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Influence of Equatorial Electro Jet on Geomagnetic Field Variations in North Eastern Part of the Amazon Region (Brazil)

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Abstract
Records of geomagnetic field variations obtained during September 2011, at six sites in the eastern parts of the Amazon region, have been employed for a better understanding of diurnal changes and the relative influences of solar quiet variations and Equatorial Electro Jet (EEJ) at low latitudes in Brazil. Analysis of these data sets provide new insights into the nature of superposition of solar quiet (Sq) and EEJ variations. Model studies reveal that the center of symmetry of EEJ variations is located at the mean latitude of approximately two degrees north. Comparison with results of earlier studies point to a northward shift of four degrees in the position of EEJ, during the period of 1999 to 2011. Inverse power law fit to selected data sets indicates that horizontal and vertical variations at the source regions of EEJ are greater by at least a factor of two when compared with values recorded by ground level magnetometers. Analysis of data sets have also allowed a better understanding of high frequency variations of geomagnetic field at ground level. Occurrences of micro pulsations, with amplitude greater than two nanotesla (nT), are found to characterize perturbed periods of geomagnetic fields relative to those of the calm periods. In addition, results of spectral analysis reveal that variations in the power spectral density (PSD) of micro pulsations have distinctly different characteristics during calm relative to those of the perturbed periods of geomagnetic fields. It has been possible to identify two distinct trends in the frequency dependence of PSD. Thus, for frequencies less than 0.0025 Hz the decrease in PSD follow a liner trend, while for those higher than 0.003 Hz changes in PSD are nearly independent of the frequency.

1. Introduction

The sources that produce variations in geomagnetic field are both internal and external to Earth, and are generally time dependent, with time-scales ranging from seconds to thousands of years [1, 2]. Usually, magnetic surveys focus on the crustal field, which varies with longtime-scales. One of the earliest time-varying fields recognized in magnetic records is the daily variation associated with the apparent movement of the sun .across the sky. At times of low magnetic disturbance, the quiet daily variation, also known as solar quiet variation, is due the Sq current system, which exhibits a repeatability. In addition to its solar components, the quiet variation also comprises lesser components of lunar origin, which arise due to ionospheric bulges associated with lunar tides. The Sq current flows clockwise during the day in the southern hemisphere and has its centers near 30◦ magnetic (dip) latitude, known as Sq focus. Its magnetic effects range up to about 100nT (nanotesla) near the Earth's surface over low latitudes.

In equatorial regions the geomagnetic field shows a strong enhancement which is attributed to a narrow electrical current sheet flowing eastward along the day side magnetic dip equator, which was termed by [3] as the Equatorial Electrojet (EEJ). It is located at about 105 km height, and is confined to a narrow belt of ± 3◦ centered over the magnetic dip equator. Its magnetic field intensity at the Earth's surface range up to about 100nT directed horizontally northward. Numerous investigations have been carried out on the responses of Sq and EEJ current systems to other phenomena, such as the magnetic storms, solar flares and planetary waves [4, 5]. Such responses are known to manifest themselves as local time and seasonal variations in the magnetic fields measured at magnetic observatories. Despite the progress obtained in recent studies there are considerable difficulties in outlining the main characteristics of such variations. On the other hand, a detailed knowledge of such variations is essential for a better understanding of the interplay of geomagnetic field and the dynamic processes taking place in the EEJ at low latitudes. It is also important in the use of magnetic and magneto telluric methods employed in mineral prospection and in the use of GPS in land surveys.

Variations of geomagnetic field at ground level in the northern sector of South American continent include notable contributions originating from sources in the interior of the Earth as well as those exterior to the planet. The prominent interior source manifests itself as the South Atlantic Magnetic Anomaly (SAMA), where the total field intensity has a global minimum [6]. It presently occupies much of the area in South America and the oceanic region between South America and South Africa [6]. External sources, prominent in the equatorial and mid-latitude regions, are solar quiet (Sq) daily variation and the equatorial electrojet EEJ. The relative locations of the internal and external sources are indicated in the map of Figure (1).

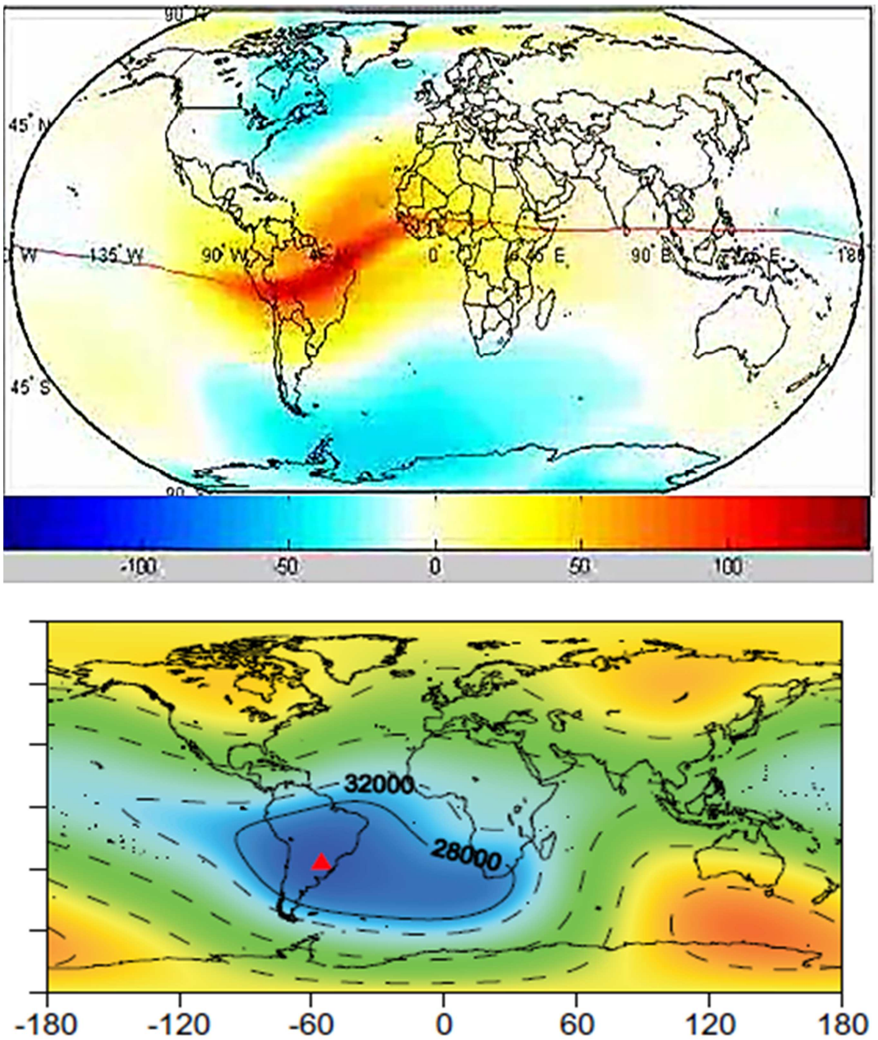

Fig. 1. External and internal sources of variations in geomagnetic field in northern parts of South America. The top panel indicates the equatorial intensification of the magnetic field due to EEJ at UT 16hs (color code in nT). The blue shaded region in the bottom panel indicates the South American Magnetic Anomaly [7].

