Occurrence of Major Geomagnetic Storms and Their Relation with Plasma Parameters, Interplanetary Magnetic Field Parameters, and Geomagnetic Index during Solar Cycle 23

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Abstract - **A geomagnetic storm is a temporary disturbance of the Earth's magnetic field which is magnetosphere usually occurred due to a disturbance in the interplanetary magnetic field (IMF). There are many parameters that can be used to predict the storms. Three geomagnetic storms are observed during three phase of the solar cycle. This paper investigates the relationship that exist among the following interplanetary magnetic field (IMF) parameters: (Bz, By, Bt), and the geomagnetic index (GI): (Kp, Dst. Ap, Ae) along side with the plasma parameters: (T, D, V) during major geomagnetic storms. In this study major geomagnetic storms were indicated by Dst below than -200nT. All the data were taken from OMNIWeb Data Explorer and National Geophysical Data Center. The relationship between IMF parameters, GI, and plasma parameters with disturbance time index (Dst) was studied. The periods of minimum phase of solar cycle 23 are between 1996-1998 and 2004-2006 while maximum phase is during 2000-2001. A correlative study between the geomagnetic indices and the peak of various plasma and field parameters during major geomagnetic storms of solar cycle 23 also presented. From this study, it shows that some parameters used play moderate role ($0.3 < r < 0.5$) in Dst morphology and some do not play significant role.**

Keywords- **Geomagnetic storm, geomagnetic index**

I. INTRODUCTION

Geomagnetic storms is a temporary disturbance in the Earth's magnetic field caused by coronal mass ejections (CMEs) or solar flare from the Sun. CME is a giant bubble emitted from the Sun to surroundings. Solar flare will increase the magnitude of solar wind tremendously. The increase in the solar wind pressure will compresses the magnetosphere and the solar wind's magnetic field will interact with the Earth's magnetic field and transfer an increased amount of energy into the magnetosphere [1]. Geomagnetic storms can cause damage to technology on Earth including satellite navigation signals and aircraft communication. The solar wind carries with it the magnetic field of the Sun and when it enters to the interplanetary medium is called as interplanetary magnetic field (IMF)

The storms generally occurred due to abnormal conditions in the interplanetary magnetic field (IMF) and solar wind plasma emissions caused by various solar phenomenon [2]. The Bt value of the IMF indicated the total strength of the IMF. The higher this value, the better it is for enhanced geomagnetic conditions [3]. The IMF is a vector quantity with a three axis component, two of them are (Bx and By) are orientated parallel to the ecliptic. The third component, the Bz value is perpendicular to the ecliptic and is created by waves and other disturbances in the solar wind [3]. Several authors have pointed out the high probability of intense storms being triggered during the southward interplanetary magnetic field (IMF) [4]. It is usually assumed that the peak value of the storm, as measured by Dst index, is obtained after the southward component of IMF, Bz has also reached peak value [5].

Geomagnetic index also related to geomagnetic storms. Geomagnetic index used are Kp index, Dst index, Ae index, and Ap index. The Kp index quantifies disturbances in the horizontal component of earth's magnetic field with an integer in the range 0-9 with 1 being calm and 5 or more indicating a geomagnetic storm. Value of Kp index for major storm is above 8. Dst is a measure of the decrease in the horizontal component of the Earth's magnetic field near the magnetic equator due to increases in the magnetospheric ring current. The minimum Dst value reached is often used to classify the strength of a magnetic storm. Based on the common classification (for example Loewe and Prölss) [1], storms are categorized as major storms if the minimum Dst below than -200nT [2]. Ae index is used to indicate the auroral, or substorm, activity. The Ap-index provides a daily average level for geomagnetic activity where days with high levels of geomagnetic activity have a higher daily Ap-value. Large geomagnetic storms are usually caused by structures in the solar wind having specific features which is long durations of strong southward IMF impact on the Earth's magnetosphere [2].

Solar cycle is that the sun's hemispheres do not always peak at the same time. In the current cycle, the south has been lagging behind the north. The second peak, if it occurs, will likely feature the southern hemisphere playing catch-up, with a surge in activity south of the sun's equator [6].

