SOUTH-WEST UNIVERSITY "NEOFIT RILSKY"
BLAGOEVGRAD, BULGARIA

VOLUME 5
2007

SCIENTIFIC Research

ISSN 1312-7535

ELECTRONIC ISSUE

HIGH ANGULAR RESOLUTION MUON TELESCOPE FOR EXPLORING THE TEMPERATURE PROFILE OF THE ATMOSPHERE

Ivo Angelov [1], Elisaveta Malamova [2]

[1]South West University "N. Rilski" , address for correspondence : i_angeloff@mail.bg
[2]Institute For Nuclear Reasearch and Nuclear Energy, BAS

Abstract

A high angular resolution muon telescope with 6m^2 sensitive area based on 120 cherenkov detectors is proposed to be constructed and used for estimation of atmosphere parameters, and space weather investigations. The telescope is foreseen to be placed at ALOMAR observatory, Norway, and correlation of the variations of the cosmic rays muon flux with data sets from LIDARs, direct measurements from balloons, and magnetometer would be studied.

1. Introduction. CR muons and their barometric and temperature coefficient.

The vertical fluxes of the main components of the cosmic rays in the atmosphere in the energy range where the particles except electrons are with greatest number are presented at *fig.1*. [1] (The electrons, have greatest number at their critical energy – about 81 MeV for air - quite different from Ee>1GeV presented at fig.1.) All particles are produced in interactions of the primary cosmic rays in the air except protons and electrons at the top of the atmosphere. Muons and neutrinos are produced by the decay of the charged π - mesons, photons are produced by the decay of the neutral π - mesons, and they generate the electron – photon component of the cosmic rays.

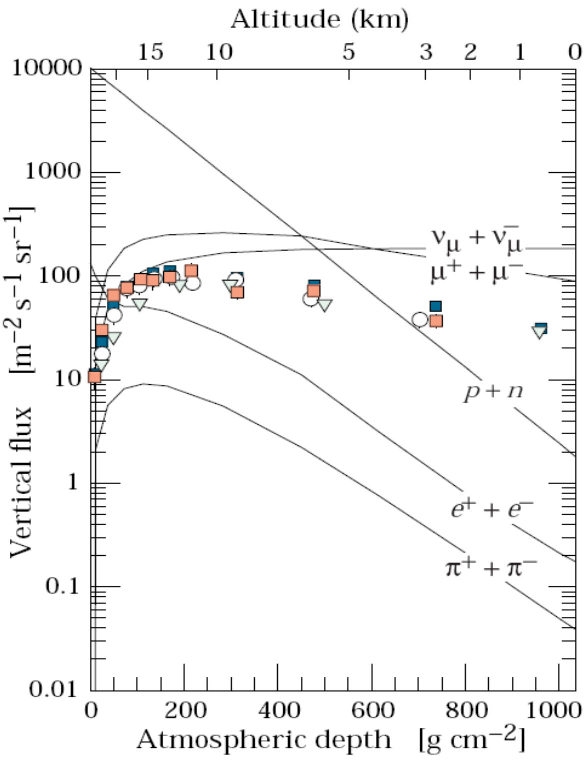

fig. 1. Vertical fluxes of cosmic rays in the atmosphere with E>1GeV, estimated from the nucleon flux. The points show measurements of negative muons with E_μ>1GeV. [1]

The muons are the most numerous charged particles at the sea level. Most of them are produced high in the atmosphere (about 20 km) and their energy looses because of the ionization are about 2 GeV to ground level. Their energy spectrum and angular distribution are result of the shape of the primary spectrum, energy loss and decay. The mean energy of the muons at ground level is ≈ 4 GeV. The energy spectrum is almost flat below 1 GeV, steepening gradually in the 10 – 100 GeV range, and steepens further at higher energies.

The angular distribution of the muons with energies ~ 3 GeV at the ground is proportional to $cos^2\theta$. At lower energies it becomes increasingly steep, while at higher energies it flattens.

