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Cosmic Ray Flux Correlation between McMurdo and Jang Bogo Neutron Monitor

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Neutron monitors are large ground-based detectors responding to primary cosmic rays by measuring atmospheric secondary particles, primarily neutrons. A charged cosmic ray striking the atmosphere from a specific sky direction with a specific rigidity (momentum per unit charge) was necessarily moving from a well-defined direction in space, called the asymptotic direction. McMurdo and Jang Bogo Antarctic stations have similar geomagnetic latitudes but slightly different longitudes. From December 17, 2015, to January 9, 2017, six of the eighteen neutron monitor units from McMurdo were transferred to Jang Bogo (with full transfer to Jang Bogo completed in December 2017). Count rate data are recorded in ten-second intervals, but in this work, we average to one-minute Cosmic Ray Flux Correlation between McMurdo and Jang Bogo Neutron Monitor intervals with cleaned and pressure-corrected data. Autocorrelation functions are well fit as the sum of three components: an exponential function peaking at zero lag, a linear function, and a sinusoid with a period of one day, centered at zero lag ($\phi = 0$). The cross-correlation of the average over-counter tubes for the two stations does not show the exponential term. Adjusting the phase (ϕ) for the best-fit yields a time lag (τ) of 167 minutes. By calculating cosmic ray trajectories in Earth's magnetic field throughout the time interval analyzed in this work, we determine the weighted-average difference in asymptotic longitudes to be 41.8°± 1.97°, corresponding to a time lag of 167.2 ± 7.86 minutes. This is in close agreement with the observed lag in the sinusoidal component of the cross-correlation. In summary, this analysis can distinguish between temporal and directional variations.

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1. Introduction

Cosmic rays are high-energy particles that travel through space at nearly the speed of light, originating from various sources in the universe. They are classified into two types: Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs). SEPs are generated by the Sun during solar flares or Coronal Mass Ejections (CMEs), which can create shock waves leading to a temporary decrease in GCR flux known as a "Forbush decrease" [1]. The phenomenon of Forbush decreases was first discovered by Scott Ellsworth Forbush in 1937. This analysis focuses on approximately 14 months of data (from December 17, 2015, to January 9, 2017) during the transition of six out of eighteen standard NM64-design neutron monitor counters [2, 3] from McMurdo to Jang Bogo fixed stations. The transfer to Jang Bogo was completed in December 2017. The neutron monitors at both stations utilize boron trifluoride, where neutrons (n) interact with ^{10}B to produce alpha particles (^{4}He) and ^{7}Li. The resulting ionization of the gas in the proportional counter leads to a cascade of charged particles, recorded as a single count. The specifications of the McMurdo and Jang Bogo stations can be found in Table 1. During this operational period, on December 20, 2015, a Forbush decrease event occurred, causing a temporary decline in GCR flux for several days. Although following the same pattern, some of the features during the Forbush decrease appeared earlier at McMurdo relative to Jang Bogo, as shown below. This work explores the auto-correlations of each detector with its count rate and presents an analysis of the cross-correlation function between the cosmic ray flux of McMurdo and Jang Bogo stations during their overlapping operational time. The correlation technique enables the differentiation of temporal and directional (anisotropy) variations.

Table 1: Specifications of McMurdo and Jang Bogo Stations used in our analysis.

NM Station	Geographic Location	Geomagnetic Location	P_c (GV)	Altitude (m)	NM Configuration
Jang Bogo	74°37.4′S 164°13.7′E	77°3′S 85°18′E	<0.2	29	5-NM64
McMurdo	77°51′S 166°40′E	78°58.8′S 72°22.8′E	<0.2	48	11-NM64

2. Data Processing

2.1 Data cleaning

The data resolution is set at a rate of 10 seconds. In this study, we analyze data collected from December 16, 2015, to January 9, 2017. We have removed inaccurate readings, identified by a value of "−1," and marked them as missing data (NaN) in the input files. We address the issue of redundant dates where the count rates do not align logically. To eliminate outliers, we calculated the standard deviation (σ) based on the 24-hour moving average and discarded data points that fell beyond $\pm 4\sigma$.