II. METHODOLOGY

The focus in this study is during solar cycle 23. Figure 1 shows the flowchart of the methodology. Firstly, the topic of this study is selected then all the parameters are set to investigated. For this study, the following parameters are being used to study the major storms: total magnetic field, Bt (nT) of IMF, negative y-component of IMF, By (nT), negative z-component of IMF, Bz (nT) used in this study are in geocentric solar ecliptic (GSE) coordinate system. The plasma parameters used are: proton temperature, T (K), proton density, D (N/cm^3), and plasma speed, V (km/s). For geomagnetic index are: Kp, Dst, Ap, and Ae index.

Then the data for this study are collected from OMNIWeb. Table 1 shows description of the parameters.

Table 1: Description of parameters

Parameters	Description
Dst Index	The Dst index is used to define the occurrence, duration and magnitude of a storm. The strength of storms are determined as follow: Weak storm minimum Dst below -30 nT, Moderate storm minimum Dst below -50 nT, Strong storm minimum Dst below -100 nT, Severe storm minimum Dst below -200 nT, Great storm minimum Dst below -350 nT
Kp Index	The Kp-index is a global geomagnetic storm index with a scale of 0 to 9. The larger the index (7+) the more active the Earth's magnetic field becomes due to a storm from the sun. Kp values greater than 7 indicate a large disturbance.
Ap Index	The Ap-index provides a daily average level for geomagnetic activity. Days with high levels of geomagnetic activity have a higher daily Ap-value.
Ae Index	The Auroral Electrojet (AE) index measure of global electrojet activity in the auroral zone.
Bt of IMF	The Bt value of the Interplanetary Magnetic Field indicated the total strength of the Interplanetary Magnetic Field. The higher this value, the better it is for enhanced geomagnetic conditions.
Bz of IMF	Bz value is perpendicular to the ecliptic and is created by waves and other disturbances in the solar wind. For a geomagnetic storm to develop it is vital that the direction of the Interplanetary Magnetic Field (Bz) turns south. Values of -10nT and lower are good indicators that a geomagnetic storm could develop.
By of IMF	By is vector quantity that oriented parallel to the ecliptic.
Proton temperature (T)	One of the solar wind parameters. Measurement the temperature of the proton.
Proton density (D)	One of the solar wind parameters. Measurement the density of the proton.
Plasma speed (V)	One of the solar wind parameters. Measurement the plasma speed.

Sunspot numbers during this cycle is observed to see the pattern of the cycle. The sunspot number of solar cycle 23 data from 1996-2007 retrieved from OMNIWeb. Maximum and minimum phase is identified based on the cycle pattern and sunspot number of the cycle. Then, major storms during maxima and minima are obtained based on the graph with the minimum Dst below -200nT. The minima phases taken are during 1996-1999 and 2004-2006. Maxima phase is from 2000-2002. To analyze the relationship between the storm and IMF, GI, and plasma parameters, the significant major storms during the three periods above are taken by indentifying the exact date of the event. The graph are plotted by using MatLab and analyzed.

In this study, correlative study has been done to see how strong the relationship between the geomagnetic indices and the peak of various plasma and field parameters during major geomagnetic storms of solar cycle 23. The mathematical formula used for computing ***r*** is:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \quad (1)$$

where n is the number of pairs of data [7].

The strong or weakness the relationship is measured by the value of r. The of r is such that $-1 \leq r \leq +1$. The + and – signs are used for positive linear correlations and negative linear correlations, respectively. Positive correlation means if x and y have a strong positive linear correlation, value of r is close to +1. Positive values indicate a relationship between x and y such that as values of x increase, values of y also increase.

Negative correlation means if x and y have a strong positive linear correlation, value of r is close to -1. Negative values indicate a relationship between x and y such that as values of x increase, values for y decrease.

