Comprehensive Analysis of Solar-terrestrial Impacts of Small-amplitude Program-processed Forbush Decreases (Postprint)

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Abstract

Forbush decreases (FDs), defined as abrupt and transient reductions in cosmic ray (CR) flux intensity, are fundamental probes for understanding the complex interplay between solar activity and terrestrial weather systems. While previous studies have predominantly focused on events with absolute sizes >3%, small-size events (amplitude $ $3%) and their potential connections to Sun-Earth interactions remain significantly understudied. This research gap arises due to the challenges associated with precise timing and accurate characterization of small-scale events, compounded by the complexities of analyzing other transient astrophysical phenomena. In this study, we employed a state-of-the-art, highly sensitive FD event selection algorithm on daily-averaged CR data spanning 1998–2006 to create catalogs of small-amplitude FDs from nine neutron monitors (NMs) located at low (0–100 m), mid (101–1000 m) and high (>1000 m) altitudes. From the data set, we identified 1956 small-amplitude FDs composed of 766, 601, and 589 events across low, mid, and high-altitude NMs, respectively. Among these FDs, 80, 38, and 19 events were observed to occur simultaneously across the respective altitude ranges. Our analysis shows that the correlation coefficient for small-amplitude FDs and the solar-geomagnetic indices varies appreciably across the three altitude ranges and among the individual NM stations. The same solar/terrestrial variable that indicates a statistically significant correlation with small FDs at some altitude ranges/stations registered marginal or even non-significant relations at other altitudes/stations. These results are indications that small FDs are location-dependent CR phenomena. The results may provide valuable insights into how solar-terrestrial interactions affect CR flux variations across different NM stations and atmospheric levels. This understanding helps improve space weather models and enhances knowledge of CR modulation processes.

Full Text

Preamble

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Comprehensive Analysis of Solar-terrestrial Impacts of Small-amplitude Program-processed Forbush Decreases

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Abstract

Forbush decreases (FDs), defined as abrupt and transient reductions in cosmic ray (CR) flux intensity, are fundamental probes for understanding the complex interplay between solar activity and terrestrial weather systems. While previous studies have predominantly focused on events with absolute sizes >3%, small-size events (amplitude <3%) and their potential connections to Sun-Earth interactions remain significantly understudied. This research gap arises due to the challenges associated with precise timing and accurate characterization of small-scale events, compounded by the complexities of analyzing other transient astrophysical phenomena.

In this study, we employed a state-of-the-art, highly sensitive FD event selection algorithm on daily-averaged CR data spanning 1998–2006 to create catalogs of small-amplitude FDs from nine neutron monitors (NMs) located at low (0–100 m), mid (101–1000 m) and high (>1000 m) altitudes. From the data set, we identified 1956 small-amplitude FDs composed of 766, 601, and 589 events across low, mid, and high-altitude NMs, respectively. Among these FDs, 80, 38, and 19 events were observed to occur simultaneously across the respective altitude ranges.

Our analysis shows that the correlation coefficient for small-amplitude FDs and the solar-geomagnetic indices varies appreciably across the three altitude ranges and among the individual NM stations. The same solar/terrestrial variable that indicates a statistically significant correlation with small FDs at some altitude ranges/stations registered marginal or even non-significant relations at other altitudes/stations. These results are indications that small FDs are location-dependent CR phenomena. The results may provide valuable insights into how solar-terrestrial interactions affect CR flux variations across different NM stations and atmospheric levels. This understanding helps improve space weather models and enhances knowledge of CR modulation processes.

Key words: atmospheric effects – Sun: activity – (Sun:) solar wind

1. Introduction

Forbush decreases (FDs) are rapid and temporary reductions in cosmic ray counts observed by neutron monitors (NMs) on Earth's surface. These decreases are sudden and usually short-lived, followed by a recovery phase that can last from several hours to a few days or sometimes weeks (Forbush 1937; Hess & Demmelmair 1937). FDs can be categorized based on their magnitudes as outlined in previous studies (e.g., Belov et al. 2001; Okike & Colliner 2011; Okike 2020b), with magnitude defined relative to the initial CR count rate and the sign typically chosen based on standard conventions set by the researcher. Events with an absolute magnitude >3% are generally classified as large/strong amplitude FDs (Van Allen 1993; Harrison & Ambaum 2010; Laken et al. 2012), whereas those with a magnitude <3% are known as small/weak amplitude FDs (Cane et al. 1993; Pudovkin & Veretenenko 1995; Oh & Yi 2008; Okike 2021b).

