Preliminary analysis of neutron time-delay histograms from Changvan latitude surveys

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Abstract. The name “Changvan” is given to a transportable neutron monitor, modernized by researchers in Thailand and housed inside a standard-size shipping container. It contains three neutron-sensitive proportional counters, which contain enriched ¹⁰BF₃ gas, to detect cosmic ray showers. Primary cosmic rays are high-energy particles arriving from outer space. By colliding with atoms in the atmosphere, they produce a shower of sub-atomic particles, called secondary particles. Some particles can reach the Earth’s surface, including neutrons. The Changvan is designed to measure atmospheric neutrons during a latitude survey. The side counter tubes are ringed with lead producer to produce evaporation neutrons when secondary particles collide with it. The center counter lacks the lead producer but can receive neutrons from nearby counters. The reflector and moderator made from polyethylene thermalize the evaporation neutrons and protect against disturbance by external low-energy neutrons. In this work, we pursue methods to determine spectral changes in Galactic cosmic rays using data from the Changvan, avoiding the systematic inconsistencies of cross-station comparisons. We examine neutron time delay histograms from the three counter tubes, as recorded by specially designed readout electronics, where the time delay refers to the time interval between consecutive neutron detections in one counter. We perform a preliminary analysis of such histograms to measure the leader fraction (L) of neutrons that do not follow a previous neutron from the same primary cosmic ray. The electronic dead time will be considered in the L calculation.
1. Introduction
Neutron monitors (NMs) are ground-based instruments for precisely tracking time variations in the flux of Galactic cosmic rays (GCRs) at GeV-range energies above the geomagnetic cutoff rigidity (momentum per unit charge) at a particular location of measurement [1-2]. The GCRs are energetic particles originating from elsewhere in our galaxy, comprising protons (hydrogen nuclei), alpha particles, and heavier nuclei. The flux changes arise due to solar wind variations often associated with solar storms. “Changvan” is the name we give to our mobile neutron monitor housed inside a standard-size insulated shipping container. When the primary cosmic rays collide with air nuclei of the Earth’s atmosphere, they produce a cascade of lighter particles, so-called secondary particles that rain down, including protons, electrons, pions, muons, and neutrons. Some of the secondary particles (including neutrons) will reach Earth’s surface, where neutron monitors can detect them. The Changvan monitor contains three cylindrical proportional counters which are filled with boron-trifluoride ($^{10}$BF$_3$) in which neutrons from cosmic-ray air showers induce nuclear fission. Electrons released when the fission products ionize the gas inside the detector are accelerated by the high potential difference (about ~2,800 Volts) maintained between a central wire and the outer cylindrical conducting surface of the detector. The resulting cascade produces a measurable pulse that is electronically counted. These counts are related to the flux of cosmic rays interacting with the Earth’s atmosphere, but the relation is complex. The proportional counters are surrounded by high-density polyethylene cylinder moderators to thermalize evaporation neutrons generated from the surrounding lead producer. The ring-shaped lead producer emits lower-energy (evaporation) neutrons when secondary particles collide with it. This increases the neutron count rate to provide higher statistical accuracy. The middle counter tube of the Changvan monitor lacks the lead producer, but still measures a higher count rate than an isolated lead-free neutron monitor because neutrons are detected from the lead rings of the neighboring side counters. We refer to this set of counters as a semi-leded monitor. The entire neutron monitor is housed in a rectangular polyethylene reflector to exclude low-energy neutrons from the environment and contain neutrons from the producer.

The survey technique has been used for improving our knowledge of spectral changes in Galactic cosmic rays and for testing geomagnetic cutoff models [3-4]. The geomagnetic cutoff rigidity is the minimum threshold momentum per unit charge that allows primary cosmic rays entering the atmosphere. The Changvan neutron monitor operated during latitude surveys that were carried out as part of the 35th (2018-2019, denoted survey year 2019) and 36th (2019-2020, denoted survey year 2020) Chinese Antarctic Research Expeditions (CHINARE), annual research missions using the icebreaking vessel Xue Long. The annual trip of the icebreaker Xue Long departs from Waigaoqiao Port in Shanghai, China down to Hobart, Australia, and to Zhongshan Station (69°22′25″S 76°22′18″E) in East Antarctica and back. The first trip of the Changvan monitor was from 11 February 2019 until 11 February 2019 starting from Zhongshan Station back to Shanghai. In the survey year 2020, we ran the Changvan monitor from the beginning of the mission in Shanghai on 21 October 2019. The ship repeated its annual journey to Hobart, Zhongshan Station, and again to Hobart. The ship then proceeded into the Ross Sea area, returned to Hobart, went once again to Zhongshan Station, and came back to Shanghai on 22 April 2020. Data used in this preliminary study are from 11 February–11 March 2019 of the survey year 2019 and from 21 October 2019–21 December 2019 of the survey year 2020. At present the Changvan monitor is reportedly running and collecting data, which will be later transferred to our research group.

