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# Vertical variance analysis of geomagnetic disturbance during solar cycle 23

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The geomagnetic field consists of temporal variations induced primarily by the variations in the solar wind and embedded interplanetary magnetic field. 34 stations across the Earth have been categorized in this paper on the basis of their geomagnetic disturbance during solar cycle 23 (1997-2008). The Vertical Variance (VV) disturbance quantifier has been used to develop such profile. The latitude profile of geomagnetic disturbance has been found to exhibit a typical 'Knee' behaviour, with the fluctuation content seen to rise sharply beyond this critical latitude determined near 52° latitude. The increasing trend in geomagnetic fluctuation content however is seen to end around the auroral oval beyond where abrupt variations has been observed indicating the transition from closed to open magnetic field lines. The physical mechanism behind this trend has also been explored. The VV analysis of geomagnetic disturbance has revealed prominent features of solar wind – magnetosphere coupling.

**Keywords:** Geomagnetic disturbance, Solar wind–magnetosphere interactions, Magnetic storms

## 1 Introduction

Magnetic fields pervade the entire universe. The Earth has its own magnetic field called the geomagnetic field. The Earth's magnetic field can be approximated to a dipole embedded within the Earth[1]. The improvement made by Gauss in 1839 on the dipolar model of geomagnetism was a quantum leap from status quo considering the fact that the mathematical base he introduced in the 19th century holds even today in spite of later advancements in theories of origin of geomagnetism including the dynamo theory.

The geomagnetic field varies over time and space. A short term disturbance in the geomagnetic field has been explored in this paper. The latitude (spatial) profile of geomagnetic disturbance endured by 34 stations across the Earth is examined here. The variation in such profile during geomagnetic quiet and storm periods is also analysed.

Besides its spatial variations, the geomagnetic field varies at different time scales ranging from seconds to millions of years[2]. The long term variations are due to the changes in the dynamo region within the Earth. The short duration fluctuations are due to the current systems in the atmosphere and the magnetosphere[3]. The long-term geomagnetic parameters like solar activity minima and maxima exhibit latitude dependence[4].

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## 2 Methodology

The amount of fluctuations in the geomagnetic field is gauged by employing the daily vertical variance (VV) index[5]. It followed from the attempts to precisely determine the degree of disturbance in various time series data sets of geomagnetic field and IMF. The linear relationship between disturbance content in geomagnetic field and IMF was established therein. The adjective "vertical" follows from the fact that it is the change in the quantity on the vertical (y) axis that is being gauged within specific end point limits of change of the quantity on the horizontal (x) axis. The method has universal applicability on any data set, a distinct advantage over other methods suited only for specific purposes

The VV is the modified general and simpler form of the VV index[6]. The VV is intended to assign a quantifying numerical value to fluctuations in data sets which are time dependent functions varying within specified temporal end points.

The VV for any data set consisting of values *y(x)*, $y_{i+1}$ and $y_i$ being adjacent data values of *y* corresponding to adjacent time values $x_{i+1}$ and $x_i$;

$$VV = \sqrt{\sum_{i=0}^{n-1} \left| y_{i+1} - y_i \right|^2} \quad \text{... (1)}$$

The VV is thus the root mean square of the variation in the dependent variable in the data under assessment. A constant value data set will have a zero value for the VV. VV value of infinity corresponds to a singular change (in zero time) in data from zero to infinity. Thus, theoretically, VV ranges from 0 to ∞.

While determining the daily VV of geomagnetic data, 24 hour temporal limits are applied. In this instance, the VV is essentially the root mean square of the daily variation in the horizontal component of geomagnetic field, B. The expression for determining VV is thus modified.

$$VV = \sqrt{\sum_{i=0}^{1439} \left| B_{i+1} - B_i \right|^2} \quad \text{... (2)}$$

The VV quantifies the amount of temporal variations in any time series. The VV being of daily nature, aberrations due to quiet-time $S_q$ variations are minimal. The VV is used in this paper in place of the VV index so that mixing of units is avoided and universality is maintained.

## 3 Analysis

The averages of the daily VV values of various geomagnetic stations for the years from 1997 through 2008 are analysed here to determine the extent of geomagnetic disturbance characteristic of these stations. These estimates serve as measures of geomagnetic stress endured by the analysed stations. This analysis also leads to a very definite latitude profile of the disturbance for various geomagnetic stations.

The VV values of the horizontal component of the geomagnetic field (H) for the stations are determined for each UT day using 1-minute observations. Computer programs are utilized for calculating the VV values. The VV value for each day is determined from 1440 data elements of H.

In this work, the 34 geomagnetic stations in Table 1 are listed in the order of decreasing absolute geomagnetic (GM) latitude. The table gives the list of analysed stations along with their ABB codes, geographic latitudes, geographic longitudes, geomagnetic latitudes, and the absolute geomagnetic latitudes.

In terms of the GM latitude, 9 stations belong to the low-latitudes, 16 to the mid latitudes and 9 to the high latitudes. The VV values of the horizontal component of the geomagnetic field are determined for the 4383 days of the years 1997 - 2008 for the34 stations. These mean values are used to categorize the geomagnetic stations.

### 3.1 Mean value analysis and validation (1997-2008)

Monthly, yearly and solar cycle means of the VV values for the above mentioned stations are determined. Yearly and the solar cycle (23) means of the VV values are given in Table 2. The table summarises the analysis of data pertaining to the 12 years in solar cycle 23 (1997-2008). Blanks in the table correspond to non-availability of data. The distinct mean of VV value of each station is characteristic and is considered as the disturbance marker for that station.