South America is one of the two areas of the world where the EEJ zone crosses a continent such that it can be studied by ground stations across its entire width [8]. The magnetic equator crosses the west coast of South America approximately 13° south of the geographic equator and then curves north to cross the geographic equator just off the NNE coast of Brazil. The relative position and orientation of the magnetic and geographic equators are important parameters, because Sq field is better represented as a function of the mean between geographic and dip latitudes whereas the electrojet system is governed by the dip equator [9]. In NNE Brazil, the angle between the magnetic and geographic equators is approximately 30°, which causes interference between the EEJ and Sq fields. As a large part of Brazil is under the influence of the EEJ, a practical reason for modelling the EEJ fields is to assess the effect that spatial inhomogeneity of the electrojet magnetic fields may have on high-resolution aeromagnetic surveys.

Studies of geomagnetic variations have been carried out in the past, in different parts of Brazil. Among the pioneering works are those by [10, 11, and 12]. This was followed by further works using ground-based magnetometer data [13, 14].This latter work refers to a comparative study of EEJ characteristics recorded at Euzebio (Brazil) and Hunacayo (Peru). In addition, progress obtained in studies of secular variations was reported [15]. Studies of geomagnetic pulsations recorded in Santa Maria, in South Brazil were carried out by [16, 17 and 18]. Studies of Pc5 pulsations in low latitudes of Brazil were also reported [19, 20]. The characteristics of the EEJ in N-NE Brazil were investigated using an array of magnetometers by [21]. According to results of this latter work, EEJ center was located at 21 ± 16 km south of the dip equator, and has a half-width of 403 ± 67 km. A study of geomagnetic micro-pulsations 3-5 recorded in a network of 10 stations in western Brazil was reported by [22]. More recently, [23] reported study of long period geomagnetic field variations in the region of South Atlantic Anomaly and [24] reported use of wavelet method for study of geomagnetic variations.

Nevertheless, few efforts have been made in investigating long-term variations in the characteristics of EEJ. In the present work, we report progress obtained in analysis of both low and high frequency geomagnetic variations recorded in 2011 at six different locations in northern Brazil, located along a longitudinal profile to the west of the area covered in the earlier work of [21]. Thus, the focus of the present work is in outlining the nature of long-term variations of EEJ over the period of 1999 to 2011 and its interactions with the Sq field. In addition, the present work also examine the spectral characteristics of short period geomagnetic variations in the northeastern parts of the Amazon region.

2. Location of the Study Area and Sources of Data

The data sets employed in the present work are derived from records of geomagnetic field obtained at six localities in northern Brazil. Also included are data acquired at the geomagnetic observatory of Tatuoca (TTB), in the state of Pará. The geographic and geomagnetic coordinates of these sites are given in Table 1, along with respective information on magnetic inclination and altitudes. The data acquisition at the repeat stations were carried out using tri-axial fluxgate magnetometers (model LEMI-417), buried in soil at depths of approximately one meter. Records include measurements of the horizontal (H) and vertical (Z) components and declination of the magnetic field, with digital sampling at intervals of one second. The focus of the present work is on analysis of data acquired during the month of September 2011.

Table 1. *Geographic (Geo) and geomagnetic (Mag) coordinates, inclinations (of local magnetic field) and altitudes of sites considered in the present work.*

Station	Latitude		Longitude		Inc. (D)	Altitude (m)
	Geo (DMS)	Mag (DD)	Geo (DMS)	Mag (DD)		
S. J. Pacuí (SJP)	00º 49.29’	10.04N	-50º45 31’	21.89E	6.45	26
Tatuoca (TTB)	-01 º12.03’	7.89N	-48º30 02’	24.03E	0.35	15
Juába (JUA)	-02º23.52’	6.77N	-49º33 30’	22.88E	0.00	10
Goianésia (GOI)	-03º50.34’	5.30N	-49º05 50’	23.25E	-2.50	82
Carmolândia (CAR)	-07º04.31’	2.05N	-48º23 01’	23.74E	-9.59	236
Centenário (CEN)	-08º59.36’	0.07N	-47º12 52’	24.76E	-14.10	326

The sites of these stations fall along an approximate north-south trend, covering an area between 1 degree north and 9 degrees south latitude and longitudes between 47 and 51 degrees west. The corresponding geomagnetic latitude range is between 1 degree north and 9 degrees south, while the geomagnetic longitudes are between21 and 25 degrees east. The locations of the sites are indicated in the map of Figure 2. Note that this region lies to the west of the area covered in the work of [21], covering an area between 0 and 8 degrees south latitude and 310 and 315 degrees west longitude.

3. Normal and Disturbed Periods of Geomagnetic Activity

Initially, the data sets were classified into groups depending on the nature of local geomagnetic variations. The separation was based on the 3-hour geomagnetic index (Kp) calculated for the six sites, as per procedures adopted at the Fredericksburg (FRD) observatory, Germany [25, 26]. Two groups were considered:

(1) Those with Kp index <2, considered as indicative of periods during which geomagnetic field variations may be considered as calm and quiet;
(2) Those with Kp index >2, considered as indicative of periods with noticeable geomagnetic perturbations.

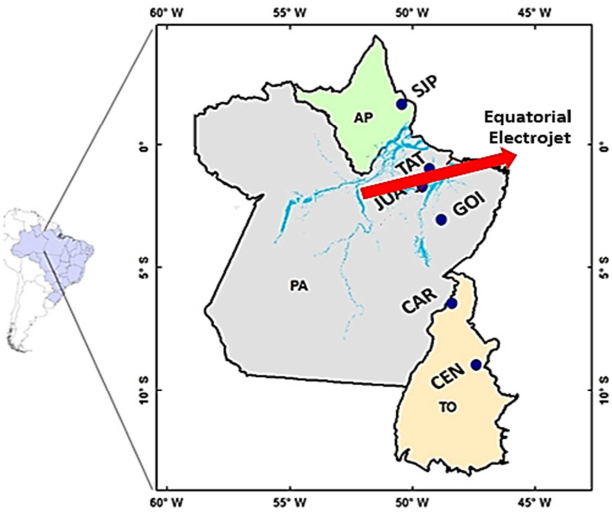

Fig. 2. Map indicating locations of the geomagnetic observatory (TTB) and the repeat stations (SJP, JUA, GOI, CAR and CEN). The red line indicates the local ground projection of the equatorial electro jet (EEJ). The two-letter abbreviations refer to the States of Amap á(AP), Para (PA) and Tocantins (TO) in northern Brazil.

