PROCEEDINGS OF SCIENCE

Forbush decreases detected by the MUONCA muon telescopes on 13 September and 22 December 2014

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Muon rate variations during Forbush decreases registered by the MUONCA muon detector have been studied. We discuss the Forbush events which occurred in September and December 2014. Since April 2014, muon telescopes located at State University of Campinas, Brazil, inside the South Atlantic Anomaly, has been recording the flux of single muons. The MUONCA experiment consists of four modular detectors arranged in mode to register the flux of vertical and 45 degrees inclined muons from East and West. The modular detector uses a slab of plastic scintillator and a 127 mm diameter photocathode photomultiplier inside a truncated trapezoidal box. Its measured muon counting efficiency is (96.8 $\pm$ 0.4)%. We present the experimental setup, its calibration and a comparative analysis with neutron monitor data. The data of the MUONCA help to extend the knowledge about Forbush decreases to energies beyond the neutron monitor region.

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1. Introduction

We build in Campinas-SP, Brazil (22^o 54' S, 47^o 03' W, 640 meters above sea level) the MUONCA (MUONs in CAmpinas) experiment to study the muon flux variations associated with solar events. This muon detector is inside the South Atlantic Anomaly [1] where the geomagnetic field is the weakest, offering to this experiment a low rigidity of response to cosmic protons and ions. The experiment is taking data continuously since April 1th, 2014 and in this work we discuss the Forbush events detected in September and December 2014. The time series of the counting rate of MUONCA were compared with the McMurdo neutron monitor installed at the South Pole [2]. In figure 1 it is shown the MUONCA monitor mode raw data and McMurdo data pressure and efficiency corrected for the period from April 1, 2014 to January 31, 2015. There is a good agreement between the two experiments, showing that the variation of the cosmic ray flux measured by McMurdo is also detected by the MUONCA muon detectors.

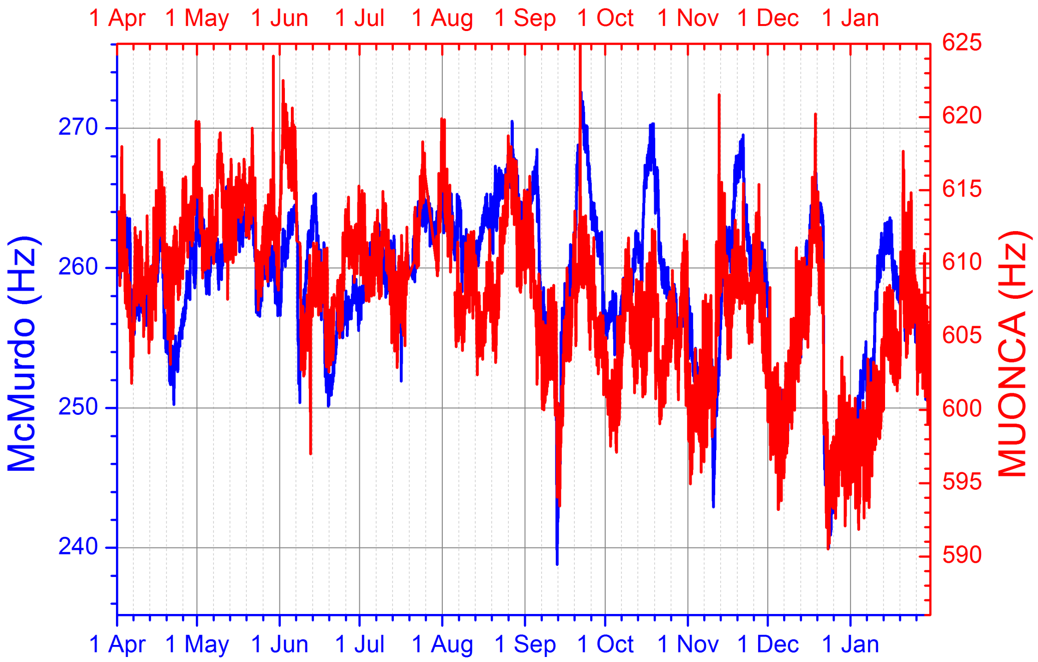

Figure 1: MUONCA and McMurdo counting rates, hour averages, from April 1, 2014 to January 31, 2015.

