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Meteorological effects of the cosmic ray muon component measured by the mountain detectors

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The temperature effect of mountain muon detectors on the example of the YangBaJing muon telescope is studied. The temperature coefficients obtained exceed the theoretically expected ones. The inverse instrument problem for experimental determination of the density of the temperature coefficient is solved. The observational data are provided by the mddb database created for the muon detectors.

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1. Introduction

The global network of the muon telescopes includes a number of mountain telescopes situated at heights of up to 4500 meters (see Table 1). The meteorological effects of such detectors have their own unique features that have yet to be investigated. The authors of [1] discovered the abnormally high (several times greater than one expected) temperature effect of the muon component registered by the high mountain YangBaJing telescope. This work discusses the reasons for such a difference, and the inverse instrument problem for experimentally determining the density of the temperature coefficient is solved.

Table 1. Mountain detectors from the world muon telescopes network.

Detector name	Lat, °	Long, °	Alt, m	P0, mb	S_V,m^2	N_{dir}+2
YangBaJing	30.11	90.53	4300	607	6	*13+2*
Putre	-18.20	-69.55	3589	665	0.25	*1+2*
BEO Mussala	42.18	23.59	2925	710	4	*9+2*
Bure	44.63	5.91	2555	740	1	*1+2*
Leonsito	-31.80	-69.30	2552	745	1.5	*1.5*
Norikura	36.1	136.6	2270	800	16	*9+2*
GRAPES-III	11.38	76.67	2200	800	560	*9+2*
Yerevan2000	*40.5*	*44.17*	*2000*	*800*	*6*	*13+2*

2. Experimental data of the YangBaJing muon telescope

The YangBaJing multidirectional muon telescope (Institute of High Energy Physics, Beijing, China) of total area 6 m^2 is located at the altitude of 4300 m.a.s.l. (607 mb) (Fig. 1). The average count rate of the telescope for the vertical direction is about I_V ~ 180 Hz and E_{th} = 14,1 GeV. Both its planes – upper and lower – consist of k_X =4 and k_Y =6 ($k_X \times k_Y$=24) detectors. Therefore we can consider $(k_X \times k_Y)^2$=575 elementary telescopes of double coincidences between the upper and the lower planes.

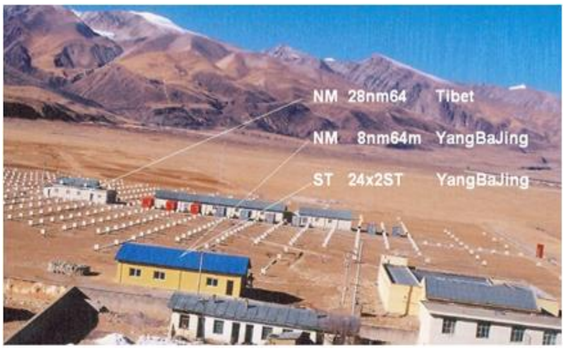

Fig. 1. The YangBaJing multidirectional muon telescope.

By means of these elementary telescopes, $(2k_X - 1) \times (2k - 1) = 77$ independent directions of particle arrival can be chosen. However practically 9 directions only are considered: the vertical and 4 directions (N, E, S, W) for the angles 21^o and 37^o. The YangBaJing muon telescope has been running since 2008. The equipment of the mountain station has been modernized during recent years, and this has led to a change in the telescope's efficiency.

The primary data of the YangBaJing muon telescope (the vertical direction) for 2012 – 2014 years are presented in Fig. 2. It is seen that approximately from the beginning of 2012 the efficiency of the telescope has been changed. As a result the amplitude of the annual (seasonal) wave of the count rate has been decreased. In spite of this the telescope is running quite stable, and its statistics is quite enough for the analysis.

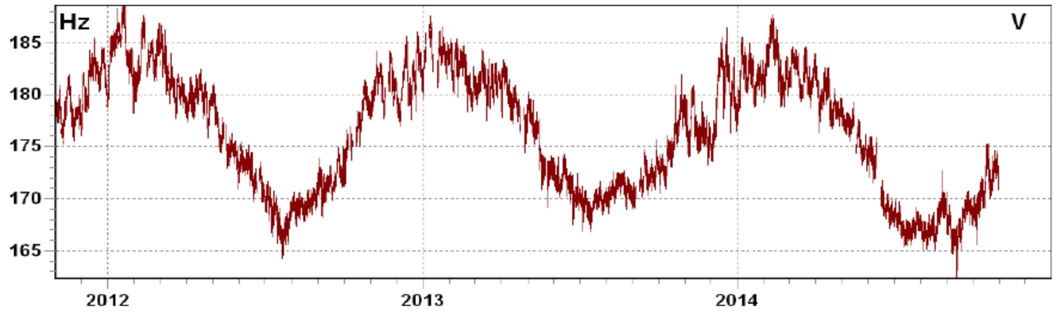

Fig. 2. The primary count rate of the YangBaJing muon telescope (the vertical direction) 2012-2014.