2.2 Barometric Pressure Correction

We correct the Jang Bogo and McMurdo neutron monitor count rates based on their respective reference pressures (p_0), removing the influence of atmospheric depth. At Jang Bogo, we use

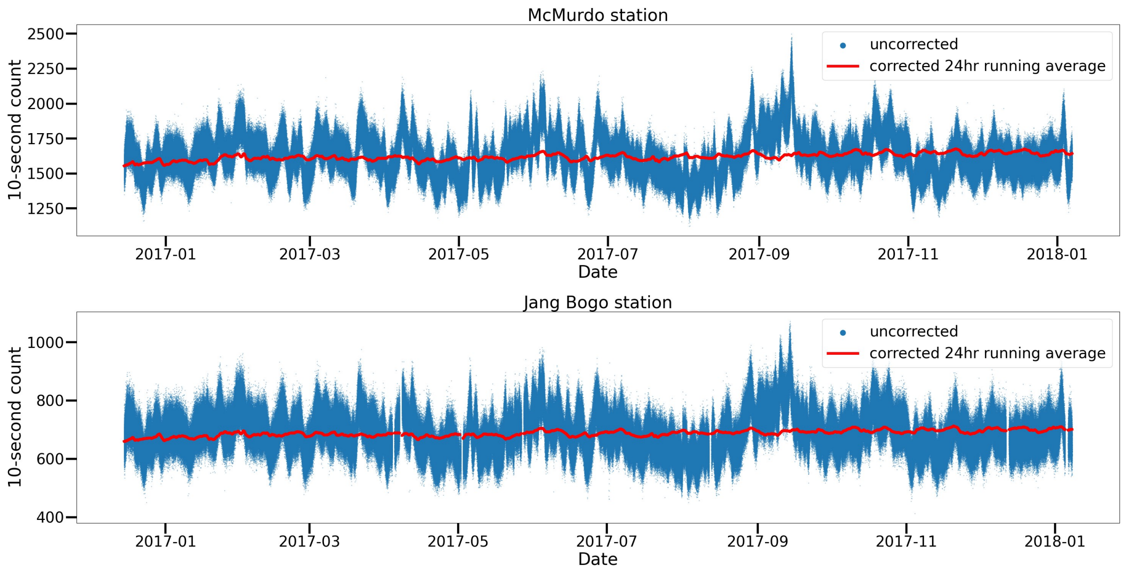

Figure 1: Ten-second resolution data set for (a) McMurdo and (b) Jang Bogo. The count rate summed over all eleven active NM64 detectors at McMurdo and five at Jang Bogo. Each ten-second count (after obviously bad readings were removed) is shown in blue. One-hour running averages, cleaned and corrected for barometric pressure as discussed in the text, appear in red.

p_0 = 738.0 mmHg, while at McMurdo, we use p_0 = 734.0 mmHg. These values are determined by averaging the pressure data from each station's dataset. For the correction, we apply empirical pressure coefficients: β = 0.99975 for Jang Bogo and β = 0.99901 for McMurdo, measured in %/mmHg. To perform the pressure correction, we employ the method described in [4], expressed by the equation: $c = ue^{\beta(p-p_0)}$. Here, c represents the monitor count rate corrected for tube anomalies and pressure, while u represents the monitor count rate corrected for tube anomalies only. The variable p represents the barometric pressure in mmHg. Figure 1 demonstrates how the data appear smoother after the pressure correction, indicated by the red line.

3. Analysis and Results

3.1 Asymptotic directions

A path of particle with higher rigidity, or energy, are less affected by Earth's magnetic field. Neutron monitors are specifically designed to measure count rates of high-energy charged particles at fixed geographic locations based on latitude and longitude. Over time, the geomagnetic field at a specific location changes due to Earth's rotation relative to the solar wind and the directions of particle arrival.

Figure 2(a) shows the asymptotic directions for the geographic locations of McMurdo and Jang Bogo on December 20, 2015, at 18:00UT, coinciding with a Forbush event and aligning with our analysis. We used the differential response function (DRF) to average directions obtained from the 2006 latitude survey, which shared a similar solar modulation level. The DRF is defined as DRF = $N_0 \alpha P^{-\kappa-1} \kappa (e^{-\alpha P^{-\kappa}})$, with P representing rigidity in GV. The Dorman parameters were

