Muon Telescopes at Basic Environmental Observatory Moussala and South-West University – Blagoevgrad

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Abstract. Two muon telescopes of cubic design were constructed and are operated in Bulgaria for studying the variations of cosmic rays muon flux. A 1m^2 telescope is located at Basic Environmental Observatory (BEO) – Moussala – 2925 *m* above sea level and is in operation since August 2006. The other muon telescope, with effective area 2.25 m^2, is located at the South-West University – Blagoevgrad – 383 *m* above sea level. Its data acquisition system was upgraded in November 2007. Both instruments use developed by our team cost effective and easy for production water Cherenkov detectors. In this paper the following topics are presented: (a) description of the instruments (detectors construction and setup, data acquisition system); (b) main characteristics of the instruments (energy thresholds, count rates, barometric coefficients, asymptotic directions); (c) response to primary cosmic rays protons – results obtained from simulations with Planetocosmics code; (d) some examples of experimental results – the Forbush Decrease in November 2003, registered by the muon telescope at the South-West University and the Forbush Decrease in December 2006, registered by the muon telescope at BEO – Moussala, the diurnal variation.

Keywords: cosmic rays variations; muon telescopes; water Cherenkov detectors

Introduction

The first continuous measurements of the cosmic rays (CR) time variations began in 1934 with the founding by Compton of the first worldwide network of CR observatories, using ionization chambers. The second CR worldwide network was established in 1952-1959 with the development by Simpson of the neutron monitor (NM IGY type). The charged components were measured with ground-based and underground telescopes of cubic or semi-cubic design on scintillators or Geiger counters. The third CR network was founded in 1960 with the construction of the neutron super-monitor (NM IQSY type) and the replacement of the NM IGY instruments with NM IQSY after 1962-63 [1].

One very significant step in the CR research development is the gradual development of the International Cosmic Ray Service (ICRS) after 1992, including real time minute and hour data exchange of all CR observatories, allowing the usage of CR data for space weather monitoring and forecasting [1, 2].

Nowadays NM are the main instruments for exploring the CR variations at all CR observatories; they detect the secondary nucleon component of CR and are sensitive to approximately the 0.5 – 20 GeV part of the primary CR spectrum. Along with them muon telescopes (MT) of different designs are used. The MT are sensitive to a higher range of the primary spectrum – about 10 – 20 GeV and above and using coincidence techniques they provide information about the intensities of the CR in different directions.

Two basic designs of MT are used. The first uses fixed coincidence combinations between detectors in two layers, counting the muons in defined angular intervals. The other (the so called muon hodoscopes) uses crossed long and narrow detectors in two layers and the determining of the arrival direction with high accuracy (usually 1 - 7 degrees) for every muon is possible. The first type of MT are constructed with scintillator detectors, as scintillators provide wide area, high light yield, fast timing, long live and high time stability. The hodoscopes usually are based on gas filled proportional counters.

One of the most successful designs of scintillator telescope is that of the Nagoya Multidirectional MT (18 m^2 effective area), with 36 detectors, 1 m^2 each, working since 1970 [3]. The Sakashita Underground MT (operated in 1979-2000) had similar design and detectors. The MT at Sao Martinho (28 m^2, since 2005) [4] and Hobart (9 m^2) [5] are based on 1x1 *m* plastic scintillator detectors. The Nor-Amberd multidirectional muon monitor [6], the Muon Space-weather Telescope for Anisotropies at Greifswald (MuSTAnG) [7], the MTs planned to be installed at Israel Cosmic Ray and Space Weather Center and Emilio Serge' Observatory [1, 8] and the muon hodoscope TEMP (Moscow, 9 m^2, 1-2 degrees angular resolution) [9] also use plastic scintillator detectors.