Variation of the cosmic rays muons flux due to changes in the atmospheric conditions is known as "atmospheric effect". There are two main sources of this effect – the variations of the atmospheric pressure and the temperature. Both of them are because the change of the altitude at which most of the muons are generated and the change of the amount of matter the muons pass before reaching the ground. The next equation can be written for the barometric and temperature effect of the cosmic rays muons, registered by detectors with energy threshold $\overline{E}$:

$$\frac{\delta I(\overline{E_0},x_0,\theta)}{I(\overline{E_0},x_0,\theta)} = -\beta(\overline{E_0},x_0,\theta)\delta P + \int_0^{x_0} \alpha(x,\overline{E_0},x_0,\theta)\delta T(x)\mathrm{d}x \qquad (1)$$

$I(\overline{E_0},x_0,\theta)$	- integral flux of the muons at depth $x_0\ (g/cm^2)$
δP	- change in the atmospheric pressure
$\delta T(x)$	- change in the temperature at depth $x\ (g/cm^2)$
$\overline{E_0}$	- the threshold energy
$\beta(\overline{E_0},x_0,\theta)$	- barometric coefficient
$\alpha(x,\overline{E_0},x_0,\theta)$	- partial temperature coefficient

2. Monitoring of the atmosphere parameters based on barometric and temperature effect of CR muons. Existing experiments.

As the primary cosmic rays flux is comparatively constant with time, the variations of the muon component can be used to explore changes in the atmosphere up to stratosphere altitudes, because the muon flux counted by a ground-based telescope will depend on the atmosphere pressure and the temperature distribution in the layer between the detector and the point of generation.

This idea was first implemented in practice by a Russian team - MIPhI, laboratory "Muon Hodoscope - Tomograph TEMP", Moscow.

The "Muon Hodoscope" is a system based on 512 scintilator detectors 2.5x300 cm each, situated in four planes. It registers the arrival direction of each counted muon with accuracy of 1-2 degrees. (see fig.2) The effective area is $9m^2$ and the count rate ≈ 600 min^{-1}.
(More detailed description of the device can be found on the web page of the laboratory : www.muon.euro.ru , www.nevod.mephi.ru/English/temp.htm)

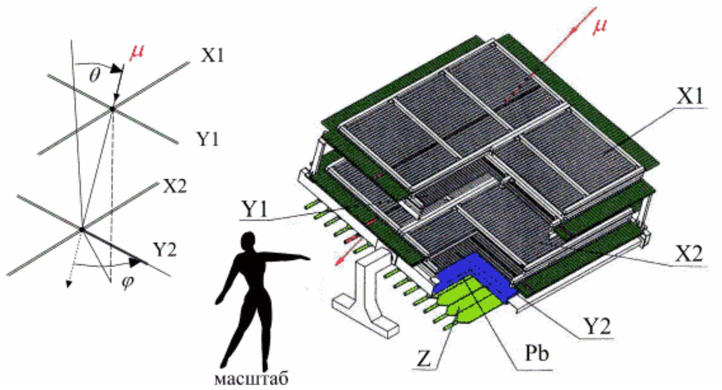

fig. 2 General view of the "Muon Hodoscope" (www.muon.euro.ru)

The Muon hodoscope "TEMP" is designed for solving the problems concerning solar-terrestrial physics and ecological monitoring using distant methods and can be used for :

- Distance estimate of continuous change of direction and velocity of a wind in the stratosphere ;
- Study of dynamics of internal gravitational waves at height 10-30km in the atmosphere ;
- Measurement of field of the temperature in the atmosphere ;
- Registration of the effective thickness of the ozone layer above a territory.

3. The proposed muon telescope and its main characteristics. Use for temperature profile of the atmosphere and internal gravity waves measurements.

A high angular resolution muon telescope is proposed to be constructed by INRNE team and ALOMAR observatory, Norway. It will be used mainly for temperature profile measurements of the atmosphere, internal gravity waves study, and possibly for ozone measurements, providing uninterruptible data set even for the time when the LIDARs are not operational because of meteorological conditions. An important advantage of this experiment is that the telescope can be calibrated using direct LIDAR measurements.