FD events are mainly caused by the presence of interplanetary coronal mass ejections (ICMEs), which are large-scale expulsions of plasma and magnetic fields from the Sun. ICMEs generally include two main structural components: a shock sheath (region of compressed plasma and magnetic field ahead of the ICME) and a magnetic cloud (MC), which is a region with a strong, organized magnetic field (Barnden 1973; Cane 2000; Raghav et al. 2014). As the MC and shock sheath move through space, they interact with the interplanetary magnetic field (IMF), modulating the CR flux detected on Earth. Conversely, solar-terrestrial variables have interrelations with interplanetary activity that can significantly influence the motion and intensity of CRs as they propagate from space to Earth's surface (Badruddin & Singh 2006; Lingri et al. 2016). For instance, the solar wind—a stream of charged particles with velocities in the range of 250–700 km s^{-1}—can compress Earth's magnetic field, causing deflections of CRs away from Earth, thereby reducing the intensity of CRs reaching the surface (Badruddin & Singh 2006). Other parameters that influence the IMF and affect CR intensity include geomagnetic indices such as the planetary Kp-index (Kp), planetary Ap-index (Ap), and disturbance storm time (Dst) index. These variables provide information about the state of Earth's magnetosphere, and analyzing them along with CR modulations allows scientists to gain deeper understanding of the characteristics and dynamics of interplanetary disturbances.

FDs have been studied for over 80 years, beginning with Forbush's discovery in 1937, long before NMs were developed in 1951. Despite numerous publications (Lockwood 1971; Cane 2000; Belov 2009; Oh & Yi 2008; Okike 2020b; Ugwoke et al. 2022a; Alhassan et al. 2022; Ugwu et al. 2024), efforts to unravel solar influence on CR data have yet to receive adequate attention. This is because many FD catalogs used in space weather studies have inaccuracies, and creating reliable FD records remains challenging. Literature review indicates that basic aspects of FDs—such as features, types, and their links to phenomena like coronal mass ejections (CMEs), ICMEs, corotating interaction regions (CIRs), solar wind, and geomagnetic storms—remain widely debated. Some studies have produced conflicting or unclear results (e.g., Pudovkin & Veretenenko 1995; Okike & Colliner 2011), raising critical questions about whether these discrepancies stem from inherent complexity of FDs, variations in detection methodologies, or a combination of both factors.

Pittock (1978) provided a critical review highlighting key issues in earlier studies exploring long-term Sun-Earth connections. His review serves as a guide for further research by identifying problems like data smoothing, selective use of data in space and time, and improper application of statistics to data sets. Further survey of CR intensity variations reveals a scarcity of published catalogs of small-amplitude FDs. Among catalogs obtained from NMs are those spanning over two decades (Lockwood 1990; Tinsley & Deen 1991; Cane et al. 1993). Within this period, Pudovkin & Veretenenko (1995) published catalogs of small FDs of size <5%, with 14 out of 65 events meeting the small-amplitude FD classification criterion. The bias toward small FD selection has been attributed to CR diurnal anisotropy, which significantly influences and complicates their detection.

An approach involving finding the average of CR data obtained from multiple NM stations was proposed by Barouch & Burlaga (1975) and has since been employed by researchers like Dumbovic et al. (2011) to identify very small-amplitude FDs using high-altitude NM data. Similarly, researchers at the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences (IZMIRAN) have employed the global survey method (GSM) to create widely used FD catalogs, including events with magnitudes as low as 0.3% (Belov et al. 2001; Lingri et al. 2016). Though the GSM of

IZMIRAN could detect low-amplitude FDs of the order of 0.3%–0.5% (Belov et al. 2018a), it is clear that the current algorithm can detect events as low as 0.01% amplitude.

The latest attempts at detecting small FDs directly from raw CR data without preprocessing have been reported by Okike (2020b). These studies applied harmonic analysis to account for anisotropy, enabling comparisons between unprocessed and Fourier-transformed CR data.

Therefore, we observe that if this selection dilemma is not carefully addressed, result reproducibility—which is sine qua non in scientific methodology—will remain elusive in FD studies and other space weather investigations. In the present era of high-speed computers, CR researchers can use different tools capable of handling big data sets and multidimensional variables to study complex interrelationships within Sun-Earth space. In this paper, while we aim to relate certain connections between FDs and solar-terrestrial interactions, the key focus is on systematically selecting small-amplitude FDs, which are essential not only for good statistical results but also for understanding their impacts on solar-terrestrial variables.

2. FD Selection Bias

FDs are widely utilized by researchers investigating CR modulation processes. However, methods of event selection and cataloging remain critical challenges in CR astrophysics. Despite improvements in big data and high-speed computing, unreliable selection methods still exist. Previous studies show that fully automated systems for identifying and cataloging small-amplitude FDs are still lacking. Our group's FD detection algorithm stands out as one of the few fully automated systems that address event detection, precise timing, amplitude estimation, and proper cataloging (e.g., Okike & Umahi 2019b; Okike 2020c; Okike & Alhassan 2022a; Menteso et al. 2023). In contrast, semi-automated approaches such as those developed by the IZMIRAN group (Belov 2009; Ramirez et al. 2013; Belov et al. 2018a; Abunina et al. 2020; Light et al. 2020) have provided significant improvements but still encounter limitations in detecting small-amplitude FDs, with their lowest detected values in the range of 0.3%–0.5%. It has been established that our team can identify FDs with amplitudes as low as 0.01% (Okike 2020d; Menteso et al. 2023). This current version is specifically optimized for analyzing small-amplitude events. Comprehensive event catalogs generated by this algorithm have enabled robust quantitative investigation of relationships between small-amplitude FDs and solar-terrestrial parameters, paving the way for deeper insights into their role in CR modulation and space weather dynamics.

