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Time Lag in Diurnal Correlations vs. Asymptotic Longitudinal Separation

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The correlation between two neutron monitor count rates vs. time lag τ can be fit by the sum of a linear function of $|\tau|$ (a triangular function of τ), representing temporal correlation, and a sinusoid with phase ϕ, representing the diurnal correlation associated with cosmic ray anisotropy at directional separation ϕ. Comparing 1-minute count rates from pairs of neutron monitors with similar cutoff rigidities but different asymptotic longitudes, we measure ϕ from the diurnal correlation between count rates and find this to be closely related to the separation of asymptotic longitudes of the primary cosmic rays. We propose that this technique provides an alternative measurement of the diurnal anisotropy at various cutoff rigidities disentangled from temporal variations.

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1. Introduction

Cosmic rays, energetic particles from outer space, provide insights into fundamental physics and have a significant impact on space weather. They are divided into two types: Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs). SEPs are released during solar flares, coronal mass ejections, and other solar events. GCRs originate from beyond our solar system and undergo acceleration within our Galaxy.

Neutron monitors (NM) at various geographic locations detect cosmic rays with different directions and energies. The study used the standard design of neutron monitors, referred to as NM64 [1, 2]. High-energy cosmic rays travel in a straight path determined by the latitude and longitude of the monitor, as they are less affected by Earth's magnetic field. Conversely, low-energy cosmic rays undergo significant refraction. When a particle arrives from a specific sky direction with a certain rigidity, it follows a distinct trajectory in space known as the "asymptotic direction," which is later deviated by Earth's magnetic field. The geomagnetic field changes over time due to the Earth's rotation relative to the solar wind, leading to variations in the arrival directions. The arrival direction is somewhat dependent on particle rigidity. To understand the angular dependence of SEPs, which have highly anisotropic fluxes, networks of ground-based detectors are necessary. One such network is Spaceship Earth (including Fort Smith, Inuvik, McMurdo, Peawanuck, etc.) [3], designed specifically to study the angular distribution of SEPs by providing global coverage with detectors that have similar energy responses. The Earth's magnetic field has a property called the "geomagnetic cutoff," which prevents particles below a certain rigidity (momentum per unit charge) from entering the atmosphere at a given location [4–8]. This cutoff is higher near the geomagnetic equator and lower near the magnetic poles. However, due to the Earth's magnetic field being approximated as a dipole, the cutoff's dependence on geographic locations is complex. By placing detectors at different cutoffs, an approximate energy spectrum can be inferred.

In this work, we introduce an alternative approach to determine the time lag (τ) by using the cross-correlation function technique on minute count rates obtained from pairs of neutron monitors. Cross-correlation is a quantitative measure of the similarity between two series, taking into account the displacement or lag between them. It assesses the degree of similarity as a function of the relative displacement between the two series. The pairs of neutron monitor stations considered in this study are as follows: McMurdo–Jang Bogo, Fort Smith–Inuvik, Fort Smith–Peawanuk, Inuvik–Peawanuk, Tibet–Doi Inthanon, and Daejeon–Tibet. These pairs have similar cutoff rigidities but different asymptotic longitudes of the primary cosmic rays. By examining the diurnal correlation between count rates, we measure ϕ, which is closely associated with the difference in asymptotic longitudes of the primary cosmic rays.

The stations are named based on the detector's location, and we use four capital letters as the corresponding abbreviation. For example, McMurdo (MCMU), Jang Bogo (JBGO), Fort Smith (FSMT), Inuvik (INVK), Peawanuk (PWNK), Tibet or Yang Ba Jing (TIBT, also sometimes abbreviated as YBJ), Doi Inthanon or Princess Sirindhorn Neutron Monitor (DOIN, also sometimes abbreviated as PSNM), and Daejeon (DAEJ).

Table 1: Characteristics of 8 neutron monitor stations used in our work.

