Research in Astronomy and Astrophysics, 25:065006 (29pp), 2025 June

https://doi.org/10.1088/1674-4527/adca92
CSTR: 32081.14.RAA.adca92

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

E. U. Iyida[1,2,3], O. Okike[2,4], I. O. Eya[2,3], E. Proven-Adzri[1], D. Y. Klutse[1], F. M. Menteso[2,3], C. J. Ugwu[5], D. C. Obiegbuna[6], P. I. Akande[4], R. E. Ugwoke[7], J. A. Alhassan[2,3], A. E. Chukwude[2,3], and P. A. Nwofe[4]
[1] Ghana Radio Astronomy Observatory, Ghana Space Science and Technology Institute, P.O. Box LG 80, Legon, Accra, Ghana; uzochukwu.iyida@unn.edu.ng
[2] Astronomy & Astrophysics Research Group, Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria
[3] Department of Physics and Astronomy, Faculty of Physical Sciences, University of Nigeria, Nsukka, Nigeria
[4] Department of Industrial Physics, Ebonyi State University, Abakaliki, Nigeria
[5] Department of Mathematical Sciences, University of South Africa, Florida Park, 1709, Roodepoort, South Africa
[6] Department of Science Laboratory Technology, Faculty of Physical Sciences, University of Nigeria, Nsukka, Nigeria
[7] Department of Physics, Federal University of Technology, Owerri, Nigeria
Received 2024 December 19; revised 2025 April 1; accepted 2025 April 7; published 2025 June 2

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 the cosmic ray (CR) counts observed by neutron monitors (NMs) on the 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 the magnitude defined relative to the initial CR count rate and the sign typically chosen based on the 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, the solar-terrestrial variables have interrelations with the interplanetary activity that can significantly influence the motion (as well as the intensity) of

CRs as they propagate from space to the 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 the Earth's magnetic field, causing deflections of the CRs away from the Earth, thereby reducing the intensity of CRs reaching the Earth's surface (Badruddin & Singh 2006). Some other parameters that influence the IMF to usurp the intensity of the CRs are the 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 the Earth's magnetosphere, and analyzing them along with the CR modulations allows scientists to gain a deeper understanding of the characteristics and dynamics of interplanetary disturbances.

FDs have been studied for over 80 yr, 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 the interactions of the 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 the creation of reliable FD records is a challenging task. A review of the literature indicates that the 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 the inherent complexity of FDs, variations in detection methodologies, or a combination of both factors. Pittock (1978) provided a critical review that highlights key issues in earlier studies that aimed to explore long-term Sun-Earth connections. His review serves as a guide for more research by identifying problems like data smoothing, selective use of data in space and time, and the improper application of statistics to data sets. A further survey of CR intensity variations reveals a scarcity of published catalogs of small-amplitude FDs. Among catalogs obtained from NMs are those from 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 $\leqslant 5\%$, with 14 out of 65 events meeting the small-amplitude FD classification criterion. The bias toward the small FD selection method has been attributed to CR diurnal anisotropy, which significantly influences and complicates their detection. An approach that involves 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, their team could detect low amplitude FDs of the order of 0.3%–0.5% (Belov et al. 2018a), and it is clear that the current algorithm can detect as low as 0.01% low amplitude events. 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 a 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 the complex interrelationships within the Sun-Earth space. In this paper, while we aim to relate certain connections between FDs and solar-terrestrial interactions, with the key focus being 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, the methods of event selection and cataloging remain a critical challenge 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) also have provided significant improvements but still encounter limitations in the detection of small-amplitude FDs with their lowest detected value 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. So, the comprehensive event catalogs generated by this algorithm have enabled a robust quantitative investigation of the relationship between small-amplitude FDs and solar-terrestrial

Table 1
Properties of the NMs

Class	Short form	Lon. (°)	Lat. (°)	Altitude (m)	Rigidity (GV)
Low-altitude	HRMS	19.20	−34.4	26	4.58
	NWRK	−75.8	39.7	50	2.09
	OULU	25.5	65.0	0	0.78
Mid-altitude	APTY	33.30	67.5	177	0.57
	MOSC	37.3	55.5	200	2.43
	NVBK	83.0	54.8	163	2.87
High-altitude	CALG	−114.1	51.1	1,128	1.08
	CLMX	−106.2	39.4	3,400	2.99
	ESOI	35.8	33.3	2,025	10.80

parameters, paving the way for deeper insights into their role in CR modulation and space weather dynamics.

3. Sample Selection and Methodology

3.1. Sample Description

For the daily averaged CR intensity data, we considered the 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.snasa.gov/ow.html. The daily averaged CR data were used to minimally reduce the effects of the CR diurnal anisotropy.

3.2. Tools and Methodology

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 a restoration of typical interplanetary conditions. A non-algorithmic method is often used to analyze these stages, involving multiple steps. These include selecting data, plotting segments of the CR data, identifying significant drops, calculating the time and magnitude of the decrease, and comparing the 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)

$$\mathrm{FDs}(\%) = \left(\frac{|C_i - C_m|}{C_m}\right) \times \frac{100}{1}, \tag{1}$$

with C_i being the daily or hourly CR intensity while C_m is the average intensity variation. The C_m can vary or not depending on the choice of the researcher. 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 that researchers must calculate the magnitude and event time separately, leading to results that depend on the researcher. The use of the equation implies that different researchers employ different onset days to arrive at different magnitudes for the same event. Quite a few of the existing FDs could be detected by this method. This is one of the reasons 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 the time series data are manually extracted and plotted, the algorithm-based method uses computer software that simultaneously calculates the FD events, the time, and the 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 the University of Auckland. The algorithm can process both the raw data that are downloaded directly from the source (without any modification) and the Fourier-transformed CR data. The machine searches for areas of drips or turning points in the CR data that indicate FD events. The program comes in two steps that involve the identification of the amplitude of the FDs and the determination of the time of the reduction.

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 the limitations of manual techniques by filtering out spontaneous signals in the CR data, such as diurnal CR anisotropies and low and high-frequency superimposed signals. The algorithm pinpoints the minimum depression in the data, computes the FD amplitude, and records the event time. These instructions are executed in a matter of seconds, depending on the volume of the data. Our group (see Okike & Umahi 2019b; Okike 2020b; Ugwoke et al. 2022a; Menteso et al. 2023, for example) 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 (B_L) of $B_L \leqslant -0.5$ was applied to identify small FDs, we adjusted the threshold to $B_L \leqslant -0.01$ 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, respectively.

4. Data Analysis and Results

4.1. Automatic Detection of Very Low Amplitude FDs

The identification of small FDs is a complex task that requires specialized expertize and careful analysis (Geppener & Mandrilava (2020). The authors argue that automating the detection of FDs is highly complex, if not infeasible, due to the intricate computational requirements involved (see also Geppener & Mandrilava 2021). Using the neural networks of vector quantization (learning vector quantization, LVQ), they detected two small FDs that happened on 2014 March 8–9 and 2013 April 13. Generally, automatic detection of small as well as big FDs remains a challenging task among 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, for example). However, these methods may be considered semi-automated, as the FD magnitudes are calculated using Equation (1), leading to the existence of 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 the FDs that happened within the period of interest are selected by the code in a fraction of a second. It is interesting to note that besides downloading the CR data from a given repository, all other data processing and analysis, including calculation of all the event magnitudes, timings and catalogings (tabulating event magnitudes and timings) are performed by the code. Different subroutines that

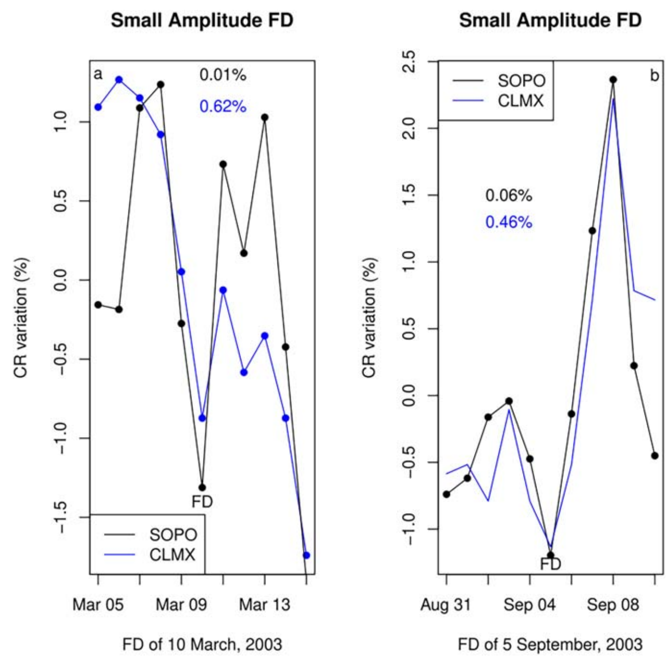

Figure 1. Graphical illustration of CR intensity variations for the small-amplitude FDs of 2003 March 10 (panel (a)) and 2003 September 5 (panel (b)) (from Okike 2020c). Note that the intensity variations are higher at SOPO than at CLMX, reflecting rigidity differences.

perform different tasks are incorporated into the program. Table 1 of Okike & Umahi (2019c) shows that FDs of low magnitudes (≈1%) as well as big 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 the article shows that events of very low amplitude <1% were detected at the CLMX station. Table 4 of the article 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, measure the intensity of this event as −0.62, −0.37, and 0.01%. It is interesting to note that stations like Potchefstroom (PTFM) and Inuvick (INVK) did not detect the event. This is probably because the event may appear in different forms (e.g., ordinary CR enhancement) at different NMs (Okike & Collier 2011). Okike (2020c) graphically illustrates the 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.

Currently, only the IZMIRAN catalog contains FDs of very low magnitude (<1%). A quick look at the FEID[8] shows that

[8] Forbush-effects and interplanetary disturbances, https://spaceweather.izmiran.

the GSM can detect FDs of a very low magnitude of 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 look like artifacts of the implemented code. Okike (2020c) presents Figure 1 to show that these are real Forbush events. The profiles of the event of 2003 March 10 at SOPO and CLMX clearly depict the CR time-intensity changes during an FD event. The four main parts of an FD (onset point, main phase, FD minimum and the recovery phase) are evident. The expected differences in the flux variations at SOPO (lower rigidity, higher 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 presented here shows a very small reduction of <1%. Belov et al. (2018) believe that it is not possible to detect an FD of such small-amplitude using data from a single NM. Indeed, the detection of such small events may be regarded as a near-impossible task without some analytical data transformation (see also Oh et al. 2008). While Fourier harmonic decomposition (Bartels 1935; Okike 2020c) accounts for superposition tendencies in the raw CR data, numerical filtering (Barouch & Bdoiaga 1975; Okike 2021a; Okike & Menteso 2024b) allows for detection of small-amplitude FDs from the data from separate NMs. With these detailed and rigorous analyses, the magnitudes of the event of 2003 October 10 are respectively calculated as 0.01 and 0.62% for SOPO and CLMX data. Whereas the raw data suggest that the intensity variation is higher at SOPO, the larger magnitude obtained for CLMX data is an indication that signal superposition phenomena in raw CR data may play a complex role in the amplitude of Forbush events. Similar interesting observations are applicable in panel b of Figure 1.

In order 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 the long-term variations (11 yr, and longer terms) which are usually superposed on short-term variations like FDs and ground level enhancement (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 is representative of the 11 yr solar cycle (e.g., Menteso et al. 2023). The 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. This is a pointer to the sinusoidal fidelity of the implemented high-pass filter. For instance, the largest event of 2003 October 31 maintains their ranking in the two panels. Other events that are known to be very large are 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

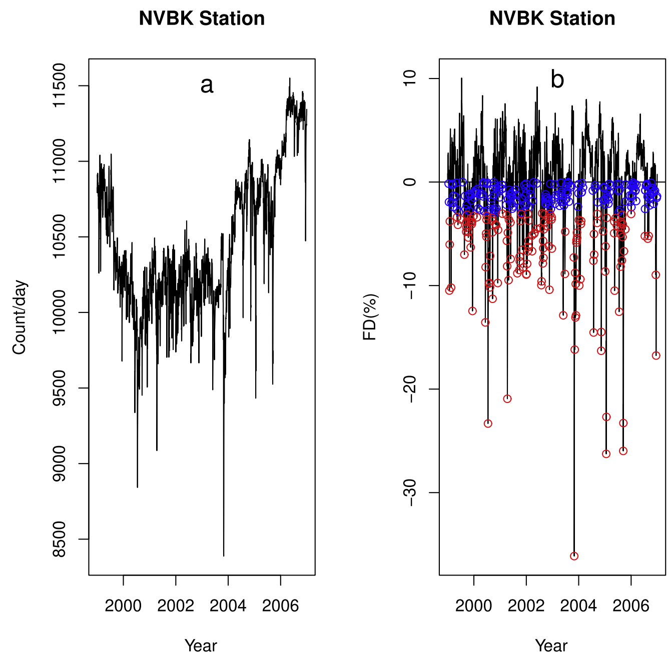

Figure 2. Raw (panel a) and numerically filtered (panel b) CR data. Blue and red circles are respectively small and large FDs.

events in panel a that seem to be larger than the events of 2005 January and September are influenced by the amplitude of the solar cycle signal which looks maximum within that period. Their real amplitude in panel b shows they are not larger than the events of January and September 2005. After disentangling the contribution from the solar cycle signal, the output of the high-pass filter is passed onto an FD-identification subroutine. The timing and magnitudes of the small (blue circles) and the large (red circles) FDs are calculated. The calculated event time and magnitude are further passed onto another subroutine, the cataloging code. This code tabulates and writes out the final output containing the event dates and the corresponding magnitude of all the 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 a very short time, depending on the volume of data and the speed of the computer. 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 this 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 the event from 2003 September 5 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 event of 2003 March 20 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,

Table 2
Simultaneous Small-Amplitude FDs Observed by Low-Altitude NMs and the Associated Solar-terrestrial Parameters