Initially, attention in data analysis was focused on understanding the nature of diurnal variations during geomagnetic calm periods. Thus, we ignored abnormal field changes that occurred during periods of 9 to 13, and 23 to 30 of September 2011. In many cases, solar flares were observed on days of abnormal variations, making analysis of data a difficult task. The variation of the geomagnetic activity index for the month of September 2011 is presented in Figure (3).

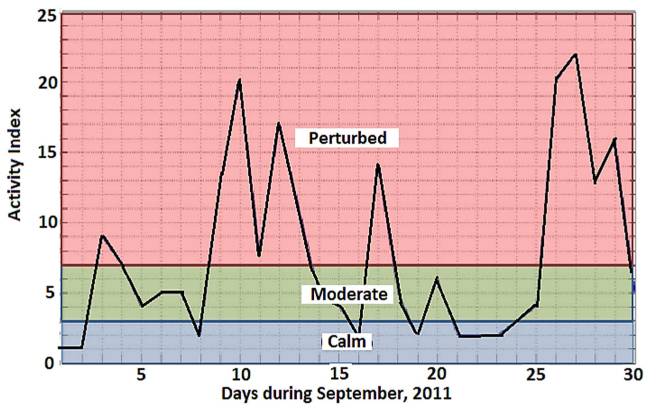

Fig. 3. Geomagnetic activity index for the month of September 2011.

Results of data analysis also allowed identification of the main characteristics of horizontal (H) and vertical (Z) components of the geomagnetic field at the sites. Positive values of these components indicate the direction of geomagnetic-north vertically downward. Examples of geomagnetic field variations observed on calm and disturbed periods are illustrated in Figures (4) and (5). For reasons of brevity, it is limited to data acquired on four days (1, 6, 9 and 17). Clearly diurnal changes during calm days (1 and 6) present much less complexity than those of the disturbed days (9 and 17). In the present work, we ignore the changes of the perturbed periods and focus attention on the field variations during the quiet periods.

Use of base lines were found to be convenient in analysis of data. Thus, quiet level baselines has been defined for each day as the mean of six nighttime values (i.e., values at local times (LT) of 0000, 0100, 0200, 2200, 2300 and 2400 hours). The difference values (ΔH, ΔD and ΔZ) of geomagnetic components were computed by subtracting the base line values from the recorded values of H, D and Z:

$$\Delta H(LT) = H(LT) - \frac{H(00)+H(01)+H(02)+H(22)+H(23)+H(24)}{6} \tag{1}$$

$$\Delta D(LT) = D(LT) - \frac{D(00)+D(01)+D(02)+D(22)+D(23)+D(24)}{6} \tag{2}$$

$$\Delta Z(LT) = Z(LT) - \frac{Z(00)+Z(01)+Z(02)+Z(22)+Z(23)+Z(24)}{6} \tag{3}$$

This procedure has also been helpful in removal of erroneous values from the data set. The baselines rely on the assumption that the nighttime ionosphere currents are too small to be significant when compared with daytime values during quiet geomagnetic conditions. This argument is widely accepted because the conducting E region of the ionosphere largely disappears at night hours except at the auroral latitudes [27] and currents flowing in the F region of the ionosphere during the night are of much smaller magnitude than the daytime dynamo currents [28].

4. Horizontal and Vertical Components of Magnetic Fields

As the first step in understanding characteristic features of diurnal variations one-minute and one-hour, median values were derived from the raw data, which has one-second time resolution. This procedure allowed removal of the effects of short-term disturbances such as sudden commencement (SC), quasi-periodic magnetic fluctuations and magnetic pulsations

[29].As illustrative example we present in Figure (6) the day-to-day distribution of the daily variation amplitudes of the horizontal component (H), observed at Juába (JUA) and Centenário (CEN) stations.

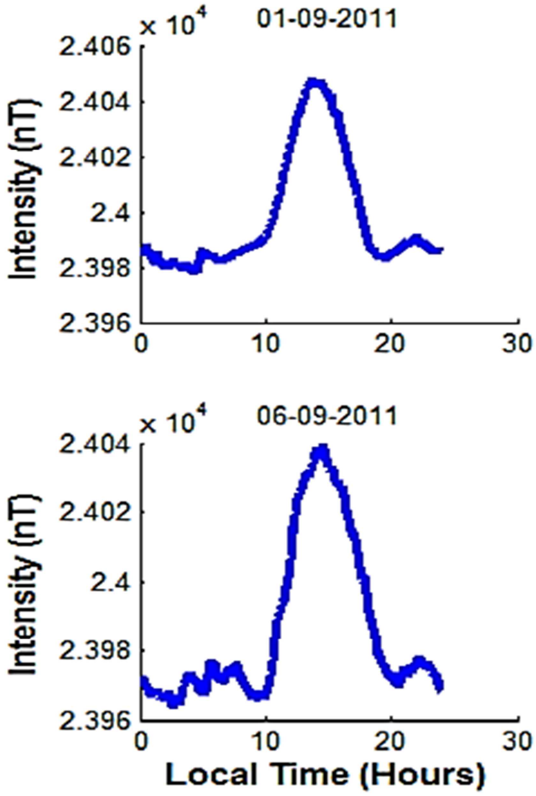

Fig. 4. *Examples of variations in the geomagnetic field observed on geomagnetic calm days of 1 and 6 of September 2011, at Centenário station.*

