# A new method for determining atmospheric pressure coefficient using fast Fourier transform for muons in the GRAPES-3 experiment

P.K. Mohanty[a,b], H.M. Antia[a,b], K.P. Arunbabu[a,b], S.R. Dugad[a,b], S.K. Gupta[a,b], B. Hariharan[a,b], Y. Hayashi[d,b], P. Jagadeesan[a,b], A. Jain[a,b], S. Kawakami[d,b], H. Kojima[f,b], S.D. Morris[a,b], P.K. Nayak[a,b], T. Nonaka[d,b], A. Oshima[e,b], B.S. Rao[a,b], S. Shibata[e,b], P. Subramanian[c,b], K. Tanaka[g,b]

[a]Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India.
[b]The GRAPES-3 Experiment, Cosmic Ray Laboratory, Raj Bhavan, Ooty 643 001, India.
[c]Indian Institute of Science Education and Research, Homi Bhabha Road, Pune 411 021, India.
[d]Graduate School of Sciences, Osaka City University, Osaka 558-8585, Japan.
[e]College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan.
[f]Faculty of Engineering, Aichi Institute of Technology, Toyota City, Aichi 470-0392, Japan.
[g]Graduate School of Information Sciences, Hiroshima City University, Hiroshima 731-3194, Japan.

## Abstract

A large area (560 m$^2$) tracking muon detector operating in the GRAPES-3 experiment at Ooty in India has been recording cosmic ray muons at a rate of $1.7\times 10^8$ h$^{-1}$ since 2000. The high statistics data have enabled sensitive measurements of several solar phenomena to be made including the solar and sidereal anisotropy and Forbush decreases following coronal mass ejections. Prior to studying of any of these phenomena, an important task is to correct the variation in measured muon rates due to atmospheric pressure. Unfortunately, the pressure coefficient usually deduced from the observed data is not very reliable due to the presence of various solar phenomena listed above. Here, we present an alternative method which avoids complications arising from solar effects. Since the pressure at Ooty displays a 12 h periodicity, using which we could separate its contribution from other effects in the muon data though a power spectrum analysis. The method yielded a clear dependence of muon rate on pressure providing an accurate estimate of the pressure coefficient almost independent of the solar modulation effects.

## Introduction

The atmospheric pressure produces an additional variation in the muon rates besides the ones present in the primary cosmic rays associated with various solar phenomena. At Ooty, the pressure data exhibits a 12 h periodicity with amplitude of about 1 hPa. The 12 h period is significant and dominant primarily in the equatorial regions.

While the pressure correction is relatively simple due to anti-correlation between the pressure measured at the detector level and the muon flux, however various solar phenomena such as solar diurnal anisotropy, transients such as Forbush decreases (FDs) and geomagnetic storms coupled with the observed muon rates can adversely impact the determination of the pressure coefficient. For a reliable estimation of pressure coefficient, the standard practice used is to select the periods of low solar activities or identify and exclude the periods of transient events [1]. Nevertheless, many decreases are difficult to localize, especially in the muon component, and even small long term variation may affect the result seriously.

## The GRAPES-3 Tracking Muon Telescope

The GRAPES-3 is an extensive air shower experiment operating at Ooty in South India (11.4°N latitude, 76.7°E longitude and 2200 m altitude) since 2000. It comprises of an array of $\sim$400 plastic scintillator detectors of 1 m$^2$ area each placed in hexagonal geometry with 8 m inter-detector spacing and a large area (560 m$^2$) tracking muon detector [2, 3]. The muon detector consists of 16 separate modules each of area 35 m$^2$. The basic elements of each module are the proportional counter (PRC) tubes (6m in length and 10 cm $\times$ 10 cm in cross section) which have been arranged in four layers in two orthogonal planes. This arrangement is used to determine the direction of the muons into 13$\times$13 (169) solid angle bins in the field of view of the detector. Concrete blocks of 550 g cm$^{-2}$ thickness have been used as absorber to shield the electromagnetic components, providing 1 GeV threshold for vertically incident muons. Each module records nearly 3000 muons per second, thus allowing to make sensitive measurements on various solar phenomena including Forbush decreases associated with coronal mass ejections, diurnal and sidereal anisotropies [4, 5, 6, 7].