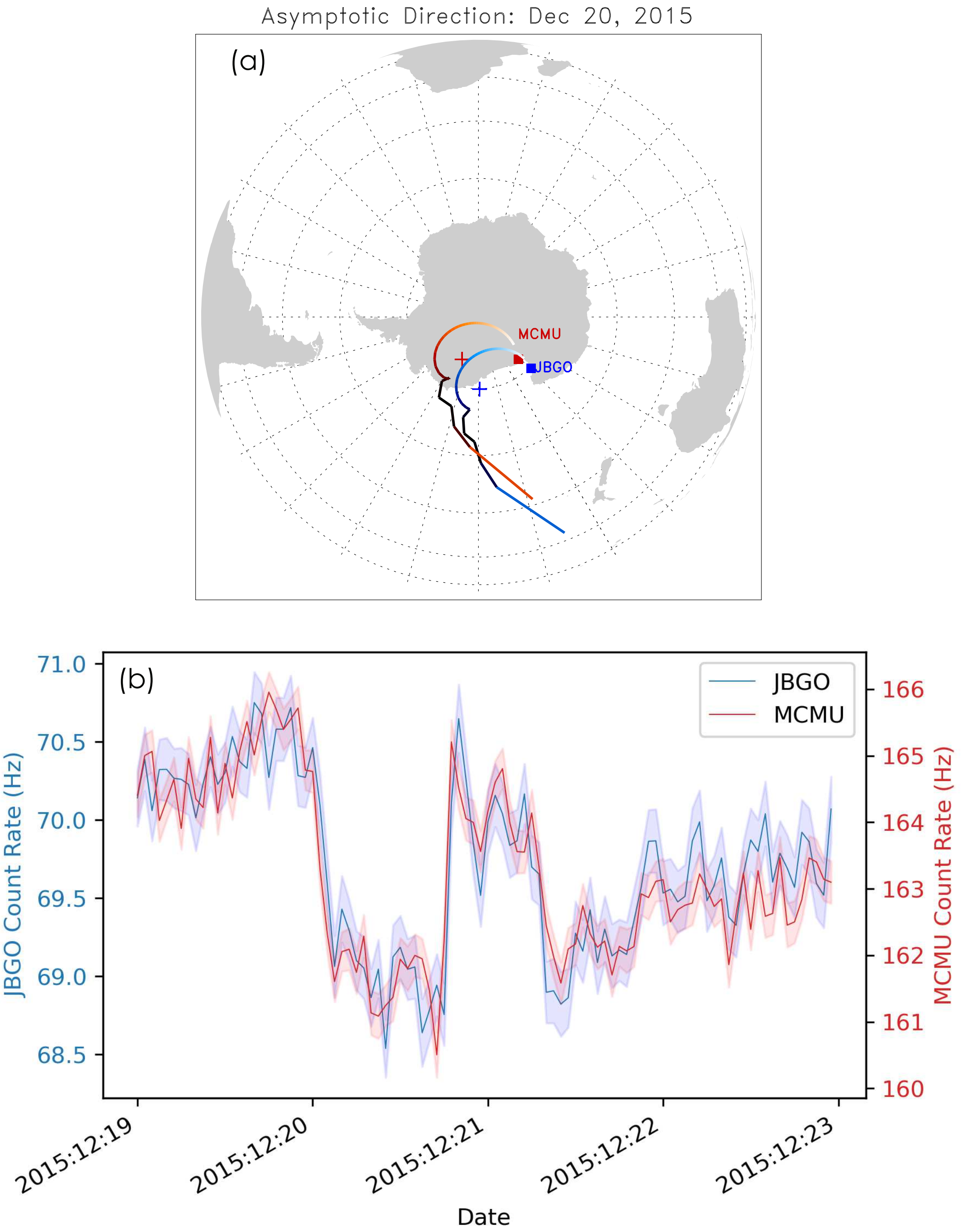

Figure 2: (a) Asymptotic directions on December 20, 2015 at 18:00 UT. Colored lines indicate asymptotic directions of primary cosmic rays arriving vertically at McMurdo (red) and Jang Bogo (blue) as a function of rigidity, and the color intensity indicates the differential response function. Two plus signs indicate response-weighted asymptotic directions for each station. (b) The hourly count rates, as seen by Jang Bogo (blue) and McMurdo (red) neutron monitors a few days before and after the Forbush decrease that occurred on December 20, 2015.