Neutron Monitor Station		Data Collection Period		Geographic		Geomagnetic		P_c	Altitude	NM
Name	Short name	From	To	Latitude [deg]	Longitude [deg]	Latitude [deg]	Longitude [deg]	[GV]	[m] asl	Configu-lation
Daejon	DJON	Dec 15, 2015	Jan 1, 2018	36.24 N	127.22 E	27.1	197.93	11.2	200.0	18-NM64
Fort Smith	FSMT	Jan 1, 2015	Dec 31, 2017	60.02 N	111.93 W	66.72	306.85	0.3	206.0	18-NM64
Inuvik	INVK	Jan 1, 2015	Dec 31, 2017	68.36 N	133.72 W	71.13	273.76	0.3	21.0	18-NM64
Jang Bogo	JBGO	Dec 16, 2015	Jan 8, 2017	74.6 S	164.2 E	-77.12	274.37	0.3	29.0	5-NM64
McMurdo	MCMU	Dec 16, 2015	Jan 8, 2017	77.9 S	166.6 E	-79.12	287.5	0.3	48.0	18-NM64
Princess Sirindhorn Neutron Monitor	DOIN	Jan 1, 2015	Dec 31, 2017	18.59 N	98.49 E	9.01	171.47	16.8	2565.0	18-NM64
Peawanuck	PWNK	Jan 1, 2015	Dec 31, 2017	54.98 N	85.44 W	64.27	342.97	0.3	53.0	8-NM64
Yangbajing	TIBT	May 10, 2016	Nov 11, 2016	30.11 N	90.53 E	20.82	164.43	14.1	4300.0	28-NM-64

2. Methods

2.1 Data Processing

In this work, we use data from 8 neutron monitor stations. The initial purpose is to analyze the 1-minute data for the same periods for the selected stations for a minimum data length of one year. However, obtaining such complete data is unfeasible. We then endeavor to define the narrowest viable time range of 2015 - 2018, which encompasses the operational lifespan of the stations. The specifications of the stations can be seen in Table 1.

We removed inaccurate readings marked as missing data (NaN) in the input files, identified by a value of "-1." We resolved redundant dates where count rates did not align logically. Data points beyond $\pm 4\sigma$, calculated based on the 24-hour moving average, were discarded to eliminate outliers.

To study variations in primary cosmic rays, it is essential to consider the atmospheric influence on secondary cosmic ray particles detected by ground-based detectors. The count rate of these secondary particles generally decreases as atmospheric depth increases due to absorption by environmental factors. The most influential variable is the total column density of air, measured by barometric pressure. To eliminate short-term fluctuations from the dataset, count rates need to be corrected accordingly for barometric pressure. We use a pressure-corrected count rate for the stations according to a method widely used in the field of neutron detectors [8].

2.2 Diurnal Correlations

In this work, we employ the cross-correlation function to examine the time lag derived from diurnal correlation (τ_{corr}). The cross-correlation function is a statistical technique used to measure the similarity between two time series as a function of the time lag. We analyze the normalized cross-correlation function (CCF) defined as

$$\text{CCF}(\tau_{\text{corr}}) = \frac{1}{N_{\tau_{\text{corr}}} - 1} \sum_m \frac{\left(x_m - \overline{x}_{\tau_{\text{corr}}}\right)\left(y_{m+\tau_{\text{corr}}} - \overline{y}_{\tau_{\text{corr}}}\right)}{\sqrt{\left(x_m - \overline{x}_{\tau_{\text{corr}}}\right)^2}\sqrt{\left(y_{m+\tau_{\text{corr}}} - \overline{y}_{\tau_{\text{corr}}}\right)^2}}.$$

The CCF determines the correlation between count rates (x_m and y_m) from different neutron monitor stations, accounting for various time lags (τ_{corr}). It uses average count rates ($\overline{x}_{\tau_{\text{corr}}}$ and $\overline{y}_{\tau_{\text{corr}}}$) and a summation term ($N_{\tau_{\text{corr}}}$) representing the number of terms considered.

