Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v35(s).2026.698
Volume 35(S), 2026

The Implication of Solar-Geophysical Parameters on Small-Amplitude Forbush Decreases

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Keywords:
Cosmic Rays,
Forbush Decreases,
Small-Amplitude Events,
Manual Method,
Automated Method,
Cosmic Ray Stations

Submitted: 12 Aug. 2026

Accepted: 20 Aug. 2026

Published: 16 Sept. 2026

ABSTRACT

Forbush decreases (FDs) are rapid, short-term reductions in cosmic ray (CR) intensity, frequently used in space weather research. However, identifying and calculating the magnitude and timing of these events remains a significant challenge. The current manual approach is subjective and inefficient, as it cannot process large datasets. Consequently, automated methods for FD selection are necessary to overcome the limitations of manual event lists. Our group has published a fully automated Forbush decrease (FD) event list, comprising high- and low-amplitude events recorded by the Moscow and Oulu neutron monitors. This catalog facilitates statistical investigations into the relationship between FDs and solar-geomagnetic variables. In this study, we analyze the small-amplitude events and demonstrate that Earth's atmospheric phenomena modulate weak FDs, whereas interplanetary magnetic field conditions appear to have a lesser effect.

INTRODUCTION

Forbush decreases (FDs) are abrupt reductions in the flux of cosmic rays (CRs) (Oh et al. 2008; Oh & Yi 2009). They represent the most significant variations in CR time-intensity flux (Ramirez et al. 2013). Their investigation is of great interest due to their impact on short-term atmospheric weather and climate changes (Dorman & Dorman 2005; Okike & Collier 2011; Okike 2019a; Okike & Umahi 2019). This is because they are associated with hazardous solar phenomena, such as Earth-directed coronal mass ejections (Dorman et al. 2008; Oh & Yi 2012; Belov et al. 2014; Okike et al. 2020). FDs consist of four parts: onset, main phase, FD minimum, and recovery phase. Oh et al. (2008) and Okike and Nwuzor (2020) present an interesting representation of these events.

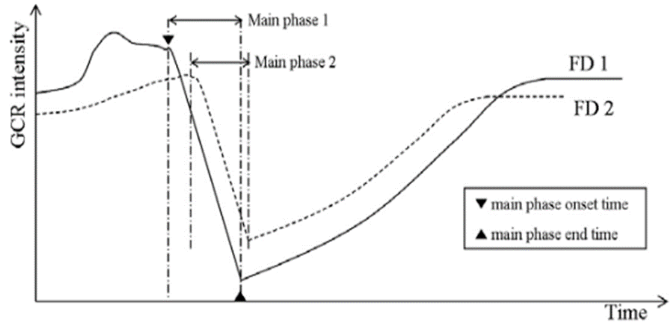

Figure 1: Schematic Diagram of FD Defining the Times of Main Phase Onset (Maximum Intensity) and Main Phase End (Minimum Intensity) and the Simultaneity (taken from Oh et al. (2008))

Figure 1 presents two idealized models of FDs (FD1 and FD2). The main phase of FD1 is indicated by black triangular symbols. The first arrow at the top denotes the main phase onset time, while the arrow at the zero baseline indicates the main phase end time, or the FD minimum. Okike and Nwuzor (2020) presented similar diagrams using observed FD events.

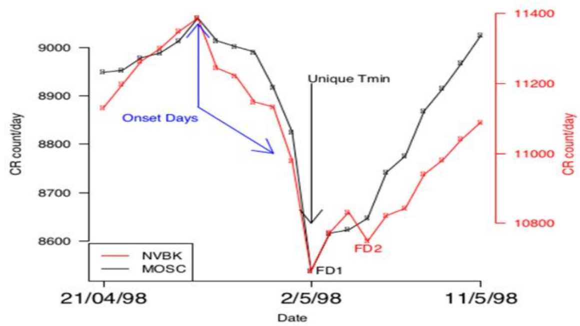

Figure 2: Illustration of CR Intensity Variations Between Two Stations that are Similar in Rigidity (Taken from Okike & Nwuzor (2020)

The event shown in Figure 2 occurred between 21/04/1998 and 11/05/1998. The blue arrow indicates the duration of the main phase, contrasting with the schematic representation in Figure 2, which implies a single onset point. The downward arrow marks the time when the events were observed simultaneously at both stations. Additionally, the diagram shows that Novosibirsk (NVBK) recorded a second FD during the recovery phase, which was not observed at MOSC.