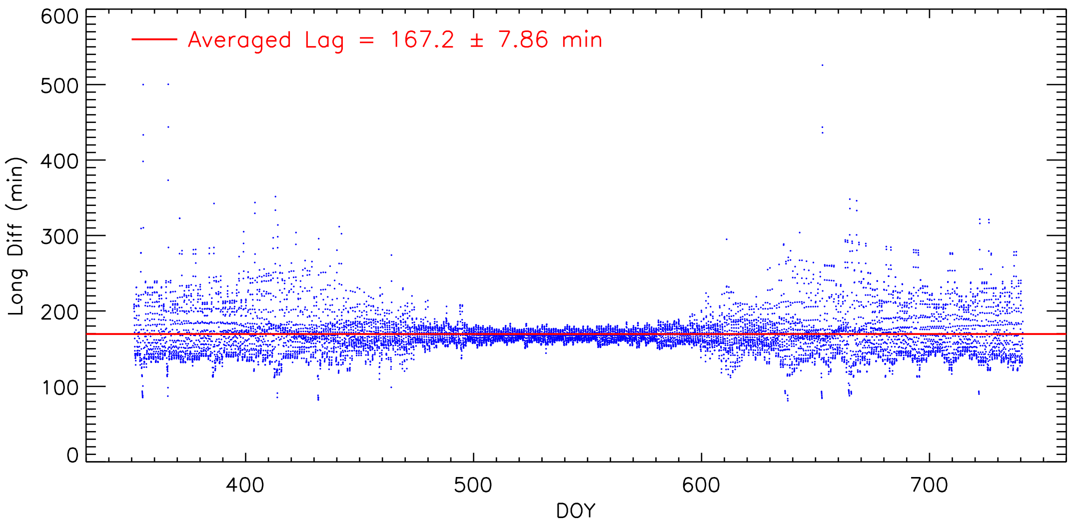

Figure 3: The response-weighted average directions between McMurdo and Jang Bogo stations as a function of time from December 17, 2015, to January 9, 2017, in a single plot. The red horizontal line represents the average lag time of 167.2±7.9 minutes.

set as $N_0 = 31.7$, $\alpha = 8.74$, and $\kappa = 0.894$ [4]. Rigidity values ranging from 1 to 100 GV were sampled at a 1 GV interval. For each rigidity value, we calculated the DRF and the unit vector of the asymptotic direction. These vectors were then weighted-averaged using the corresponding DRF values to obtain the average asymptotic direction. The data presented in Figure 2(b) represents hourly data observed by the Jang Bogo (blue) and McMurdo (red) neutron monitors a few days prior to and following the occurrence of the Forbush decrease on December 20, 2015. The average count rate for both stations is approximately 14.7 Hz per counter.

The calculated weighted average directions, obtained for every hour between December 16, 2015, and January 9, 2017, exhibit a significant difference of 41.8°± 2.0° in terms of geographic longitude. This difference is exemplified by the two plus signs in Figure 2(a), and the average value is displayed in Figure 3. Considering Earth's rotation, this suggests that time-independent anisotropy effects will introduce a lag of approximately $41.8 \times 4 \frac{\text{minutes}}{\text{degree}} = 167.2 \pm 7.9$ minutes.

3.2 Correlations and lag time

Correlation refers to the relationship between two variables or time series. In this work, we employ the Pearson correlation method. For two data sets, represented as $\{a_i\}$ and $\{b_i\}$, the Pearson correlation at lag τ is denoted as r_τ is defined by the following equation:

$$r_\tau = \frac{n \sum_i a_i b_{i+\tau} - \sum_i a_i \sum_i b_{i+\tau}}{\sqrt{n \sum_i a_i^2 - (\sum_i a_i)^2} \sqrt{n \sum_i b_{i+\tau}^2 - (\sum_i b_{i+\tau})^2}}.$$

Each increment of τ corresponds to a 10-second lag. To address missing data, if either a_i or $b_{i+\tau}$ is missing, both data points are omitted from the analysis. In this study, we employ a fitting approach