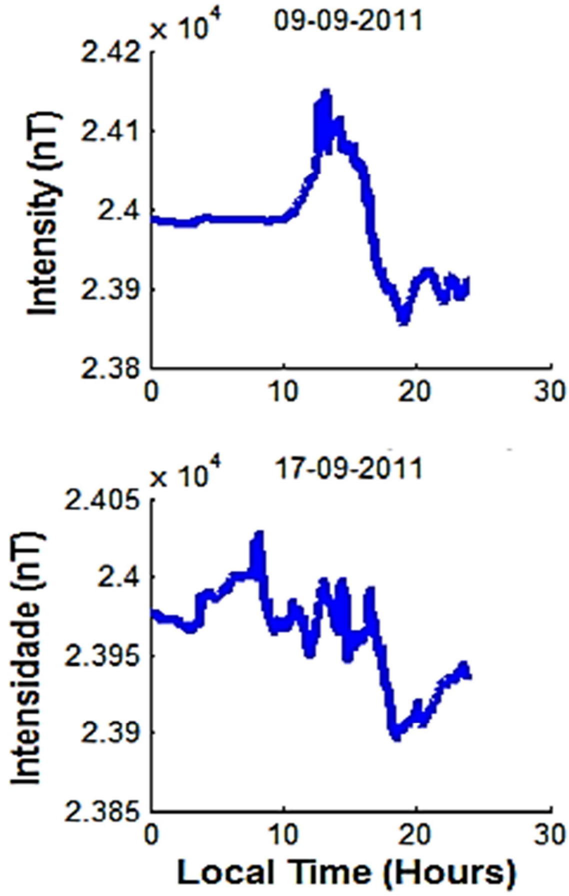

Fig. 5. *Examples of variations in the geomagnetic field observed on geomagnetic disturbed days of nine and seventeen September 2011, at the Centenário station.*

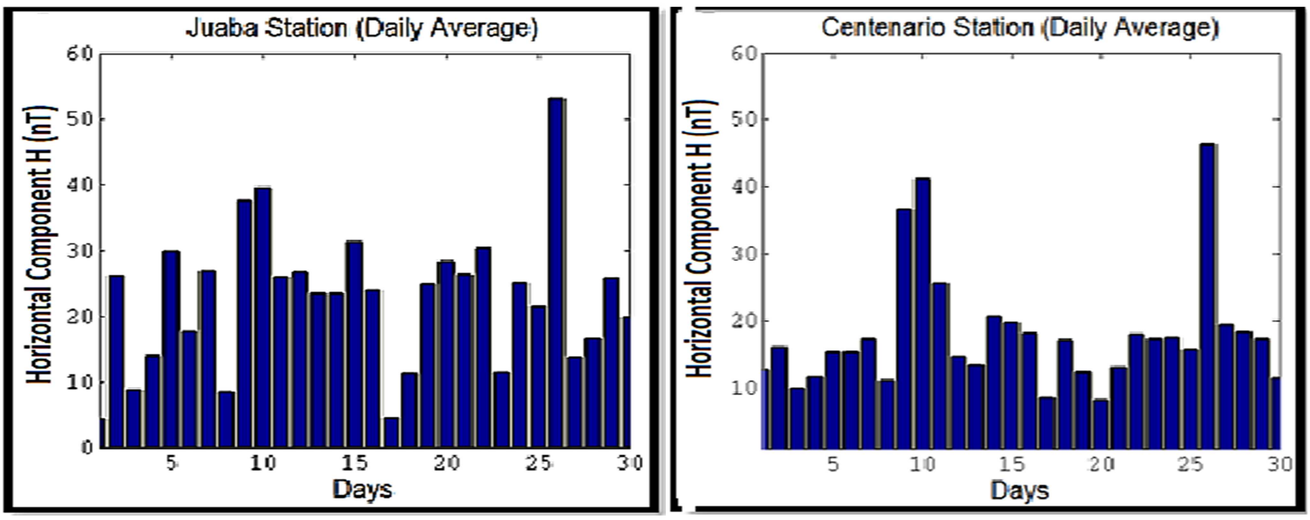

Fig. 6. *Daily variations of the horizontal component of the magnetic field observed at Juába (JUA) and Centenário (CEN) stations, during the month of September 2011.*

Comparisons of the variations in the horizontal component are presented in table (2) for days 10 and 16 of September 2011, for stations SJP, JUA and CEN. Note that the amplitudes of ΔH are much larger at the station JUA (located below the EEJ) relative to those at SJP and CEN.

Table 2. *Mean value of horizontal component (H) and amplitudes of its variation (ΔH) observed on 10 and 16 September 2011, at stations STP, JUA and CEN.*

Date	Station	Mean H (nT)	ΔH (nT)
	São Joaquim do Pacuí (SJP)	27332.2	173.8
10/09/2011	Juába (JUA)	26250.6	208.3
	Centenário (CEN)	23959.6	170.8
	São Joaquim do Pacuí (SJP)	27362.9	100.3
16/09/2011	Juába (JUA)	26289.4	165.3
	Centenário (CEN)	23989.4	93.5

The nature of diurnal variations in the horizontal component (H), observed at the stations of Juába, São Joaquim do Pacuí and Centenário, are illustrated in Figure (7). Note that the overall shapes of variations in H are similar in the three stations. During the early morning hours (0 to 8 hours local time), the field is relatively stable at all three stations. However, small dips in the H component can be seen during the early period of 8 to 10 hours. This is followed by a significant increase during 10 to 16 hours and eventual decay to baseline values during 20 to 24 hours. The field remains stable after 20 hours.

The nature of diurnal variations in the vertical component (Z) observed at the stations of Juába, São Joaquim do Pacuí and Centenário are illustrated in Figure 8. Note that the overall shapes of variations in Z are similar in the three stations. During the early morning hours (0 to 7 hours local time), the field is relatively stable at all three stations. However, a decrease in the Z component can be seen during the period of 8 to 14 hours. This is followed by a significant increase in the Z component during 14 to 20 hours. Note that the amplitudes of variations in H at the station Juába, located within the zone beneath EEJ are significantly larger relative to those at the other two stations, situated at larger distances from the dip equator.

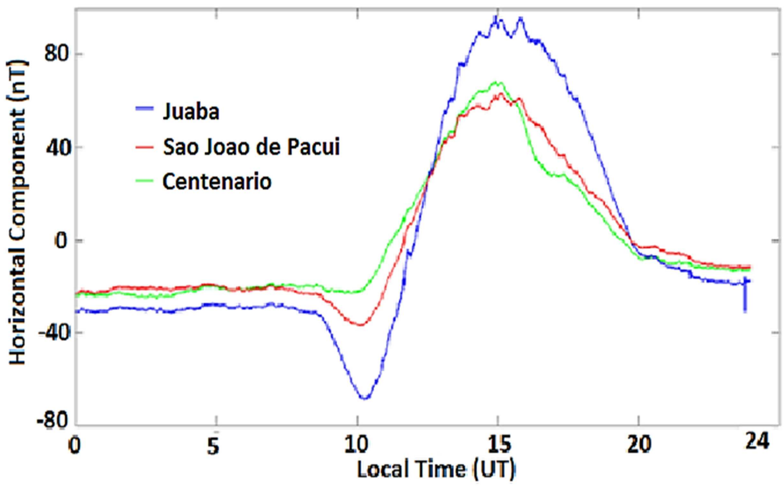

Fig. 7. *Diurnal variations in the horizontal component of the geomagnetic field on 16 September2011, at three stations.*