Referring to Table 2, two patterns are clearly visible in the results. One, for most stations, progressing from 1997 through 2008, there is distinct peak in the mean VV values during the year 2003. This is particularly true for high-latitude and mid-latitude stations. This pattern is broken for low latitude stations. Year 2003 has been one of exceptional geomagnetic disturbance as evidenced by the large aa index, solar wind speed and IMF values[7]. Simultaneous peaking of conventional geomagnetic disturbance markers and the VV mean values validate the applicability of VV as a disturbance marker.

Further, correlation between the solar wind and the VV values are examined in the pattern of year-wise variations. Stations are selected and grouped into categories such as post-auroral (2 stations, Resolute Bay and Cambridge Bay), pre-auroral (3 stations, Iqaluit, Mawson and Sodankyla), mid-latitude (3 stations, Ottawa, Niemegk and Crozet), and low-latitude (2 stations, Bangui and Ascension Island) on the basis of their GM latitudes. The averages of the yearly VV values of these four groups of stations are shown in Table 3. The solar wind speed data obtained from the ACE data center are given in Table 4. Group averages of the yearly VV values of the four different categories of stations in Table 3 and the solar wind speed in Table 4 normalised to their respective maxima are plotted against the corresponding years in Fig. 1. It is evident from the figure that the averages of the yearly VV values for most station groups (post-auroral, pre-auroral and mid-latitude) strongly follow the solar wind velocity variations. Only the average VV for the low-latitude group of stations deviate from the solar wind pattern.

Pearson correlation attempted between the average VV of the different station groups and the solar wind is obtained in Table 5. The disturbances in the post-auroral stations and the pre-auroral stations have correlation coefficients of 0.96 and 0.91 with the solar wind speed respectively, the coupling being strongest for the post-auroral stations. This observation made[8] is thus ascertained by the VV method. The VV method is hence validated as a faithful quantification of

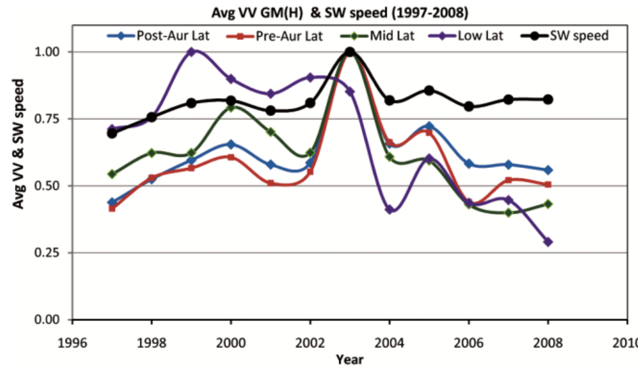


Fig. 1 — Normalised station category averages of yearly VV values and solar wind speed for the years from 1997 through 2008.

Table 1 — The name, ABB code, geographic latitude, geographic longitude and geomagnetic latitude, and the absolute geomagnetic latitude of the analysed stations.

| Station | ABB Code | GG Latitude | GG Longitude | GM Latitude | GM lat (Abs) |
|---|---|---|---|---|---|
| Alert | ALE | 82.50 | 297.65 | 87.38 | 87.38 |
| Thule | THL | 77.48 | 290.83 | 87.02 | 87.02 |
| Resolute Bay | RES | 74.69 | 265.11 | 82.61 | 82.61 |
| Cambridge Bay | CBB | 69.12 | 254.97 | 76.21 | 76.21 |
| Hornsund | HRN | 77.00 | 15.55 | 74.02 | 74.02 |
| Dumont d'Urville | DRV | -66.67 | 140.01 | -73.87 | 73.87 |
| Iqaluit | IQA | 63.75 | 291.48 | 73.25 | 73.25 |
| Mawson | MAW | -67.60 | 62.88 | -73.04 | 73.04 |
| Baker Lake | BLC | 64.32 | 263.99 | 72.66 | 72.66 |
| Yellowknife | YKC | 62.48 | 245.52 | 68.62 | 68.62 |
| Abisko | ABK | 68.36 | 18.82 | 66.04 | 66.04 |
| Sodankyla | SOD | 67.37 | 26.63 | 63.96 | 63.96 |
| Meanook | MEA | 54.62 | 246.65 | 61.17 | 61.17 |
| Macquarie Island | MCQ | -54.50 | 158.95 | -59.51 | 59.51 |
| Nurmijarvi | NUR | 60.51 | 24.66 | 57.79 | 57.79 |
| Port Aux rancais | PAF | -49.35 | 70.26 | -56.46 | 56.46 |
| Ottawa | OTT | 45.40 | 284.45 | 54.88 | 54.88 |
| Niemegk | NGK | 52.07 | 12.68 | 51.64 | 51.64 |
| Crozet | CZT | -46.43 | 51.87 | -51.06 | 51.06 |
| Furstenfeldbruck | FUR | 48.17 | 11.28 | 48.09 | 48.09 |
| Hurbanovo | HRB | 47.87 | 18.19 | 46.66 | 46.66 |
| Martin De Vivies | AMS | -37.80 | 77.57 | -45.83 | 45.83 |
| Tihany | THY | 46.90 | 17.89 | 45.76 | 45.76 |
| Gnangara | GNA | -31.78 | 115.95 | -41.18 | 41.18 |
| Learmonth | LRM | -22.22 | 114.10 | -31.70 | 31.70 |
| Charters Towers | CTA | -20.09 | 146.26 | -27.37 | 27.37 |
| Tamanrasset | TAM | 22.79 | 5.53 | 24.30 | 24.30 |
| Kakadu | KDU | -12.69 | 132.47 | -21.34 | 21.34 |
| M'Bour | MBO | 14.38 | 343.03 | 19.59 | 19.59 |
| Papeete | PPT | -17.57 | 210.43 | -15.04 | 15.04 |
| Kourou | KOU | 5.21 | 307.27 | 14.27 | 14.27 |
| Phu Thuy | PHU | 21.03 | 105.95 | 11.22 | 11.22 |
| Bangui | BNG | 4.33 | 18.57 | 4.04 | 4.04 |
| Ascension Island | ASC | -7.95 | 345.62 | -2.74 | 2.74 |

