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Latitudinal dependence of cosmic noise absorption in the ionosphere over the SAMA region during the September 2008 magnetic storm

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[1] In this work we present and discuss some results of latitudinal dependence in the cosmic noise absorption (CNA) as observed by the South American Riometer Network (SARINET) operated in the South American Magnetic Anomaly (SAMA) region, during a moderate intensity geomagnetic storm that occurred on 3 September 2008. In our analysis, we used the data acquired by the imaging riometers installed at São Martinho da Serra (SSO - geographic coordinate: 29.4°S, 53.1°W), Concepcion (CON - geographic coordinate: 36.5°S, 73.0°W) and Punta Arenas (PAC - geographic coordinate: 53.0°S, 70.5°W) and by the single beam riometer installed at Trelew (TRW - geographic coordinate: 43.1°S, 65.2°W). A comparison among the selected riometer data showed that the mean CNA was more pronounced at SSO, which is the site located nearest to the center of the SAMA, but the second highest value was found at the farther station. Also, a second-order polynomial curve fitting was performed in order to establish an empirical relationship between the mean CNA and the total intensity of the geomagnetic field at the riometer stations.

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1. Introduction

[2] Energetic particles from the Van Alley radiation belts can penetrate into the ionosphere down to about 100 km where they precipitate causing enhanced ionization in the E- and D- regions. This source of ionization and the resulting increase of electron density can be a dominant cause of cosmic noise absorption (CNA) in the ionosphere over the South America Magnetic Anomaly (SAMA) region [*Abdu et al.*, 2005]. The CNA depends on the product of electron density and the electron frequency collision, integrated along the path of the cosmic radio wave propagation and it can be measured using the technique based on Riometers (Relative Ionospheric Opacity Meter) that use broad beam antenna arrays. The technique of measuring the CNA was first introduced early in the 1950s by *Mitra and Shain* [1953] that utilized simple and sensitive receivers. The riometer technique was subsequently implemented during the International Geophysics Year [*Little and Leinbach*, 1959]. *Detrick and Rosenberg* [1988] described the first Imaging Riometer for Ionospheric Studies (IRIS), which used several individual antennas and a phasing system to build a multiple narrow beam array to observe the CNA arising from spatial structures in the ionosphere.

[3] The SAMA is a wide geographic region in which the intensity of geomagnetic field has the lowest value over the Globe. As a result, enhanced atmosphere-magnetosphere interaction occurs leading to the precipitation of inner radiation belt energetic particles that can modify the ionization distribution and hence the conductivity spatial structure in the ionosphere over SAMA. Therefore, it has been a topic of great research interest and investigations have been conducted during the last decades by means of different diagnostic techniques. *Abdu et al.* [1973] carried out pioneering investigations in the SAMA Brazilian sector over the Itapetinga Radio Observatory, located at Atibaia (−23° 11′ S, 45°W). They detected an azimuthal drift in the electron precipitation inside SAMA during the sudden commencement of the great magnetic storm that occurred on 4 August 1972. *Nishino et al.* [2002] presented results on spatial structures of CNA and described the dynamics of the electron precipitation over the Southern Space Observatory (SSO/CRS/CCR/INPE – MCT), using the first IRIS operated in the American sector. They observed an eastward drift of unusual absorption regions caused by precipitation of electrons of ∼20 keV. In a more recent study, *Nishino et al.* [2006] reported ionospheric

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Table 1. Basic Features of SARINET Equipment

	IRIS	Single Channel
Antenna array	two-dimensional co-linear co-array of 16 half-wavelength dipoles (4 × 4)	One dimensional wide beam dipole
Antenna at HPBW	~22°N-S and ~ 22°E-W	180°N-S and ~120°E-W
Operating frequency	38.2 MHz	38.2 MHz
Time resolution	4 s	1 s
Field-of-view at 100 km	~200 km in both N-S and E-W directions	~340 km in N-S direction
Number of receptors	4	1

absorptions detected during the great magnetic storm of 15 July 2000 (the "Bastille Day Storm") with the IRIS system at the SSO, which were attributed to the precipitation of low energy protons (~40 keV).