3.1. Sample Description

For the daily averaged CR intensity data, we considered solar cycle 23 (between 1996 and 2006) because this period presents several energetic events, particularly during the declining phase (from 2003 October to 2005 November, 2006 January and December). We selected pressure-corrected CR data observed by nine stations: Hermanus (HRMS), Newark (NWRK), Oulu (OULU), Apatity (APTY), Moscow (MOSC), Novosibirsk (NVBK), Calgary (CALG), Climax (CLMX), and Emiliosegre (ESOI) from the IZMIRAN general website: http://cr0.izmiran.ru/mxco/main.htm. Table 1 summarizes the properties of the stations. These NMs were classified into three groups based on their height above sea level: low (0–100 m) including HRMS, NWRK, and OULU; mid (101–1000 m) including APTY, MOSC, NVBK; and high (>1000 m) including CALG, CLMX, and ESOI. The daily mean values of interplanetary parameters (SWS, IMF) and geomagnetic storm indices (Ap, Kp, and Dst) were downloaded from the OMNI database http://omniweb.gsfc.nasa.gov/ow.html. The daily averaged CR data were used to minimally reduce the effects of CR diurnal anisotropy.

3.3. Non-algorithm FD Selection Method

FDs have four key profiles: onset point, main phase, FD minimum, and recovery phase. The onset marks the start of a drop in CR levels, indicating the initial response to a solar event. The main phase occurs when CR levels sharply decline to their lowest point. In the recovery phase, CR levels gradually return to normal, signaling restoration of typical interplanetary conditions. A non-algorithmic method is often used to analyze these stages, involving multiple steps including selecting data, plotting segments of CR data, identifying significant drops, calculating the time and magnitude of the decrease, and comparing results with a predefined threshold. This approach is labor-intensive and repetitive, as each stage must be carefully reviewed for every case. Additionally, the stages often involve trial and error, with researchers discarding many tested data sets to improve accuracy. Data normalization and event magnitude calculations are typically performed after visually examining the CR data.

The normalization baseline is chosen based on average CR variations during the event period. The baseline CR count is taken from the day of the minimum in FDs, and the event magnitude is calculated using the established equation below (Harrison & Ambaum 2010; Okike 2020b):

$$FD\% = \frac{C_i - C_m}{C_m} \times 100$$

where C_i is the daily or hourly CR intensity while C_m is the average intensity variation. The C_m can vary or remain constant depending on the researcher's choice. The static mean is the value of C_m obtained when averaging the data over the entire period. On the other hand, using certain moving or running averages (day, month, year) causes C_m to change over time, making the method subjective. Furthermore, the absence of a time factor in the equation means researchers must calculate magnitude and event time separately, leading to results that depend on the researcher. The use of this equation implies that different researchers employing different onset days arrive at different magnitudes for the same event. Consequently, only a few existing FDs could be detected by this method, which is one reason for the small FD samples in the literature.

3.4. Algorithm-based FD Selection Method

In contrast to the old, laborious, time-consuming ordinary FD selection method where portions of time series data are manually extracted and plotted, the algorithm-based method uses computer software that simultaneously calculates FD events, timing, and amplitude. The FD location software accepts CR raw data as input and is specifically designed to detect very small-amplitude events. The code is written in the open-source software R (R Core Team 2014) and was developed by Robert Gentleman and Ross Ihaka at University of Auckland. The algorithm can process both raw data downloaded directly from the source (without modification) and Fourier-transformed CR data. The machine searches for areas of dips or turning points in the CR data that indicate FD events. The program operates in two steps involving identification of FD amplitudes and determination of reduction timing.

The algorithm uses the average CR count over the selected period as the normalization threshold. The first step calculates the magnitude of each event, while the second determines the time of occurrence. This method is the most precise and efficient for identifying FDs because it overcomes limitations of manual techniques by filtering out spontaneous signals in CR data, such as diurnal CR anisotropies and low/high-frequency superimposed signals. The algorithm pinpoints the minimum depression in the data, computes the FD amplitude, and records the event time. These instructions execute in seconds, depending on data volume. Our group (see Okike & Umahi 2019b; Okike 2020b; Ugwoke et al. 2022a; Menteso et al. 2023) has extensively used this sophisticated method to analyze large data sets of both small and large-amplitude FDs. In line with the approach by Okike & Umahi (2019b), where a baseline threshold (BL) of BL < -0.5 was applied to identify small FDs, we adjusted the threshold to BL < -0.01 for detecting very small-amplitude FDs in this study.

