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Research Article

Analysis of coherence areas between conjugate stations affected by the South Atlantic Magnetic Anomaly

Análise de áreas de coerência entre estações conjugadas afetadas pela Anomalia Magnética do Atlântico Sul

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Abstract: The South Atlantic Magnetic Anomaly (SAMA) is a region in the South Atlantic Ocean where the Earth's magnetic field is significantly weaker than in other parts of the world. This anomaly has interested scientists and researchers studying the Earth's magnetic field. The SAMA can affect navigation systems and satellite operations, and it is an important area of study for understanding the dynamics of the Earth's magnetic field. This paper investigates the signal characteristics of conjugate stations influenced by the SAMA in a moderate geomagnetic storm through record analysis of geomagnetically conjugate stations interlinking both hemispheres. This study uses the horizontal magnetic components measured in the same time interval in two typical longitudes: the America-SAMA region and the Asia-Pacific one. This procedure allows us to do a comparative analysis between regions. Our procedure uses the data recorded simultaneously in four conjugate-station pairs to characterize the magnetic variability coherence domain surrounding conjugate stations. Here, we present and discuss the first maps of the SAMA region, which corresponds to the coherence area at low latitudes. Indeed, this coherence area concept refers to the edges (close-to-the-ground geometric area) around the conjugate point, where geophysical phenomena generally exhibit similar fluctuating behavior. The correlation coefficients technique was used to calculate those areas, using the H component of the geomagnetic field. Our main results indicate that the areas in the Asia-Pacific region are similar in size and shape, which characterize typical patterns. In the America-SAMA region, the coherence areas for the conjugate stations are not similar in shape and size. These differences between coherence areas could be due to the region's unique characteristics, *i.e.* it presents an enhanced ionospheric conductivity. Additionally, geomagnetic stations inside a large area of South America, involving the São Martinho da Serra region, will present, in principle, magnetic fluctuations with similarity in the records.

Keywords: South Atlantic Magnetic Anomaly; conjugate stations; correlation coefficients; coherence areas; wavelet coherence; space geophysics.

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Resumo: A Anomalia Magnética do Atlântico Sul (AMAS) é uma região do Oceano Atlântico Sul onde o campo magnético da Terra é significativamente mais fraco do que em outras partes do mundo. Esta anomalia tem despertado o interesse de cientistas e pesquisadores que estudam o campo magnético da Terra. A AMAS pode afetar sistemas de navegação e operações de satélites, sendo uma importante área de estudo para a compreensão da dinâmica do campo magnético terrestre. Este artigo pesquisa as características do sinal de estações conjugadas influenciadas pela AMAS em uma tempestade geomagnética moderada através da análise de registros de estações geomagneticamente conjugadas interligando em ambos os hemisférios. Este estudo utiliza a componente magnética horizontal medidos no mesmo intervalo de tempo e em duas longitudes típicas: a região América-SAMA e a região Ásia-Pacífico. Este procedimento permite fazer uma análise comparativa entre regiões. Nosso procedimento utiliza os dados registrados simultaneamente em quatro pares de estações conjugadas para caracterizar o domínio de coerência da variabilidade magnética em torno das estações conjugadas. Aqui apresentamos e discutimos os primeiros mapas da região SAMA, que corresponde à área de coerência em baixas latitudes. Na verdade, este conceito de área de coerência refere-se às bordas (área geométrica próxima ao solo) em torno do ponto conjugado, onde os fenômenos geofísicos geralmente exibem comportamento flutuante semelhante. Para o cálculo dessas áreas foi utilizada a técnica dos coeficientes de correlação, utilizando a componente H do campo geomagnético. Nossos principais resultados indicam que as áreas da região Ásia-Pacífico são semelhantes em tamanho e formato, o que caracteriza padrões típicos. Na região América-SAMA, as áreas de coerência das estações conjugadas não são semelhantes em formato e tamanho. Estas diferenças entre as áreas de coerência podem ser devidas às características únicas da região, ou seja, apresenta uma condutividade ionosférica melhorada. Adicionalmente, estações geomagnéticas dentro de uma grande área da América do Sul, envolvendo a área de coerência de Santa Maria, apresentarão, em princípio, flutuações magnéticas com semelhança nos registros.

Palavras-chave: Anomalia Magnética do Atlântico Sul; estações conjugadas; coeficientes de correlação; áreas de coerência; coerência *wavelet*; geofísica espacial.

1. Introduction

Triggered by interplanetary phenomena originating on the Sun, several electrodynamic processes involving the coupling of the magnetized solar plasma and the terrestrial magnetized plasma environment will produce geomagnetic disturbances, which can be recorded on the ground (Campbell, 2003; Russell *et al.*, 2016). The analysis of those magnetic measurements, mainly considering points on the Earth's surface connected by the same geomagnetic field line, is expected to be very useful in understanding the coupling processes and the processes connected to the geomagnetic disturbance effects, mainly over South America, where peculiarities arise due to the weakening of the geomagnetic field intensity.

Earth’s geomagnetic field acts as a huge shielding guard around the planet, repelling and trapping charged particles emitted by the Sun. However, over South America, the South Atlantic Ocean, and South Africa there is an unusually weak region in the geomagnetic field, which is known as the South Atlantic Magnetic Anomaly (SAMA). This anomaly was first discovered in the 1950s by scientists studying variations in the Earth’s geomagnetic field using early low-earth orbit satellite missions (Vernov & Chudakov 1960; Yoshida *et al.*, 1960).

