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Analysis of Pc5 magnetic pulsations under the influence of the Equatorial Electrojet (EEJ)

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Abstract Summary

This study presents preliminary results on the influence of the Equatorial Electrojet (EEJ) on continuous Pc5 magnetic pulsations. Geomagnetic data from two stations located near the dip equator (magnetic inclination I=0º) were analyzed to compare pulsation characteristics under the influence of the EEJ. Wavelet transform techniques were applied to evaluate the spectral characteristics and temporal dynamics of the pulsations. The results indicate that pulsation amplitudes and wavelet coefficients are significantly higher at the station located directly beneath the dip equator. These differences are attributed to the enhanced ionospheric conductivity associated with the EEJ in this region.

Introduction

Solar surface phenomena such as coronal mass ejections (CMEs) and solar flares release large quantities of charged particles, forming high-speed solar wind. When directed toward Earth, this solar wind interacts with the earth's magnetic field, transferring plasma energy into the magnetosphere. This energy accumulation can trigger intense geomagnetic disturbances, a space weather process known as a geomagnetic storm.

During periods of geomagnetic disturbances, magnetic pulsations can be generated. Pc5 magnetic pulsations are a specific type of Ultra Low Frequency (ULF) geomagnetic oscillation in Earth's magnetosphere, classified as magnetohydrodynamic (MHD) waves with frequencies ranging from 2 to 7 mHz. Pc5 pulsations in the magnetosphere are primarily attributed to the Kelvin-Helmholtz instability at the magnetopause. They are also associated with solar wind-driven magnetospheric compression, which enhances the magnetopause current and is often linked to Storm Sudden Commencements (SSC) and Sudden Impulses (SI). The analysis of magnetic pulsations provides insight into energy transfer between regions at different latitudes via waveguides and magnetic flux lines, including potential interactions with charged particles in both the ionosphere and the upper magnetospheric regions. This study focuses on Pc5 magnetic pulsations (2–7 mHz) due to their potential to provide insights into the electrodynamic environment and energy transfer between the solar wind and the magnetosphere-ionosphere system (Kamide and Chian, 2007; McPherron, R., 2005; Menk and Waters, 2013).

The Equatorial ElectroJet (EEJ) is a unique geophysical phenomenon characterized by a significant enhancement of the geomagnetic H-component during the daytime, over a narrow band of ±3º–5º latitudes centered on the dip equator (Chapman, 1948). This intense eastward current, driven by the large-scale ionospheric dynamo electric field at E-region altitudes (∼103–105 km), is influenced by the Cowling effect, which significantly enhances ionospheric conductivity (Chapman, 1948; Tulasi R. et al., 2024). The EEJ strongly affects geomagnetic pulsations near the magnetic equator, enhancing signal amplitudes, especially during daytime and magnetic storm (Trivedi et al.,1997, Da Silva et al., 2020). Studying these pulsations provides insights into the EEJ's behavior and its connection to solar wind variations.

The main objective of this study is to perform a comparative spectral analysis of Pc5 magnetic pulsations observed simultaneously at magnetic stations influenced by the Equatorial Electrojet (EEJ) in South America. Horizontal geomagnetic field (H) components were recorded at two equatorial stations. A time-frequency analysis using the continuous wavelet transform (CWT) was applied to highlight the non-linear and nonstationary characteristics of the observed signals.

Geomagnetic data-sets

In this study, we analyze the horizontal component (H) of the geomagnetic field using data from two magnetic stations: Macapá (MAA; 0.038° S, 51.095° W) and Kourou (KOU; 5.210° N, 52.720° W), both located near the magnetic equator. Notably, the MAA station lies beneath the equatorial electrojet (EEJ) region throughout the year 2024. The geomagnetic data from MAA and KOU are provided by GFZ Potsdam (German Research Centre for Geosciences) and INTERMAGNET (International Real-time Magnetic Observatory Network).

The data were sampled at a rate of 1 second at both stations, which is adequate for analyzing Pc5 pulsations. The dataset corresponds to May 2024 and includes measurements collected during the geomagnetic storm that occurred from 10 to 13 May 2024. This event, the most intense of Solar Cycle 25, reached a minimum Dst index of −412 nT and a Kp index of 9.

Method

To extract the Pc5 pulsations, we applied a band-pass filter to the H component of the geomagnetic field. Among the available filtering techniques, an infinite impulse response (IIR) band-pass filter was selected for its superior performance in preserving signal characteristics. spectral analysis was conducted using a time-scale analysis technique based on the continuous wavelet transform (CWT). The wavelet coefficients $\mathcal{W}(a,\tau)$ were computed from the CWT of the Pc5 pulsations, defined by:

$$\mathcal{W}_f^{\psi}(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\, \overline{\psi(\frac{t-\tau}{a})}\, \mathrm{d}t \qquad a > 0\,,$$

where "a" is scale parameter, "τ" denotes the translation (time localization), and Ψ is the analyzing wavelet function. The CWT is a robust mathematical method for time-frequency analysis of both stationary and nonstationary time series.

The Global Wavelet Spectrum (GWS) is a mathematical tool that provides an unbiased and consistent estimation of the true power spectrum of a time-series signal. By using wavelet transforms, the GWS evaluates how the energy (or power) of the signal is distributed across different time scales, offering both temporal and frequency information, we can define the *wavelet power spectrum* as $|\mathcal{W}|^2$.