[4] The above studies are the few reports so far available from ground-based observations concerning CNA events in the SAMA region. Although these studies are of great relevance they were carried out at a single site. Furthermore, they could not measure the spatial scale of the absorption, because the region of the absorption extended to several degrees of longitude and latitude beyond the field-of-view of the riometers. This difficulty has been overcome using an observational network consisting of seven IRIS and 17 single beam riometers in the American sector: the South American Riometer Network (SARINET). It was established as an important tool to investigate CNA phenomena of the SAMA region.

[5] The present work takes advantages of the SARINET network to measure the spatial extension of the CNA events over SAMA region during a disturbed period that occurred on 3 September 2008. Data from the IRIS installed at SSO, Concepcion (CON) and Punta Arenas (PAC) and simple riometer at Trelew (TRW) are used in this study. The disturbed period around 3 September is characterized as a moderate intensity geomagnetic storm with peak intensity in the *Dst* of −51 nT at ~04 UT on 4 September. The duration of main phase was ~3 h and the recovery phase extended until 6 September, i.e., all the data covers the same disturbed period.

2. Observations and Data Analysis

[6] The basic features of SARINET equipment are summarized in the Table 1. The equipment installed at SSO, CON and PAC is of IRIS type, whereas the riometer installed at TRW is of a single antenna type. Therefore, we have used the data acquired from the most central antenna for the IRIS array to allow a direct comparison between all the equipment.

[7] The first step in the data analysis is the determination of the Quiet Day Curve (QDC) for each antenna used, which represents the cosmic noise intensity variation expected over a sidereal day in the absence of any geomagnetic disturbance. It should be noticed that the QDC may present a small seasonal variation due to the solar ionization variation in the lower ionosphere. A technique based on two criteria of data selection and statistical methods of data analysis was used in this work in order to obtain the QDC. The first criterion is the monthly selection of IRIS data according to the geomagnetic activity level based on the 3-hourly *Kp* index values. Accordingly, in this work the QDC was determined with the cosmic noise data acquired on quiet days for which *Kp* was ≤3 (in August 2008), close to the geomagnetic storm. The second criterion is the application of a mathematical process to eliminate radio interference on the cosmic noise measurements. For more information and detailed description, see J. Moro et al. (A comparison of two different techniques for deriving the quiet day curve from SARINET riometer data, submitted to *Annales Geophysiae*, 2011).

[8] The UT diurnal variations of the cosmic noise intensity from the riometers installed at SSO, CON, TRW and PAC during 3–6 September are shown in the graphs of Figure 1. The vertical axis of each graph shows the signal power. The graphs are shown from top to bottom with increasing geographic latitude of the stations. The daily variations of cosmic noise are shown in blue and the estimated QDC is in red. The time line at CON, TRW and PAC has been individually shifted in order to align with their respective peaks of the cosmic noise received from the galactic center with that of the curve at SSO. The voltage level shown in all the stations is with respect to its baseline value taken as zero. In addition to the daily variations of cosmic noise and QDC shown in the graphs, we present the *Dst* index variations during the discussed days.

[9] Finally, we use the cosmic noise power on individual days (through 3 to 6 September), P, and the corresponding power from the QDC, P_Q, to calculate the CNA using the equation CNA = 10 log (P_Q/P) (in dB units).

3. Results and Discussions

[10] A simple analysis of the results shown in the Figure 1 reveals that the antenna aperture (HPBW, half power beam width) may certainly interfere in the results obtained from riometers. Since the IRIS antenna HPBW is smaller than that of the single antenna riometer, the galactic center is much better resolved in their curves from SSO, CON and PAC, i.e., the peak in the cosmic noise curve obtained at TRW is broader compared with the other stations. Other features in the Figure 1 are associated to the time variations of the amplitudes of the cosmic noise when compared with the QDC, directly related to the magnitude of the CNA, which is the focus of the present paper.

