

Application of Water Cherenkov Detectors for Muon Telescopes

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Abstract—Two muon telescopes of cubic design are operated at present in Bulgaria for studying the variations of cosmic rays muon flux. A 1 m^2 telescope is located at BEO – Moussala – 2925 m. a.s.l 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 a.s.l. Its data acquisition system was upgraded in November 2007. The telescopes are based on water Cherenkov detectors of original design. Descriptions of the telescopes, and their main characteristics are presented. Calculation of the energy threshold for the muon telescopes was done. Simulations with Planetocosmics Geant4 application code were performed to obtain the sensitivity to the energy spectrum of primary protons. Experimental results for two Forbush decreases (October/November 2003 and December 2006) are presented.

THE neutron monitors are the main instruments for exploring the cosmic rays (CR) variations, detecting the secondary nucleon component of CR. They 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. Muon telescopes are used for studying the variations in higher energy range of the primary spectrum, above 10 – 20 GeV. They are system of detectors, based on coincidence technique and provide also information on the arrival direction of the particles.

There are two basic designs of MT. 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 1979-2000) had similar design and detectors. The MT at São Martinho (28 m^2 since 2005) [4] and Hobart (9 m^2) [5] are based on $1\times 1\text{ m}$ plastic scintillator detectors. The Nor-Amberd multidirectional muon monitor [6], the Muon Spaceweather Telescope for Anisotropies at Greifswald (MuSTAnG) [7], the MTs planned to be installed at Israel Cosmic Ray & Space Weather Center and Emilio Serge' Observatory [1], [8] and the muon hodoscope TEMP (Moscow, 9 m^2 , 1-2 deg. 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 $10\times 10\times 600\text{ cm}$ and $10\times 10\times 500\text{ cm}$ 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 deg. 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 $10\times 500\text{ cm}$ 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.

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 a.s.l. (730 g/cm^2), $42^\circ 11' \text{N}$, $23^\circ 35' \text{E}$. The other is at the South West University, (SWU, Blagoevgrad, Bulgaria) $42^\circ 01' \text{N}$, $23^\circ 06' \text{E}$, 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.

2. DESCRIPTION OF THE INSTRUMENTS

Both instruments use one and the same type detectors - a glass mirror tank with dimensions $50\times 50\times 12.5\text{ cm}$ and only 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

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pulse, providing minimum number of random coincidences, is formed if the amplified PMT pulse exceeds the threshold voltage (Actual thresholds is 28mV for the BEO MT and 22 mV for the University MT). A typical amplified oscillogram of Cherenkov pulses from muon passing two detectors, is shown on Fig. 1. (The storage oscilloscope was synchronized by the signal from coincidence circuit.)

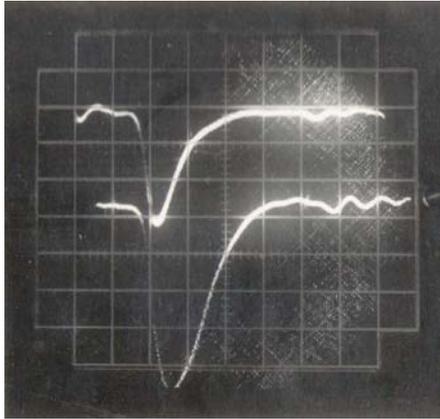


Fig. 1. Typical oscillogram at the output of the amplifiers, from a muon passing through a pair of detectors. Time 10 ns/div, Amplitude 10 mV/div.

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 high voltage was varied at fixed thresholds, and the number of coincidences of a detector pair counting in vertical direction was recorded. A typical counting characteristic of pair detectors from the University telescope is presented on Fig. 2. The random coincidences $N_{rand} = 2 \cdot \tau \cdot N_1 \cdot N_2$ were calculated, knowing the individual count rates (N_1, N_2) of each of the detectors – the dash line.

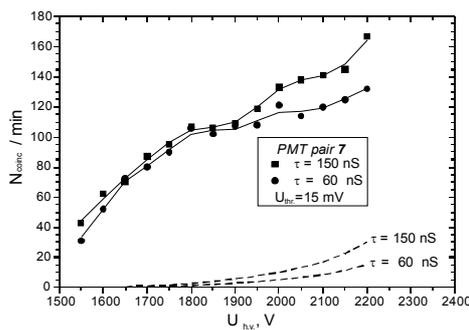


Fig. 2. Typical counting characteristic.

The detectors were set up at the beginning of the plateaus, to achieve minimal number of random coincidences and good efficiency of the detectors.

The telescope at the University has effective area 2.25 m², the detectors configuration is 3x3 detectors in each plane and the distance between the detector planes is 1.5 m (Fig. 3) [15]. The telescope at the BEO-Moussala is with 1 m², effective area, 2x2 detectors in each plane, the distance between the

detector planes is 1m [16]. A 5 cm lead layer is mounted between the detectors planes in each telescope. Both instruments are placed at the basement of the buildings, using the concrete above them as absorber of the soft CR component.