## Muon and pressure data sets

After correcting for the various instrumental effects such as gaps, spikes, jumps, fluctuations and efficiency variations, an almost continuous stream of muon rates (4 min average) combining from the 16 modules for 1 January to 31 December 2006 were used in this analysis. An uninterrupted pressure data for the same period obtained from two independent digital barometers with resolution of 0.1 hPa obtained with a self-consistent calibration procedure described elsewhere [6] was used. Muon and pressure profile for a period of one week is demonstrated in Figure 1.

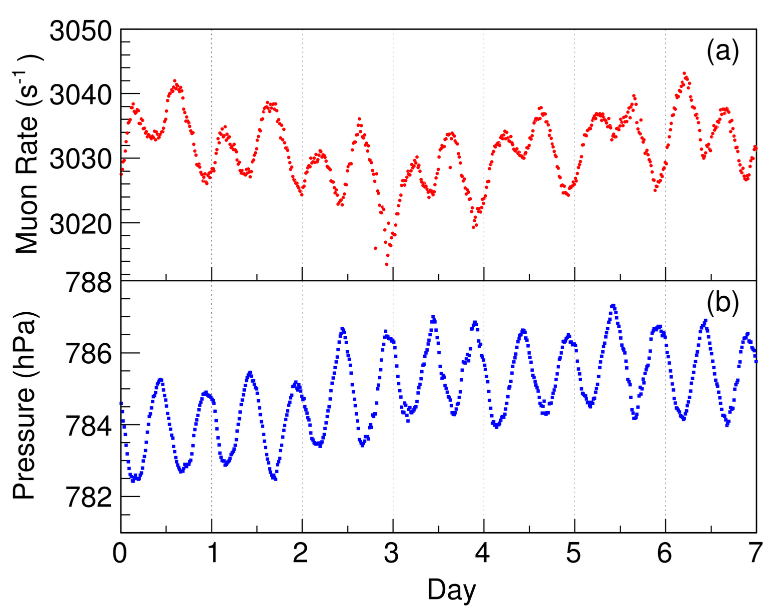


Figure 1 : Variation of (a) mean muon rate, (b) pressure (hPa) for the week 1–7 March 2006

## Conventional determination of pressure coefficient

The dependence of muon rates on pressure obtained using the data of entire 2006 is shown in Figure 2. The complex profile is attributed to the various solar and seasonal effects. A linear least square minimization to the data exhibited a poor fit as shown in Figure 2 with a large chisquare. The pressure coefficient obtained from the fit is 2.13 counts s$^{-1}$/hPa and a translated fractional value of 0.07%/hPa for the mean value of 3028.09 counts $s^{-1}$.

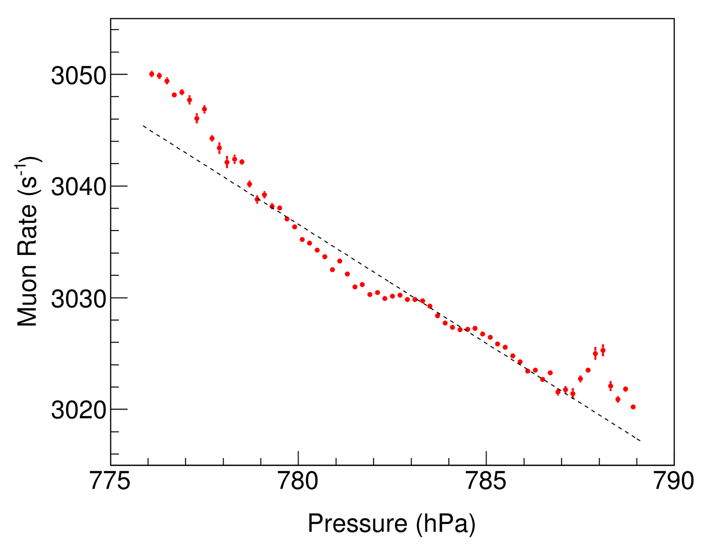


Figure 2 : Variation of muon rate as a function of atmospheric pressure (hPa) with complete 2006 data. The dashed line represents a linear least square fit to the data. Slope of the fit=0.07%/hPa and normalized $\chi^2$=81 per degrees of freedom.

