Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v35(s).2026.699
Volume 35(S), 2026

# The Implication of Solar-Geophysical Parameters on High-Amplitude Forbush Decreases

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

**ABSTRACT**
Space weather research is crucial to Earth's civilization. Forbush decreases (FDs) short-term, rapid depressions in the time-intensity flux of cosmic rays (CRs) are key indicators of space weather conditions. However, the identification, selection, and calculation of FD magnitude and timing present significant challenges to their use as space weather probes. The manual methods that dominate the field are subjective, leading to inconsistent and controversial solar-terrestrial correlations. Recently, accurate Forbush decrease (FD) catalogs were developed for Moscow (MOSC) and Oulu (OULU) neutron monitor data. This study identifies high-amplitude FDs from these catalogs to test correlations with solar-geomagnetic variables, including solar ejections, interplanetary magnetic fields, geomagnetic activity, and cosmic ray anisotropies. The results suggest that the magnitude of FDs and their correlation with solar-geomagnetic variables are location-dependent. Due to differences in geomagnetic cutoff rigidity and the sensitivity of the MOSC and OULU stations, event magnitude varies appreciably between the two locations. We conclude that, rather than judging event strength by magnitude alone, the test of event simultaneity across both stations is a more reliable indicator of FD event size.

**Submitted**: 12 Aug. 2026

**Accepted**: 20 Aug. 2026

**Published**: 16 Sept. 2026

## INTRODUCTION

Forbush decreases (FDs) are short-term reductions in the intensity of cosmic ray (CR) flux. These events typically occur within a few hours and recover over several days (Forbush 1937, 1938, 1958; Belov et al. 1979, 2001a; Okike & Collier 2011; Abunin et al. 2013; Bhaskar et al. 2016a,b). Lockwood (1971) provided a comprehensive review of FD characteristics, and the global nature of these events was established in early research. Figure 1 illustrates an event occurring between January 19 and 23, 1957, displaying the time-intensity profiles recorded at four neutron monitors. A casual examination of the diagram might suggest that the stations observe the events simultaneously. This global occurrence of FDs at multiple stations was termed "global simultaneity" by Oh et al. (2008) and Okike and Collier (2011). However, a closer inspection reveals that the time of the FD minimum may vary appreciably among the stations. Furthermore, it is difficult to estimate the event magnitude at any station from the diagram.

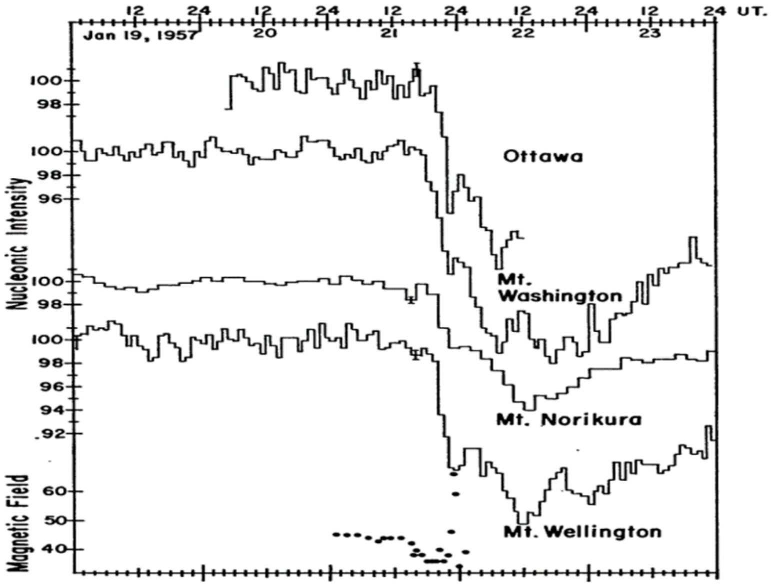


Figure 1: CR flux Variations at Different Stations for FD Event of January 19-23, 1957(Taken from Lockwood, 1971)

