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On the effects of solar flare on geomagnetic components across all latitudes during solar minimum and maximum

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The mutual dependence of solar flare and geomagnetic H and Z components during the period of least (2009) and maximum (2002) solar activity using archived and observed data were examined. Solar flares were identified by sudden ionosphric monitor (SIDMON) constructed by staff of Centre for Basic Space Sciences, University of Nigeria, Nsukka, Nigeria. However, SIDMON results were still confirmed by satellite data since it was still at the rudimentary stage. Results show that during solar minimum and solar maximum solar flare affects the geomagnetic H component but appears to have little or no effect on the Z component across all the latitudes. The effect is pronounced at the equatorial latitude more than at the high latitudes. Results from SIDMON is though not very reliable but encouraging, thus the instrument needs a lot of improvement.

Key words: Geomagnetic field, geomagnetic components, solar activity, solar flare.

INTRODUCTION

Solar flares (SFs) are known to have adverse effects on ground-based and space-based communication, navigation and power distribution systems. They distort long distance short-wave radio communications, degrade accuracy of Global Positioning System (GPS) measurements and damage electronic components as well as reduce life span of satellites. They cause power failures by tripping off circuit breakers and damaging transformers. Thus, the economic and social losses from SFs are enormous.

Balasis et al. (2019) reported an enhancement of equatorial spread F in the South Atlantic anomaly with a high latitude activity which is related to field alignment currents. Shock activity produces both positive and negative storms during solar minimum and increasing phases but ionospheric currents are unaffected during solar maximum (Gyébré et al., 2018). Doumbia et al. (2017) opined that induced space-weather related

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geomagnetic activity is more pronounced in brisk impulses like storm sudden commencement and solar flare effect in geomagnetic fields, variations which are enhanced across all latitudes (Ugonabo et al., 2016).

SFs affect the geomagnetic field by increasing ionization mainly in the E region, partially in the D region and occasionally in the F regions (Sengupta, 1970; Das et al., 2010) but the level at which x-ray ionization becomes dominant depends on the level of solar activity and on solar angle and is dominant above 85 km for all levels of solar activity (Sengupta, 1980). SFs are produced mainly in two preferred longitude ranges; the so-called active regions (Zhang et al., 2011). They produce radiations across the entire electromagnetic spectrum, affect all the layers of the solar atmosphere and are responsible for ionospheric events during periods of high and low solar activity.

Disturbance in the vertical component of the atmospheric electric field associated with solar flare and coronal mass ejections is mostly observed close to the onset of the causative solar flare (Kasatkina et al., 2009). Several researchers (Brown, 1981; Butcher and Brown, 1981; Butcher, 1982; Rastogi, 1997; Rastogi et al., 1999; Okeke and Hamano, 2000; Abdu et al., 2017) observed a reversal of the electric field around local noon hour, particularly over equatorial electrojet (EEJ) stations, with the horizontal and vertical components of the geomagnetic field showing maximum value at the noontime. This is a very rare phenomenon. The counter EEJ (the pre-noon and afternoon maximum in dH events observed in the geomagnetic H field, the absence of equatorial sporadic E region (Esq) reflections and the reversal of the ionospheric drift direction during daytime hours at an equatorial station were concurrent phenomena (Rastogi et al., 1971). Abdu et al. (2017) observed that the expected eastward growth in electric current due to flare induced ionization enhancement is strongly shielded by an electric current of westward polarity.

Okeke and Okpala (2006) found that strong correlation exists between solar flare amplitude of the Z component (dZ_{sfe}) and the monthly mean of the Sq variation. In addition, strong responses of the Z and Y fields to solar activity were observed.

Purpose of the study

SFs have very serious effects on local space weather since they affect the earth's magnetic field and the atmosphere of the earth. For instance, during solar flares proton storms are released and can change the magnetic field of the earth. The purpose of this work is to: (i) identify solar flares using Sudden Ionospheric Disturbance Monitor (SIDMON from a Nigeria-based observatory, Centre for Basic Space Science, (CBSS), University of Nigeria, Nsukka, (UNN), (ii) investigate the effects of solar flare on geomagnetic H and Z components during solar maxinum and solar minimum by calculating the ratios of solar flare enhancement amplitudes (ΔH_{sfe} and ΔZ_{sfe}) to pre-flare amplitudes (ΔH_o and ΔZ_o) respectively. The results will throw more light on a better understanding of the effects of solar flare on geomagnetic activity. SIDMON was locally constructed by staff of CBSS, UNN. It was being tested for detecting small ionospheric disturbances by way of increased ionization like C and M classes of flares and disturbances from transformers, fluorescent tubes, and computers among others. It must be noted that SIDMON can only identify C and M classes of solar flares; the X class of flares causes a plateau effect on a SIDMON and cannot be identified by it. It was the first time SIDMON was used to identify solar flares from a Nigeria-based observatory.