Although investigations of FDs began over eight decades ago (Forbush 1937, 1938, 1958), event selection has predominantly relied on manual, subjective methods (e.g., Lockwood 1990; Tinsley & Deen 1991; Pudovkin & Veretenenko 1995; Svensmark et al. 2009, 2012, 2016). Several methodological flaws associated with these manual approaches have been identified (Okike 2019b, 2020, 2025, 2026; Okike et al. 2025; Samuneti et al. 2026). A primary drawback of the manual method is its time-consuming and tedious nature. In the provided cosmic ray (CR) data, a researcher using a manual approach must visually inspect the time-series to identify the Forbush decrease (FD) event. After isolating the relevant portion, the researcher plots the data to determine the onset point, the main phase, and the FD minimum. The average intensity variation for the period is also calculated. Depending on the chosen equation, these values are used to determine the FD magnitude. Two frequently employed equations are:

$$FD_{amplitude}(\%) = \frac{FD_{min+1} - FD_{min-1}}{FD_{min}} \times 100\%, \quad (1)$$

$$FD_{amplitude}(\%) = \frac{FD_{onset} - mean_I}{mean_I} \times 100\%, \quad (2)$$

Equation 1 uses the FD minimum point (the unique point indicated in Figure 2.

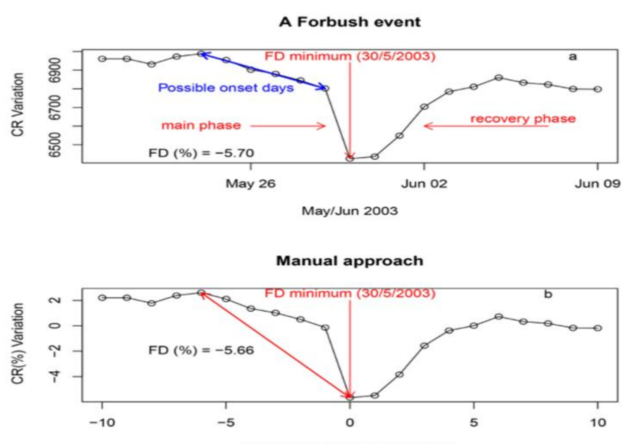

Figure 3: Illustration of the Manual Method of FD Event Identification (APTY Station)

To improve upon the manual approach, researchers at the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) introduced a semi-automated method. Large catalogs of FDs have been developed using this technique, generally referred to as the Global Survey Method (GSM) (Belov 2008; Lingri et al. 2016; Belov et al. 2018a,b). The event list created using the GSM is available in the Forbush-effects and interplanetary disturbances database (http://spaceweather.izmiran.ru/eng/dbs.html). Despite the success of the GSM, Okike and Menteso (2024) have identified several pitfalls in the technique. For instance, the GSM follows the case event approach of the manual method and utilizes its corresponding mathematical equations. A major limitation of these equations is the absence of a time domain, implying that while FD magnitudes are calculated mathematically, the time of occurrence must be determined separately. Consequently, the subjective nature of the manual method persists in the GSM.

Other researchers have also attempted to develop automated methods for FD event identification. Works by Light et al. (2020), Wang et al. (2023), and Dumbovic et al. (2024) introduced such approaches; however, these methods suffer from pitfalls similar to those of the group's semi-automated method. For instance, each method adopts a case-by-case approach, selecting only one event at a time.

Selection of small-amplitude FDs (≥ −3%) is another difficult problem in the field. Almost all the existing event catalogs contain only high-magnitude FDs (≤−3%) (Cane et al. 1993, 1996; Laken et al. 2012; Lee et al. 2015). Geppener & Mandrilava (2020) observed that identification of small-amplitude FDs is such a complex task that only experts in the field can handle. Using the using the continuous wavelength transform method, the authors detected some FDs. Nevertheless, the method follows case event approach.

Okike et al. (2020), Menteso et al. (2023), and Okike et al. (2024) were among the first to apply statistical approaches to detect small-amplitude FDs. These studies identified very low-amplitude events; for instance, Okike et al. (2020) reported event magnitudes as low as 0.01%. Recently, to analyze CR variation patterns between the Moscow (MOSC) and Oulu (OULU) stations, Okike et al. (2026) - hereafter referred to as Paper I - published an extensive catalog of FDs containing both high- and low-magnitude events. Of the 586 and 593 events selected at the MOSC and OULU stations, respectively, 189 simultaneous events are presented in Table 1. This study examines the relationship between small-amplitude FDs and solar-geomagnetic variables at both stations.