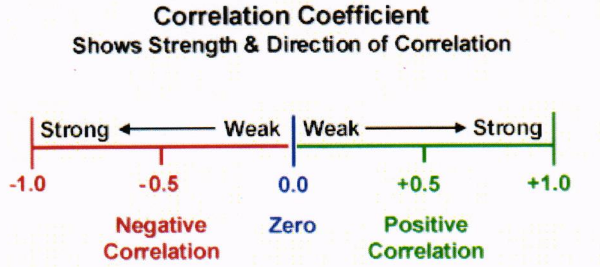

Figure 1: Strength and direction of correlation coefficient

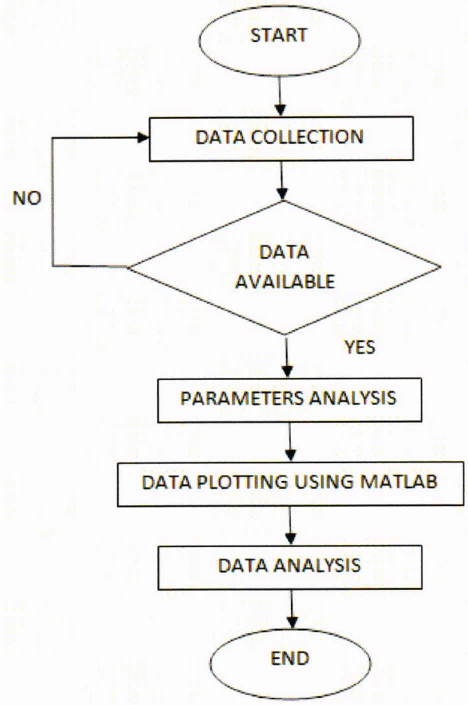

Figure 2: Methodology flowchart

III. RESULTS AND ANALYSIS

A. Sunspot Numbers

Data from 1996-2007 of sunspot number during solar cycle 23 was retrieved from OMNIWeb. High sunspot numbers give the maximum phase of the cycle and low sunspot numbers is declining phase. Based on the Figure 3, it can be seen that the maximum phase of solar cycle 23 is during 2000-2002 and minimum phase are during 1996-1998 and 2004-2006. From the graph pattern, it shows that the solar maxima have double peaked.

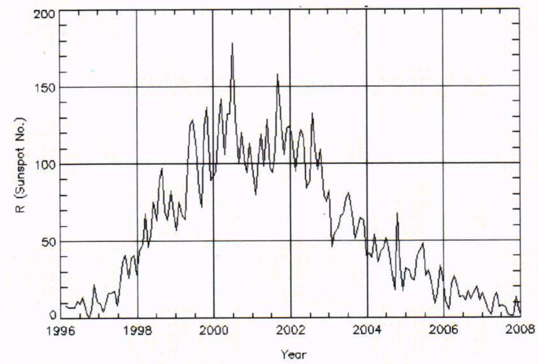

Figure 3: Sunspot Numbers during Solar Cycle 23

B. Major Storms during Maxima and Minima

Hourly data for severe storms during maxima and minima phase of solar cycle 23 were obtained from OMNIWeb to see how often geomagnetic storms occur during the year, and the frequency of their severity. This study only focused on minimum Dst -200nT. Minima phase occurred on 1996-1998 and 2004-2006 while maxima phase was on 2000-2002.

i. Observation period during minima phase 1996-1998

Figure 4 shows the occurrence major storms during minima phase of solar cycle 23. Three major storms occurred from year 1996-1998 based on hourly average. The storms occurred in May 1998 and October 1998 with the largest minimum Dst -205 nT.

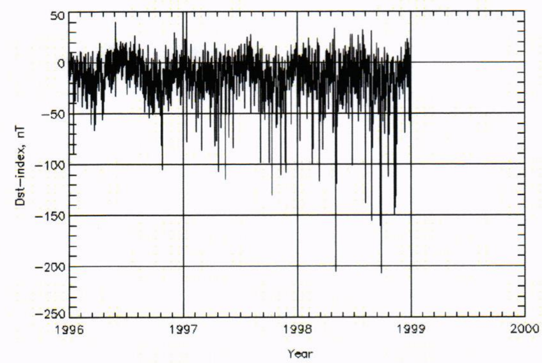

Figure 4: Major storms (Dst below -200nT) during minima, 1996-1998

For minima phase during 1996-1998, the significant event of storm occurred on May 1998, thus the analysis of data is made from 3 May 1998 to 5 May 1998. The data are represented in Figure 5-7.

During the period of 3 May 1998 to 5 May 1998, major geomagnetic storm occurred on 4 May 1998. Based on Figure 5, there is sudden increment in the readings on 4 May 1998 at 0300 UT for Bt, Bz and By and followed by the Dst index with delay of one hour. The readings for the IMF (Bt, Bz, and By) reached their peak at 0400 UT and Dst reached its peak at 0500 UT. During the main phase of the storm which occurred on 4 May 1998 at 0500 UT with the value of Dst is -205 nT it can be seen that the readings of Bt, Bz, and By started to decrease.

