CaLMa Neutron Monitor: current status, first observations and future improvements

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Abstract. Castilla-La Mancha Neutron Monitor (CaLMa) is a 15 boron trifluoride counter neutron monitor located in Guadalajara, Spain (40°38′N, 3°9′W) at 708 m above sea level (asl) and a vertical rigidity cut-off of 6.95 GV. CaLMa is able to measure neutrons produced by primary cosmic rays with energies above 6 GeV if protons are these primary cosmic rays. CaLMa has been continuously monitoring solar activity since October 2011, having reported more than 25 Forbush decreases. This work presents the preliminary results inferred from CaLMa’s count rate variations, shows the latest improvements carried out in CaLMa and outlines our future plans to improve the station.

1. Introduction

Neutron monitors are ground level instruments, and the vertical cut-off rigidity at its geographical location together with the atmospheric cut-off energy impose an energy threshold to the primaries that are able to produce secondary cosmic rays recorded that each neutron monitor is able to record. A neutron monitor measures secondary cosmic rays produced by primary cosmic rays with energies up to about 100 GeV with a maximum ranged between 4 and 7 GV at sea-level and shows a strong dependence on the solar cycle [1].

The Castilla-La Mancha neutron monitor (CaLMa) is a 15NM64 station located in Guadalajara, Spain (40°38′N, 3°9′W) at 708 m asl with a vertical cut-off rigidity of 6.95 GV (http://www.calmanm.es). It has been operating since 26 October 2011 in a commissioning phase reaching its full operational status (i.e. 15 counters) on 11 July 2012 [2].

A dedicated new registration system based on a field-programmable gate array (FPGA) card has been designed for recording pulses from CaLMa’s counters [3]. This system controls 15 counters, the high accuracy BM35 barometer device (http://www.meteolabor.ch/fileadmin/user_upload/pdf/meteo/WX/bm35_e.pdf) and three additional channels which are used to test new sensors that could be added to CaLMa in the future. This new registration system has been operating at the Kiel neutron monitor in parallel with the old one, for which it has been shown to be an adequate replacement [3]. On the other hand, the acquisition system is able to interface via internet with the Neutron Monitor Database (NMDB) [4] uploading measurements every minute, both count rate and pressure, so...
that real time data is available to the end users. The NMDB is a database where many neutron monitor stations upload their measurements, making them available to scientists and other interested parties ([http://www.nmdb.eu](http://www.nmdb.eu)). CaLMa data are reduced according to the median filter algorithm procedure described by Belov et al. [5]. The median rates are subsequently corrected from atmospheric pressure effects [6] applying a factor $\exp(-\beta(P - P_0))$, where $P_0 = 935\pm 6hPa$ is the station standard pressure and $\beta = -0.0067 \pm 0.0002 hPa^{-1}$ is the barometric correction factor.

2. Following the solar activity with CaLMa

CaLMa measures mainly secondary neutrons produced by cosmic rays with rigidities higher than 6.95 GV. At such energies, cosmic rays are affected by solar activity. This lets us infer the effect of solar activity on Earth, based on temporal variations in CaLMa’s count-rate. Since CaLMa has been in operation for almost 4 years, long term and short term variations in solar activity can be studied using its measurements. It is well established that solar activity follows a cycle of eleven years directly related with a higher (maximum) and lower (minimum) sunspot number. Monthly sunspot numbers along the last solar cycle are shown in Fig. 1 (continuous blue line). According to Fig. 1, the last solar activity minimum occurred around 2009 when the lowest sunspot number was recorded. Then, a first maximum happened at the end of 2011, followed by a relative low and then almost flat solar activity from the beginning of 2012 up to the end of 2013. Then, the solar activity grew up reaching a second maximum during early 2014. It can be said that this maximum presents a Gnevyshev gap [7] as did the precedent solar maximum. During this period the solar activity is, on average, lower than during other periods, and this affects the solar magnetic field, the rate of solar flares, coronal mass ejections and solar energetic particle events [8].

CaLMa started to operate during the current solar maximum. CaLMa count-rate shows a behaviour similar to other neutron monitors; for example, CaLMa in Fig.1 is compared to Rome neutron monitor in monthly averaged count rate (blue and green lines respectively). Both neutron monitors have similar vertical cut-off rigidities, 6.27 GV in Rome and 6.95 GV in CaLMa, and because of that, similar cosmic ray variations are expected to be measured by both stations. CaLMa and Rome count-rates do not clearly anti-correlate with the sunspot number. Maybe this is caused by the short recording period of only four years, due to which neutron monitor count rates could be more dependent on the number of interplanetary coronal mass ejection arriving at the Earth than the sunspot number. On the other hand, a four year period is not long enough to make a meaningful assessment related to the eleven year solar cycle.