From our data set, we identified 1956 small-amplitude FDs, comprising 766, 601, and 589 events across low, mid, and high-altitude NMs, respectively, as shown in Tables 8, 9, and 10.

4.1. Automatic Detection of Very Low Amplitude FDs

The identification of small FDs is a complex task requiring specialized expertise and careful analysis (Geppener & Mandrilava 2020). The authors argue that automating FD detection is highly complex, if not infeasible, due to intricate computational requirements (see also Geppener & Mandrilava 2021). Using neural networks of vector quantization (learning vector quantization, LVQ), they detected two small FDs that occurred on 2014 March 8–9 and 2013 April 13. Generally, automatic detection of both small and large FDs remains challenging for researchers in the field. Some investigators have introduced different versions of automatic detection codes (see Belov et al. 2018a; Light et al. 2020; Wang et al. 2023; Dumbovic et al. 2024; Mandrikova et al. 2025). However, these methods may be considered semi-automated, with FD magnitudes calculated using Equation (1), leading to case-event methods.

The first fully automated method (FAM) (see Okike & Menteso 2024a for more details on Forbush event detection) was published in 2019 (Okike & Umahi 2019c). The selection approach here is statistical—all FDs occurring within the period of interest are selected by the code in a fraction of a second. It is interesting to note that besides downloading CR data from a given repository, all other data processing and analysis, including calculation of all event magnitudes, timings, and cataloging (tabulating event magnitudes and timings), are performed by the code. Different subroutines performing various tasks are incorporated into the program.

Table 1 of Okike & Umahi (2019c) shows that FDs of low magnitudes (1%) as well as large events (>3%) were detected. The code was extended to other applications by Okike & Umahi (2019b), Okike (2019), and Okike & Umahi (2019a). A more sensitive and sophisticated version of the algorithm was developed later by Okike (2020c). Table 2 of that article shows that events of very low amplitude <1% were detected at the CLMX station. Table 4 shows that even magnitudes as low as 0.01% (see the event of 2003 March 10 at SOPO, S/N 17) were detected by the code. The magnitude of this event varies appreciably across different NMs. CLMX, Magadan (MGDN), and South Pole NMs respectively measured the intensity of this event as -0.62%, -0.37%, and 0.01%. It is interesting to note that stations like Potchefstroom (PTFM) and Inuvik (INVK) did not detect the event, probably because the event may appear in different forms (e.g., ordinary CR enhancement) at different NMs (Okike & Collier 2011). Okike (2020c) graphically illustrates CR intensity variations at different NMs during this event (2003 March 10) and the event of 2003 September 5 in panel a of Figure 1.

[Figure 1: see original paper]

Currently, only the IZMIRAN catalog contains FDs of very low magnitude (<1%). A quick look at the FEID shows that the GSM can detect FDs of very low magnitude down to 0.3%. Other existing FD lists focus on events of higher magnitude (>1%). In view of the predominant large-amplitude events in other FD catalogs, smaller amplitude FDs (0.01%) may appear as artifacts of the implemented code. Okike (2020c) presents Figure 1 to demonstrate that these are real Forbush events. The profiles of the 2003 March 10 event at SOPO and CLMX clearly depict CR time-intensity changes during an FD event. The four main parts of an FD (onset point, main phase, FD minimum, and recovery phase) are evident. The expected differences in flux variations at SOPO (lower intensity fluctuations) and CLMX (higher rigidity, lower intensity fluctuations) are also discernible in panel a of Figure 1.

It is quite obvious that this event is small—the normalized percentage variation of the raw data shows a very small reduction of <1%. Belov et al. (2018) believe it is not possible to detect an FD of such small amplitude using data from a single NM. Indeed, detection of such small events may be regarded as near-impossible without analytical data transformation (see also Oh et al. 2008). While Fourier harmonic decomposition (Bartels 1935; Okike 2020c) accounts for superposition tendencies in raw CR data, numerical filtering (Barouch & Burlaga 1975; Okike 2021a; Okike & Menteso 2024b) allows detection of small-amplitude FDs from data from separate NMs. With these detailed and rigorous analyses, the magnitudes of the 2003 October 10 event are respectively calculated as 0.01% and 0.62% for SOPO and CLMX data. Whereas the raw data suggest that intensity variation is higher at SOPO, the larger magnitude obtained for CLMX data indicates that signal superposition phenomena in raw CR data may play a complex role in Forbush event amplitude. Similar interesting observations apply in panel b of Figure 1.