The GRAPES-3 muon detector (Ooty, India, 560 *m*^{2}) [10] and the Akeno MT (Japan, 75 *m*^{2}) [11] use proportional chambers with dimensions 10x10x600 *cm* and 10x10x500 *cm,* respectively, as basic detector element. The muon hodoscope URAGAN (Moscow) consists of two super modules, each with about 11 *m*^{2} effective area and 0.7 degree angular resolution. The basic elements of the super modules are 3.5 *m* long streamer tube chambers with two coordinate external strip readout system, assembled in 8 layers [12]. The Kuwait University muon hodoscope (9 *m*^{2}) [4] is based on 10x500 *cm* cylindrical proportional counters.

The Cherenkov Effect was discovered in 1936 and is widely used for charged particles detectors (see: [13] for details). Many CR experiments use Cherenkov detectors for registering the secondary CR components, as radiators are used water (man-made tanks – Super KAMIOKANDE, MILAGRO; natural water reservoirs – ANTARES, NESTOR), ice (AMANDA, Ice Cube), or the atmosphere (H.E.S.S, MAGIC).

We have constructed two MTs with water Cherenkov detectors. One of the telescopes is situated at Basic Environmental Observatory (BEO) at peak Moussala, 2925 *m* above sea level (*a.s.l.*) (730 *g/cm*^{2}), 42^{0}11'N , 23^0 35'E. The other is located at the South-West University, (SWU, Blagoevgrad, Bulgaria) 42^{0}01'N, 23^{0}06'E, 383 *m a.s.l.*

The telescope at the University was constructed in 2001, but was not operated continuously. In November 2007 the data acquisition system was upgraded. The telescope at the BEO is in continuous operation since August 2006.

Description of the telescopes

Both instruments use one and the same type detectors - a mirror tank with dimensions 50x50x12.5 *cm* and 10 *cm* distilled water radiator. 2.5" photomultiplier tubes (PMT) FEU-110 or FEU-139, operated with positive power supply and 300 *Ohm* anode load are used; the anode is connected to a fast amplifier with gain 50. The discriminator consists of fast comparator and one-shot multivibrator. A short, 60 *ns* TTL pulse, providing minimum number of random coincidences, is formed if the amplified PMT pulse exceeds the threshold voltage (actual thresholds is 28 *mV* for the BEO MT and 22 *mV* for the University MT). The PMTs are set up in photon counting mode, adjusting the gain by the high voltage (HV), using the described in [14] method of the plateau characteristics.

The telescope at the University has effective area 2.25 *m*^{2}, the detectors configuration is 3x3 detectors in each plane and the distance between the detector planes is 1.5 *m* (Fig. 1) [15]. The telescope at the BEO-Moussala is with 1 *m*^{2} effective area, 2x2 detectors in each plane, the distance between the detector planes is 1 *m* [16]. Both instruments are placed at the basement of the buildings, using the concrete above them as absorber of the soft CR component.

The 18 detectors of the MT at the University are connected to 33 coincidence circuits, and the intensity of the CR muons is measured in 5 directions: Vertical, North-South (NS), South-North (SN), West-East (WE) and East-West (EW). The same 5 directions are defined for the 8 detectors of the BEO MT using 12 coincidence circuits.

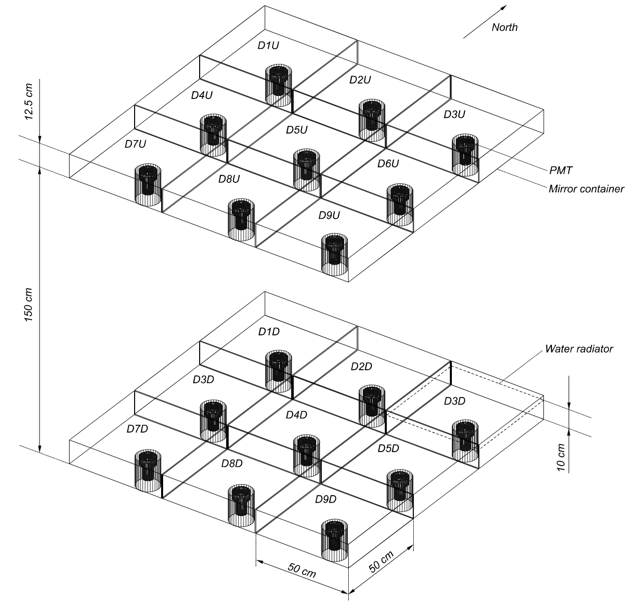

Fig.1.Detectors configuration of the SWU muon telescope.