The SAMA is characterized by a significant decrease in Earth's magnetic field intensity, less than 24,000 nT (reaching less than 60% of geomagnetic field intensity at similar latitudes) and weakening rapidly, with an average reduction of 26nT/year (Hartmann & Pacca, 2009; Caraballo *et al.*, 2013; Sanchez *et al.*, 2020). In addition, SAMA has shown a drift to the west. Badhwar (1997) found that the drift speed was 0.28° ± 0.03° per year westward and 0.08° ± 0.03° per year northward. The SAMA center has been defined as the local minimum of the geomagnetic field intensity within the anomaly (Heynderickx, 1996; Ye *et al.*, 2017). Currently, this center is located in Northern Argentina (Sanchez *et al*., 2020), with a minimum value of around 22,500 nT. In the last five years, a second center of minimum intensity within the SAMA has been discovered in southwest Africa, with an intensity of 24,000 nT, indicating that the SAMA could be divided into two separate cells (Terra-Nova *et al.*, 2019). The weak geomagnetic field intensity associated with the anomaly could be traced to a patch of opposite magnetic flux compared to the dipole direction at the core-mantle boundary (CMB) (Pavón-Carrasco & De Santis, 2016; Domingos *et al.*, 2017; Campuzano *et al.*, 2019; Finlay *et al.*, 2020). An important consequence of the presence of this anomaly is that high-energy particles from the Van Allen radiation belt penetrate deeper into the upper atmosphere of this region than anywhere else on Earth (Kivelson & Russel, 1995), which can disrupt communication systems. Also, these particles could induce currents in pipelines, transmission lines, and electrical networks on the surface of the Earth (Hartmann & Pacca, 2009; Caraballo *et al.*, 2013). Besides, it may affect satellites and spacecraft passing through this region (Trivedi *et al.*, 2005; De Santis & Qamil, 2010;). Some aspects of electrodynamics phenomena at low latitudes lack to be investigated, particularly under the SAMA influences.

Two points on Earth are "geomagnetically conjugate points" if they are on opposite ends of the same magnetic field line, and each is one located in a distinct geomagnetic hemisphere. Measurements at conjugate points can help us understand magnetosphere-ionosphere coupling processes and solar wind-magnetosphere reconnection processes and could also help us improve global magnetic field models (Sato *et al.*, 2005). In general, geophysical phenomena can exhibit similar behavior during an event or phenomena in a delimited area around the conjugate points (Wescott, 1966). Some studies have shown the existence of a high correlation between magnetic activities, form, and amplitude of magnetic signals H component) at conjugate points (Wescott, 1961; Nagata *et al.*, 1962). In addition, analysis of magnetic pulsations Pc5 at conjugate points showed similar and symmetric behavior, especially their amplitudes are similar and oscillating in phase (Wescott, 1966; Nagata, 1967; Liu *et al.*, 2003; Mtumela *et al.*, 2015). Few studies have been reported analyzing data from conjugate stations at low latitudes, and most of them had limitations in the analysis techniques (Wescott & Mather, 1965a; Yumoto *et al*., 1985). However, most studies at conjugate points have primarily focused on high and middle-latitude regions (Wescott, 1961; Nagata *et al*., 1962; Wescott & Mather, 1965a,c; Nagata, 1967; Liu *et al.*, 2003; Obana *et al.*, 2005; Hajkowicz, 2006; Takasaki *et al*., 2008)

The secular variation of the geomagnetic field generates displacements in the geomagnetic field lines. Ono (1987) concluded that over 25 years, between 1960 and 1985, the conjugate point of the Syowa station moved a distance of 200 km into Iceland. Another source of displacement of the conjugated points is the interaction of the solar wind with the magnetosphere, the tail current, and any other current in the magnetosphere due to the solar wind pressure and interplanetary magnetic field (IMF) over the geomagnetic field. Observations at high latitudes suggest that conjugate point displacement can reach over 100 km in solar quiet (Sq) periods. Minatoya *et al*. (1996) found that when geomagnetic conditions changed from a disturbed state to the recovery phase, a large longitudinal displacement occurred, reaching 500 - 800 km from the point indicated by the geomagnetic field model. However, Belon *et al.* (1969) found evidence of displacement even greater than 1000 km at high latitudes (66° and 71°).

Therefore, it is very important to analyze data from conjugate stations in this region to improve the understanding of the conjugate phenomena and their interaction with the magnetosphere-ionosphere system, mainly considering the role and importance of the SAMA for dynamical processes. Due to the displacements, the phenomena concerning conjugate points and conjugate coordinate systems should preferably be statistically examined by comparing the geomagnetic behavior as patterns projected within indeed a two-dimensional representation, designated as a coherence variability region. For this reason, in an original procedure, the current work adopts the concept of coherence areas (or conjugate areas) instead of conjugate points as the appropriate way to physically observe the conjugate phenomena at low latitudes. This concept has been largely overlooked since 1970 (Wescott, 1961; Nagata, 1967; Oguti, 1969). Moreover, geophysical phenomena generally exhibit a coherence, or similar behavior, of the event or phenomenon in a delimited area over the conjugate points (Wescott, 1966).

To determine the location and size of a coherence area quantitatively, correlation coefficients are calculated from the variations in the magnetic field between stations around the conjugate point. This procedure makes it possible to plot contour maps (of iso-lines or equi-correlation) about the conjugate point or station conjugate, and it can define a coherence area, and study changes for different geomagnetic disturbance conditions, such as geomagnetic storms and sub-storms (Wescott & Mather, 1965c). Moreover, those maps show the shape (or morphology) and size of these areas defined by the correlation coefficients. Wescott & Mather (1965a,1965b,1965c) concluded that they are not stationary. They vary in size, shape, and location over time, but the size is generally elongated along a line of constant L-shell value. Geomagnetically dynamic regions around the conjugate points are undoubtedly affected by magnetic activities and depend on the type of magnetic disturbance, as pointed out by Ondoh & Maeda (1962), Nagata et al. (1962), and Nagata (1967). Although the primary source of the disturbance in both hemispheres is the same and the disturbance (which involves charged particles or magnetic pulsations) develops along the field lines, the conductivity of their correspondent conjugate ionospheres can vary considerably over time and then modulate the relative size of an area around the conjugate points (Wescott & Mather, 1965c).

A fundamental question seems fascinating for investigation: will the coherence areas be similar in terms of their morphology and size when one of them is under the influence of the SAMA? The main objective of this work is to analyze the variation of those areas surrounding the conjugate points at middle-to-low latitudes (L-shell < 2) and the influence of the SAMA during an event with geomagnetic storms. In addition, defining an external reference for comparing results was necessary. In this sense, three conjugate station pairs far away from the anomaly were selected, but with latitudes equivalent to the affected station by the SAMA. The reason is to obtain a typical behavior and its characterization. To achieve our goal, we use the conjugate point concept and correlation calculation techniques. Above all, this article presents a novel approach to expand the discussion about geomagnetic measurements at conjugate points and coherence areas in low-latitude regions, including one station within the SAMA region. Afterwards we make analyze the results between conjugate stations and how they are affected by the SAMA.

For our case study, the magnetic data used were simultaneously recorded at four conjugate pair stations. Three pairs of stations are located in the Asia-Pacific region, and the other pair is located in the America-SAMA region to obtain a typical characterization, which allows us to do a comparative analysis between regions. Besides, this study aims to characterize the spatial representation (size and morphology) of such coherence and to understand the role of the ionosphere in these structures. One cannot forget that at very low latitudes, a significant portion of the magnetic lines lies within the ionosphere.