Sources of data

Through observational technique, SFs were identified using SIDMON of CBSS, UNN. Solar flare data were downloaded from NGDC of the NOAA, Boulder, USA. This enabled us to compare results from CBSS, Nsukka, Nigeria with that of NOAA, Boulder, USA.

The data set of geomagnetic elements H and Z one minute averages were obtained from four observatories namely: Addis Ababa, Bangui, Belsk and Hel, courtesy of INTERMAGNET (http://ottawa.intermagnet.org/apps/dl_data_prel_e.php). These stations lie within latitude 4°N–55°N and longitude 14°E–39°E (Table 1) and cover all the latitudes. They have uninterrupted data for 2002 and 2009, which were periods of solar maximum and solar minimum respectively and the period for this study. The year 2009 was a period of spotlessness (low sunspot count), mostly slow solar wind, and low solar irradiance. No significant solar flare was recorded between 2008 and 2009 by satellites and only very few of these flares were identified by SIDMON.

Sunspot number was obtained from http://www.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONL courtesy of NGDC, NOAA, Boulder, Colorado, USA.

THEORY AND METHOD OF ANALYSIS

Using the International quiet days, SFs that have effect on geomagnetic field were selected and analyzed for the four different stations.

The deviations on the geomagnetic components H and Z with respect to the 0000 h value on same day according to Rastogi (1997) are denoted as ΔH_0 and ΔZ_0 and are defined as:

$$\Delta H_0 = H_{bf} - H_{00} \text{ and } Z_0 = Z_{bf} - Z_{00} \quad (1)$$

where H_{bf} and Z_{bf} are the values of the field components just

Table 1. The stations used and their locations.

Station	IAGA Code	Country	GG Lat. (°N)	GG. Long. (°E)	GM. Lat. (°N)	GM Long. (°E)
Addis Ababa	AAE	Ethiopia	9.03	38.77	5.35	111.57
Bangui	BNG	Central African Rep.	4.23	18.57	4.24	90.92
Belsk	BEL	Poland	51.84	20.79	50.23	105.20
Hel	HLP	Poland	54.51	18.22	53.22	104.59

Table 2. Regression analysis.

Station	Slope (K)	Intercept (φ)	Coefficient of determination (r^2)
AAE	-0.0285	1.5857	0.1355
BNG	0.0258	-2.0818	0.0431
BEL	-0.0103	0.0	-0.294
HLP	-0.0217	2.2694	0.00035

before the start time of the solar flare, and Z_{00} and H_{00} are the values at 0000 h UT. Equation 1 was used to calculate the deviations.

The enhancements due to solar flare on the components, H and Z were calculated using Equation 2 as defined by Rastogi (1997) as:

$$\Delta H_{sfe} = H_{pf} - H_{bf} \text{ and } \Delta Z_{sfe} = Z_{pf} - Z_{bf} \quad (2)$$

where ΔH_{sfe} and ΔZ_{sfe} are the enhancements and, H_{pf} and Z_{pf} are the values at the peak of the solar flare.

The ratios $\Delta H_{sfe}/\Delta H_0$ and $\Delta Z_{sfe}/Z_0$ were calculated. If a ratio is greater than zero, then there is enhancement of the geomagnetic component; but if it is less than zero there is reduction of the field component. A ratio of zero implies no effect on the component.

