Forbush decreases detected at the Princess Sirindhorn Neutron monitor in the 24th Solar Cycle

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Abstract. Neutron monitors (NMs) are ground-based detectors designed to measure the cosmic ray (CR) intensity by measuring secondary particles. A Forbush decrease (FD) is a sudden decrease in the CR-intensity count rate and the amplitude of the decreases changes with the different cutoff rigidity of each NM station. The Princess Sirindhorn NM (PSNM) was established in 2007, an NM64-type and 3 bare tubes located at the world's highest geomagnetic vertical cutoff rigidity 16.8 GV was installed at Doi Inthanon in Thailand, 2565 m above sea level. In this work, we study the FDs in CR intensity detected at PSNM that occurred during the 5 years of 2010-2015 in the 24th solar cycle. We analyse the FDs at the Oulu NM in Finland in order to identify and compare them. We identify 46 FDs at both PSNM and Oulu NMs then we used the student's t-test to assess difference in the mean between simultaneous or non-simultaneous of FDs event. We found that the 46 FDs, 22 are simultaneous and 24 non-simultaneous. Furthermore, we also found that student's t-test analysis reveals that FDs at PSNM have smaller intensity variation of main phase duration of main phase than at Oulu NM. The results of the present statistical analysis that support the PSNM can provide CR data of reliability comparable to that of the Oulu NM. This work also provides unique data of FDs and solar modulation.

1.Introduction

Forbush decrease (FD) [1] represents a sharp decrease in the intensity of galactic cosmic ray (GCR), followed by disturbance in the strong solar events and usually associated with passage of interplanetary coronal mass ejection (ICME) [2, 3]. FDs can be observed on Earth by using ground-based particle detectors. Neutron monitors (NMs) are ground-based detectors designed to estimate the primary cosmic ray (CR) intensity by measuring secondary particles. These CR decreases are recorded on Earth by NM stations of the worldwide network. The amplitude of the decreases changes with the different cutoff rigidity of each NM stations. The Princess Sirindhorn NM (PSNM) was installed at Doi Inthanon, Thailand (18.59N, 98.49E, 2565 m altitude) where the effective cutoff rigidity is 16.8 GV [4]. PSNM provides a basis for comparison with count rates of other NMs worldwide which are similarly calibrated. In this work, we examine simultaneous and non-simultaneous FDs using the CR data observed by PSNM in Thailand compared with Oulu NM (OULU) in Finland that occurred during the five years of 2010-2015 in the 24th Solar Cycle. We analyse the statistical properties of CR data observed by both NM stations for simultaneous and non-simultaneous FDs.
2. Data and Selection of FD

FD consists of a main phase and recovery phase. In the main phase, there is a rapid decrease in the intensity of CR. The onset of the main phase is the time that the maximum intensity is recorded before the CR-intensity begins to decrease. The end of the main phase is the time of minimum CR-intensity. The onset time is determined within 6 h from onset of the decrease, and the end time is determined within 12 h from the termination of the decrease [5]. We used the hourly pressure-coerced values of the CR intensity observation data from 2010-2015 at the PSNM and OULU. The variation in CR-intensity is normalized to the zero level of the pre-event, the CR-intensity to the monthly average for each NM station. In this study, we selected the well-defined FDs with an amplitude >3% at the OULU. Then we find the FDs at the PSNM that correspond to those at the OULU. The simultaneity of FDs are generally associated with ICMEs, thus we consider FDs due to the passage of ICMEs such as magnetic cloud and ejecta, the ICME list by Ian Richardson and Hilary Cane [6]. In this work, we used the criteria to select of simultaneous and non-simultaneous of FDs suggested by Lee SS et al., (2015). When the decrease in the CR intensity of main phase on the FD profile of NM overlapped in Universal Time (UT), the FDs were classified as simultaneous FDs and if the FDs that non-overlap in UT were classified as non-simultaneous FDs [7].