The preliminary design for the telescope is presented on fig. 3. It will consist of 120 cherenkov detectors, each using 80mm x 2400 mm plexiglas stick as radiator, placed in 4 planes. Passing a muon through any crossed pair of the upper planes detectors will be used as a master condition, the combination of the four triggered detectors (one in each plane) will determine the arrival direction of the muon. (see fig. 4)

The distance between the two pairs of detector planes determines the angular resolution of the device and should be chosen carefully taking into account the expected statistical errors. The count rate for a single elementary detector pair is :

$$dN = \frac{dS_1 dS_2}{R_{1,2}^{\;2}} \cdot \cos^2(\theta) I(\theta)$$

Where dS_1 and dS_2 are the areas of the detectors, $R_{1,2}$ is the distance between them, $I(\theta)$ is the intensity of the muon component.

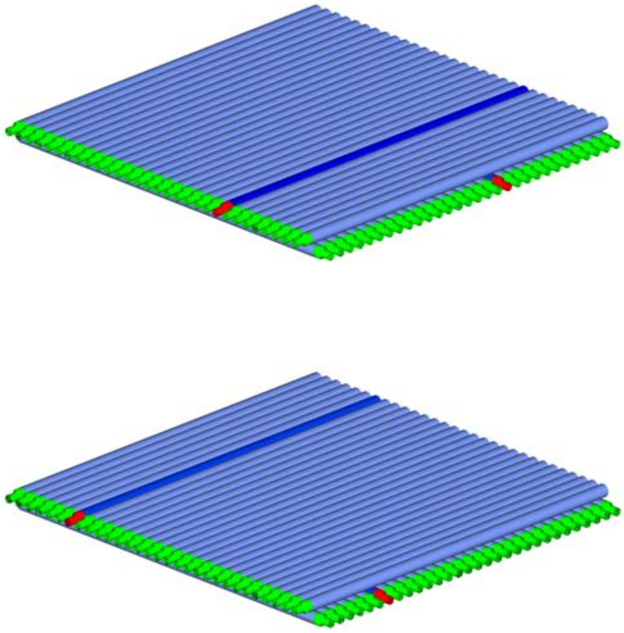

fig 3. Placement of the detectors of the proposed muon telescope

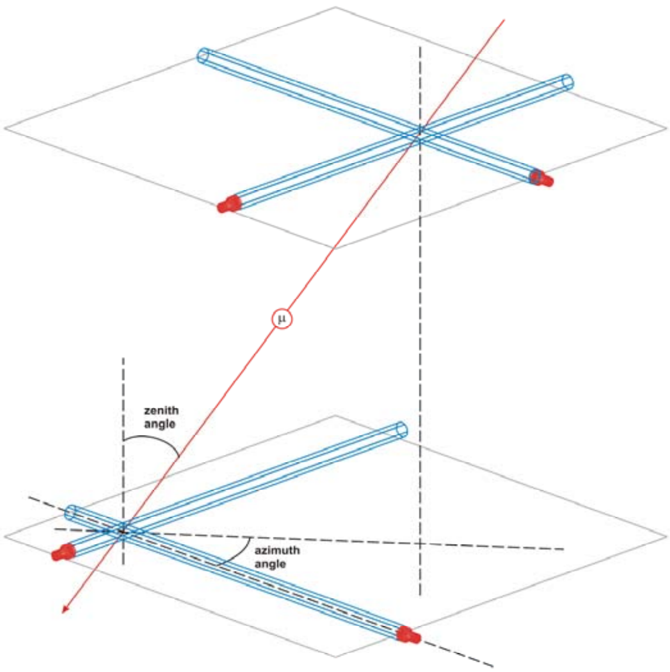

fig 4. Determining the arrival direction of a muon by 4 detectors.

Higher angular resolution leads to smaller count-rate for a single elementary detector pair. The count rate is yet smaller at high zenith angles, since the efficiency of the telescope decreases (smaller number of detector pairs count at these angles) and because of the angular distribution of the muon flux : $I(\theta) = I_0 \cos^2(\theta)$. Smaller count-rates lead to larger statistical errors $\sigma = \frac{\sqrt{N}}{N}$.

Small statistical errors and high angular resolution can be achieved by increasing the number of detectors, but it should be kept reasonable, because of the price of the telescope.