2. The MUONCA telescopes

This experiment has four identical particle detectors, each one consisting of an Eljen EJ-208 plastic scintillator slab of 150 cm x 75 cm x 5 cm and a Hamamatsu R877 photomultiplier of 127 millimeters in diameter, packaged in a box with trapezoidal truncated shape and internally coated with DuPont Tyvek^{TM} diffuse reflective material.

All scintillator faces are polished, its refractive index is 1.58 and it is surrounded by air, so 75% of the scintillation light is piped to the edges [4]. There are five centimeters between the scintillator edges and the trapezoidal truncated box to allow some photons reflect diffusively toward the photomultiplier (PMT) increasing the muon signal. The scintillator maximum spectral emission is at 435 nm and it yields 9,200 photons/MeV, which for vertical muons at around 10^5 photons are produced. The PMT high voltage divider, amplifier and high voltage power supplier are in the ORTEC ScintiPack^{TM} Photomultiplier Base 296.

Figure 2: The MUONCA experiment.

The detectors work high voltages were determined by the plateau of the muon counting efficiency, the graph of the counting efficiency versus high voltage. In this measure two small auxiliary plastic scintillator detectors, called rackets, of $40 \times 38 \times 2.5$ cm^3 were used and positioned on the vertical axis of the detector to be studied, one above and other below the detector. The detector count efficiency for muons was calculated as the ratio of three-fold coincidence (rackets and detector) by the rackets two-fold coincidence, subtracting the spurious ones. The muon count efficiency is $(96.8 \pm 0.4)\%$. After that we got the detector single count plateau, the graph of the single count rate versus the high voltage. Figure 3 shows the single count plateau curves of each detector, which was used to determine the work voltage of the detectors in order to have the best efficiency and keep them with the same gain. The good results got with the plateau graphics are confirmed by the muon pulse height spectrum showed in figure 4, which the valley between the PMT noise and the muon pulse is clearly seen.

The MUONCA is inside the laboratory site below at about 60 centimeters of concrete, that represents a threshold of 290 MeV in kinetic energy of the detected muons. Figure 2 shows the geometrical arrangement of the four detectors forming with the center of each module a vertical square of 283 centimeters.

The hardware of the data acquisition system uses a CAMAC system composed by two Dual Gate Generator LeCroy model 2323A, a CAEN logic unit model C85 and a LeCroy 100 Mhz scaler model 2551. The detector pulses are discriminated, with thresholds of 10 mV, the 300 ns formatted outputs go to an universal programmable logic unit, which sends the programmed logic pulses to a scaler. Every second the counting of vertical telescopes, East and West telescopes and the monitor mode (similar to neutron monitor stations) are recorded. The monitor mode is the

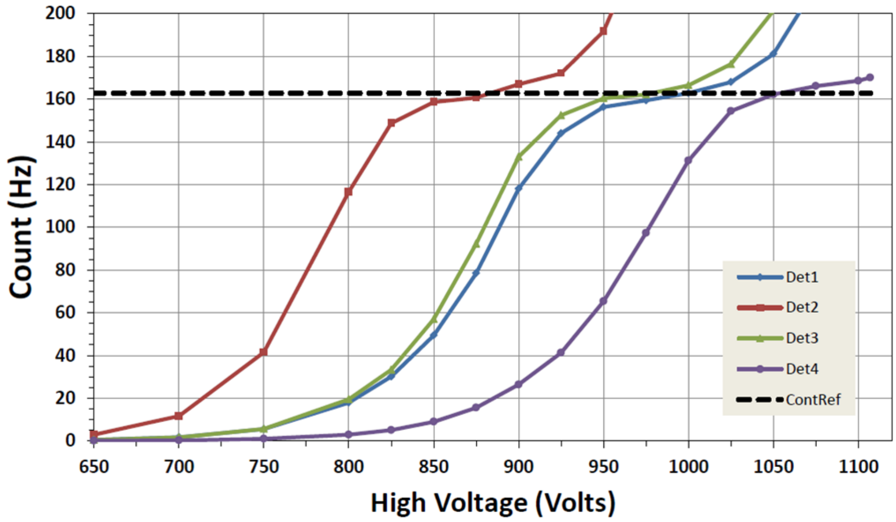

Figure 3: Count rate plateaus of the MUONCA detectors.