2. Data

In this section, we present both the data set and the ground stations used in this work, and the spatial environment related to the chosen case study.

2.1 Geomagnetic data-set

In this work, we use the geomagnetic horizontal (H) component with a record sampling rate of 60 seconds. The reason for this choice is that this component is more susceptible to the modulation effects and, therefore, seems more appropriate for the study of the behavior in regions surrounding the conjugate points (Wescott, 1961).

The data interval refers to the period between 09:00 UT on the 25th and 21:00 UT on the 26th of October 2016, corresponding to the initial, main, and recovery phases of a geomagnetic storm. At 09:22 UT, October 25th, those data showed an abrupt increase in the magnetic field associated with a compression event of the magnetopause produced by a pressure pulse from the solar wind plasma (see Fig. 1). The storm period was close to the September equinox, which also guarantees almost identical illumination by the Sun in the two hemispheres of the Earth. As a result, symmetry between both hemispheres in the ionospheric conductivity and in the Earth's current systems is created (Hartinger *et al.* 2017; Timoçin *et al*., 2018). Under these circumstances, we have a simpler physical system for studying. Information and plots about magnetic indices conditions for this selected data period are presented in Figure 1.

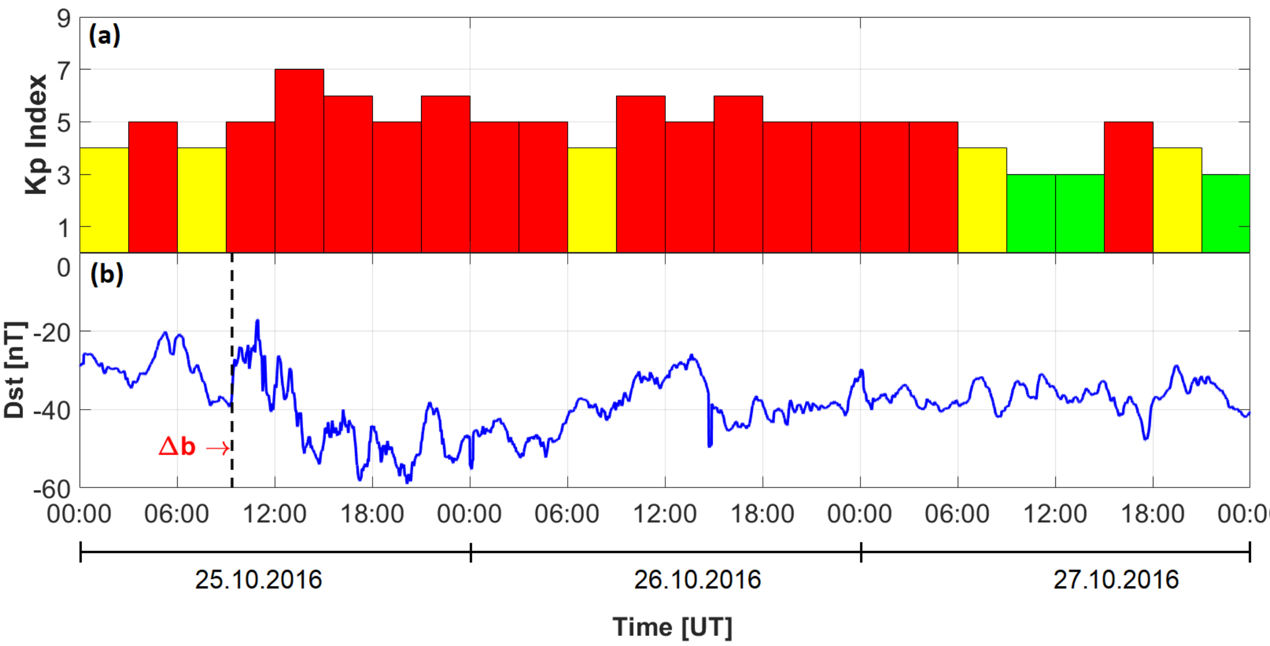

Figure 1. Variation of planetary Kp-index (a) and Dst-index (b) during the geomagnetic storm from October 25th to 27th, 2016.

Figura 1. Variação do índice Kp (a) e índice Dst (b) durante a tempestade geomagnética de 25 a 27 de outubro de 2016.

Kp and Dst geomagnetic indices are used to evaluate the periods of geomagnetic disturbance (Campbell, 2003; Kamide & Chian 2007). In Figure 1, the Kp index shows values of three to seven, which characterizes a global geomagnetic disturbance. The Dst index decreases to a minimum value of approximately -60 nT, indicative of a moderate geomagnetic storm. An abrupt magnetic increase Δb occurred at 09:22 UT on October 25th.

2.2 Geomagnetic dataset

To achieve the goals in this investigation, the chosen stations are located at middle-to-low latitudes and have values L-shell < 2. In theory, these stations are located near the foot-point of the same geomagnetic field line, forming conjugate stations.

The best method for identifying conjugate points at low latitudes is to trace magnetic field lines in a geomagnetic model. Initially, this approach provides the most effective results. To achieve our objectives, we have opted for the use of Altitude adjustment corrected geomagnetic (AACGM) coordinate representation, as suggested by Laundal & Richmond (2017), due to its advantages in studying space weather. Tracing the trajectories of charged particles and pulsations along the field lines allows us to understand how different regions of the ionosphere and magnetosphere are coupled. The AACGM coordinates for a specific geographic location on Earth's surface are determined by tracing the geomagnetic field line, using the coefficients of an expansion of the IGRF model, from that location to the magnetic dipole equator, and then returning back to the surface along the intersecting dipole field line at the magnetic equator (Shepherd, 2014; Laundal & Richmond, 2017; Maffei *et al.*, 2023). The coordinate system was initially established by Baker & Wing (1989) to assess conjugacy between data from SuperDARN radars situated in Goose Bay, Labrador, and Halley Bay, Antarctica. Later refinements to this technique targeted the equatorial region and the South Atlantic Anomaly (Bhavnani & Hein, 1994; Heres & Bonito, 2007). The definition of AACGM coordinates is mathematically the same as that described for CGM (Corrected Geomagnetic Coordinates) coordinates. AACGM model can also calculate the maximum altitude h_{eq} of magnetic lines between stations. In their research, Sheperd (2014) and as well as Laundal & Richmond (2017) address the concept of a forbidden region, an area where AACGM coordinates cannot be determined at low latitudes near the magnetic equator. Forbidden regions are shown in the authors' works. However, due to updates in the AACGM and IGRF model, the forbidden region has shrunk in recent years compared to previous calculations. Our investigation confirmed that none of the stations utilized in this study are located within the forbidden region. Additionally, the software mentioned is capable of identifying when a station's coordinates fall within this restricted area, serving the practical needs of users. Finality, ACCGM model is available in Python wrapper tool (aacgmv2).