MATERIALS AND METHODS

Data Source

The FD data employed in the current work is taken from Paper I. The solar-geomagnetic data (geo-magnetic storm index, D stand interplanetary magnetic field (IMF) data) are taken from OMNI website (https://omniweb.gsfc.nasa.gov/form/dx1.html).

Analysis Method

All the small-amplitude (≥ −3%) FD events in the FD catalog developed in Paper I are sorted out using a simple R-code. A simple script is used to process the D st and IMF data to yyyy.mm.dd date format. Due to the large size of the data, a simply coincident algorithm is used to select the common dates across the data for each of the station. A sample of the final data employed in the analysis are presented in Table 1.

Table 1: A Sample of Small-Amplitude at MOSC and OULU with the Associated Solar-Geomagnetic Parameters. Date1 and Date2 Stand for Date of Events at MOSC and OULU Respectively

S/N	Date1	FD_MOSC	Dst	IMF	Date2	FD_OULU	Dst	IMF
1	1996-01-12	-1.08	-4	5.2	1996-01-11	-0.03	0	5
2	1996-01-14	-0.92	-33	8.9	1996-01-14	-0.19	-33	8.9
3	1996-01-21	-0.63	-11	4.8	1996-01-21	-0.10	-11	4.8
4	1996-01-24	-0.95	-3	4.6	1996-01-25	-0.09	-4	5.4
5	1996-02-23	-0.97	-15	6.2	1996-02-23	-0.27	-15	6.2
6	1996-02-27	-0.05	-20	5.6	1996-02-25	-0.32	-32	5.5
7	1996-03-03	-0.13	-8	5.2	1996-03-03	-0.03	-8	5.2
8	1996-03-08	-0.32	-11	6.7	1996-03-08	-0.02	-11	6.7
9	1996-03-16	-2.34	-11	5.5	1996-03-13	-0.03	-28	5.4
10	1996-03-23	-0.52	-28	4.2	1996-03-16	-0.45	-11	5.5
11	1996-03-31	-0.23	-3	3.6	1996-03-19	-0.32	-20	5.3
12	1996-04-08	-0.02	9	7.3	1996-03-22	-0.32	-33	3.9
13	1996-04-25	-0.11	-9	3.8	1996-04-13	-0.15	-18	4.8
14	1996-05-11	-0.15	1	4.8	1996-04-15	-0.08	-33	4.4
15	1996-05-16	-0.62	-14	3.6	1996-04-19	-0.11	-26	5.1
16	1996-05-27	-0.06	-10	5.3	1996-05-12	-0.10	5	5.3
17	1996-05-29	-0.82	20	8.8	1996-06-09	-0.08	3	4.7