2. Analysis of neutron time-delay histograms of Changvan neutron detector during 2019–2020
The Changvan neutron detector uses specialized electronics to record the time delays (time interval between successive neutron detections) in each counter. The Changvan neutron detector is the first mobile neutron detector to employ the current version of this system. We analyze the hourly time-delay histograms collected during the survey years 2019 and 2020 to extract the leader fraction ($L$). The leader fraction refers to neutron counts that do not follow a preceding neutron count in the same counter from
the same atmospheric secondary particle [5]. It is an inverse multiplicity. The value of \( L \) is related to the cosmic ray spectral shape [4]. The time-delay histogram shows the neutron counts per delay time in s. We calculate the leader fraction from the parameters obtained from an exponential function fitting of time-delay histograms. We strictly follow the technique of [6].

2.1. Determination of electronics dead time

For a particle detection system that records discrete events, the dead time can be important. The dead time is the time after each count, during which the system is not able to count another electric pulse. The electronic dead time has been considered in the \( L \) calculation throughout this work.

There are three neutron counters for each survey year. Our data-acquisition system outputs two single-counter time delay histograms for each counter, over short and long timescales, recording the frequency of time delays in 1023 time bins of width \( t_g = 0.0021701 \) ms and 1024 bins of nominal width \( t_i = 64t_g = 0.1389 \) ms, as shown in figures 1 and 2, respectively. After a time corresponding to 1024 of the latter bins, \( t_o = 2^{16}t_i = 0.142 \) s, the time delay overflows, and a count is recorded in an overflow bin.

Figure 1 shows an example of histograms giving the frequency distribution of short-time delays for the three counters in the Changvan as a function of delay time. The red vertical band shows the electronics dead time \( (t_d) \) for each tube, which is about \( 87 \) \( \mu \)s (following the methods of [5]). Each entry is the sum of neutron counts over 16 time bins in the original histogram divided by the bin width. The square root of accumulated neutron counts in each bin provides the standard deviation estimate of the uncertainty. The neutron count rates from the Changvan detector change according to time and latitude. When the ship is near the equator with high geomagnetic cutoff, the observed count rate will be lower than near the Pole with low geomagnetic cutoff. The short-time delay histograms can tell us in detail about the following-neutron production of lower-energy neutrons from the lead producer in the monitor. From the height of the first-time bin in the histograms, we can see clearly that the middle counter (figure 1(b)) produces fewer such neutrons. That is because it does not have its own lead ring, but receives neutrons from the tubes on either side.

2.2. Determination of leader fraction

In our method for determination of the leader fraction (\( L \)) value, we analyze long time-delay histograms, shown in figure 2 where we plot the y-scale as logarithmic. We treat them the same way as the short time-delay histograms explained in Section 2.1 except that we consider \( t_d \) instead of \( t_o \) to convert from pulses to count rates. We fitted \( N(t) \) to the function \( A_0 e^{at} \), shown in red, from 5 ms to the next to last time bin (excluding the overflow time bin).

We derived \( L \) from the method suggested by [6], normalizing each histogram to account for missing values at \( t > t_o \):

\[
L = \frac{\int_{t_d}^{\infty} A_0 e^{at} \, dt}{\int_{t_d}^{t_o} N(t) \, dt + \int_{t_o}^{\infty} A_0 e^{at} \, dt}
\]

or for the discrete histogram,

\[
L = \frac{A_0}{\alpha} \frac{e^{at_d}}{\sum_{t=t_d}^{t_o} N_i + \frac{A_0}{\alpha} e^{at_o}}
\]

(1)

where \( \alpha \) and \( A_0 \) are the parameters from the hourly long-time histogram fit. As said earlier, \( t_o = 0.142 \) s is the overflow time in the electronic system, and dead time \( t_d = 87 \) \( \mu \)s [4-6]. The term \( \sum_{t=t_d}^{t_o} N_i \) is the sum of the neutron pulses for all time bins from \( t_d \) to \( t_o \) from the recorded histogram files.
Figure 1. Frequency histograms of short time delays collected for each neutron counter tube during one hour (2\textsuperscript{nd} hour of universal time (UT) on the 20\textsuperscript{th} December 2019 of the survey year 2020): (a) tube 1, (b) tube 2, and (c) tube 3. The red vertical band shows the electronics dead time for each tube, about 87 $\mu$s. Statistical error bars are shown.

Figure 2. Example of analysis of long time delay histograms collected for each neutron counter tube during one hour (2\textsuperscript{nd} hour UT on the 20\textsuperscript{th} December 2019 of the survey year 2020) of (a) tube 1, (b) tube 2, and (c) tube 3. Error bars are shown.