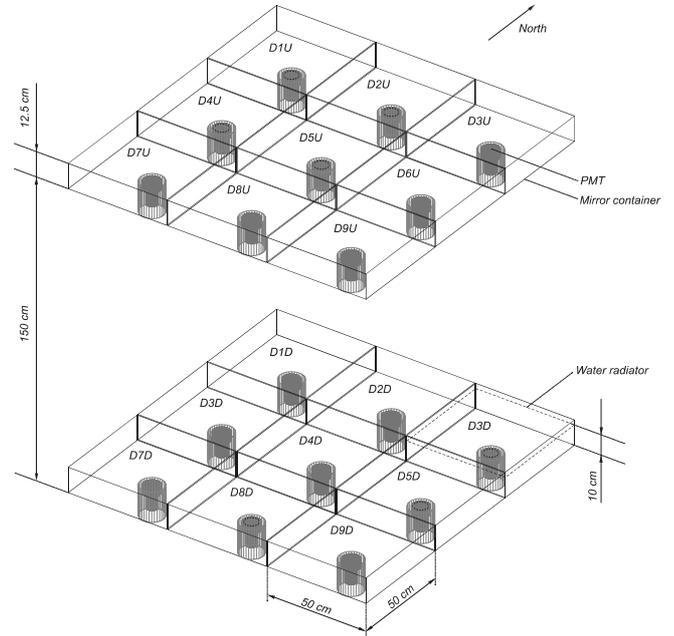


Fig. 3. Detectors configuration of the SWU muon telescope

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.

The data acquisition system of the SWU MT is shown on Fig. 4. 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 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.

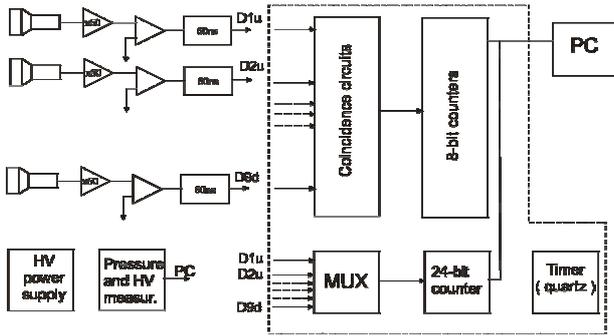


Fig. 4. The SWU muon telescope data acquisition system.

The high voltage power supply provides main stabilized 1950V voltage with separate down-regulated in 25 steps of 25V 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 was 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 in the number of coincidence circuits and counters [16].

3. CHARACTERISTICS

A. Energy threshold.

The energy thresholds for cosmic rays muons are determined mainly by the concrete layer above the telescopes. (~430 g/cm² for the University and ~110 g/cm² for BEO) 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 (158.7 MeV) and the 5cm lead absorber between the detectors planes.

The energy of vertical incident muons after passing the concrete and the lead layer and reaching the lower detectors planes is plot on Fig. 5. – top for the SWU telescope, bottom for BEO telescope.

The obtained values for the energy are $E_{th} \sim 1$ GeV for the telescope at the University and $E_{th} \sim 0.45$ GeV for the telescope at BEO for vertical muons.

B. 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.

The count rate at the laboratory of the University was compared with that achieved with a small telescope made of two NaI scintillators with diameter 80 mm and height 90 mm, with 50 mm distance between them. The measured intensity of CR muons with this scintillator telescope was $I_0 \approx 0,01$ cm²s⁻¹ster⁻¹. The calculated with this intensity count rate for vertical direction for pair of detectors for the telescope at SWU is ~ 133 min⁻¹. The Cherenkov detector threshold energy of ~ 158 MeV is not taken into account when count rate was calculated. The experimental count rate ~ 110 min⁻¹ is in agreement with the calculated. As mentioned above, the detectors are adjusted in the beginning of the plateau, to minimize the number of random coincidences, and the mean count rate for vertical detector pair is about 98-100 min⁻¹. Measuring the *relative* CR variations, not the absolute muon intensity, the long time stability of the detectors but not the 100% efficiency is more important.