Angular resolution of ~4 degrees is selected for our design. Using 80mm radiators coupled to 2.5” photomultipliers, this gives 2292 mm distance between the detector planes.

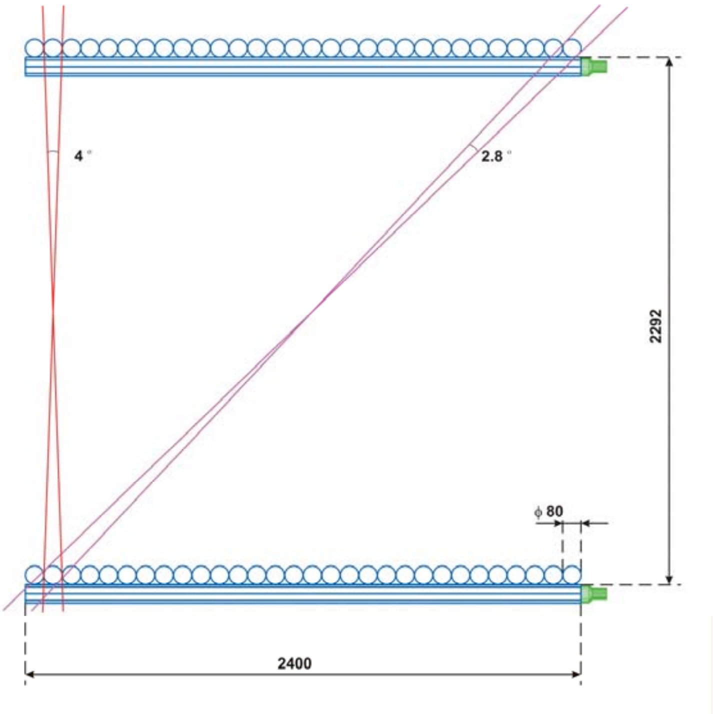

fig. 5. Geometry and angular intervals of the telescope.

The expected count rates and statistical errors for some zenith angular intervals are presented in the following table (Azimuth angle fixed to 0 degrees.) :

Zenith angle, deg. Azimuth=0	1/2 Angular interval, +- deg.	Count rate, min-1	Statistical error, 10 minutes measurements, %	Statistical error, 60 minutes measurements, %
0	2	42.104	4.873	1.99
5.978	1.998	36.674	5.222	2.132
11.828	1.957	29.613	5.811	2.372
21.004	1.866	17.652	7.527	3.073
30.684	1.719	7.381	11.639	4.752
39.953	1.533	1.709	24.191	9.876
45.348	1.405	0.169	76.896	31.392

The total expected count rate is $1.89 \cdot 10^4 \cdot min^{-1}$ ($315 \cdot s^{-1}$), at energy threshold ≈ 0.5 GeV.

The method for exploring the temperature profile of the atmosphere, described in [2], will be used.

The atmosphere is divided into layers with thickness 100 g/cm^2 (100 mbar) each. The experimental data for the variations of the cosmic ray muons are taken for 10 zenith angular intervals of 4 degrees and one 8 degrees. (see fig. 6)