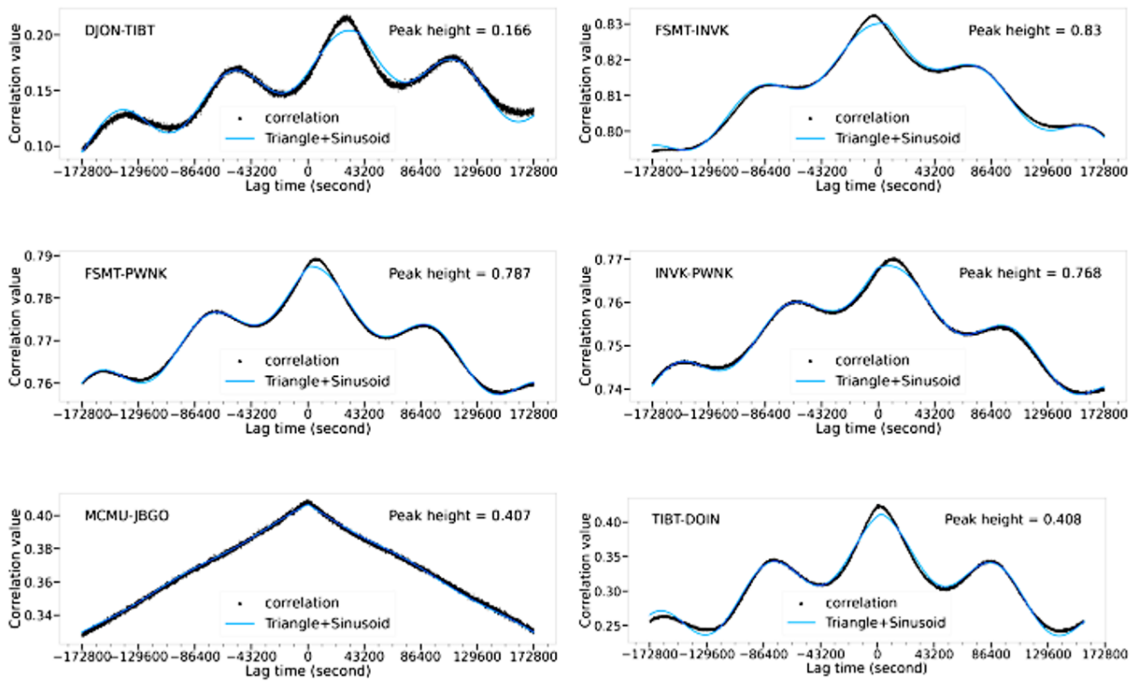


Figure 1: The cross-correlation values Vs. the lag time (in seconds) for six pairs of neutron monitor stations. The correlation values are fitted using two terms: a linear term and a sinusoidal term with a two-day period (equivalent to ±172,800 seconds).

We analyze the CCF obtained from station pairs to examine directional variations (anisotropy) in cosmic ray flux. The CCF value is then fitted using two terms, linear and sinusoid terms with a two-day period: $(y_0 - m\,|\tau_{\mathrm{corr}} - \tau_0|) + (A\cos\,[2\pi f\,|\tau_{\mathrm{corr}}| + \phi])$. The linear function describes temporal changes in cosmic ray flux, where the parameter m represents the rate of flux change, and τ_0 denotes the associated time lag. The parameter y_0 accounts for the peak height of the cross-correlation value. It is widely accepted that the temporal variation of the solar magnetic field is responsible for interplanetary and geomagnetic activities, as well as solar eruptions like flares and coronal mass ejections [9]. The sinusoid term represents diurnal or directional variations in cosmic ray flux with a period of one day according to Earth's rotation [10]. The parameters A, f, and ϕ correspond to the amplitude, frequency, and phase of the sinusoid, respectively. The correlation technique enables statistical differentiation between temporal and directional (anisotropy) variations.