S/N	Date1	FD_MOSC	Dst	IMF	Date2	FD_OULU	Dst	IMF
18	1996-06-07	-0.10	-2	5.2	1996-07-03	-0.11	-7	6
19	1996-06-11	-0.60	9	4.3	1996-07-14	-0.17	7	7.2
20	1996-07-03	-0.54	-7	6	1996-07-31	-0.12	-13	7.6
21	1996-07-14	-1.10	7	7.2	1996-08-11	-0.51	7	3.6
22	1996-07-31	-0.51	-13	7.6	1996-08-17	-0.24	-10	6.4
23	1996-08-11	-0.90	7	3.6	1996-08-29	-0.47	-34	7.2
24	1996-08-16	-0.03	-5	5.9	1996-09-06	-0.39	-8	5.9
25	1996-09-13	-2.33	-25	4.8	1996-09-10	-1.00	-25	7.9
26	1996-09-17	-0.49	-14	5.6	1996-09-13	-0.92	-25	4.8
27	1996-09-27	-0.01	-28	4	1996-09-18	-0.21	-26	4.5
28	1996-10-14	-2.22	-25	5.7	1996-09-22	-0.12	-29	5
29	1996-10-23	-2.46	-57	6.7	1996-09-27	-0.19	-28	4
30	1996-10-30	-0.91	-25	4.8	1996-10-09	-1.21	-25	6.7
31	1996-11-11	-2.32	-4	3	1996-10-12	-0.86	-17	5.3
32	1996-11-14	-2.73	-31	7.1	1996-10-18	-0.16	-28	6.4
33	1996-11-19	-1.19	-23	5.3	1996-10-20	-0.31	-34	3.9
34	1996-11-28	-0.84	-16	4.5	1996-10-23	-1.01	-57	6.7
35	1996-11-30	-2.11	-3	6.7	1996-10-29	-0.59	-23	5.7
36	1996-12-03	-2.43	-14	5.9	1996-11-02	-1.17	-11	5.2
37	1996-12-05	-1.90	-7	4.4	1996-11-05	-1.29	-16	3.9
38	1996-12-07	-1.96	0	6.1	1996-11-09	-0.64	-12	5.7
39	1996-12-10	-1.55	-23	8.3	1996-11-14	-1.22	-31	7.1
40	1996-12-16	-0.20	-17	4.8	1996-11-19	-0.45	-23	5.3
41	1996-12-24	-0.24	1	9.7	1996-11-30	-1.12	-3	6.7
42	1996-12-28	-1.81	-2	3.3	1996-12-02	-1.25	3	8.6
43	1996-12-31	-2.25	-12	4.9	1996-12-08	-0.94	-5	3.5
44	1997-01-02	-2.09	-2	4.9	1996-12-12	-0.51	-17	3.8
45	1997-01-08	-1.70	-2	4.5	1996-12-24	-0.01	1	9.7
46	1997-01-13	-1.44	-19	3.6	1996-12-28	-0.62	-2	3.3
47	1997-01-23	-0.08	-3	3.9	1996-12-31	-0.74	-12	3.2
48	1997-01-28	-2.04	-26	6.8	1997-01-02	-0.56	-2	4.9
49	1997-01-30	-1.70	-20	4.9	1997-01-06	-0.18	8	5.4
50	1997-02-02	-0.56	-14	5.4	1997-01-08	-0.16	-2	4.5
51	1997-02-04	-0.31	-11	3.9	1997-01-12	-0.04	-17	5.2
52	1997-02-06	-1.19	-12	4.9	1997-01-27	-0.31	-22	4.9
53	1997-03-02	-0.89	-27	5.3	1997-01-30	-0.24	-20	4.9
54	1997-03-07	-0.06	-19	5.1	1997-02-02	-0.13	-14	5.4
55	1997-04-01	-0.76	-3	8.6	1997-02-04	-0.14	-11	3.9
56	1997-04-12	-1.08	-18	3.9	1997-02-06	-0.23	-12	4.9
57	1997-04-19	-0.80	-34	4.7	1997-02-10	-0.29	-54	6.6
58	1997-04-23	-0.27	-17	7.5	1997-03-01	-0.53	-33	4.1
59	1997-05-02	-0.85	-36	4.3	1997-03-07	-0.24	-19	5.1
60	1997-05-13	-2.41	5	2.8	1997-03-30	-0.14	-31	5
61	1997-05-15	-2.36	-62	19.9	1997-04-02	-0.08	-16	4.7
62	1997-05-23	-0.94	-1	2.2	1997-04-04	-0.07	-16	5
63	1997-05-26	-0.59	-2	7.8	1997-04-11	-0.79	-39	13.8
64	1997-05-29	-0.59	-11	2.5	1997-04-17	-0.48	-44	6.3
65	1997-06-08	-0.20	-28	6.2	1997-04-19	-0.46	-34	4.7
66	1997-06-11	-0.34	-7	3.4	1997-04-21	-0.36	-34	7.1
67	1997-06-14	-0.48	1	2.6	1997-05-12	-0.37	1	3.9
68	1997-06-26	-0.55	-2	2.8	1997-05-15	-0.56	-62	19.9
69	1997-07-10	-1.91	-14	4.5	1997-05-26	-0.13	-2	7.8
70	1997-07-15	-1.31	-13	8.8	1997-06-08	-0.12	-28	6.2
71	1997-07-19	-1.02	-8	6.5	1997-06-12	-0.15	-4	4.4
72	1997-08-01	-0.51	-12	4.4	1997-06-14	-0.12	1	2.6