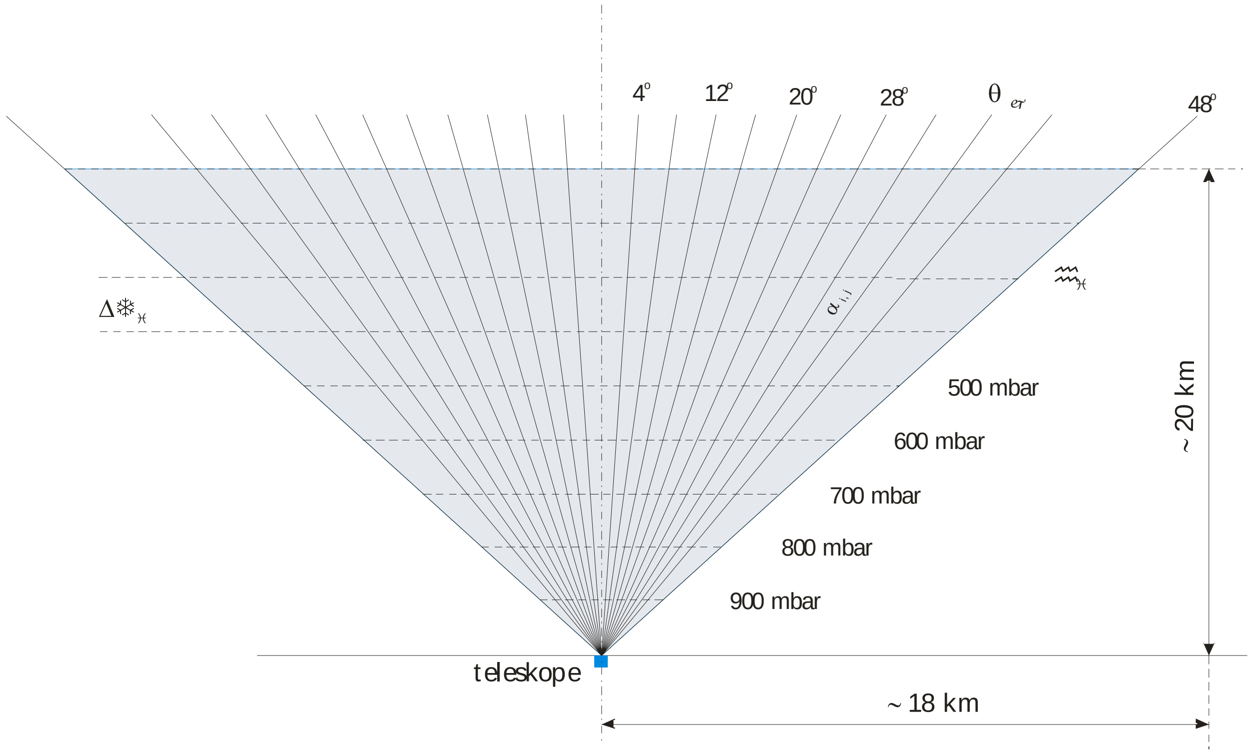

fig.6. Angular and altitude intervals for measuring the temperature profile of the atmosphere

Equation (1) can be written for each angular direction, taking the average partial temperature coefficient in each layer, substituting the integral with sums.

$$\frac{\Delta N_j(\theta_j)}{N_j(\theta_j)} + \beta \cdot \Delta P = \sum_{i=1}^{9} \alpha_{i,j}(h_i, \theta_j)\Delta T_i(h_i)\Delta h_i \qquad (2)$$

Here

$\alpha_{i,j}(h_i, \theta_j)$ is the average partial temperature coefficient at altitude h_i and angular direction θ_j. It should be known from simulation and checked during the calibration of the telescope by direct LIDAR measurements.

$\Delta T_i(h_i)$ is the change of the temperature in the layer with thickness Δh_i and altitude h_i (This is in fact the searched value.)

$\frac{\Delta N_j(\theta_j)}{N_j(\theta_j)}$ is the variation of the cosmic ray muons at direction with zenith angle θ_j , within angular interval 4 degrees. These are the experimental data.

β − the integral barometric coefficient ; $\beta = 0.15\,\% / mbar$

ΔP − change in the atmospheric pressure ; precise measurements of the pressure should be made continuously during the experiment.

Writing (2) for each angular interval θ_j , gives a system of 11 linear equations. Solving it we receive the temperature changes in 9 layers. The method is sensitive to changes in the temperature of the air in a cone volume with height ~ 20 km and diameter ~ 18 km.

The accuracy is dependant mainly on the statistical error of the telescope. Calculations for the count rate N and $\sigma = \frac{\sqrt{N}}{N}$ for two hours measurements of the variation of the muons in each angular interval are presented on fig. 7. The counts from angular intervals 40-44 deg. and

44-48 deg. will be taken together for better statistics; σ calculated on this plot is for 40-48 deg. interval.