Most of the conjugate stations used in this work belong to INTERMAGNET (International Real-time Magnetic Observatory Network)[1]. Otherwise, São Martinho da Serra station belongs to the Embrace network (Brazilian Study and Monitoring of Space Weather)[2] (Denardini *et al.*, 2018). Table 1 shows the geographic coordinates, the conjugate coordinates, magnetic field intensity ***B*** (used IGRF-13), maximum altitude h_{eq} of the magnetic line between the conjugate stations and L-shell values. Figure 2 shows the conjugate stations used here. Furthermore, the boundary of the SAMA on the map is indicated by a blue line, represented by the isoline of 32,000 nT according to the IGRF-13 model (De Santis *et al.*, 2012, 2013; Pavón-Carrasco & De Santis, 2016).

[1] www.intermagnet.org/index-eng.php

[2] www2.inpe.br/climaespacial/portal/en/

Table 1. Coordinates of the magnetic stations.

Tabela 1. Coordenadas das estações magnéticas

			Coordinates						
	Stations		**Geographic**		**Conjugate**				
Regions	**Codes**	**Names**	**Lat[°]**	**Lon[°]**	**Lat[°]**	**Lon[°]**	**B [nT]**	**h_{eq} [km]**	**L[R_E]**
Asia-Pacific	PET	Paratunka	52.97	158.24	-36.84	149.56	51941	6757	2.04
	CNB	Canberra	-35.32	149.36	51.38	157.22	58160		
	KAK	Kakioka	36.23	140.18	-20.21	138.97	46737	2417	1.47
	ASP	Alice Springs	-23.77	133.88	39.93	134.36	53139		
	KNY	Kanoya	31.42	130.88	-15.94	130.99	46612	1183	1.24
	KDU	Kakadu	-12.69	132.47	28.21	132.46	46179		
America-SAMA	SJG	San Juan	18.11	-66.15	-35.20	-55.06	37284	1260	1.28
	SMS	São Martinho da Serra	-29.44	-53.82	14.38	-64.40	22460		

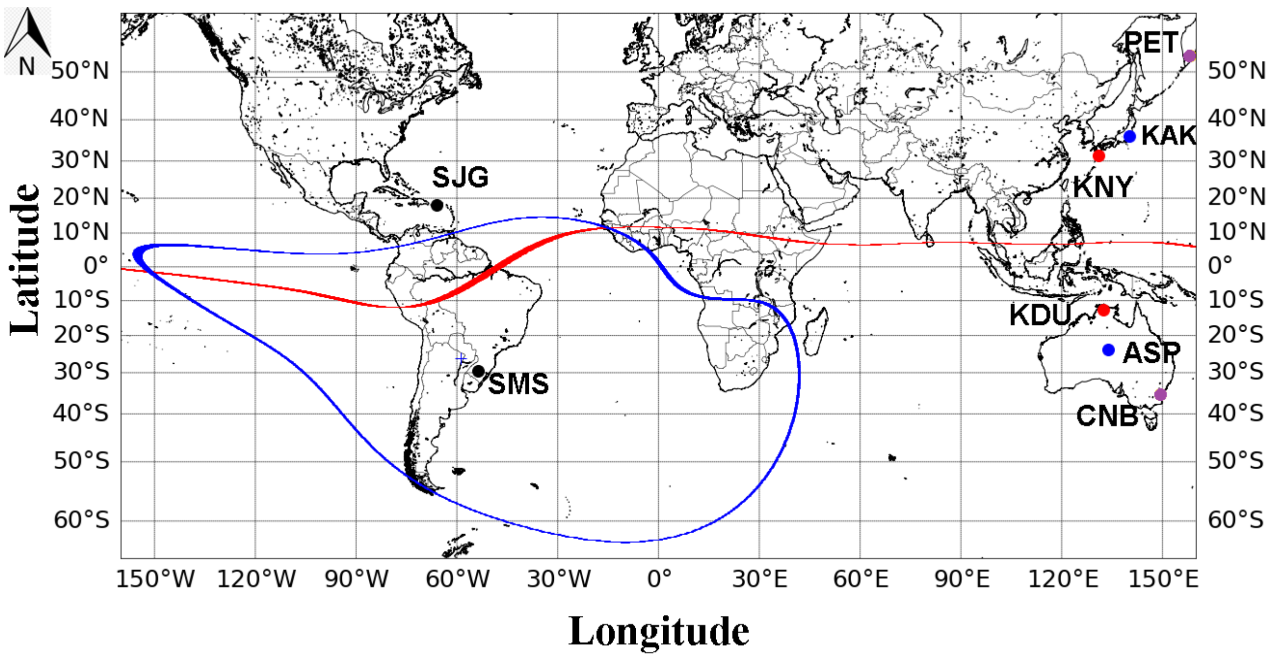

Figure 2. Map of conjugate stations, indicated by circles. The line (in red) is the dip magnetic equator, and the closed line (in blue) surrounds the SAMA region.

Figura 2. Mapa de estações conjugadas, indicadas por círculos. A linha (em vermelho) é o equador magnético e a linha fechada (em azul) mostra a região da SAMA.

The stations shown in Table 1 have already been used to analyze conjugate phenomena. Camacho *et al.* (2023) found that Pc5 pulsations showed simultaneous and similar patterns in the occurrence intervals in the Asia-Pacific region. In the America-SAMA region, the pulsation amplitudes were higher in the SAMA region than those in the Northern Hemisphere. Besides, the Pc5 pulsations showed moderate to low signal coherences and phase lags, between the stations SJG-SMS.