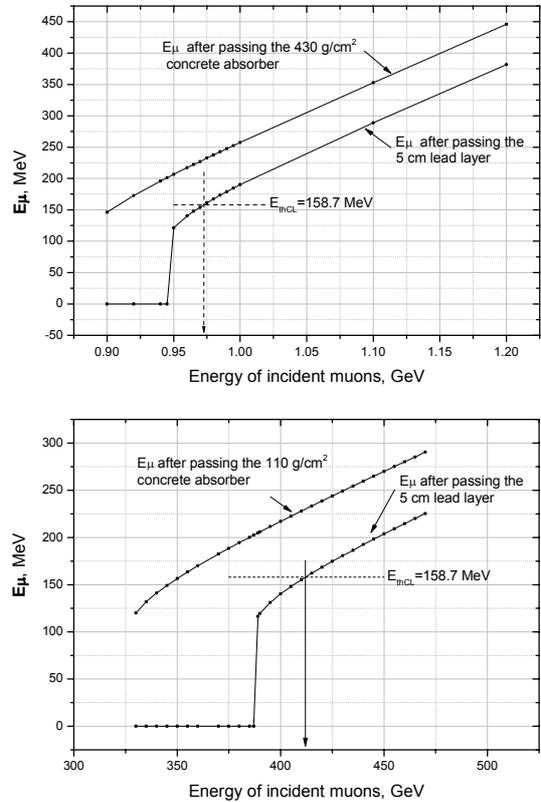


Fig. 5. Dependences of the energy with which muons reach the lower detector plane on the incident energy. Top – SWU MT, bottom – BEO MT

TABLE I
COUNT RATES FOR THE MT AT THE SWU

Direction	Angular interval, °	Detector pairs	Count-rate, min ⁻¹	Statistical error for 1h
Vertical	+18.4 -18.4	9	878	0.44%
N-S	0 - 33.7	6	438	0.61%
S-N	0 - 33.7	6	438	0.61%
W-E	0 - 33.7	6	455	0.6%
E-W	0 - 33.7	6	455	0.6%

TABLE2
COUNT RATES FOR THE MT AT THE SWU

Direction	Angular interval, °	Detector pairs	Count-rate, min ⁻¹	Statistical error for 1h
Vertical	+25.6 -25.6	4	2387	0.27%
N-S	0 - 45	2	814	0.45%
S-N	0 - 45	2	704	0.49%
W-E	0 - 45	2	756	0.47%
E-W	0 - 45	2	734	0.48%

C. Barometric coefficients.

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.

TABLE3
BAROMETRIC COEFFICIENTS FOR THE MT AT THE SWU

Direction	β , % / 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

TABLE4
BAROMETRIC COEFFICIENTS FOR THE MT AT THE BEO

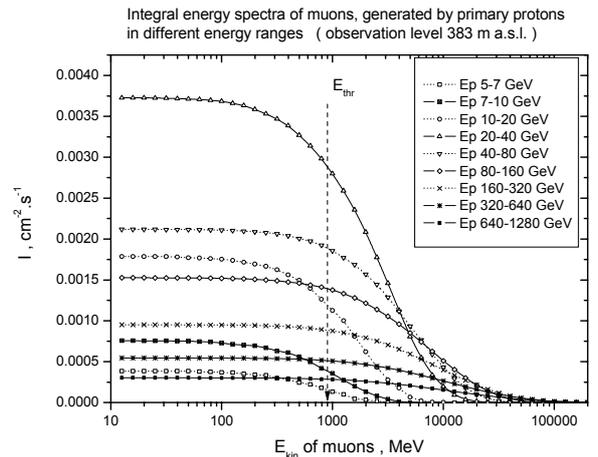
Direction	β , % / hPa	Error	Correlation coefficient
Vertical	-0.2889	0.0014	-0.8805
NS	-0.2552	0.0023	-0.7040
SN	-0.3190	0.0014	-0.8947
WE	-0.3258	0.0018	-0.8532
EW	-0.2796	0.0015	-0.8609

D. Rigidity cut off.

The rigidity cut-off for the observation sites was calculated using Planetocosmics software code [19]. The values obtained are $R_c \sim 6.34$ GV for the University site and $R_c \sim 6.24$ GV and for the BEO site.

E. Response to primary spectrum.

The response to primary protons was calculated with Planetocosmics, dividing the primary protons spectrum in sub-ranges. Simulations for the energy spectrum of muons generated by primary protons from the different sub-ranges were done and the obtained differential spectrums were integrated. (In these simulations we used flat geometry and no magnetic field settings.) The obtained muon spectra are shown on Fig. 6, top for the University MT, bottom – for the BEO MT. 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. 7. 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.



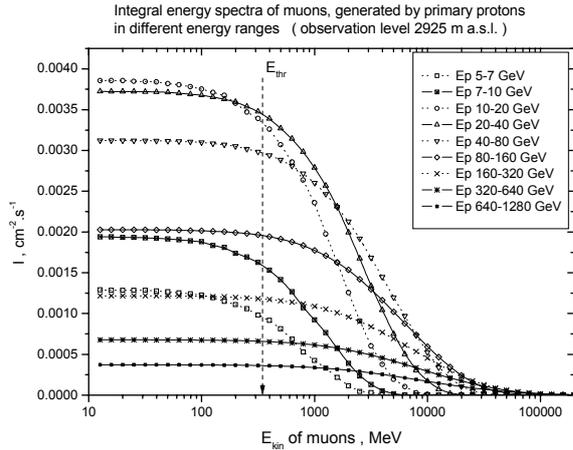


Fig. 6. Integral energy spectra of muons, generated by primary protons with different energies. Top – SWU site, 383 m a.s.l., bottom – BEO site, 2925 m a.s.l.

