavelet Coherence (WTC) analysis

Figure 6 shows that among the frequency points 3.4 Hz, 7.8 Hz, 9.8 Hz and 13.6 Hz, the highest correlation with Dst is at the frequency point of 3.4 Hz. In all four frequency sequences, the wavelet coherent high-energy region occurs around November 4, with a total of periods around 4 and 8. The frequency sequence at 3.4 Hz has a strong wavelet coherence spectrum at a common period of about 20, although the other three frequencies also show up at a common period of 20, but do not reach the significance level. In the future the 3.4 Hz electric field power spectrum sequence may become a new indicator for recording magnetic storms.
5. Conclusion

Through the analysis in this paper, we find that magnetic storms have a significant effect on ULF, ELF, and VLF bands, and a negligible effect on HF bands, and that the electric field anomalies caused by magnetic storms are mainly below 18 kHz, and the effect is weak and decreases gradually to negligible beyond 18 kHz. In the ULF band, Schumann waves affect different frequencies in different hemispheres, mainly 7 - 8 Hz for the southern hemisphere and 13 - 14 Hz for the northern hemisphere, and magnetic storms enhance the influence of Schumann waves. Excluding the influence of Schumann waves, the electric field anomalies caused by magnetic storms are mainly below 5 Hz, and the frequency point with the greatest influence is 3.4 Hz. In the ELF band, the impact of magnetic storms in the southern hemisphere is larger than that in the northern hemisphere, and the electric field anomalies in the southern hemisphere are mainly concentrated in the range of 300 Hz - 900 Hz and above 1.8 kHz, with the anomalies at about 780 Hz being the most significant in the 300 Hz – 900 Hz band. In the VLF band, the impact of magnetic storms in the southern hemisphere is also larger than that in the northern hemisphere, and the electric field anomalies are mainly concentrated in the range of 2.5 - 10 kHz, and the impacts are smaller and diminishing in the range of 18 kHz and above. Magnetic storms are weaker at low and middle latitudes for the ELF and VLF bands, and more pronounced for the ULF band. The timing of the maximum electric field anomaly is not consistent for different hemispheres. During the main phase of the magnetic storm, the absolute magnitude of changes in the ELF and VLF bands is greater than that in the ULF band, but the relative magnitude of changes in the ULF band is greater than that in the ELF and VLF bands.

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