2.1. Short term solar activity

Since the work by Forbush in 1938 [9] it is well known that solar activity can produce decreases in the number of cosmic rays reaching Earth. These decreases are characterized by a fast decreasing phase with respect to the background count-rate level previous to the Forbush decrease (FD), followed by a slow recovery phase which finishes when the cosmic ray count-rate shows again small variations and, in most the cases, recovers the measured background values before the beginning of the FD. The decrease phase usually takes less than one day, while the recovery phase can last from several days up to three weeks [10]. These FDs observed with neutron monitors are caused by the interaction between solar wind transients such as interplanetary coronal mass ejections (ICME), and stream interaction regions (SIR), with the geomagnetosphere [11]. Magnetic clouds (MC) are observed in ICMEs very often. A MC is characterized by large magnetic field intensity and smooth magnetic field rotation. An effective interaction between MCs and Earth magnetosphere can be expected because of its magnetic topology. An example of a FD observed by CaLMa at the end of February 2014 is depicted in Fig.2. This FD was produced by a shock+MC+MC combo. CaLMa count-rate decreased by 4%. The decrease
Figure 1. Monthly averaged sunspot number (continuous blue line), monthly averaged CaLMa count-rate (continuous red line) and monthly averaged CaLMa count-rate (continuous green line). Rome's count-rate has been divided by a factor 2 to make its count-rate visually comparable with CaLMa's data.

started with the shock arrival to Earth (first dotted vertical line), followed by a fast reduction in the count-rate during the passage of the first MC and the minimum was reached in coincidence with the second MC. The MCs borders are marked by the second and the third dotted vertical lines, nose and rear of the first MC respectively, and the third and fourth dotted vertical lines show the borders of the second MC. The recovery phase started after the second MC arrival, lasting about five days. The magnetic clouds are confirmed by the relative strong magnetic field intensity and the rotation of the magnetic field components.

The same event also produced a strong geomagnetic storm as can be observed in the Dst and Kp index variations showed in the second and third panels in Fig. 2. The geomagnetic storm started later than the shock arrival and in coincidence with the first MC's nose. The minimum in Dst index was detected in coincidence with the first MC. The recovery phase of the geomagnetic storm begun with the second MC cloud arrival.

CaLMa has observed 29 FDs up to now. Twenty seven of them were induced by ICMEs with clear signatures of magnetic cloud, i.e. high magnetic field strength and smooth magnetic field rotation, both with other solar wind transients as shocks or SIR, or simply isolated ICMEs. Only in one case the solar wind transient associated to the FD could not be identified. About 50% of the events were observed with geomagnetic storms (Table 1). This Table 1 lists the solar wind structure observed with each FD, i.e. interplanetary shocks (sh), magnetic clouds (MC) stream interaction regions (SIR) or no clear when there are not clear signatures of the previous solar wind structures in the first column, the date when the FD minimum is observed in second column, the percentage of decrease in CaLMa count-rate in third column and finally, if a geomagnetic storm is observed with the FD (Yes/No) in the fourth column. It is clear from the table that only some of the FDs happened in coincidence with strong geomagnospheric responses.

The strongest energetic solar events such as flares and very fast coronal mass ejections can accelerate a huge amount of particles up to energies of some GeV. These particles, solar cosmic rays, can produce an increment in the count-rate recorded by neutron monitors. These enhancements in neutron monitor count-rates are referred as ground level enhancements (GLE). Only one GLE (17 May 2012) has been clearly observed during the current solar cycle by the worldwide network of neutron monitors. A recent work about this GLE can be found in [12].
Figure 2. FD observed by CaLMa. From top to bottom CaLMa count-rate, Dst index, Kp index, solar wind proton density, temperature and speed, plasma beta, GSE magnetic field components and field intensity at 1 AU.

However, this GLE was not observed in CaLMa because of the high cut-off rigidity of our station.

3. Close future work

CaLMa is nowadays a fully operational 15NM64 station. Nevertheless, this is not the final stage of CaLMa. The station is going to be complemented with a muon telescope which will give information about the muon component of showers produced by primary cosmic rays. It is expected to obtain valuable information about cosmic ray anisotropy, especially during a FD. In parallel with the muon telescope implementation, a new data acquisition system will be developed to control both instruments, the neutron monitor and the muon telescope. This new system will be able to record individual events with a resolution of a few nanoseconds and will combine counts from both instruments, detect multiplicities in the neutron monitor and in the muon telescope, and store directional muon information from a new coincidence logic system.