In Figure 1, the cross-correlation values are plotted against the time lag for six neutron monitor station pairs. By determining the maximum length of diurnal variations using the phase parameter ϕ from the sinusoid term, we obtain the time lag of cross-correlation, which results differently for each station pair. At higher cutoff values, diurnal variations become more prominent compared to other variations that are relatively weaker. The time lag can be simply calculated using the formula $\tau_{\mathrm{corr}} = -\phi T/(2\pi)$. Table 2 presents the phase shift ϕ (in radians) and time lag τ_{corr} (in minutes) in diurnal correlation. It is crucial to note that τ_{corr} represents an absolute value.

Table 2: Time lags in diurnal correlations and the response-weighted average directions compared to asymptotic longitudinal separation. The data collection duration for each pair of NM stations is indicated.

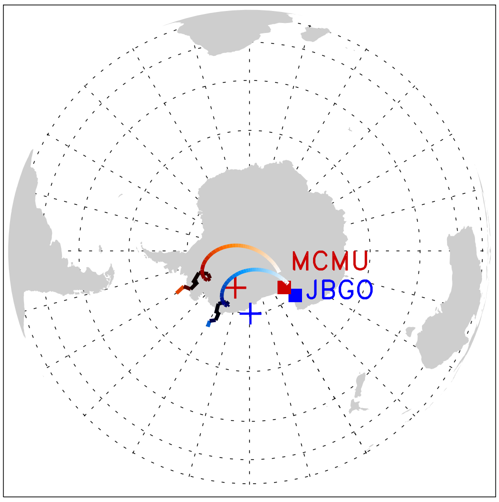
Pair of NM station	Duration of cross correlation		Asymptotic longitudinal separation	Phase shift (ϕ) [rad]	τ_{asymp} [mins]	τ_{corr} [mins]
	From	To				
DJON×TIBT	May 10, 2016	Nov 11, 2016	35.3200	-1.16	141.28 ± 0.31	266.49 ± 1.05
FSMT×INVK	Jan 1, 2015	Dec 31, 2017	27.3775	-0.58	109.51 ± 0.19	132.48 ± 0.89
FSMT×PWNK	Jan 1, 2015	Dec 31, 2017	36.7900	0.68	147.16 ± 0.18	155.5 ± 0.53
INVK×PWNK	Jan 1, 2015	Dec 31, 2017	64.1800	1.17	256.72 ± 0.29	267.89 ± 0.61
MCMU×JBGO	Dec 16, 2015	Jan 8, 2017	41.5825	-0.7	166.33 ± 0.25	160.62 ± 5.39
TIBT×DOIN	May 10, 2016	Nov 11, 2016	8.8975	0.28	35.59 ± 0.09	61.86 ± 0.64