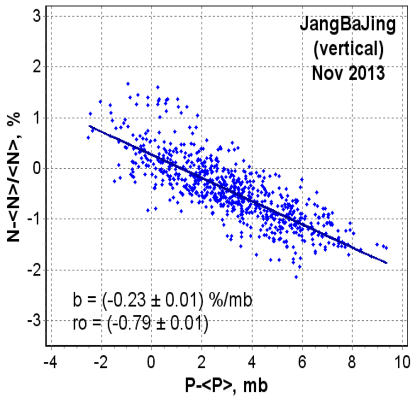

Fig. 3. The correlation dependence of the relative variations of the YangBaJing telescope's hourly count rate from the pressure changes.

3. Barometric effect

When analyzing the meteorological effects of the YangBaJing muon telescope in this paper the data for two years 2012-2013 were used. To exclude the barometric effect from the primary data of the telescope the barometric coefficient was calculated by the standard procedure described in [2]. As a result the barometric coefficient for the vertical was obtained as β=(-0.23±0.01)%/mb with the correlation coefficient ρ=(-0.79±0.01). The correlation dependence of the relative variations of the telescope's hourly count rate (for the vertical) from the pressure changes is presented in Fig. 3. According to the procedure [3], the primary telescope's data were corrected for the barometric effect as: $N_C = N_U \exp\left(-\beta(P_0 - P)\right)$ where N_C и N_U – the count rates corrected and uncorrected for the pressure changes correspondingly, P_0 – the average pressure and P – the measured pressure.

4. Temperature effect

There are several methods for analyzing the temperature effect of the muon component. The universal integral procedure was developed in the 1950s [4, 5]. Introduction of a function $W_T^{\mu}(h)$ as the density of the temperature coefficient allowed to identify the temperature variations as

$$\left.\frac{\delta N_{\mu}}{N_{\mu}}\right|_{Temp} = \delta_T = \int_0^{h_0} W_T^{\mu}(h,\theta)\cdot \delta T(h)\cdot dh \tag{1}$$

where $\delta T(h)$ is the change in the temperature track in the atmosphere against the basic temperature profile. The function $W_T^{\mu}(h,\theta)$ is determined via calculations.

The effective temperature method was developed at the same time [6], and can be considered as another form of the integral method:

$$\delta N_\mu / N_\mu \Big|_{Temp} = \int_0^{h_0} W_T^\mu(h)\delta T(h)dh = \alpha_T \cdot \delta T_{eff}\,, \tag{2}$$

where the temperature coefficient is $\alpha_T = \int_0^{h_0} W_T^\mu(h)dh$ [%/°K] and the change of the effective temperature is $\delta T_{eff} = \int_0^{h_0} W_T^\mu(h)\delta T(h)dh / \alpha_T$. Once we determine effective temperature T_{eff}, we can find temperature coefficient α_T experimentally using correlation dependence (2). This procedure is commonly used today for underground detectors.

The mass-average temperature method [7], which is based on determining the mass-average temperature Tm in the atmosphere, can be considered as a special case of the integral method. Because the density of the temperature coefficient $W_T(h)$ for the ground-based detectors does not change much with atmosphere depth h, the average value $\overline{\alpha}_T$ can be put before the integral sign:

$$\delta N_\mu / N_\mu \Big|_{Temp} = \overline{\alpha}_T \int_0^{h_0} \delta T(h)dh = \overline{\alpha}_T \delta T_m\,, \tag{3}$$

The mass-average temperature is determined either with sounding data or experimentally.
The empirical effective generation level method [8, 9] was developed earlier than the others. This procedure is based on the assumption that muons are generated at a specific isobaric level (generally considered to be 100 mb), altitude H_{100} of which changes along with the atmospheric temperature regime. The change in the muon component intensity correlates with the change in the altitude for the level of generation δH_{100} and the ambient temperature δT_{100} of this layer:

$$\delta N_\mu / N_\mu \Big|_{Temp} = \alpha_{H100}\delta H_{100} + \alpha_{T100}\delta T_{100}\,, \tag{4}$$

where α_{H100}(%/km), the so-called decay factor, is a negative effect, and $\alpha_{T100}$is a positive temperature coefficient.