Table 2 — The ABB code, absolute geomagnetic latitude, and the year and solar cycle (23) means of the VV values of the analysed stations.

| Sl No. | Station | GM Lat (Abs) | Year Avg VV GM(H) | | | | | | | | | | | | Avg VV GM(H) Solar cycle 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | |
| 1 | ALE | 87.38 | 157.73 | 219.61 | 241.07 | 280.96 | 262.52 | 245.41 | 367.27 | 247.68 | | | | | 250.28 |
| 2 | THL | 87.02 | | | 126.91 | 162.75 | 103.66 | 103.18 | 159.44 | 102.28 | 159.44 | 82.85 | 81.54 | 79.38 | 116.14 |
| 3 | RES | 82.61 | 96.35 | 118.24 | 134.10 | 146.22 | 137.81 | 136.76 | 213.27 | 139.74 | 155.29 | 119.94 | 120.18 | 118.84 | 136.39 |
| 4 | CBB | 76.21 | 151.89 | 179.02 | 203.41 | 224.57 | 190.37 | 195.37 | 353.04 | 232.57 | 253.84 | 210.20 | 207.88 | 197.83 | 216.67 |
| 5 | HRN | 74.02 | 231.42 | 259.38 | 277.98 | 292.59 | 246.34 | 278.66 | 485.73 | 344.47 | 372.26 | 287.32 | 305.32 | 303.24 | 307.06 |
| 6 | DRV | 73.87 | 140.38 | 135.89 | 151.20 | 177.67 | 152.10 | 236.26 | 257.40 | 276.14 | 185.98 | 273.21 | 177.23 | 131.10 | 191.21 |
| 7 | IQA | 73.25 | 277.97 | 300.81 | 330.56 | 350.91 | 285.13 | 324.94 | 577.90 | 413.27 | 422.51 | | 353.51 | 349.37 | 361.52 |
| 8 | MAW | 73.04 | | 304.11 | 313.69 | 321.06 | 287.86 | 294.60 | 530.68 | 358.46 | 393.54 | 290.32 | 298.48 | 291.09 | 334.90 |
| 9 | BLC | 72.66 | 224.50 | 254.94 | 278.18 | 293.60 | 249.75 | 269.56 | 476.25 | 337.46 | 376.19 | 296.56 | 289.32 | 294.72 | 303.57 |
| 10 | YKC | 68.62 | 256.86 | 297.90 | 331.45 | 340.99 | 275.45 | 309.94 | 558.26 | 375.28 | 393.88 | 285.04 | 278.33 | 279.65 | 333.03 |
| 11 | ABK | 66.04 | 192.58 | 248.54 | 271.75 | 299.37 | 244.47 | 269.20 | 494.21 | 293.66 | 307.73 | 205.57 | 186.16 | 169.91 | 265.26 |
| 12 | SOD | 63.96 | 137.42 | 190.07 | 205.53 | 238.06 | 192.54 | 209.55 | 391.39 | 221.98 | 231.38 | 149.55 | 129.90 | 117.16 | 201.21 |
| 13 | MEA | 61.17 | 120.98 | 173.65 | 181.81 | 225.08 | 176.65 | 183.51 | 339.59 | 339.70 | 207.60 | 118.69 | 96.96 | 91.29 | 187.96 |
| 14 | MCQ | 59.51 | | 197.39 | 204.30 | 236.53 | 198.53 | 207.24 | 396.88 | 213.76 | 234.39 | 140.72 | 120.69 | 112.52 | 205.72 |
| 15 | NUR | 57.79 | 42.41 | 57.78 | 58.33 | 81.66 | 73.85 | 66.75 | 115.18 | 67.26 | 66.26 | 43.50 | 39.96 | 38.10 | 62.59 |
| 16 | PAF | 56.46 | 41.56 | 63.16 | 62.59 | 91.77 | 86.76 | 77.66 | 134.50 | 81.52 | 74.96 | 57.53 | 47.34 | 41.89 | 71.77 |
| 17 | OTT | 54.88 | 40.22 | 55.38 | 54.38 | 70.47 | 60.65 | 52.62 | 89.58 | 56.31 | 55.70 | 35.66 | 34.65 | 40.94 | 53.88 |
| 18 | NGK | 51.64 | 41.67 | 36.74 | 35.29 | 44.22 | 34.50 | 28.70 | 56.17 | 31.91 | 34.01 | 25.22 | 24.73 | 23.79 | 35.72 |
| 19 | CGT | 51.06 | 21.31 | 26.00 | 28.49 | 35.60 | 28.70 | 27.54 | 43.92 | 27.20 | 23.07 | 20.79 | 16.42 | 17.28 | 26.94 |
| 20 | FUR | 48.09 | 21.79 | 25.37 | 26.23 | 31.75 | 31.11 | 29.28 | 39.24 | 21.90 | 23.88 | 17.80 | 17.67 | 16.87 | 24.89 |
| 21 | HRB | 46.66 | | 24.36 | 28.93 | 34.58 | 28.36 | 29.33 | 42.57 | 24.23 | 26.49 | 19.45 | 18.97 | 18.24 | 27.11 |
| 22 | AMS | 45.83 | 21.99 | 24.77 | 27.33 | 31.50 | 31.78 | 30.17 | 39.48 | 26.98 | 22.26 | 17.99 | 23.36 | 18.59 | 26.00 |
| 23 | THY | 45.76 | | 28.51 | 29.23 | 35.24 | 27.39 | 25.35 | 43.24 | 24.57 | 26.52 | 19.49 | 19.01 | 18.31 | 27.82 |
| 24 | GNA | 41.18 | | 28.01 | 24.44 | 28.48 | 28.98 | 26.73 | 33.36 | 20.24 | 21.05 | 15.97 | 15.79 | 14.93 | 23.18 |
| 25 | IRM | 31.70 | 27.62 | 30.78 | 26.63 | 30.17 | 25.84 | 22.82 | 35.29 | 20.79 | 22.25 | 16.95 | 15.84 | 15.32 | 24.78 |
| 26 | CTA | 27.37 | | 27.89 | 22.73 | 27.91 | 25.62 | 24.50 | 30.38 | 16.87 | 18.84 | 13.95 | 13.81 | 13.09 | 21.28 |
| 27 | TAM | 24.30 | 19.45 | 32.75 | 23.05 | 30.57 | 22.29 | 20.31 | 31.44 | 18.01 | 22.29 | 14.22 | 15.40 | 13.59 | 22.50 |
| 28 | KDU | 21.34 | 17.82 | 19.12 | 21.23 | 24.32 | 26.78 | 25.75 | 25.67 | 13.82 | 15.24 | 11.11 | 10.90 | 10.33 | 17.65 |
| 29 | MBO | 19.59 | 19.11 | 22.34 | 23.92 | 29.60 | 83.68 | 22.78 | 31.33 | 18.16 | 19.62 | 14.69 | 14.77 | 15.80 | 21.82 |
| 30 | PPT | 15.04 | 30.58 | 28.61 | | 60.79 | 30.46 | 22.45 | 23.70 | 14.10 | 13.66 | 9.79 | 11.48 | 10.24 | 28.13 |
| 31 | KDU | 14.27 | 19.87 | 37.46 | 29.91 | 26.51 | 30.11 | 27.40 | 24.77 | 14.85 | 14.85 | 12.79 | 11.01 | 9.93 | 21.07 |
| 32 | PHU | 11.22 | | 20.03 | 26.50 | 29.04 | 26.60 | 28.51 | 31.04 | 18.90 | 19.56 | 13.90 | 13.34 | 12.75 | 22.07 |
| 33 | BNG | 4.04 | 19.59 | 22.73 | 23.46 | 27.94 | | | 30.34 | | 23.92 | 16.67 | 15.53 | | 23.51 |
| 34 | ASC | 2.74 | 25.29 | 25.02 | 39.57 | 28.73 | | | 23.36 | 12.98 | 14.04 | 10.85 | 12.64 | 9.17 | 20.17 |