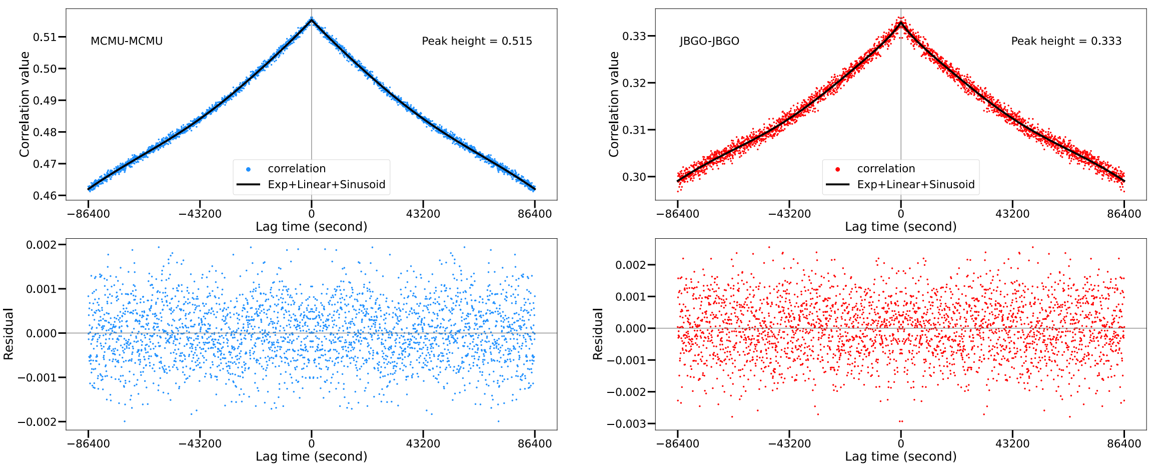

Figure 4: Autocorrelation values for the average data of all counters within each station are examined with respect to time lag (in seconds) for two scenarios: (LEFT) MCMU-MCMU and (RIGHT) JBGO-JBGO. Our analysis focuses on time lags ranging from -86,400 to +86,400 seconds (equivalent to -1 day to +1 day). Both the left- and right-hand functions have identical parameter values. Three types of functions are considered: exponential, linear, and sinusoidal, with autocorrelation functions exhibiting a 24-hour period. Prior to fitting, the maximum jump value in auto-correlation is excluded from the analysis.

using a function that combines exponential, linear, and sinusoidal terms:

$$f(\tau) = \left\{\alpha e^{-|\tau|/t_1}\right\} + \{y_0 - m|\tau|\} + \left\{A\cos\left(\frac{2\pi}{T}\tau + \phi\right)\right\}$$

The leftmost brace possibly represents the local environmental conditions, including the atmosphere and magnetosphere. The middle brace signifies the temporal variation of cosmic ray flux over time. The rightmost brace represents cosmic ray flux's directional variation or anisotropy.

The auto-correlation functions are well fit by the sum of three components: an exponential function peaking at zero lag, a linear function, and a sinusoid with a period of one day centered at zero lag ($\phi = 0$). However, in the cross-correlation analysis of the average over-counter tubes for the two stations, the exponential term is not observed. The auto-correlation results are shown in Figure 4, which shows the values, the fit, and the residuals. Similarly, Figure 5 shows the cross-correlation results. The maximum in the diurnal variation is at $\tau = -\phi T/(2\pi)$, where the period T equal 1 day. Using the parameter value ϕ from Table 2, the τ value at the maximum relative diurnal variation is approximately $-0.73° = 0.116$ days = 167 minutes. Remarkably, this estimate closely matches the value obtained from the asymptotic longitude difference (Sec 3.1), which is approximately 167.2 ± 7.9 min.

Table 2 displays the parameter values obtained from the fits of auto- and cross-correlation, shown in Figures 4 and 5, respectively.

4. Discussion and Conclusions

The response-weighted average directions between McMurdo and Jang Bogo stations align with flux cross-correlation analysis, indicating consistency. The correlation technique holds promise for