## Determination of pressure coefficient with FFT method

Frequency spectra were obtained performing fast Fourier transform (FFT) on time series muon and pressure data sets which are shown in Figure 3. The pressure data clearly show a dominant peak at 2 cycles per day (cpd). In addition to 2 cpd peak expected due to 12 h period pressure variation, the muon data show another prominent peak at 1 cpd which is due to the solar diurnal anisotropy. A narrow band filter was used around 2 cpd peaks to segregate the non-atmospheric effects in the muon data to obtain a better estimate of the pressure coefficient.

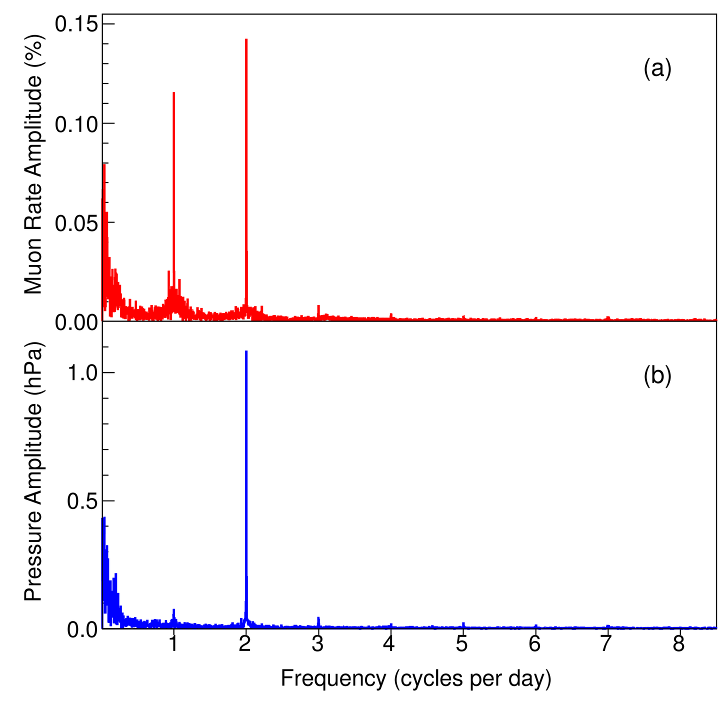


Figure 3 : FFT spectrum of, (a) muon rate, (b) atmospheric pressure for $2^{17}$ of 4 min samples over 364.01 d in 2006.

An inverse fast Fourier transform (IFFT) was performed on the filtered frequency spectrum to obtain the data in time domain. The resultant time series for entire 2006 was folded modulo 24 h as shown in Figure 4. The pressure curve showed minima at 4 AM and 4 PM, while the maxima are at 10 AM and 10 PM local time. The peaks in the muon rate curve are almost anti-correlated. This showed that the 12 h period (2 cpd) in the muon rate was caused primarily by the pressure variation.

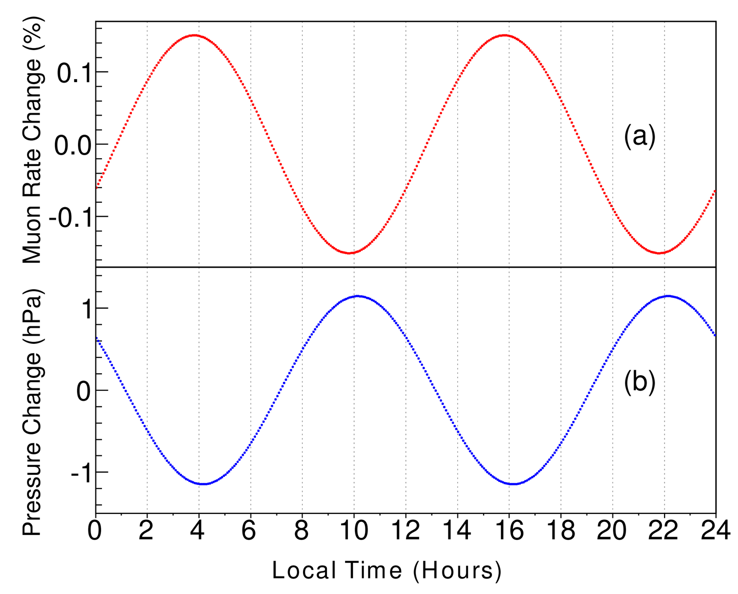


Figure 4 : Time domain data after IFFT, folded modulo 24 h for, (a) muon rate, (b) pressure.