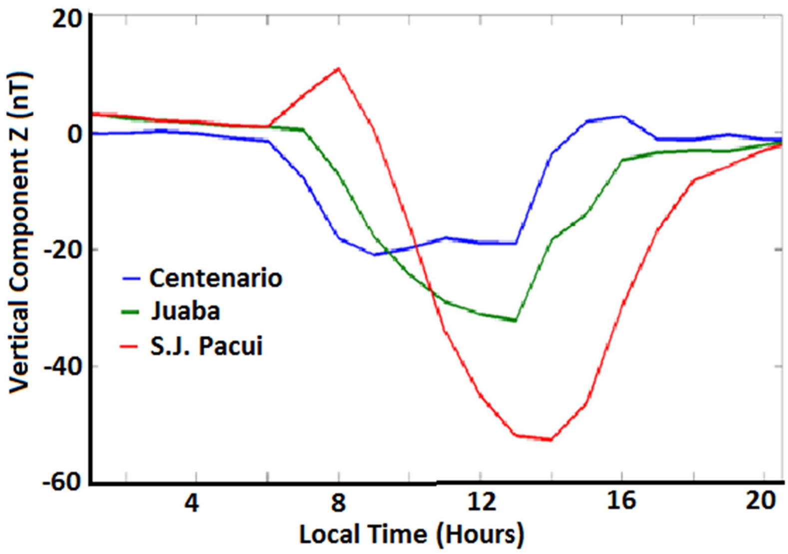

Fig. 8. *Diurnal variations in the vertical component of the geomagnetic field on 16 September, at three stations.*

5. Models of Solar Quiet (Sq) and Equatorial Electrojet (EEJ) Fields

The EEJ current flow eastwards along the dip equator is confined to a thin layer assumed infinite along the E-W direction. The current density varies with latitude and is symmetric about the central axis where the maximum occurs. It can be shown that (see for example, [30]) the thin layer approximation introduces an error of less than 2% in the derived ground magnetic fields, compared to more complex current distributions. In the present work, we assume that the main characteristics of the EEJ may be described by fitting an equivalent current model to the observed magnetic fields. In such an approach, effects of only simple currents systems are allowed, so that the surface magnetic field components can be computed from closed expressions.

The model proposed by [9] has been considered in the present work, as it allows straightforward understanding of magnetic field changes by EEJ currents. The current distribution in this model may be expressed as:

$$J = J_0 \frac{a^2\left(a^2+\alpha x^2\right)}{\left(a^2+x^2\right)^2}, \quad \alpha \le -1 \tag{4}$$

In the above equation, $J_0$is the maximum current density at the center of the distribution, a the constant meridian scale length and x the distance. It is related to the half-width ω as $a = \omega\ (-\alpha)^{1/2}$, with α indicating a dimensionless constant, determining the proportion of westward current in the flanks of the current distribution. Note that a negative α causes the current to reverse sign at a certain distance x.

The relations for the northward X and vertical Z magnetic field components of the current distribution may be given as:

$$(sign_z)\,X = Ka\frac{(h+a\,h+2\alpha\,a)(u+b)^2\ \ (h+a\,h+2\,a)(h+a)^2}{2\left[(u+b)^2+(h+a)^2\right]^2} \tag{5}$$

$$-\,(sign_x)\,Z = Ka\frac{(u+b)\left[(1+\alpha)(u+b)^2\ +(h+a\,h+3a-\alpha\,a)(h+a)\right]}{2\left[(u+b)^2+(h+a)^2\right]^2} \tag{6}$$

In the above equations:

K is the magnetic field of an infinite current sheet with constant intensity J_0, $K = 0.2\pi\, J_0$;

x is the northward distance from the central axis of the current distribution;

z the vertical distance (positive downwards) from the current distribution;

sign $_{x,\,z}$ are the signs of the coordinate x and z respectively;

b a vertical scale length related to the half-thickness;

u the magnitude of the northward distance x;

h the magnitude of the vertical distance z;

An inversion process was employed by [21] in modeling simultaneously effects of both Sq and EEJ. Their results reveal that the total positive current intensity of EEJ is 67000A (for diurnal range M4) and its half-width is 403 km. The EEJ center was reported as located 21 km south of the dip equator (the center of symmetry being at the latitude of about 2°S). The Sq latitudinal variations, estimated from several permanent observatories, were found to be centered at a mean latitude of 5.5°S.In addition, an example of superposition of geomagnetic variations of Sq and EEJ origin observed on 6 January 1991was presented.

A similar approach has also been employed in the present work in mapping superposition of variations associated with Sq and EEJ. However, the latitude profile chosen in the present work refer to a selected set of data acquired on calm days within the study area. The results obtained are illustrated in Figure (9), where possible interpretations of the field intensity variations associated with EEJ are indicated by the curves in red color and that associated with the Sq variations by the continuous black curve. The blue dashed curve in this figure refer to EEJ variations observed by [21], where the center of symmetry is at the mean latitude of approximately 2°S. Limitations in the data set do not allow an unambiguous choice of the two possible forms of variations indicated by the curves in red color. According to the possible variation indicated by the continuous red curve, the amplitude of EEJ is smaller in 2011 compared to that observed by [21] in 1999. The dashed red curve indicates an alternate interpretation. In this case, the amplitude of EEJ variation is comparable to that of the previous work by [21], but its center of symmetry seems to be located at the mean latitude of approximately 2°N. This latter alternative point to a possible shift of approximately 4°in the location of the peak, implying a northward migration in the position of the EEJ of about 450 km during the period of 1999 to 2011. Such a possibility is not altogether surprising in view of substantial evidences indicating secular variation with northward migration of geomagnetic field in Brazil [15]. In fact,[31] pointed out northward migration of 400 km in equatorial type sporadic E layer, based on results of ionospheric sounding in northern Brazil.

