ON THE DETERMINATION OF LOWER IONOSPHERIC PERTURBATIONS DETECTED AS FAST AMPLITUDE VARIATIONS OF VLF SIGNALS

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ABSTRACT

We analyze the occurrence of very low frequency (VLF) events and their association with geomagnetic activity. VLF events are detected as fast amplitude variations of VLF signals from Hawaii (NPM Navy transmitter) and received at Comandante Ferraz Brazilian Antarctic Station (EACF) in the period from September through November 2003. The results show VLF events occurring predominantly during the recovering phase of geomagnetic storms produced by high speed solar wind streams (HSSWSs), and by coronal mass ejections (CMEs) which were accompanied by HSSWSs impacts before returning to quiet geomagnetic level. Based on these results, and upon the good association of VLF events with enhancements in the energetic electron flux of the radiation belts, we suggest they might be the ionospheric response to the energetic electrons precipitated from the radiation belts which were predominantly scattered by whistler-mode waves generated by the electrons injected in the magnetosphere during geomagnetic activity produced by HSSWSs.
Key-words: Ionosphere, particle precipitation, geomagnetic storms.

RESUMO

DETERMINAÇÃO DAS PERTURBAÇÕES DA BAIXA IONOSFERA DETECTADAS COMO VARIAÇÕES RÁPIDAS DOS SINAIS VLF. Analisamos a ocorrência de eventos de freqüência rádio muito baixa (VLF) e sua associação com a atividade geomagnética. Os eventos VLF são detectados como variações rápidas de amplitude dos sinais VLF transmitidos da estação do Havaí (NPM – Marinha dos EUA) e recebidos na Estação Antártica Brasileira Comandante Ferraz no período de setembro a novembro de 2003. Os resultados mostram que os eventos VLF ocorreram predominantemente durante a fase de recuperação das tempestades geomagnéticas produzidas pelo vento solar de alta velocidade (HSSWSs), e por ejeções de massa da coroa solar que foram acompanhadas pelo impacto de HSSWSs antes da atividade geomagnética retornar ao nível calmo. Baseando-se nestes resultados, e devido à boa associação dos eventos VLF com os aumentos no fluxo dos elétrons energéticos dos cinturões de radiação, sugerimos que eles podem ser a resposta ionosférica aos elétrons precipitados dos cinturões de radiação os quais foram predominantemente espalhados por ondas no modo *whistler* que foram geradas pelos elétrons injetados na magnetosfera durante atividade geomagnética produzida por HSSWSs.
Palavras-chave: Ionosfera, precipitação de partículas, tempestades geomagnéticas.

INTRODUCTION

Perturbations in the low ionosphere can be monitored by very low frequency (VLF - 3 trough 30 kHz range) waves propagating over long distances within the Earth-ionosphere waveguide. Bursts of energetic electrons (> 40 keV) produce local density enhancements in the low ionosphere, which cause significant variations in the amplitude and phase of the VLF waves. These bursts are electrons from radiation belts that precipitated into the atmosphere basically by wave-particle interaction. The fast amplitude variations of VLF waves (called here VLF events) are detectable only during nighttime when the ionosphere is not saturated by the solar radiation. VLF events are chacterized by fast amplitude and phase variations, and have been attributed to the interaction between the radiation belts electrons and the whistler waves generated by lightning, the called lightning-induced electron precipitation events - LEP (e.g. Helliwell *et al.* 1973, Inan *et al.* 1978, Inan & Carpenter 1987). On the other hand, statistical analysis of VLF events has shown they occur predominantly during the equinoxes similarly the geomagnetic storms (Fernandez *et al.* 2003), and some case studies had shown a lack of correlation between their occurrence and the lightning incidence (Peter & Inan 2004) with a suggestive better association with geomagnetically disturbed periods (Peter & Inan 2004, Correia *et al.* 2007). In order to study in more detail the association between the VLF events and the geomagnetic activity we analyze the occurrence of the events detected at Comandante Ferraz Brazilian Antarctic Station (EACF), located on the Antarctic Peninsula (62°34'S, 58°23.5'W), in the period from September trough November 2003, which was a very geomagnetically active period.