Results and discussions

Figure 1 shows the Pc5 pulsations (top panels "a" and "b"), the corresponding wavelet scalograms (middle panels "c" and "d"), and plots of the global wavelet spectrum (bottom panels "e" and "f") observed at both stations during the selected period, which includes the initial, main, and recovery phases of a superstorm. The magnetic storm began with a Sudden Storm Commencement (SSC) at 17:05 UTC on May 10.

As observed in the upper panels (a) and (b) of Figure 1, Pc5 pulsations occur simultaneously and exhibit similar patterns at both stations. This similarity may suggest a common generation source. However, the wave packets at the MAA station generally show higher amplitudes compared to those at the KOU station. Notably, the largest pulsations are observed at MAA during the initial and main phases of the magnetic storm.

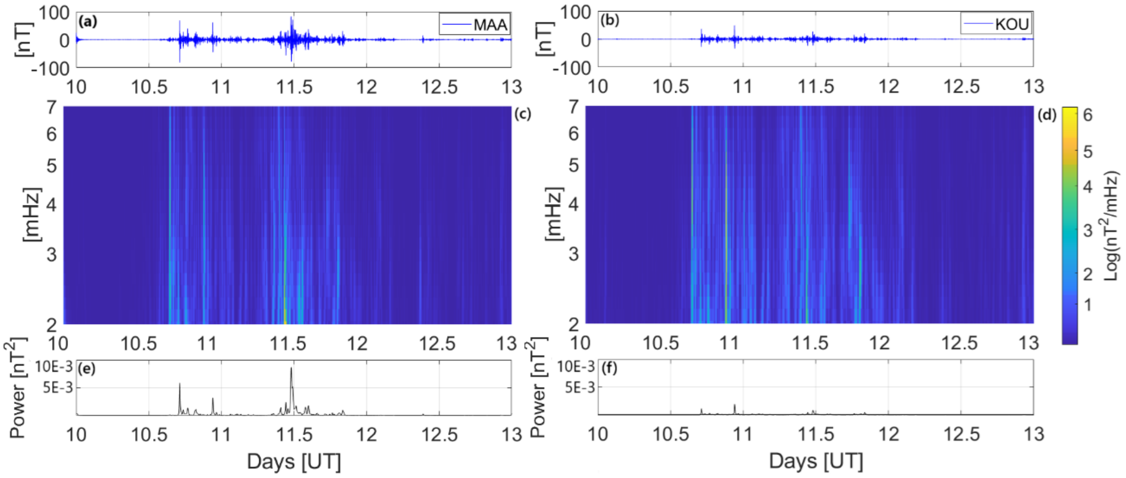

Figure 1: Pc5 pulsations (a-b), squared-wavelet coefficients – scalograms (c-d) and global wavelet spectra (e-f). Data from May, 2024

Figure 1 shows the wavelet scalograms (panels "c" and "d") corresponding to Pc5 pulsations at each station. The horizontal axis represents time (in days), while the vertical axis indicates wavelet scale, expressed in millihertz (mHz). The magnitude of the wavelet coefficients is shown using a color bar with a consistent range (nT^2/mHz) across both stations, allowing for direct comparison.

The maximum values of the wavelet coefficients (indicated by the yellow color) coincide with the most intense Pc5 wave packets observed at each station (panels "c" and "d"). The scalograms showed here emphasize the most prominent Pc5 pulsations observed during the initial and main phases of the magnetic storm. The dominant spectral power is concentrated within the 2–7 mHz frequency range. A clear similarity is evident between the scalograms from the two stations, with wavelet coefficients exhibiting comparable energy distributions in terms of amplitude, duration, and scale. Notably, the wavelet coefficients at the MAA station are more intense, indicating subtle but discernible differences between the two scalograms.

The global wavelet spectra plots (panels "e" and "f") showed several peaks that are similar between the stations, corresponding to the Pc5 pulsation wave packets observed at each location. However, the peak powers at the MAA station are noticeably more intense. Based on the observed energy patterns, scalograms, and global wavelet spectra, we conclude that both the MAA and KOU stations are influenced by similar conditions in the magnetosphere–ionosphere system. Nevertheless, the responses at the MAA station are significantly more intense.

In summary, an enhanced amplitude of Pc5 pulsations is observed at the MAA station compared to the KOU station. This difference suggests a potential influence of the Equatorial Electrojet (EEJ), as MAA is located below the dip equator. The results may be attributed to increased particle precipitation and ionospheric conductivity, likely driven by elevated ionization rates in the E-region of the equatorial ionosphere.

Conclusions

We analyzed Pc5 pulsations using data from magnetic stations to compare their behavior under the influence of the EEJ. The Wavelet transform technique was applied to determine the spectral characteristics of the pulsations. The case study focused on May 10 and 13, 2024, during a geomagnetic superstorm, one of the most intense events of the past two decades. Based on the applied methodology, the following main conclusions were drawn:

1.- Pc5 pulsations occurred simultaneously at both stations and exhibited similar wave structures and durations. However, significantly higher amplitudes were observed at the MAA station, which is located below the EEJ.

2.- Scalograms showed similar energy distribution patterns at both stations; however, the wavelet coefficients were more intense at the MAA station, indicating slight differences in signal characteristics, between stations.

We suggest that the Pc5 pulsations observed in this study were driven by interactions between the solar wind and Earth’s magnetosphere. These pulsations may have propagated to very low latitudes, where they were detected on the ground. The differences between the stations could be due to the unique characteristics of the magnetic equator region, such as the enhanced Cowling conductivity in the E layer of the ionosphere, near the dip equator, induced by the geomagnetic storm.

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