Temperature effect correction for the cosmic ray muon data observed at the Brazilian Southern Space Observatory in São Martinho da Serra

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Abstract. The negative atmospheric temperature effect observed in the muon intensity measured by surface-level detectors is related to the atmospheric expansion during summer periods. According the first explanation given, the path of muons from the higher atmospheric level (where they are generated) to the ground becomes longer, and more muons decay, leading to a muon intensity decrease. A significant negative correlation, therefore, is expected between the altitude of the equi-pressure surface and the muon intensity. We compared measurements of the altitude of 100 hPa equi-pressure surface and data from the multidirectional muon detector installed at the Brazilian Southern Space Observatory in São Martinho da Serra, RS. Significant correlation coefficient were found (up to 0.95) when using data observed in 2008. For comparison, data from the multidirectional muon detector of Nagoya, located in the opposite hemisphere, is studied and an anti-phase in the cosmic ray variation related with the temperature effect is expected between data from detectors of Nagoya and São Martinho da Serra. The temperature influence is higher for the directional channels of Nagoya than for ones of São Martinho da Serra.

1. Introduction
The observed intensity of muons at ground level is subject to atmospheric temperature effects. Atmospheric expansion with increasing temperatures causes an increase of the mean altitude of muon production from the decay of parent pions. The increased flight time results in the decay of more muons into electrons and neutrinos before they reach the detector. This effect is known as the "negative temperature effect" and causes a decrease of muon count rate with increasing temperature and vice-versa [1]. The consequence is a yearly variation of the observed cosmic ray count rate which is higher (lower) in the summer (winter) than the yearly mean. The temperature and atmospheric expansion can be measured indirectly by the altitude of a specific equi-pressure surface: the higher the surface altitude, the higher the expansion of the atmosphere. Thus, a significant negative correlation is expected between the altitude of an equi-pressure surface and the muon intensity.

The objective of this paper is to correct the atmospheric temperature effect in the multidirectional muon detectors at São Martinho da Serra and Nagoya (which are located in opposite hemispheres) by
using the observed altitudes of the equi-pressure surface. More details about the detectors can be found in [2].

### 2. Methodology and results

There are several ways to describe the atmospheric temperature effect on muon count rate, some of them are empirical [3], some are theoretical [4,5] and both use observation of the temperature as a function of atmospheric depth. Some models also assume this function and do not require experimental data, as required particularly for real-time purposes [6]. As it is seldom to have the temperature variation in all atmospheric depths for both muon detectors and as real time temperature correction is out of the scope of the present article, we simply adopt a way using the altitude of a specific equi-pressure surface. More specifically, this method relates the observed muon count rate with the altitude of 100 hPa equi-pressure surface [2], as:

\[
\Delta I_T = \beta_T \cdot \Delta H
\]

where \(\Delta I_T\) is the percent deviation of muon rate from the yearly average, \(\beta_T\) is the linear regression coefficient (given in %/km) and \(\Delta H\) is the deviation of the altitude of 100 hPa equi-pressure surface from its annual average. The atmospheric temperature data is collected once every 12 hours (close to midday and midnight) using radiosonde, in many sites around the world, generally nearby airports.

We use hourly muon count rates in 17 directional channels for each detector after correcting for the atmospheric pressure effect, as explained in [7]. In order to minimize influences from solar-interplanetary related phenomena, we select the year of 2008 which is within the last minimum solar activity period. The statistical count rate error of muons ranges from 0.06 % to 0.49 %. For the Nagoya muon detector, we use data of the three closest stations available: Shionomisaki (33.5° N; 140.1° E), Taten (36.0°N; 140.1°E) and Wajina (37.4° N; 136.9° E). The distances from these stations to the Nagoya muon detector are, respectively, ~200 km, ~400 km and ~300 km. For the São Martinho da Serra muon detector, the closest high-altitude measurement site is Santa Maria (29.72° S; 53.70° W, ~32 km). As there are some data gaps in the measurements at this site and we want a continuous data correction, we decided to include four more sites: Porto Alegre (30.00° S; 51.18° W, distant ~264 km), Uruguaiana (29.78° S; 57.03° W, distant ~313 km), Florianópolis (27.67° S; 48.55° W, distant ~553 km) and Resistência (27.45° S; 59.05° W, distant ~558 km). Confirming that the altitudes of 100 hPa equi-pressure surface measured at these sites are consistent to each other, we decided to use the median value of five station data for the correction.