No	Date	FDs_{HRMS} (%)	FDs_{NWRK} (%)	FDs_{OULU} (%)	IMF (nT)	SWS (km s^{-1})	Kp	Dst	Ap
1	1999-03-06	−0.16	−0.34	−1.17	6.8	475	27	−27	13
2	1999-03-24	−1.31	−1.27	−2.07	5.5	411	7	2	
3	1999-04-16	−0.42	−0.50	−0.52	7.8	424	30	12	18
4	1999-05-10	−1.35	−1.32	−1.57	5.2	419	10	5	
5	1999-05-24	−1.44	−1.38	−2.04	7.0	435	23	21	11
6	1999-08-25	−2.09	−1.63	−2.61	7.7	538	20	−15	9
7	1999-09-16	−1.29	−1.63	−2.03	6.2	572	40	−46	31
8	1999-09-29	−0.38	−0.81	−1.25	6.8	539	37	−30	25
9	1999-11-12	−0.62	−0.63	−1.55	4.9	554	23	−34	10
10	1999-11-20	−1.20	−1.40	−2.38	8.1	443	20	−16	9
11	1999-12-03	−0.95	−0.97	−2.56	12.7	425	30	−7	16
12	2000-02-12	−0.87	−0.68	−2.33	14.7	553	50	−76	60
13	2000-03-01	−0.36	−0.09	−0.66	7.6	480	33	−22	21
14	2000-03-30	−0.38	−0.03	−0.54	5.2	446	27	−2	12
15	2000-04-07	−0.18	−0.83	−1.82	9.9	573	50	−162	74
16	2000-05-03	−0.86	−0.66	−0.66	6.2	520	30	−12	17
17	2000-05-08	−1.61	−1.13	−1.30	9.8	360	10	19	4
18	2000-05-30	−0.90	−0.61	−1.17	6.2	617	37	−29	22
19	2000-06-24	−1.95	−1.59	−2.79	9.0	551	27	−20	15
20	2000-06-26	−1.88	−1.58	−2.99	11.5	512	43	−36	40
21	2000-07-11	−1.65	−1.46	−2.43	13.7	458	43	13	34
22	2000-09-03	−0.21	−0.52	−0.19	6.8	413	17	−14	7
23	2000-09-09	−0.94	−0.99	−1.91	4.4	425	13	−9	5
24	2000-09-15	−1.61	−1.31	−1.82	6.7	363	20	4	12
25	2000-11-11	−1.55	−1.35	−2.58	7.2	804	30	−35	16
26	2000-11-16	−0.77	−0.53	−1.08	4.8	391	7	2	3
27	2000-12-27	−0.60	−0.17	−1.57	7.7	390	20	−1	8
28	2001-08-18	−1.02	−1.30	−1.70	11.8	518	27	−43	15
29	2001-09-07	−0.38	−0.18	−0.38	6.1	369	7	6	3
30	2001-10-09	−1.42	−0.62	−2.18	8.3	445	30	−37	18
31	2001-12-06	−0.83	−0.84	−1.21	6.4	432	27	−20	11
32	2001-12-17	−0.75	−0.65	−1.04	8.8	471	30	−30	16
33	2002-01-21	−0.79	−1.50	−0.73	7.9	452	27	−10	11
34	2002-03-30	−0.39	−0.39	−0.37	11.6	521	33	−5	20
35	2002-04-20	−1.48	−1.62	−2.46	10.1	563	53	−106	70
36	2002-05-23	−1.78	−1.60	−2.19	17.0	606	47	−38	78
37	2002-05-28	−0.80	−0.77	−0.90	5.6	662	23	−26	9
38	2002-07-18	−0.62	−0.60	−1.00	5.7	441	13	−8	5
39	2002-07-23	−1.52	−1.19	−1.99	4.8	472	30	−12	17
40	2002-09-08	−1.32	−1.56	−2.72	11.7	479	33	−101	36
41	2002-10-01	−0.41	−0.71	−1.11	19.5	388	50	−100	67
42	2002-10-03	−1.00	−0.96	−1.75	11.5	464	47	−78	45
43	2002-10-21	−2.51	−1.58	−2.72	5.8	571	20	−18	8
44	2003-01-27	−0.24	−0.35	−1.92	8.7	507	20	−5	10
0 45	2003-02-02	−0.17	−0.58	−1.96	11.4	516	53	−56	52
46	2003-02-18	−0.52	−1.46	−1.60	8.5	652	33	−1	21
47	2003-03-20	−0.01	−0.26	−0.04	10.6	694	37	−29	25
48	2003-04-11	−1.17	−1.23	−1.53	5.1	663	27	−15	14
49	2003-05-09	−0.31	−0.89	−0.45	8.3	791	40	−27	31
50	2003-06-16	−0.77	−0.73	−0.84	10.2	514	43	−27	40
51	2003-07-03	−0.72	−0.99	−1.56	8.6	539	30	−6	19
52	2003-07-27	−0.06	−0.40	−0.13	8.8	677	33	−36	22
53	2004-07-20	−0.08	−0.24	−0.03	6.0	527	20	−4	8
54	2004-08-17	−0.35	−0.11	−0.20	9.1	332	20	−8	10
55	2004-09-15	−1.51	−1.39	−2.47	4.9	549	27	−23	14
56	2004-09-22	−0.76	−0.62	−1.78	7.2	477	27	−11	16
57	2004-12-06	−0.25	−0.34	−1.43	9.7	424	33	−26	20
58	2004-12-29	−0.52	−0.34	−1.07	7.6	429	30	−34	16

Table 2
(Continued)

No	Date	FDs_{HRMS} (%)	FDs_{NWRK} (%)	FDs_{OULU} (%)	IMF (nT)	SWS (km s^{-1})	Kp	Dst	Ap
59	2005-01-28	−0.93	−1.69	−1.62	7.4	379	17	−3	6
60	2005-01-31	−0.40	−1.69	−1.00	7.8	611	30	−17	19
61	2005-02-02	−0.61	−1.54	−1.13	6.3	507	20	−11	9
62	2005-02-24	−0.33	−0.19	−0.59	10.5	394	13	11	5
63	2005-05-30	−0.86	−0.69	−2.19	15.7	469	57	−73	90
64	2005-06-17	−0.92	−0.71	−1.33	7.2	573	27	−27	14
65	2005-07-11	−0.51	−0.49	−0.63	8.7	414	33	−45	21
66	2005-07-13	−1.17	−1.37	−1.93	6.9	560	40	−32	31
67	2005-07-30	−0.96	−0.82	−1.02	5.3	507	23	−12	10
68	2005-08-03	−1.31	−1.34	−2.00	5.0	449	20	−9	9
69	2005-09-03	−1.58	−1.30	−2.95	6.9	596	37	−51	27
70	2006-01-05	−0.61	−0.46	−1.85	5.1	340	10	2	3
71	2006-01-10	−0.12	−0.11	−0.65	5.8	292	3	3	1
72	2006-07-17	−0.97	−0.78	−1.34	3.1	353	7	−4	3
73	2006-07-28	−0.42	−0.72	−0.68	5.9	612	30	−29	25
74	2006-08-08	−0.50	−0.48	−1.03	4.1	602	23	−27	10
75	2006-08-30	−1.47	−1.35	−1.85	4.4	500	17	−5	6
76	2006-09-18	−0.77	−0.66	−1.37	5.9	568	37	−22	23
77	2006-09-25	−0.41	−0.26	−0.60	3.8	593	20	−21	8
78	2006-11-11	−0.78	−0.54	−2.20	4.6	610	37	−30	21
79	2006-11-15	−0.94	−0.56	−2.10	5.9	356	17	−14	7
80	2006-11-29	−0.31	−0.24	−0.78	10.9	440	17	−8	7

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. Its magnitude in the field is 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 the raw data) as the magnitude of this event. Okike (2020a) also indicates that there are stations where the same very small-amplitude appears as large as −4.33%. This illustrates the high variability of CR flux across different geomagnetic cut-off rigidities. Before leaving this section, it is important to note that if either of the big or other small events identified as FDs in Figure 2 are culled out and expanded as illustrated in Figure 1, each of them will show a full time profile of a Forbush event, including onset point, main phase, FD minimum and the recovery phase. The FD Location code treats the FD signal as a sinusoidal wave comprising two distinct parts—the decreasing phase (onset with the main phase) and the increasing part (the recovery phase). The program toggles the FD minimum point (the turning point or the crest), which is the connecting point between the main and the recovery phases of an event. Any intensity reduction without these defining characteristics of FDs will not be selected by the code. For example, square waveforms arising in the data due to data gaps are not picked by the code.

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

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

Table 3
Simultaneous Small-Amplitude FDs by Mid-altitude NMs and the Associated Solar-terrestrial Parameters

No	Date	FDs_{APTY} (%)	FDs_{MOSC} (%)	$FDs_{NV\ BK}$ (%)	IMF (nT)	SWS (km s^{-1})	Kp	Dst	Ap
1	1999-03-19	−2.09	−2.60	−2.41	5.4	377	17	−7	6
2	1999-10-12	−2.54	−2.92	−1.39	7.3	578	50	−48	46
3	2000-03-24	−1.69	−1.55	−2.69	6.6	649	23	−3	11
4	2000-05-08	−1.93	−1.02	−1.38	9.8	360	10	19	4
5	2000-10-05	−0.40	−0.06	−0.03	13.4	486	67	−138	116
6	2000-10-07	−0.94	−0.76	−1.25	3.8	391	10	−36	4
7	2000-11-01	−1.03	−2.47	−2.94	6.3	425	17	−16	7
8	2000-12-27	−1.31	−2.75	−1.47	7.7	390	20	−1	8
9	2001-04-22	−0.52	−1.75	−1.65	11.8	360	43	−55	37
10	2001-08-03	−0.85	−1.63	−0.73	7.2	405	27	0	12
11	2001-12-07	−1.49	−2.30	−2.21	6.7	459	17	−19	6
12	2001-12-17	−1.26	−1.34	−1.34	8.8	471	30	−30	16
13	2002-09-24	−1.76	−2.90	−2.04	9.3	376	7	−8	2
14	2002-10-01	−0.38	−1.14	−1.46	19.5	388	50	−100	67
15	2002-10-03	−1.71	−1.19	−2.12	11.5	464	47	−78	45
16	2002-10-25	−1.98	−1.53	−1.58	6.8	689	43	−68	39
17	2002-11-03	−2.16	−1.37	−1.82	9.7	478	43	−65	35
18	2003-02-03	−2.95	−1.70	−2.10	8.9	484	37	−42	22
19	2003-03-20	−2.87	−0.13	−1.28	10.6	694	37	−29	25
20	2003-05-02	−1.20	−1.32	−1.13	4.7	583	27	−24	15
21	2003-05-09	−0.77	−1.70	−1.91	8.3	791	40	−27	31
22	2003-06-10	−1.15	−2.20	−2.26	6.3	695	37	−21	24
23	2003-07-30	−0.03	−0.68	−1.13	6.9	763	40	−27	27
24	2003-08-18	−0.35	−2.43	−1.89	18.5	468	67	−108	108
25	2004-09-22	−2.53	−0.66	−1.95	7.2	477	27	−11	16
26	2005-01-31	−2.64	−2.02	−1.23	7.8	611	30	−17	19
27	2005-02-02	−2.49	−1.72	−1.56	6.3	507	20	−11	9
28	2005-02-19	−1.76	−1.30	−2.09	6.4	497	30	−25	16
29	2005-03-21	−0.12	−0.54	−0.35	7.2	444	17	−13	8
30	2005-07-13	−2.81	−2.35	−2.89	6.9	560	40	−32	31
31	2005-07-30	−1.40	−1.97	−2.68	5.3	507	23	−12	10
32	2005-10-17	−0.10	−0.70	−0.24	6.0	372	27	−24	14
33	2006-07-14	−2.83	−2.94	−2.60	6.1	428	23	−8	13
34	2006-10-01	−0.59	−0.56	−1.22	6.4	504	33	−36	23
35	2006-10-14	−0.12	−0.28	−0.59	6.2	539	37	−36	23
36	2006-11-11	−1.22	−1.51	−2.10	4.6	610	37	−30	21
37	2006-11-15	−1.74	−1.34	−0.93	5.9	356	17	−14	7
38	2006-11-29	−0.29	−1.61	−0.84	10.9	440	17	−8	7

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). NVBK and APTY, respectively, registered the largest and smallest intensity changes at the time of this event. 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 ($R_c = 0.57$ GV, where R_c is cut-off rigidity) and OULU ($R_c = 0.78$ GV) are expected to see the highest intensity variation since they have the least geomagnetic cut-off rigidity in Table 1. Since this is not the case, it is suggestive of the fact that there are factors other than rigidity that 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, on average, is more sensitive than the other stations. This result is plausible since CALG has high-altitude and moderate rigidity ($R_c = 1.08$ GV). It may serve as evidence that the CR modulation of an NM is an interplay between the altitude and R_c. Nevertheless, none of the stations consistently observed large or small intensity variations. This is an indicator of the spectacular intensity variability at different locations and varieties of FDs (Belov 2009; Okike & Collier 2011; Ramirez et al. 2013).

For completeness, we present another result similar to Figure 3 but for large FDs in Figure 4. While CALG sees larger

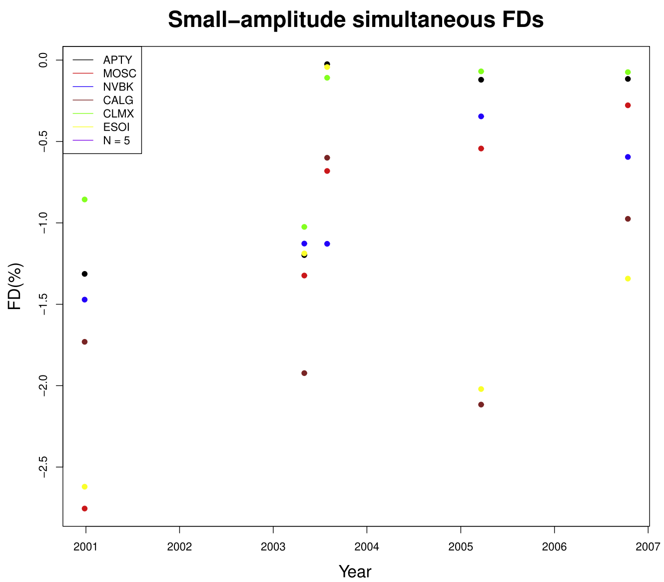

Figure 3. Variation of small-amplitude FDs across many altitude bands. $N = 5$ stands for the number of small FDs that are simultaneously seen by the six NMs.

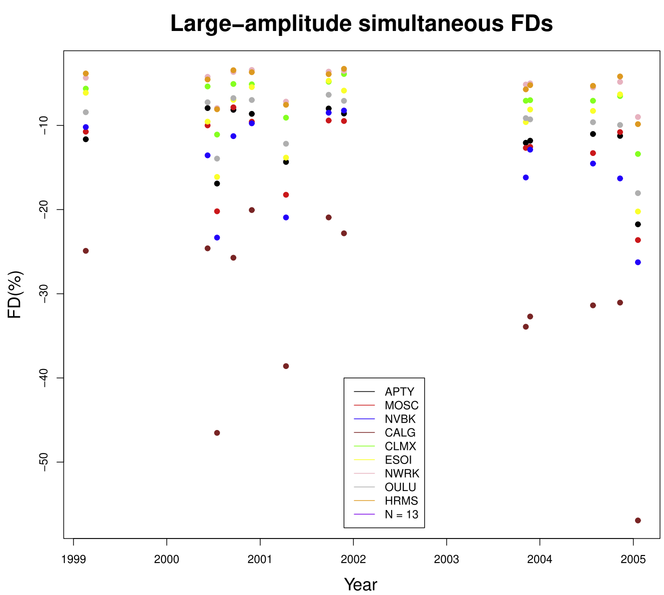

Figure 4. Variation of large-amplitude FDs across many altitude bands. $N = 13$ stands for the number of simultaneous large FDs.

intensity variations for all the large FDs, HRMS (R_c = 4.58 GV, Alt. = 26 m) and NWRK (R_c = 2.09 GV, Alt. = 50 m) see the least intensity variations. This is followed by CLMX. It should also be observed that the number of simultaneous FDs is larger for large FDs than for small-amplitude events. This explains why we have five events in Figure 3 for six stations and 13 FDs in Figure 4 for nine NMs. The number of events will drastically reduce if we extend the analysis to all the nine stations (see also Okike 2020c).

The values of the small-amplitude FDs observed by the 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 the mid-altitude NMs, the 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 the 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 the Low, Mid and High-Altitude NM Stations

FD simultaneity refers to a 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 some other locations worldwide. So, 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 is used to identify non-simultaneous FDs. The two algorithms scan two or more data sets concerning a predefined criterion. Setting the identification threshold for the FDs at CR $< -3\%$, we effectively isolated the large-magnitude events from the data set, while the small-amplitude FDs are collated and used for this study. The script systematically scanned the FD data sets from the 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 that only temporally coincident parameters and indices corresponding to the FDs were retained. The compiled data sets, encompassing the FD events and their respective interplanetary and geomagnetic parameters, are presented in Tables 2–4.