[11] The daily peak values of the noise power measured by the riometers at each station during the geomagnetic storm are summarized in the Table 2. The results clearly show that the peak value measured by the IRIS at SSO decreased from 7.16 V^2 on 3 September to 4.94 V^2 during the main phase (on 4 September). It decreased even more reaching 3.81 V^2 on 5 September, which is the first day of the recovery phase, already. On 6 September, still during the recovery phase, the cosmic noise shows some recovery, but not to the level prior to the storm yet. The results seen at other stations are dissimilar. Since we believe that the daily cosmic noise peak variation with respect to the geomagnetic storm phases originate from varying degrees of ionospheric absorption, we calculate the corresponding CNA in order to check its evolution with the geomagnetic storm phases at the different stations.

[12] Figure 2 shows the time variation of the hourly CNA from 3 through 6 September 2008 as obtained at each

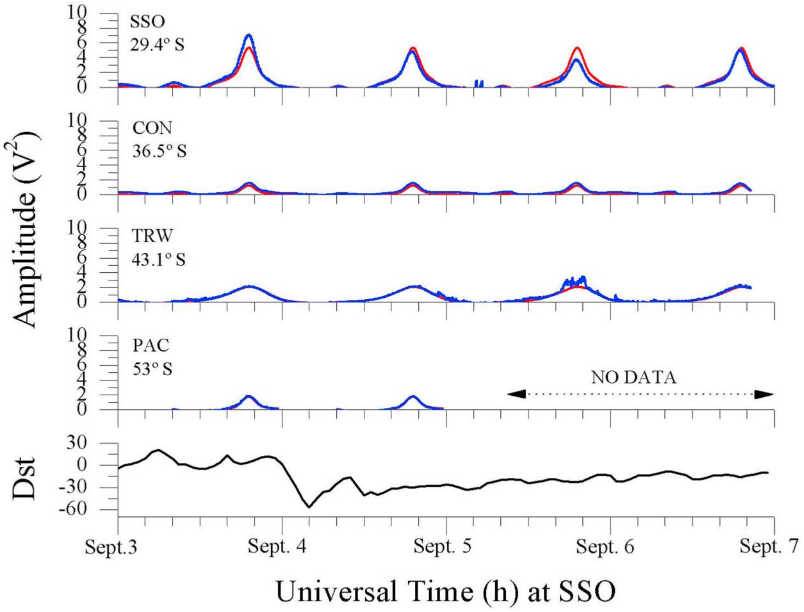

Figure 1. Daily variation of cosmic noise acquired by the riometers installed at SSO, CON, TRW and PAC for 3 to 6 September (blue line), superimposed by the QDC (red line). The name of the stations, its geographic latitude and the *Dst* index are also marked in the figure.

station. The vertical axes in the graphs are set in dB, and the horizontal axes as well as the letters and numbers at each graph are the same as those shown in Figure 1. The CNA at SSO, which was obtained as defined in the previous section, started to increase in the end of 3 September, achieved ~2 dB in the end of 4 September, and reached the highest value (~3 dB) on 5 September. Further, at SSO the CNA continued with values around 1 dB on 6 September, with a peak that reach 2 dB. However, like we observed for the voltage level, CNA with similar intensity as that at SSO are not seen at CON, TRW and PAC.

[13] We calculated the mean CNA (μCNA) for each station when simultaneous CNA values were detected over at least two or more stations. The results are presented in Figure 3. In this figure we show four graphs of the obtained μCNA plotted against the: a) radial distance to the center of SAMA (R), considering that the central region of SAMA is located close to 25°S and 55°W; b) the total intensity of the geomagnetic field (F); c) the inclination angle of the geomagnetic field (DIP); and d) the declination angle of the geomagnetic field (D). These values of the geomagnetic field were taken by the IGRF model. The standard deviation associated with each point is also shown. Furthermore, the number of data points used to calculate the μCNA is provided in the Figure 3a.