5. Results and discussion

The data of the atmosphere vertical temperature profile were gotten from the Global Forecast System (GFS) temperature model representing by the National Centers for Environmental Prediction — NCEP (USA) [10]. In Fig. 4 the temperature altitude distribution in the atmosphere by the isobaric levels for 2012-2013 is presented on the bottom panel. And on the upper panel the high of the level of muon generation Z_{100} is depicted by the black line, and the mass-average temperature – by the red one.

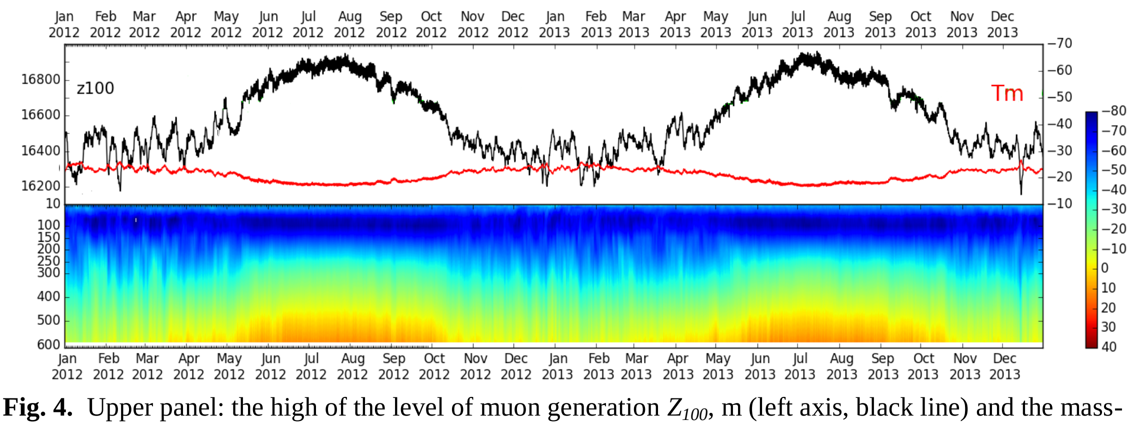

Fig. 4. Upper panel: the high of the level of muon generation Z_{100}, m (left axis, black line) and the mass-average temperature (right axis, red line). Bottom panel: temperature altitude distribution in the atmosphere by the isobaric levels for the YangBaJing muon telescope 2012-2013.

To appreciate the temperature effect of the muon component, measured by the YangBaJing mountain telescope, we use three methods described above: the effective temperature method (that is practically the same as the integral method, as one can see from equations (1) and (2)), the mass-average temperature method and the effective generation level method (i.e. the Blackett-Duperier method). The corresponding regression coefficients (α) and correlation ones (ρ) obtained are presented in a Table 2.

Table 2. Coefficients, obtained by the effective temperature method (1), the mass-average temperature method (2) and the Blackett-Duperier method (3) for the muon telescope YangBaJing

method	coefficients	α	ρ
1	α_{Teff} (%/K)	-0.847±0.004	-0.920±0.001
2	α_{Tm} (%/K)	-0.725±0.003	-0.923±0.001
3	α_{H100} (%/km)	-0.019±0.001	-0.943±0.001

In Fig. 5 three time series are presented as an example for 2013: the blue curve is the effective temperature variations, the red and the green curves are relative variations of the YangBaJing telescope's intensity uncorrected and corrected for the temperature effect correspondingly.

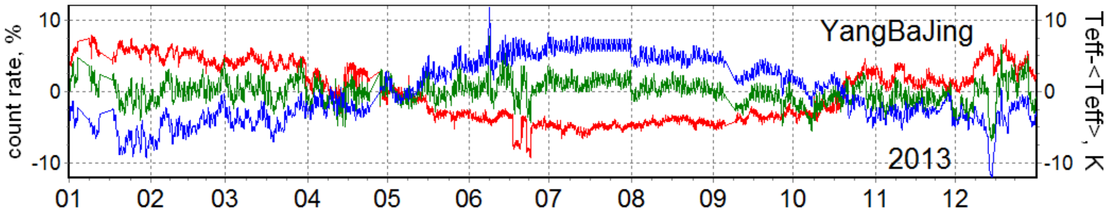

Fig. 5. Variations of the effective temperature T_{eff} (blue line), count rate variations (vertical) of the YangBaJing muon telescope - uncorrected (red line) and corrected (green line) for the temperature effect for 2012-2013.