2.3 Asymptotic Directions Analysis

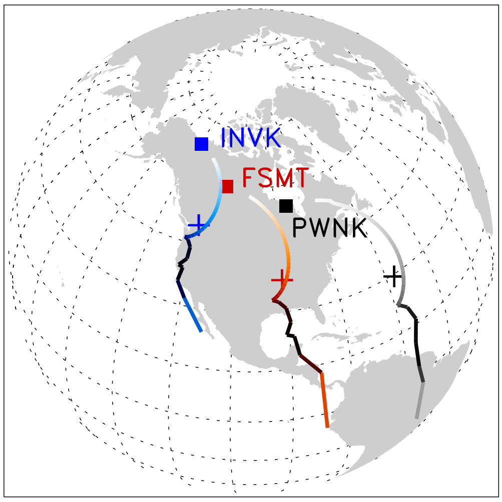
The time lag between neutron monitor stations can be determined by calculating the difference in longitude between their response-weighted asymptotic directions, denoted as τ_{asym}. The response-weighted asymptotic direction refers to the average direction of cosmic rays arriving at each station, considering their differential response to rigidity values. For this analysis, we calculated the response-weighted asymptotic direction for a single month within the duration specified in Table 2 for each station pair. Figure 2 displays the asymptotic directions for the neutron monitor stations mentioned in this study. The stations are categorized into three groups based on their location on different continents: (a) Antarctic stations: McMurdo - Jang Bogo (MCMU×JBGO), (b) Canadian stations: Fort Smith - Inuvik (FSMT×INVK), Fort Smith - Peawanuk (FSMT×PWNK), and Inuvik - Peawanuk (INVK×PWNK), and (c) Asian stations: Tibet - Doi Inthanon (TIBT×DOIN), and Daejeon - Tibet (DAEJ×TIBT). The colored lines represent the asymptotic directions of primary cosmic rays reaching the specific neutron monitor stations, with rigidity ranging from 0 to 100 GV. The intensity of the color indicates the differential response function. We applied the differential response function (DRF) to average the directions obtained from the 2006 latitude survey, which had a similar solar modulation level during the available data period from 2015-2017. The duration data for investigating the cross-correlation function for each station pair in this study are presented in Table 2. The DRF is defined as $DRF = N_0 \alpha P^{-\kappa-1} \kappa (e^{-\alpha P^{-\kappa}})$, where P represents rigidity in GV. The Dorman parameters were set as $N_0 = 31.7$, $\alpha = 8.74$, and $\kappa = 0.894$ [8]. 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 representing the asymptotic direction. These vectors were then weighted-averaged using the corresponding DRF values to obtain the average asymptotic direction.

3. Discussion and Conclusion

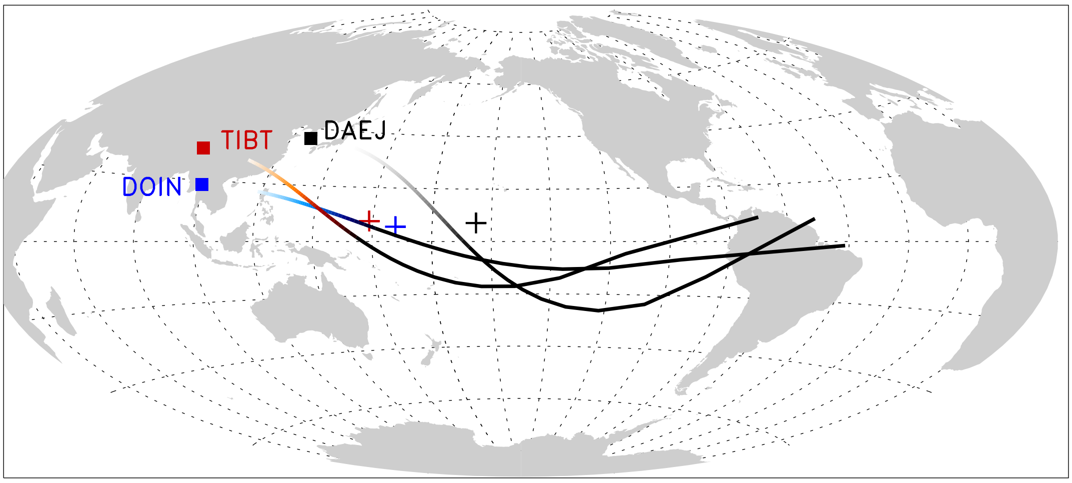
Table 2 displays pairs of neutron monitor stations and their corresponding time operation intervals for cross-correlation analysis. It also provides columns for asymptotic longitudinal separation, phase shift (ϕ in radians), τ_{asym} (in minutes), and τ_{corr} (in minutes). These data are essential for plotting the relationship between the time lag (in minutes) and the asymptotic longitudinal separation, as shown in Figure 3. The figure indicates a high level of agreement between the time lags obtained