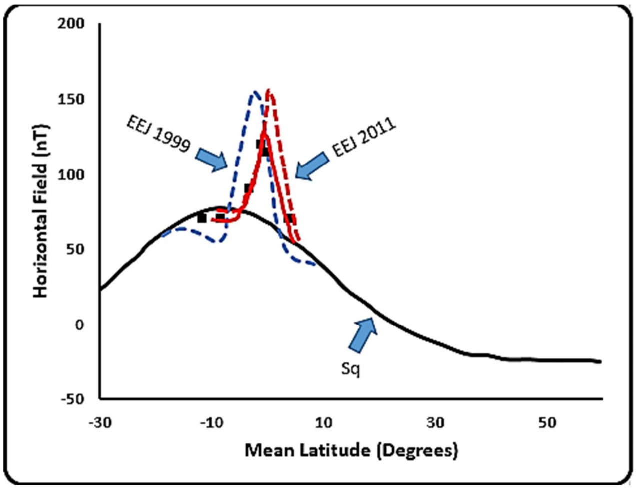

Fig. 9. Interpretations of latitudinal variations in the horizontal component of geomagnetic fields associated with EEJ (continuous and dashed curves in red color) and Sq (continuous black curve). The blue dashed curve refer to the EEJ variations reported by [21].

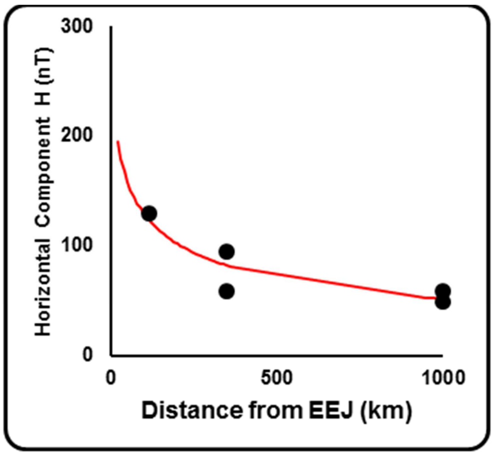

Fig. 10. Variation of horizontal component H with approximate vector distance from the central position of EEJ. Note that the trend indicated by the red curve is valid only for distances greater than approximately 20km for the center of EEJ.

Analysis of a selected set of simultaneous records obtained on calm days of magnetic fields at different stations have allowed estimates of the intensity of the magnetic variations at heights closer to the source region of EEJ, at its mean altitude of 110km. The results obtained are illustrated in Figure (10). In view of the limitations of the data set, two possible forms of variations were considered: linear and inverse power law. A fit assuming linear variation would imply a magnitude of 150 - 170 nT at the source region of EEJ. On the other hand, fit based on an empirical inverse power law relation is found to be of the type:

$$Y = \frac{C_1}{1 + C_2 * V^{c_3}} \text{ (V > 20 km)} \qquad (7)$$

where Y is the field variation at the vector distance (V) from the mid plane of the electrojet at its mean altitude of 110 km. The numerical values of the constants C_1, C_2 and C_3 in equation (7), chosen to provide reasonable fit to the data, are 300, 0.1 and 0.56. Note that the inverse power law relation is valid for distances of V .greater than approximately 20 km, since the field intensity drops to zero at the mid plane of EEJ. However, it is clear that the magnitude of horizontal component (H) at heights closer to the source region of EEJ is in excess of 200 nT, higher than the values recorded at the ground level.

6. Micro Pulsations

We now turn our attention to progress obtained in analysis of high frequency variations, often termed micro pulsations, which are generated by naturally occurring magneto-hydrodynamic (MHD) waves in the Earth's magnetosphere. In the present work, attention is focused on variations of the type classified as Pc5, which has a period band of 150 to 600 seconds.

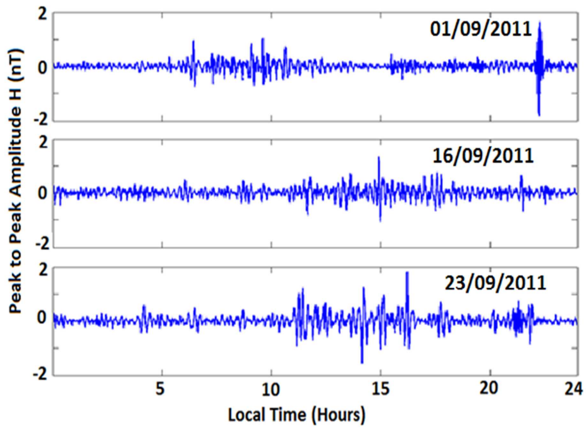

Fig. 11. Micro pulsations on calm days (01, 16 and 23 of September 2011) at station SJP.

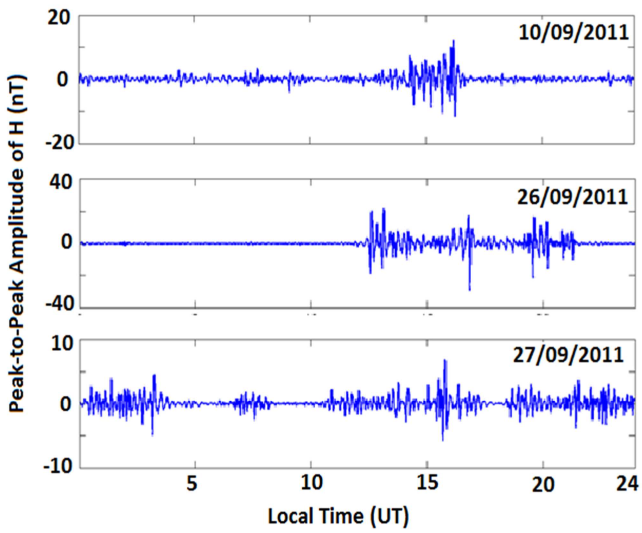

Fig. 12. Micro pulsations observed on perturbed days (10, 26 and 27 of September 2011) at station SJP.

The separation of low and high frequency components was achieved by applying a suitably chosen band pass filter to the recorded data sets. In the present case, the cutoff values chosen for the band pass filter had periods of 150 and 1000 seconds. The results obtained indicated that the peak-to-peak amplitudes of micro pulsations ranges from less than one nT to a few tens of nT. The magnitudes and occurrences of such pulsations are found to depend on the degree of magnetic disturbance (calm or perturbed). Examples of micro pulsations observed at station SJP on calm days (01, 16 and 23) of September 2011 are illustrated in Figure (11).Similar results obtained for the station SJP on perturbed days (10, 26 and 27) of September 2011 are presented in Figure (12).

Note that the amplitudes of micro pulsations are much higher on perturbed days relative to those on calm days. For example, the maximum amplitude of micro pulsations is greater than 10 nT on 10 September 2011, while it is greater than 20 nT on 26 September, 2011. The record for 26 September 2011 indicates the presence of a relatively large number of micro pulsations with magnitude greater than two nT. The numbers of micro pulsations with amplitudes greater than two nT, are given in Table (3), for three of the stations SJP, JUA and CEN. It is clear that the occurrences of micro pulsations are significantly lower during calm days relative to perturbed days. As expected there is a reasonably good correspondence between variations in the Kp index (see Figure 3) and changes in the numbers of micro pulsations listed in Table (3) for the calm and perturbed days.