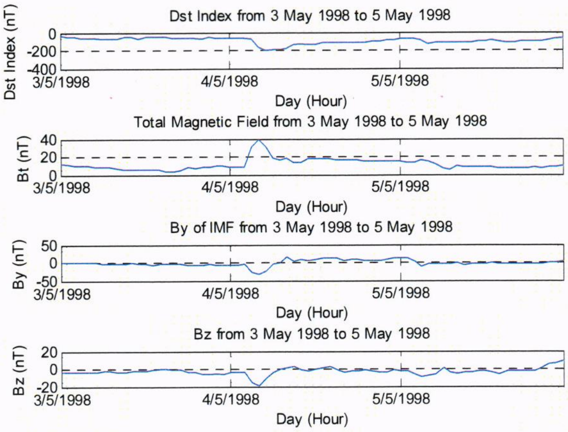

Figure 5: The graph of Dst and Bt, By, and Bz from 3 May 1998 to 5 May 1998

From Figure 6, it can be seen that during the main phase of the storm on 4 May 1998, the plasma parameters increase rapidly which signifying the occurrence of the storm. But not all the parameters are at their peak value when Dst reached its maximum value at 0500 UT. The plasma speed reached its peak at 0400 UT, the proton temperature reached the maximum value at 0600 UT, while the proton density has flactuate pattern.

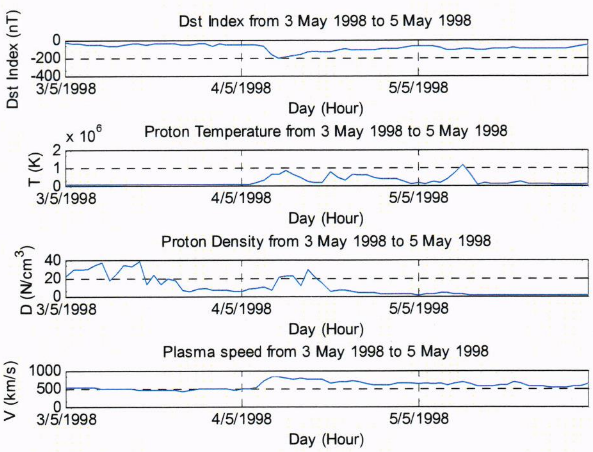

Figure 6: The graph of Dst and T, D, and V from 3 May 1998 to 5 May 1998

According to Figure 7, during the main phase of storm on 4 May 1998, all the geomagnetic index (Kp, Ap, Ae) increase and considered show positive peak signifying the storm commencement. Delay of the indices were due to the different latitude location of the index measurements.

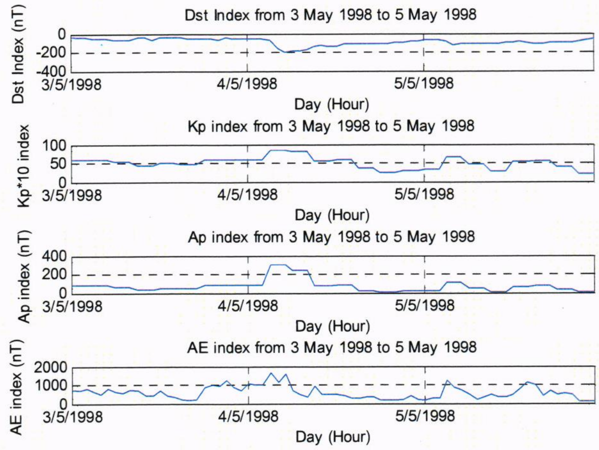

Figure 7: The graph of Dst and Kp, Ap, and Ae from 3 May 1998 to 5 May 1998

ii. Observation period during minima phase 2004-2006

Figure 8 shows the occurrence major storms during minima phase of solar cycle 23. Twenty one major storms occurred from year 2004-2006 based on hourly average. The storms occurred in November 2004 and May 2005. The largest minimum Dst recorded is -374 nT.