3 Methodology

To identify a region that presents a coherence value higher than a certain critical value, we compute an estimated area using Pearson's correlation coefficient (CC) based on the H component records obtained from the stations surrounding each conjugate station. The correlation coefficient method is a statistical technique showing whether and how strongly pairs of variables are related based on covariance methods (Kendall & Stuart, 1979). Correlation coefficients are computed for the initial, main, and recovery periods of the geomagnetic storm using the H component. By plotting contour maps of the equi-correlation coefficient, we could define those coherence areas (or conjugate areas). Wescott & Mather (1965c,1965b) and Nagata (1967) also used this method. The Pearson's correlation coefficients are given by:

$$CC = \frac{cov(Hx, Hy)}{\sigma_{H_x}\,\sigma_{H_y}} \qquad (Equation\ 1)$$

Where σ_{Hx} and σ_{Hy} are the standard deviations of the *H* component of each station. Coefficient values can range from -1 (perfect negative relationship) through 0 (there is no relationship) to +1 (perfect positive relationship) (Kendall & Stuart. 1979). Usually, if the coefficient value lies between ± 0.7 and ± 1, then someone can interpret the signals as correlated, as pointed out by Nagata (1967). In this work, the correlations between conjugate stations are significant when the correlation coefficient is about or higher than 0.9, which means an interrelationship about or higher than 81% between the fluctuations of the magnetic signals, statistical approach can be seen in Bevington (1969); Reiff (1983). Since the correlation coefficient evaluates the simultaneous behavior, for instance, between two signals, regardless of relative amplitude, we must note that the conjugate area so defined is based only on the shape, and not on the data amplitude between stations (Wescott & Mather, 1965b).

To obtain similar coherence regions, the correlation coefficients of different stations near the conjugate station are calculated to generate isoline maps. Correlation coefficients are computed for the interval comprising the initial, main, and recovery periods of the magnetic storm, from 09:00 UT on the 25th to 21:00 UT on the 26th of October. By plotting contour maps of the equi-correlation coefficient, we can calculate and identify precisely the regions surrounding the conjugate points. Correlation coefficients help us to draw contour lines, which define areas of a particular signal coherence around each of the conjugate stations. The contour lines physically represent the calculated areas.

In this study, similar conjugate coherence areas are defined by the 0.99 confidence-contour line, and those were drawn using Surfer Golden Software, applying the gridding method designated as kriging calculation. Moreover, all these stations belong to INTERMAGNET or EMBRACE. Table *A1 (supplemental material*) shows the codes and geographic coordinates for the stations involved in the calculations. Later, as a result of the mapping, Figures 2 and 3 show the auxiliary stations as orange stars. The results achieved by this mathematical procedure aid in extending the physical interpretation concerning the characteristics of the conjugate points.

4. Results and discussion

Figures 3 and 4 show the analysis results of the similar coherence domains, designated hereinafter as coherence areas. The left panels present the map for the region studied, while in the right panels, specific details are highlighted. The dots represent the station locations identified by the station code, and auxiliary stations used in calculations are indicated by stars. A curved line close to zero grade (in geographical coordinates) is the dip equator. Coherence areas are identified by the close contours around the conjugate stations. Correlation coefficients were computed with 1-minute sampling intervals at the chosen event. By plotting contour maps of equi-correlation coefficients, they could define these areas of interest and study their morphologies and size. The results concern the behavior in both hemispheres simultaneously in both longitudinal regions, Asia-Pacific and America-SAMA, respectively. Complementary in *supplemental material*, Table *A1* shows the codes and geographic coordinates for the stations involved in the calculation.

4.1 Asia-Pacific region

Figure 3 presents the results of the coherence areas analysis in both hemispheres in the Asia-Pacific region, obtained by the correlation coefficients. The correlation coefficients were run for the periods 09:00 UT on the 25^{th} and 21:00 UT on the 26^{th} (36 hours).

As seen in Figure 3, coherence areas, which are defined by a closed contour line, have predominantly a similar morphology. As noticed on the map, the station locations are practically symmetric around the dip magnetic equator. The similarity of the coherence areas in both hemispheres could imply that electric currents in the ionosphere in both hemispheres are similar, as are the variations in the ionosphere of each hemisphere. Contour lines, as defined by the same confidence value for the pairs, also reveal that areas increase when L-shell values decrease. This statement agrees that conjugate pairs with a lower L-shell have a higher influence on the ionosphere, and magnetic line morphology presents a more dipolar behavior.

In this study, we observe that the morphology of coherence areas changes with latitude. As seen in Panels (b) and (c) in Figure 3, the coherence areas of PET-CNB are elongated, i.e., they have the geometric shape of an ellipse (approximately 4° and 2° in N-S and E-W directions, respectively) in the direction of the constant geomagnetic latitude. This pair of stations is the only one that shows coherence areas that do not have similar circular sizes. This shape of the areas has been reported in several studies at high latitudes (Nagata, 1967; Wescott, 1966; Wescott & Mather, 1965b). These elongations of the areas seem to reflect the nature of the electrojet current system of the auroral zone, as was mentioned by Nagata (1967) and Wescott & Mather (1965c,1965b). PET and CNB stations are at approximately 50° and 40° latitudes, respectively, it is certainly not located in the auroral region, but stations at higher latitudes were used to calculate correlation coefficients, such as YAK, MGD, and MGD (see *supplemental material Tab. A1*). Therefore, the H component of higher latitude stations could be influenced by current systems at high latitudes.

