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New empirical methods for correction of meteorological effects on cosmic ray muons

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Introduction

Changing conditions in the atmosphere affect the propagation of muon component of secondary cosmic rays (CR). These meteorological effects (primarily barometric and temperature effect) need to be corrected for in order to increase the sensitivity of ground based muon detectors to the variations of primary cosmic rays. There are several well established and widely used techniques developed over the years for correction of these effects, most notably the integral method.

We introduce two somewhat different new approaches to modeling and correction of atmospheric effects on cosmic ray muons:

- PCA method (based on principal component analysis)
- MVA method (based on machine learning approach)

Both methods are fully empirical, easy to implement and can be applied to any muon detector, as they do not depend on the topology of the terrain or experimental infrastructure. They only require the knowledge of atmospheric pressure and atmospheric temperature profile for a given location.

Analysis was done on cosmic ray muon data measured by the Belgrade cosmic-ray station at the Institute of Physics Belgrade.

Methods

PCA method

Principal component analysis (PCA) is a technique widely used for decorrelation and dimensionality reduction of highly correlated sets of variables.

We have applied it to a set of 26 atmospheric variables - atmospheric pressure and temperatures for 25 isobaric levels (from the top of the atmosphere to the ground level). The result was a set of 26 principal components, where first six components are responsible for close to 95% of total variance (Figure 1).

Set was further reduced to five components, as there was almost no dependence of muon count rate on second principal component, and corrected count was calculated using formula:

$$N_\mu^{(corr)} = N_\mu - \langle N_\mu \rangle \sum_i k_i PC_i, \qquad i=1,3,4,5,6$$

where $N_\mu^{(corr)}$, N_μ, $\langle N_\mu \rangle$, are corrected, measured and mean muon count rate, PC_i are principal components and coefficients k_i are determined from linear fits shown in Figure 2.

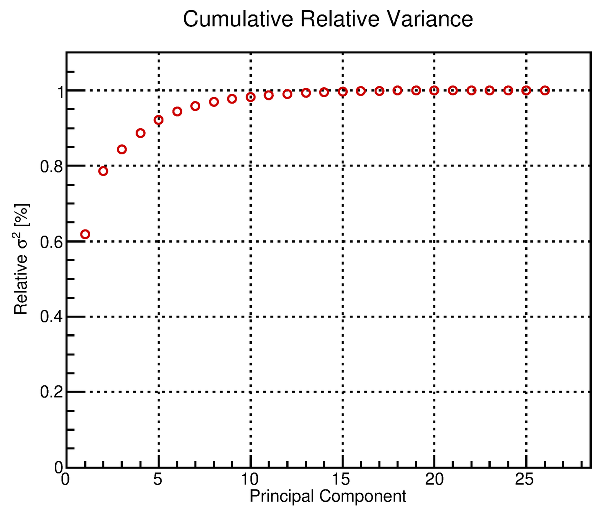


Figure 1: Cumulative relative variance for principal components

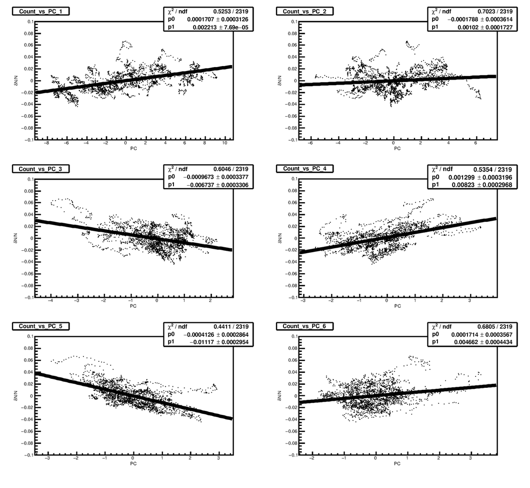
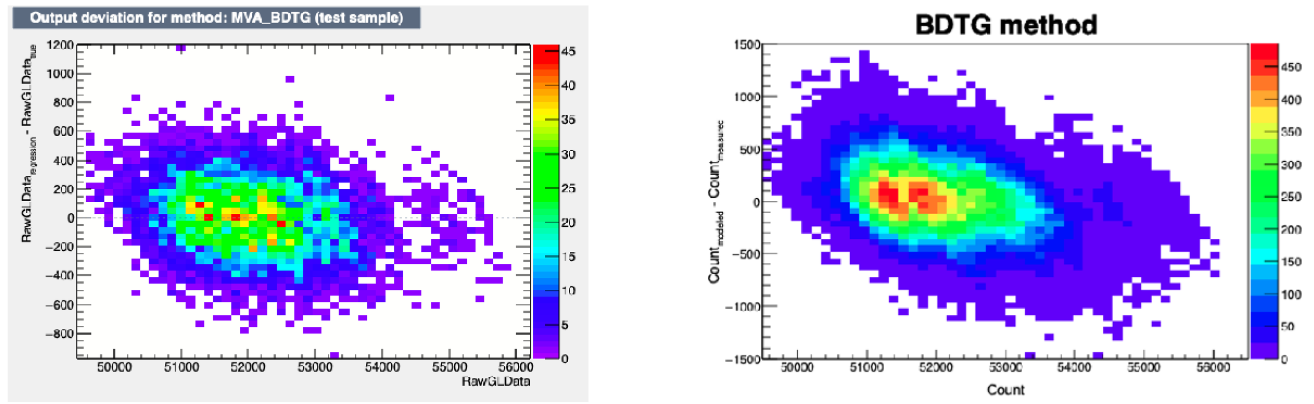


Figure 2: Muon count dependence on first six principal components

MVA method

Another way to successfully model complex systems with large number of correlated variables is by the way multivariate analysis employing machine learning.