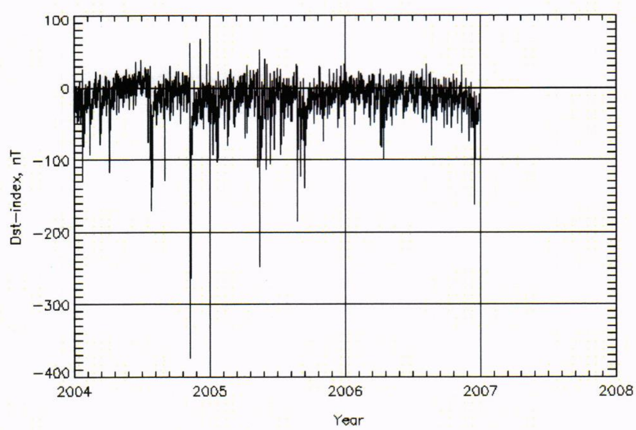

Figure 8: Major storms (Dst below -200nT) during minima, 2004-2006

For minima phase during 2004-2006, the significant event of storm occurred on November 2004, thus the analysis of data is made from 7 November 2004 to 9 November 2004. The data are represented in Figure 9-11.

Based on Figure 9, the sudden increment can be seen started with Bt on 7 November 2004 at 1300 UT. In the same day, the By and Bz component starting to increase in negative value at

2300 UT and 2000 UT respectively. Dst show its peak on 8 November 2004 at 0600 UT with value of -374 nT.

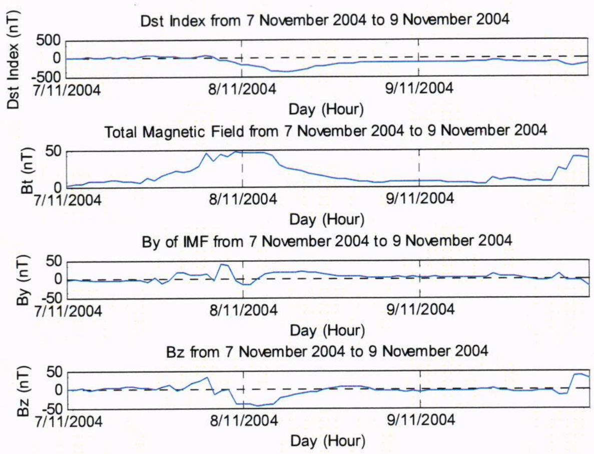

Figure 9: The graph of Dst and Bt, By, and Bz from 7 November 2004 to 9 November 2004

Figure 10 shows that during the main phase of the storm on 8 November 2004, only plasma speed can be considered at its peak while the other two parameters show their the minimum values. The pattern of the graph very contra compared to year 1998.

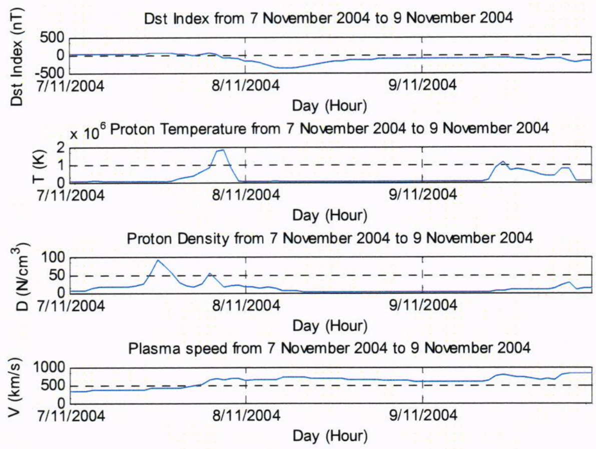

Figure 10: The graph of Dst and T, D, and V from 7 November 2004 to 9 November 2004

From Figure 11, all the index increase during the main phase except the Ae index that slightly decrease during the peak of Dst then it increase back two hours later which is it reached its peak value. Both Kp and Ap reached their peak at 0500 UT which is one hour earlier of the Dst peak value. Delay of the indices were due to the different latitude location of the index measurements.

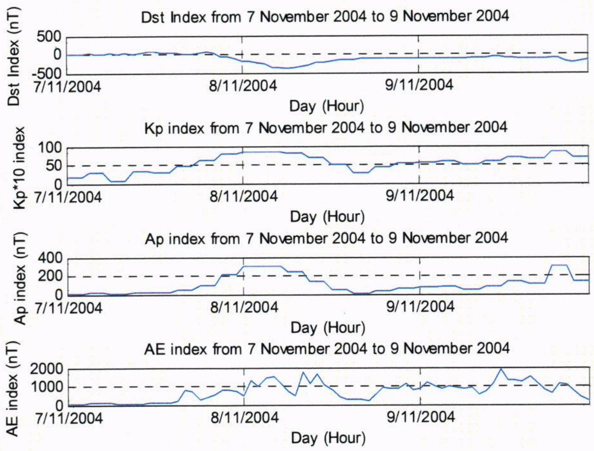

Figure 11: The graph of Dst and Kp, Ap, and Ae from 7 November 2004 to 9 November 2004

iii. Observation period during maxima phase 2000-2002

Figure 12 shows the occurrence major storms during maximum phase of solar cycle 23. Fifty six major storms occurred from year 2000-2002 based on hourly average. It can be seen that the major storms actively occurred from 2000-2001 with highest minimum Dst -387 nT.