3. Observational results

Figure 3 shows $L$ data as a function of time. Throughout this work, the time is indicated by “day of year” or “DOY,” where we count “1” from the start of January 1, 2019. In the survey year 2019 (received data from 11 February–11 March 2019), the day of year is from 42 to 70 (shown in the x-axis of figure 3(a)–(d)). Likewise, the survey year 2020 started in late 2019, and data recorded from 21 October 2019–21 December 2019 range from day of year 286 to 355 (shown in the x-axis of figure 3(e)–(h)). Figure 3 (a)–(c) and (e)–(g) show the leader fraction ($L$) as a function of time for survey years 2019 and 2020 for tubes 1, 2 and 3, respectively. For the two surveys, $L$ measured by the Changvan neutron monitor is in the range 0.78–0.86 depending on the latitude of the ship, which corresponds to an article published earlier [4] confirming that the $L$ value of portable neutron detectors varies with latitude according to changes in the Galactic cosmic ray spectrum entering Earth’s atmosphere, because of the changing spectral cutoff.

In figure 3(a)–(c), the observed $L$ value decreased during day of year 55–70 when the ship was passing near the Earth’s equator (low latitude), where there is a high geomagnetic cutoff rigidity (figure 3(d)). The cutoff rigidity can be accurately calculated using detailed models of the geomagnetic field.
and GPS-derived latitude and longitude. There are two types of cutoff calculations shown in figures 3(d) and 3(h). The apparent cutoff takes obliquely incident particles into account by weighting effective cutoffs calculated for nine discrete arrival directions, and the vertical cutoff takes only vertically incident particles into account [3]. Near the equator, the magnetic field of the Earth is more effective in keeping cosmic rays from reaching the atmosphere than it is near the poles (e.g., during day of year 42–55). Since the count rate near the pole is usually higher than near the equator, resulting in more statistical reliability, the data are less scattered when the ship was in Antarctica. For tube 2 during day of year 55–70, there were some technical problems while the ship was passing by the Australian continent and all the way back to Shanghai, China. Hence leader fractions were not available for tube 2 for that time period. The $L$ value of tube 2 is higher than that of the other tubes since the middle tube has no lead producer itself, therefore there is no local production of follower neutrons. As the number of follower neutrons (denominator) decreases, the $L$ value increases.

![Figure 3](image_url)

**Figure 3.** Hourly leader fraction ($L$) of tube 1 (blue), tube 2 (black), and tube 3 (green), and geomagnetic cutoff rigidities as a function of time. (a)–(d) Data for the survey year 2019. (e)–(h) Data for the survey year 2020.

Regarding the survey year 2020, the trends of $L$ values as a function of cutoff are similar to the survey year 2019. The relationship between the $L$ value and the geomagnetic cutoff rigidity can be explained in much the same way. $L$ values were lower during day of year 294–308 because the ship travelled across the Earth’s equator. In this survey year, we used the same set of neutron detectors in the experiment, which means that tube 2 has no lead producer. Therefore, the $L$ value is higher than that of the tubes on the side. Many small data gaps occurred due to an electronics issue.

4. **Conclusion**

We can conclude that the leader fraction $L$ obtained from the Changyan neutron detector from the survey year 2019 and the survey year 2020 changes with geomagnetic cutoff rigidity. This confirms the dependence of the leader fraction measured by the portable neutron monitor on the geomagnetic cutoff.
rigidity in [4]. We studied $L$ determined from time-delay histograms with a transportable neutron detector to achieve the ultimate goal of indicating spectral changes in Galactic cosmic rays.

An essential factor that directly affects measurements by neutron monitors is barometric pressure. Because atmospheric secondary particles are speedily absorbed in the atmosphere, a neutron monitor count rate is primarily corrected for the pressure, which provides a measure of the weight of the atmosphere above the detector's area. The ship-borne Changvan neutron monitor also operated with a barometer to measure barometric pressure to a precision of 0.01 mmHg. Shortly, we will correct $L$ for barometric pressure variations and collect data from subsequent surveys to explore the variations of the leader fraction with solar modulation.

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References
[1] Simpson J A 1954 Cosmic radiation intensity-time variations and their origin. V. the daily variation of intensity Phys. Rev. 94 426
[2] Hatton C J and Carmichael H 1964 Experimental investigation of the NM-64 neutron monitor Can. J. Phys. 42 2443
[3] Clem J, Bieber J W, Evenson P, Hall D, Humble J E and Duldig M 1997 Contribution of obliquely incident particles to neutron monitor counting rate J. Geophys. Res. 102 A12
[4] Mangeard P S, Ruffolo D, Sáiz A, Nuntiyakul W, Bieber J W, Clem J, Evenson P, Pyle R, Duldig M L and Humble J E 2016 Dependence of the neutron monitor count rate and time delay distribution on the rigidity spectrum of primary cosmic rays J. Geophys. Res. 121 11620
[5] Ruffolo D et al 2016 Monitoring short-term cosmic ray spectral variations using neutronmonitor time delay measurements Astrophys. J. 817 38
[6] Banglieng C et al 2020 Tracking cosmic-ray spectral variation during 2007-2018 using neutron monitor time-delay measurements Astrophys. J. 820 21