According to Volland and Taubenheim (1958), the Sq current, i_0 is made up of the current flowing in the maximum level of the E-region, i_{OE} and the current flowing in the other regions, i_{OR}. Thus, the total Sq current is

$$i_O = i_{OE} + i_{OR} \quad (3)$$

Also, additional current, i flows as a result of geomagnetic solar flare effect (SFE) which is made up of a part flowing in the maximum level of E-region, i_E and a part flowing in the other regions, i_D. The total SFE current, i is given by

$$i = i_E + i_D \quad (4)$$

$$i_O + i = i_{OE} + i_E + i_{OR} + i_D \quad (5)$$

$$i\left(1 + {}^{i}/_{i_O}\right) = i_{OE}\left(1 + {}^{i_E}/_{i_{OE}}\right) + i_{OR} + i_D \quad (6)$$

But the magnetic horizontal intensity is proportional to the current, then

$$\frac{i}{i_O} = \frac{\Delta H_{sfe}}{\Delta H_O} = \frac{i_E}{i_{OE}} \quad (7)$$

$$\therefore \Delta H_{sfe} = \frac{\Delta H_O\, i_E}{i_{OE}} \quad (8)$$

In a more general form, Equation 8 can be written as

$$\Delta H_{sfe} = K\Delta H_O + \varphi \quad (9)$$

where $K \approx \frac{\Delta H_{sfe}}{\Delta H_O}$ is the slope and φ is the intercept which is zero in theory.

Therefore, a linear regressed plot of ΔH_{sfe} against ΔH_O is a statistical measure of enhancement or reduction of geomagnetic H or Z component. If $K > 0$, then a positive correlation exists which means there is enhancement; but if $K < 0$, a negative correlation exists and the field is reduced.

RESULTS AND DISCUSSION

From Table 2 which is summarized in Figure 1(a-d), it is clear that only the equatorial latitude station of BNG exhibited a positive correlation with a positive slope which suggests that geomagnetic H component is enhanced while the rest stations showed negative correlation implying reduction of the H component. The intercepts which are zero in theory deviated from the prediction in three stations. This may be due to the effects of longitudinal variations, approximation of local time and possible effect of external ionization of the SIDMON used in observing some of the flares locally. However, with