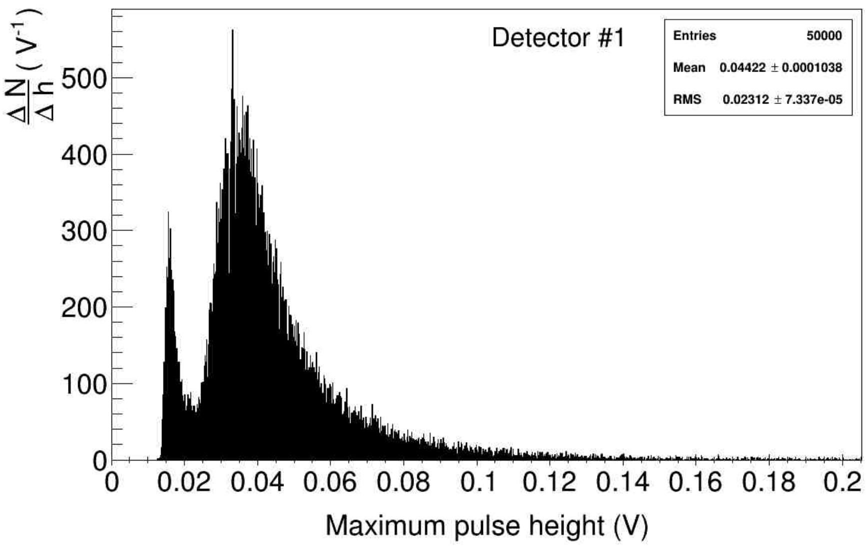

Figure 4: Pulse height spectrum of a MUONCA detector.

sum of all detector counting. The weather data of temperature, pressure, humidity, wind speed and direction and rainfall, provided by a weather station [5], is recorded every ten minutes. With these four muon detectors vertical muons with zenith angle of 45 degrees towards East and West are detect.

Barometric coefficient - The muon flux on Earth surface depends on the state of its atmosphere, mainly of the barometric pressure. A higher pressure indicates a greater quantity of matter between the production of secondary cosmic rays and the particle detector. The barometric coefficient of neutrons is much larger than that of muons, some tens of times bigger [3]. We show below

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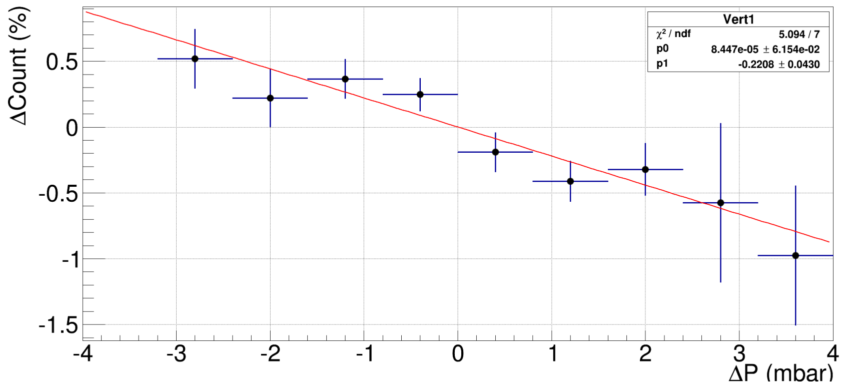

Figure 5: Barometric coefficient for muons.

that the barometric coefficient of muons detected by MUONCA is small, allowing an initial study of Forbush events without this correction. Figure 5 shows the muon rate versus barometric pressure for MUONCA telescope. It was used the least squares method to obtain the barometric coefficient $\alpha = (-0.22 \pm 0,04)\%/mbar$.

Atmospheric variations of the muon flux are local variations, i.e. depends on the geographic location of the detector. However Forbush events happen globally, reaching detectors throughout the planet at almost the same moment, having an intensity which depends on the geographic location of the particle monitor.

3. Forbush events

Figure 6 shows a comparison of MUONCA monitor and McMurdo data for the months of September and December 2014. There is a decline in the counting registered in both detectors on the 6th and 12th days of September and on the 21th and 22th December 2014. The MUONCA data, without correction for atmospheric effects, clearly shows the daily atmospheric variation. However the Forbush events have durations of the order of magnitude of a week and it is clearly seen by MUONCA.