Lockwood (1990), Tinsley and Deen (1991), Cane et al. (1993, 1994, 1996), and Pudovkin and Veretenenko (1995) were among the first to establish quantitative characteristics of FDs, specifically regarding magnitude and event timing. The availability of FD catalogs subsequently enabled quantitative analyses of the relationship between these events and terrestrial weather. Marcz (1997) examined the link between FDs and short-term atmospheric electricity fluctuations using the Lockwood and Tinsley catalogs, finding that results were dependent on the specific event list employed. This implies significant differences between the magnitudes and event times recorded in the catalogs of Lockwood (1990) and Tinsley & Deen (1991). Furthermore, it reveals that different researchers may calculate different magnitudes and times for the same event using identical data. These observed discrepancies in the magnitude and timing of FDs across various catalogs constitute a significant bias in space weather research. Such differences in event lists are understandable when cosmic ray (CR) data are obtained from different detectors. These differences may be attributed to the rigidity, sensitivity, and operational characteristics of various detectors (see Belov et al., 1979; Okike & Collier, 2011). Okike (2019b, 2020c) attributed bias in event magnitude and timing to the traditional Forbush decrease (FD) event selection method. This manual approach is subjective, as results depend on the investigator rather than the event's actual characteristics. With an accurate, objective method, different researchers would derive consistent event magnitudes from the same cosmic ray (CR) data. A significant challenge in manual analysis is determining the onset date and time, as Okike and Nwuzor (2020) demonstrated that an event onset may correspond to a range of days. The magnitude of an event depends on the chosen onset day. The time of the FD minimum is typically more precise and less prone to bias. Another significant source of bias in the manual method is the formula used to calculate magnitude, which lacks a time factor (see Equation 1). Consequently, event size and time must be calculated separately, with the latter often determined visually. Currently, manual techniques lack a formal method for accounting for event time.

$$FD_{amplitude}(\%) = \frac{FD_{onset} - mean_I}{mean_I} \times 100\%, \qquad (1)$$

To address the drawbacks of manual FD event analysis, our team developed a Fully Automated Method (FAM) in 2019 (Okike & Umahi 2019; Okike 2019a,c), which has since been applied in subsequent research (Okike et al. 2020; Okike 2020a,b; Okike et al. 2021; Okike 2021; Okike & Alhassan 2022; Okike & Menteso 2024). The event lists generated by the FAM are accurate (Okike et al. 2025). Recently, Okike et al. (2024) - hereafter Paper I - developed extensive event lists based on data from the Moscow (MOSC) and Oulu (OULU) neutron monitor stations. These catalogs were used to analyze cosmic ray variability patterns at both locations. This study utilizes the FD list from Paper I to examine the relationship between FDs and solar-geomagnetic variables at both stations.

## MATERIALS AND METHODS

### Data Source

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

**Analysis Method**

All the high-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 Dst 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 is presented in Table 1.