We have tested a number of multivariate regression algorithms included in the TMVA analysis framework. Algorithms were trained and tested on a subset of full data set, using minimal average quadratic deviation of modeled vs measured data as a criterion for optimization. Trained algorithms were applied to the whole data set. Figure 3 shows the residual deviation of modeled data from measured data for one selected algorithm. Overall, LD and BDTG algorithms showed the best performance.



a) b)

Figure 3: Deviation of modeled (regression) from measured (target) muon count rate as a function of muon count rate (for BDTG method) for the test (a) and full data set (b).

Assuming all the variation in the modeled output is due to variation of atmospheric parameters, corrected muon count rate was calculated using formula:

$$N_\mu^{(corr)} = \Delta N_\mu + \langle N_\mu \rangle, \quad (\Delta N_\mu = N_\mu^{(mod)} - N_\mu)$$

where $N_\mu^{(corr)}$ and $\langle N_\mu \rangle$ are corrected and mean muon count rate, and ΔN_μ is the difference between modeled ($N_\mu^{(mod)}$) and measured (N_μ) muon count rate.

Results

We have tested the effectiveness of the new atmospheric correction on both periodic (annual), as well as aperiodic (Forbush decrease) cosmic ray variations, comparing them with the integral method and reference neutron monitor data.

Effect of correction on periodic variations

Figure 4 shows time series for raw, pressure corrected and pressure and temperature (PT) corrected data for the period of one year. Time series were fitted with sine function, amplitude parameter used as a estimate of annual variation.