(a) Antarctic Stations



(b) Canadian Stations



(c) Asian Stations

Figure 2: The asymptotic directions for six neutron monitor station pairs. The stations are divided into three groups separated by continent. (a) Antarctic station: MCMU×JBGO, (b) Canadian station: FSMT×INVK, FSMT×PWNK, and INVK×PWNK, (c) Asian stations: TIBT×DOIN, and DAEJ×TIBT. The colored lines represent the asymptotic directions of primary cosmic rays reaching the specific neutron monitor stations. The color intensity indicates the differential response function, which is described in more detail in the text. Plus signs indicate the response-weighted asymptotic directions for each station.

from the response-weighted asymptotic direction and those determined through diurnal correlation analysis in most cases. Station pairs with a percentage difference of less than 19% show consistent agreement. However, there are two exceptions: the DJON×TIBT and TIBT×PSNM pairs, which exhibit higher percentage differences of 61% and 54%, respectively. The higher percentage difference observed in the DJON×TIBT and TIBT×PSNM pairs can be attributed to the limited duration of data used in the analysis, which was less than six months. In contrast, other stations had minute data available for at least one year resulting in more reliable and accurate results.

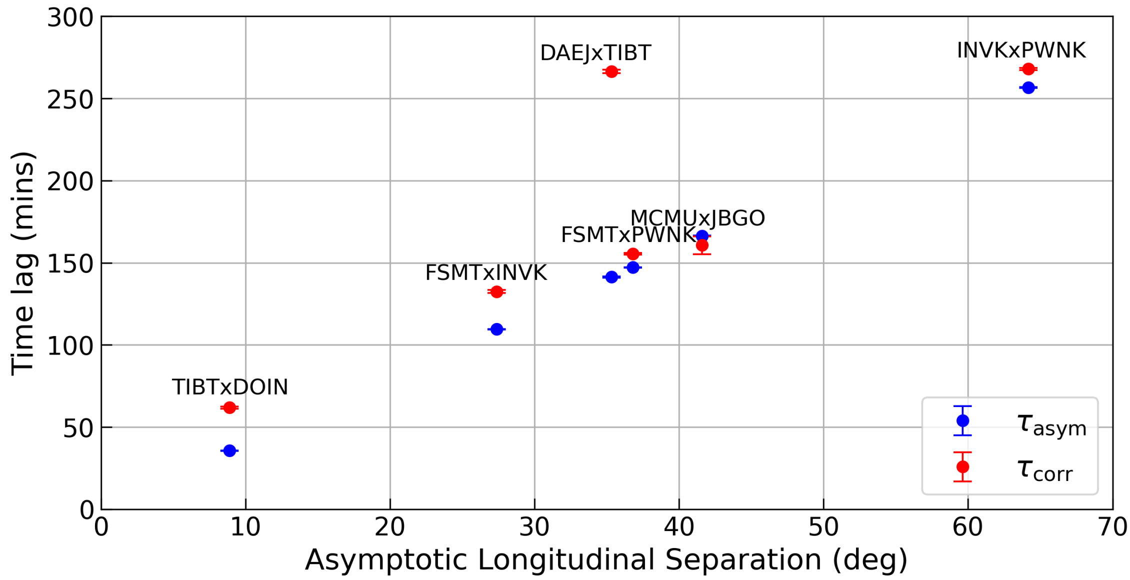


Figure 3: The time lags (in minutes) plotted against the asymptotic longitudinal separation (in degrees). The red symbol represents the time lag (τ_{asym}) calculated using the response-weighted asymptotic direction for each station pair, while the blue symbol indicates the time lag obtained from diurnal correlation. The error bars represent the standard error.

In the future, we require more data for DJON×TIBT and TIBT×PSNM station pairs, with a minimum duration extension of one year. Additionally, investigating the longitudinal separation of other station pairs, such as Yangbajing and Haleakala (TIBT×HALE), which could have a separation of 90 degrees in longitude), holds promising potential for this work.

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