**Table 1: A Sample of High-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 | 1996-09-10 | -3.49 | -25 | 7.9 | 1998-05-02 | -3.67 | -36 | 14.5 |
| 2 | 1996-10-09 | -3.21 | -25 | 6.7 | 1998-05-04 | -3.73 | -118 | 17.4 |
| 3 | 1996-11-05 | -3.77 | -16 | 3.9 | 1998-08-27 | -4.97 | -129 | 14.1 |
| 4 | 1997-11-23 | -4.34 | -88 | 12.3 | 1998-09-25 | -3.63 | -118 | 18 |
| 5 | 1998-04-19 | -3.51 | -2 | 4.9 | 1999-01-24 | -3.51 | -38 | 7.6 |
| 6 | 1998-05-02 | -11.48 | -36 | 14.5 | 1999-02-18 | -4.40 | -84 | 17.1 |
| 7 | 1998-05-17 | -3.30 | -17 | 5.8 | 1999-12-13 | -3.46 | -46 | 11.4 |
| 8 | 1998-05-21 | -3.95 | -25 | 5.7 | 2000-06-09 | -3.63 | -34 | 10.2 |
| 9 | 1998-06-07 | -4.25 | -30 | 7.9 | 2000-07-16 | -6.97 | -172 | 21.8 |
| 10 | 1998-06-14 | -3.27 | -27 | 9.3 | 2000-07-20 | -4.14 | -67 | 8.1 |
| 11 | 1998-06-19 | -4.32 | 3 | 11.1 | 2000-07-22 | -3.73 | -40 | 5.7 |
| 12 | 1998-06-21 | -4.33 | -23 | 6.7 | 2000-09-18 | -3.38 | -103 | 19.2 |
| 13 | 1998-06-23 | -3.66 | -12 | 8 | 2000-11-29 | -3.49 | -81 | 9.2 |
| 14 | 1998-06-25 | -4.78 | 7 | 13.7 | 2001-04-12 | -6.09 | -131 | 15.1 |
| 15 | 1998-08-23 | -6.44 | -23 | 7.2 | 2001-09-26 | -3.18 | -72 | 10.7 |
| 16 | 1998-08-27 | -12.04 | -129 | 14.1 | 2001-10-01 | -3.11 | -99 | 11.1 |
| 17 | 1998-09-25 | -9.71 | -118 | 18 | 2001-11-25 | -3.54 | -106 | 11.5 |
| 18 | 1999-01-24 | -10.22 | -38 | 7.6 | 2002-08-02 | -3.32 | -59 | 12.1 |
| 19 | 1999-02-13 | -3.24 | -12 | 5.8 | 2002-11-18 | -3.09 | -37 | 9.3 |
| 20 | 1999-02-18 | -11.39 | -84 | 17.1 | 2003-05-30 | -3.55 | -74 | 16.7 |
| 21 | 1999-03-19 | -3.06 | -7 | 5.4 | 2003-10-31 | -11.47 | -117 | 15.8 |
| 22 | 1999-08-20 | -4.19 | -37 | 5.8 | 2003-11-07 | -4.57 | -9 | 5.8 |
| 23 | 1999-08-22 | -5.07 | -27 | 6 | 2003-11-17 | -4.33 | -35 | 6 |
| 24 | 1999-08-25 | -3.51 | -15 | 7.7 | 2003-11-21 | -3.83 | -140 | 9.6 |
| 25 | 1999-09-16 | -3.01 | -46 | 6.2 | 2003-11-24 | -4.64 | -29 | 9.1 |
| 26 | 1999-09-21 | -3.05 | -7 | 7.2 | 2004-01-08 | -3.25 | -16 | 5.8 |
| 27 | 1999-10-16 | -5.65 | -33 | 5.3 | 2004-01-10 | -3.27 | -24 | 11.3 |
| 28 | 1999-10-21 | -4.63 | 9 | 18.4 | 2004-01-25 | -3.10 | -65 | 9.9 |
| 29 | 1999-10-23 | -4.35 | -65 | 7.3 | 2004-07-27 | -4.81 | -120 | 17.4 |
| 30 | 1999-10-25 | -4.34 | -45 | 4.5 | 2004-11-10 | -4.98 | -176 | 18.4 |
| 31 | 1999-11-01 | -3.59 | -15 | 7.2 | 2005-01-19 | -9.02 | -64 | 12.6 |
| 32 | 1999-11-14 | -4.45 | -62 | 5.9 | 2005-01-22 | -6.46 | -72 | 13.2 |
| 33 | 1999-11-18 | -4.43 | -31 | 6 | 2005-05-16 | -3.86 | -85 | 10.2 |
| 34 | 1999-11-20 | -4.21 | -16 | 8.1 | 2005-07-17 | -3.87 | -9 | 10 |
| 35 | 1999-11-22 | -4.45 | -12 | 9.8 | 2005-09-13 | -7.64 | -76 | 6 |
| 36 | 1999-12-02 | -3.16 | 13 | 10 | 2005-09-15 | -7.08 | -49 | 7.8 |
| 37 | 1999-12-13 | -9.89 | -46 | 11.4 | 2005-09-22 | -3.39 | -20 | 5.4 |
| 38 | 1999-12-27 | -3.82 | 2 | 7.9 | 2006-12-15 | -5.51 | -116 | 9.4 |

The table is prepared following the number of large FDs at OULU station. There are only 38 high-magnitude FDs at OULU stations whereas there are 143 large FDs at MOSC station. The first 38 events are, therefore, presented for each of the station. The associated solar-geomagnetic variables are also listed.

The large events that are simultaneous at the two stations are and the associated solar-terrestrial variables are also selected and presented in presented Table 2.

**Table 2: List of Large FDs that Happen Simultaneously at MOSC and OULU Station with the Associated Solar-Geomagnetic Parameters. Note that FD_MOSC and FD_OULUFD at MOSC and OULU Station Respectively**