OBSERVATIONAL RESULTS

At EACF we have monitored the amplitude of propagating VLF transmitter signals operated by the United States Navy in Washington (NLK at 24.8 kHz), Maine (NAA at 24.0 kHz), Hawaii (NPM at 21.4 kHz), and Puerto Rico (NAU at 40.75 kHz). The data are detected with 10 ms time resolution using a tunable VLF receiver (Johnson *et al.* 1999). Here we analyze the amplitude of VLF signals received from Hawaii NPM transmitter, which has the best signal/noise ratio at EACF. The daily VLF data were inspected during the nighttime in the NPM-EACF great circle path (00:40 to 12:00 UT, from 00:00 to 8:00 MLT) in the period from September trough November 2003. The nighttime duration was about 5 hours in the beginning of September and decreased to about 2 hours in the middle of November (Figure 1), when it is starting the summer season in the southern hemisphere and there is almost no night at EACF. The decreasing nighttime duration means that after the middle of October the period VLF events are detectable is reduced, which results in a smaller observation time window and thus relatively lower numbers.

In this analysis were selected all VLF events with signal/noise ratio above 3. Examples of VLF events detected on October at EACF from NPM transmitter are in Figure 2, which shows they have fast amplitude variation (1 s) and a slower recovering time (10 – 600

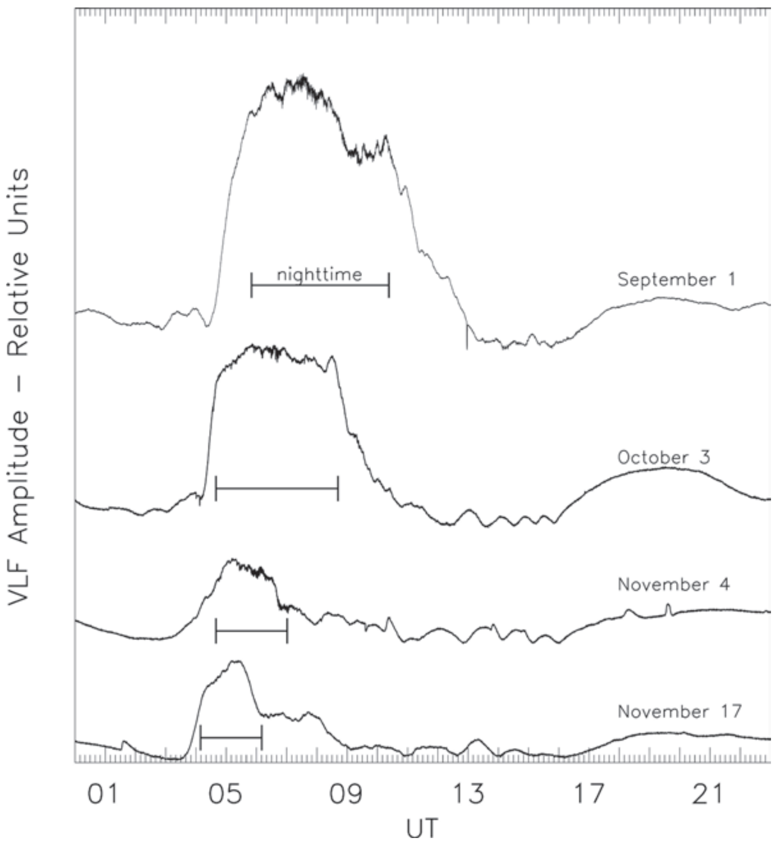

Figure 1. Examples of daily VLF signals detected at EACF from NPM transmitter showing the nighttime duration from September through middle November 2003.