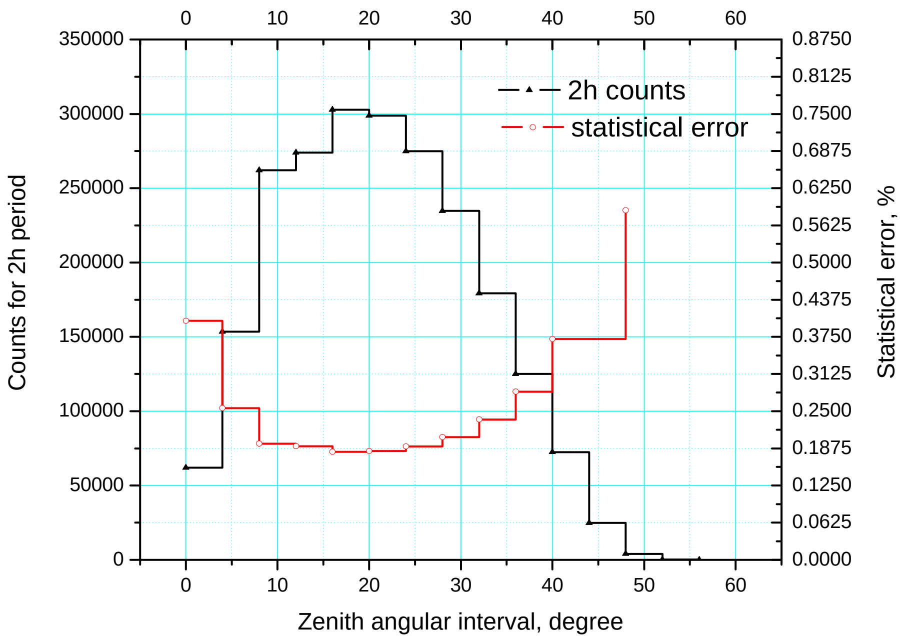

fig.7. Muons counted for two hours and statistical errors for each angular interval (calculations).

To estimate the accuracy in a first approximation, taking into account an average value of the temperature coefficient $\alpha \approx 0.18\% / deg$ and the calculated count rates, ~ 2^{o} C error measuring temperature profile is expected.

For more precise calculations of the expected accuracy and during data processing, each single detector pair has to participate to the total number counted muons N_θ in a given angular interval by its weight coefficient, corresponding to its area, included in the angular interval. This should be done by calculations, separating each single detector pair into 10x10 elementary detectors, and is needed for more precise interpolation of the zenith angle interval count rate. (fig 8.)

Corrections for the intensity of the geo-magnetic field have to be done, as they influence the geomagnetic threshold for the primary cosmic rays. Measurements of temperature profiles can be carried out during periods of low solar activity, to avoid modulation effects.

The data for the variation of the muon flux, when internal gravity waves registration campaigns (like described in [3]) are held, can be processed using spectrum analysis, trying to explore IGW propagation by the device.