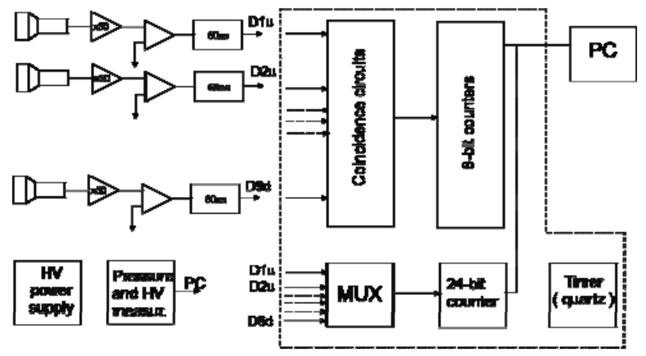

Fig. 2.The SWU muon telescope data acquisition system.

The data acquisition system of the SWU MT is shown on Fig. 2. The following considerations were taken into account when it was designed:

- because of the comparatively short pulses formed by the discriminator and the high number of counters needed, the coincidence circuits and the counters have to be realized by hardware ;
- the possible implementation using FPGA [17] is modern and economic as components, but needs more time for development.

The data acquisition system was made on classical TTL chips, fast series, with future plans to be upgraded on FPGA board with full combinations of coincidence circuits and USB interface. The coincidence circuits consists of 33 AND elements, and their outputs are connected to 33 8-bit counters. The formed TTL pulses from each discriminator are also multiplexed every minute to a 24-bit counter, used to control the individual count rate (signal + dark pulses) for every detector. The outputs of the counters are connected to a 8-bit bus, interfaced to a personal computer by the parallel port.

The counting time intervals are formed by quartz stabilized timer.

The high voltage power supply provides main stabilized 1950 *V* voltage with separate down-regulated in 25 steps of 25 *V* outputs for each PMT.

A 8-bit microcontroller (MCU) based board was constructed for measuring the atmospheric pressure. The MPX4115A silicon pressure sensor (Freescale Semiconductor) and 16-bit Sigma-Delta analog to digital converter are used. The board is with USB interface and measures continuously also the outer temperature (LM335 sensor), the room temperature (the embedded in the MCU sensor), and the high voltage.

The data acquisition software is written in Delphi 7, using open source libraries and free drivers, works in any MS Windows operating system and records the data on the hard disk drive of the PC in formatted ASCII files.

The data acquisition system and software for the BEO MT are similar to the described above; the main difference is in the number of coincidence circuits and counters [16].

3. Characteristics

3.1. Energy threshold

The energy thresholds for cosmic rays muons are determined mainly by the concrete layer above the telescopes. They were calculated with the MMC (Muon propagation Monte Carlo) software [18], taking in mind the threshold energy for generation of Cherenkov photons in water by muons. The obtained values are Eth~1 *GeV* for the telescope at the University and Eth~0.45 *GeV* for the telescope at BEO.

3.2. Count rates

The count rates for the two telescopes, averaged for the time period November 2007 – April 2008 in the different directions are shown in Table 1 and Table 2.