For the first operational test, we have built a muon telescope laboratory model made up of a pile of two 30x30x3 cm plastic scintillators which are 12 cm apart, with a lead block with dimensions of 30x30x5 cm in between. The prototype is presented in Fig.3. The upper scintillator and photomultiplier tube (PMT) box can be seen on the upper left corner of the picture, the high power supply is close to it and also on the table. The bottom scintillator
Table 1. FDs in percentage observed by CaLMa from November 2011 to June 2014. gntorm=geomagnetic storm and sh=shock

| Event          | Date        | FD   | gntorm |
|----------------|-------------|------|--------|
| sh+MC+SIR     | 25/01/2012  | 2.3  | Yes    |
| sh+MC+sh+MC   | 08/03/2012  | 8.9  | Yes    |
| sh+MC         | 13/03/2012  | 3.1  | No     |
| MC            | 06/04/2012  | 4.7  | No     |
| sh+SIR+MC     | 26/04/2012  | 1.9  | Yes    |
| sh+MC         | 17/06/2012  | 3.0  | Yes    |
| sh+MC+MC      | 14/07/2012  | 3.0  | Yes    |
| sh+MC+MC      | 05/09/2012  | 2.9  | Yes    |
| sh+MC         | 13/11/2012  | 3.6  | Yes    |
| sh+MC + SIR   | 24/11/2012  | 3.3  | No     |
| MC            | 17/01/2013  | 1.9  | No     |
| sh+SIR+sh+MC  | 18/03/2013  | 5.1  | Yes    |
| sh+MC         | 14/04/2013  | 3.7  | No     |
| sh           | 24/06/2013  | 2.3  | No     |
| sh+MC         | 28/06/2013  | 2.1  | Yes    |
| sh+MC         | 13/07/2013  | 2.4  | No     |
| MC            | 03/09/2013  | 2    | No     |
| SIR+sh+MC     | 02/10/2013  | 2.5  | Yes    |
| MC            | 15/12/2013  | 2.9  | No     |
| No clear      | 10/01/2014  | 2    | No     |
| sh+MC+MC      | 15/02/2014  | 2.7  | No     |
| sh+MC+MC      | 28/02/2014  | 4    | Yes    |
| sh+MC         | 05/04/2014  | 2    | No     |
| SIR+MC+sh+MC? | 18/04/2014  | 4.5  | No     |
| sh+MC         | 07/06/2014  | 3.3  | No     |
| sh+MC         | 13/07/2014  | 1.9  | No     |
| sh+MC         | 07/09/2014  | 2    | No     |
| sh+MC         | 13/09/2014  | 4.1  | Yes    |
| sh+sh+MC      | 23/12/2014  | 6    | Yes    |

box is placed just below. On the right side of the picture, the data acquisition chain composed by NIM modules and a computer to visualize the multichannel analyser output is shown. The scintillators are operated in coincidence, while the upper one and the lead block can be moved horizontally allowing different fields of view for testing the directionality of muon flux. The observed angular distribution of muons is plotted in Fig.4.

Photons from the scintillators are collected by a photomultiplier tube connected to a typical Canberra chain, i.e. pre-amplifier, amplifier connected to an analogical digital converter (ADC) and to a single channel analyser (SCA) both connected (ADC and SCA) to a coincidence module. The final output from the ADC is recorded by a dedicated acquisition system [13] with a Beaglebone black (BBB) as core of the system (upper block diagram in Fig.5). We refer this acquisition chain as hardware coincidence. The BeagleBone Black is a low-cost, community-supported development platform for developers that runs linux (http://beagleboard.org/black). Using the BBB capabilities, the acquisition chain has been highly simplified taking out the SCA and the coincidence module from the initial acquisition
Figure 3. Muon telescope laboratory model.

Figure 4. Observed angular distribution of muons arriving CaLMa.

Chain (bottom block diagram Fig.5). We refer this acquisition chain as software coincidence. Both these acquisition systems were operated alternatively. The software coincidence chain recorded count-rates (green circles in Fig.4) similar to those recorded by the hardware coincidence chain (black squares in Fig.4). When considering the geometric factor, a clear angular dependence of muon flux arriving to the detector is not observed. This is expected for an isotropic muon flux. Both the coincidence hardware chain (black pointed up triangle) and the coincidence software chain (red pointed down triangle) obtain the same result. We have to point out that no atmospheric corrections have been done yet and therefore differences between muon path length caused by different angles of incidence are not considered.
Figure 5. Block diagram of the muon telescope acquisition chain. From the photomultiplier tube (PMT) through the preamplifier (PA), amplifier (AMP), analog to digital converter (ADC), single channel analyser (SCA) and a coincidence module (COINC). The chain ends in a dedicated acquisition system based on a Beaglebone black (BBB) named Software-coincidence Adquisition System (SAS).

4. Conclusions
We have presented the current status and close future plans for the Castilla-La Mancha neutron monitor (CaLMa). CaLMa has been operational since October 2011 producing one minute resolution measurements. These counts are uploaded in real time to the NMDB allowing the use of CaLMa data as source for space weather alarms. CaLMa is observing both solar cycle variations and short term variations of cosmic rays produced by the solar activity. Up to now, CaLMa has detected 29 Forbush decreases, most of them caused by a shock+MC combo. Only 50% of the FDs detected by CaLMa happened during strong geomagnetic storms. CaLMa is growing to be a dual station composed by a neutron monitor and a muon telescope and controlled by a new data acquisition system which is now under development. The muon telescope will add directional information allowing us to study anisotropies in cosmic rays during a Forbush decrease.

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