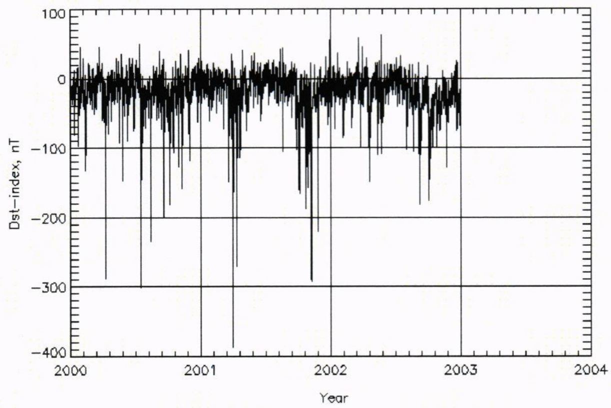

Figure 12: Major storms (Dst below -200nT) during maxima, 2000-2002

For maxima phase during 2000-2002, the analysis of data is made from 30 March 2001 to 1 April 2001. The data are represented in Figure 13-15.

From Figure 13, the sudden commencement is seen on 31 March 2001 as this sudden increase in Dst value corresponding increase in Bz was observed. The main phase of the storm is on 31 March 2001 at 0800 UT with the Dst value recorded is -387 nT.

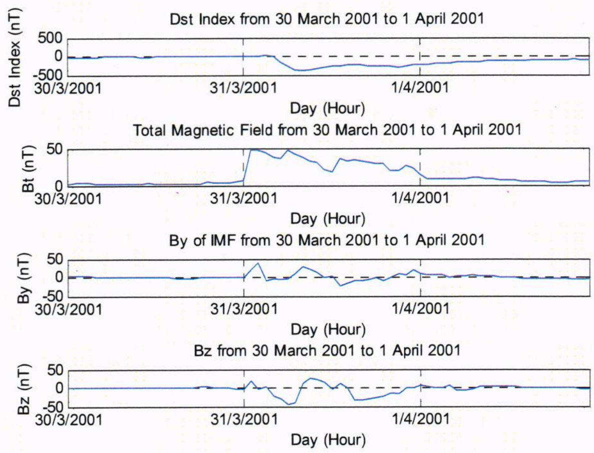

Figure 13: The graph of Dst and Bt, By, and Bz from 30 March 2001 to 1 April 2001

Based on Figure 14, it can be seen that during the main phase of the storm on 31 March 2001, only plasma speed can be considered at its peak while the other two parameters show their the minimum values. The behaviour is similar during 2004 (Figure 11).

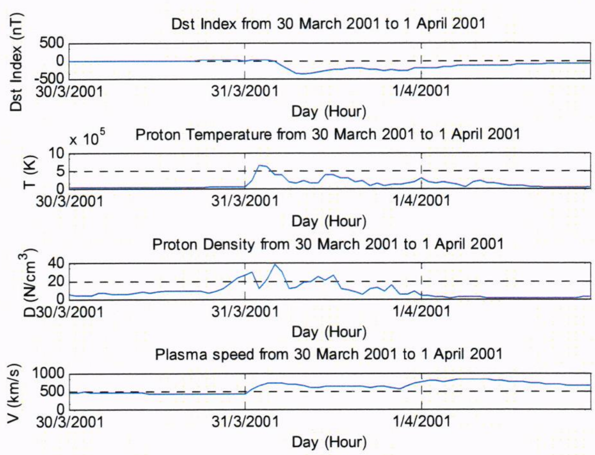

Figure 14: The graph of Dst and T, D, and V from 30 March 2001 to 1 April 2001

According to Figure 15, during the main phase of storm on 31 March 2001, all the geomagnetic index increase and show the positive peak signifying the storm commencement except the Ae index. Kp and Ap index reached the peak at the same time with Dst at 0800 UT while the Ae index reached its peak on 31 March 2001at 1800 UT. Delay of the indices were due to the different latitude location of the index measurements.