TABLE 1

Count rates for the MT at the SWU

Direction	Angular interval, deg	Detector pairs	Count-rate, min^{-1}	Statistical error for 1h
Vertical	+18.4 -18.4	9	878	0.44%
N-S	0 - 45	6	438	0.61%
S-N	0 - 45	6	438	0.61%
W-E	0 - 45	6	455	0.6%
E-W	0 - 45	6	455	0.6%

The count rates for the SWU MT for a single detector pair and vertical coincidences were ~110-120 min^{-1} at HV of the PMT close to the maximum allowed, in 1998, when the first detectors were constructed at the SWU laboratory. A typical counting characteristic is shown on Fig. 3. The CR muons intensity in the laboratory was measured with a small telescope of two *NaI* scintillators (type SDN-30), ϕ=82 mm and height=90 *mm* each, with a distance between them 50 *mm*. The count rate was ~24 min^{-1}, and corresponds to intensity $I_0 \approx 0.01$ $cm^{-2}s^{-1}ster^{-1}$. The calculated with this intensity expected count rate for a detector pair at vertical direction is ~ 133 min^{-1}. To receive a smaller number of the random coincidences

TABLE 2

Count rates for the MT at the BEO

Direction	Angular interval, deg	Detector pairs	Count-rate, min^{-1}	Statistical error for 1h
Vertical	+25.6 -25.6	4	2387	0.27%
N-S	0 - 33.7	2	814	0.45%
S-N	0 - 33.7	2	704	0.49%
W-E	0 - 33.7	2	756	0.47%
E-W	0 - 33.7	2	734	0.48%

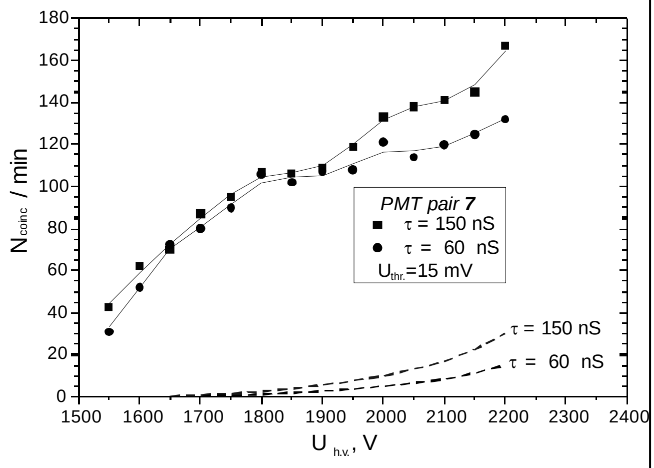

Fig 3.Counting characteristic of a detector pair of SWU MT.

(Fig. 3, dashed lines) the detectors of the telescope are operated with smaller HV, and the actual count rates are ~97-98 min^{-1} for a detector pair.

The count rate for a detector pair, vertical direction, for the BEO MT is ~ 580 min^{-1} and the calculated CR muons intensity is $I_0 \approx 0{,}0188$ $cm^{-2}s^{-1}ster^{-1}$, without corrections for the efficiency of the detectors. In [16] we have compared it with results calculated from measurements with the Bess Spectrometer and the value we have obtained is reasonable.

Here we should note that the main purpose of the MTs is not measuring the absolute intensity of CR muons, but measurement of its relative variations with high time stability.

3.3. Meteorological corrections

The barometric coefficients were determined using correlation analysis. The data used are from November 2007 to May 2008 for the SWU MT and from August 2006 to June 2008 for the MT at BEO. The values for the different directions are shown in Table 3 and Table 4. The data are in good agreement with these published in the literature [1, 3].

Temperature corrections are not applied since no data for the temperature at high altitudes in the atmosphere are available.

TABLE 3

Barometric coefficients for the SWU MT

Direction	ß, % / hPa	Error	Correlation coefficient
Vertical	– 0.1248	0.0013	– 0.5973
NS	– 0.1369	0.0015	– 0.5753
SN	– 0.1169	0.0013	– 0.5735
WE	– 0.1399	0.0012	– 0.6632
EW	– 0.1204	0.0018	– 0.4596

TABLE 4

Barometric coefficients for the BEO MT

Direction	ß, % / hPa	Error	Correlation coefficient
Vertical	– 0.2889	0.0014	– 0.8805
NS	– 0.2552	0.0023	– 0.7040
SN	– 0.3190	0.0014	– 0.8947
WE	– 0.3258	0.0018	– 0.8532
EW	– 0.2796	0.0015	– 0.8609