[14] From the separations of the points regarding to the ordinates axis in the Figure 3a, we may note that SSO is the station closest to the center of the SAMA, being at about 600 km, and CON and TRW are close to each other, at about 2000 km from the SAMA center, while PAC is the most distant station, located at about 3500 km farther away from the center. However, it seems not to be the proximity of the SAMA the only factor that controls the intensity of the μCNA. SSO shows the highest values of μCNA with 0.56 dB, but the second highest value of μCNA is 0.27 dB obtained at PAC station. The μCNA values from CON and TRW are both close to 0.22 dB, despite these stations to be closer to the center of the SAMA than the PAC station.

[15] It is expected that the lower the geomagnetic field, the deeper the penetration depth and hence the precipitation of the energetic particles in the atmosphere. As a result the level of ionization produced in the D region increases resulting in higher absorption level of cosmic radio waves. Therefore, to provide the relationship of the μCNA and the geomagnetic field total intensity at each riometer site location, we present the Figure 3b. It may be noted that the PAC station registers

Table 2. Geomagnetic Latitude and Maximum Amplitude (V^2) of Cosmic Noise of the Individual Days and of QDC Measured by the Riometers Installed at SSO, CON, TRW and PAC for 3 to 6 September

			Cosmic Noise Level (V^2)			
Code	Geomagnetic Latitude	QDC (V^2)	3 September	4 September	5 September	6 September
SSO	−20.9°	5.32	7.16	4.94	3.81	5.09
CON	−23.5°	1.22	1.60	1.57	1.58	1.50
TRW	−30.6°	2.06	2.20	2.21	2.29	2.38
PAC	−39.2°	1.75	1.85	1.88	none	none

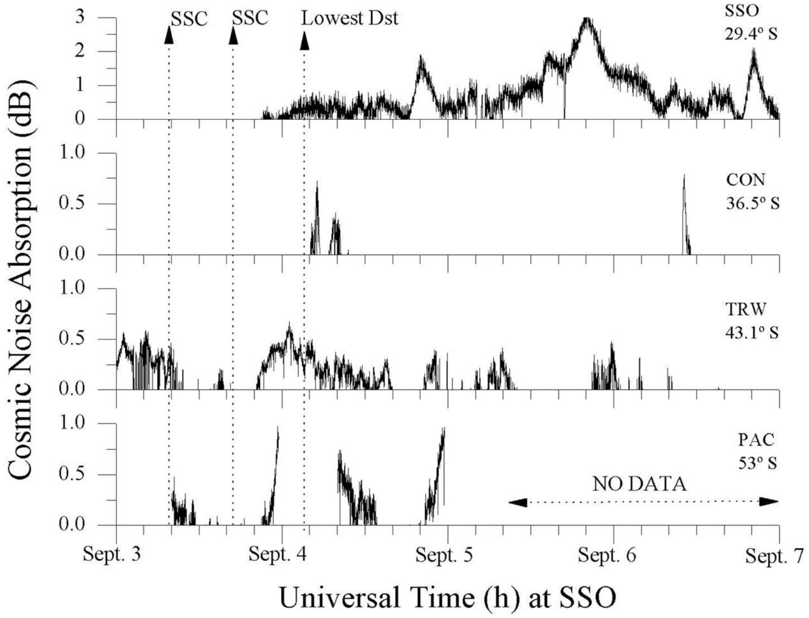

Figure 2. Cosmic noise absorption calculated with the data acquired by IRIS installed at SSO, CON and PAC and the single antenna riometer at TRW for 3 to 6 September. The times of SSC and the lowest *Dst* are indicated by the dotted lines.