The The CR-intensity variation (%) for neutrons and muons was calculated as follow

$$CR - intensity\ \ variation(\%) = \frac{Count(t) - Monthly\ \ average}{Monthly\ \ average} \times 100 \tag{3.1}$$

CME	Shock Arrival Time	Observed Kp	Associated Flare
2014-09-02 16:00	2014-09-06 04:33	3.0	—
2014-09-09 00:16	2014-09-11 22:56	5.0	M4.6 2014-09-08 23:12
2014-09-10 18:24	2014-09-12 15:26	7.0	X1.6 2014-09-10 17:21
2014-12-17 05:00	2014-12-21 04:13	—	M8.7 2014-12-17 04:50
2014-12-19 00:27	2014-12-21 18:22	5.0	M6.9 2014-12-18 21:41
2014-12-20 00:48	2014-12-22 14:28	—	X1.8 2014-12-20 00:24

Table 1: Coronal mass ejections observed in September and December 2014 [7].

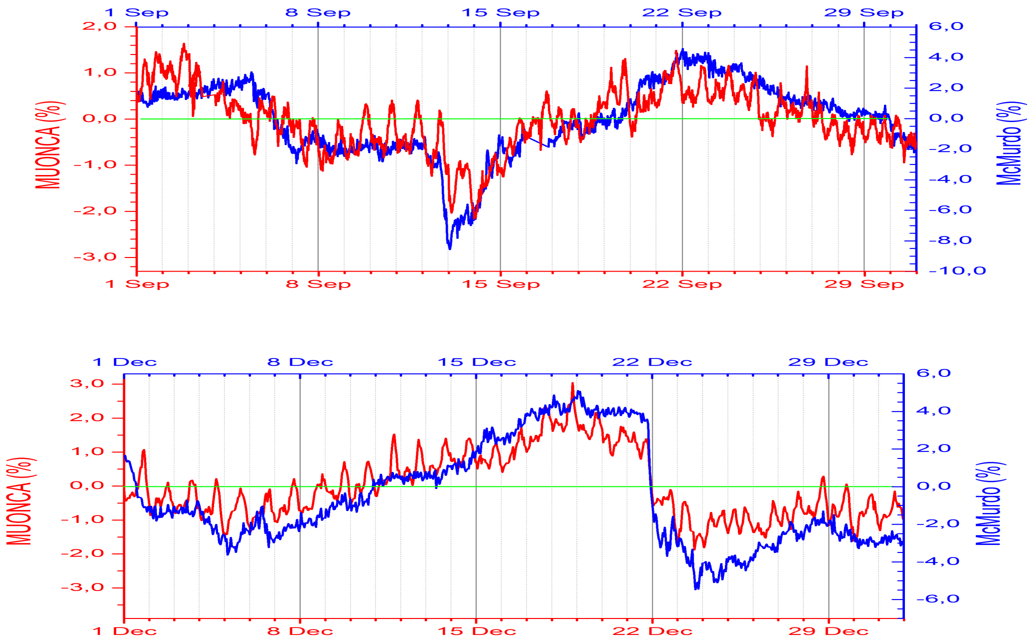

Figure 6: The MUONCA monitor and McMurdo variation percentages, in September (upper) and December 2014 (down).

The Forbush decrease occurred in September has a maximum variation of -8.6% and -2.2% in McMurdo and MUONCA counting respectively. During September three Coronal Mass Ejection hit the Earth, the first arrived on 6th, the second on 11th and the last one arrived on 12th, being it the most intense, causing a strong geomagnetic storm with Kp=7. Indeed occurred a superposition of the last two CME effects. During December three CMEs arrived in a short interval of time and moreover an overlapping effect also occurred. Two of them arrived on 21th and the last one hit the Earth on the 22th. The maximum variation was of -5.5% and -1.9% for McMurdo and MUONCA respectively. The MUONCA decrease counting was 26% of the variation detected by McMurdo in September and 35% in December.

The list of CMEs arrived on September and December is shown in Table 1 which contains the CMEs time, the shock arrival time, the Kp index [8] and associated flares observed [7]. There is a good time coincidence between the shock arrival times and the Forbush decreases detected by MUONCA.

These Forbush events are related to solar events that were registered by the Geostationary Operational Environmental Satellite (GOES 15) [6] and to Dst (Disturbance Storm Time) index. Figure 7 and Figure 8 show the X-ray and proton fluxes, the Dst index and the MUONCA measures in September and December 2014. It is possible see that the CMEs after being detected by the GOES instruments arrive at Earth causing the MUONCA count rate and the Dst decrease.