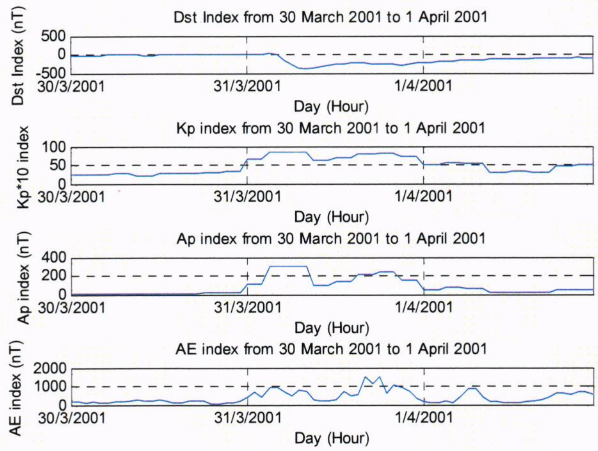

Figure 15: The graph of Dst and Kp, Ap, and Ae from 30 March 2001 to 1 April 2001

D. Correlations between Geomagnetic Indices, Field and Plasma Parameters

The correlative coefficient is studied to measure the strengh of the relationship between geomagnetic indices, field and plasma parameters. All the data are shown in Table 2, Table 3, and Table 4.

From Table 2, it is shown that Dst show moderate negative correlation value with Kp and Ap, and weak negative correlation value with Ae. These results represent an anti-phase relationship wich means that positive enhancement in geomagnetic index results in increasing negative magnitude of Dst that eventually result in major storm. Geomagnetic index are well correlated with each other and it indicates that the three indices can be interchangeably used,

Table 2: Correlation coefficient between Dst and Geomagnetic Index

	Dst	Kp	Ae	Ap
Dst	1			
Kp	-0.4239043	1		
Ae	-0.1307164	0.58967272	1	
Ap	-0.4543616	0.93950341	0.59970451	1

Table 3 is the result of the correlation between Dst index and the field parameters. The Dst is not correlated with By and weakly negative correlated with Bt but moderately correlated with Bz. Bt also not correlated with By and moderately correlated with Bz.

Table 3: Correlation coefficient between Dst and Field Parameters

	Dst	Bt	By	Bz
Dst	1			
Bt	-0.1343442	1		
By	0.03815607	0.18017774	1	
Bz	0.30008396	-0.3492673	0.14467784	1

Based on Table 4, it is seen that Dst and all plasma parameters show anti-phase relation with weak negative correlation. But the plasma parameters are well correlated with each other.

Table 4: Correlation Coefficient between Dst and Plasma Parameters

	Dst	D	V	K
Dst	1			
D	-0.0331874	1		
V	-0.0488441	0.94315997	1	
K	-0.0515976	0.94460805	0.99905902	1

IV. CONCLUSION

It is proven that majority of major storms occurred during maximum phase of solar cycle based on the result from Figure 3, 7, 11. Based on the analysis of major geomagnetic storms during three different periods, it can be seen that there are delay about 1-5 hours between the peak of Bz and the peak Dst which the peak of the storm's intensity, as measured by the Dst index, will occur about 1-5 hours after the driving Bz component has reached its peak value. The correlative study done shows that during major geomagnetic storms of solar cycle 23, there are no strong correlation between Dst index, geomagnetic index, field, and plasma parameters. However, Kp index and Ap index show moderate negative linear relationship with Dst index and could be used to predict geomagnetic storms. From the result of Table 3, it is agreed that the peak of Dst is correlated to the maximum negative component of Bz of the IMF. This result is in agreement with Manshilla where he found that the Bz component is the strongest connection and better than the solar wind density and solar wind speed [8].

FUTURE RECOMMENDATION

From this research it can clearly seen that the delay of Dst index could influence to get the great results. Several factors affect the timing of the data and the delay between individual measurements on board the satellites and the update of composite value on the website: the program is run at a half-hour cadence, the natural resolution of the data, and the total latency is defined by the delay between real-time and the time stamp [9]. For future research the calibration of Dst index may be done by Dst index with the effect of the magnetopause currents removed with a correction proportional to the square root of the solar wind dynamic pressure [10]. The corrected Dst index contains mainly the ring current contribution.

.ACKNOWLEDGMENT

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