Figure 5 shows the plot of small-amplitude FDs against event number for the 80, 38, and 19 simultaneous FDs. The significant difference in the number of simultaneous FDs at the different altitude bands is attractive. Inspection of Table 1 suggests that the differences in the 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 of the FDs are presented in Figures 3 and 4 across all altitudes, the

Table 4
Simultaneous Small-amplitude FDs observed by high-altitude NMs and the associated solar-terrestrial parameters

No	Date	FDs_{CALG} (%)	FDs_{CLMX} (%)	FDs_{ESOI} (%)	IMF (nT)	SWS (km s^{-1})	Kp	Dst	Ap
1	1999-12-05	−2.17	−0.51	−1.54	5.5	658	33	−24	20
2	2000-03-01	−1.67	−0.13	−0.12	7.6	480	33	−22	21
3	2000-03-30	−0.39	−0.24	−0.12	5.2	446	27	−2	12
4	2000-05-30	−0.08	−0.72	−1.70	6.2	617	37	−29	22
5	2000-12-27	−1.73	−0.86	−2.62	7.7	390	20	−1	8
6	2001-07-04	−1.54	−0.32	−0.05	6.9	381	17	8	6
7	2002-03-31	−0.87	−0.56	−2.51	10.0	680	33	−11	20
8	2002-06-11	−1.49	−0.14	−0.06	7.7	386	20	−19	8
9	2002-12-09	−1.72	−0.60	−0.81	5.3	556	13	−25	6
10	2003-03-31	−1.86	−0.55	−1.56	9.3	564	43	−57	43
11	2003-05-02	−1.92	−1.02	−1.19	4.7	583	27	−24	15
12	2003-07-27	−1.31	−0.44	−0.31	8.8	677	33	−36	22
13	2003-07-30	−0.60	−0.11	−0.04	6.9	763	40	−27	27
14	2004-07-20	−2.76	−0.15	−0.11	6.0	527	20	−4	8
15	2005-03-21	−2.12	−0.07	−2.02	7.2	444	17	−13	8
16	2005-03-29	−0.17	−0.09	−1.60	5.0	488	10	6	4
17	2005-12-21	−1.44	−0.66	−1.05	7.4	485	23	−15	9
18	2006-08-08	−1.68	−0.33	−1.90	4.1	602	23	−27	10
19	2006-10-14	−0.98	−0.07	−1.34	6.2	539	37	−36	23

Table 5
Correlation Matrix of Large-amplitude FDs Observed by Low-altitude NMs and the Associated Solar-terrestrial Parameters

S/N	Variables	IMF	SWS	Kp	Dst	Ap
1	FDs_{HRMS}	0.18	0.00	−0.14	−014	0.12
2	FDs_{NWRK}	−012	−069	−031	0.30	−029
3	FDs_{OULU}	−030	−057	−045	0.48	−046

Table 6
Correlation Matrix of Large-amplitude FDs Observed by Mid-altitude NMs and the Related Solar-terrestrial Parameters

S/N	Variables	IMF	SWS	Kp	Dst	Ap
1	FDs_{APTY}	−029	−061	−042	0.47	−045
2	FDs_{MOSC}	−026	−056	−037	0.38	−038
3	$FDs_{NV\ BK}$	−031	−060	−043	0.47	−046

events are grouped according to different altitude bands here. It is clear from the first panel (low-altitude stations) that OULU observes the highest intensity variation among the three stations. This agrees with the relatively low rigidity of OULU. The intensity variations at the mid-altitude band are similar for APTY, MOSC, and NVBK. This is contrary to expectation. APTY with the lowest rigidity should see higher intensity variations. The high-altitude NMs show that ESOI sees the highest intensity variations for some of the FDs. There are also cases where ESOI observed lower intensity variations than CALG and CLMX. In consideration of the high rigidity of ESOI, some of the events that register higher intensity variations at ESOI deserve more attention/explanation. Speculations are that this may be due to the varieties of FDs (Belov 2009). Technical characteristics of the ESOI NM, weather conditions, or other features of operation may also be blamed for such outliers (Vaisanen et al. 2021). However, we may not reach any definitive conclusion pending when ESOI data at other CR repositories are used to validate ESOI data at 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 the HRMS, NWRK, and OULU stations, respectively.

Table 7
Correlation Matrix of Large-amplitude FDs Observed by High-altitude NMs and the Related Solar-terrestrial Parameters

S/N	Variables	IMF	SWS	Kp	Dst	Ap
1	FDs_{CLAG}	−034	−046	−038	0.46	−043
2	FDs_{CLMX}	−024	−064	−038	0.29	−035
3	FDs_{ESOI}	−039	−062	−041	0.50	−044

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 the ones observed by the HRMS and OULU stations. 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 magnitude of FD on this day, with the HRMS station recording the lowest of the three

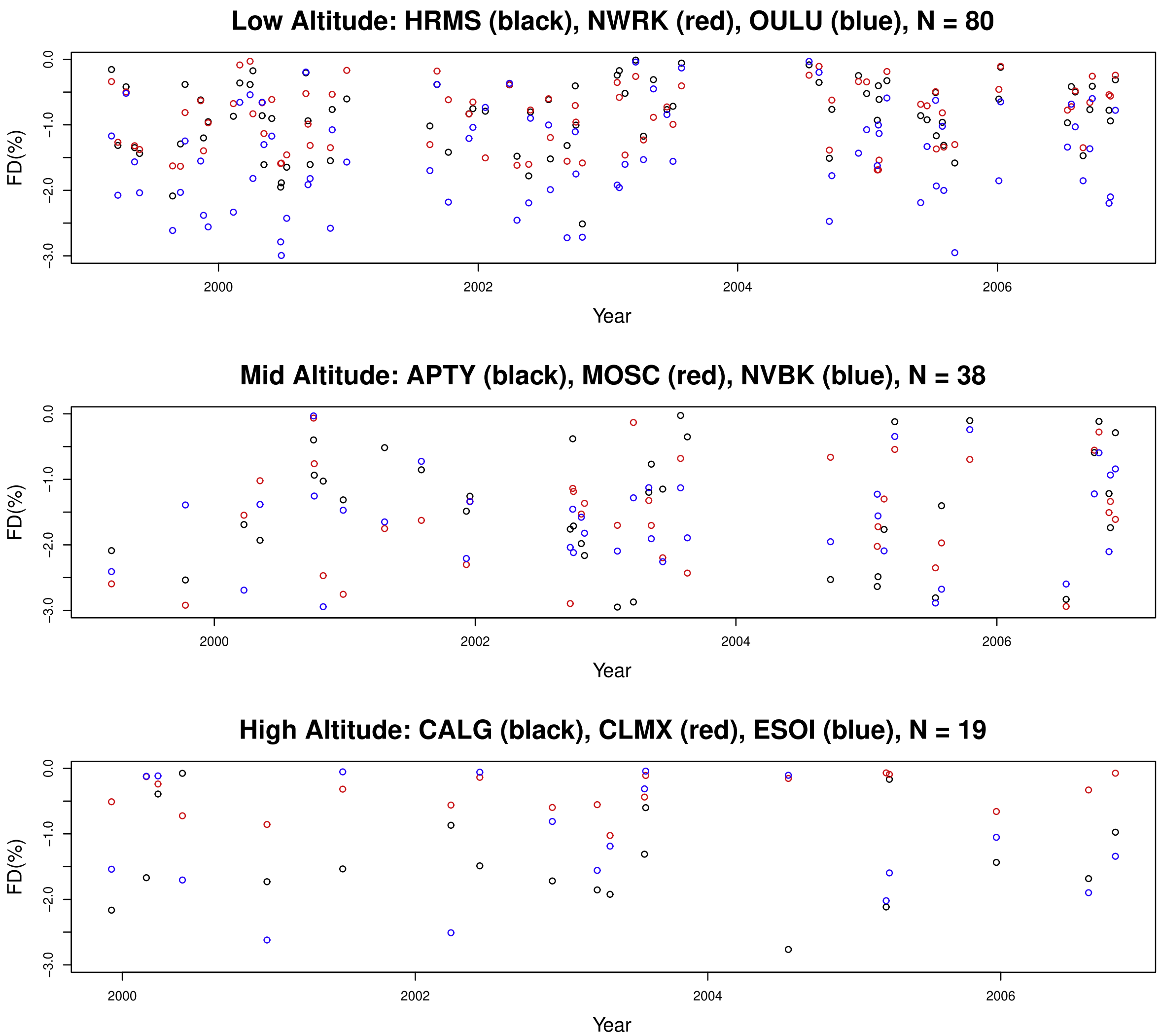

Figure 5. Statistical relations for small-amplitude FDs across low, mid- and high-altitude bands. N = number of FDs

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).

In the case of 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 recorded were on 2000 October 1 with magnitudes of 0.40%, 0.06%, and 0.03% for APTY, MOSC, and NVBK, respectively. The 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 the 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 was on 2004 July 20, which were 2.76%. 0.15% and 0.11% for CALG, CLMX, and ESOI NMs, respectively.

These highlighted spectacular events could give readers information to follow through other events on different days as recorded by these stations. However, the differences in magnitudes of FDs 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 the magnitude of FDs as 2.33%, 2.76%, and 2.34% for this event using MGDN, OULU, and INVK

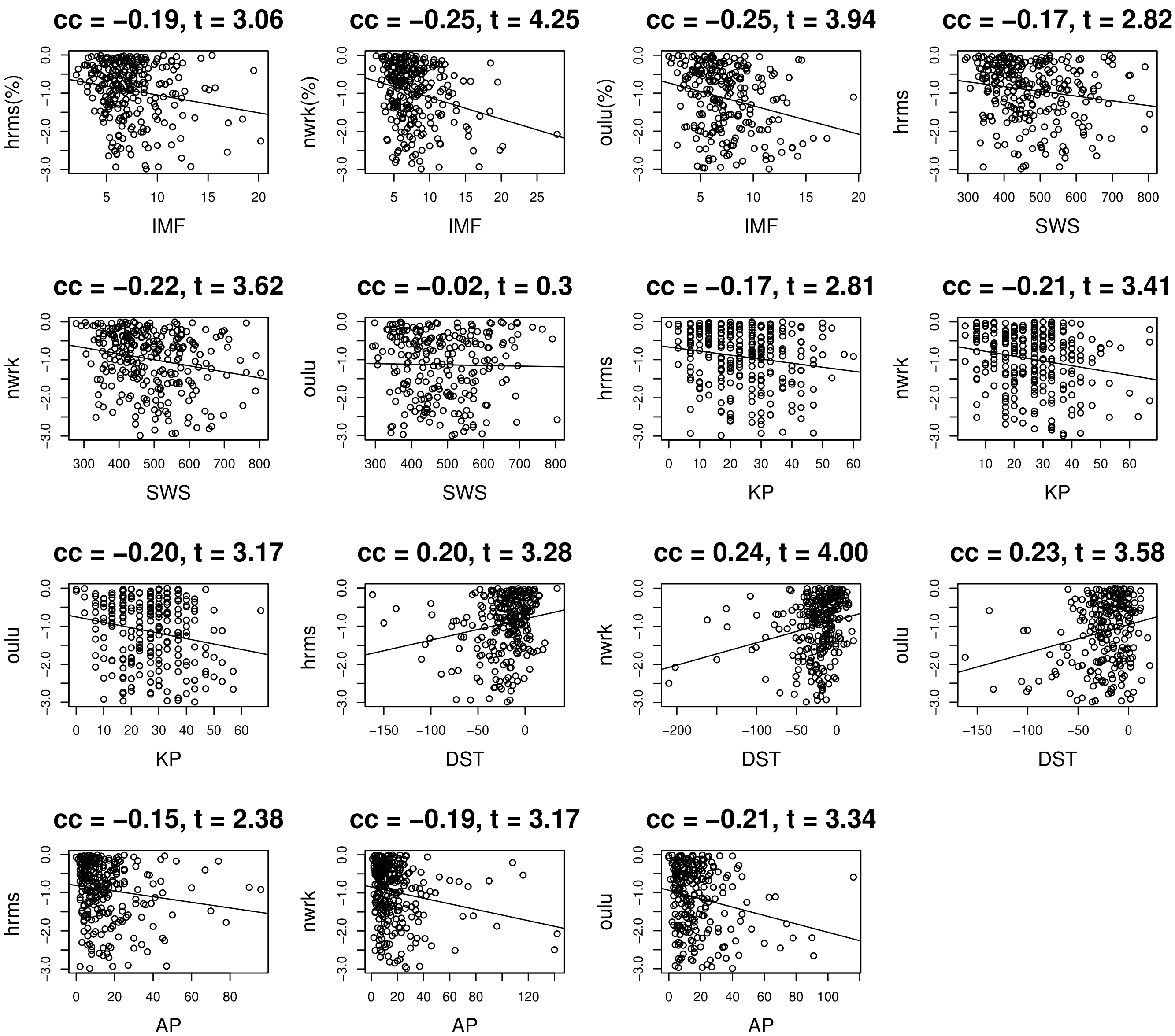

Figure 6. Relation between small-amplitude simultaneous FDs and the related solar-terrestrial parameters observed by low-altitude NMs.

which are located at very low altitudes of 220, 0 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 the Solar-terrestrial Parameters

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

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

X_i is the FDs from the NMs while Y_i is the solar-terrestrial variables. The composite scatter plot illustrating the

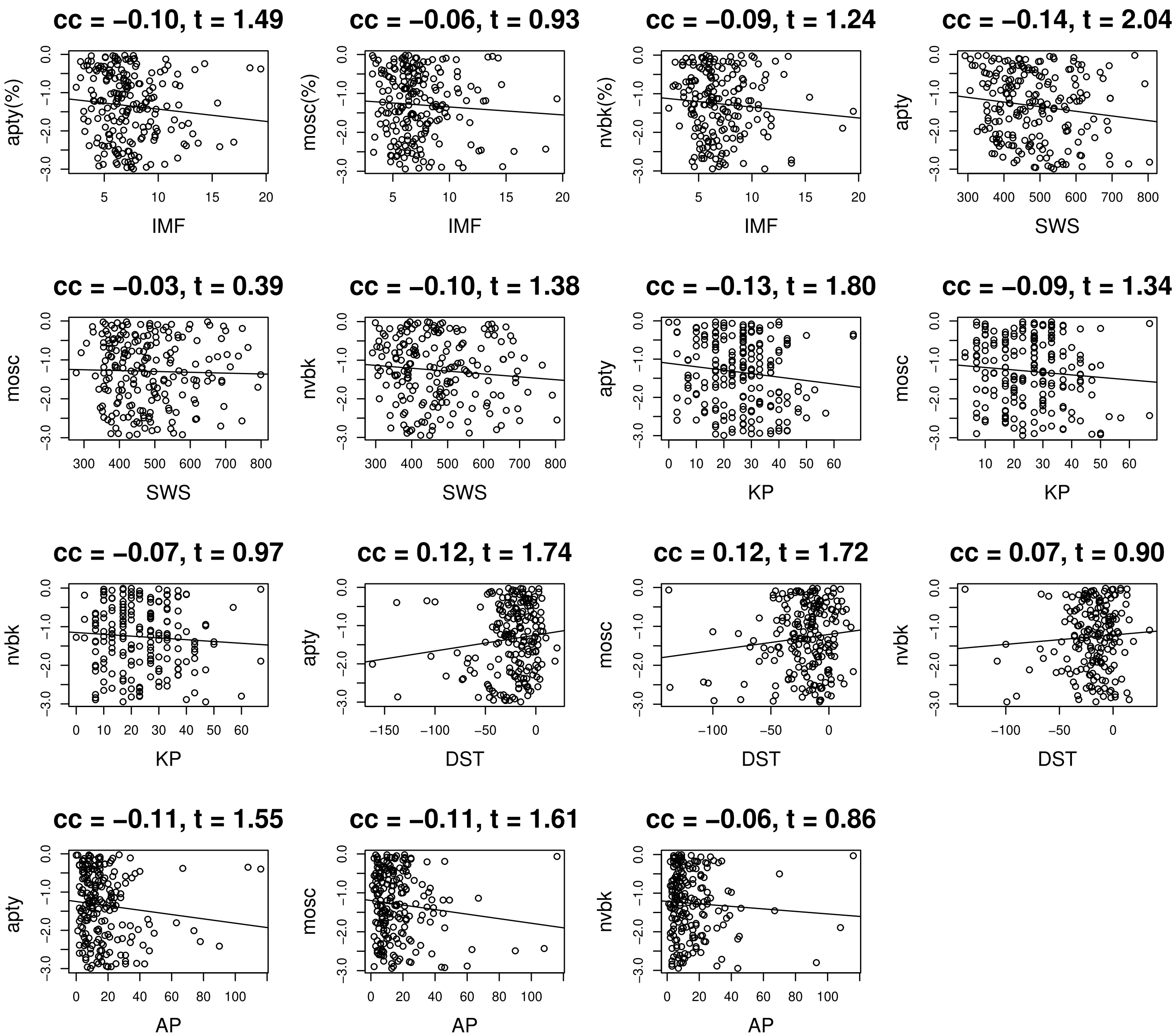

Figure 7. Relation between small-amplitude simultaneous FDs and the related solar-terrestrial parameters observed by mid-altitude NMs.

relationship between small-amplitude FDs observed at low-altitude NMs and solar-terrestrial variables is presented in Figure 6. The intensity variability across these three altitude bands is easy to observe from the graph. OULU is more sensitive among the three low-altitude stations (HRMS and NWRK). Identifying the more sensitive NMs among APTY, MOSC, and NVBK at the mid-altitude band is a little difficult. CALG and ESOI observe higher intensity variation at the high-altitude band.