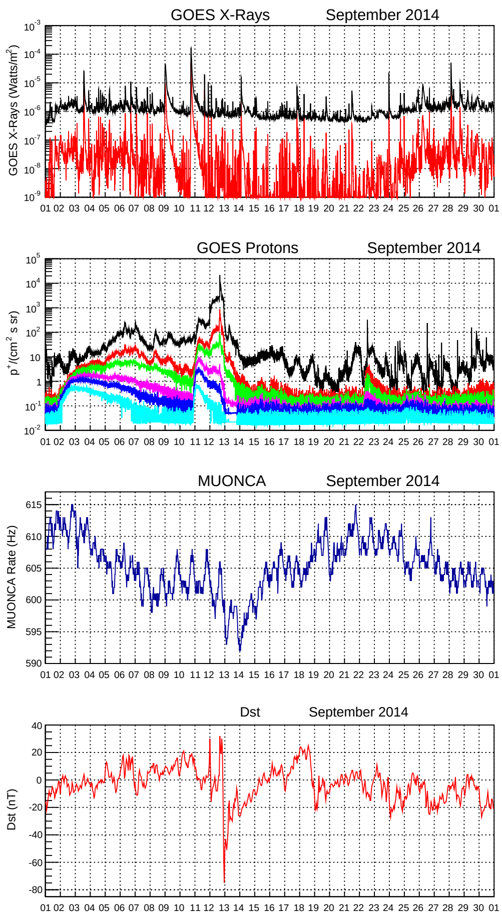

Figure 7: GOES-15 (X-ray and proton fluxes),MUONCA count rate and Dst index in September 2014.

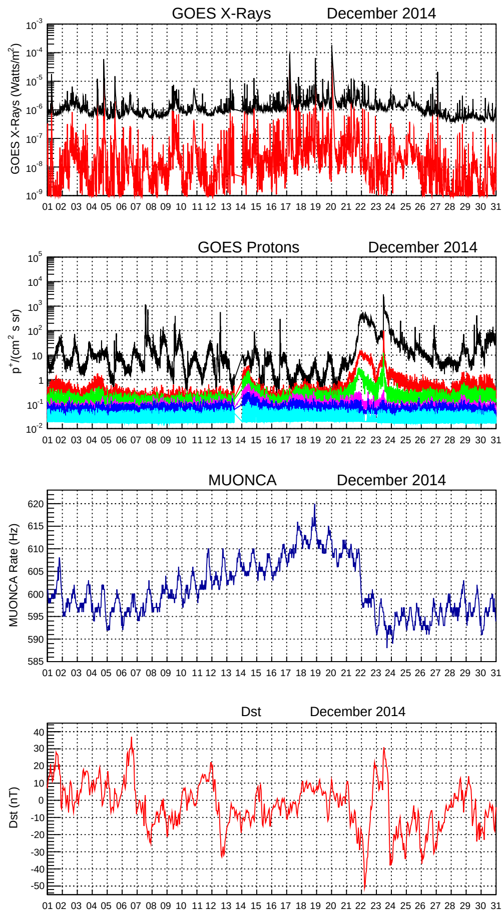

Figure 8: GOES-15 (X-ray and proton fluxes), MUONCA count rate and Dst index in December 2014.

X-rays: XL(0.1-0.8nm) black line, XS(0.05-0.4nm) red line.
Proton energies: (from upper to down) [>1 , >5 , >10 , >30 , >50 , >100] MeV

4. Conclusions

In this paper we present the installation and calibration of the MUONCA experiment, a telescope of muons sited at Universidade Estadual de Campinas - UNICAMP for the study muon flux variations associated with solar events. The performance study of these detectors showed they have a muon counting efficiency of $(96.8 \pm 0.4)\%$ and the data acquisition system is stable enough for detect transient signals caused by solar energetic events. In September and December 2014 six CMEs occurred which caused effects on ground based detectors and enabled the MUONCA experiment to detect muon count rate variations greater than 1%.

We will implement the pressure correction due to the barometric effect for MUONCA future analyses to improve the experimental sensibility. With increasing statistics over time we will have conditions to conduct studies in the search for a possible correlation between solar activity and the global climate change. The detection of these muons at ground level associated with solar activity will allow to study the South Atlantic Anomaly and solar events at higher energies than space and neutron monitor experiments. The experiment is currently in continuous data acquisition.

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