The altitude of 100 hPa equi-pressure surface for Nagoya is shown in the bottom panel of figure 1, while the observed deviation for the vertical channel of Nagoya is shown by the red curve in the upper panel. The observed red curve in the upper panel clearly shows a seasonal variation with a maximum in the winter period and a minimum in the summer. Nagoya is a station located in the northern hemisphere where the summer is in the middle of the year, when the altitude of 100 hPa is maximal. The anti-correlation between the observed muon deviation and the altitude of 100 hPa is evident. We calculate a regression coefficient with data from each radiosonde station and then take the median of the calculated coefficients. For the vertical directional channel of Nagoya, the correlation coefficient is -0.95 and the regression coefficient is -5.72±0.76 %/km. Previous results using muon data from 2006 and temperature data only from Shionomizaki are -0.95 for the correlation coefficient and -6.83 %/km for the regression coefficient [2]. For all directional channels, the correlation and regression coefficients are calculated in the same way and listed in table 1. After applying the temperature correction by using the calculated \(\beta_T\), the seasonal variation seems to be eliminated (black curve with green envelope in the upper panel of figure 1).
Figure 1. Temperature correction for the vertical directional channel of Nagoya. Upper panel: the corrected (black curve) and uncorrected (red curve) percent deviations of muon rate from yearly average. The green envelope of black curve indicates a range expected from the standard deviation of $\beta_T$ from three radiosonde measurements (see text). Lower panel: the altitude (km) of the 100 hPa equi-pressure surface (black). The standard deviation of three radiosonde measurements is indicated by a red envelope.

Figure 2. Temperature correction for the vertical directional channel of São Martinho da Serra. Upper panel: the corrected (black curve) and uncorrected (red curve) percent deviations of muon rate from yearly average. The green envelope of black curve indicates a range expected from the standard deviation of $\beta_T$ from five radiosonde measurements (see text). Lower panel: the altitude (km) of the 100 hPa equi-pressure surface (black). The standard deviation of five radiosonde measurements is indicated by a red envelope.

Table 1. Correlation ($\alpha$) and regression ($\beta_T$) coefficients calculated for all the directional channels of São Martinho da Serra and Nagoya detectors.

| Channel | Nagoya | São Martinho da Serra | Channel | Nagoya | São Martinho da Serra |
|---------|--------|-----------------------|---------|--------|-----------------------|
|         | $\alpha$ | $\beta_T$ (%/km) | $\alpha$ | $\beta_T$ (%/km) | $\alpha$ | $\beta_T$ (%/km) |
| V       | -0.95  | -5.72±0.76          | -0.73  | -4.54±0.64       | N2      | -0.96  | -6.46±0.88       |
| N       | -0.95  | -6.00±0.80          | -0.73  | -4.31±0.62       | S2      | -0.96  | -6.28±0.85       |
| S       | -0.95  | -5.89±0.78          | -0.75  | -4.37±0.63       | E2      | -0.96  | -6.33±0.86       |
| E       | -0.95  | -6.01±0.80          | -0.75  | -4.27±0.62       | W2      | -0.96  | -6.43±0.88       |
| W       | -0.95  | -6.03±0.81          | -0.73  | -4.46±0.63       | N3      | -0.95  | -6.28±0.87       |
| NE      | -0.96  | -6.10±0.82          | -0.70  | -3.86±0.59       | S3      | -0.95  | -6.05±0.84       |
| NW      | -0.96  | -6.10±0.82          | -0.70  | -4.01±0.59       | E3      | -0.95  | -6.22±0.86       |
| SE      | -0.96  | -6.26±0.84          | -0.70  | -3.98±0.59       | W3      | -0.95  | -6.23±0.87       |
| SW      | -0.95  | -6.24±0.84          | -0.72  | -4.29±0.63       |
In a similar way, the temperature correction for each of all directional channels of São Martinho da Serra was performed. The result for the vertical channel is illustrated in figure 2. This detector is located in the southern hemisphere and the altitude of 100 hPa yearly variation corresponding to this site is out of phase to Nagoya data in figure 1: the altitude of 100 hPa has the lowest values in the middle of the year during the winter in the southern hemisphere.

The maximum difference between the temperature corrected and not corrected deviations is about 2% for the Nagoya data and about 1% for São Martinho da Serra. We note the following differences in figures 1 and 2: (i) the regression coefficients $\beta_t$ are smaller for all directional channels of São Martinho da Serra's detector and (ii) the amplitude of the yearly variation in the 100 hPa surface altitude is significantly smaller (0.40 km) for São Martinho da Serra than for Nagoya (0.70 km).

3. Conclusions
A clear anti-correlation between the altitude of 100 hPa surface and the muon count rate is observed in 2008 for each of detectors at Nagoya and São Martinho da Serra. The twice-a-day 100 hPa altitude measurements seem to be useful for properly correcting temperature effect in a yearly perspective. The yearly variations in the altitude of the 100 hPa surface for Nagoya and São Martinho da Serra are out of phase to each other: the muon count rate at Nagoya has a maximum in the middle of the year, while the count rate at São Martinho da Serra shows maximum it in the start/end of the year. This is consistent with the atmospheric expansion causing the maximum altitude of the 100 hPa equi-pressure layer during the summer in each hemisphere. The amplitude of yearly variation due to the temperature effect is larger in Nagoya than that in São Martinho da Serra.

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