To detect small FDs in the current work, the numerical filtering technique developed by Okike (2021a) is employed. This technique uses a high-pass filter of 360 days to remove long-term variations (11-year and longer terms) which are usually superposed on short-term variations like FDs and ground level enhancements (GLE) (see also Harrison & Ambaum 2011). For clarity, the raw CR and numerically filtered CR data are respectively presented in panels a and b of Figure 2. The dome shape in panel a represents the 11-year solar cycle (e.g., Menteso et al. 2023). This signal is completely absent in panel b. A comparison of the two panels shows that besides removing the solar cycle signal, the short-term intensity reductions in the two diagrams are visually unaltered, indicating the sinusoidal fidelity of the implemented high-pass filter. For instance, the largest event of 2003 October 31 maintains its ranking in both panels. Other known very large events include those of 2005 January 19 and 2005 September 13 (see Figure 3 of Okike et al. 2021). This event ranking is reflected in panel b. The two events in panel a that appear larger than the 2005 January and September events are influenced by the amplitude of the solar cycle signal, which appears maximum within that period. Their real amplitude in panel b shows they are not larger than the January and September 2005 events.

[Figure 2: see original paper]

After disentangling the contribution from the solar cycle signal, the output of the high-pass filter is passed to an FD-identification subroutine. The timing and magnitudes of small (blue circles) and large (red circles) FDs are calculated. The calculated event times and magnitudes are further passed to another subroutine—the cataloging code. This code tabulates and writes out the final output containing event dates and corresponding magnitudes of all small FDs to a file in the format displayed in Tables 8, 9, and 10. It should be noted that all these analyses are performed in very short time, depending on data volume and computer speed. Another advantage of the current program is that it can be applied to CR data from any type of detector.

It should be noted that the small event from 2003 September 5 illustrated in panel b of Figure 1 is also detected by the current code. Table 8 records the magnitude of this event as -0.65% and -0.91% at NWRK and OULU stations respectively. Table 9 registers its magnitude as -1.78% at the MOSC station. Other very small FDs (e.g., 0.04% for the 2003 March 20 event at OULU station) are also detected in the current work. The magnitude of this small FD at HRMS and NWRK is respectively -0.01% and -0.26%, as listed in Table 2. In Table 3, the magnitude of this event at APTY, MOSC, and NVBK is respectively -2.87%, 0.13%, and -1.28%. The lowest magnitude observed by the HRMS NM seems to reflect the comparatively low rigidity of the station.

This event was also detected by the GSM, with magnitude 3.3% on the same date (2003 March 20). Table 2 of Okike (2020c) records -3.65% (after adjusting for CR anisotropy) and -0.47% (from raw data) as the magnitude of this event. Okike (2020a) also indicates that at some stations, the same very small-amplitude event appears as large as -4.33%, illustrating high variability of CR flux across different geomagnetic cut-off rigidities. Before leaving this section, it is important to note that if any of the big or small events identified as FDs in Figure 2 are culled out and expanded as illustrated in Figure 1, each will show a full time profile of a Forbush event, including onset point, main phase, FD minimum, and recovery phase. The FD Location code treats the FD signal as a sinusoidal wave comprising two distinct parts—the decreasing phase (onset with main phase) and the increasing part (recovery phase). The program toggles the FD minimum point (the turning point or crest), which is the connecting point between the main and recovery phases of an event. Any intensity reduction lacking these defining characteristics of FDs will not be selected by the code. For example, square waveforms arising from data gaps are not picked by the code.

4.2. Comparison of FD Catalogs from Low, Mid, and High-Altitude NMs

Here we compare catalogs of small-amplitude FDs observed by the NMs to identify patterns and assess consistency in observations. This enhances our understanding of station sensitivity by revealing variations unique to each NM, ensuring more robust and accurate interpretations while uncovering underlying influences or biases that may affect catalog reliability. Percentage increase in FD magnitude at NMs may be used to compare sensitivity of NMs with different cut-off rigidity and altitude (Pyle 1997; Okike & Umahi 2019c; Okike & Nwuzor 2020). The sensitivity of each NM determines the level of CR modulation it observes. The accurate event magnitude that characterizes FDs selected by the FAM (see Okike & Menteso 2024a) allows comparison of the same event's magnitude at different stations.

Figure 3 shows the magnitude of five simultaneous small-amplitude FDs observed by six of the nine NMs. The six stations—APTY, MOSC, NVBK, CALG, CLMX, and ESOI—are indicated on the diagram. The magnitudes of each event at each station appear vertically for easy reference. For the first event from left

(FD on 2000 December 27), MOSC observed the highest intensity variation, followed by ESOI and CALG. The CLMX NM observed the least magnitude for this event. CALG and CLMX respectively recorded the highest and lowest intensity variation for the second event (FD on 2003 May 2). We have a completely different scenario for the third event (2003 July 30), where NVBK and APTY registered the largest and smallest intensity changes. For the fourth and fifth events (2005 March 21 and 2006 October 14), CALG and CLMX observed the largest and smallest CR modulation during the FD.