Table 3. *Numbers of micro pulsations with amplitudes > 2nT at stations SJP, JUA and CEN.*

Station	Magnetic field	Days in the month of September, 2011	Number of pulsations with amplitude > 2nT	Total
Sao Joao Pacuí (SJP)	Calm	01, 16, 23	0, 0, 0	0
	Perturbed	10, 26, 27	10, 33, 29	72
Juába	Calm	01, 16, 23	3, 1, 6	10
(JUA)	Perturbed	10, 26, 27	12, 20, 17	49
Centenário	Calm	1, 16, 23	0, 0, 0	0
(CEN)	Perturbed	10, 26, 27	9, 12, 12	33

7. Spectral Analysis of Micro Pulsations

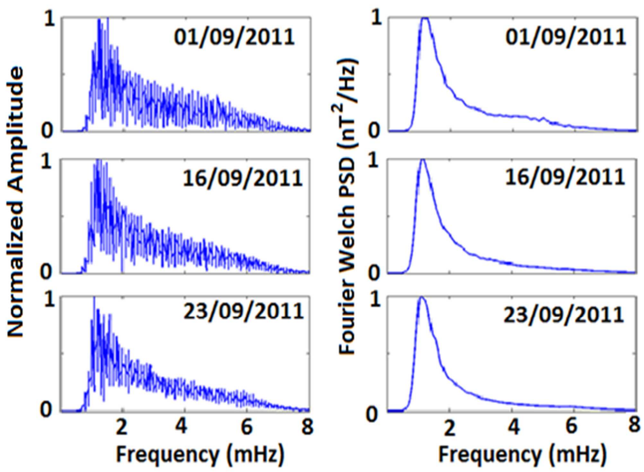

Fig. 13. *Normalized values of amplitude and PSD of horizontal component H on calm days (1, 16 and 23) of the month of September 2011, at station Centenário (CEN).*

Spectral analysis was carried out with the purpose of understanding mechanisms of generation and propagation of micro pulsations Pc5 and Pc6 at low latitudes of the Amazon region in northern Brazil and their interactions with SAMA anomaly. The frequency band chosen for this purpose is 1mHz to 6.7mHz.The technique employed is based on the classical Fourier – Welch method [32, 33 and 34] that included the normal steps of segmentation and windowing of the data sets and the techniques of overlap for minimizing the variance in observational data. For reasons of brevity, we present here only the results of spectral analysis for data gathered at the stations of Centenário (CEN) andJuába (JUA).

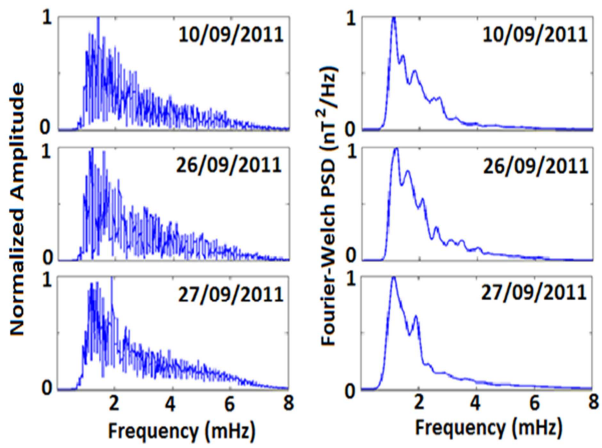

Fig. 14. *Normalized values of amplitude and PSD of horizontal component H on perturbed days (10, 26 and 27) of the month of September 2011, at station Centenário (CEN).*

Figure (13) refer to results of spectral analysis of data obtained for calm days (1, 16 and 23) of the month of September 2011, at station Centenário (CEN). The left panel of this figure illustrates the variations in spectral amplitude before filtering and the right panel illustrates the changes in power spectral density (PSD) after filtering. It is simple to note that the dominant frequency is 1mHz and the amplitudes in both panels decrease with increase in frequency.

Figure (14) refer to similar results of spectral analysis of data obtained for perturbed days (10, 26 and 27) of the month of September 2011 at station Centenário (CEN). In this case, however, the right panel of power spectral density point to the presence several weaker frequency components, in the interval of 0.001 to 0.006 Hz. The periods associated with the main frequency components are listed in Table (4). It is clear that the power spectrum is relatively smooth during periods of calm days (1, 16 and 23), but has several secondary peaks during perturbed days (10, 26 and 27).

Such variations in power spectral density hold important information on the physical processes taking place near the EEJ. Unfortunately, there are no consensus in interpretation of such variations. In view of the limitations of the data set, we considered fits assuming exponential and linear trends, illustrated respectively in the upper and lower panels of Figure (15). The linear fit in the lower panel imply that PSD spectrum may contain two distinct trends: a sharp linear decrease in the frequency range of 0.001 to 0.0025 Hz, followed by a very weak linear dependency for frequencies higher than 0.003 Hz.

Table 4. *Periods and power spectral densities (PSD) of the main frequency components of micro pulsations, for perturbed day 16 of September 2011, at station Centenário (CEN).*

Period (s)	PSD	Period (s)	PSD
907.1	1	628.6	0.694
888.6	0.993	616.8	0.699
865.2	0.975	609.6	0.701
658.7	0.692	606.8	0.701
650.5	0.690	604	0.701
640.9	0.691	601.2	0.701