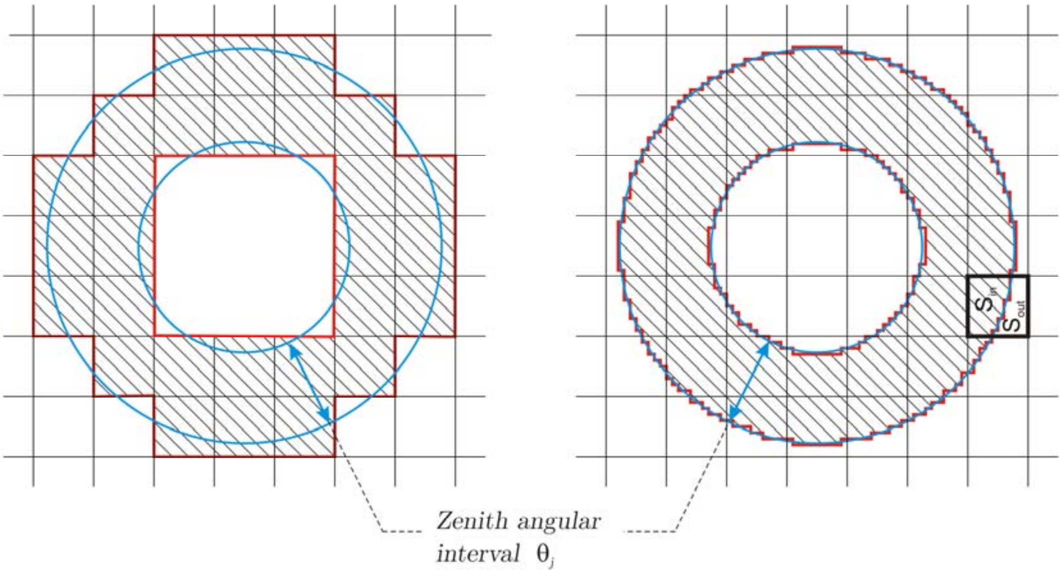

fig. 8 Weight coefficients for each elementary pair of detectors, corresponding to its area, included in a given angular interval ; $k=S_{in}/(S_{in}+S_{out})$

4. Research and development.

Two methodical experiments have to be performed before beginning of the construction of the device.

First the efficiency of a single detector over its length has to be explored. This will be done using a small scintillator telescope, registering cosmic ray muons in a small area within defined zenith angle (see fig. 9.)

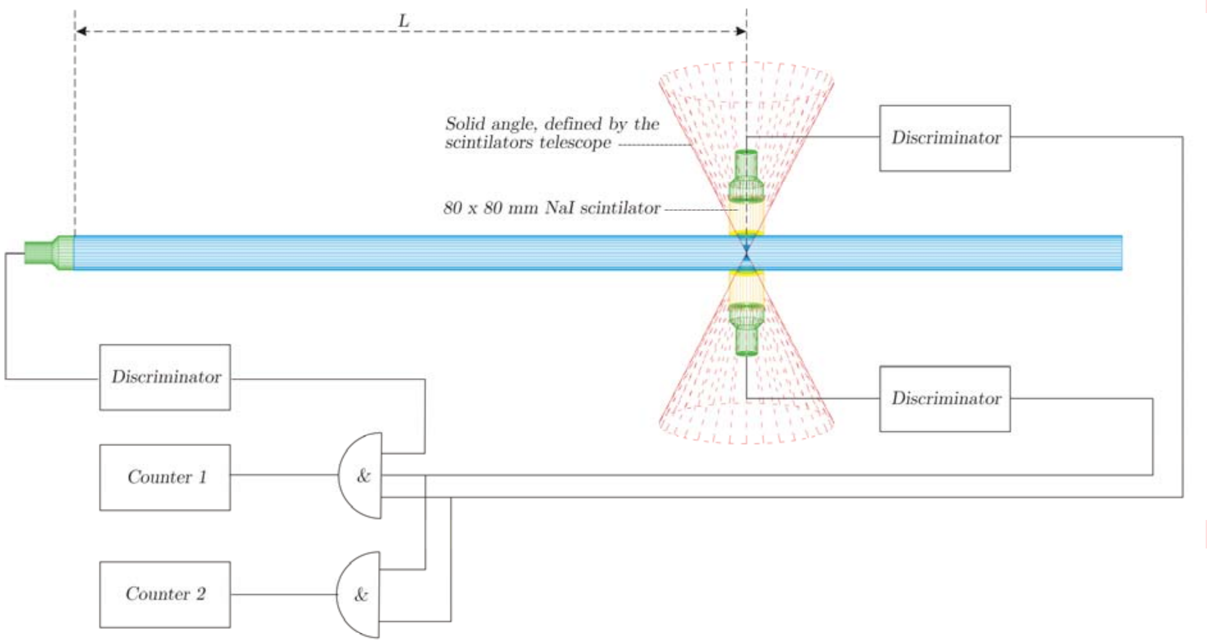

fig. 9. Experimental setup for exploring the detector efficiency over its length.

Muons registerd by the small telescope, composed of two scintillators, are counted by *counter 2.* The pulses from the explored detector are connected to a triple input coincidence circuit together with the pulses from the scintilator detectors. *Counter 1* counts muons registered by the small telescope and the cherenkov detector. As the efficiency of the scintilator detector is near 100% for CR muons, by measuring the dependence *(Counts 1)/(Counts 2)* as a function of *L*, we can determine the efficiency of the cherenkov detector over its length.