Stations like APTY (Rc = 0.57 GV, where Rc is cut-off rigidity) and OULU (Rc = 0.78 GV) are expected to show the highest intensity variation since they have the lowest geomagnetic cut-off rigidity in Table 1. Since this is not the case, it suggests that factors other than rigidity influence the level of CR modulations measured by an NM. Altitude is one such factor. CLMX (3400 m) and ESOI (2025 m) are located at the highest altitudes compared to others in Table 1. However, Figure 3 shows that the CALG station is on average more sensitive than other stations. This result is plausible since CALG has high altitude and moderate rigidity (Rc = 1.08 GV), serving as evidence that CR modulation at an NM is an interplay between altitude and Rc. Nevertheless, none of the stations consistently observed large or small intensity variations, indicating the spectacular locations and varieties of FDs (Belov 2009; Okike & Collier 2011; Ramirez et al. 2013). For completeness, we present a similar figure for large FDs in Figure 4. While CALG sees larger intensity variations across all three altitude bands, the number of simultaneous FDs would drastically reduce if we extended the analysis to all nine stations (see also Okike 2020c).

The values of small-amplitude FDs observed by low-altitude NMs range from 0.01% to 2.99%, 0.03% to 2.51%, and 0.04% to 2.64% with average values of 1.21%, 2.13%, and 1.87% for HRMS, NWRK, and OULU NMs, respectively. For mid-altitude NMs, FDs range from 0.03% to 2.95% for APTY, 0.06% to 2.94% for MOSC, and 0.03% to 2.94% for NVBK, with average values of 1.89%, 2.22%, and 1.97%, respectively. For high-altitude NMs, FD values range from 0.08% to 2.76% for CALG with an average of 1.39%, 0.07% to 1.02% for CLMX with an average of 0.32%, and 0.04% to 2.62% with an average value of 1.65% for ESOI.

4.3. Selection of Simultaneous FDs by Low, Mid, and High-Altitude NM Stations

FD simultaneity refers to simultaneous reduction in CR intensity at multiple locations on or near Earth's surface. This means that when FD events are observed at one location, they are also observed at other locations worldwide. To overcome the problem of visually comparing two or more FD lists in search of simultaneous or non-simultaneous events, we employed a simple coincident algorithm (coincident and non-coincident code). While the coincident algorithm handles simultaneous events, the non-coincident code identifies non-simultaneous FDs. The two algorithms scan two or more data sets according to a predefined criterion. Setting the identification threshold for FDs at CR < -3% effectively isolated large-magnitude events from the data set, while small-amplitude FDs were collated and used for this study. The script systematically scanned FD data sets from different altitude ranges and identified events with coinciding dates. Each identified FD was associated with its respective date of occurrence across the NMs under investigation. The investigation identified 80, 38, and 19 small-amplitude FDs occurring concurrently at low, mid, and high-altitude NMs, respectively. These specific dates were utilized as benchmarks for extracting interplanetary parameters and solar geomagnetic indices associated with the observed FD events. Data from non-relevant dates were excluded to ensure only temporally coincident parameters and indices corresponding to the FDs were retained. The compiled data sets encompassing FD events and their respective interplanetary and geomagnetic parameters are presented in Tables 2–4.

Figure 5 shows plots of small-amplitude FDs against event number for the 80, 38, and 19 simultaneous FDs. The significant difference in number of simultaneous FDs at different altitude bands is notable. Inspection of Table 1 suggests that differences in geomagnetic cut-off of the stations may be responsible. For example, several events detected as large FDs at CALG may appear as small FDs at the ESOI NM. While a few FDs are presented in Figures 3 and 4 across all altitudes, the intensity variations for all large FDs show that HRMS (Rc = 4.58 GV, Alt. = 26 m) and NWRK (Rc = 2.09 GV, Alt. = 50 m) see the least intensity variations, followed by CLMX. It should also be observed that the number of simultaneous FDs is larger for large FDs than for small-amplitude events, explaining why we have five events in Figure 3 for six stations and 13 FDs in Figure 4 for nine NMs. The number of events is grouped according to different altitude bands. It is clear from the first panel (low-altitude stations) that OULU observes the highest intensity variation among the three stations, agreeing with OULU's relatively low rigidity. The intensity variations at the mid-altitude band are similar for APTY, MOSC, and NVBK, contrary to expectation—APTY with the lowest rigidity should show higher intensity variations. The high-altitude NMs show that ESOI sees the highest intensity variations for some FDs, but there are also cases where ESOI observed lower intensity variations than CALG and CLMX. Considering the high rigidity of ESOI, some events registering higher intensity variations at ESOI deserve more attention. Speculations suggest this may be due to varieties of FDs (Belov 2009), technical characteristics of the ESOI NM, weather conditions, or other operational features (Vaisanen et al. 2021). However, no definitive conclusion can be reached until ESOI data from other CR repositories are used to validate ESOI data from the IZMIRAN database.