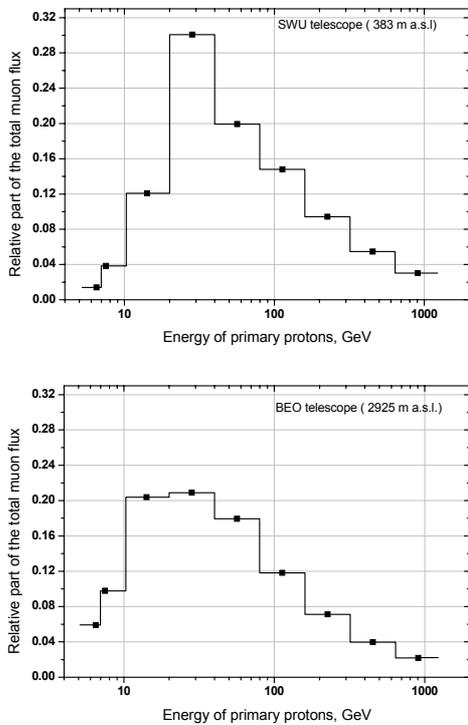


Fig 7. Response to primary protons. Top - SWU MT, bottom – BEO MT

F. Asymptotic directions.

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 on Fig. 8., the rigidity ranges plotted are 20-60 GV for BEO MT and 40-160 GV for SWU MT.

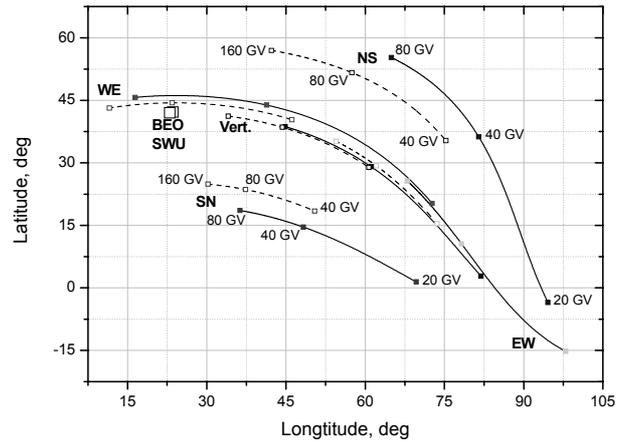


Fig 8. Asymptotic directions. Dashed lines - SWU MT, Solid lines – BEO MT

4. EXAMPLES OF EXPERIMENTAL DATA

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 on Fig. 9., top. For comparison, the same FD as registered by the SVIRCO neutron monitor (Rome, Latitude: 41.90N, Longitude: 12.52E, Altitude: 60 m Rigidity: 6.32 GV) is also shown (Fig. 9. – bottom).

The second is detected by the BEO MT after December 2006 Solar proton event, its amplitude in vertical direction is about 4% [16].

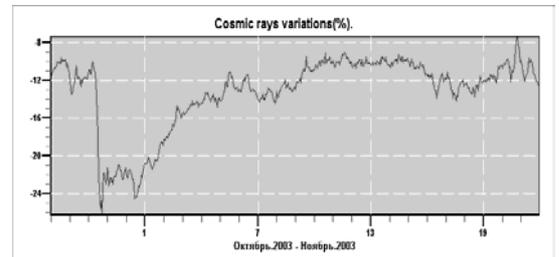
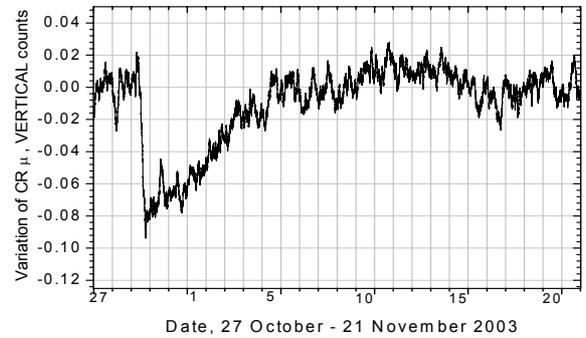


Fig 9. FD detected by the SWU MT, Oct.-Nov. 2003 – top. Bottom - the same FD, registered by the Rome neutron monitor.

5. SUMMARY

We have constructed two muon telescopes at observation site with $R_c \approx 6.3$ GV :

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

The constructed telescopes are stable in time and are used successfully for CR variations measurements. 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.

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