S/N	Date1	FD_MOSC	Dst	IMF	Date2	FD_OULU	Dst	IMF
73	1997-08-11	-0.48	-11	4.2	1997-06-16	-0.05	-1	5.7
74	1997-09-04	-0.62	-50	5.6	1997-06-24	-0.14	-4	5
75	1997-09-07	-0.07	-8	3.3	1997-06-29	-0.12	-23	5.3
76	1997-09-11	-0.57	-25	4.6	1997-07-10	-0.57	-14	4.5
77	1997-09-15	-0.41	-32	5.2	1997-07-15	-0.29	-13	8.8
78	1997-09-18	-1.49	-40	11.2	1997-07-20	-0.30	-12	5.8
79	1997-09-26	-0.28	-5	4.9	1997-10-01	-0.57	-48	9.2
80	1997-09-28	-0.74	-28	4.8	1997-10-08	-0.05	-24	6.6
81	1997-10-02	-1.85	-32	9.7	1997-10-11	-0.82	-74	11.4
82	1997-10-04	-0.59	-18	5.7	1997-10-25	-0.94	-45	8.6
83	1997-10-11	-1.57	-74	11.4	1997-11-02	-0.12	-11	4.4
84	1997-10-25	-2.34	-45	8.6	1997-11-05	-0.60	-19	7.2
85	1997-11-08	-2.46	-29	12.1	1997-11-08	-1.73	-29	12.1
86	1997-12-07	-0.40	-9	3.1	1997-11-11	-0.79	-28	5.9
87	1997-12-11	-2.43	-43	11.2	1997-11-14	-0.32	-21	8.1
88	1997-12-20	-0.64	0	4.8	1997-11-20	-1.67	-8	5.2
89	1998-01-01	-0.36	-16	6	1997-11-23	-2.69	-88	12.3
90	1998-01-29	-0.49	1	7.5	1997-12-03	-0.04	-12	5.4
91	1998-03-27	-0.17	-25	7.4	1997-12-11	-0.74	-43	11.2
92	1998-04-09	-2.56	-10	7.2	1998-01-01	-0.45	-16	6
93	1998-04-12	-2.61	-22	9	1998-01-07	-0.04	-45	16.6
94	1998-05-27	-2.25	-12	4.6	1998-01-22	-0.24	2	8.6
95	1998-05-30	-2.82	-22	7.2	1998-01-29	-0.02	1	7.5
96	1998-07-03	-1.15	-9	8.9	1998-02-19	-0.13	-34	8.7
97	1998-07-05	-2.87	-13	9.1	1998-04-09	-0.63	-10	7.2
98	1998-07-14	-0.67	2	3.7	1998-04-12	-0.86	-22	9
99	1998-07-24	-1.80	-24	5.2	1998-04-19	-1.27	-2	4.9
100	1998-08-06	-0.47	-73	12.2	1998-04-21	-1.08	-9	6.8

RESULTS AND DISCUSSION

The number of small-amplitude FDs recorded at the MOSC and OULU stations are 388 and 507, respectively. Of these, 182 small FDs occurred simultaneously at both stations. The regression results for these simultaneous events are presented in Figure 4.

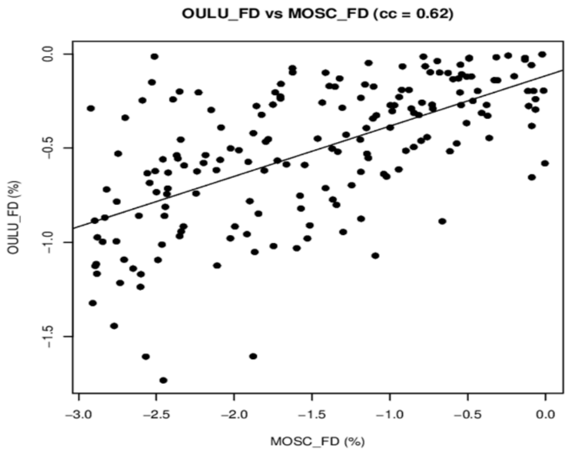

Figure 4: Correlation Between Small-Amplitude FDs that are Simultaneously Observed at MOSC and OULU Stations

The strong correlation coefficient (cc = 0.62) indicates that the events are related (Todd & Kniveton, 2001; Kristjansson et al., 2008). The mean values of small FDs at the MOSC and OULU stations are -1.26% and -0.71%, respectively, implying that MOSC is more sensitive than OULU (Pyle, 1997; Okike & Nwuzor, 2020).

The correlation between the 388 FDs at the MOSC station and solar-geomagnetic variables (Dst and IMF) is presented in Figure 5. A sub-sample of the events is provided in Table 1 due to space constraints.