geomagnetic disturbance. The open magnetic field topology in the polar region is primarily responsible for the strong coupling exhibited by the post-auroral stations.

The coupling between geomagnetic disturbance and solar wind holds in the mid-latitudes also as demonstrated by the correlation coefficient value of 0.59 in Table 5. However, the said correlation weakens to a very negligible value of 0.06 in the low latitudes indicating that the solar wind speed does not exert significant control on the geomagnetic fluctuations in the equatorial region.

A second pattern of variation is also evident from the VV analysis on the basis of Table 2. Even as there are some erratic variations in-between, there is a sharp fall in the mean VV values (yearly and cycle averages) starting from the auroral oval (Iqaluit station at Abs GM latitude of 73.25°) to the equatorial stations(Ascension Island station at Abs GM latitude of 2.74°)**.** Iqaluit station exhibits the highest mean VV value indicating the highest disturbance for any year (mean VV=577.90, year 2003) and also for the entire solar cycle (mean VV=361.52). Ascension Island station exhibits the lowest mean VV value indicating

Table 3 — The yearly means of VV values of selected stations from 1997 through 2008 and their latitude category VV averages.

| Year | Post-Auroral Lat | | | Pre-Auroral Lat | | | | Mid Lat | | | | Low Lat | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RES | CBB | Avg VV | IQA | MAW | SOD | Avg VV | OTT | NGK | CZT | Avg VV | BNG | ASC | Avg VV |
| 1997 | 96.35 | 151.89 | 124.12 | 277.97 | | 137.42 | 207.70 | 40.22 | 41.67 | 21.31 | 34.40 | 19.59 | 25.29 | 22.44 |
| 1998 | 118.24 | 179.02 | 148.63 | 300.81 | 304.11 | 190.07 | 265.00 | 55.38 | 36.74 | 26.00 | 39.37 | 22.73 | 25.02 | 23.88 |
| 1999 | 134.10 | 203.41 | 168.75 | 330.56 | 313.69 | 205.53 | 283.26 | 54.38 | 35.29 | 28.49 | 39.39 | 23.46 | 39.57 | 31.51 |
| 2000 | 146.22 | 224.57 | 185.40 | 350.91 | 321.06 | 238.06 | 303.34 | 70.47 | 44.22 | 35.60 | 50.10 | 27.94 | 28.73 | 28.34 |
| 2001 | 137.81 | 190.37 | 164.09 | 285.13 | 287.86 | 192.54 | 255.17 | 60.65 | 37.86 | 34.54 | 44.35 | 26.60 | | 26.60 |
| 2002 | 136.76 | 195.37 | 166.07 | 324.94 | 294.60 | 209.55 | 276.36 | 52.62 | 37.03 | 28.70 | 39.45 | 28.51 | | 28.51 |
| 2003 | 213.27 | 353.04 | 283.16 | 577.90 | 530.68 | 391.39 | 499.99 | 89.58 | 56.17 | 43.92 | 63.22 | 30.34 | 23.36 | 26.85 |
| 2004 | 139.74 | 232.57 | 186.15 | 413.27 | 358.46 | 221.98 | 331.23 | 56.31 | 31.91 | 27.20 | 38.47 | | 12.98 | 12.98 |
| 2005 | 155.29 | 253.84 | 207.57 | 422.51 | 393.54 | 231.38 | 349.14 | 55.70 | 34.01 | 23.07 | 37.59 | 23.92 | 14.04 | 18.98 |
| 2006 | 119.94 | 210.20 | 165.07 | | 290.32 | 149.55 | 219.93 | 35.66 | 25.22 | 20.79 | 27.22 | 16.67 | 10.85 | 13.76 |
| 2007 | 120.18 | 207.88 | 164.03 | 353.51 | 298.48 | 129.90 | 260.63 | 34.65 | 24.73 | 16.42 | 25.22 | 15.53 | 12.64 | 14.09 |
| 2008 | 118.84 | 197.83 | 158.33 | 349.37 | 291.09 | 117.16 | 252.54 | 40.94 | 23.79 | 17.28 | 27.33 | | 9.17 | 9.17 |