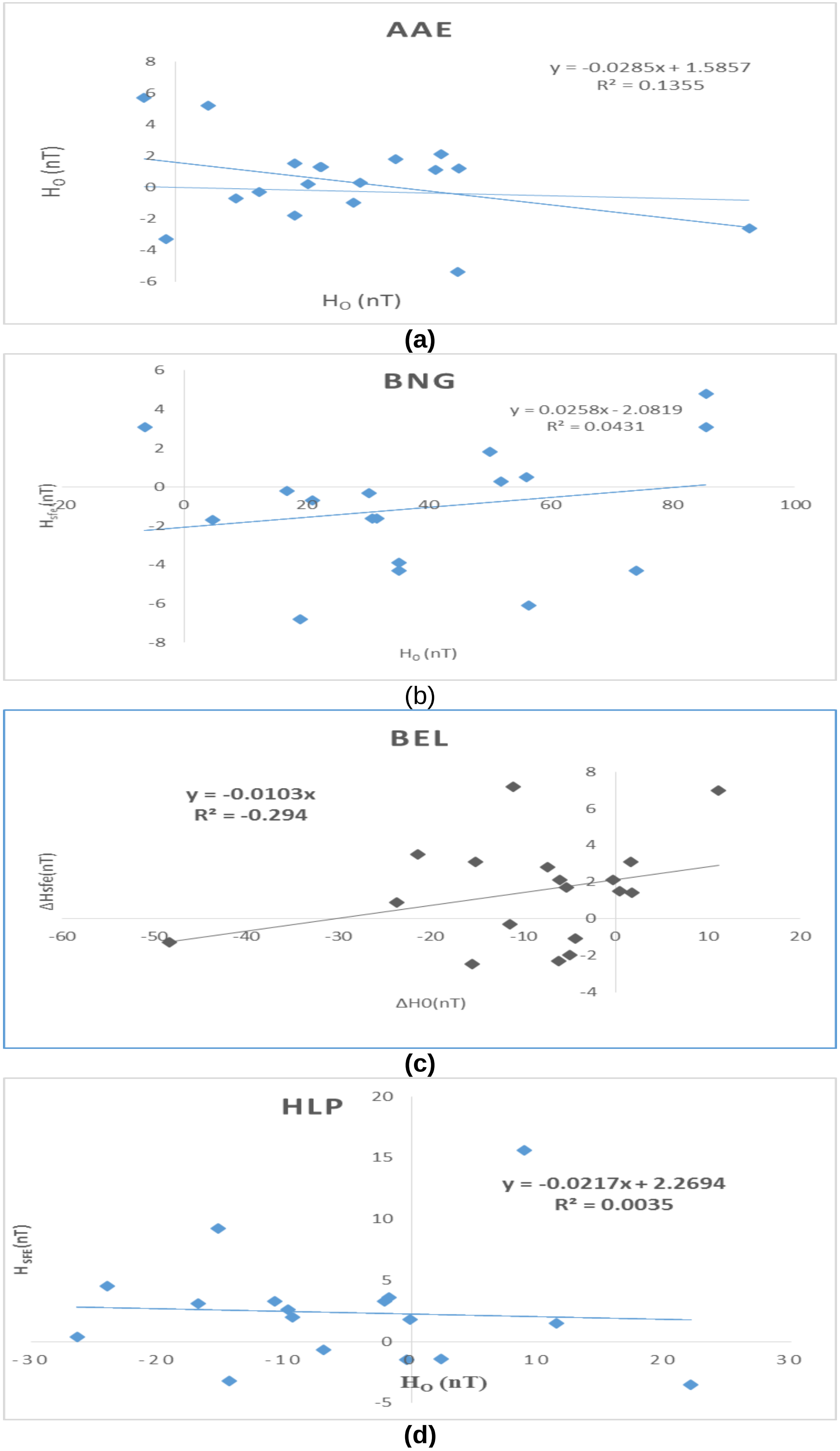

Figure 1(a-d). Plots of ΔH_{sfe} against ΔH_O for the four stations.