It is clear that in order to assess the temperature effect using the integral method, we must know the density of the temperature coefficient. The effective temperature method requires that we know the density of the temperature coefficient within the accuracy of the multiplier, which is determined experimentally. Those two methods produce the same results, as opposed to the mass-average temperature method which does not require us to know the density of the temperature coefficient and is quite suitable for ground detectors. The Blackett-Duperier empiric method can be also derived from the integral method if we assume that $W_T \propto h^{-1}$, and this is well satisfied at high energies.

Analyses were performed for the YangBaJing mountain telescope (600 mb), and the Nagoya telescope (1013 mb) data were used for comparison and control. The 2013 seasonal trends for Nagoya and YangBaJing telescopes are given on the upper panel of Fig. 6. It is seen that the amplitude of the seasonal variations for the YangBaJing telescope is ~7% and for the Nagoya telescope - less than 3%. Variations were found using different methods, but the details of such comparisons virtually identical. The lower panel in Fig. 6 illustrates the comparison of the temperature effect obtained by the different methods: integral, effective and mass-average temperature as well as the Blackett-Duperier method. It is clear that the integral and the effective temperature methods yield the same result, as can be seen from the straight line in the lower panel of Fig. 6. The mass-average temperature method (white diamonds) produced results that were not so good. The Blackett-Duperier empirical method was even less accurate (black triangles). The same conclusion can be drawn for the Nagoya detector, as the instrumental density of its temperature coefficient was 0.81 against the calculated function, which is quite understandable for the low latitude Nagoya muon detector.

With the YangBaJing telescope, the instrumental density of the temperature coefficient was 2.19 times higher than the calculated values. The apparatus temperature variations are a less likely reason for the abnormally high temperature effect. It is quite possible that the difference between the expected and observed effects for the high mountain detectors is associated with the calculated density of the temperature coefficient, which is better determined experimentally.

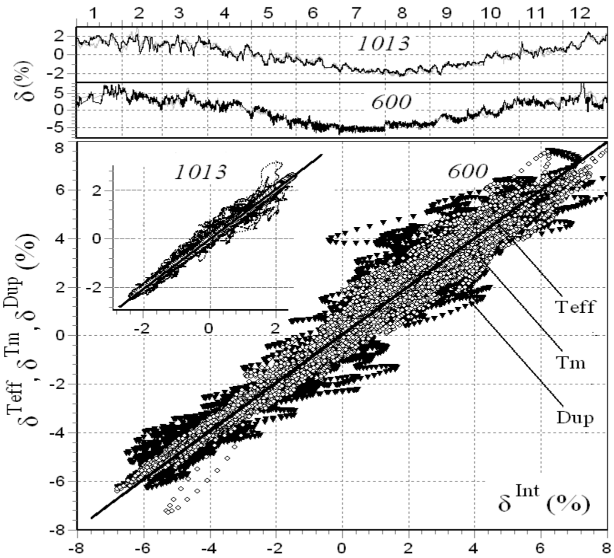

Fig. 6. Comparison of the temperature variations obtained by different methods for the Nagoya (1013 mb) and the YangBaJing (600 mb) telescopes. The time series of the temperature variations in muon intensity at these stations are shown on the upper panel. The temperature effects obtained by the integral method or by the effective temperature method (bold straight lines), the mass-average temperature method (white diamonds), and the Blackett-Duperier method (black triangles) are compared in the lower panel to reveal details.