Analysis of the data from the three stations reveals a consistent trend in the interaction between these variables and small-amplitude FDs. Before presenting detailed results for small-amplitude FDs, we show the relations for large FDs and solar-terrestrial variables. Simple linear regression analysis indicates varying degrees of correlations of FDs from both individual and combined NMs with the correlation coefficients (cc) evaluated using Equation (2) (see Tables 5–7). Besides HRMS that registers insignificant ccs with SWS, KP, Dst and AP, large FDs at other stations indicate significant relations with the solar/geomagnetic variables. These unexpected relations for large FDs at HRMS deserve more attention, especially as it shall be seen shortly that small-amplitude FDs from the same station indicate significant ccs with the solar/geomagnetic data. Nevertheless, Table 1 shows that HRMS has its peculiar physical characteristics. It is, for example, the only high rigidity station in Table 1 (second to ESOI) located at a

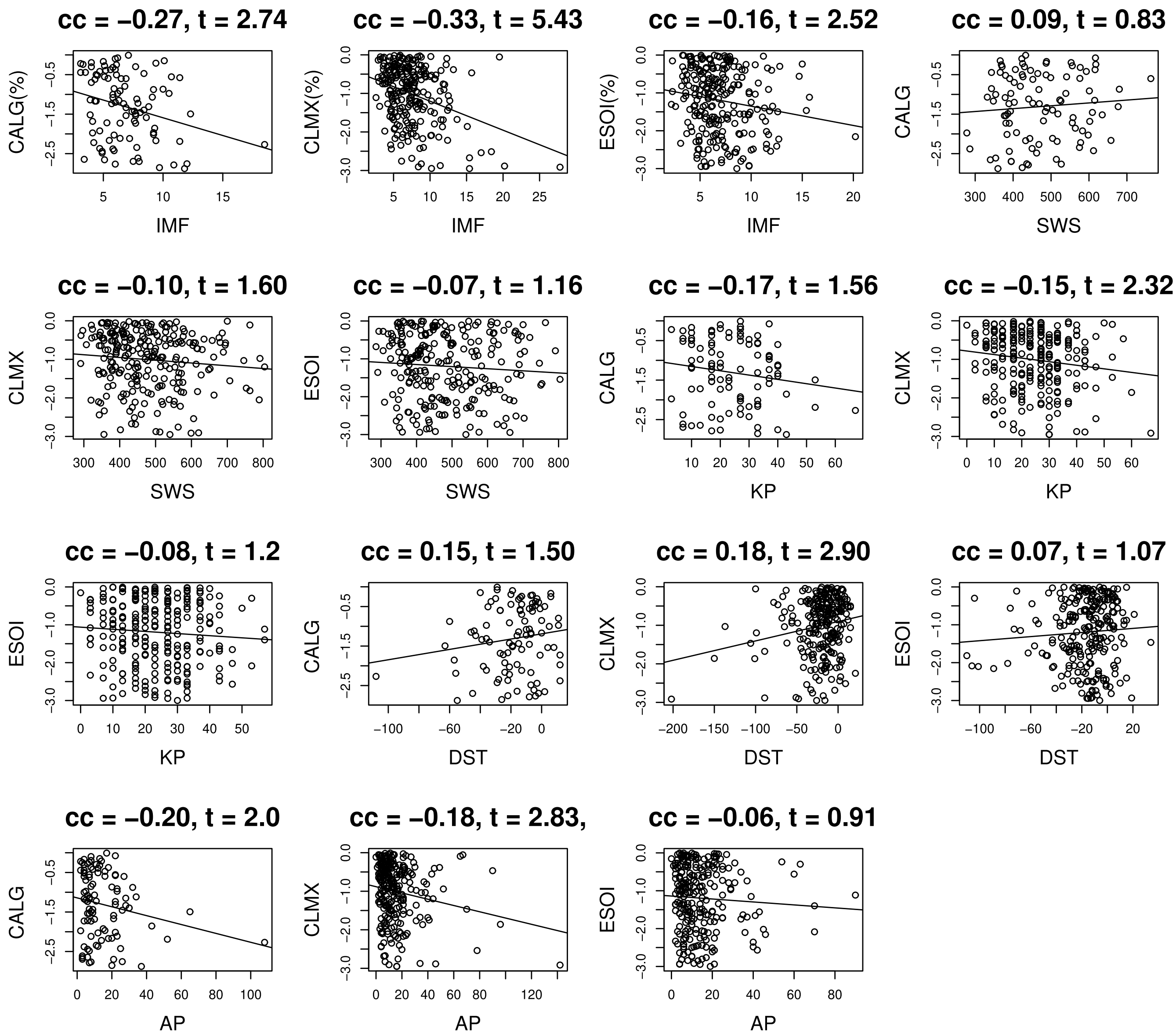

Figure 8. Relation between small-amplitude simultaneous FDs and the related solar-terrestrial parameters observed by high-altitude NMs.

low-altitude. The impact of this on HRMS data calls for detailed inspection of the CR measurement at the station. Data quality and consistency checks (see Vaisanen et al. 2021), for instance, should be conducted for the HRMS station before reaching any firm conclusion with the results presented here. We may conduct such a validation test 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. The ccs and the t_{values} are indicated. The plots reveal a negative correlation between small FDs and the IMF, SWS, and some geomagnetic indices (AP and KP). In contrast, the relationship with the Dst index is positive. It is interesting to observe, however, that these relations vary appreciably across different altitude bands and at different NM stations. These results may 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 some more pronounced effects which other CR superposed signals may have on weak FDs, CR intensity changes during small Forbush events may vary significantly between different locations. These unpredictable intensity fluctuations seem to be reflected in the correlation results of Figures 6–8. The trend across stations suggests a shared influence of these

Table 8
Small-Amplitude FDs Observed by Low (⩽100 m) Altitude NMs Between 1999-2006

S/N	Date	FDs_{HRMS}	Date	FDs_{NWRK}	Date	FDs_{OULU}
1	1999-01-17	−0.25	1999-01-09	−0.49	1999-01-04	−0.08
2	1999-03-04	−0.07	1999-01-15	−0.69	1999-01-14	−1.16
3	1999-03-06	−0.16	1999-01-18	−0.37	1999-01-16	−1.29
4	1999-03-08	−0.09	1999-01-21	−0.20	1999-01-20	−0.26
5	1999-03-19	−1.28	1999-02-13	−0.70	1999-02-23	−1.85
6	1999-03-24	−1.31	1999-03-03	−0.21	1999-03-02	−0.85
7	1999-04-11	−0.20	1999-03-06	−0.34	1999-03-06	−1.17
8	1999-04-16	−0.42	1999-03-09	−0.11	1999-03-10	−0.84
9	1999-04-19	−0.33	1999-03-15	−0.95	1999-03-19	−2.97
10	1999-04-22	−0.76	1999-03-20	−1.10	1999-03-24	−2.07
11	1999-05-10	−1.35	1999-03-24	−1.27	1999-03-30	−0.29
12	1999-05-24	−1.44	1999-04-04	−0.09	1999-04-16	−0.52
13	1999-05-29	−0.08	1999-04-12	−0.22	1999-04-21	−1.48
14	1999-05-31	−0.04	1999-04-16	−0.50	1999-05-10	−1.57
15	1999-06-27	−0.77	1999-04-22	−1.08	1999-05-24	−2.04
16	1999-08-22	−2.59	1999-05-10	−1.32	1999-06-05	−0.28
17	1999-08-25	−2.09	1999-05-24	−1.38	1999-06-27	−1.97
18	1999-08-27	−2.10	1999-05-31	−0.29	1999-08-25	−2.61
19	1999-08-31	−0.89	1999-06-03	−0.43	1999-09-05	−0.91
20	1999-09-06	−0.58	1999-06-06	−0.44	1999-09-13	−1.56
21	1999-09-16	−1.29	1999-06-28	−1.41	1999-09-16	−2.03
22	1999-09-18	−1.05	1999-07-02	−0.03	1999-09-21	−1.65
23	1999-09-20	−1.01	1999-08-22	−2.02	1999-09-29	−1.25
24	1999-09-25	−0.40	1999-08-25	−1.63	1999-10-12	−0.58
25	1999-09-29	−0.38	1999-08-31	−0.01	1999-10-17	−2.96
26	1999-10-06	−0.16	1999-09-05	−0.65	1999-10-22	−2.66
27	1999-10-12	−0.04	1999-09-07	−0.73	1999-10-24	−2.77
28	1999-10-16	−1.64	1999-09-10	−0.39	1999-11-01	−1.58
29	1999-10-18	−1.57	1999-09-16	−1.63	1999-11-09	−0.30
30	1999-10-21	−1.68	1999-09-21	−1.19	1999-11-12	−1.55
31	1999-10-23	−0.92	1999-09-25	−0.37	1999-11-17	−1.96
32	1999-10-25	−0.80	1999-09-29	−0.81	1999-11-20	−2.38
33	1999-11-01	−0.74	1999-10-03	−0.14	1999-12-03	−2.56
34	1999-11-12	−0.62	1999-10-11	−0.47	1999-12-10	−0.39
35	1999-11-14	−0.77	1999-10-17	−1.90	1999-12-31	−0.61
36	1999-11-18	−1.05	1999-10-21	−1.47	2000-01-02	−0.49
37	1999-11-20	−1.20	1999-10-25	−1.00	2000-01-04	−0.53
38	1999-11-22	−1.13	1999-10-31	−0.91	2000-01-06	−0.43
39	1999-12-03	−0.95	1999-11-10	−0.29	2000-02-12	−2.33
40	1999-12-27	−0.97	1999-11-12	−0.63	2000-02-21	−0.12
41	2000-02-12	−0.87	1999-11-14	−1.06	2000-03-01	−0.66
42	2000-02-21	−0.09	1999-11-20	−1.40	2000-03-13	−0.27
43	2000-03-01	−0.36	1999-11-22	−1.31	2000-03-24	−1.18
44	2000-03-03	−0.08	1999-12-03	−0.97	2000-03-30	−0.54
45	2000-03-09	−0.05	1999-12-21	−0.04	2000-04-05	−0.22
46	2000-03-13	−0.04	1999-12-27	−0.82	2000-04-07	−1.82
47	2000-03-24	−0.94	2000-01-04	−0.20	2000-05-03	−0.66
48	2000-03-30	−0.38	2000-02-12	−0.68	2000-05-08	−1.30
49	2000-04-03	−0.13	2000-02-19	−0.11	2000-05-16	−0.55
50	2000-04-07	−0.18	2000-03-01	−0.09	2000-05-30	−1.17
51	2000-05-03	−0.86	2000-03-25	−0.58	2000-06-20	−2.74
52	2000-05-08	−1.61	2000-03-30	−0.03	2000-06-24	−2.79
53	2000-05-15	−0.60	2000-04-04	−0.34	2000-06-26	−2.99
54	2000-05-30	−0.90	2000-04-07	−0.83	2000-07-11	−2.43
55	2000-06-01	−0.70	2000-05-03	−0.66	2000-08-26	−0.47
56	2000-06-20	−2.13	2000-05-08	−1.13	2000-09-03	−0.19
57	2000-06-24	−1.95	2000-05-14	−0.42	2000-09-09	−1.91
58	2000-06-26	−1.88	2000-05-17	−0.49	2000-09-15	−1.82
59	2000-07-11	−1.65	2000-05-19	−0.76	2000-09-26	−0.06

Table 8
(Continued)

S/N	Date	FDs_{HRMS}	Date	FDs_{NWRK}	Date	FDs_{OULU}
60	2000-07-29	−2.90	2000-05-30	−0.61	2000-09-29	−0.22
61	2000-08-06	−2.60	2000-06-01	−0.65	2000-10-01	−0.40
62	2000-08-11	−2.92	2000-06-21	−1.69	2000-10-05	−0.59
63	2000-08-13	−2.93	2000-06-24	−1.59	2000-10-07	−0.88
64	2000-08-15	−2.41	2000-06-26	−1.58	2000-10-29	−2.45
65	2000-08-25	−0.25	2000-07-11	−1.46	2000-11-04	−0.49
66	2000-09-03	−0.21	2000-07-29	−2.99	2000-11-11	−2.58
67	2000-09-09	−0.94	2000-08-07	−2.69	2000-11-13	−1.04
68	2000-09-12	−0.76	2000-08-15	−2.56	2000-11-16	−1.08
69	2000-09-15	−1.61	2000-08-24	−0.31	2000-11-24	−0.57
70	2000-10-07	−0.33	2000-08-30	−0.32	2000-12-06	−2.78
71	2000-10-30	−0.74	2000-09-03	−0.52	2000-12-11	−0.52
72	2000-11-01	−0.64	2000-09-09	−0.99	2000-12-23	−1.13
73	2000-11-03	−0.52	2000-09-12	−0.97	2000-12-25	−1.18
74	2000-11-07	−2.26	2000-09-15	−1.31	2000-12-27	−1.57
75	2000-11-11	−1.55	2000-09-26	−0.23	2001-01-03	−0.28
76	2000-11-16	−0.77	2000-10-01	−0.01	2001-01-10	−0.25
77	2000-11-23	−0.20	2000-10-05	−0.53	2001-01-14	−0.02
78	2000-12-03	−1.69	2000-10-29	−1.29	2001-01-25	−1.89
79	2000-12-22	−0.06	2000-11-01	−0.42	2001-03-28	−0.28
80	2000-12-25	−0.29	2000-11-04	−0.56	2001-04-19	−2.38
81	2000-12-27	−0.60	2000-11-07	−2.39	2001-04-22	−0.54
82	2001-01-18	−0.13	2000-11-11	−1.35	2001-05-25	−0.58
83	2001-01-25	−0.52	2000-11-14	−0.58	2001-08-03	−0.15
84	2001-03-28	−0.12	2000-11-16	−0.53	2001-08-06	−0.20
85	2001-04-01	−0.54	2000-12-05	−1.23	2001-08-18	−1.70
86	2001-04-05	−1.88	2000-12-27	−0.17	2001-08-24	−0.86
87	2001-04-18	−1.58	2001-01-19	−0.05	2001-09-07	−0.38
88	2001-05-25	−1.26	2001-01-24	−0.68	2001-10-09	−2.18
89	2001-05-28	−2.44	2001-04-01	−1.01	2001-10-28	−2.65
90	2001-06-02	−0.14	2001-04-05	−1.04	2001-11-22	−0.72
91	2001-06-20	−0.08	2001-04-09	−2.78	2001-12-06	−1.21
92	2001-07-03	−0.44	2001-04-16	−2.21	2001-12-17	−1.04
93	2001-08-03	−0.53	2001-04-19	−1.02	2002-01-19	−0.62
94	2001-08-06	−0.15	2001-04-22	−0.89	2002-01-21	−0.73
95	2001-08-18	−1.02	2001-04-29	−2.66	2002-01-24	−0.39
96	2001-08-22	−0.67	2001-05-04	−0.34	2002-02-01	−2.75
97	2001-08-24	−0.83	2001-05-26	−0.79	2002-03-22	−2.30
98	2001-09-07	−0.38	2001-05-28	−2.06	2002-03-30	−0.37
99	2001-10-09	−1.42	2001-06-02	−0.23	2002-04-18	−1.12
100	2001-10-12	−2.36	2001-06-20	−0.23	2002-04-20	−2.46
101	2001-10-22	−0.92	2001-07-04	−0.32	2002-04-24	−2.34
102	2001-10-26	−0.56	2001-08-04	−0.58	2002-05-20	−1.36
103	2001-10-28	−0.70	2001-08-07	−0.04	2002-05-23	−2.19
104	2001-11-07	−1.87	2001-08-18	−1.30	2002-05-28	−0.90
105	2001-11-22	−0.07	2001-08-23	−0.93	2002-07-18	−1.00
106	2001-12-06	−0.83	2001-09-07	−0.18	2002-07-23	−1.99
107	2001-12-17	−0.75	2001-10-09	−0.62	2002-08-07	−2.92
108	2001-12-29	−0.01	2001-10-12	−2.32	2002-08-09	−2.25
109	2002-01-01	−2.61	2001-10-22	−1.88	2002-09-04	−2.27
110	2002-01-03	−2.93	2001-10-29	−0.67	2002-09-08	−2.72
111	2002-01-09	−0.40	2001-11-06	−2.08	2002-09-11	−1.77
112	2002-01-12	−2.40	2001-12-06	−0.84	2002-09-19	−0.39
113	2002-01-21	−0.79	2001-12-17	−0.65	2002-09-24	−1.77
114	2002-01-29	−1.73	2002-01-03	−2.18	2002-09-28	−0.95
115	2002-03-24	−2.19	2002-01-11	−1.92	2002-10-01	−1.11
116	2002-03-30	−0.39	2002-01-13	−1.73	2002-10-03	−1.75
117	2002-04-20	−1.48	2002-01-21	−1.50	2002-10-21	−2.72
118	2002-04-25	−1.53	2002-01-30	−1.52	2002-10-25	−1.96