Table 4 — The year averages of the solar wind velocity for the years from 1997 through 2008.

| Year | SW speed (Km/s) |
|---|---|
| 1997 | 379.71 |
| 1998 | 412.69 |
| 1999 | 441.36 |
| 2000 | 446.36 |
| 2001 | 426.00 |
| 2002 | 441.69 |
| 2003 | 545.43 |
| 2004 | 446.92 |
| 2005 | 466.93 |
| 2006 | 434.54 |
| 2007 | 448.47 |
| 2008 | 448.62 |

Table 5 - The correlation coefficients obtained for average VV values of the post-auroral, pre-auroral, mid-latitude and low-latitude station groups with the solar wind velocity during the years 1997-2008.

| Avg VV GM(H)-SW correlation | |
|---|---|
| Station category | Correlation |
| Post-Auroral Lat | 0.96 |
| Pre-Auroral Lat | 0.91 |
| Mid Lat | 0.59 |
| Low Lat | 0.06 |

the least disturbance for any one year (mean VV=9.17, year 2008). The solar cycle mean VV of Ascension Island station is also very low (mean VV=20.17), just a 1/18$^{th}$ of the value for Iqaluit station. The least disturbed station for the entire solar cycle is Kakadu (mean VV=17.65) which has a GM latitude of -21.34. Thus the pole-ward stations are markedly more disturbed than the equator-ward as expected owing to the weak solar wind coupling at low latitudes. This result obtained[9] has been confirmed by the VV method. Further observations on the variation of geomagnetic field with latitude are detailed in sections 3.2 and 3.3.

**3.2 Spatial disturbance marking**

It is evident from the mean value analysis that high latitude stations have a distinctly high value of VV over and above the low latitude stations clearly indicating a relatively disturbed GM field. Each station has a very distinct VV disturbance marker values during the entire solar cycle and through the analysed years. The Iqaluit station has already been noted as the most disturbed one. Considering the entire solar cycle, the Kakadu station which has GM latitude of -21.34° has been found to be least disturbed. The most equator-ward station of Ascension Island also has a very small disturbance value of 20.17. These values point to a coupling between the solar wind and GM field, strongest at high latitudes and weakening towards the low latitudes.

Beyond this general observation, each GM station is disturbed to different extents, as indicated by differing VV values. A disturbance marker intends a pictographic representation of the level of GM disturbance borne by each station. Figure 2 shows the location of the 34 GM stations analysed in Section 3.1 above at their respective positions on the world map. Each station is shown in the form of a dot, the colour of which is indicative of the mean VV value and thereby the level of GM disturbance endured by that station as shown in the last column of Table 2. The VV value corresponding to the colour of the dot is shown in the colour bar given alongside the map.

Figure 2 shows the disturbance markers of the analysed GM stations for the solar cycle 23 through