The IFFT data of muon rate was plotted against pressure as shown in Figure 5. A linear fit to the data in Figure 5 represented by a solid line displayed a nearly perfect fit. The slope of line which represents the pressure coefficient was found to be -0.1284%/hPa.

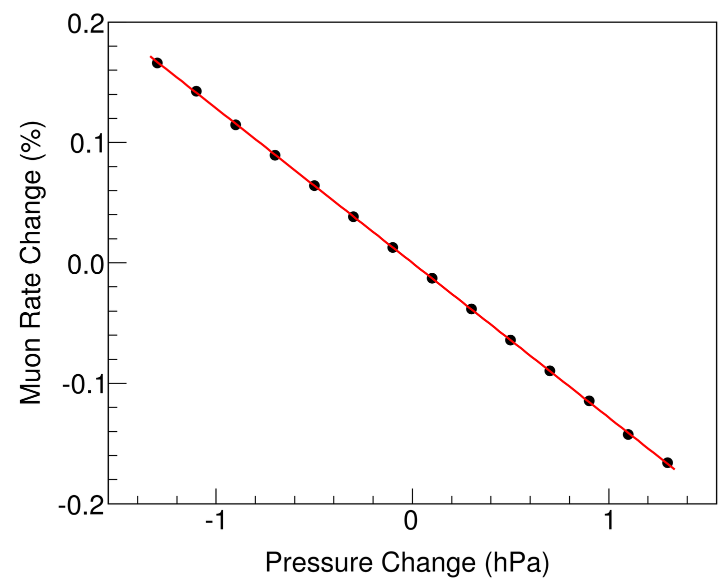


Figure 5 : Variation in muon rate as a function of pressure relative their mean values.

FFT was performed on the pressure corrected muon rates. The FFT spectrum before pressure correction is shown Figure 6a and after the pressure correction is shown in Figure 6b. As expected, the amplitude corresponding to the frequency of 1 cpd remained almost unaffected after the correction, primarily because the corresponding pressure amplitude was very small. However, the effect on the frequency of 2 cpd was dramatic since the pressure amplitude was dominant for this frequency. The residual amplitude after the correction shows the presence of a sizeable amplitude of solar semi-diurnal component (2 cpd). Another peak at 3 cpd was also visible. Peaks at still higher frequencies could not be observed indicating that the higher frequency peaks in the uncorrected spectrum were caused by pressure effects.

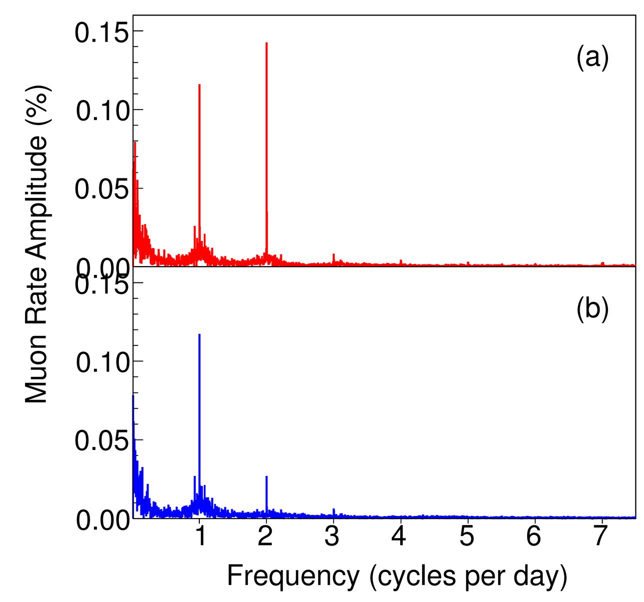


Figure 6 : Frequency spectrum for muon data, (a) before pressure correction, (b) after pressure correction.

## Summary

Various solar effects such as solar diurnal anisotropy, Forbush decreases and seasonal variations complicated the anti-correlation between muon rate and pressure. Thus the extraction of pressure coefficient by conventional method yielded an inaccurate value. By performing frequency analysis using FFT, the component in the muon data due to the dominant 12 h periodicity of pressure at Ooty was segregated from solar and seasonal effects. A strong anti-correlation between muon and pressure data was obtained using the 12 h periodic component, which yielded an accurate value of pressure coefficient almost independent of solar activities.

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