Atmospheric Variations as observed by the BUST. Barometric Effect

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Abstract: According to the Baksan underground scintillation telescope’s (BUST) data for ten years (2003-2012) barometric coefficients for six intervals of zenith angles of particle registration were obtained. There is a noticeable increase of the absolute values of the measured barometric coefficients with the energy increase.

Keywords: high-energy muons, BUST, barometric effect.

1 The Baksan underground scintillation telescope

The Baksan Underground Scintillation Detector of the Institute for Nuclear Research RAS is located in the Caucasus mountains (43.28° N and 42.69° E) inside the mine (dimensions 24x24x16 m3) under the Andyrcha mountain. There is 350 m of rock, vertical depth (850 mwe) over the telescope. The BUST is parallelepiped (16.7x16.7x11.1 m3) consisting of 8 planes (4 inner and 4 outer) of detectors (each of 70x70x30 m3) with liquid scintillator (figure 1). The observatory level is 1700 m above sea level, average pressure is 820 mb. The muon threshold energy is 220 GeV. But because of the complex topography over the installation (according to angles and directions) one can obtain results to a depth >6000 g/cm^2 [1]. The BUST’s experimental data cover a wide range of threshold energies (0.2 - 10 TeV) and zenith angles (0° - 90°). Data for angles θ > 70° are characterized by low intensity and therefore - the small statistics.

As the primary BUST’s data are integrated over the azimuthal angles and presented by six intervals of zenith angles (vertical v0 (0° < θ < 34°)); interval 01 (34° < θ < 48°); interval 02 (48° < θ < 60°); interval 03 (60° < θ < 71°); interval 04 (71° < θ < 80°); interval 05 (80° < θ < 90°) then each interval has a wide range of threshold energies because of the complex topography over the telescope. Thus the main contribution to the count rate (∼ 80%) comes from zenith angles 0°-60° that approximately corresponds to the range of the threshold energies from 0.7 to 10 TeV [2]. A calculation of the BUST’s muon energy spectrum was made in a preprint P-0379 [3]. According to [3] a dependence of the threshold energies of the registered particles on the azimuthal angles for the full range of zenith angles (from 10° to 85°) are built in figure 2.

The curves (in steps of 5°) are grouped by the presented intervals of zenith angles: vertical v0 corresponds to the red color; the interval 01 - green; the interval 02 - orange; the interval 03 - blue; the interval 04 - grey; the interval 05 - brown. As in the preprint P-0379 data on the zenith angles are given in steps of 5° then each of the six intervals (except the interval 05) corresponds to two or more curves. It is clearly seen in figure 1 that threshold energies vary by orders of magnitude within one interval for angles θ > 45° (depending on the amount of the rock). This complicates determination of the effective threshold energy for each of the intervals considered. Nevertheless in this paper the following values of the effective threshold energies were adopted for each of the zenith angle intervals: a) for the vertical v0 - E_{th} ∼ 230 GeV; b) for the interval 01 - E_{th} ∼ 280 GeV; c) for the interval 02 - E_{th} ∼ 380 GeV; d) for the interval 03 - E_{th} ∼ 850 GeV; e) for the interval 04 - E_{th} ∼ 1700 GeV; f) for the interval 05 - E_{th} ∼ 7000 GeV.

2 Barometric effect as observed by underground detectors

The barometric effect is well studied within the theory’s framework of the meteorological effects of secondary cosmic ray component [4]. According to the theory, it is assumed that the barometric effect of high-energy muons is negligible, as its absolute value decreases with increasing the threshold energy of the registered particles. In [4] the barometric coefficients for high-energy muons obtained by different authors for counter telescopes at various depths are presented. Their values are in good agreement with the theory, i.e. with the depth (or energy) increasing the absolute value of the barometric coefficient decreases.

But J.E.Humble et al. in 1979 and P.R.A.Lyons et al. in 1981 in [5] and [6] tried to explain an unusually large value of the barometric coefficient observed at Poatina, Tasmania (357 m.w.e. in depth, Eth > 100 Gev) which was about 7 times more than the theoretically predicted one. Thus according to the Poatina’s data from 1972 to 1976, taking into account only the pressure change, the barometric coefficient...
It was reported about a large value of the barometric coefficient for groups of muons (the registered events corresponded to the primary particles energies of $\sim 10^{15}$ eV) determined at the DECOR installation (Moscow Engineering Physics Institute), unlike the barometric coefficient for single muons \([\text{11}]\). With the double linear regression (taking into account variations of pressure and temperature at the same time) for groups of muons the barometric coefficient was obtained as $\beta = (-0.314 \pm 0.002) \%/\text{mb}$. The observed effect was explained by a change of the spatial distribution function for muons in extensive air showers.