If the efficiency is not uniform, then some other designs of cherenkov (or possibly scintillation) detectors with size 80x240 mm will be explored. It is also possible a little different design of the detectors to be used from the beginning, because of some technological considerations for easier production, and reasonable price.

The next experiments will be carried out after developing of the prototype of the detector. Eight detectors are planned to be produced and connected in a configuration at fig. 10. The construction will allow placing each of the detectors at different places in its plane, defining with each pair of detectors different zenith and azimuth angles. With this setup mounted at ALOMAR observatory, the intensity of the cosmic ray muons, barometric and temperature coefficients and their angular distribution could be justified for the given geographical latitude and for the telescope.

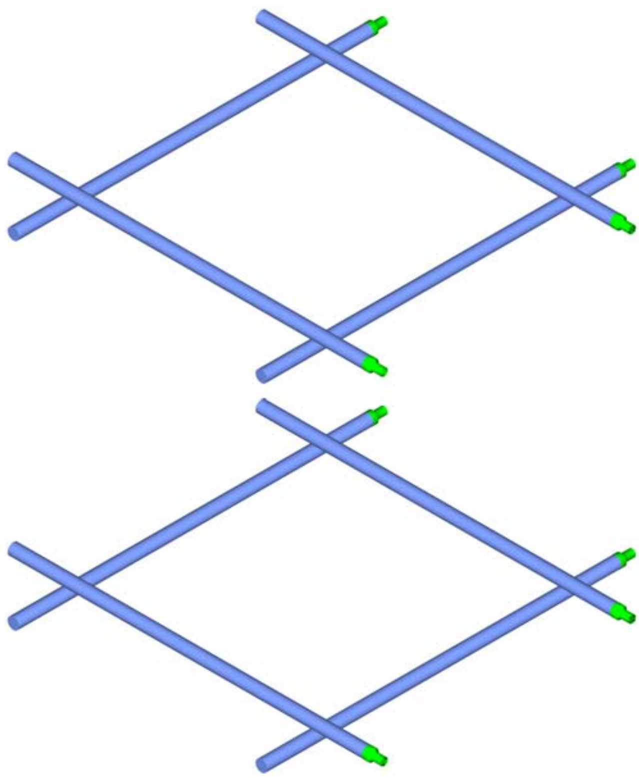

fig. 10. Configuration of eight detectors, which will be used for justifying the intensity of the CR muons, barometric and temperature coefficients and their angular distribution.

Conclusions

A high angular muon telescope is proposed to be constructed for exploring the troposphere and lower stratosphere temperature profiles and possibly internal gravity waves propagation, based on temperature and barometric effect. The main advantage is the possibility for simultaneous measurements with LIDARs and usage of direct measurements for calibration.

The estimated accuracy exploring the temperature profile of the atmosphere for 10 layers, 100 g/cm^2 each, and 2 hours time intervals is ~ 2^o C , for the proposed design.

Of course this experiment does not exclude the classic application of the muon telescopes – investigation of the variation of the cosmic ray muons : Forbush effect, modulation effects, anisotropy and spaceweather investigations.

Acknowledgements

We acknowledge the useful discussions and advices, concerning this proposal, with the head of the ALOMAR observatory Dr Michael Gausa and the Director of the Institute for Nuclear Research and Nuclear Energy – Bulgarian Accademy of Science, corresponding member Jordan Stamenov.

References

1. COSMIC RAYS, S. Eidelman *et al.*, Physics Letters **B592**, 1 (2004), available on the PDG WWW pages (URL: http://pdg.lbl.gov/) ; Revised March 2002 by T.K. Gaisser and T. Stanev (Bartol Research Inst., Univ. of Delaware); revised September 2005 by P.V. Sokolsky (Univ. of Utah) and R.E. Streitmatter (NASA)

2. Study of Atmospheric Temperature at Different Altitudes using Muon Angular Distribution at Sea Level, V. V. Borog et all, Proceedings of the 29th International Cosmic Ray Conference, Pune 2005

3. Gravity waves in the troposphere and stratosphere during the MaCWAVE/MIDAS summer rocket program, A. Schëoch et all, GEOPHYSICAL RESEARCH LETTERS, VOL. ???, XXXX, DOI:10.1029/