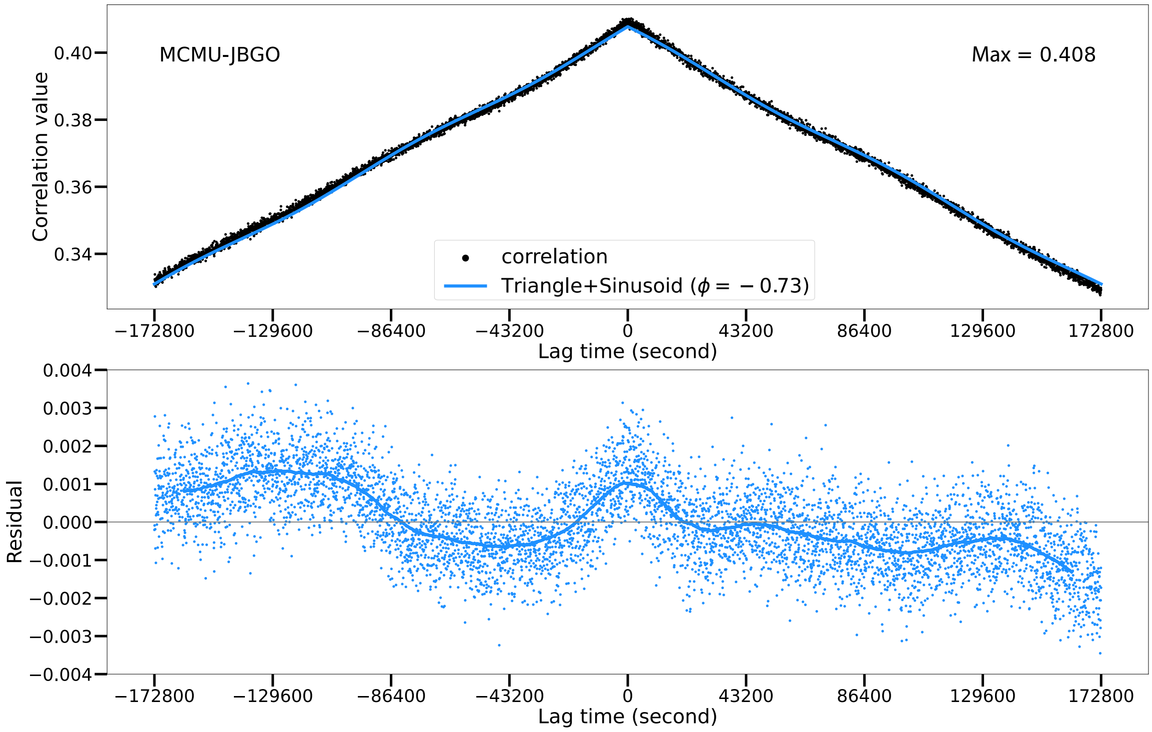

Figure 5: Cross-correlation values between McMurdo and Jang Bogo for averaged count rates are analyzed across different lag times (in seconds). The range of lag times displayed spans from −172,800 to +172,800 seconds (−2 days to +2 days). The values are represented by black symbols, while the blue line represents the best fit with a phase angle (ϕ) of −0.73 rad, indicating sinusoidal peaks occurring at a lag of 167 minutes. The lower panel displays the residual plot, illustrating the differences between the observed values and their corresponding fit.

Table 2: Derived Correlation Function Parameters

	Description	Unit	MCMU-MCMU	JBGO-JBGO	MCMU-JBGO
x_0	Time lag	s	0	0	0
y_0	Peak height	–	5.09E-01 ± 7.78E-04	3.29E-01 ± 1.14E-04	4.07E-01 ± 2.92E-05
α	Exp. amplitude	–	4.57E-03 ± 8.64E-04	2.57E-03 ± 1.59E-04	–
t_1	Time	s	1.55E+04 ± 3.21E+03	6.12E+03 ± 9.83E+02	–
m	Linear slope	s^{-1}	1.07E-06 ± 2.09E-08	1.09E-06 ± 5.71E-09	1.09E-06 ± 7.19E-10
A	Sin. amplitude	–	1.14E-03 ± 1.17E-04	1.12E-03 ± 4.80E-05	8.68E-04 ± 2.07E-05
T	Period	d	1	1	1
ϕ	Phase shift	rad	0	0	−0.73 ± 0.0238

distinguishing between temporal and directional (anisotropy) variations. Each fitting term within the correlation technique serves a specific purpose: the exponential term reveals local environmental conditions, including the atmosphere and magnetosphere (only for auto-correlation). The linear term captures temporal variations of cosmic ray flux, while the sinusoid with a 24-hour period indicates directional variations. Moving forward, our future investigations will expand beyond the phase shift ϕ discussed in this study, and use this technique to investigate further other stations pairs.

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