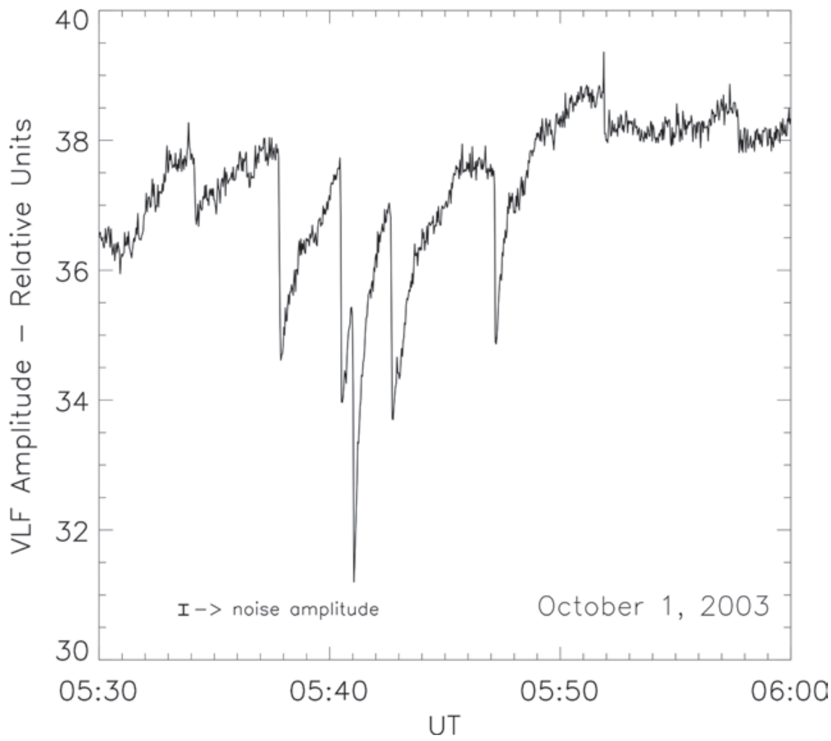

Figure 2. Examples of fast VLF events detected at EACF on October 1st 2003 in the great circle path EACF-NPM.

