Mid- and low-latitude response of the ionosphere to solar proton events on January 2012

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Abstract. We present and discuss the ionosphere behavior under the impact of two X-ray solar flares (M8.7 and X1.7) that occurred on January 23 and 27, respectively, and were accompanied by Solar Proton Events (SPEs). The ionosphere response to these solar phenomena was detected using riometers (30 and 38.2 MHz), ionosonde and VLF systems operating at the Comandante Ferraz Brazilian Station in Antarctica and at the Itapetinga Radio Observatory in São Paulo (SP)/Brazil. The results suggest the ionosphere was affected by both SPEs, as evidenced by absorption detected in the cosmic noise, F2 layer critical frequency and VLF amplitude measurements. These absorptions started before the beginning of the main X-ray flare events and > 100 MeV proton events detected by GOES, suggesting the ionosphere was impacted by protons with energies above 2 GeV in Antarctica and above 10-12 GeV in SP as estimated from the particle geomagnetic rigidity (Rc) at each place. The results also suggest a long-lasting presence (hours) of high energy protons.

1. Introduction
During solar proton events (SPEs), high-energy particles can penetrate deep in the Earth’s atmosphere, depending on the local vertical geomagnetic cutoff rigidity [1,2]. Particles with energies of several tens MeV can reach lower altitudes in the atmosphere only at higher latitudes, while the few GeV particles can do it even at mid-latitude and equatorial region.

Effects of Solar Proton Events (SPEs) in the lower ionosphere at polar region have been detected using riometers [3-6], as well as very low frequency (VLF) radio signals [7-10]. During a SPE there is a lowering of the effective height of the low ionosphere due the enhanced ionization at lower altitudes [11]. The changes in the ionization process affect the radio wave propagation, which can be detected as variation of the cosmic noise, F2 layer critical frequency (foF2) and VLF amplitude.

In this study we evaluate the impact on the ionosphere of energetic protons produced during two SPEs that occurred on 23 and 27 January 2012.

2. Instrumentation and data analysis
The ionosphere behavior is characterized from measurements of the: (a) cosmic noise absorption (CNA) provided by two broad-beam solid state riometers at 30 MHz (La Jolla) and 38.2 MHz (Takushoku University) operating at Comandante Ferraz Brazilian Antarctic Station (EACF, 62.1°S,
58.3°W, Rc~2 GV) and at Itapetinga Radio Observatory (ROI, 23.2°S, 46.6°W, Rc~10 GV), São Paulo/Brazil; (b) foF2 parameter estimated from ionograms obtained at each 5 minutes with a CADI ionosonde operating at EACF; and (c) amplitude of VLF signals transmitted from Hawaii (NPM, 20.4°N, 158.2°W, 21.4 kHz, Rc~13 GV) and detected with AWESOME receivers at EACF and ROI. The VLF propagation paths used here were the NPM-EACF, which is totally over the Pacific Ocean extending from low to middle latitudes; and the NPM-ROI that is predominantly in lower latitudes and partially crossing the South America sector over the Magnetic Anomaly. These instruments provide information of the ionospheric behavior between 60 and 300 km altitude.

The observations at distinct locations with different magnetic rigidity give information about the energy of the precipitating particles. The geomagnetic cutoff rigidity at EACF and at ROI implies that only high-energy protons (E ≥ 2 and E ≥ 10 GeV, respectively) can cross the magnetosphere at those locations.

To analyze the effect of the SPEs in the ionosphere the absorption variations obtained with each instrument at EACF and ROI are compared with the temporal evolution of the solar X-ray emission, and 5-30 MeV and 100-900 MeV proton fluxes observed at geostationary orbit with GOES satellite [13] on 23 and 27 January. These events occurred during a quiet geomagnetic period, in particular the second one occurred when the Kp ≤ 2 and Ap < 10.

The ionosphere behavior was estimated comparing the curves of the days the SPEs occurred with a quiet day curve, which was obtained considering the average of the nearest quiet geomagnetic days.

3. Observational results

3.1. Solar event on January 23, 2012

The SPE on January 23 occurred in association with a M8.7 GOES class solar flare originated in the active region NOAA 11402 located at N25W20 [13]. The solar event characteristics and the observed ionosphere behavior are shown in Figure 1: (a) 1-8 Å solar X-ray flux (Fx), (b) proton fluxes (Fp) at two different energies, (c) CNA at 30 and 38.2 MHz, (d) amplitude and differential amplitude of VLF signals, and (e) foF2 parameter at EACF; and (f) CNA at 30 and 38.2 MHz and (g) amplitude and differential amplitude of VLF signal at ROI. The X-ray event started at ~03:38 UT with maximum at ~04:00 UT, and the >100 MeV proton flux started ~04:10 UT, reaching its peak of ~2 cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) at ~04:50 UT, and remaining high till the end of the day. This X-ray event started during the night hours at EACF (01:00 to 07:05 UT) and ROI (00:00 to 09:00 UT), so the riometer and ionosonde measurements show the effect of energetic particles in the ionosphere. But the ionosphere behavior obtained from the VLF measurements includes the combined effect of X-ray radiation plus energetic particle till 04:18 UT, the sunset time at NPM transmitter location.