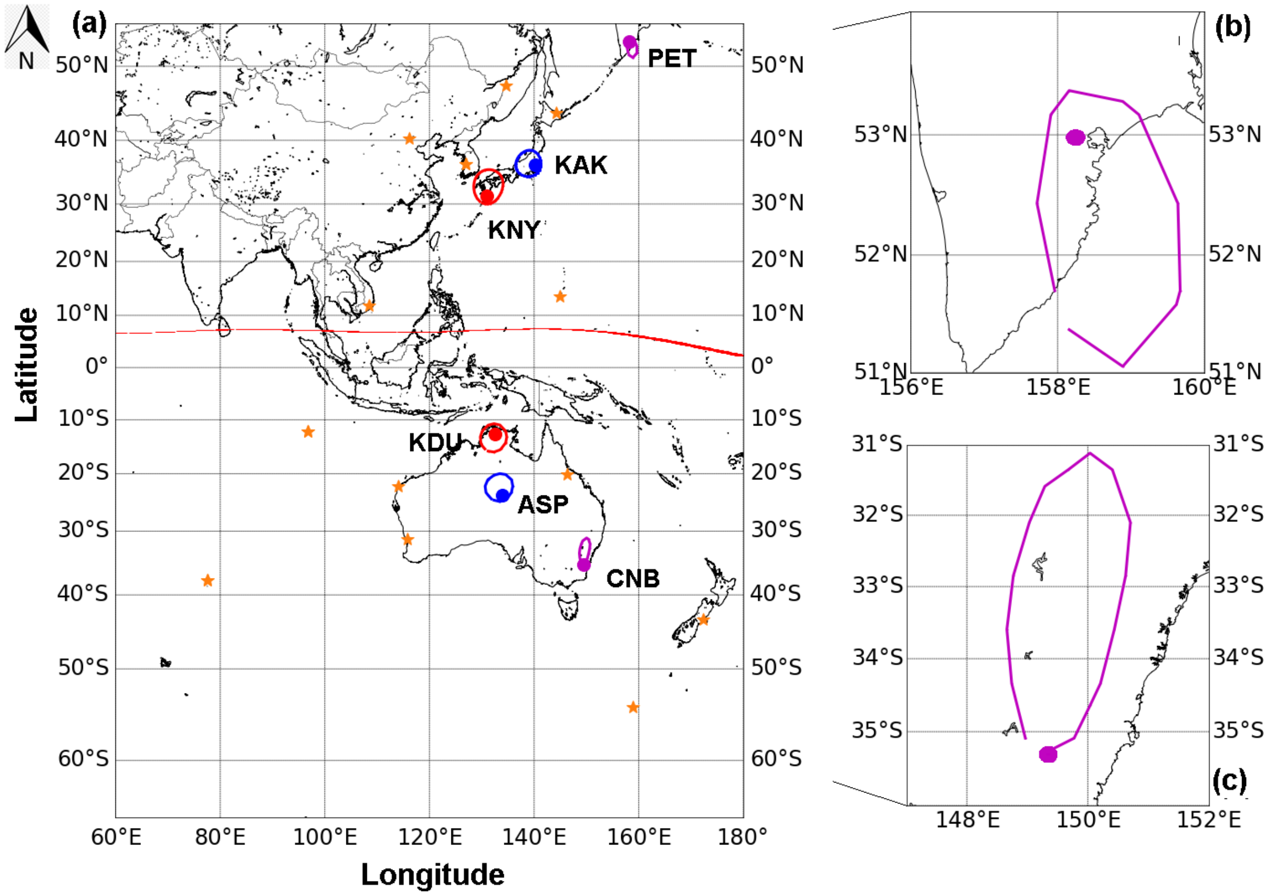

Figure 3. a) Contour maps of equi-correlation coefficients H − H related to the stations PET-CNB (purple), KAK-ASP (blue), and KNY-KDU (red). The orange stars are the stations used to calculate the correlation coefficients (supplemental material Tab. A1). (b) and (c) Details for PET-CNB are shown.

Figura 3. a) Mapas de contorno dos coeficientes de equi-correlação H − H relativos às estações PET-CNB (roxo), KAK-ASP (azul) e KNY-KDU (vermelho). As estrelas laranja são as estações utilizadas para calcular os coeficientes de correlação (material complementar Tab. A1). (b) e (c) Detalhes para PET-CNB são mostrados.

The conjugate pairs KAK-ASP and KNY-KDU showed that the areas are very similar in size in both hemispheres, and the shape of the areas is approximately circular (radius ~ 5°), rather than elliptical. The shape of the areas would be the main difference between morphologies at low and high latitudes. Besides, the areas at low latitudes are greater than at high latitudes. Therefore, at low latitudes, there is a larger area where the conjugate point oscillates or wanders during the magnetic storm.

4.2 America-SAMA region

Figure 4 shows the locations of the stations and calculated contour map of equal-correlation coefficients for each conjugate station in both hemispheres for the America-SAMA region. Correlation coefficients were run for the period 09:00 UT on the 25th - 21:00 UT on the 26th (36 hours). Table A1 (*supplemental material*) shows the station groups that were used for defining the coherence areas, as well as the relevant correlation values. The large curve (blue line) involving the southern American and southern African regions delimits the influence zone of the South Atlantic Magnetic Anomaly.

As detailed in Panels (b) and (c) in Figure 4, coherence areas are not similar between them in their sizes and morphology. In principle, the magnetic magnitude in the stations in the southern hemisphere is less intense than the magnitude in the stations of the northern hemisphere, caused by the presence of the SAMA (see magnetic field intensity ***B*** in Tab. 1). Nevertheless, this exploratory study reveals a significant effect of the SAMA on the coherence area concerning the SMS station, differing the typical behavior, as the SJG station follows.