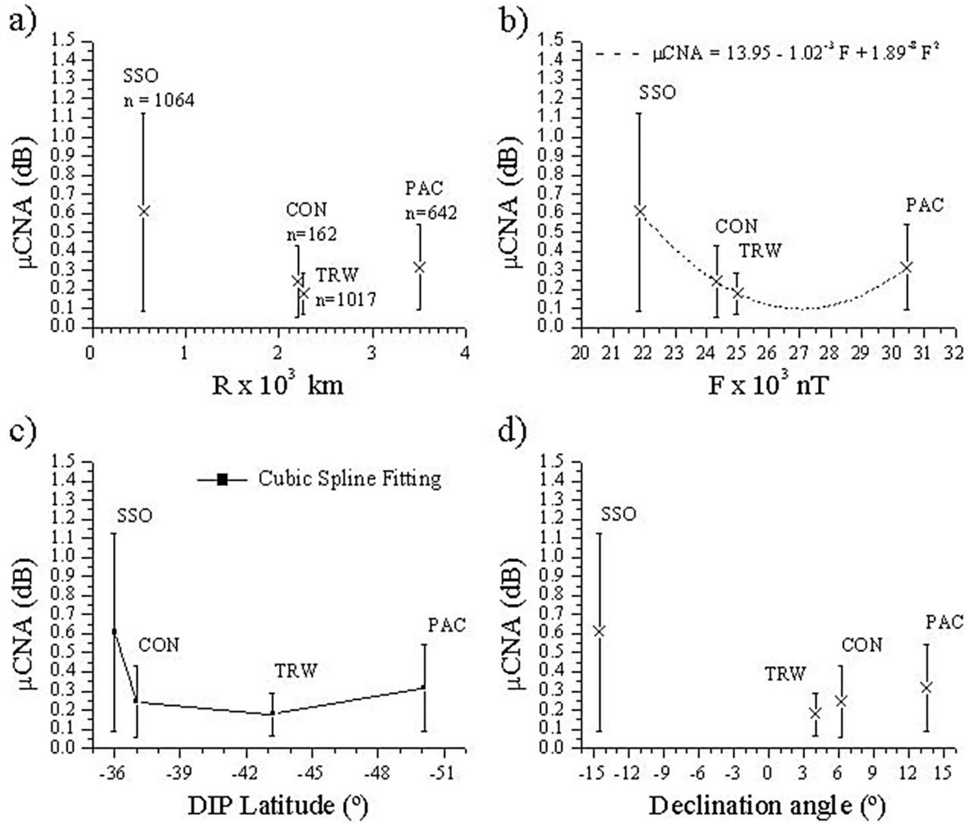

Figure 3. The μCNA over SSO, CON, TRW and PAC plotted against the (a) radial distance to the center of the SAMA; (b) total geomagnetic field intensity at the site location; (c) DIP latitude of the corresponding station; and (d) declination at the riometer site. The dotted line in Figure 3b is the polynomial fitting to the μCNA and the equation is provided in the graph. The station name is indicated in each panel.

higher values of absorption than CON and TRW, even under a total field (30000 nT) being higher than that of the latter stations. So, it reinforces the theory that something else other than the total field is driving the energetic particle precipitations in the present case, whose contribution appears to increase with latitude.

[16] Based on the data from only the four stations that we used, we attempted to establish an empirical relationship between the μCNA and F, by performing a second-order polynomial curve fitting to the data (the dashed line superimposed in the graph of Figure 3b). It resulted in the following equation:

$$\mu\text{CNA} = 13.95 - 1.02^{-3}\,\text{F} + 1.89^{-8}\,\text{F}^2, \quad (1)$$

with an adjusted R-coefficient of determination equal to 0.99. Based on this polynomial relationship, a minimum of μCNA (0.2 dB) should be found around 27000 nT. However, it should be noted that this result is obtained using only four points and this may introduce bias to the fitting. In spite of that, we believe that there could be some minimum close/around to this magnetic field level since the μCNA measurements made at CON and TRW are truly lower than that made at PAC. Therefore, admitting the limitations of the accuracy of this empirical relationship we may state that it certainly gives a general picture on how the riometers measurements should behave during a magnetic storm when the station are located between SSO and PAC close to the SAMA region.

[17] In addition to the result obtained of the μCNA with respect to the magnetic field total intensity of location of the riometer stations as provided by equation (1), we also evaluated the μCNA versus the corresponding values of DIP angle (Figure 3c) and versus the declination angle (Figure 3d) measured at each riometer station.