6. Solving the inverse instrument problem

The algorithm for excluding the temperature effect requires us to know the instrumental density of the temperature coefficients for each detector accounting for the unit’s specific geometry, threshold energy (determined by the screen of shielding and electronic track), and the geomagnetic cutoff rigidity. Experience shows that the instrument densities of the temperature coefficients of different detectors can differ by as much as 20%. Not all of these details are considered when calculating temperature coefficient densities. Experimental determination of the temperature coefficient density is not an easy task [11]. In a simple case in which the curve shape does not changed (i.e., instrumental density W_T is associated with the calculated density through the multiplier only), it may be determined by the effective temperature method. Generally, however, we must solve Eq. (1) in order to determine the instrumental density of the temperature coefficient experimentally. It is assumed that experimental data are free of the barometric effect and adjusted for initial variations. In general terms, Eq. (1) is an integral Fredholm equation of the first kind. Determining $W_T^{\mu}(h,\theta)$ (i.e., the equation kernel), is a typical instrumental problem. Procedures have been developed to solve such problems. The simplest one is describing the kernel by some general approximating function and determining the function parameters. Such polynomial functions can be developed on the basis of the physical considerations. Using the theory of meteorological effects, we can derive an approximating function of the type [2]:

$$W_T(h) = W_T^{\mu}(h) + W_T^{\pi}(h) = (x_0 + x_1 \frac{h}{L_\mu Cos\theta} + x_2 e^{-\frac{h_0-h}{L_\mu Cos\theta}}) + x_3 \frac{\Lambda Cos\theta}{h^{1.07}}(e^{-\frac{-h}{L_\pi Cos\theta}} - e^{-\frac{h}{L_N Cos\theta}}) \quad (5)$$

in which the absorption lengths in $g \cdot cm^{-2}$ is L_π =160, L_N =120, a $\Lambda = L_\pi L_N /(L_\pi - L_N)$ и L_μ =800, $L_{\mu s}$ =250. We have a model of mass-average temperature if it is limited by the first summand. If the first two summands are considered, this model describes the linear change in the temperature coefficient density. The third summand considers the input from soft muons that changes the form of the density of the temperature coefficient near the level of observation. The sum of the first three summands determines the negative muon effect, while the fourth determines the positive temperature effect. If we insert (5) into (1), we get the simultaneous linear equations *Ax = y:*

$$\left.\frac{\delta N_i}{N_i}\right|_T = x_0 \underbrace{\int_0^{h_0} \delta T_i(h)dh}_{A_0^i} + x_1 \underbrace{\int_0^{h_0} \frac{h}{L_\mu Cos\theta} \delta T_i(h)dh}_{A_1^i} +$$

$$+ x_2 \underbrace{\int_0^{h_0} e^{-\frac{h_0-h}{L_\mu Cos\theta}} \delta T_i(h)dh}_{A_2^i} + x_3 \underbrace{\int_0^{h_0} \frac{\Lambda Cos\theta}{h^{1.07}}(e^{-\frac{h}{L_\pi Cos\theta}} - e^{-\frac{h}{L_N Cos\theta}})\delta T_i(h)dh}_{A_3^i}, \quad (6)$$

or $\sum_n x_n A_n^i = y^i$. The solution of the equation $Ax = y$ is based on the SVD.

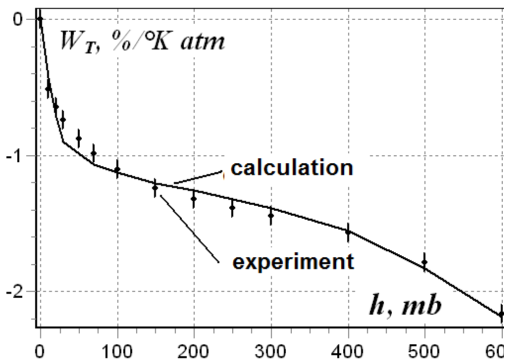

Fig. 7. Altitude dependence of the estimated (continuous) and experimental densities of the temperature coefficient on the standard isobaric levels.

We analyzed hourly data for a period of one year, but without considering possible seasonal changes in the temperature coefficient density. Fig. 7 compares the calculated (with due account of the 2.19 multiplier) and experimental densities of the temperature coefficients for the YangBaJing vertical telescope. The approximation coefficient in terms of $\% / K^\circ atm$ is *X*=(–1.55, 1.29, –1.59, 1.48). On the whole, proposed function (5) approximates the experimental data but is not entirely reliable. To obtain a more accurate positive temperature effect in the last summand of Eq. (5), however, we must enhance its dependence on depth by introducing the level $h^{-1.07}$ and inspect the underground detectors when the positive temperature effect dominates.

Conclusions

Since all of the above procedures for evaluating the temperature effect of the muon component yield close results, the temperature effect of the muon component registered by mountain detectors must be high indeed. In order to correctly solve this problem, however, we should conduct a separate investigation of different mountain detectors (e.g., the newly commissioned Sierra Negra high mountain telescope).

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