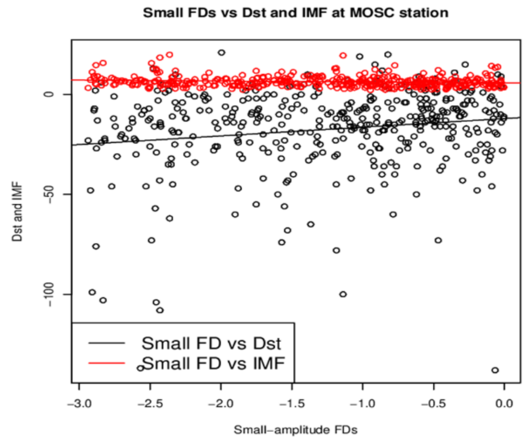

Figure 5: Correlation Between Small-Amplitude FDs and Solar-Geomagnetic Variables (Dst and IMF) at MOSC Station

The ccs for FD and Dst and for and IMF at MOSC station are respectively 0.17 (t-value = 3.44, p-value = 0.0006) and -0.07 (t-value = 1.35, p-value = 0.18). While the relation between FDs and D st is significant at 99.9% level, that of FD and IMF is only significant at 80% level.

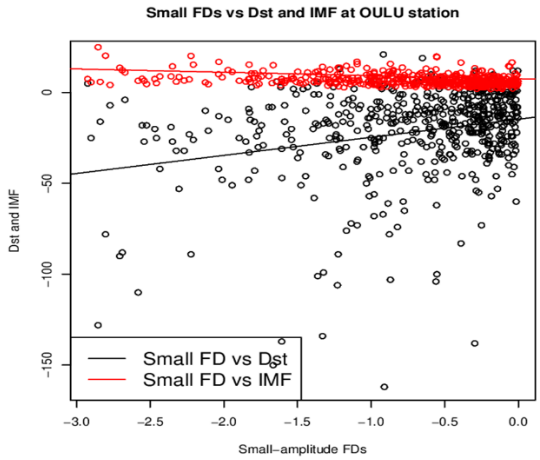

Figure 5: Correlation Between Small-Amplitude FDs and Solar-Geomagnetic Variables (Dst and IMF) at OULU Station

The correlation between the 507 FDs at OULU station and solar-geomagnetic variables (Dst and IMF) are presented in Figures 6. A sub-sample of the events are also presented in Table 1.

The correlation coefficient (cc) for FD and Dst at the Oulu station is 0.26 (t-value = 6.17, p-value = 1.39×10^{-9}), which is significant at all levels. For the relationship between FD and IMF, the cc is -0.026 (t = 0.59, p-value = 0.55), which is not significant at any level. The relationship between small-amplitude FDs and solar-geomagnetic data is significant, as it may address outstanding problems in CR physics. The connection between CRs and Dst has been a subject of speculation (e.g., Geranios & Mavromichalaki, 1982). The significant correlation between weak FDs and Dst, contrasted with the insignificant correlations between FDs and the interplanetary magnetic field (IMF), indicates that Earth's magnetic field exerts a stronger influence on small FDs than the IMF. Given the lopsided focus as well as numerous contradictory submissions on the relationship between FDs and short-term weather (e.g. Svensmark et al. 2012, Svensmark et al. 2016), the current result calls for a reappraisal of some the previous findings. Small-amplitude FDs might be the missing link. Several of the FDs classified as large FDs in the literature, for instance, might be weak FDs. CR diurnal anisotropies are believed to inhibit small FDs. The current catalog of small-amplitude FDs provides a testbed for empirical demonstration of the influence of CR diurnal anisotropies on weak FDs. Furthermore, the large differences between the correlations for FD and Dst at Moscow and Oulu suggest that these magnetic field effects vary globally. This result is of crucial importance when interpreted in light of cosmic ray anisotropies, which are believed to have more pronounced effects on small-amplitude FDs (Belov 2008; Okike and Umahi 2019).

CONCLUSION

Research into the relationship between small-amplitude FDs and solar-geomagnetic parameters is limited by a scarcity of relevant catalogs. This deficiency has hindered the validation of CR theories concerning small FDs, solar-geomagnetic data, and CR diurnal anisotropies. The significant correlation between weak FDs and Dst suggests that the Earth's geomagnetic field exerts a strong influence on these events, while the lack of a significant relationship between small-amplitude FDs and the interplanetary magnetic field (IMF) provides further insight. This indicates that the condition of the interplanetary medium and solar plasma ejections has minimal influence on weak FDs. Further analysis of large FDs from the same stations is required to complement these results.

ACKNOWLEDGMENT

We acknowledge the use of the website https://omniweb.gsfc.nasa.gov/form/dx1.html. We appreciate the teams hosting these websites.

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