[18] We may observe an interesting feature in Figure 3c that shows the variation of the μCNA as a function of DIP angle. The station CON substantially approaches the SSO station (the closest station to the SAMA center), while TRW is set at larger separation with respect to the CON. However, the most important feature is that the station PAC is still the most distant one, being located at about 50° S, and that the polynomial "shape" is respected.

[19] The last evaluation of the μCNA was performed against the declination angle (Figure 3d) since it is well known that the Brazilian sector is characterized by a large declination (about $-20°$, depending on the longitudinal sector). This last graph clearly shows that SSO is the only station with negative declination, i.e., the magnetic fields are westward oriented at SSO while they are eastward oriented for the other stations. This evaluation was included to provide a picture on how the plasma should flow in case of transport from an area away from the station to the area overhead the riometer. Since the collision frequencies are expressively high compared to the cyclotron frequencies at D region, plasma transport should not be an important issue when considering the drifts at this height. However, the same is not true for the F region and the plasma drift at the F region may occur. But the result of the Figure 3c make it clear that the SSO riometer overhead area is sufficiently far from Antarctic location than are that of CON, TRW and PAC riometers, so that we may rule out any possibility of plasma drift controlled by magnetic field lines from PAC through SSO.

[20] Based on the results presented in the Figure 3, we may state that the μCNA absorption reach its higher value closer to the SAMA region, which explicitly imposes the influence of the magnetic anomaly to the radio wave absorption. Also, there certainly is higher μCNA absorption at PAC than those ones at CON and TRW, independent of the radial distance of the riometer sites to the SAMA center and of the "candidate" variable (F, DIP and D) used to locate each station with respect to the geomagnetic field. A tentative explanation for this higher μCNA absorption can be thought of in terms of expansion of auroral oval to lower latitudes during the magnetic storm and its effect to influence the energetic particle precipitations close to PAC and/or the plasma transport to overhear PAC region. Also, based on the result shown in the Figure 3d, we may say that if the plasma transport is performed at the F region height the auroral region feeding SSO and PAC are different.

[21] With respect to the expansion of auroral oval and in order to evidence this idea, we present 1 min time resolution of magnetometer data in the graphs of Figure 4. The graphs show the H-component of geomagnetic field acquired from 3 to 6 September (thick line), superimposed by quiet time data as reference (thin line). The H-component was measured at TRW and Port Stanley Magnetic Observatory (PST - geographic coordinate: 51.7°S, 57.9°W, and geomagnetic coordinate: 42.1°S, 12.0°E). An analysis of the results shown in Figure 4 reveals that the H-component variations obtained during the geomagnetic storm are consistent from one station to another. The H-component showed magnetic fluctuations during the first four hours of 3 September, with similar variations to the quiet time values for both stations. Also, positive excursions were observed between 4 and ~8 UT, when the first sudden storm commencement (SSC) occurred. Nevertheless, when the SSC occurred (~17 UT), positive excursions were observed only at PST. During the main phase of geomagnetic storm, a sharp decrease to a minimum intensity in H-component was observed at TRW and PST (see also *Dst* index in Figure 1). These behaviors were probably caused by injections of energetic particles into the radiation belt, followed by energetic particles precipitation especially in the oval auroral. Moreover, the H-component also had large fluctuations during the recovery phase, always below than the quiet time period. Based on these results, we may state that it is an evidence of ionospheric currents development during the recovery phase of geomagnetic storm and consequently, higher μCNA absorption at PAC than those ones at CON and TRW.