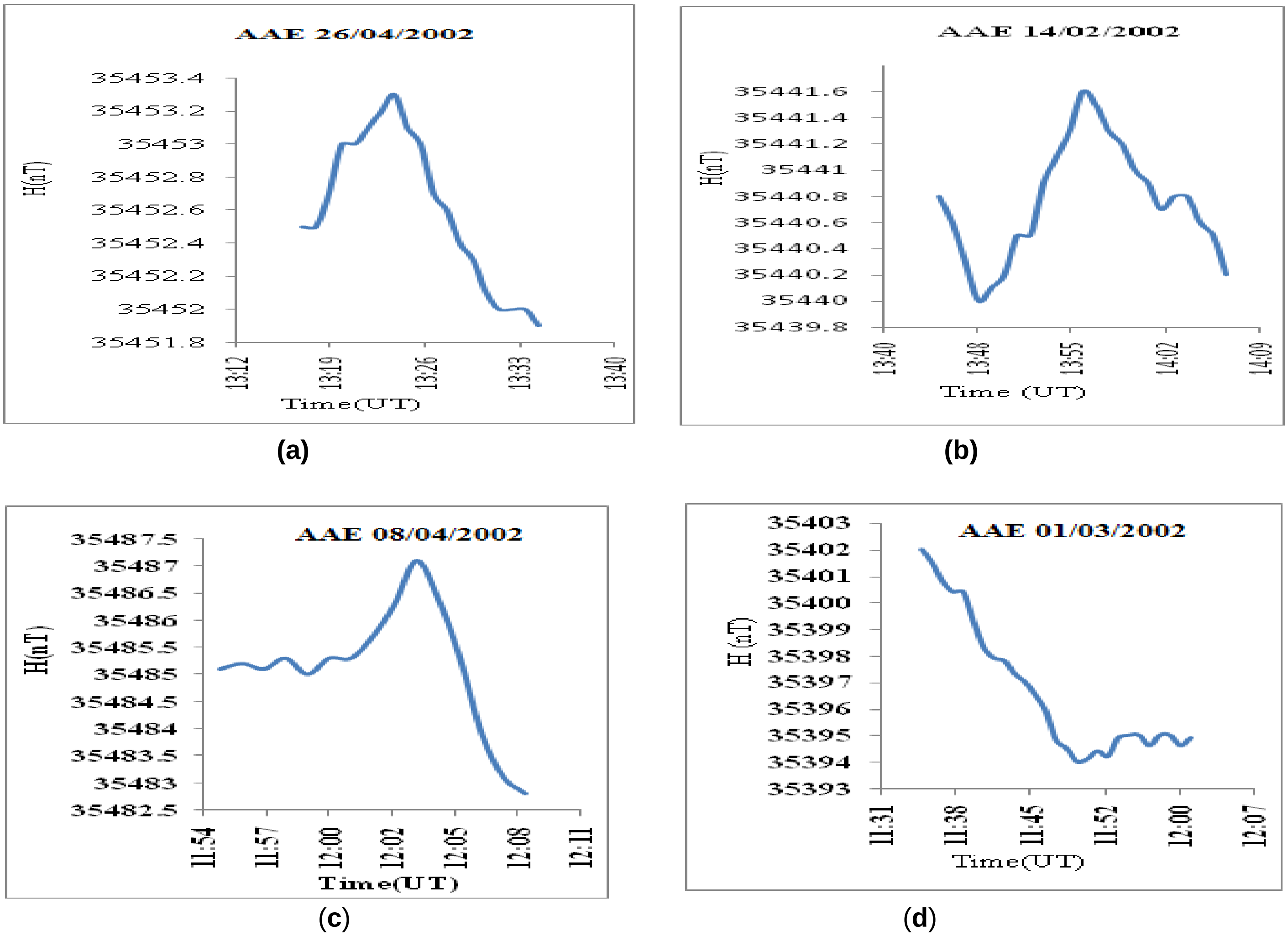

Figure 2(a-d). Some of the SFs that show signatures on geomagnetic field at the dip equator station of AAE.

very small values of coefficient of determination, r^2, the regression line may not be the best parameter to describe the relationship between geomagnetic field component and solar flare.

Figures 2 to 5 illustrate the variations of geomagnetic H component during solar flare events. Only some of the SFs are shown. A total of 22 solar flares were selected out of which eight were detected by SIDMON after comparing with satellite data. The selected flares were those that had signatures on geomagnetic H component since the Z component showed erratic behavior with solar flares. At AAE, a dip latitude station, 11 or 61% of the 18 flares analyzed have ratios greater than zero while only 7 or 39% SFEs have ratios less than zero. BNG is an equatorial station and 12 or 71% out of 17 SFs recorded ratios greater than zero and only 5 or 29% of the flares had ratios less than zero. From the results, there was more enhancement than reduction of the H component of the geomagnetic component at AAE and this trend was followed by BNG, an equatorial latitude station. At the mid-latitude station of BEL, 18 solar flares were analyzed; 50% had ratios greater than zero and 50% recorded ratios less than zero. At the high latitude station of HLP, 17 solar flares were analyzed and only 6 or 35% recorded ratios greater than zero while 11 or 65% had ratios less than zero implying that almost half of the flares reduced the component. Summarily, 54% of all the flares enhanced the geomagnetic field while only 46% reduced the field. This observation has been linked to the existence of zonal and meridonal currents which accounts for the Sq currents. Also, in some cases where ΔH_o showed negative excursions, they mostly change to positive excursions in ΔH_{sfe} after the flare. Hence, solar flare events consist mostly of positive impulse in H components.

From the analyses, it is clearly obvious that solar flares slightly enhanced the H component of geomagnetic field more than they reduce the component and has no effect