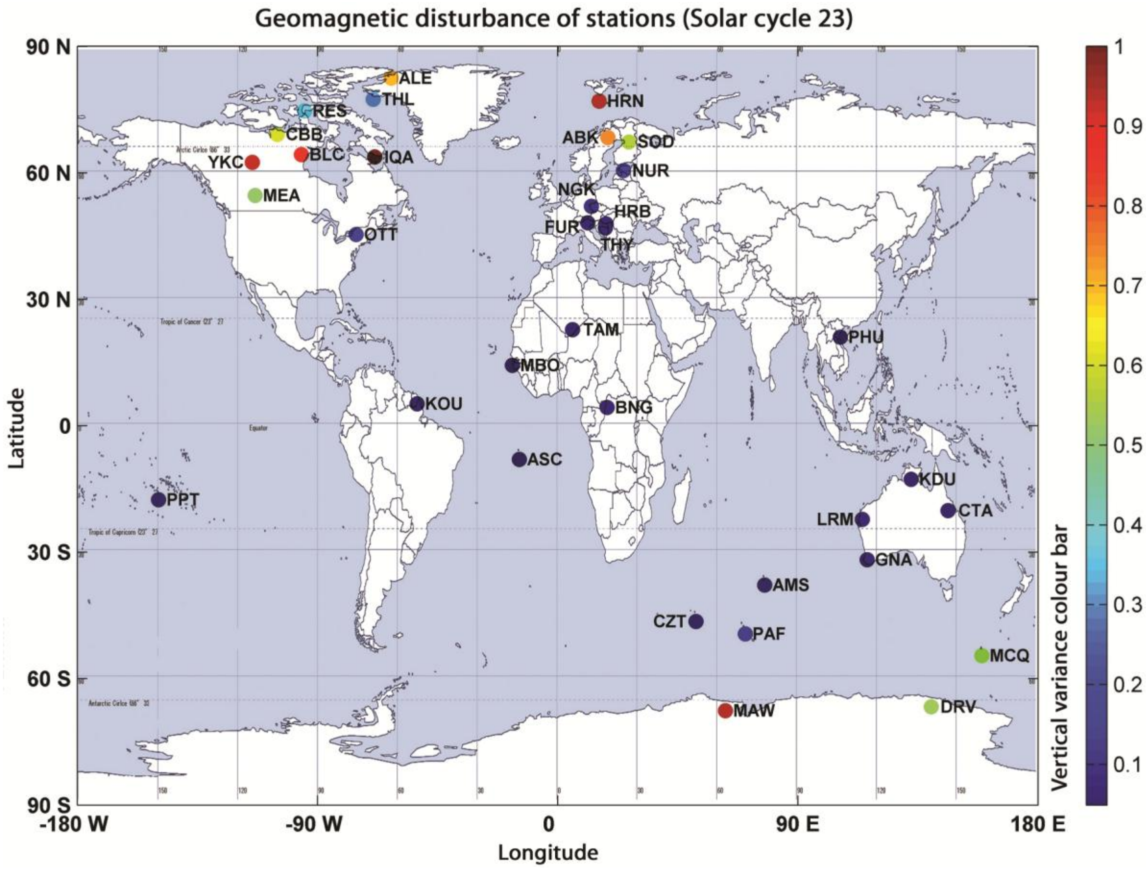


Fig. 2 — The disturbance markers for the analysed GM stations based on the mean VV values for solar cycle 23.

the years from 1997 to 2008. The colour code varies from deep blue through dark brown as the normalised VV varies from 0 through 1. The dark brown dot of Iqaluit station is indicative of it being most disturbed while the deep blue dot of Kakadu station shows it to be least disturbed. All other stations range between in terms of colour in accordance with disturbance as shown by the colour bar on the right edge of the figure. Greenish blue dots like that of Resolute bay show that the station is moderately disturbed. Light blue dots for stations like that of Ottawa and Port Aux Francais show the stations to be lightly disturbed. Red dots for stations like Yellowknife and Mawson show these stations to be highly disturbed. These VV markers facilitate easy estimation of GM disturbance of each analysed station on a spatial plane.

### 3.3 Spatial extend of high geomagnetic disturbance

It is observed from the station disturbance markers in Fig. 2 that stations with low values of GM latitude have low average VV values while those with high values of GM latitude have high average VV values. A progressive increase in disturbance from the low-latitude stations to the auroral stations is thus evident. The average yearly geomagnetic VV values are used as estimates of the geomagnetic disturbance for the analysed stations. The VV averages from Table 2 for year 2000 (column 7) and the entire solar cycle (last column) for the 34 geomagnetic stations are used in the analysis. The estimation of the spatial extend of geomagnetic disturbance is repeated here, once for a particular year (2000) and then for the entire solar cycle (23) to ascertain the findings.

A plot of the year (2000) average of the VV values against the absolute value of GM latitudes of the stations is shown in Fig. 3. The plot as observed is very remarkable in nature. The stations have low VV values from equatorial stations to those around 50˚ GM latitude. Beyond this latitude, it is observed that the stations exhibit a marked increase in the mean VV values.

Trend line analysis is used to determine the stations which are more prone to geomagnetic disturbance. In view of the abrupt changes in the mean VV values, the stations are grouped into quiet category (VV values up to 50), the pre-auroral category (stations with VV values from 50 to the peak value, Iqaluit station) and the post-auroral category (stations with GM latitudes greater than that of Iqaluit). The VV value of 50 marks a sharp increase in such value of over 50% above the average VV values up to that station. Linear best fits are attempted for these categories of stations marked separately in green (quiet), red (pre-auroral) and blue (post-auroral) colours against their absolute GM latitude.

Separate line fit equations are obtained for the quiet and pre-auroral categories of stations as follows.

$$y = 0.087x + 30.18 \text{ (Quiet)} \quad \ldots (3)$$

$$y = 13.81x - 656.8 \text{ (Pre-auroral)} \quad \ldots (4)$$

On determining the intersection of these two linear best fits (between quiet and pre-auroral stations), the threshold latitude which offsets the geomagnetic disturbance is located. Solving equations (3) and (4), this threshold GM latitude is obtained as 50.06˚ using data for the year 2000.

Similar analysis is performed using entire data for solar cycle 23 (1997-2008). The plot of the mean VV values against the absolute GM latitude using the data is shown in Fig. 4. The nature of the plots so obtained

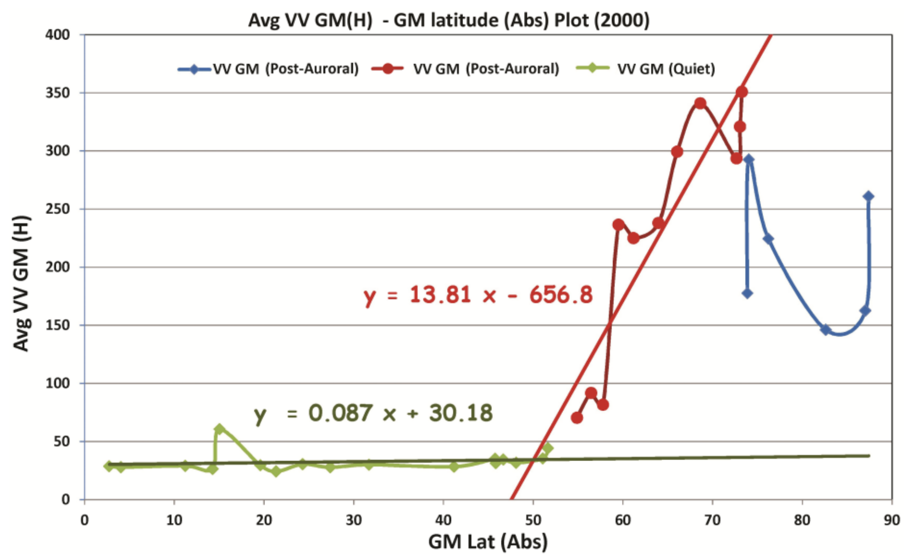


Fig. 3 — The plot of the average of VV values and the best fits of the analysed stations for year 2000 against absolute GM latitudes.