[22] With respect to the particle precipitation alone, *Rodger et al.* [2006] investigated detailed comparison between theoretical cutoff rigidities and IRIS measurements at Halley, in Antarctica, during the geomagnetic storm occurred on 4–10 November 2001. They pointed out that the cutoff rigidities moves equatorward as the geomagnetic activity levels increase. They state that this equatorward movement of the cutoff rigidities is due to the fact that the protons with higher energies can penetrate to very low latitudes during disturbed periods. These high energy protons are the kind of energetic particles that should cause the

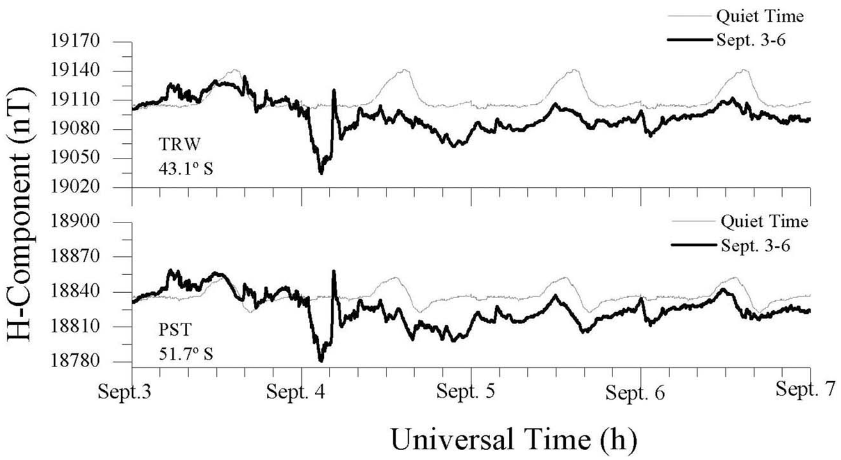

Figure 4. H-component of geomagnetic field from 3 to 6 September 2008 (thick line), superimposed by quiet time data (thin line), measured at TRW and PST. The name of each station and its geographic latitude is also marked in the figure. The time resolution is 1 min.

increase of μCNA, especially at the SAMA and at the auroral region.

[23] *Buonsanto* [1999] pointed out that the energetic particle precipitation at high latitudes should expand the auroral zone equatorward and increase the ionospheric conductivities. Both effects could transport the plasma to lower magnetic latitudes during disturbed periods. However, the effect is expected to be dominant at higher heights well above the E layer, and as such may explain in part the higher μCNA absorption observed at PAC, when compared to those ones at CON and TRW (Figure 3b). The μCNA absorption at SSO is the highest due to the lower magnetic field imposed by the SAMA, which in turn allows the particle to penetrate deeper in the atmosphere.

[24] Indeed, *Hashimoto et al.* [2011] used the magnetometer array and the SuperDARN observations to study the northern auroral region and reported overshielding from the subauroral to the equatorial latitudes at the onset of substorms, which is accompanying by the increase in the convection electric fields at the F region. This is an indication that the transport due to convection electric fields plays important role in the plasma drifts at and close to the auroral region. Unfortunately, similar study was not performed at southern hemisphere so far. Notwithstanding, we believe that the same mechanism pointed out by *Hashimoto et al.* [2011] might be acting during the event we study in present paper. Therefore, the plasma transport from auroral region to overhead PAC riometer would be a probable explanation for the increasing the μCNA during the geomagnetic storm over PAC.

4. Summary and Conclusions

[25] We have shown that the antenna aperture of the riometer belonging to the SARINET array may modify the shape of the diurnal curve of the cosmic noise intensity in relation to that of the single beam riometer, as a result of the broadness of the IRIS antenna beam being smaller than that of the conventional one.

[26] We calculated the μCNA for four riometer stations in the South America (close to SAMA and southward) during the magnetic storm that occurred on 3 September 2008. The station closest to the SAMA center presented highest μCNA (0.56 dB) but the second highest value of μCNA (0.27 dB) was found at the farther station. Also, we performed a second-order polynomial curve fitting in order to establish an empirical relationship between μCNA obtained along with the four stations and the total intensity of geomagnetic field.

[27] The larger μCNA absorption observed closer to the SAMA region demonstrated the influence of the geomagnetic anomaly to the storm time radio wave absorption. In addition, the higher μCNA absorption observed at PAC when compared to those at CON and TRW is explained in terms of an expansion of auroral oval to lower latitudes during the geomagnetic storm. As a result, this expansion plasma transport may occur to lower magnetic latitudes at the F region heights.

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