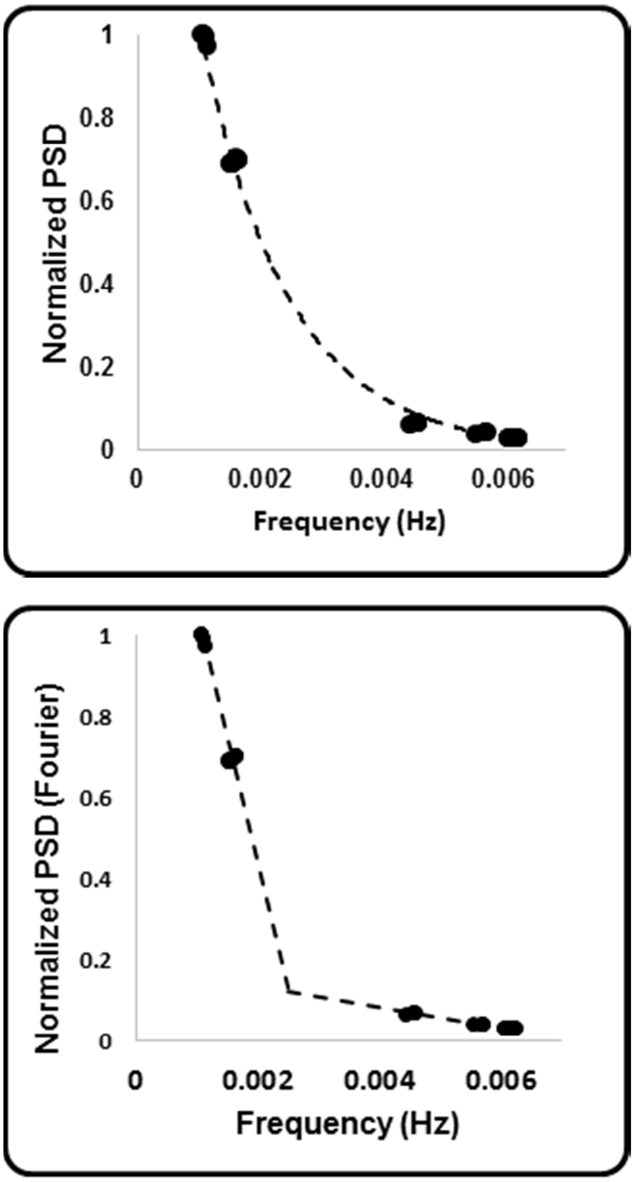

Fig. 15. *Possible interpretations of PSD variations with frequency. The trend illustrated in the upper panel assumes an exponential dependence while those in the lower panel indicate possible linear fits.*

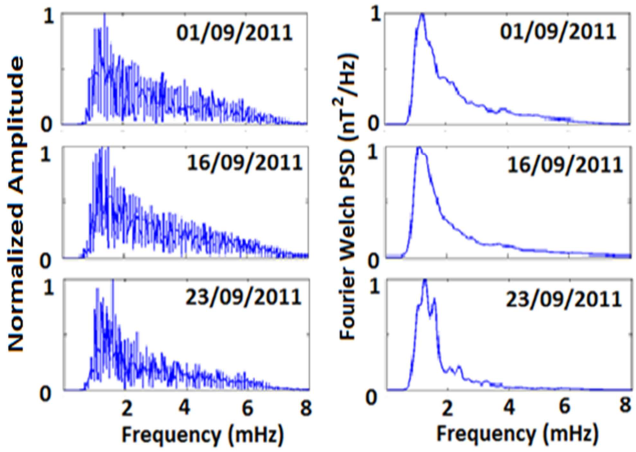

Fig. 16. *Normalized values of amplitude and PSD of horizontal component H on calm days (1, 16 and 23) of the month of September 2011, at station Juába (JUA).*

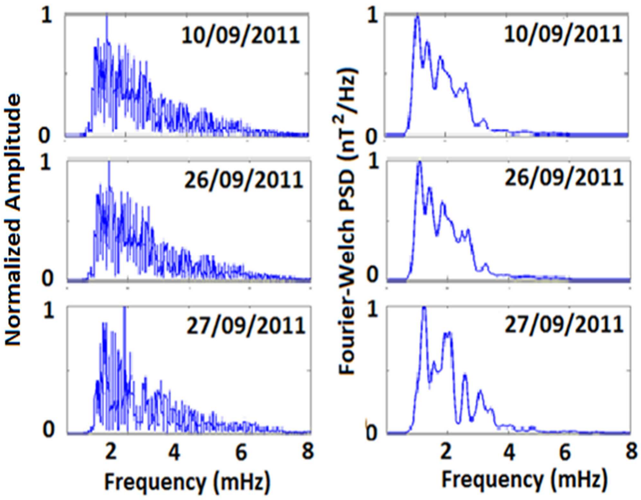

Fig. 17. *Normalized values of amplitude and PSD of horizontal component H on perturbed days (10, 26 and 27) of the month of September 2011, at station Juába (JUA).*

Presented in Figures (16) and (17) are results of spectral analysis of data obtained, respectively for calm days (1, 16 and 23) and perturbed days (10, 26 and 27) of the month of

September 2011, at station Juába (JUA).

The periods associated with the main frequency components are listed in table (5). It is clear that the power spectrum is relatively smooth during periods of calm days (1, 16 and 23), but has several secondary peaks during perturbed days (10, 26 and 27). Note that the PSD values of secondary peaks in the records obtained at JUA are larger, when compared with those at CEN. It is considered as a consequence of the attenuation of micro pulsations with distance from EEJ.

Table 5. *Periods and power spectral densities (PSD) of the main frequency components of micro pulsations, for perturbed day 10 of September 2011, at station Juába (JUA).*

Period (s)	PSD	Period (s)	PSD
989.2	1	247.8	0.05304
740.5	0.7946	219.9	0.04154
553	0.46932	212.1	0.0388
375.6	0.25991	209.9	0.03892
302.7	0.12511	191.3	0.02954
269.4	0.0626	177.4	0.02714

8. Conclusions

The present work has its focus on analysis of geomagnetic field variations recorded at six sites in the eastern parts of the Amazon region. The results have contributed to a better understanding of diurnal variations and the relative influence of Equatorial Electro Jet (EEJ) at low latitudes in northern Brazil. Limitations of the data set do not allow rigorous statistical tests on the nature of this variation. Nevertheless, there are indications that the decrease in the horizontal and vertical components of geomagnetic fields with distance from EEJ may follow an inverse power law. It implies that horizontal and vertical variations in magnetic fields at heights closer to the source regions of EEJ are likely to be greater when compared with values recorded by ground level magnetometers. Model studies reveal that the center of symmetry of EEJ variations is located at the mean latitude of approximately two degrees north. Comparison with results of earlier studies point to a northward shift of four degrees in the position of EEJ, during the period of 1999 to 2011.

Analysis of data sets of the present work have also contributed to a better understanding of higher frequency variations in geomagnetic field at ground level. The occurrences of micro pulsations with amplitude greater than two nT are found to be larger in number during perturbed periods relative to those of the calm periods. Results of spectral analysis reveal that variations in amplitude and power spectral density of micro pulsations have distinctly different characteristics during calm and perturbed periods of geomagnetic fields. There are indications of two distinct trends in the frequency dependence of PSD. For frequencies less than 0.0025 Hz the decrease in PSD follow a liner trend. However, for frequencies higher than 0.003 Hz the variations in PSD are nearly independent of frequency.

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