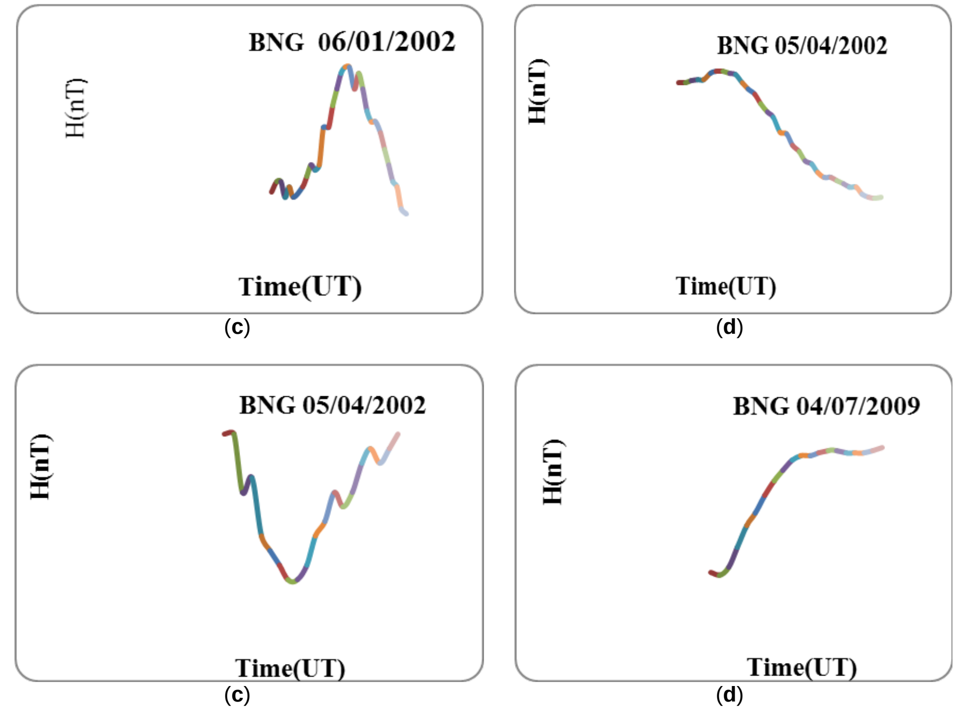

Figure 3(a-d). Some of the solar flares that show signatures on geomagnetic field at the dip latitude station of BNG.

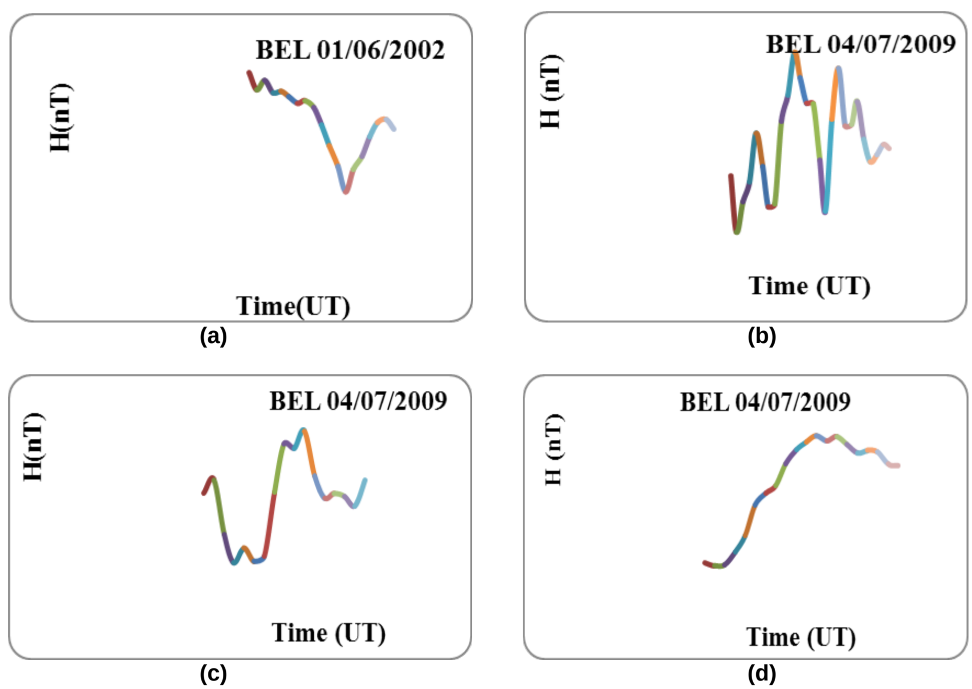

Figure 4(a-d). Some of the solar flares that show signatures on geomagnetic field at the mid latitude station of BEL.

on the Z component. This does not wholly agree with Rastogi (1996, 2003) and Rastogi et al. (1997) who concluded that solar flares only enhanced geomagnetic field. They enhanced the H component mostly at the dip