As noted in Section 4.1, the weakest simultaneous FD event occurred on 2003 March 20, as detected by the three low-altitude NMs. The algorithm obtained 0.01%, 0.26%, and 0.04% for HRMS, NWRK, and OULU stations, respectively. The second weakest FD recorded by our algorithm was on 2000 March 30, with values of 0.38%, 0.03%, and 0.54% for HRMS, NWRK, and OULU stations, respectively. The FD observed by NWRK has the smallest values compared to those observed by HRMS and OULU. The third weakest FD event was selected by our algorithm for HRMS, NWRK, and OULU on 2003 July 27, with magnitudes of 0.06%, 0.04%, and 0.13%, respectively. NWRK has the highest FD magnitude on this day, with HRMS recording the lowest of the three low-altitude stations. The event on 2006 June 26 has the highest of the simultaneous FDs with magnitudes 1.88% (HRMS), 1.58% (NWRK), and 2.99% (OULU).

For mid-altitude NMs, our algorithms detected the weakest simultaneous FDs on 2003 July 30 with magnitudes of 0.03%, 0.68%, and 1.13% for APTY, MOSC, and NVBK, respectively, with APTY recording the smallest FD. The second smallest FDs were recorded on 2000 October 1 with magnitudes of 0.40%, 0.06%, and 0.03% for APTY, MOSC, and NVBK, respectively. NVBK has the smallest FD amplitude on this day, while APTY has the largest. On 2003 February 3, the largest simultaneous FDs were detected, with APTY recording 2.95% while MOSC recorded the smallest (1.70%) compared to NVBK (2.10%).

For high-altitude NMs, 19 simultaneous small-amplitude FDs were observed. The ESOI NM station recorded the smallest magnitude of 0.04% while CLMX and CALG have 0.11% and 0.60%, respectively, as observed on 2003 July 30. The second smallest observed FDs by these NMs occurred on 2001 July 4 with magnitudes of 1.54%, 0.32%, and 0.05% for CALG, CLMX, and ESOI stations, respectively. The largest observed small-amplitude FDs by the stations were on 2004 July 20, which were 2.76%, 0.15%, and 0.11% for CALG, CLMX, and ESOI NMs, respectively.

These highlighted spectacular events provide information for readers to follow through other events on different days as recorded by these stations. However, differences in FD magnitudes observed at the three NMs indicate the level of Forbush event manifestations and their location-dependent effects (e.g., Belov 2009). The event observed on 2000 March 30 by our coincident algorithm is remarkable. Some authors, for example, Oh et al. (2008) and Kristjansson et al. (2008), obtained FD magnitudes of 2.33%, 2.76%, and 2.34% for this event using MGDN, OULU, and INVK, which are located at very low altitudes of 220 m, 0 m, and 21 m, respectively. Similarly, the IZMIRAN team, using their techniques, obtained a value of 2.60% on 2000 October 5 at the onset time.

4.4. Forbush Decreases and Solar-terrestrial Parameters

This section uses correlation analysis to quantify relationships between solar-terrestrial parameters and CR intensity variations to examine effects of these parameters on FDs. This method can reveal patterns and assess the degree of correlation between solar-terrestrial factors and FDs. Pearson's correlation theory, which offers numerical evaluation of association strength, is used to analyze data. According to some authors (see Press et al. 1994; Pavlidou et al. 2012; Iyida et al. 2022), product-moment correlation coefficient (cc) can evaluate correlation magnitude, and Pearson's correlation coefficient is computed at a 5% significance level using:

$$cc = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where X_i represents FDs from the NMs while Y_i represents solar-terrestrial variables. The composite scatter plots illustrating relationships between small-amplitude FDs observed at low-altitude NMs and solar-terrestrial variables are presented in Figure 6. Intensity variability across these three altitude bands is easily observable from the graphs. OULU is more sensitive among the three low-altitude stations (HRMS and NWRK). Identifying more sensitive NMs among APTY, MOSC, and NVBK at the mid-altitude band is more difficult. CALG and ESOI observe higher intensity variation at the high-altitude band.

Analysis of data from the three stations reveals consistent trends in interactions between these variables and small-amplitude FDs. Before presenting detailed results for small-amplitude FDs, we show relations for large FDs and solar-terrestrial variables. Simple linear regression analysis indicates varying degrees of correlation between FDs from both individual and combined NMs with correlation coefficients (cc) evaluated using Equation (2) (see Tables 5–7). Besides HRMS, which registers insignificant ccs with SWS, Kp, Dst, and Ap, large FDs at other stations show significant relations with solar/geomagnetic variables. These unexpected relations for large FDs at HRMS deserve more attention, especially as small-amplitude FDs from the same station indicate significant ccs with solar/geomagnetic data. Nevertheless, Table 1 shows that HRMS has peculiar physical characteristics—it is, for example, the only high-rigidity station in Table 1 (second to ESOI) located at low altitude. The impact of this on HRMS data calls for detailed inspection of CR measurements at the station. Data quality and consistency checks (see Vaisanen et al. 2021) should be conducted for HRMS before reaching firm conclusions about these results, which we plan to address in future work.