Let us recall that for single muons (at the Earth’s surface, $E_{\text{th}} \sim 0.4$ GeV) barometric coefficient is approximately equal to $\beta \sim -0.2 \%/\text{mb}$. And, according to the theory of meteorological effects \([\text{4}]\), the absolute value of the barometric coefficient should be decreased with increasing energy of the registered particles.

### 3 Barometric effect as observed by the BUST

In a paper \([\text{12}]\) the barometric effect for such depths as the BUST was estimated as too small value ($\beta \sim -0.004 \%/\text{mb}$), therefore it could be neglected. For the same reason the barometric effect was not considered in a later paper \([\text{13}]\). In the study of the temperature effect for the BUST \([\text{14}]\) according to the total count rate over all directions for 2009-2010, the authors also assumed that the barometric effect for high-energy muons ($\sim 200$ GeV) is negligible. However, before starting the temperature effect analysis for the ten-year observation period (2003-2012) (for six channels - vertical and five intervals of zenith angles), it was decided to release the monitoring data even from a small barometric effect. Using the hourly data, barometric coefficients for all the intervals of zenith angles were obtained by a simple linear regression. Table 1 shows the average values of the barometric and correlation coefficients (for the vertical and for five intervals of zenith angles). The obtained experimental barometric coefficients exceed an order of magnitude or more the theoretical ones, and this agrees with \([\text{9}]\).

Analyzing the data obtained it is clear that the more statistics the better correlation, and vice versa. And it is difficult to talk about any correlation for the largest angles, as their count rate is negligible. In simple linear regression the model used to describe the relationship between two variables (in our case - data and pressure), but at the same time, one can not ignore the influence of unaccounted temperature effect. With that, for hourly data on a monthly interval diurnal and semi-diurnal temperature variations are always present \([\text{5}, \text{6}]\). To avoid a possible influence of temperature effect on the correlation between pressure and the telescope’s data the linear regression was performed on the average annual data for 10 years. In this approach an influence of daily and annual temperature variations was excluded as they are averaged over such a long interval. Figure 3 shows the correlations between annual averages of pressure and average annual BUST’s data for all six intervals of zenith angles for 2003-2012. The barometric coefficients obtained by the correlation analysis of average annual count rate for each direction and the corresponding correlation coefficients are presented in Table 2.

It is seen from Tables 1 and 2 that the correlation coefficients $\rho$ for all directions between annual data are much

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**Figure 2**: Dependence of the threshold energies on azimuthal angles for the full range of zenith angles in steps of $5^\circ$ for the BUST: vertical $v_0$ - red curves; the interval $01$ - green curves; the interval $02$ - orange curves; the interval $03$ - blue curves; the interval $04$ - grey curves; the interval $05$ - a brown curve.

$\beta = (-0.047 \pm 0.0016) \%/\text{mb}$ was obtained by using linear regression, while a theoretical value was $(-0.007) \%/\text{mb}$. In the paper \([\text{5}]\) it was also reported about large seasonal variations of the barometric coefficient. To explain this result an assumption was made that the barometric coefficient is also affected by unaccounted parameters of the upper atmosphere (100 mb and above). To check this assumption, in the paper a multiple regression analysis of the data was carried out over the same period taking into account all three parameters - pressure at the observation level, altitude and temperature of the 100 mb layer (information about the higher layers were not available). As a result, the barometric coefficient was not too different from the previous value. The authors concluded that the discrepancy of the observed and theoretical barometric coefficients may be caused by unaccounted muons from kaons, as well as the unaccounted impact of temperature of the upper atmosphere layers above 100 mb, where muons of such high energies are mostly produced.

In a paper \([\text{6}]\) a significant negative correlation between pressure and temperature of the upper atmosphere was defined. Considering this result and the possible temperature errors, the authors evaluated the barometric coefficient for Poatina and got $\beta$ in the range from $(-0.0214 \pm 0.0020)$ to $(-0.0257 \pm 0.0019) \%/\text{mb}$. These values are two times less than those obtained earlier, but still several times higher than the theoretical ones. In a paper \([\text{7}]\) it was reported that for the underground telescope Matsushiro (250 m.w.e. in depth) a barometric coefficient was obtained as $\beta = (-0.045 \pm 0.005)$ that is five times more than the theoretically expected value.