| S/N | Date | FD_MOSC | FD_OULU | Dst | IMF |
|---|---|---|---|---|---|
| 1 | 1998-05-02 | -11.48 | -3.67 | -36 | 14.5 |
| 2 | 1998-08-27 | -12.04 | -4.97 | -129 | 14.1 |
| 3 | 1998-09-25 | -9.71 | -3.63 | -118 | 18 |
| 4 | 1999-01-24 | -10.22 | -3.51 | -38 | 7.6 |
| 5 | 1999-02-18 | -11.39 | -4.40 | -84 | 17.1 |
| 6 | 1999-12-13 | -9.89 | -3.46 | -46 | 11.4 |
| 7 | 2000-06-09 | -10.00 | -3.63 | -34 | 10.2 |
| 8 | 2000-07-16 | -20.20 | -6.97 | -172 | 21.8 |
| 9 | 2000-07-20 | -12.81 | -4.14 | -67 | 8.1 |
| 10 | 2000-09-18 | -7.85 | -3.38 | -103 | 19.2 |
| 11 | 2000-11-29 | -9.56 | -3.49 | -81 | 9.2 |
| 12 | 2001-04-12 | -18.24 | -6.09 | -131 | 15.1 |
| 13 | 2001-09-26 | -9.42 | -3.18 | -72 | 10.7 |
| 14 | 2001-11-25 | -9.48 | -3.54 | -106 | 11.5 |
| 15 | 2002-08-02 | -9.95 | -3.32 | -59 | 12.1 |
| 16 | 2002-11-18 | -8.20 | -3.09 | -37 | 9.3 |
| 17 | 2003-10-31 | -30.69 | -11.47 | -117 | 15.8 |
| 18 | 2003-11-07 | -12.67 | -4.57 | -9 | 5.8 |
| 19 | 2003-11-17 | -9.96 | -4.33 | -35 | 6 |
| 20 | 2003-11-24 | -12.55 | -4.64 | -29 | 9.1 |
| 21 | 2004-01-10 | -9.63 | -3.27 | -24 | 11.3 |
| 22 | 2004-01-25 | -9.59 | -3.10 | -65 | 9.9 |
| 23 | 2004-07-27 | -13.29 | -4.81 | -120 | 17.4 |
| 24 | 2004-11-10 | -10.79 | -4.98 | -176 | 18.4 |
| 25 | 2005-01-19 | -23.62 | -9.02 | -64 | 12.6 |
| 26 | 2005-01-22 | -17.21 | -6.46 | -72 | 13.2 |
| 27 | 2005-05-16 | -9.50 | -3.86 | -85 | 10.2 |
| 28 | 2005-07-17 | -10.38 | -3.87 | -9 | 10 |
| 29 | 2005-09-13 | -21.36 | -7.64 | -76 | 6 |
| 30 | 2005-09-15 | -19.32 | -7.08 | -49 | 7.8 |
| 31 | 2006-12-15 | -16.08 | -5.51 | -116 | 9.4 |

**RESULTS AND DISCUSSION**

Figure 2 presents the correlation results for 143 large FDs with Dst and the interplanetary magnetic field (IMF). The black and red empty circles represent the relationships between FDs and Dst and IMF, respectively, with corresponding regression lines. The correlation coefficients (cc) are 0.43 for FD and Dst and -0.33 for FD and IMF; both are statistically significant. The positive correlation between FDs and Dst suggests that the same solar phenomena generate both events at Earth, while the inverse relation between FDs and IMF indicates increased solar activity. This causes larger cosmic ray (CR) reductions at Earth. These two relations are important for space weather predictions. The strong, significant correlation obtained here between FDs and Dst contrasts with the poor relations reported by Kane (2010) and Belov et al. (2001). This discrepancy likely stems from differences in the methods used to calculate FDs, as the fully automated approach implemented in Paper I is more accurate than the manual methods used by Kristjansson et al. (2008), Kane (2010), and Svensmark et al. Compared to the results of Svensmark et al. (2012, 2016) and the semi-automated IZMIRAN method used by Belov et al. (2001) to calculate the magnitude of FDs, the results obtained here represent an improvement.

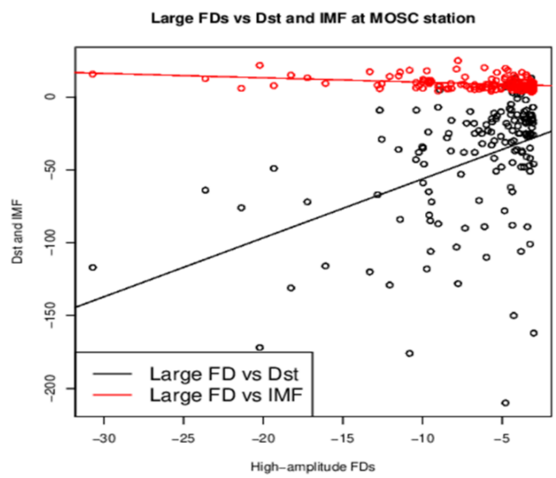


Figure 2: Correlation Plot for FD vs Dst/IMF at MOSC Station

Results for similar analysis for OULU station is presented in Figure 3. The cc for FD and Dst is 0.3 while it is -0.19 for FD and IMF. While FD vs Dst is significant at 90%, FD vs IMF is not significant at any level. Comparatively, the results obtained for MOSC and OULU stations are quite different, especially for FD vs IMF. Since the method used to calculate the two event catalogs are the same, the differences in the results are pointers to the location-dependent of large CR phenomena.