Figures 6–8 present scatter plots of small-amplitude FDs versus solar-terrestrial variables for low-, mid-, and high-altitude NMs, respectively, with ccs and t-values indicated. The plots reveal negative correlation between small FDs and IMF, SWS, and some geomagnetic indices (Ap and Kp), while the relationship with the Dst index is positive. Interestingly, these relations vary appreciably across different altitude bands and NM stations. These results serve as evidence that small FDs are location-dependent CR phenomena, as previously suggested by Belov (2009), Oh et al. (2008), and Okike & Collier (2011). As a result of pronounced effects that other superposed CR signals may have on weak FDs, CR intensity changes during small Forbush events may vary significantly between locations. These unpredictable intensity fluctuations seem reflected in the correlation results of Figures 6–8. The trend across stations suggests shared influence of these parameters on FDs, indicating that small-amplitude FD events may be related to a combination of geomagnetic activity and SWS on individual NMs. Consequently, intensity of solar-terrestrial parameters contributes significantly to small FD occurrence. The relations between small FDs and solar/terrestrial parameters vary between locations and altitude bands. While all variables at low-altitude band (Figure 6) show statistically significant relations with small FDs (except at OULU), only a few variables (e.g., IMF and Ap at CLMX at high-altitude band) show significant ccs with FDs at mid- and high-altitudes. These results suggest that understanding factors influencing small-amplitude FDs at different locations deserves more detailed attention. Rather than individual interplanetary/terrestrial agents playing significant roles, a combination of these parameters may be important. Thus, the two-variable regression model employed here may not be suitable for analyzing influence of these parameters on small FDs. The multivariable regression model employed by Okike & Alhassan (2022b) may be more useful.

[Figure 6: see original paper] [Figure 7: see original paper] [Figure 8: see original paper]

5. Discussion and Conclusion

NM measurements are notably robust and reliable compared to other CR detectors and satellite observations. Consequently, sporadic CR signals like FDs are well-suited for timing solar phenomena: CMEs, interplanetary shocks (IPs), and ejecta. However, detection, precise magnitude estimation, and accurate timing of FDs remain challenging. The reliability of FD-based analyses, such as those linking FDs with CMEs, hinges critically on accuracy and comprehensiveness of the FD catalogs utilized. This study emphasizes the importance of developing accurate FD catalogs and encourages rigorous comparison of existing event catalogs before conducting subsequent analyses. The detailed investigations in this work highlight complexities faced by astrophysicists in constructing reliable FD catalogs.

Traditional algorithm-based methods for identifying FDs are often insufficient to address these challenges, particularly when raw CR data are influenced by superposed signals such as CR anisotropy and the 11-year solar cycle. Failure to account for these effects introduces significant biases into FD catalogs. This study demonstrates that signal decomposition is essential for isolating FD signals from other components. The algorithms introduced here apply standardized, objective criteria consistently across all events, in contrast to manual or semi-automated methods prone to subjective bias. Unlike traditional approaches that extract event profiles solely from onset to FD minimum, this methodology eliminates biases and ensures events are neither missed nor mischaracterized. Furthermore, these algorithms are designed to process large volumes of CR data rapidly and systematically, enabling scalability as monitoring stations and data resolution increase. This methodology allows other researchers to replicate and extend FD catalogs for different periods or stations, aligning with best practices for reproducible scientific research.

While deploying the most advanced and precise FD selection technique, we identified a large sample of small-amplitude FDs from nine NM stations spanning 1999–2006. Using this methodology, a total of 1959 small-amplitude FDs were detected, with stations grouped into low, mid, and high-altitude categories. FD distribution among these groups comprised 766, 601, and 589 events, respectively. Additionally, a simple coincident detection algorithm identified FDs simultaneous across each NM group, finding 80, 38, and 19 simultaneous small-amplitude FDs in low, mid, and high-altitude NMs, respectively. This coincident algorithm effectively demonstrated that simultaneous FD detection across NMs is obtainable. Assuming FDs are a global phenomenon, effects of interplanetary parameters on CR intensity at one station should mirror those at others during simultaneous events.

The ccs between FDs and solar/terrestrial parameters presented here suggest these relations should be investigated using a multivariate regression model. Some interplanetary data like SWS and IMF are factors that mutually influence CR intensity modulations. Finally, reliability of studies examining relationships between solar events, space weather parameters, and FDs fundamentally depends on accuracy of the FD catalog used. To enhance robustness of investigations into FDs and their terrestrial impacts, future research should focus on detailed quantitative analyses of effects of superposed signals on magnitude, timing, and frequency of FD events. This approach will ensure more elaborate and meaningful interpretations of connections between FDs and solar-terrestrial interactions. Additionally, catalogs of simultaneous small FDs in different altitude ranges could be used for further investigations.

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