Table 1. Statistical properties of simultaneous and non-simultaneous FD events.

| NM  | Statistical properties | SFD ² | NSFD ² | Total | Confidence level (%) of $I_S > I_{NS}$ ² |
|-----|------------------------|-------|--------|-------|-----------------------------------------|
| PSNM | Mean of CR intensity (%) | 2.3±0.8 | 1.7±0.4 | 2.0±0.7 | 99.6% |
| OULU | during main phase (%)  | 5.0±1.9 | 4.1±0.9 | 4.5±1.5 | 96.4% |

| NM  | Statistical properties | SFD ² | NSFD ² | Total | Confidence level (%) of $I_S > I_{NS}$ ² |
|-----|------------------------|-------|--------|-------|-----------------------------------------|
| PSNM | Duration time (h) | 19.7±9.7 | 14.9±5.7 | 17.2±8.2 | |
| OULU | of main phase (h)  | 18.7±8.1 | 12.9±3.4 | 15.7±6.7 | |

² simultaneous Forbush decrease,
³ Non-Simultaneous Forbush decrease.
⁴ CR-intensity variation of main phase

Figure 1. CR-intensity variation profiles of a simultaneous FD event on 18 February 2011 observed at four NM station in (a) UT and (b) LT.
3. Results
Table 1 shows the statistical properties of the FDs, including the number of FDs, the mean of the CR-intensity and the result Student's t-test. We used the Student's t-test to assess differences in the mean between the types of FDs. Of the 46 FDs, 24 FDs were classified as simultaneous FDs, and 22 FDs as non-simultaneous. The intensity variation of main phase at the PSNM is smaller than the variation at the OULU and the mean of CR-intensity variation of the simultaneous events are higher than the variation from non-simultaneous events at both NM stations by Student's t-test. The results from the student t-test show that, these difference between two types of events is statistically significant with 95% confidence. Figure 1 shows a typical example for the CR-intensity profile of a simultaneous FD on 18 February 2011 observed at four NMs with different vertical cutoff rigidities. All NM stations have the main phase of FD events overlapped on the CR intensity profile based in UT (Figure 1a). According to that the FD events of 18 February 2011 has a simultaneous FD was recorded at all NM around the world [8]. Figure 1b show the CR-intensity variation of both NM stations based in LT. Whilst in LT the main phases occur at different times at difference NM stations, the main phases of FD did not overlap, due to the difference. Figure 2 shows for the CR-intensity profile of a non-simultaneous FD that occurred on event on 18 April 2014. These phenomenon is caused by the differences in time imposed by longitude of NM stations.

Figure 2. CR-intensity variation profiles of a non-simultaneous FD event on 18 April 2014 observed at the PSNM and OULU NM stations in (a) UT and (b) LT.

Figure 3 shows the distributions and the diurnal variation of onset time of the main phase in LT. Figure 3a shows of the CR-intensity, for FDs recorded at PSNM in the polar coordinates. The unfilled circle and filled mark the onset times and mean CR-intensity observed from both stations. From the plot, most non-simultaneous events have onset time on dayside and most simultaneous events have higher CR-intensity decrease. The maximum intensity of diurnal variation manifests at 12 LT at PSNM and 13 LT at OULU as shown in figure 3b, that the distribution for onset time in LT at PSNM of non-simultaneous FDs peaks near 12 LT.

4. Conclusion
In this paper, we reported the results of our study of FDs observed at PSNM, the world's highest magnetic cutoff rigidity 16.8 GV. In order to consider the reliability of CR data recorded by OULU (Finland), we selected FDs that occurred during 5 years between 2010-2015 in the 24th Solar Cycle. We repeated analysis to test the FDs at the PSNM in order to identify and compare with the OULU. We also classified into simultaneous and non-simultaneous FD events using overlapping main phase on the cosmic ray profile in UT. The study results are summarized as follows.
(1) We identify during the period of analysis, 46 FD events occurred, 22 are simultaneous FDs and 24 FD events are non-simultaneous FDs. The CR intensity variation is larger in of the simultaneous FD events, than the non-simultaneous FD events at the PSNM and OULT NM stations with very high confidence levels in the student t-test.

(2) Of the 46 FD events during the analysis period at the PSNM and the OULT. Student t-test results indicate FD events at the PSNM have smaller CR intensity variation of main phase, while the duration of the main phase longer than do those at the OULU. The main phase onset time of non-simultaneous FD event distributed mostly within 12-hour intervals, in dayside onset time, in line with the typical properties of non-simultaneous FDs guidance by Kang J Set al. and Oh S Yet al. [9, 10].

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Figure 3. Distributions of the onset time (LT) of the FD main phases at PSNM. Figure a, the radial shows the magnitude of the CR-intensity variation, and the angular coordinate component show the LT at PSNM (left). Figure b, the diurnal variation at both NM stations (red at PSNM and blue of OULU) during the analysis period (right).