Table 8
(Continued)

S/N	Date	FDs_{HRMS}	Date	FDs_{NWRK}	Date	FDs_{OULU}
119	2002-05-15	−0.22	2002-02-01	−1.52	2002-11-03	−1.55
120	2002-05-21	−1.14	2002-03-25	−1.95	2002-11-05	−2.89
121	2002-05-23	−1.78	2002-03-30	−0.39	2002-11-25	−0.76
122	2002-05-26	−0.53	2002-04-20	−1.62	2002-11-27	−2.06
123	2002-05-28	−0.80	2002-04-25	−1.25	2002-12-01	−0.69
124	2002-06-11	−0.27	2002-05-12	−0.03	2002-12-08	−1.31
125	2002-07-11	−0.07	2002-05-21	−0.81	2002-12-15	−1.95
126	2002-07-18	−0.62	2002-05-23	−1.60	2003-01-24	−0.68
127	2002-07-20	−1.94	2002-05-28	−0.77	2003-01-27	−1.92
128	2002-07-23	−1.52	2002-06-11	−0.36	2003-02-02	−1.96
129	2002-07-25	−1.53	2002-07-18	−0.60	2003-02-18	−1.60
130	2002-08-07	−1.77	2002-07-20	−1.82	2003-03-20	−0.04
131	2002-08-20	−2.45	2002-07-23	−1.19	2003-03-31	−0.36
132	2002-08-23	−2.35	2002-08-20	−2.14	2003-04-11	−1.53
133	2002-08-28	−2.99	2002-08-23	−2.10	2003-05-02	−0.26
134	2002-09-08	−1.32	2002-08-28	−2.50	2003-05-06	−0.33
135	2002-09-12	−0.98	2002-09-04	−1.07	2003-05-09	−0.45
136	2002-09-22	−1.23	2002-09-08	−1.56	2003-06-06	−0.69
137	2002-09-24	−1.19	2002-09-23	−1.04	2003-06-10	−1.16
138	2002-09-27	−0.87	2002-09-27	−0.85	2003-06-16	−0.84
139	2002-10-01	−0.41	2002-10-01	−0.71	2003-06-27	−2.65
140	2002-10-03	−1.00	2002-10-03	−0.96	2003-07-03	−1.56
141	2002-10-21	−2.51	2002-10-21	−1.58	2003-07-07	−0.11
142	2002-10-25	−1.28	2002-10-26	−0.69	2003-07-10	−0.07
143	2002-10-31	−0.19	2002-12-08	−1.54	2003-07-15	−0.86
144	2002-11-03	−1.29	2002-12-15	−0.83	2003-07-17	−0.26
145	2002-11-05	−1.76	2002-12-18	−0.79	2003-07-27	−0.13
146	2002-11-12	−2.70	2002-12-20	−1.37	2003-07-30	−0.20
147	2002-11-25	−0.68	2002-12-23	−1.79	2003-08-02	−0.15
148	2002-11-27	−1.36	2002-12-25	−1.83	2003-10-22	−1.01
149	2002-12-14	−0.04	2003-01-27	−0.35	2003-12-08	−2.42
150	2002-12-18	−0.21	2003-01-30	−0.12	2003-12-24	−0.44
151	2002-12-20	−0.46	2003-02-02	−0.58	2004-01-04	−1.60
152	2002-12-23	−1.49	2003-02-18	−1.46	2004-02-13	−0.55
153	2003-01-27	−0.24	2003-03-20	−0.26	2004-03-01	−0.00
154	2003-02-02	−0.17	2003-03-31	−0.06	2004-04-04	−0.13
155	2003-02-18	−0.52	2003-04-11	−1.23	2004-07-17	−0.43
156	2003-03-20	−0.01	2003-04-15	−0.36	2004-07-20	−0.03
157	2003-04-11	−1.17	2003-05-02	−0.66	2004-08-10	−0.42
158	2003-04-14	−0.10	2003-05-07	−0.46	2004-08-17	−0.20
159	2003-05-09	−0.31	2003-05-09	−0.89	2004-08-22	−0.10
160	2003-06-08	−0.53	2003-06-11	−1.09	2004-09-15	−2.47
161	2003-06-11	−0.89	2003-06-16	−0.73	2004-09-18	−2.28
162	2003-06-16	−0.77	2003-06-20	−2.42	2004-09-22	−1.78
163	2003-07-01	−1.09	2003-06-23	−2.84	2004-12-06	−1.43
164	2003-07-03	−0.72	2003-06-30	−1.33	2004-12-08	−0.50
165	2003-07-14	−0.29	2003-07-03	−0.99	2004-12-10	−0.49
166	2003-07-27	−0.06	2003-07-07	−0.44	2004-12-14	−0.89
167	2003-10-09	−0.12	2003-07-10	−0.32	2004-12-29	−1.07
168	2003-10-23	−1.93	2003-07-14	−0.51	2005-01-28	−1.62
169	2003-11-12	−2.19	2003-07-27	−0.40	2005-01-31	−1.00
170	2003-12-04	−1.65	2003-07-30	−0.03	2005-02-02	−1.13
171	2003-12-10	−1.13	2003-08-18	−0.21	2005-02-13	−2.37
172	2003-12-23	−0.02	2003-08-30	−0.14	2005-02-19	−1.89
173	2004-01-05	−0.71	2003-10-22	−0.86	2005-02-24	−0.59
174	2004-07-16	−0.19	2003-10-25	−2.13	2005-03-07	−0.03
175	2004-07-20	−0.08	2003-11-12	−2.45	2005-03-21	−0.54
176	2004-07-24	−2.55	2003-11-30	−2.34	2005-03-30	−0.05
177	2004-08-01	−1.71	2003-12-06	−2.04	2005-05-30	−2.19

Table 8
(Continued)

S/N	Date	FDs_{HRMS}	Date	FDs_{NWRK}	Date	FDs_{OULU}
178	2004-08-04	−2.30	2003-12-08	−2.19	2005-06-13	−0.03
179	2004-08-17	−0.35	2003-12-10	−2.20	2005-06-17	−1.33
180	2004-09-15	−1.51	2003-12-24	−0.24	2005-06-29	−0.12
181	2004-09-18	−0.78	2003-12-30	−0.01	2005-07-11	−0.63
182	2004-09-22	−0.76	2004-01-04	−0.96	2005-07-13	−1.93
183	2004-12-06	−0.25	2004-01-10	−2.94	2005-07-30	−1.02
184	2004-12-29	−0.52	2004-01-18	−0.05	2005-08-03	−2.00
185	2004-12-31	−0.31	2004-01-22	−2.51	2005-08-10	−2.47
186	2005-01-09	−2.01	2004-01-28	−2.61	2005-08-13	−1.70
187	2005-01-28	−0.93	2004-02-01	−2.35	2005-08-16	−1.23
188	2005-01-31	−0.40	2004-02-06	−1.21	2005-08-19	−0.46
189	2005-02-02	−0.61	2004-07-13	−0.18	2005-08-31	−1.25
190	2005-02-08	−0.16	2004-07-16	−0.38	2005-09-03	−2.95
191	2005-02-10	−0.25	2004-07-20	−0.24	2005-10-05	−0.78
192	2005-02-19	−0.54	2004-07-24	−2.93	2005-10-11	−1.88
193	2005-02-24	−0.33	2004-08-01	−2.01	2005-10-17	−0.08
194	2005-02-26	−0.14	2004-08-04	−2.51	2005-10-31	−0.86
195	2005-03-21	−0.08	2004-08-10	−0.18	2005-11-07	−0.03
196	2005-03-29	−0.10	2004-08-17	−0.11	2005-12-03	−0.01
197	2005-05-09	−2.02	2004-08-21	−0.00	2005-12-07	−0.08
198	2005-05-30	−0.86	2004-09-15	−1.39	2005-12-12	−0.40
199	2005-06-17	−0.92	2004-09-22	−0.62	2005-12-22	−0.49
200	2005-06-20	−0.27	2004-11-08	−2.49	2005-12-24	−0.41
201	2005-06-22	−0.03	2004-12-06	−0.34	2006-01-05	−1.85
202	2005-07-11	−0.51	2004-12-29	−0.34	2006-01-10	−0.65
203	2005-07-13	−1.17	2004-12-31	−0.35	2006-01-25	−0.73
204	2005-07-23	−0.26	2005-01-08	−1.76	2006-02-22	−0.04
205	2005-07-30	−0.96	2005-01-13	−0.67	2006-07-14	−2.04
206	2005-08-03	−1.31	2005-01-28	−1.69	2006-07-17	−1.34
207	2005-08-07	−2.65	2005-01-31	−1.69	2006-07-20	−0.63
208	2005-08-11	−1.47	2005-02-02	−1.54	2006-07-25	−0.38
209	2005-08-13	−1.13	2005-02-08	−0.37	2006-07-28	−0.68
210	2005-08-16	−0.99	2005-02-21	−0.87	2006-08-01	−0.21
211	2005-08-21	−0.45	2005-02-24	−0.19	2006-08-04	−0.23
212	2005-08-25	−2.16	2005-03-01	−0.20	2006-08-08	−1.03
213	2005-09-03	−1.58	2005-03-29	−0.12	2006-08-11	−0.43
214	2005-09-05	−1.42	2005-05-09	−1.81	2006-08-27	−0.26
215	2005-09-25	−1.58	2005-05-30	−0.69	2006-08-30	−1.85
216	2005-09-28	−1.20	2005-06-17	−0.71	2006-09-01	−1.66
217	2005-10-01	−0.85	2005-07-11	−0.49	2006-09-04	−2.43
218	2005-10-10	−1.23	2005-07-13	−1.37	2006-09-10	−0.78
219	2005-10-12	−1.13	2005-07-25	−0.10	2006-09-13	−0.67
220	2005-10-23	−0.24	2005-07-30	−0.82	2006-09-18	−1.37
221	2005-12-15	−0.07	2005-08-03	−1.34	2006-09-21	−0.21
222	2005-12-19	−0.11	2005-08-07	−2.81	2006-09-25	−0.60
223	2005-12-22	−0.24	2005-08-11	−1.49	2006-09-28	−0.46
224	2006-01-01	−1.10	2005-08-14	−1.33	2006-10-01	−1.41
225	2006-01-05	−0.61	2005-08-21	−0.41	2006-10-08	−0.05
226	2006-01-10	−0.12	2005-08-25	−2.75	2006-10-10	−0.01
227	2006-01-25	−0.04	2005-08-31	−1.00	2006-10-14	−0.68
228	2006-06-01	−0.20	2005-09-03	−1.30	2006-10-23	−0.15
229	2006-06-05	−0.27	2005-09-05	−1.26	2006-10-29	−0.25
230	2006-07-08	−0.52	2005-09-23	−2.24	2006-11-08	−0.03
231	2006-07-11	−2.37	2005-09-25	−1.92	2006-11-11	−2.20
232	2006-07-14	−1.40	2005-10-10	−1.19	2006-11-15	−2.10
233	2006-07-17	−0.97	2005-10-22	−0.04	2006-11-22	−0.17
234	2006-07-25	−0.63	2005-12-09	−0.05	2006-11-29	−0.78
235	2006-07-28	−0.42	2005-12-18	−0.10	2006-12-26	−0.56
236	2006-07-30	−0.42	2006-01-01	−1.17		

Table 8
(Continued)

S/N	Date	FDs_{HRMS}	Date	FDs_{NWRK}	Date	FDs_{OULU}
237	2006-08-03	−0.47	2006-01-05	−0.46		
238	2006-08-06	−0.61	2006-01-10	−0.11		
239	2006-08-08	−0.50	2006-06-01	−0.09		
240	2006-08-12	−0.21	2006-07-08	−0.35		
241	2006-08-18	−0.88	2006-07-11	−2.38		
242	2006-08-20	−1.78	2006-07-17	−0.78		
243	2006-08-22	−1.72	2006-07-28	−0.72		
244	2006-08-30	−1.47	2006-08-01	−0.41		
245	2006-09-03	−1.65	2006-08-08	−0.48		
246	2006-09-09	−0.70	2006-08-10	−0.28		
247	2006-09-11	−0.68	2006-08-15	−0.02		
248	2006-09-16	−0.57	2006-08-20	−1.92		
249	2006-09-18	−0.77	2006-08-22	−1.66		
250	2006-09-21	−0.37	2006-08-30	−1.35		
251	2006-09-25	−0.41	2006-09-02	−1.39		
252	2006-09-30	−0.59	2006-09-05	−1.33		
253	2006-10-10	−0.25	2006-09-10	−0.56		
254	2006-10-14	−0.18	2006-09-13	−0.30		
255	2006-10-22	−0.34	2006-09-16	−0.48		
256	2006-11-05	−0.03	2006-09-18	−0.66		
257	2006-11-07	−0.07	2006-09-25	−0.26		
258	2006-11-11	−0.78	2006-09-28	−0.18		
259	2006-11-15	−0.94	2006-09-30	−0.24		
260	2006-11-19	−0.18	2006-10-02	−0.38		
261	2006-11-23	−0.13	2006-10-09	−0.04		
262	2006-11-29	−0.31	2006-10-20	−0.14		
263	2006-12-11	−2.45	2006-10-22	−0.20		
264	2006-12-24	−0.10	2006-11-11	−0.54		
265			2006-11-15	−0.56		
266			2006-11-29	−0.24		
267			2006-12-11	−2.35		

Table 9
Small-Amplitude FDs Observed by Mid-Altitude (100–1000 m) NMs Between 1999–2006