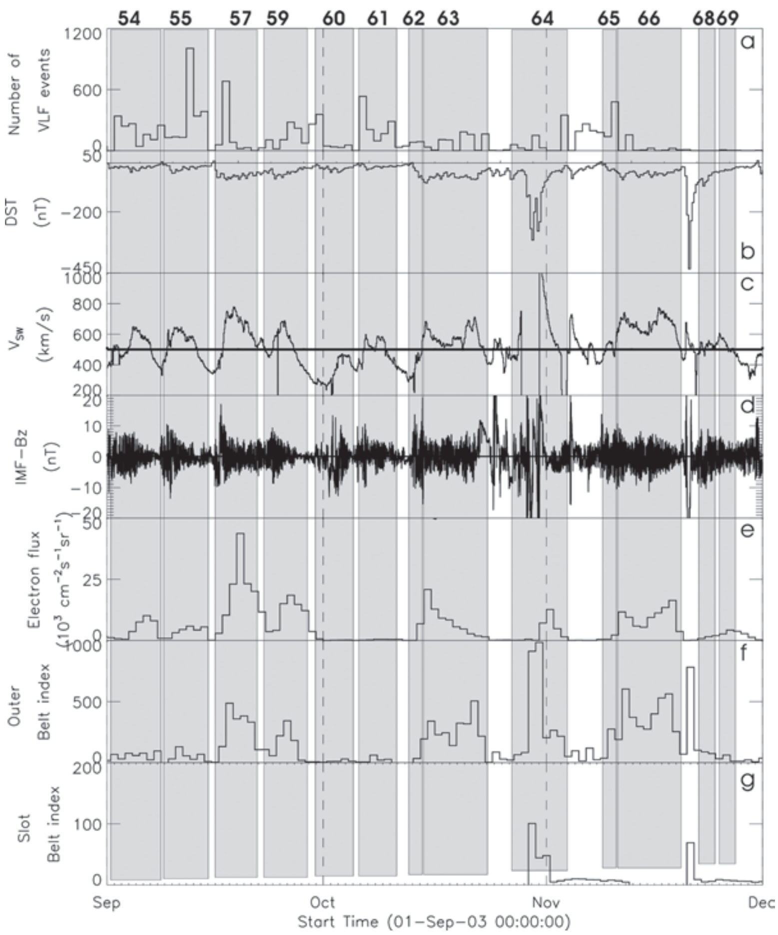

Figure 3. Number of fast VLF events detected per day at EACF (a) and their association with the: (b) geomagnetic activity index - Dst, (c) solar wind speed (ACE data), (d) Bz component of the IMF (ACE data), (e) E > 2 MeV electron flux at geostationary orbit (GOES data), and belt indices representative of E > 100 keV electron flux in the outer (f) and slot (g) regions of radiation belts (POES data).

s). The number of selected events per night is in Figure 3, which shows: (a) daily number of VLF events, (b) geomagnetic activity as estimated from Disturbance Storm Time (Dst) index, (c) solar wind speed (ACE data), (d) Bz component of the interplanetary magnetic field – IMF-Bz (ACE data), (e) E > 2 MeV electron flux at geostationary orbit (GOES data), and E > 100 keV electron population of the (f) outer and (g) slot zones of the radiation belts (POES satellite) given by the POES Belt Indices (defined in http://www.sec.noaa.gov/tiger/BeltIndices.html).

The daily number of VLF events (Figure 3a) shows increases in close association with geomagnetic activity (Figure 3b), and they occur predominantly during the recovering phase of the geomagnetic storms, but in some cases also in the main phase. The geomagnetic activity in this case study was predominantly of moderate storms (-50 > Dst > -100 nT) due the impact of high speed solar wind streams (HSSWS) from coronal holes, but also presented two strong storms (Dst < -300 nT), in the end of October and middle of November, which were produced by coronal mass ejections (CME) that are accompanied by the impact of HSSWSs before returning to quiet geomagnetic levels. The geomagnetic activity produced by HSSWS is characterized by periods the solar wind speed stays above 500 km/s and IMF-Bz (Figure 3d) highly fluctuating with amplitude ≥ 5 nT (Gonzalez *et al.* 1999), which are marked by shaded areas in Figure 3 and the coronal hole they originated are identified by numbers in the top of figure (Solar Terrestrial Activity Report, http://www.dxlc.com/solar/coronal_holes.html)

Figure 3 suggests VLF events occur predominantly in association with geomagnetic activity produced by the impact of HSSWSs, achieving relatively higher rates when solar wind speed stays longer times above 500 km/s and IMF-Bz show fluctuations with higher amplitude (≥ 10 nT). Due the reduction of the nighttime duration we can not say much about the number of VLF events during the strongest storms produced by CMEs, but figure suggest they also occur in relatively higher number during the recovering phase of the storm of October, which was accompanied by HSSWS.

The number of VLF events increase in close association with the enhancements of the E > 2 MeV electron flux (Figure 3e) at geostationary orbit (McIlwain parameter L ~ 6), which means during the geomagnetic activity produced by HSSWSs, like in previous observations (Blake *et al.* 1997). The E > 100 keV electron population of the outer region of the radiation belts (2.5 < L < 6), as given by the Outer Belt index (Figure 3f), also shows enhancements in close association with the enhancements of the E > 2 MeV electron flux and the number of VLF events. The maxima of the Outer Belt Indices occur during the main phase of the geomagnetic storms, while the E > 2 MeV electron flux reached their maximum just after that. The population of E > 100 keV electrons of the outer region of radiation belts show most pronounced enhancements during the main phase of the strongest storms, which were produced by the impact of CMEs while the solar wind was under or not completely recovered from the impact of HSSWSs. These pronounced enhancements in the E > 100 keV electron flux in the outer zone were accompanied by the appearance of E > 100 keV electrons in the slot zone of the radiation belts.