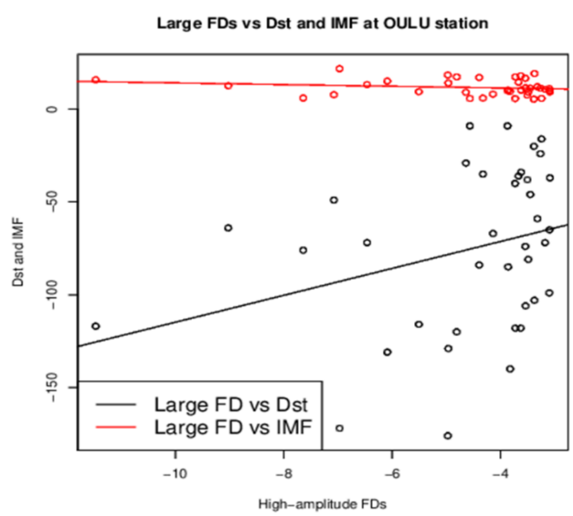


Figure 3: Correlation Plot for FD vs Dst/IMF at MOSC Station

**Simultaneous High-Magnitude FDs**

In a bid to further examine the observed differences obtained in the correlation results at MOSC and OULU stations, simultaneous FDs at the two stations are examined. The data is is presented in Table 2. The first event in Table 2 (FD of 2/5/1998) register significantly different magnitudes at the two stations. The magnitude of the event at MOSC and OULU are respectively -11.48 and -3.67%. This implies that the event at MOSC is larger than those at OULU by a factor of 3. The magnitude of the second event (37/8/1998) at MOSC and OULU are respectively -12.04 and -4.97%. In this case, the event at MOSC is larger by a factor of 2. This points to the unpredictable variability of FDs (Belov 2008; Okike & Collier 2011; Ramirez et al. 2013) at different regions of the earth. Figure 4 presents the correlation results of the high-magnitude FDs that are simultaneously detected at the two NMs. Out of the 143 and 38 large FDs at MOSC and OULU stations respectively, 31 events are observed at the same time at the two NMs. The cc is very high (cc = 0.98). This high cc point to the accuracy of the FD magnitudes calculated by Paper I. In spite of the large differences in the event magnitudes at the two stations, the cc is approximately 1. Using data from different databases, Okike (2020c) demonstrated that magnitude of the same events may be significantly different for different resolutions or detectors. Figure 6 of the article shows that events whose magnitude is a small as 0.6% at high resolution database can be as high as 25% in the low-resolution website. It is interesting to note that irrespective of the large differences between the two catalogs, the cc between them is very high (cc = 0.999). This emphasize the need for accuracy of FD event list. Contrary to the submission of Abunin et al. (2013), the high cc is an indication that two events lists that are carefully calculated can be united to form one continuous catalog.

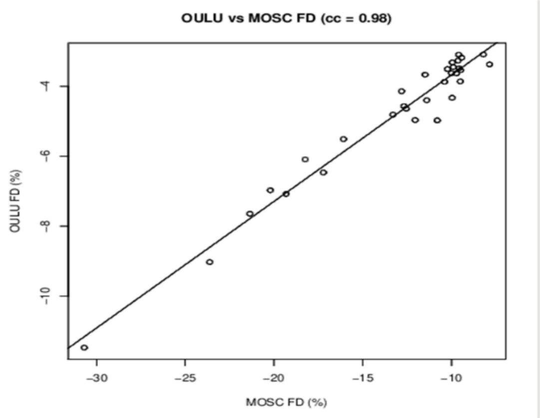


Figure 4: The Correlation Between High-Amplitude Simultaneous FDs at the MOSC and OULU Stations

**FDs at the MOSC and OULU Stations**

We also tested the cc for FD and Dst at both stations. The results obtained for FD at MOSC vs Dst is 0.29 while it is 0.33 for OULU station. While the positive cc further confirms that FDs and Dst are caused by the same solar ejections, the differences in the cc suggest that the geomagnetic field varies across the earth. The interaction between simultaneous large FDs shows only marginal correlation at both stations. It is respectively -0.13 and 0.18 at MOSC and OULU.

**CONCLUSION**

The results clarify the need for researchers to carefully select and calculate the magnitude and timing of FD events before conducting correlation or regression analyses. With an accurate event list, differences in the obtained correlations can be confidently attributed to geomagnetic or interplanetary field conditions. The analysis also questions the use of pre-defined baselines to categorize large and small amplitude FDs across locations or detectors with varying rigidity. This occurs because an event may appear large at one station but small at another, depending on the detector's rigidity and characteristics. Simultaneity tests suggest that event simultaneity is a more effective alternative to classifying Forbush decrease (FD) magnitude across different Earth locations. Furthermore, correlation results at MOSC and OULU indicate that solar-geomagnetic variable strength is location-dependent.

**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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