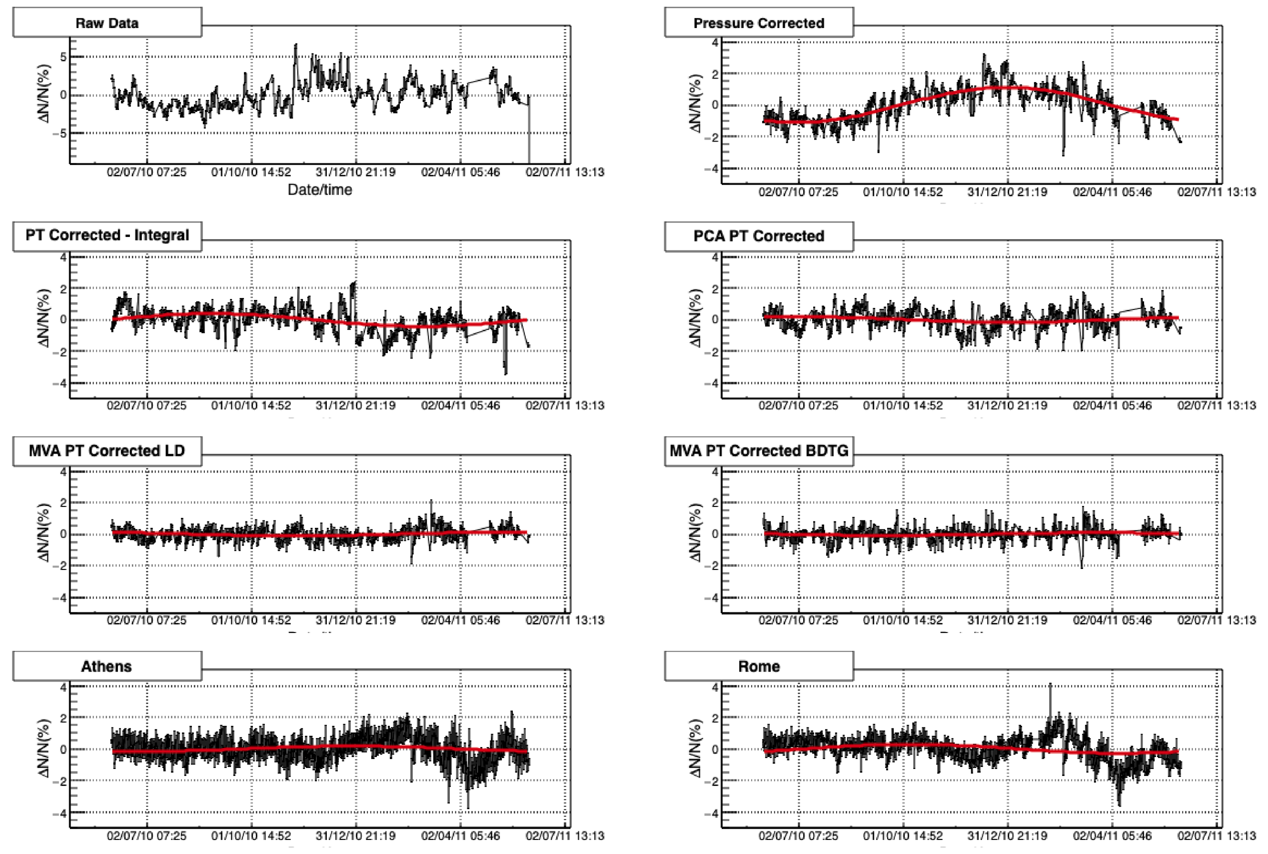


Figure 4: Muon count rate time series for raw, pressure and pressure and temperature corrected data for the period of one year. Reference neutron monitor data also shown for comparison.

Table 1 shows annual variation for corrected data for different methods, as well as annual variation reduction calculated relative to pressure corrected data. Athens and Rome neutron monitor data is also included for reference.

Method	P_{corr}	Int.	PCA	LD	BDTG	Ath.	Rome
Amplitude [%]	1.11(9)	0.40(3)	0.18(5)	0.11(3)	0.09(1)	0.17(5)	0.29(1)
Relative reduction [%]	-	64(10)	84(28)	90(30)	92(17)	-	-

Table 1: Annual variation and variation reduction relative to pressure corrected data for different atmospheric correction methods

Effect of correction on aperiodic variations

Figure 5 shows time series for raw and pressure and temperature corrected data around the Forbush decrease (FD) event in February 2011, with indicated intervals used to calculate the FD amplitude.

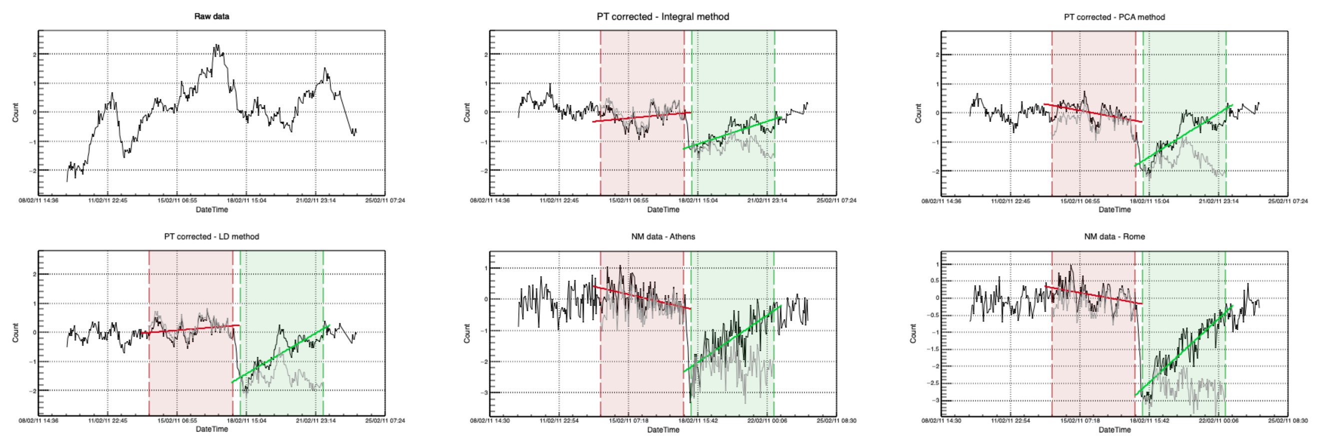


Figure 5: Muon count rate time series for raw and pressure and temperature corrected data around the February 2011 FD event.

Table 2 shows FD amplitude calculated for this event for pressure and temperature corrected data for different methods. Amplitude calculated relative to the standard deviation of data prior to the decrease is used as a measure of sensitivity to FD event.

Method/ NM	Int.	PCA	LD	BDTG	Ath.	Rome
FD Amplitude [%]	1.38(14)	1.52(21)	1.96(18)	1.10(13)	1.97(15)	2.68(15)
Relative FD Amplitude	4.31(44)	4.90(66)	7.09(65)	4.78(56)	5.30(40)	8.65(48)

Table 2: Amplitudes and relative amplitudes for February 2011 FD event for PT corrected muon data and reference neutron monitors.

Conclusions

Two new methods for correction of meteorological effects on cosmic ray muons are introduced. Both are fully empirical, require knowledge about the atmospheric pressure and atmospheric temperature profile, and can be applied to any muon monitor.

The effect on the reduction of annual variation of CR data, as well as the effect on the sensitivity of FD event detection was compared to the integral method and reference neutron monitor data.

Their effectiveness was comparable or possibly better than for the integral method, allowing for the possibility there is a a part of meteorological effects not taken into account by theory.