DISCUSSION

We have presented the analysis of fast amplitude variations of VLF signals (VLF events) from NPM transmitter detected at EACF, in the period from September through November 2003, a very geomagnetically active period. The results show VLF events occur in close association with enhancements of the geomagnetic activity produced by impact of HSSWSs, which are characterized by solar wind speed above 500 km/s and IMF-Bz highly fluctuating (Gonzalez *et al.* 1999). This study covers a period where the geomagnetic activity was predominantly produced HSSWSs, but also occurred two strong geomagnetic storms. These strong storms present a long duration recovering phase (more than 10 days), like ‘typical’ storms produced by simultaneous impacts of CMEs and HSSWS before returning to quiet geomagnetic level (Gonzalez *et al.* 1999).

VLF events occurred in higher number during the recovering phase of all geomagnetic storms (Figure 3), in close association the E > 2 MeV electron flux increases, which are also accompanied by increases in the E > 100 keV electron population of the outer region of the radiation belts. The close association of VLF events with the enhancements of the energetic electrons in the radiation belts (2.5 < L ≤ 6) suggests they might have a common drive. The enhancements of energetic outer-zone electron flux by several orders of magnitude (Li *et al.* 1997, Meredith *et al.* 2002) are due to acceleration processes inside the Earth´s magnetosphere, which have been attributed to the resonant interaction of 10 – 100 keV electrons with whistler-mode chorus waves generated during the geomagnetic storms produced by HSSWSs (Baker *et al.* 1998, Meredith *et al.* 2002). During this resonant interaction part of the electrons might be accelerated to E > 2 MeV (Nakamura *et al.* 2000, Horne & Thorne 2003, Lyons *et al.* 2005), and part of them might be scattered into the loss cone region producing the electron precipitating bursts (Lorentzen *et al.* 2001, Nakamura *et al.* 2000), which disturb the low ionosphere and produce the observed VLF events.

CONCLUSION

The analysis showed VLF events occur in close association with geomagnetic activity produced by HSSWSs, and achieve higher numbers during the recovering phase of all geomagnetic storms. This behavior, in addition with the good correlation with the increases in the flux of the relativistic electrons of the radiation belts, suggest they are closely related with mechanisms in the inner magnetosphere where intense whistler-mode chorus waves are generated during the impact of HSSWSs (Summers *et al.* 2004). Based on that, we suggest VLF events are mostly the ionospheric response to the electron precipitating bursts induced by the electron resonant interaction with whistler-mode chorus waves generated by the anisotropic 10 -100 keV electrons injected in the magnetosphere during the impact of HSSWSs (Baker *et al.* 1998), than that whistler-waves produced by lightning. A more detailed analysis of the occurrence of VLF events during different geomagnetically disturbed periods is important to better characterize their influence.

In the context of the International Polar Year 2007-2009 and of the International Heliophysical Year, we will give continuity to the VLF and GPS ionospheric soundings at EACF, and we will extended them over the Brazilian territory, using the Brazilian GPS Network operated by Instituto Brasileiro de Geografia e Estatística (IBGE), and the new South American VLF Network (SAVNET), which is already operational with 6 stations (2 - Peru, 1 - Argentina and 3 - Brazil). The main scientific objectives of these two networks, GPS and VLF, are to provide a long-term monitoring of ionospheric parameters related to quiescent and active solar phenomena during daytime and transient perturbations associated with geomagnetic activity and propagation anomalies during nighttime. Another scientific interest is the study of the ionosphere over the South Atlantic Magnetic Anomaly where the effects of geomagnetic perturbations are generally enhanced.

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