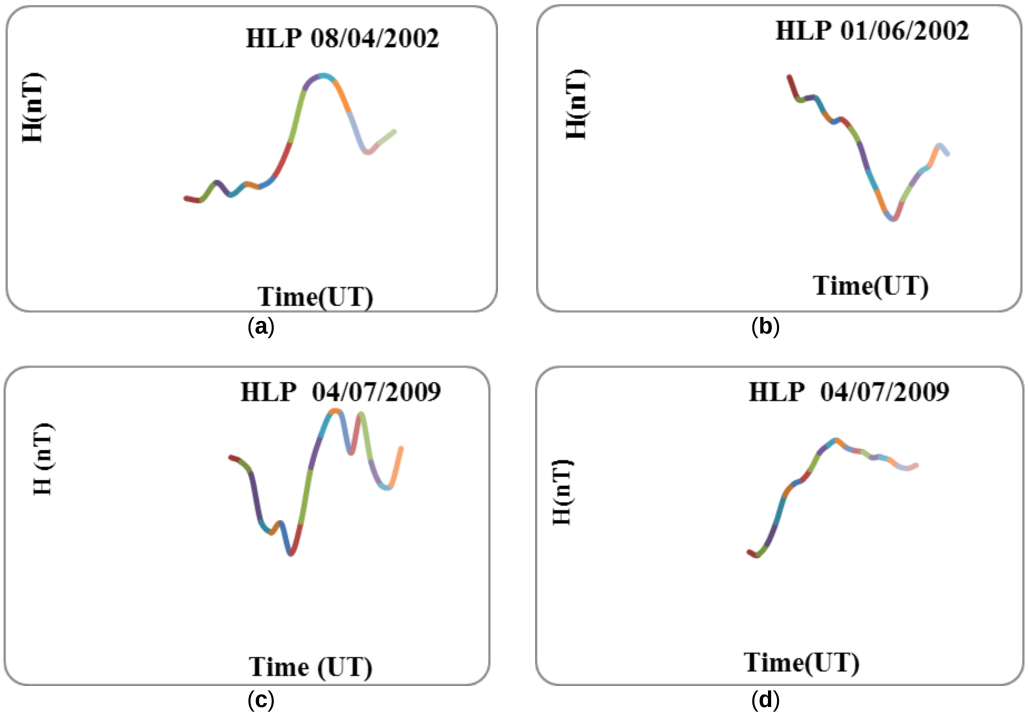

Figure 5(a-d). Some of the solar flares that show signatures on geomagnetic field at the high latitude station of HLP.

and equatorial latitudes only. Reduction of geomagnetic components spells doom for life on earth as geomagnetic field protects us from the hazards associated with solar flares and geomagnetic storms which sometimes accompany flares. The world is dynamic, hence there is need to carry out more studies on the effect of solar flare on geomagnetic components.

The Z components of the geomagnetic field showed no remarkable changes in the values of Z_{bf}. Though there appeared to be a consistent increase in the values, there were erratic variations in Z during and after most of the flares. It does appear that solar flare events had no signatures on the Z components in all the stations.

Results from SIDMON

From Figure 6a, the SIDMON had recorded high values of ionization at the two points labeled flares. The peak of ionization at 1220UT in Figure 6a is likely the same as the solar flare with peak at 1204UT at BEL in Figure 4d because flare requires some minutes to arrive at the ionosphere for SIDMON to identify it. The flare arrived at the ionosphere about eight (8) minutes after it has been recorded by satellite. Figure 6b shows the plot of SIDMON values between 1225 UT and 1243 UT and it was suspected that flares occurred at the points labeled flare though the GOES satellite had identified a flare that occurred between 1231 UT and 1238 UT. This flare had its peak at 1233 UT at AAE (Figure 2f) and 1237 UT at both BEL and HLP (Figures 4e and 5e respectively). Comparing Figures 2f, 4d and 5d with Figure 6b, it was clearly obvious that the flare which started at 1231 UT and ended at 1238UT as recorded by GOES satellite was identified at 1238 UT by SIDMON at CBSS, UNN as increased ionization. There was a lag time of about seven (7) minutes before it arrived at the ionosphere for it to be identified by SIDMON. GOES satellite recorded flare between 1503 UT and 1512 UT with peaks at 1507 UT at AAE (Figure 2d) and HLP (Figure 5c), 1511UT at BNG (Figure 3d) and 1508 UT at BEL (Figure 4f) respectively but SIDMON recorded peak ionization at 1502 UT (Figure 6c). There was no time lag as expected. It is possible that SIDMON was affected by other disturbances like transformers, fluorescent tubes, computers and occasionally, geomagnetic storms. Any of them can mimic increased ionization records of a SIDMON, hence the need to compare SIDMON plots with the plots of satellite values before finally concluding that there was a solar flare or not. This may also be the reason for having points of high values labeled flares in Figure 6a-c; but after comparing with satellite value plots, there were no flares.