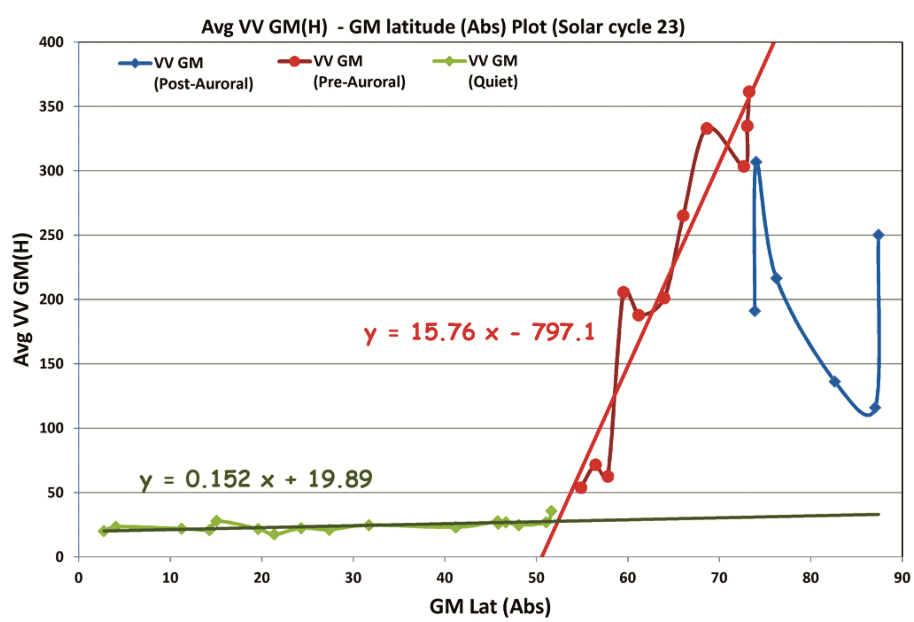


Fig. 4 — The plot of the average of VV values and the best fits of the analysed stations for solar cycle 23 against absolute GM latitudes.

is very much similar to that for the year 2000. Linear fit analysis is performed on the quiet, pre-auroral and post-auroral categories of stations. The line fit equations are obtained for the quiet and pre-auroral categories of stations as follows.

$$y = 0.152x + 19.89 \text{ (Quiet)} \quad \ldots (5)$$

$$y = 15.76x - 797.1 \text{ (Pre-auroral)} \quad \ldots (6)$$

On determining the intersection of the two linear best fits, the threshold latitude is located. Solving equations (5) and (6), the threshold GM latitude is obtained as 52.34˚ using data for the solar cycle 23. This value is in close agreement with the value of 50.06˚ obtained for the year 2000.

### 3.4 Latitude penetration of disturbance during storms

There are periods during which the magnetic environment of the Earth comes under severe stress marked by critical fall in $D_{st}$ values. The disturbance levels suffered by geomagnetic stations besides depending on its latitude also depends on the disturbance levels in the magnetosphere. Times during which the $D_{st}$ index typically falls below -50nT are designated as geomagnetic storms[10]. The solar cycle average VV value is highest for Iqaluit station (VV=361.52) as already observed from Table 2 (last column).However, the daily values of VV of the stations render more information.

The daily values of VV for the 19 selected stations with absolute GM latitudes greater than 50˚ are chosen for analysis. Stations below this latitude experience negligible geomagnetic disturbance. VV values for one quiet day (18 May 2004) and two storm days (27 Jul 2004, 7 Nov 2004) for these stations were determined and is given in Table 6. Figure 5 shows the normalised disturbance curves of these stations for the 3 analysed days.

During the quiet day, Iqaluit (Abs GM lat: 73.25) remains the most disturbed station (VV=191.84) in agreement with the pattern observed in the solar cycle average. On the first storm day considered (27 Jul 2004), of all stations, Macquarie Island (Abs GM lat: 59.51) experienced the greatest disturbance (VV=2593.30). Similarly, on the second storm day considered (7 Nov 2004), Nurmijarvi (Abs GM lat: 57.79) experienced the greatest disturbance (VV=1007.60).

## 4 Results and Discussion

A measure of the fluctuations, (the disturbance to which a geomagnetic station in subject) has been obtained from the result of analysis of the value of the geomagnetic field VV. The daily, monthly, yearly and solar cycle average disturbance levels of each station in the form of the corresponding mean VV values are determined herein. Two remarkable features of the latitude profile of geomagnetic disturbance is brought forth and explored in this analysis.

Primarily, it is evident from Section 3.3 that stations at higher latitudes are more disturbed than those at low latitudes. Threshold GM latitude has been identified at which the disturbance level begins to rise sharply exhibiting 'knee' behaviour. This threshold latitude has been determined to be at 50.06˚ for the year 2000 and 52.34˚ for the solar cycle 23, the two results being in close agreement.