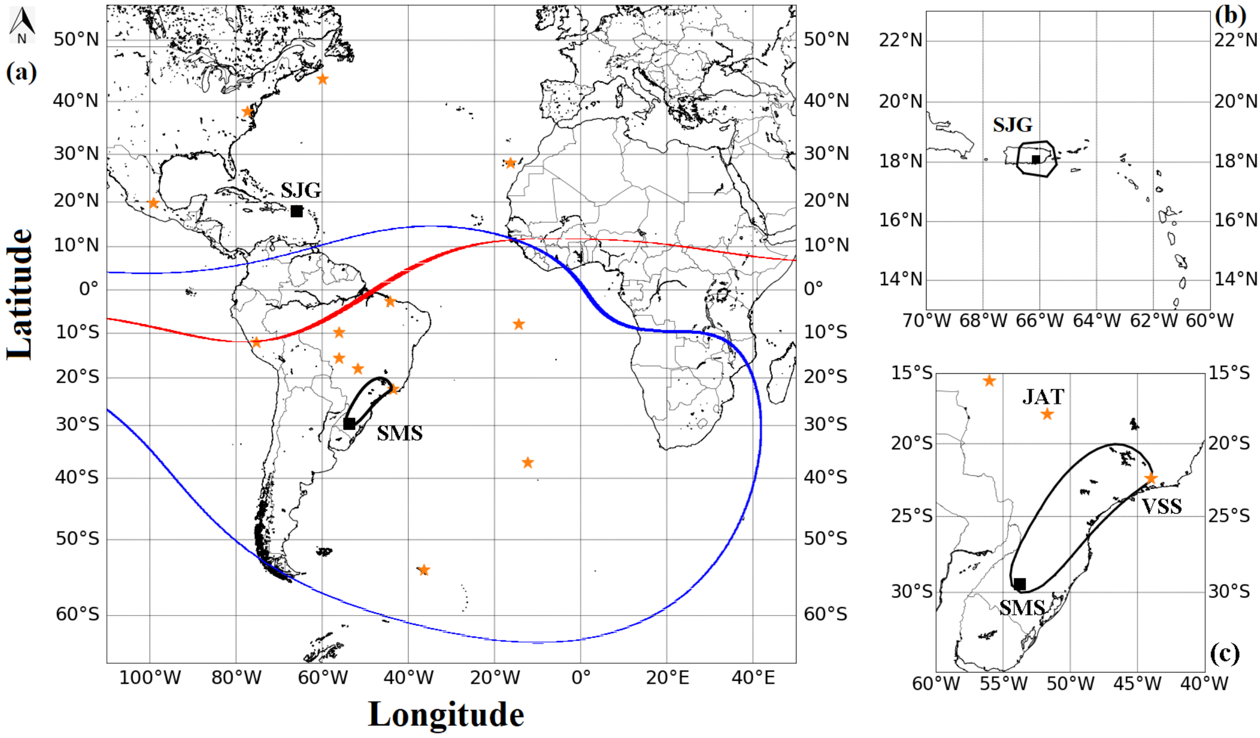

Figure 4. a) Contour maps of equi-correlation coefficients H − H related to the stations SJG-SMS. (b) Details for SJG and SMS are shown. The orange stars are the stations used to calculate the correlation coefficients (supplementary material Tab. A1).

Figura 4. a) Mapas de contorno dos coeficientes de equicorrelação H − H relativos às estações SJG-SMS. (b) Detalhes para SJG e SMS são mostrados. As estrelas laranja são as estações utilizadas para calcular os coeficientes de correlação (material suplementar Tab. A1).

The conjugate pair SJG-SMS (L-Shell = 1.28) showed areas with different morphologies (Panels b and c). In particular, the station SMS shows an elongated with the geometric shape of an ellipse (approximately 10° and 4° in N-S and E-W directions, respectively) and is much bigger than the area of its conjugate, which has a circular morphology (radius ~ 1°). SAMA could be the main contribution to the difference in the morphology and size of the coherence areas of the stations. Observing the SMS station, one can notice its area assumes a behavior similar to an area at a higher latitude, as observed at the PET and CNB stations (Fig. 3). This fact could be explained because the SMS station is located very close to the SAMA center, which is characterized by enhanced ionospheric conductivity in the D and E layers. Through the methodology applied, this work gives support objective to the propositions reported previously by Pinto & Gonzalez (1989) and Klausner *et al.* (2009) that suggested that the SAMA region can be compared to the auroral regions, especially during magnetic storms, as it develops some instabilities in the ionospheric currents in the SAMA region similar to the instabilities generated in the auroral regions. The elongated shape of the areas has usually been reported in a few studies, and only at high latitudes (Wescott & Mather, 1965b; Wescott, 1966; Nagata, 1967). Additionally, geomagnetic stations inside this large area of South America will present, in principle, magnetic fluctuations with similarity in the records.

4.2.1 Spectral characteristics of stations at the SAMA region

It could be suspected that the elongated shape of the coherence area within the SAMA region is strongly influenced by the VSS station and by the few stations in this region, which would not allow for better sampling in the spatial domain. However, when we talk about coherence areas, we could expect that stations within a defined coherence area will have similar behavior. For this reason, we decided to do a spectral analysis between the stations that are within this coherence area in the SAMA region.

To examine whether the Pc5 pulsations of the H component observed in SMS and VSS have a similar spectral structure, we calculated the wavelet coherence between these stations that are within a domain surrounding the SMS station. It is generally accepted that the H component of Pc5 magnetic pulsations mainly reflects magnetic field oscillations in the magnetosphere. Thus, the H component magnetic data are more suitable for studying magnetic pulsations. Considering that the pulsation frequencies depend on the length of the magnetic field line, the Pc5 pulsations are appropriate for analysis in the chosen stations (L-shell < 2) in this work. Furthermore, this is the only type of pulsation that can be investigated with data sampled with a one-minute sampling interval.

Figure 5 shows the Pc5 magnetic pulsations (panel a), and wavelet coherence (panels b and c). Both stations (SMS and VSS) are within an area defined by the contour line 0.99 (coherence area); for the SMS station. Besides, Jataí station (JAT) is outside the contour line (see Fig. 3, panel c), and it is the closest to the VSS station, it is used to compare the Pc5 pulsations and wavelet coherence. The selected interval is 09:00 UT on the 25th and 21:00 UT on the 26th of October 2016, and the selected band is 1.6-7 mHz (Pc5 pulsations). The methodology used to calculate the Pc5 magnetic pulsations and wavelet coherence was explained in detail in Camacho et al. (2023).

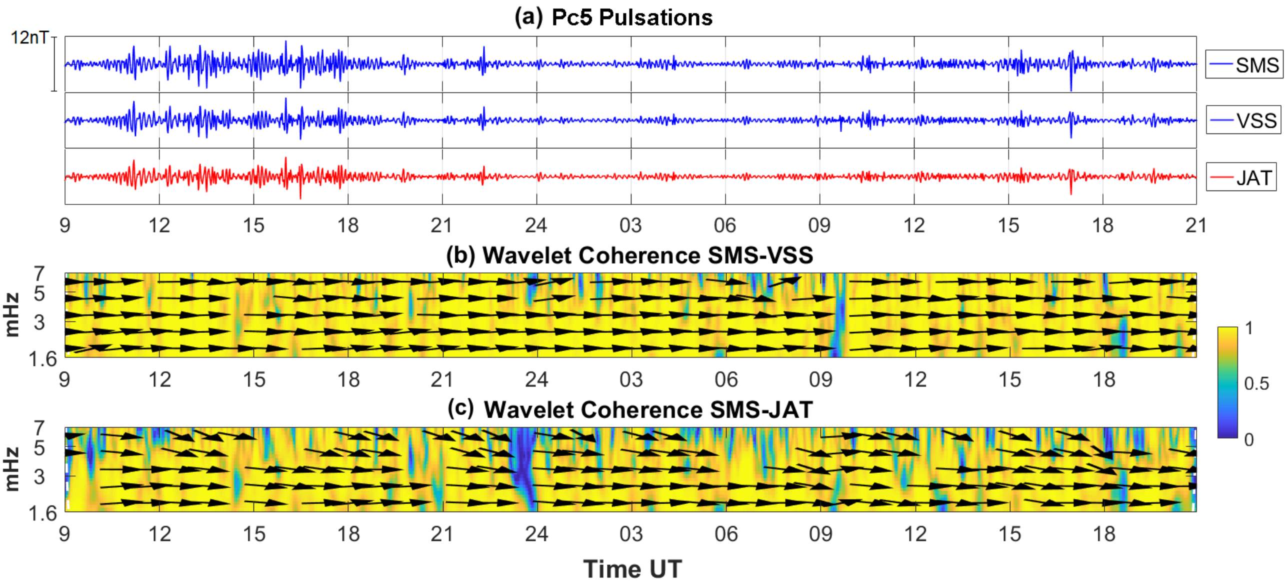

Figure 5. (a) Pc5 pulsations. (b) - (c) Wavelet coherence representations for Pc5 pulsations between the conjugate stations SMS-VSS, and SMS-JAT.