Later S.Sagisaka in a work \([\text{8}]\) presented barometric coefficients for a large number of underground detectors at different depths. All the data presented in \([\text{8}]\) were in good agreement with theoretical calculations. But, for the deepest detectors Matsushiro (250 mwe in depth) and Poatina (365 mwe in depth) the barometric coefficients were significantly more than theoretically calculated values: $\beta = (-0.027 \pm 0.004) \%/\text{mb}$ for Matsushiro \([\text{9}]\) and $\beta = (-0.047 \pm 0.002) \%/\text{mb}$ for Poatina \([\text{10}]\). S.Sagisaka explained this discrepancy as the possible influence of the temperature effect, because observed barometric coefficients were obtained by simple correlations between the variations of the measured muon intensity $\Delta I$ and the pressure $\Delta P$, without taking into account temperature changes.
higher than between hourly ones. This may confirm the assumption that the temperature affects the barometric coefficients. At the same time the barometric coefficients turned out to be much larger.

4 Results and discussion

To combine all results obtained and referred to, a figure from [3] was extended (figure 4). The barometric coefficients for hourly data obtained in this work for all the intervals of zenith angles (red points 15-20) for the threshold energies (from 230 to 7000 GeV) have been added in figure 4. The points from 0 to 14 and the calculated curves are from [3]. The energy scale in figure 4 has been extended right up to 10^17 GeV that allowed to plot barometric coefficients for EAS (black triangles 21-27) [4]. A black point 28 corresponds to the barometric coefficient obtained in [11] for groups of muons. For the Andrychvi air shower array (energies from 2 to 100 TeV) the barometric coefficient of $\beta = -1.11$ %/mb (black line 29) was obtained in [11]. In the upper left corner of figure 4 a line (nm65) marks the barometric coefficients for the neutron cosmic ray component.

Increase of the absolute values of the barometric coefficients can be explained that single muons are mainly observed up to energies of secondary particles of about 100 GeV. And at higher energies the contribution of muon groups of extensive air showers is more significant. Barometric coefficient for the frequency of extensive air showers depends weakly on the parameters of showers, and it is close to the barometric coefficient for nucleon component.

Let us denote intensity of single muons $I_{\mu}$ and EAS muons $I_{EAS}$, the corresponding barometric coefficients $\beta_{\mu}$ and $\beta_{EAS}$, the total intensity of single and EAS muons as $I$, and the corresponding barometric coefficient $\beta$. Then we can write down a system of equations in which the first equation determines a sum of relative contributions of the intensities of single and EAS muons, and the second one - a sum and proportion of single and EAS muons in the full barometric coefficient of the detector:

$$\begin{cases} I_{\mu}/I + I_{EAS}/I = 1 \\ I_{\mu}/I \cdot \beta_{\mu} + I_{EAS}/I \cdot \beta_{EAS} = \beta \end{cases}$$

(1)

The equation gives a solution for the relative contributions of the two sources of muons:

$$\frac{I_{\mu}}{I} = \frac{\beta_{EAS} - \beta_{\mu}}{\beta_{EAS} - \beta_{\mu}} \text{ and } \frac{I_{EAS}}{I} = \frac{\beta - \beta_{\mu}}{\beta_{EAS} - \beta_{\mu}}$$

(2)

The EAS barometric coefficient is $\beta = -0.901$ %/mb. And $\beta_{\mu}$, $\beta$ and ratio $I_{\mu}/I$ obtained for Matsushiro, Poatina and the BUST (vertical and 5 intervals of zenith angles) are shown in the table 3.

The right scale has been also added in figure 4 to present the contribution of muon groups to the total intensity (gray icons of EAS and gray curve). The results obtained confirm the hypothesis about the contribution of the muon groups to the barometric effect observed according to the BUST. Thus, as expected, the share of muon groups of extensive air showers increases with the energy of the registered particles. After the barometric coefficients were determined, the primary data of the six intervals of zenith angles of the

<table>
<thead>
<tr>
<th>channel</th>
<th>$0^\circ &lt; \theta &lt; 34^\circ$</th>
<th>$34^\circ &lt; \theta &lt; 48^\circ$</th>
<th>$48^\circ &lt; \theta &lt; 60^\circ$</th>
<th>$60^\circ &lt; \theta &lt; 71^\circ$</th>
<th>$71^\circ &lt; \theta &lt; 80^\circ$</th>
<th>$80^\circ &lt; \theta &lt; 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eth, GeV</td>
<td>230</td>
<td>280</td>
<td>380</td>
<td>850</td>
<td>1300</td>
<td>&gt;7000</td>
</tr>
<tr>
<td>d, m.w.e.</td>
<td>940</td>
<td>1170</td>
<td>1400</td>
<td>1980</td>
<td>3260</td>
<td>7000</td>
</tr>
<tr>
<td>$\beta$, %/mb</td>
<td>-0.044 ± 0.008</td>
<td>-0.043 ± 0.008</td>
<td>-0.049 ± 0.009</td>
<td>-0.049 ± 0.010</td>
<td>-0.067 ± 0.017</td>
<td>-0.080 ± 0.051</td>
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<tr>
<td>$\rho$</td>
<td>-0.23</td>
<td>-0.22</td>
<td>-0.22</td>
<td>-0.19</td>
<td>-0.16</td>
<td>-0.06</td>
</tr>
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Table 1: Average barometric and correlation coefficients (for the vertical and for five intervals of zenith angles) obtained by using the hourly data.