S/N	Date	FDs_{APTY}	Date	FDs_{MOSC}	Date	$FDs_{NV\ BK}$
1	1999-01-04	−0.76	1999-01-16	−1.84	1999-01-14	−0.16
2	1999-01-14	−1.86	1999-01-19	−1.32	1999-01-19	−1.93
3	1999-01-17	−2.36	1999-01-21	−1.35	1999-02-23	−2.00
4	1999-03-02	−0.18	1999-02-13	−2.52	1999-03-06	−0.29
5	1999-03-07	−1.04	1999-02-23	−2.09	1999-03-10	−0.17
6	1999-03-10	−0.11	1999-03-02	−0.27	1999-03-19	−2.41
7	1999-03-19	−2.09	1999-03-06	−0.95	1999-03-22	−2.00
8	1999-03-24	−2.10	1999-03-11	−0.12	1999-03-25	−1.31
9	1999-04-21	−0.90	1999-03-19	−2.60	1999-04-23	−1.41
10	1999-05-10	−0.65	1999-03-24	−2.48	1999-05-01	−0.06
11	1999-05-24	−1.58	1999-04-11	−0.20	1999-05-08	−2.65
12	1999-06-27	−1.35	1999-04-16	−0.62	1999-06-06	−2.89
13	1999-08-25	−2.99	1999-04-22	−1.78	1999-07-28	−0.01
14	1999-09-03	−0.53	1999-05-10	−1.47	1999-08-31	−1.35
15	1999-09-08	−1.52	1999-05-24	−2.16	1999-09-08	−2.61
16	1999-09-13	−1.85	1999-06-06	−0.56	1999-09-24	−2.22
17	1999-09-16	−2.88	1999-06-27	−2.79	1999-10-12	−1.39
18	1999-09-20	−2.20	1999-09-01	−0.16	1999-10-29	−2.79
19	1999-09-25	−1.03	1999-09-05	−1.78	1999-10-31	−2.81

Table 9
(Continued)

S/N	Date	FDs_{APTY}	Date	FDs_{MOSC}	Date	$FDs_{NV\ BK}$
20	1999-10-08	−0.41	1999-09-07	−1.29	1999-11-05	−1.12
21	1999-10-12	−2.54	1999-09-09	−1.78	1999-11-10	−1.29
22	1999-11-09	−2.65	1999-09-13	−1.90	1999-11-25	−1.78
23	1999-11-27	−2.60	1999-09-18	−2.82	2000-01-07	−1.51
24	1999-11-29	−1.44	1999-09-25	−1.06	2000-01-09	−0.97
25	2000-01-04	−1.99	1999-09-29	−2.24	2000-01-13	−1.07
26	2000-01-07	−2.92	1999-10-03	−1.96	2000-01-24	−0.79
27	2000-01-13	−0.07	1999-10-05	−1.67	2000-02-17	−1.09
28	2000-01-26	−0.03	1999-10-12	−2.92	2000-02-22	−0.66
29	2000-01-31	−0.39	1999-11-06	−2.19	2000-03-01	−2.54
30	2000-02-07	−0.58	1999-11-09	−2.53	2000-03-24	−2.69
31	2000-02-21	−0.24	1999-12-31	−0.98	2000-03-29	−1.17
32	2000-03-08	−0.25	2000-02-12	−2.88	2000-05-03	−1.16
33	2000-03-13	−0.17	2000-02-21	−0.09	2000-05-08	−1.38
34	2000-03-24	−1.69	2000-03-01	−0.37	2000-05-11	−0.03
35	2000-03-30	−0.69	2000-03-24	−1.55	2000-05-22	−2.82
36	2000-04-07	−2.01	2000-03-30	−0.38	2000-05-24	−2.80
37	2000-05-03	−1.30	2000-04-04	−0.45	2000-05-27	−0.09
38	2000-05-08	−1.93	2000-04-20	−0.41	2000-07-04	−0.19
39	2000-05-15	−1.15	2000-04-24	−0.12	2000-07-07	−0.06
40	2000-05-30	−1.15	2000-05-08	−1.02	2000-07-11	−2.71
41	2000-08-24	−0.77	2000-05-30	−1.67	2000-08-25	−2.84
42	2000-08-29	−0.63	2000-08-29	−0.20	2000-08-30	−1.88
43	2000-09-03	−0.68	2000-09-03	−0.74	2000-09-02	−1.57
44	2000-09-09	−2.18	2000-09-07	−1.32	2000-09-27	−0.68
45	2000-09-16	−2.21	2000-09-09	−1.92	2000-09-29	−2.68
46	2000-09-29	−0.57	2000-09-15	−1.51	2000-10-05	−0.03
47	2000-10-01	−0.43	2000-10-05	−0.06	2000-10-07	−1.25
48	2000-10-05	−0.40	2000-10-07	−0.76	2000-10-09	−0.31
49	2000-10-07	−0.94	2000-11-01	−2.47	2000-11-01	−2.94
50	2000-10-29	−2.32	2000-11-03	−1.76	2000-11-03	−2.76
51	2000-11-01	−1.03	2000-11-16	−2.37	2000-11-11	−2.55
52	2000-11-04	−0.82	2000-11-23	−0.28	2000-11-14	−0.58
53	2000-11-11	−2.82	2000-12-11	−1.43	2000-12-20	−0.91
54	2000-11-24	−1.03	2000-12-27	−2.75	2000-12-27	−1.47
55	2000-12-11	−1.21	2001-01-03	−0.33	2001-01-25	−0.27
56	2000-12-23	−0.95	2001-01-05	−0.36	2001-01-27	−0.67
57	2000-12-25	−1.32	2001-01-07	−0.26	2001-01-29	−0.65
58	2000-12-27	−1.31	2001-01-09	−0.48	2001-03-28	−2.19
59	2001-01-03	−0.49	2001-01-17	−1.19	2001-04-22	−1.65
60	2001-01-05	−0.18	2001-01-24	−2.37	2001-05-08	−0.75
61	2001-01-09	−0.63	2001-04-01	−2.57	2001-05-15	−1.19
62	2001-01-25	−1.75	2001-04-22	−1.75	2001-06-02	−1.54
63	2001-04-01	−2.86	2001-05-25	−0.72	2001-06-09	−1.18
64	2001-04-05	−2.94	2001-06-20	−0.25	2001-06-12	−2.10
65	2001-04-19	−2.77	2001-07-04	−0.49	2001-06-18	−1.38
66	2001-04-22	−0.52	2001-07-25	−1.00	2001-06-20	−2.57
67	2001-05-25	−1.14	2001-08-03	−1.63	2001-06-23	−0.94
68	2001-07-05	−0.85	2001-08-06	−1.62	2001-07-04	−2.36
69	2001-08-03	−0.85	2001-08-19	−2.62	2001-08-03	−0.73
70	2001-08-06	−0.69	2001-08-23	−2.04	2001-08-18	−1.84
71	2001-08-18	−2.71	2001-09-07	−0.88	2001-08-23	−1.26
72	2001-08-24	−1.69	2001-10-28	−2.91	2001-10-09	−2.43
73	2001-09-07	−1.02	2001-12-07	−2.30	2001-10-26	−1.56
74	2001-10-09	−1.44	2001-12-17	−1.34	2001-10-28	−2.95
75	2001-11-22	−0.81	2002-01-21	−0.51	2001-12-04	−0.29
76	2001-12-04	−1.35	2002-01-24	−0.08	2001-12-07	−2.21
77	2001-12-07	−1.49	2002-01-29	−2.54	2001-12-17	−1.34
78	2001-12-17	−1.26	2002-04-18	−2.46	2001-12-22	−0.60

Table 9
(Continued)

S/N	Date	FDs_{APTY}	Date	FDs_{MOSC}	Date	$FDs_{NV\ BK}$
79	2002-01-21	−0.32	2002-04-24	−2.60	2001-12-27	−0.16
80	2002-01-29	−2.59	2002-05-15	−0.29	2001-12-29	−1.09
81	2002-02-01	−1.97	2002-05-28	−1.46	2002-01-09	−2.15
82	2002-02-05	−1.27	2002-06-11	−0.19	2002-02-12	−2.39
83	2002-03-28	−1.42	2002-07-23	−2.76	2002-02-25	−0.74
84	2002-03-30	−0.78	2002-08-09	−2.89	2002-03-02	−1.18
85	2002-04-18	−1.80	2002-09-03	−2.48	2002-04-01	−1.83
86	2002-04-24	−2.96	2002-09-12	−1.55	2002-04-11	−0.02
87	2002-05-15	−0.16	2002-09-24	−2.90	2002-05-28	−0.14
88	2002-05-20	−1.43	2002-09-28	−0.57	2002-09-21	−1.66
89	2002-05-23	−2.29	2002-10-01	−1.14	2002-09-24	−2.04
90	2002-05-27	−1.12	2002-10-03	−1.19	2002-09-27	−1.19
91	2002-06-11	−0.12	2002-10-25	−1.53	2002-10-01	−1.46
92	2002-06-19	−0.41	2002-11-03	−1.37	2002-10-03	−2.12
93	2002-07-18	−1.61	2002-11-05	−2.77	2002-10-25	−1.58
94	2002-07-23	−2.38	2002-11-25	−0.09	2002-11-03	−1.82
95	2002-08-09	−2.69	2002-11-27	−1.60	2002-11-23	−2.15
96	2002-09-04	−2.39	2002-12-08	−0.09	2002-12-01	−0.17
97	2002-09-11	−2.25	2002-12-14	−0.82	2002-12-09	−2.60
98	2002-09-19	−0.40	2002-12-16	−1.01	2003-01-27	−1.58
99	2002-09-24	−1.76	2002-12-18	−0.91	2003-01-30	−0.23
100	2002-09-28	−0.12	2002-12-20	−1.88	2003-02-03	−2.10
101	2002-10-01	−0.38	2002-12-28	−0.86	2003-02-19	−1.24
102	2002-10-03	−1.71	2003-01-11	−0.78	2003-03-20	−1.28
103	2002-10-22	−2.40	2003-01-24	−2.70	2003-04-11	−2.30
104	2002-10-25	−1.98	2003-02-03	−1.70	2003-04-29	−0.06
105	2002-10-29	−0.72	2003-02-18	−1.34	2003-05-02	−1.13
106	2002-11-03	−2.16	2003-03-20	−0.13	2003-05-07	−0.94
107	2002-11-25	−0.13	2003-04-01	−1.54	2003-05-09	−1.91
109	2002-11-27	−1.43	2003-04-06	−0.39	2003-06-07	−1.92
110	2002-12-08	−0.81	2003-04-23	−1.01	2003-06-10	−2.26
111	2002-12-15	−1.24	2003-04-25	−1.08	2003-07-07	−1.01
112	2002-12-20	−2.58	2003-04-27	−0.95	2003-07-10	−0.42
113	2003-01-24	−1.75	2003-04-30	−1.53	2003-07-14	−1.61
114	2003-02-03	−2.95	2003-05-02	−1.32	2003-07-20	−0.17
115	2003-02-18	−2.18	2003-05-07	−1.18	2003-07-27	−0.86
116	2003-03-20	−2.87	2003-05-09	−1.70	2003-07-30	−1.13
117	2003-03-31	−2.88	2003-06-06	−1.11	2003-08-05	−0.01
118	2003-04-05	−1.05	2003-06-10	−2.20	2003-08-10	−0.08
119	2003-05-02	−1.20	2003-07-04	−0.90	2003-08-18	−1.89
120	2003-05-06	−1.15	2003-07-15	−1.28	2003-09-05	−0.36
121	2003-05-09	−0.77	2003-07-27	−0.92	2003-09-17	−0.50
122	2003-06-10	−1.15	2003-07-30	−0.68	2003-12-22	−2.39
123	2003-06-16	−0.46	2003-08-01	−1.38	2003-12-29	−1.09
124	2003-06-27	−2.65	2003-08-05	−0.35	2004-01-01	−0.21
125	2003-07-03	−1.40	2003-08-09	−0.45	2004-02-10	−1.00
126	2003-07-14	−0.56	2003-08-11	−0.43	2004-02-13	−0.98
127	2003-07-17	−0.27	2003-08-18	−2.43	2004-02-17	−0.10
128	2003-07-30	−0.03	2003-08-22	−0.19	2004-03-01	−0.52
129	2003-08-18	−0.35	2003-08-30	−0.82	2004-07-16	−0.82
130	2003-10-22	−1.88	2003-10-23	−0.62	2004-08-15	−0.32
131	2003-12-19	−2.01	2003-12-20	−0.05	2004-08-17	−0.61
132	2003-12-23	−1.68	2003-12-23	−1.50	2004-09-22	−1.95
133	2003-12-25	−2.40	2003-12-28	−0.09	2004-12-08	−1.74
134	2003-12-28	−1.56	2004-01-18	−0.36	2004-12-13	−0.50
135	2004-01-04	−1.90	2004-02-10	−0.58	2004-12-15	−0.57
136	2004-02-15	−0.47	2004-02-13	−0.11	2004-12-29	−2.16
137	2004-07-17	−1.48	2004-03-01	−0.02	2004-12-31	−1.75
138	2004-07-20	−0.05	2004-04-04	−0.77	2005-01-31	−1.23

Table 9
(Continued)

S/N	Date	FDs_{APTY}	Date	FDs_{MOSC}	Date	$FDs_{NV\ BK}$
139	2004-08-22	−0.31	2004-08-15	−0.34	2005-02-02	−1.56
140	2004-09-15	−2.87	2004-08-17	−1.41	2005-02-04	−0.68
141	2004-09-18	−2.53	2004-08-22	−1.14	2005-02-08	−1.46
142	2004-09-22	−2.53	2004-09-15	−2.60	2005-02-19	−2.09
143	2004-12-06	−2.11	2004-09-18	−2.65	2005-02-24	−1.67
144	2004-12-08	−1.22	2004-09-22	−0.66	2005-03-03	−0.18
145	2004-12-11	−0.82	2004-12-09	−0.89	2005-03-07	−0.98
146	2004-12-14	−2.34	2004-12-13	−1.20	2005-03-21	−0.35
147	2004-12-30	−2.13	2004-12-29	−2.18	2005-06-13	−0.21
148	2005-01-28	−2.29	2005-01-28	−2.44	2005-07-11	−0.87
149	2005-01-31	−2.64	2005-01-31	−2.02	2005-07-13	−2.89
150	2005-02-02	−2.49	2005-02-02	−1.72	2005-07-23	−0.77
151	2005-02-11	−1.06	2005-02-04	−1.22	2005-07-26	−0.18
152	2005-02-19	−1.76	2005-02-08	−1.57	2005-07-30	−2.68
153	2005-03-21	−0.12	2005-02-16	−0.45	2005-10-10	−1.90
154	2005-05-30	−2.41	2005-02-19	−1.30	2005-10-17	−0.24
155	2005-06-17	−1.44	2005-02-22	−1.47	2005-12-15	−1.29
156	2005-07-13	−2.81	2005-03-03	−0.23	2005-12-21	−1.92
157	2005-07-23	−0.19	2005-03-06	−0.88	2005-12-28	−0.37
158	2005-07-30	−1.40	2005-03-21	−0.54	2006-01-05	−2.43
159	2005-08-03	−2.60	2005-03-25	−0.44	2006-01-09	−1.28
160	2005-08-13	−2.34	2005-03-29	−0.62	2006-01-14	−1.40
161	2005-08-16	−2.03	2005-05-12	−1.88	2006-01-17	−0.44
162	2005-08-19	−0.61	2005-05-30	−2.49	2006-01-25	−0.04
163	2005-08-31	−2.08	2005-06-01	−0.95	2006-01-30	−0.18
164	2005-10-01	−2.31	2005-06-13	−0.78	2006-02-06	−0.37
165	2005-10-05	−0.29	2005-07-11	−0.85	2006-02-10	−0.65
166	2005-10-12	−2.39	2005-07-13	−2.35	2006-02-21	−0.18
167	2005-10-17	−0.10	2005-07-30	−1.97	2006-03-01	−0.86
168	2005-10-21	−0.29	2005-08-14	−2.31	2006-03-03	−0.80
169	2005-10-31	−0.69	2005-08-16	−2.12	2006-03-12	−1.84
170	2005-12-03	−0.30	2005-08-21	−0.35	2006-03-16	−0.26
171	2005-12-12	−1.23	2005-08-31	−1.19	2006-07-14	−2.60
172	2005-12-16	−1.67	2005-10-17	−0.70	2006-07-17	−0.81
173	2005-12-21	−1.07	2005-10-20	−0.03	2006-07-19	−0.81
174	2005-12-24	−0.48	2005-10-23	−0.56	2006-07-28	−0.34
175	2005-12-28	−0.63	2005-10-29	−0.50	2006-08-03	−0.26
176	2006-01-05	−1.90	2005-11-07	−2.51	2006-08-08	−0.18
177	2006-01-10	−0.03	2005-11-12	−1.21	2006-08-18	−1.41
178	2006-01-25	−1.29	2005-11-21	−1.79	2006-09-12	−1.28
179	2006-05-07	−0.27	2005-11-24	−1.51	2006-09-16	−1.65
180	2006-06-17	−0.39	2005-11-27	−0.70	2006-09-18	−2.25
181	2006-07-14	−2.83	2005-12-04	−1.53	2006-09-25	−0.69
182	2006-07-17	−1.49	2005-12-06	−2.12	2006-10-01	−1.22
183	2006-07-25	−0.31	2005-12-09	−1.33	2006-10-09	−0.08
184	2006-07-28	−1.00	2005-12-12	−2.35	2006-10-14	−0.59
185	2006-07-31	−0.48	2005-12-16	−1.68	2006-10-23	−1.08
186	2006-08-04	−0.30	2005-12-20	−2.30	2006-10-29	−0.56
187	2006-08-08	−1.23	2005-12-22	−2.59	2006-11-11	−2.10
188	2006-08-11	−0.36	2005-12-24	−2.23	2006-11-15	−0.93
189	2006-08-27	−0.86	2006-01-04	−0.92	2006-11-29	−0.84
190	2006-08-30	−2.71	2006-01-10	−0.81	2006-12-24	−1.53
191	2006-09-01	−2.24	2006-02-15	−0.02	2006-12-27	−1.37
192	2006-09-04	−2.95	2006-07-14	−2.94		
193	2006-09-09	−0.86	2006-08-18	−0.67		
194	2006-09-12	−0.49	2006-08-31	−1.78		
195	2006-09-18	−1.35	2006-09-04	−2.05		
196	2006-09-25	−0.18	2006-10-01	−0.56		
197	2006-10-01	−0.59	2006-10-14	−0.28		