Conclusions

Effects of solar flare on geomagnetic field using satellite

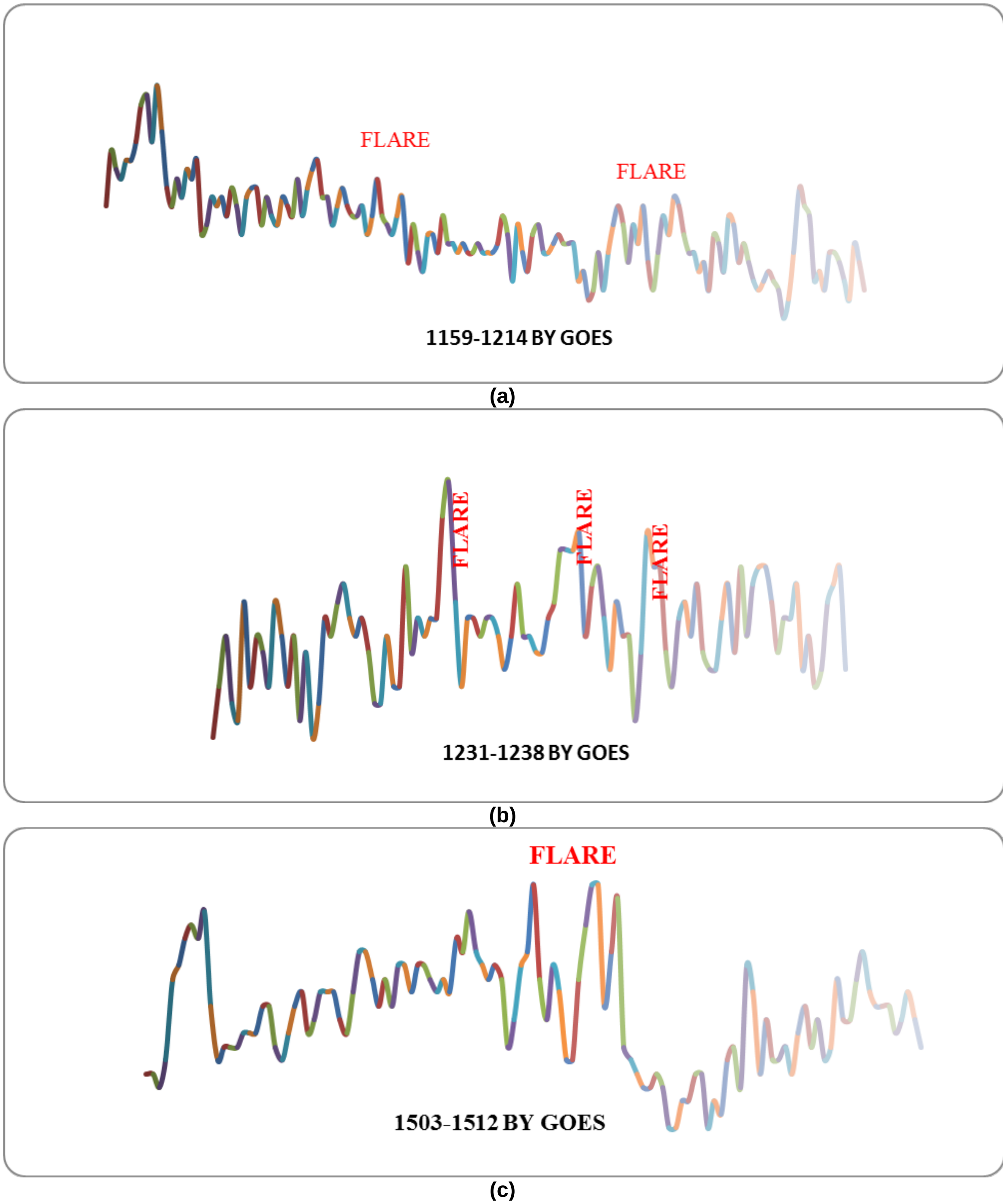

Figure 6(a-c). Recordings of ionization of the ionosphere by SID Monitor at CBSS, UNN on 04/07/09 at different periods of the day. The peak

and ground data were studied. Based on the analyses of the data available to us, the following conclusions were made: (i) SIDMON can identify SFs but they have to be confirmed with satellite data. (ii) Solar flares enhances the H component of geomagnetic field more than they reduce it at the equatorial and dip latitude stations. (iii) Outside the equatorial and dip latitude stations, solar flares appear to reduce the H component more than they enhance it. (iv) Solar flares do not appear to have any appreciable impact on the Z component; and (v) No two solar flares are exactly the same as flares differ in their signatures on geomagnetic field.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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