<table>
<thead>
<tr>
<th>channel</th>
<th>$0^\circ &lt; \theta &lt; 34^\circ$</th>
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</tr>
<tr>
<td>d, m.w.e.</td>
<td>940</td>
<td>1170</td>
<td>1400</td>
<td>1980</td>
<td>3260</td>
<td>7000</td>
</tr>
<tr>
<td>$\beta$, %/mb</td>
<td>-0.061 ± 0.031</td>
<td>-0.075 ± 0.019</td>
<td>-0.124 ± 0.033</td>
<td>-0.089 ± 0.015</td>
<td>-0.063 ± 0.019</td>
<td>0.078 ± 0.084</td>
</tr>
<tr>
<td>$\rho$</td>
<td>-0.63</td>
<td>-0.85</td>
<td>-0.84</td>
<td>-0.93</td>
<td>-0.80</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 2: Barometric and correlation coefficients obtained by using the annual data for the vertical and for five intervals of zenith angles.
Barometric Effect as observed by the BUST

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Figure 4: Barometric coefficients for different underground detectors (left scale) - black points 0-14 \[8\], and for EAS arrays - points 21-27 \[4\]. The solid and dashed curves - calculation for the level of 1013 mb and 600 mb, respectively \[8\]. The barometric coefficients for the hourly data obtained in this work - red points 15-20. Point 28 - barometric coefficient for group of muons \[11\], and point 29 - for the Andyrchi air shower array \[13\]. A line nm64 - the barometric coefficients for the neutron cosmic ray component. Gray icons of EAS and gray curve - the contribution of muon groups to the total intensity (right scale).

<table>
<thead>
<tr>
<th>Detector</th>
<th>Matsushiro</th>
<th>Poatina</th>
<th>BUST v0</th>
<th>BUST 01</th>
<th>BUST 02</th>
<th>BUST 03</th>
<th>BUST 04</th>
<th>BUST 05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eth, GeV</td>
<td>62</td>
<td>91</td>
<td>230</td>
<td>280</td>
<td>380</td>
<td>850</td>
<td>1300</td>
<td>&gt;7000</td>
</tr>
<tr>
<td>d, m.w.e.</td>
<td>232</td>
<td>365</td>
<td>940</td>
<td>1170</td>
<td>1400</td>
<td>1980</td>
<td>3260</td>
<td>7000</td>
</tr>
<tr>
<td>$\beta_{\mu}$, %/mb</td>
<td>-0.011</td>
<td>-0.0069</td>
<td>-0.0025</td>
<td>-0.0018</td>
<td>-0.0013</td>
<td>-0.00065</td>
<td>-0.00033</td>
<td>-0.00034</td>
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<tr>
<td>$\beta$, %/mb</td>
<td>-0.0262</td>
<td>-0.0469</td>
<td>-0.0435</td>
<td>-0.0433</td>
<td>-0.0485</td>
<td>-0.0487</td>
<td>-0.0669</td>
<td>-0.0798</td>
</tr>
<tr>
<td>$I_{\mu}/I$, %</td>
<td>98.3</td>
<td>95.5</td>
<td>95.4</td>
<td>95.4</td>
<td>94.7</td>
<td>94.6</td>
<td>92.6</td>
<td>91.1</td>
</tr>
</tbody>
</table>

Table 3: Barometric coefficients $\beta_{\mu}$, $\beta$ and ratio $I_{\mu}/I$, obtained for Matsushiro, Poatina and the BUST (vertical and 5 intervals of zenith angles).

BUST have been corrected for the barometric effect according to \[15\].

5 Conclusions

Barometric coefficients obtained for the BUST are more than an order of magnitude higher than the theoretically predicted values for these energies. Barometric effect observed according to the BUST, can be explained by the fact that for the secondary particles with energies $> 100$ GeV a contribution of muon groups of extensive air showers is becoming more significant. The share of muon groups of extensive air showers increases with the energy of the registered particles. And the share of muon groups of EAS can be estimated by the experimental barometric coefficient for high-energy muons, registered by the underground detectors. According to the obtained values of the barometric coefficients the primary data of the six intervals of zenith angles of the BUST telescope have been corrected for the barometric effect.

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References