Table 9
(Continued)

S/N	Date	FDs_{APTY}	Date	FDs_{MOSC}	Date	$FDs_{NV\ BK}$
198	2006-10-14	−0.12	2006-10-22	−0.41		
199	2006-11-11	−1.22	2006-10-27	−0.15		
200	2006-11-15	−1.74	2006-10-30	−0.09		
201	2006-11-25	−0.08	2006-11-11	−1.51		
202	2006-11-29	−0.29	2006-11-15	−1.34		
203	2006-12-04	−0.04	2006-11-19	−0.13		
204	2006-12-26	−0.41	2006-11-26	−0.50		
205			2006-11-29	−1.61		
206			2006-12-02	−0.11		

Table 10
Small-Amplitude FDs Observed by High-Altitude (Above 1000 m) NMs Between 1999–2006

S/N	Date	FDs_{CALG}	Date	FDs_{CLMX}	Date	FDs_{ESOI}
1	1999-03-04	−1.40	1999-01-14	−0.25	1999-02-15	−2.44
2	1999-03-07	−1.23	1999-01-16	−0.29	1999-03-03	−0.16
3	1999-03-10	−1.12	1999-01-18	−0.45	1999-03-07	−0.03
4	1999-04-30	−0.91	1999-03-04	−0.37	1999-03-30	−0.58
5	1999-05-07	−2.48	1999-03-06	−0.81	1999-04-12	−0.33
6	1999-05-30	−1.73	1999-03-09	−0.33	1999-04-15	−0.86
7	1999-07-02	−1.46	1999-03-11	−0.36	1999-05-07	−1.08
8	1999-09-07	−2.17	1999-03-20	−2.06	1999-05-24	−0.72
9	1999-09-10	−0.47	1999-03-24	−2.08	1999-08-21	−1.69
10	1999-10-28	−2.70	1999-04-12	−0.71	1999-09-02	−1.58
11	1999-11-09	−1.15	1999-04-16	−0.86	1999-09-06	−2.82
12	1999-12-05	−2.17	1999-04-19	−0.68	1999-09-08	−2.84
13	2000-01-04	−0.32	1999-04-22	−1.21	1999-09-25	−2.94
14	2000-01-24	−0.15	1999-04-27	−0.05	1999-09-29	−1.72
15	2000-02-19	−2.61	1999-05-10	−1.90	1999-10-05	−0.59
16	2000-03-01	−1.67	1999-05-24	−2.25	1999-10-11	−0.94
17	2000-03-09	−0.60	1999-05-29	−0.70	1999-10-31	−2.74
18	2000-03-13	−0.44	1999-05-31	−0.65	1999-11-03	−0.83
19	2000-03-16	−1.98	1999-06-03	−0.50	1999-11-10	−1.63
20	2000-03-27	−0.50	1999-06-06	−0.53	1999-11-12	−1.60
21	2000-03-30	−0.39	1999-06-28	−1.56	1999-11-14	−1.74
22	2000-04-04	−2.01	1999-08-22	−2.35	1999-11-18	−2.30
23	2000-05-09	−0.85	1999-08-25	−2.04	1999-11-22	−2.92
24	2000-05-30	−0.08	1999-09-07	−0.48	1999-11-24	−2.25
25	2000-08-25	−2.70	1999-09-16	−1.36	1999-11-27	−1.08
26	2000-10-08	−0.44	1999-09-21	−1.30	1999-12-03	−2.22
27	2000-11-04	−2.76	1999-09-29	−0.49	1999-12-05	−1.54
28	2000-11-15	−0.30	1999-10-17	−2.17	2000-02-12	−0.56
29	2000-12-27	−1.73	1999-10-21	−2.51	2000-03-01	−0.12
30	2001-01-02	−2.38	1999-10-25	−1.60	2000-03-28	−0.33
31	2001-01-05	−1.20	1999-10-31	−1.35	2000-03-30	−0.12
32	2001-01-09	−0.70	1999-11-06	−0.05	2000-05-03	−1.64
33	2001-01-18	−1.00	1999-11-12	−1.20	2000-05-08	−2.93
34	2001-01-29	−1.97	1999-11-14	−1.46	2000-05-15	−0.39
35	2001-04-22	−2.88	1999-11-17	−1.51	2000-05-30	−1.70
36	2001-05-04	−1.54	1999-11-20	−2.11	2000-06-24	−2.81
37	2001-06-02	−0.58	1999-11-23	−1.23	2000-06-26	−2.36
38	2001-06-04	−0.62	1999-11-27	−0.32	2000-07-02	−1.33
39	2001-07-04	−1.54	1999-12-03	−1.19	2000-07-04	−0.89
40	2001-08-04	−2.44	1999-12-05	−0.51	2000-07-06	−1.03

Table 10
(Continued)

S/N	Date	FDs_{CALG}	Date	FDs_{CLMX}	Date	FDs_{ESOI}
41	2001-08-07	−0.55	1999-12-27	−1.89	2000-08-24	−0.26
42	2001-09-07	−0.25	2000-01-04	−0.21	2000-09-03	−0.72
43	2001-10-20	−0.30	2000-01-07	−0.05	2000-09-07	−2.06
44	2002-01-21	−1.22	2000-01-24	−0.04	2000-09-09	−1.36
45	2002-03-31	−0.87	2000-02-13	−0.94	2000-09-13	−1.33
46	2002-06-11	−1.49	2000-03-01	−0.13	2000-10-30	−1.03
47	2002-08-16	−2.34	2000-03-13	−0.08	2000-11-01	−0.36
49	2003-02-02	−2.19	2000-03-30	−0.24	2000-11-11	−1.54
50	2003-03-31	−1.86	2000-04-04	−0.38	2000-12-11	−1.44
51	2003-04-05	−1.34	2000-04-08	−0.65	2000-12-15	−0.56
52	2003-05-02	−1.92	2000-05-03	−0.94	2000-12-17	−0.64
53	2003-07-17	−0.37	2000-05-09	−1.39	2000-12-21	−2.15
54	2003-07-27	−1.31	2000-05-15	−0.96	2000-12-25	−2.54
55	2003-07-30	−0.60	2000-05-30	−0.72	2000-12-27	−2.62
56	2003-08-18	−2.27	2000-06-21	−2.34	2000-12-31	−0.33
57	2003-08-20	−0.01	2000-06-24	−2.17	2001-01-02	−0.68
58	2003-09-09	−0.56	2000-06-26	−1.68	2001-01-06	−0.34
58	2003-09-12	−0.42	2000-08-02	−1.57	2001-01-18	−1.11
59	2003-12-23	−1.17	2000-08-25	−0.64	2001-01-24	−2.61
60	2004-07-20	−2.76	2000-08-30	−0.40	2001-01-30	−0.38
61	2004-08-17	−1.07	2000-09-03	−0.43	2001-02-01	−0.77
62	2004-08-22	−2.37	2000-09-08	−1.11	2001-02-04	−0.34
63	2004-12-06	−2.85	2000-09-10	−1.09	2001-04-02	−0.11
64	2004-12-09	−0.10	2000-09-12	−1.21	2001-04-19	−2.68
65	2004-12-14	−1.42	2000-09-15	−1.96	2001-05-25	−2.07
66	2005-02-24	−0.98	2000-09-27	−0.16	2001-06-20	−0.10
67	2005-03-21	−2.12	2000-09-29	−0.32	2001-06-22	−0.12
68	2005-03-29	−0.17	2000-10-07	−0.75	2001-07-04	−0.05
69	2005-06-02	−1.24	2000-10-29	−1.68	2001-08-03	−0.78
70	2005-06-13	−0.88	2000-11-02	−0.75	2001-08-18	−1.48
71	2005-08-21	−0.80	2000-11-04	−0.77	2001-08-23	−1.05
72	2005-11-07	−0.24	2000-11-07	−2.88	2001-10-12	−1.75
73	2005-12-12	−0.51	2000-11-11	−1.20	2001-11-07	−1.81
74	2005-12-21	−1.44	2000-11-14	−0.71	2001-11-22	−0.64
75	2006-01-05	−2.66	2000-11-16	−0.60	2001-12-17	−2.08
76	2006-03-01	−0.37	2000-11-24	−0.27	2001-12-29	−1.47
77	2006-04-14	−1.49	2000-12-22	−0.25	2002-01-22	−1.37
78	2006-05-19	−0.28	2000-12-27	−0.86	2002-01-24	−0.62
79	2006-06-09	−1.52	2001-01-24	−1.08	2002-02-23	−0.01
80	2006-06-15	−1.59	2001-02-01	−0.30	2002-03-02	−1.51
81	2006-07-07	−2.64	2001-04-01	−1.03	2002-03-05	−0.25
82	2006-07-26	−1.17	2001-04-05	−1.84	2002-03-07	−0.53
83	2006-07-28	−2.43	2001-04-19	−1.83	2002-03-12	−0.04
84	2006-07-31	−0.21	2001-04-22	−0.76	2002-03-31	−2.51
85	2006-08-04	−0.22	2001-05-04	−0.52	2002-04-18	−0.30
86	2006-08-08	−1.68	2001-05-26	−0.99	2002-04-20	−2.09
87	2006-08-28	−2.03	2001-05-28	−2.40	2002-04-24	−2.15
88	2006-09-11	−1.08	2001-06-20	−0.01	2002-04-27	−1.71
89	2006-09-26	−1.14	2001-07-04	−0.32	2002-05-12	−0.44
90	2006-09-28	−0.52	2001-08-04	−0.81	2002-05-15	−2.13
91	2006-10-01	−2.11	2001-08-07	−0.02	2002-05-21	−2.50
92	2006-10-14	−0.98	2001-08-18	−1.69	2002-05-26	−2.25
93	2006-10-22	−2.22	2001-08-23	−0.92	2002-05-28	−2.08
94	2006-11-24	−0.59	2001-10-09	−1.41	2002-06-11	−0.06
95	2006-11-27	−0.19	2001-10-12	−2.87	2002-07-11	−0.05
96	2006-11-29	−2.79	2001-10-22	−1.86	2002-07-23	−2.49
97			2001-10-26	−0.93	2002-08-07	−2.64
98			2001-10-28	−1.20	2002-08-11	−0.60
99			2001-11-06	−2.91	2002-09-03	−1.50

Table 10
(Continued)

S/N	Date	FDs_{CALG}	Date	FDs_{CLMX}	Date	FDs_{ESOI}
100			2001-12-07	−0.84	2002-09-06	−0.91
101			2001-12-17	−0.64	2002-09-08	−2.10
102			2002-01-12	−2.76	2002-09-12	−0.88
103			2002-01-19	−0.06	2002-09-21	−1.32
104			2002-01-21	−0.72	2002-09-23	−1.53
105			2002-01-25	−0.37	2002-09-27	−0.78
106			2002-01-29	−1.71	2002-10-03	−2.02
107			2002-02-01	−2.13	2002-10-25	−1.15
108			2002-03-22	−2.69	2002-11-05	−0.16
109			2002-03-25	−2.67	2002-12-09	−0.81
110			2002-03-31	−0.56	2002-12-15	−1.56
111			2002-04-20	−1.47	2002-12-18	−2.41
112			2002-04-24	−1.90	2002-12-20	−1.81
113			2002-04-30	−0.15	2002-12-28	−0.80
114			2002-05-15	−0.11	2003-01-04	−1.85
115			2002-05-20	−1.42	2003-01-15	−0.96
116			2002-05-23	−2.54	2003-01-21	−2.11
117			2002-05-28	−0.94	2003-02-03	−2.10
118			2002-06-11	−0.14	2003-02-18	−2.57
119			2002-07-18	−0.07	2003-02-20	−2.77
120			2002-07-20	−2.05	2003-03-14	−0.03
121			2002-07-24	−1.64	2003-03-16	−0.27
122			2002-08-07	−2.44	2003-03-20	−1.43
123			2002-08-23	−2.83	2003-03-31	−1.56
124			2002-08-26	−2.95	2003-04-11	−2.94
125			2002-09-03	−1.37	2003-04-14	−1.25
126			2002-09-08	−1.87	2003-05-02	−1.19
127			2002-09-12	−0.89	2003-05-06	−0.40
128			2002-09-23	−1.28	2003-05-09	−0.79
129			2002-09-28	−0.62	2003-05-28	−0.51
130			2002-10-01	−0.06	2003-06-08	−1.69
131			2002-10-03	−0.41	2003-06-11	−2.02
132			2002-10-21	−1.84	2003-06-16	−2.48
133			2002-10-25	−0.81	2003-06-28	−2.57
134			2002-11-03	−1.04	2003-07-03	−3.00
135			2002-11-06	−1.35	2003-07-15	−0.79
136			2002-11-12	−2.22	2003-07-17	−0.33
137			2002-11-28	−0.79	2003-07-22	−0.24
138			2002-12-09	−0.60	2003-07-27	−0.31
139			2002-12-14	−0.90	2003-07-30	−0.04
140			2002-12-18	−1.06	2003-08-17	−0.34
141			2002-12-20	−1.16	2003-09-05	−0.63
142			2002-12-23	−2.10	2003-09-12	−1.54
143			2003-01-24	−0.32	2003-09-17	−1.40
144			2003-01-27	−1.73	2003-10-23	−2.48
145			2003-02-02	−0.94	2003-11-30	−2.47
146			2003-02-18	−1.24	2003-12-04	−2.30
147			2003-03-20	−0.63	2003-12-08	−1.64
148			2003-03-31	−0.55	2003-12-10	−1.65
149			2003-04-11	−1.93	2003-12-12	−1.11
150			2003-04-24	−0.95	2003-12-15	−0.44
151			2003-04-27	−0.30	2003-12-22	−0.52
152			2003-04-29	−0.53	2003-12-24	−0.16
153			2003-05-02	−1.02	2004-01-05	−1.71
154			2003-05-06	−0.57	2004-01-17	−0.10
155			2003-05-09	−0.98	2004-02-06	−2.94
156			2003-06-06	−0.72	2004-03-02	−0.09
157			2003-06-11	−1.27	2004-06-20	−0.01
158			2003-06-16	−1.19	2004-07-01	−0.24