Figura 5. (a) Pulsações Pc5. (b) - (c) Representações de coerência wavelet para pulsações Pc5 entre as estações conjugadas SMS-VSS, e SMS-JAT.

The colormap plot (Fig. 5, panels “b” and “c”) represents the wavelet coherence values of Pc5 pulsations between the stations. The yellow color indicates a value around one, which is the maximum wavelet coherence between the Pc5 pulsations. Arrows indicate the phase between the signals (Pc5). In-phase is the right arrow, the anti-phase is to the left, and the inclined arrow gives intermediate values. For a convenient visualization, arrows are shown only where the coherence is larger than or equal to 0.8. Through a visual inspection of this (Fig. 5), Pc5 pulsations show that they are similar and simultaneous between the stations during the geomagnetic storm. As seen in panel b, SMS-VSS stations show practically high wavelet coherence (value $\sim$ 1) and in-phase signals for pulsations in the stations. On the other hand, SMS-JAT stations show lower coherence than SMS-VSS stations (panel c). Therefore, we could conclude that stations within a common area can have Pc5 pulsations with very similar spectral characteristics. With these graphs, we can affirm that this similarity could be due to the fact that the stations are located within a similar signal coherence area in the SAMA region, with similar spectral characteristics.

Oliva *et al.* (2014) have already pointed out similarities in the spectral characteristics of the Pc4-5 pulsations between SMS and VSS stations. However, the authors could not explain why the spectral characteristics of the Pc5 pulsations are so similar. Now, with this result, we can affirm that both stations are within a coherence area in which the spectral characteristics of the Pc5 pulsations are similar.

4.3 A summary of the comparisons

We found that in the South American region, the coherence area affected by the SAMA is larger than the other areas concerning the regions studied here. In principle, this result shows that the conjugate point has a larger area where it can oscillate or wander during the magnetic storm. Besides, an observed characteristic of the areas surrounding stations, defined by the 0.99 confidence contour line, is the stations located within this area have very similar Pc5 pulsations (coherence wavelet $\sim$ 1, Fig. 5), for example, the SMS and VSS stations in the southern hemisphere (in Brazil).

As a general comment, in all the computations and comparisons of correlation coefficients for conjugate stations from previous research, the authors could not calculate coherence areas for both hemispheres, much less within the influence of the SAMA. This is because calculating coherence areas requires numerous ground stations. These results represent the first instance where several conjugate-station pairs were simultaneously measured to demonstrate the dynamic behaviors of similar conjugate areas (referred to as coherence areas) in both hemispheres, particularly in the SAMA region. Even with this study, it is worth noticing that it was not feasible to use an equal number of stations in each hemisphere or a homogeneous network for calculations. It was also impossible to find stations closer to the conjugate stations to perform correlation coefficient calculations. Such conditions, unfortunately, limit what could be said about the effects of the electrical current system distributions upon conjugate station coherence areas. However, even then, the efforts in this exploratory study give us a minimum perception contributing towards a more comprehensive interpretation. On the other hand, the inter-hemispherical illumination symmetry condition used in this work aided enough to simplify the electric current conditions of the ionosphere above the conjugate pairs of the Asian-Pacific region and allowed the comparison of their typical values and behaviors in the America-SAMA region.

5. Conclusions

The analysis conducted here, using the correlation coefficient method to study the effects of geomagnetically conjugate phenomena on Earth's surface, helps characterize and understand peculiarities of the magnetosphere-ionosphere processes by considering the importance of the SAMA.

We studied data on the significant horizontal component of the geomagnetic field (H), obtained from October 25th to 26th, 2016, corresponding to a geomagnetic storm, which occurred fortunately close to the equinox, a condition that provides a very convenient inter-hemispherical symmetry to mitigate the complexity of the ionosphere. By using the signal analysis approach, we calculate coherence areas, which are areas surrounding conjugate stations where magnetic fluctuations could present similar behaviors. In a novel approach, coherence areas were calculated in two regions (America-SAMA and Asia-Pacific) at low latitudes to compare results. The results presented here include the first maps, analyses, and discussions of conjugate phenomena at low latitudes derived from magnetic data, particularly in the SAMA region.

In the Asia-Pacific region, we found that the conjugate stations present areas of similar coherence behaviors in signals regarding their morphology and size. In this study case, they are in a symmetric position at the hemispheres under interhemispherical illuminating symmetry. Besides, their morphology and size vary with L-shell values, with smaller sizes at stations with larger L-shell values. Typical patterns have been characterized.

In the America-SAMA region, coherence areas are not similar in size and morphology. While the area size in the northern hemisphere follows the typical pattern, in the southern hemisphere, the area's characteristics are affected by the SAMA, with its distortion influenced by high ionospheric conductivity (D and E layers) close to the SAMA center. Additionally, an interesting result found using this methodology was that geomagnetic stations inside a large coherence area of South America will present, in principle, spectral characteristics with similarities in the records.

As a general statement, for potential space geophysics purposes, during magnetic storms, which present global effects, the plasmasphere-ionosphere system conditions in the America-SAMA region are less symmetrical than those in the Asia-Pacific region. The electrodynamics of particle precipitation due to magnetic decrease during a magnetic storm is added to the electrical conductivity alterations of the ionosphere and the presence of electric fields. Even under an inter-hemispherical illumination symmetry, the differences between interlinked stations (conjugate stations) are electrodynamically significant. The results obtained in this study are essential for comparing values and highlighting the importance of the most significant magnetic anomaly on Earth and its influence on the regions of its intense action.

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