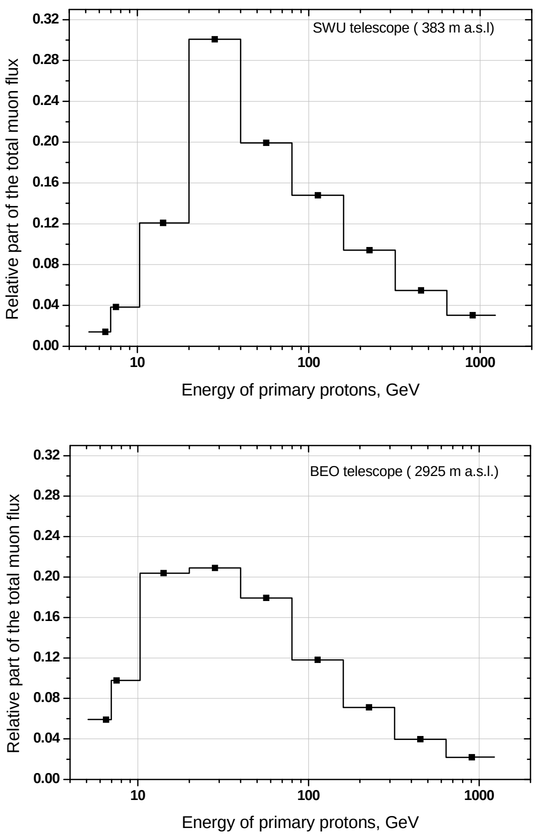

Fig. 4. Response to primary protons. Top - SWU MT, bottom – BEO MT.

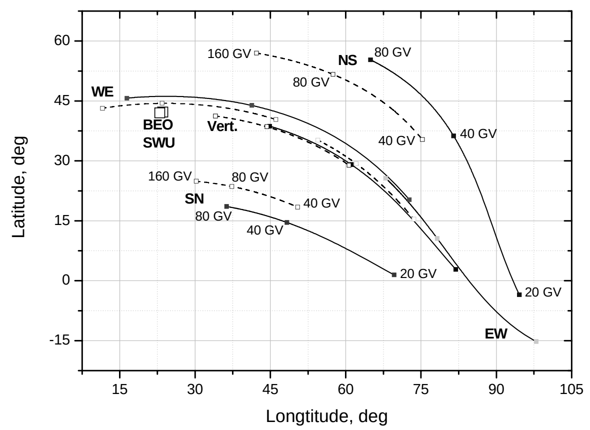

Fig. 5. Asymptotic directions. Dashed lines - SWU MT, Solid lines – BEO MT

3.4. Rigidity cut-off

The rigidity cut-off for the observation sites was calculated using *Planetocosmics* software code [19] and is Rc ~ 6.34 *GV* and Rc ~ 6.24 *GV* for the University and for the BEO site respectively.

3.5. Response to primary CR

The response to primary protons was calculated with Planetocosmics, dividing the primary protons spectrum in sub-ranges. The obtained differential spectrums were integrated, and for each sub-range we calculated its fraction of the total intensity above the energy threshold of the telescope. The obtained results are shown on Fig. 4. For the University telescope, 90% of the counted muons generated by protons are from the energy range 15-20 *GeV* to ~360 *GeV* primary protons, and for the telescope at BEO from 8-10 *GeV* to ~180 *GeV*.

We have calculated the asymptotic directions for the telescopes with the software code Magnetocosmics [20]. The calculated results for December 2006 (no external magnetic field) are presented in Fig. 5, the rigidity ranges plotted are 20-60 *GV* for BEO MT and 40-160 *GV* for SWU MT.

4. Examples of experimental data

4.1. Forbush decreases

Two Forbush Decreases (FD) were detected during the periods in which the telescopes were in operation. The first is in October-November 2003, detected by the SWU MT. The results for the vertical direction are plotted in Fig. 6 (top). The second is detected by the BEO MT during December 2006 [16] (Fig. 6, bottom plot).