Table 10
(Continued)

S/N	Date	FDs_{CALG}	Date	FDs_{CLMX}	Date	FDs_{ESOI}
159			2003-06-30	−1.81	2004-07-12	−0.18
160			2003-07-03	−1.24	2004-07-16	−0.88
161			2003-07-10	−0.51	2004-07-18	−0.09
162			2003-07-14	−0.79	2004-07-20	−0.11
163			2003-07-27	−0.44	2004-08-17	−0.59
164			2003-07-30	−0.11	2004-09-15	−2.25
165			2003-10-23	−1.28	2004-09-19	−0.99
166			2003-10-25	−2.95	2004-09-22	−0.36
167			2003-12-10	−1.75	2004-11-17	−0.01
168			2003-12-16	−0.58	2004-12-01	−0.05
169			2003-12-23	−0.46	2004-12-06	−1.56
170			2004-01-04	−0.53	2004-12-08	−2.48
171			2004-01-30	−2.09	2004-12-11	−0.64
172			2004-02-06	−1.60	2004-12-25	−1.58
173			2004-07-17	−0.38	2004-12-27	−1.34
174			2004-07-20	−0.15	2004-12-29	−1.01
175			2004-09-15	−1.61	2005-01-28	−2.41
176			2004-09-17	−1.50	2005-02-28	−2.45
177			2004-09-19	−1.19	2005-03-04	−0.67
178			2004-09-22	−0.87	2005-03-06	−0.74
179			2004-12-14	−0.23	2005-03-09	−0.35
180			2004-12-29	−0.43	2005-03-13	−0.52
181			2004-12-31	−0.10	2005-03-17	−0.14
182			2005-01-09	−2.43	2005-03-21	−2.02
183			2005-01-14	−0.57	2005-03-23	−1.94
184			2005-01-28	−1.26	2005-03-27	−1.49
185			2005-01-31	−0.57	2005-03-29	−1.60
186			2005-02-03	−0.54	2005-05-09	−1.81
187			2005-02-11	−0.75	2005-05-13	−0.41
188			2005-02-19	−0.94	2005-05-30	−1.11
189			2005-02-23	−0.52	2005-06-12	−0.24
190			2005-03-21	−0.07	2005-06-17	−0.91
191			2005-03-29	−0.09	2005-06-20	−0.99
192			2005-05-09	−2.91	2005-10-02	−0.65
193			2005-05-30	−0.47	2005-10-04	−0.18
194			2005-06-17	−1.13	2005-10-10	−2.73
195			2005-07-13	−1.77	2005-10-22	−1.64
196			2005-08-03	−1.68	2005-10-26	−0.60
197			2005-08-11	−1.98	2005-10-30	−0.03
198			2005-08-13	−1.44	2005-11-07	−0.31
199			2005-08-21	−0.33	2005-11-23	−0.11
200			2005-08-31	−0.38	2005-12-03	−0.88
201			2005-09-05	−1.50	2005-12-07	−0.15
202			2005-09-25	−2.10	2005-12-10	−0.40
203			2005-09-28	−1.48	2005-12-15	−1.37
204			2005-10-01	−1.02	2005-12-18	−1.00
205			2005-10-10	−1.41	2005-12-21	−1.05
206			2005-12-21	−0.66	2006-01-02	−0.91
207			2005-12-24	−0.29	2006-01-06	−0.06
208			2006-01-01	−1.79	2006-01-11	−0.27
209			2006-01-05	−1.29	2006-01-14	−0.27
210			2006-01-10	−0.38	2006-01-16	−0.31
211			2006-01-25	−0.14	2006-01-27	−1.08
212			2006-04-14	−0.09	2006-03-15	−0.37
213			2006-05-07	−0.57	2006-03-26	−0.08
214			2006-05-13	−0.64	2006-04-05	−0.97
215			2006-05-15	−0.69	2006-05-07	−0.29
216			2006-05-19	−1.01	2006-06-01	−0.12
217			2006-05-23	−0.53	2006-06-07	−0.02

Table 10
(Continued)

S/N	Date	FDs_{CALG}	Date	FDs_{CLMX}	Date	FDs_{ESOI}
218			2006-06-01	−0.57	2006-07-04	−1.02
219			2006-06-04	−0.55	2006-07-07	−1.15
220			2006-06-09	−0.48	2006-07-14	−2.85
221			2006-06-13	−0.14	2006-07-19	−1.36
222			2006-06-15	−0.03	2006-07-24	−0.50
223			2006-06-17	−0.28	2006-07-28	−0.73
224			2006-06-19	−0.05	2006-08-02	−2.29
225			2006-07-17	−1.34	2006-08-04	−2.33
226			2006-07-19	−1.11	2006-08-06	−2.08
227			2006-07-24	−0.42	2006-08-08	−1.90
228			2006-07-26	−0.65	2006-08-11	−1.47
229			2006-07-31	−0.29	2006-09-03	−2.29
230			2006-08-02	−0.20	2006-09-08	−0.96
231			2006-08-06	−0.06	2006-09-11	−1.16
232			2006-08-08	−0.33	2006-09-17	−1.69
233			2006-08-17	−0.45	2006-09-20	−1.30
234			2006-08-22	−2.15	2006-09-25	−1.78
235			2006-08-31	−1.35	2006-09-28	−1.60
236			2006-09-03	−1.44	2006-09-30	−1.35
237			2006-09-10	−0.39	2006-10-03	−0.81
238			2006-09-12	−0.27	2006-10-11	−0.82
239			2006-09-19	−0.38	2006-10-14	−1.34
240			2006-10-14	−0.07	2006-10-20	−0.91
241			2006-10-23	−0.29	2006-10-27	−0.66
242			2006-10-27	−0.22	2006-10-30	−0.01
243			2006-11-07	−0.11	2006-11-06	−0.42
244			2006-11-12	−0.58	2006-11-11	−0.89
245			2006-11-15	−0.97	2006-11-15	−1.84
246			2006-11-19	−0.26	2006-12-03	−0.04
247			2006-11-22	−0.45		

parameters on FDs, indicating that small-amplitude FD events may be related to a combination of geomagnetic activity and SWS on individual NMs. Consequently, the intensity of solar-terrestrial parameters contributes significantly to the occurrence of small FDs. The relations between small FDs and solar/terrestrial parameters vary between locations/altitude bands. Whereas all the variables at the low-altitude band (Figure 6) show statistically significant relation with small FDs (except at OULU), only a few of the variables (e.g., IMF and AP at CLMX at high-altitude band) show significant ccs with FDs at mid- and high-altitudes. The results presented suggest that understanding the factors that influence small-amplitude FDs at different locations should be given more detailed attention. Rather than either of the interplanetary/terrestrial agents playing a significant role, a combination of these parameters may be important. Thus, the two-variable regression model employed here may not be suitable for analysis of the influence of these parameters on small FDs. The multivariable regression model employed by Okike & Alhassan (2022b) may be useful here.

5. Discussion and Conclusion

The 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, the 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 the accuracy and comprehensiveness of the FD catalogs utilized. This study emphasizes the importance of developing accurate FD catalogs and encourages a rigorous comparison of existing event catalogs prior to conducting subsequent analyses. The detailed investigations in this work highlight the 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 the raw CR data are influenced by superposed signals such as CR anisotropy and the 11 yr solar cycle. Failure to account for these effects introduces significant biases into FD catalogs. This study demonstrates that signal decomposition is essential for isolating the FD signal 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 the onset to the FD minimum, this methodology eliminates biases and ensures that events are neither missed nor mischaracterized. Furthermore, these algorithms are designed to process large volumes of CR data rapidly and systematically, enabling scalability as the number of monitoring stations and data resolution increase. The methodology allows for other researchers to replicate and extend the FD catalog 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 the period 1999–2006. Using this methodology, a total of 1959 small-amplitude FDs were detected, with the stations grouped into low, mid, and high-altitude categories. The distribution of FDs among these groups comprised 766, 601, and 589 events, respectively. Additionally, a simple coincident detection algorithm was employed to identify FDs that are simultaneous across each NM group. This approach identified 80, 38, and 19 simultaneous small-amplitude FDs in the low, mid, and high-altitude NMs, respectively. This coincident algorithm effectively demonstrated that simultaneous FD detection across NMs is obtainable. Assuming that FDs are a global phenomenon, the 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 that the relations should be investigated using a multivariate regression model. Some of the interplanetary data like SWS and IMF are factors that mutually influence CR intensity modulations.

Finally, the reliability of studies examining the relationship between solar events, space weather parameters, and FDs fundamentally depends on the accuracy of the FD catalog used. To enhance the robustness of investigations into FDs and their terrestrial impacts, future research should focus on detailed quantitative analyses of the effects of superposed signals on the magnitude, timing, and frequency of FDs events. This approach will ensure more elaborate and meaningful interpretations of the connection between FDs and solar-terrestrial interactions. Additionally, the catalogs of the simultaneous small FDs in the different altitude ranges could be used to conduct some further investigations.

Acknowledgments

We thank the anonymous referee for a very careful review, with helpful and constructive comments. The authors also acknowledge the use of the http://cr0.izmiran.rssi.ru/ and https://omniweb.gsfc.nasa.gov/html/owdata.html. We appreciate the teams hosting these websites. EUI acknowledges support from GRAO/GSSTI through the Development in Africa with Radio Astronomy (DARA) project Phase 3 funded by the UK's Science and Technologies Facilities Council (Reference number ST/Y006100/1).

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

EUI: Conceptualization, data analysis, interpretation of results, and writing original draft. OO: Data curation, methodology, software, reviewing and interpretation of results. IOE: Data analysis, writing review and editing. EA: Editing, reviewing, administration. DYK: Reviewing and editing. FMM: Data analysis. CJU: Data compilation, investigation and editing. DCO: Data analysis. PIA: editing and reviewing. REU: Data compilation and graph plotting. JAA: Editing. AEC: Validation and editing. PAN: Resources and editing.

Data Availability Statement

The data sample used in the paper are available at http://cr0.izmiran.rssi.ru/, https://omniweb.gsfc.nasa.gov/form/dx1.html and http://spaceweather.izmiran.ru/eng/FDs2003.html

References

Abunina, M. A., Belov, A. V., Eronshenko, E. A., et al. 2020, SoPh, 295, 69
Alhassan, J. A., Okike, O., & Chukwude, A. E. 2022, RAA, 5, 055014
Badruddin, & Singh, Y. P. 2006, in ILWS Workshop on Solar Influence on the Heliosphere and Earth's Environment (Goa, India) (Goa: ILWS) pp.182–188
Barnden, L. 1973, ICRC, 2, 1277
Barouch, E., & Burlaga, L. 1975, JGR, 4, 449
Barouch, E., & Bdoiaga, L. F. 1975, JGR, 80, 449
Bartels, J. 1935, JGR, 1, 1
Belov, A. V. 2009, in IAU Symp., 257, 257
Belov, A., Eronshenko, E., et al. 2018, SoPh, 293, 68
Belov, A., Eroshenko, E. A., Yanke, V. G., et al. 2018a, Ge&Ae, 58, 356
Belov, A. V., Eroshenko, E. A., Oleneva, V. A., Struminsky, A. B., & Yanke, V. G. 2001, AdSpR, 27, 625
Cane, H. 2000, SSRv, 93, 55
Cane, H., Richardson, I. G., & von Rosenvinge, T. T. 1993, JGR, 98, 13295
Dumbovic, M., Vrsnak, B., Calogovic, J., & Karlica, M. 2011, A&A, 531, 1
Dumbovic, M., Kramaric, L., Benko, I., Heber, B., & Vrsnak, B. 2024, A&A, 683, 168
Forbush, S. E. 1937, PhRv, 51, 1108
Geppener, V., & Mandrilava, B. 2020, in XI International Conf. "Solar-Terrestrial Relations and Physics of Earthquake Precursors", 196 (Les Ulis Cedex: E3S Web Conf.), 02003
Geppener, V., & Mandrilava, B. 2021, CMMPh, 61, 1129

Harrison, R., & Ambaum, M. 2010, JASTP, 72, 1408
Harrison, R. G., & Ambaum, M. H. P. 2011, RSPSA, 467, 2777
Hess, V. F., & Demmelmair, A. 1937, Natur, 503, 316
Iyida, E.U., Odo, F.C., Chukwude, A.E., & Ubachukwu, A.A. 2022, NewA, 90, 101666
Kristjansson, J.E., Stjern, C.W., Stordal, F., et al. 2008, ACPD, 8, 13265
Laken, B. A., Palle, E., Calogovic, J., & Dunne, E. 2012, JSWSC, 2, A18
Light, C., Bindi, V., Consolandi, C., et al. 2020, ApJ, 896, 133
Lingri, D., Mavromichalaki, H., Belov, A., et al. 2016, SoPh, 291, 1025
Lockwood, J. A. 1971, SSRv, 12, 658
Lockwood, J. A. 1990, Solar Geophysical Data, 54, 233
Mandrikova, O. V., Madrikova, B. S., & Stepanenko, A. A. 2025, in press
Menteso, F., Chukwu, A., Okike, O., & Alhassan, J. 2023, MNRAS, 521, 6330
Oh, S., & Yi, Y. 2008, SSRv, 118, 608
Oh, S., Yi, Y., & Kim, H. Y. 2008, JGR, 113, A01103
Okike, O. 2019, JGRA, 124, 3910
Okike, O. 2020a, DIB, 33, 106463
Okike, O. 2020b, MNRAS, 491, 3793
Okike, O. 2020c, JASTP, 211, 105460
Okike, O. 2020d, DIB, 33, 106463
Okike, O. 2021a, ApJ, 60
Okike, O. 2021b, ApJ, 915, 60
Okike, O., & Collier, A. B. 2011, JASTP, 73, 796
Okike, O., & Colliner, A. 2011, JASTP, 73, 796
Okike, O., & Umahi, A. E. 2019a, JASTP, 189, 35
Okike, O., & Umahi, A. E. 2019b, SoPh, 294, 1
Okike, O., & Umahi, A. E. 2019c, SoPh, 294, 16
Okike, O., & Nwuzor, O. C. 2020, MNRAS, 493, 1948
Okike, O., & Alhassan, J. A. 2022a, EPJP, 137, 317
Okike, O., & Alhassan, J. A. 2022b, EPJP, 137, 317
Okike, O., & Menteso, F. M. 2024a, RASTI, 3, 853
Okike, O., & Menteso, F. M. 2024b, EPJP, 396
Okike, O., Nwuzor, O. C., Odo, F. C., et al. 2021, MNRAS, 502, 300
Pavlidou, V., Richards, J.L., Max-Moerbeck, W., et al. 2012, ApJ, 751, 149
Pittock, A.B, 1978, RvGSP, 16, 400
Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., 1994. Numerical Recipes in Fortran, The Art of Scientific Computing (Cambridge: Cambridge Univ. Press)
Pudovkin, M. I., & Veretenenko, S. V. 1995, JATP, 57, 1349
Pyle, K. R. 1997, in 25th Conf. in the ICRC Series (Geneva: ICRC)
Raghav, A., Bhaskar, A., Lotekar, A., Vichare, G., & Yadav, V. 2014, JCAP, 2014, 074
Ramirez, O. O. U., Galicia, J. F., Munoz, G., Huttunen, E., et al. 2013, in 33rd ICRC, 66 (Rio de Janeiro: ICRC), 450
R Core Team, 2014 R: A language and Environment for Statistical Computing, Available at: https://www.R-project.org/
Tinsley, B. A., & Deen, G. W. 1991, JGR, 96, 22283
Ugwoke, R.E., Ubachukwu, A.A., & Urama, J.O. 2022a, RAA, 22, 105008
Ugwu, J. C., Ogbonnaya, O., Menteso, F. M., et al. 2024, Ap&SS, 369, 45
Vaisanen, P., Usoskin, I., & Mursula, K. 2021, JGRA, 126, e28941
Van Allen, J. 1993, GeoRL, 20, 2797
Wang, S., Bindi, V., Consolandi, C., et al. 2023, ApJ, 950, 23