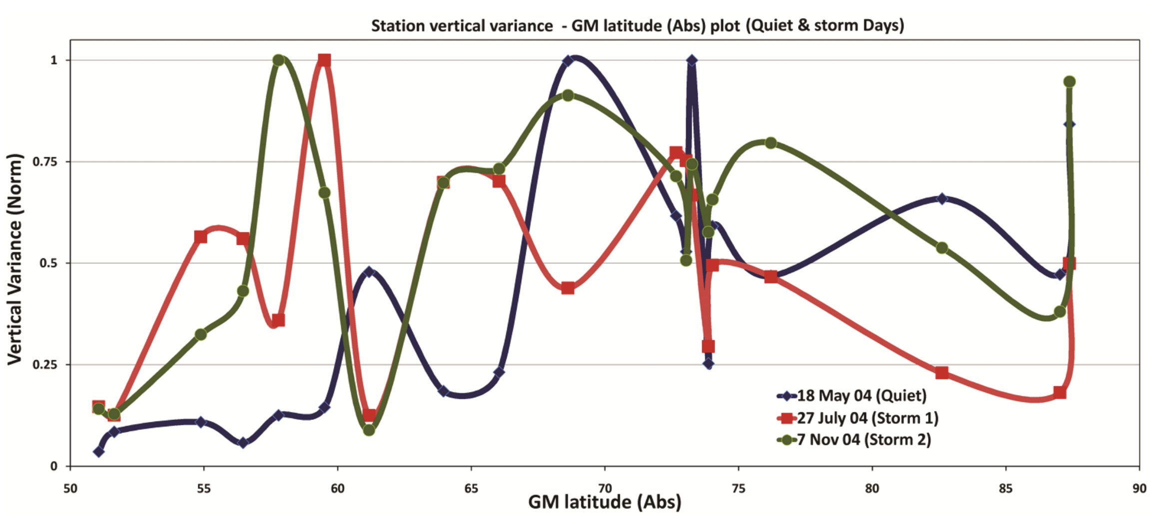


Fig. 5 — The plot of the normalised daily VV values of 19 selected stations for three days, one quiet day and two storm days.

Table 6 — The daily VV values of 19 selected stations for three days, one quiet day and two storm days.

| Station | Abs GM lat | VV (Quiet) 18 May 04 | VV (Storm 1) 27 July 04 | VV (Storm 2) 7 Nov 04 |
|---|---|---|---|---|
| Alert | 87.38 | 161.58 | 1294.90 | 954.08 |
| Thule/Qanaq | 87.02 | 90.63 | 471.22 | 383.71 |
| Resolute Bay | 82.61 | 126.35 | 596.37 | 541.94 |
| Cambridge Bay | 76.21 | 89.96 | 1209.80 | 802.17 |
| Hornsund | 74.02 | 113.42 | 1284.30 | 661.74 |
| Dumont d'Urville | 73.87 | 48.59 | 765.46 | 580.88 |
| Iqaluit | 73.25 | 191.84 | 1731.20 | 749.91 |
| Mawson | 73.04 | 101.44 | 1951.20 | 510.79 |
| Baker Lake | 72.66 | 118.28 | 2003.00 | 719.51 |
| Yellowknife | 68.62 | 191.56 | 1137.80 | 920.21 |
| Abisko | 66.04 | 44.52 | 1819.20 | 738.14 |
| Sodankyla | 63.96 | 35.55 | 1813.20 | 703.25 |
| Meanook | 61.17 | 91.92 | 324.24 | 89.89 |
| Macquarie Island | 59.51 | 27.88 | 2593.30 | 678.56 |
| Nurmijarvi | 57.79 | 24.13 | 932.86 | 1007.60 |
| Port Aux Francais | 56.46 | 11.11 | 1453.10 | 435.15 |
| Ottawa | 54.88 | 20.86 | 1464.50 | 326.79 |
| Niemegk | 51.64 | 16.34 | 326.52 | 129.81 |
| Crozet | 51.06 | 6.99 | 379.82 | 142.46 |

The disturbance content also peaks at the auroral oval with sharp changes beyond. The magnetic field lines have a trapping geometry in the vicinity of the auroral oval where there is a concentration of such lines owing to the dipolar nature of the geomagnetic field[11]. This accentuates the effect of any fluctuation in the solar wind and the IMF causing extreme geomagnetic disturbance near the auroral oval. This causes a peak in the VV values in the case of stations such as Iqaluit (solar cycle mean VV=361.52, Abs GM latitude=73.25˚) as seen in Fig. 3 and Fig. 4.

Pole-ward of the auroral oval, the closed dipolar field topology changes to an open field one. The abrupt change in the nature of the field causes sharp changes in the level of disturbance just beyond the auroral oval in the direction of the geomagnetic poles. It can be noted in Fig. 3 and Fig. 4 that disturbance levels as manifested in the VV values change vertically in this region (around 73˚ Abs GM latitude) for the slightest change in latitude. Equator-ward of the auroral oval, a decreased density of field lines characteristic of a dipolar topology weakens the magnetic disturbance in that direction.

Secondly, the comparison of daily VV values for quiet periods and storm time provides critical information as noted in Section 3.4. The storm time VV values are on the much higher side as expected. Besides, the disturbance values on the quiet day are greater towards higher latitudes. The blue line representing the quiet day in Fig. 5 evidences this trend. However, during storm days, lower latitude stations are more disturbed as shown in Table 6 and the red and green lines in Fig. 5. Besides, the most disturbed station also shifts towards lower latitudes (Iqaluit to Macquarie Island/Nurmijarvi). Thus, geomagnetic storms cause a visible penetration of disturbance towards lower latitudes as against quiet times.

## Acknowledgements

The solar wind velocity data has been obtained from the ACE data center. The geomagnetic field data for the same period is available[12] and provided by World Data Centre (WDC), Kyoto. The ACE data centre provided the solar wind velocity. The open source world map outline has been obtained[13].

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