4.2. Diurnal variations

The diurnal variation and the 27-days variation of the muon component are clearly visible in the telescopes data (the periodic variations are to be published with more details in the future). As an example, the diurnal variation for the SWU MT is presented in Fig. 7. The method of superimposed epochs was used for the time period November 2007 – May 2008. The time difference of the maximums for the different directions is in logical agreement with the calculated asymptotic directions (Fig. 4), taking in mind the 15^0/h angular velocity of rotation of the Earth.

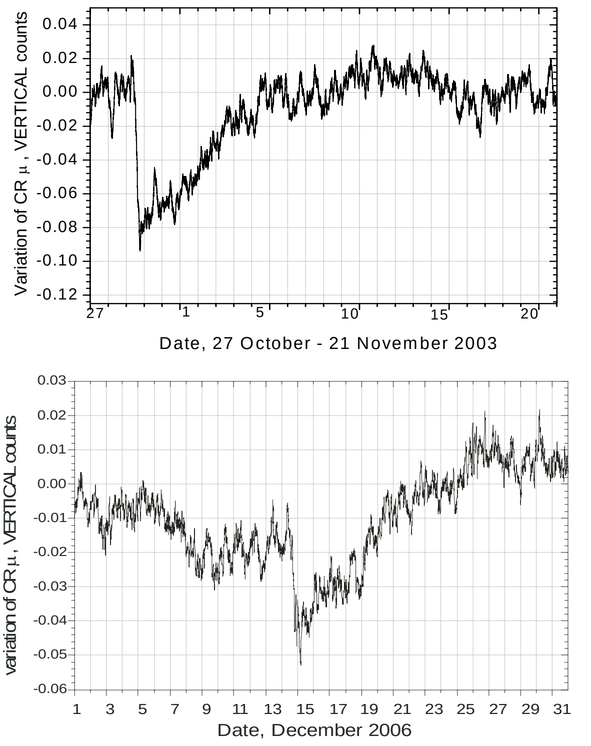

Fig. 6. FDs detected by the telescopes; top - SWU MT, Oct.-Nov. 2003, bottom – BEO MT, Dec. 2006.

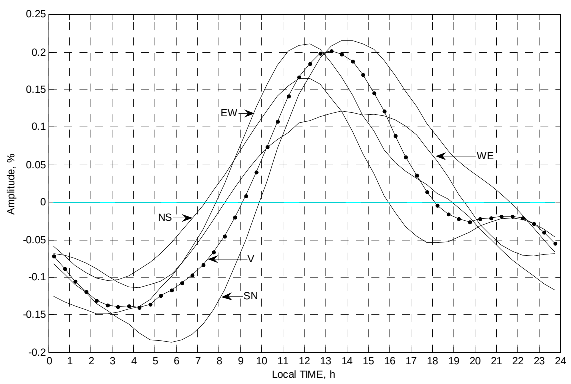

Fig 7.Diurnal variation of the CR muons, SWU MT.

5. Summary and future activities

We have constructed two muon telescopes in Bulgaria (Rc ≈ 6.3 *GV*):

- at ~ 380 *m a.s.l.*, 2.25 m^2 detectors , 1 *GeV* energy threshold, 0.45% statistical error for 1 *h* (operational after reconstruction since November 2007) ;
- at ~ 2925 *m a.s.l.*, 1 m^2 detectors, 0.45 *GeV* energy threshold, 0.27% statistical error for 1h intervals, (operational since August 2006).

Although the water Cherenkov detectors have a smaller photons yield compared to scintillators, if a high reflective coatings of the detectors tanks are used and the PMTs are precisely tuned in single photoelectron counting mode, they can be used as alternative to the plastic scintillators, when low cost is the main consideration.

The constructed telescopes are stabile in time and are used successfully for CR variations measurements. As there is an Internet connection at the observation sites, connection in the networks for real time CR data exchange is possible in the future. The correlations between CR and different atmospheric processes [1], [21], can be studied using data from the MTs and existing and future instruments at BEO.

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