The observations suggest the ionosphere was affected by the SPE. At EACF the CNA at 38.2 MHz started at ~3:00 UT and almost one hour after started at 30 MHz, reaching the maximum level of ~1.0 dB and ~0.5 dB at ~10:00 UT, respectively at each frequency. The CNA at 38.2 MHz also presents peaks of absorption at 03:30, 05:00 and 08:00 UT, the first one occurred almost one hour before the beginning of the >100 MeV proton event detected by GOES, and the other two peaks occurred in close association with the time the >100 MeV and > 5 MeV proton fluxes reached the highest level, respectively. From 10:00 to 15:00 UT the CNA at both frequencies remained stable at maximum levels, but later on the absorption at 38.2 MHz becomes variable, when the >100 MeV proton flux started to decrease. At ROI, the CNA at 30 MHz presents a gradual increase from ~03:00 to 10:00 UT, only starting at 38.2 MHz at ~11:00 UT. After that the CNAs at both frequencies present comparable high level attenuation but highly variable, probably due the interference of the local thunderstorms.

The effect of SPE is also clearly detected in the foF2 parameter during the nighttime, which stayed below the quiet day level from 03:00 to 11:00 UT.
Figure 1. Solar event on January 23, 2012. (a) Solar X-ray (Fx) and (b) proton flux (Fp) observed by GOES, (c) CNA, (d) VLF amplitude and (e) foF2 variations observed at EACF, and (f) CNA and (g) VLF amplitude variations observed at ROI. The bar labelled 3σ is the VLF amplitude significance level. The rectangle indicates the period of high energy protons influence.

Significant ionospheric absorption effects were also detected in the VLF amplitude measurements, which in this case are a combined effect of the X-ray radiation and energetic particles till 04:18 UT. Despite of that the VLF amplitude presents a significant (>3σ) decrease below the quiet day curve, which starts at ~03:30 UT and stays below that till ~10:00 UT at both VLF paths (NPM-EACF and NPM-ROI). The amplitude at NPM-EACF path decreases ~10 dB at ~04:20 UT, while at NPM-ROI path the amplitude decreases ~5 dB.

3.2. Solar event on January 27, 2012
The SPE on January 27 accompanied a X1.7 solar flare also produced in the active region NOAA 11402 but now located at N27W71 [13]. The solar event characteristics and the observed ionosphere behavior are shown in Figure 2 using the same sequence as in Figure 1. The X-ray event started at ~17:30 UT with maximum at ~18:30 UT. In this case the >100 MeV proton event started at ~18:30 UT and reached the maximum flux of ~10 cm⁻² s⁻¹ sr⁻¹ at ~22:00 UT, remaining high till the middle of the next day. This event occurred during the daytime at all sites (EACF, ROI and at NPM transmitter...
location), implying that the ionosphere effects were produced by the combined influence of X-ray radiation plus energetic particles at all times.

The CNA at EACF was ~0.5 dB since the beginning of the day, while at ROI it started only at ~12:00, when a high flux of energetic electrons was observed by GOES. CNA shows a strong increase that started at ~16:30 UT achieving ~2.5 dB and ~4 dB at ~18:40 UT, respectively at EACF and ROI. This strong CNA peaks ~10 minutes after the time of the X-ray peak flux and before the > 100 MeV proton event started. Since the CNA started before the beginning of the X-ray event, it might be produced by an additional ionization due protons with energy above the local rigidity. These few GeV protons, probably produced just at the beginning of the solar event, reach the Earth before those protons with MeV energy detected at geostationary orbit. So from 16:00 to 17:30 UT, before the X-ray event started, the CNA and VLF amplitude variations might be produced by the high energy protons. After that, the variations are a combined effect of radiation and energetic particle, which was more pronounced at ROI than at EACF in this event that occurred during daytime.

These effects were also suggested in the foF2 parameter measured at EACF, which stays above the quiet day level from ~15:00 UT till 20:00 UT.

4. Summary

The study of the ionosphere behavior during the SPEs that occurred on 23 and 27 January 2012, strongly suggests that it was disturbed by GeV protons in Antarctica and at lower latitudes in the South America Sector. The ionospheric absorption measurements done with riometers and VLF receivers at two distinct sites with high rigidity (E ≥ 10 GV) are an evidence of ≥10 GeV protons penetrating in the Earth’s atmosphere. The long-duration of the absorption effects (~03:30 to 10:00 UT on 23 January and from ~16:30 to 23:00 UT on 27 January) also suggests long-lasting presence of higher-energy protons in the Earth’s atmosphere. This suggestion is supported by the ionosonde measurements done at EACF and by significant increases of cosmic rays detected with CARPET experiment (see paper [14] for details) operating at the Argentinean Andes (Re ~10) during the same events.

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