Geomagnetic Storms:
A Study of the Relationship between Geomagnetic Storms and the Interplanetary Magnetic Field, and Monitoring Geomagnetic Storms in the Ionosphere with GPS Errors

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INTRODUCTION

Although the Sun is 93 million miles away from the Earth, storms that occur on the sun, such as solar flares, solar energetic particles (SEP), and coronal mass ejections (CME), can significantly impact our lives. SEPs are high-energy particles coming from the Sun and reach the Earth in less than an hour. CMEs are explosive eruptions of gas and magnetic matter on the sun, which cause large parts of the solar matter or plasma to blast away. CMEs take up to three days to reach Earth on average depending on their radial speed. When these solar storms impact the Earth's magnetosphere, they can cause geomagnetic storms, which are disturbances of the Earth's magnetic field. With the huge amount of human reliance on technology, the disturbances caused by geomagnetic storms have a huge impact on our lives although we may not realize it. Some such disturbances caused by geomagnetic storms include disruptions in High Frequency communications affecting trans-oceanic and trans-polar aviation routes, faults in electronic systems at aviation altitudes, localized power outages, disturbances to small-part electronic systems, and damage to satellites especially GPS satellite systems (Marhavilas, 2004). In addition, the radiation from these storms also affects human health especially that of pilots and astronauts.

The magnitude of a geomagnetic storm in our case is measured in planetary K index or Kp index, which is the mean of K-indices of twelve observing stations or magnetometers. Kp-index ranges from 0 to 9; 0 being the lowest and least consequential, and 9 being the highest and most consequential. Kp-indices equal to or above 5 are considered geomagnetic storms. The higher the Kp-index, the more the geomagnetic storm has an effect on the Earth's system. The interplanetary magnetic field (IMF), which is the magnetic field from the Sun, is measured in Bx, By, and Bz components, which are vector quantities with Bx and By oriented parallel to the poles (ecliptic) and Bz oriented perpendicular to the ecliptic. The Bt value indicates the total strength of the three Bx, By and Bz components of the IMF. When the Bz component of CMEs is positive (northward), it has less effect on the Earth's magnetosphere. However, when the Bz component is negative (southward), it opposes the direction of Earth's magnetic field, causing changes and reconnection of IMF and the Earth's magnetic field. In 1991, Klimas et al. showed that the negative turning of Bz causes an increase of Kp. Since then several scientists in the field have proposed models relating Kp to the interplanetary magnetic field (IMF) Bz component, such as Muhtarov and Andonov (2000) and Andonov et al. (2004).

PROBLEM STATEMENTS AND HYPOTHESES

This study was designed to address the following two problem statements: (i) What is the relationship between Kp index of geomagnetic storms and the duration for which the Bz and Bt values stay below zero, as well as the range of fluctuations in Bz and Bt values during the duration of the storm? Since the negative turning of the interplanetary magnetic field component Bz is related to the strength (Kp-index) of geomagnetic storm (Klimas et al, 1991), we believe that the longer the Bz values are below zero, the higher the Kp index would be. (ii) Can the magnitude of Global Positioning System (GPS) error signal be used as a reliable indicator of Geomagnetic Storm activity? Since the geomagnetic storms can create large disturbances in the ionosphere and disrupt the GPS radio signals traveling from the satellite to the receiver on the ground (Marhavilas, 2004), we believe that the magnitude of errors in the GPS signals will be higher (or lower) for the Geomagnetic Storms with higher (or lower) Kp-index.

MATERIALS AND METHODS

Analysis of geomagnetic storms
For the analysis of geomagnetic storms the Space Weather Database of Notification, Knowledge, and Information (SW-DONKI; http://kauai.ccmc.gsfc.nasa.gov/DONKI/) database and the Integrated Space Weather Analysis System (iSWA; http://iswa.gsfc.nasa.gov/iswa/iSWA.html) tool were used. The SW-DONKI database consists of data from solar storms, geomagnetic storms, and other forms of space weather from 2010 to present. The iSWA tool consists of data cygnets from different sources related to space weather analysis, including imagery from different missions, observational data and model output.

Geomagnetic Storms of Kp index 6 to 8, reported on the SW DONKI website, were selected for analysis. It was then determined whether these storms were connected to Coronal Mass Ejections (CMEs). The ACE Magnetic Field cygnet was used to analyze the Bz and Bt magnetic field components of the CMEs for each of these geomagnetic storms. The minimum and maximum values of the Bz and Bt components for each of these CMEs were noted. An example is shown in Figure 1 for the geomagnetic storm of Kp 8 caused by the CME from June 22, 2015. The Bz- and Bt-range for each CME was calculated as the difference between maximum and minimum values (Table 1). The duration for which the Bz values stayed >0, 0 to -10, -10 to -20, or <-20 nT during the duration of the entire storm was also determined to explore its relationship with the intensity of the geomagnetic storm (Table 1).

Tracking geomagnetic storms
In this study, a Global Positioning System (GPS, Garmin nuvi 310) device was used to measure the signal errors between the WAAS (Wide-Area Augmentation System)-Enabled and WAAS-disabled location data (about GPS, n.d.). The WAAS feature of the GPS amplifies the signals so that there is little or no disturbance. The data recorded from the GPS were the latitude, longitude and elevation (in feet). The WAAS-enabled and WAAS-disabled GPS readings were taken every day at 9:30 pm for more than 60 days. The readings were taken at the exact same outside location each time. The location and time were kept constant. Each reading was taken for two minutes, and at the end of the two minutes, the latitude, longitude, and elevation values were recorded. After the two readings (WAAS-enabled and WAAS-disabled) were taken, the latest

Kp-index level was noted from the NOAA website (http://www.swpc.noaa.gov/products/planetary-k-index). Kp index 0 was observed on 4 nights, Kp 1 on 21 nights, Kp 2 on 15 nights, Kp 3 on 10 nights, Kp 4 on 11 nights, and Kp 5 on 2 nights. The error (positive difference) between the WAAS-enabled and WAAS-disabled GPS readings of each locational component (latitudue, longitude and elevation) was calculated and compared for storms of Kp indices of 0 to 5 using Microsoft Excel and GraphPad Prism 6 (GraphPad Software, La Jolla, CA).

RESULTS

Relationship between Geomagnetic Storms and the Interplanetary Magnetic Field (IMF)
Twenty-five different geomagnetic storms were analyzed out of the sixty-three geomagnetic storms available on the SWDONKI database as of December 31, 2015. Of these 25 storms, 3 storms were of the Kp index 8, 11 were of Kp 7, and 11 were of Kp 6.

For determining relationship between geomagnetic storms and the IMF, the minimum, maximum and range values for Bz and Bt components were pooled based on the Kp index of the Geomagnetic storms they are associated with, and the mean, median and other statistics were obtained using GraphPad Prism 6 (GraphPad Software, La Jolla, CA). The column statistics for Bz and Bt values (maximum, minimum and range) distributed by Kp-index 6, 7, or 8 are shown in Table 2. Figure 2 shows a comparison of Bz and Bt values (minimum, maximum and range) of all CMEs distributed by Kp-index 6, 7, or 8, respectively.

Looking at the results from Table 2 and Figure 2, CMEs associated with storms of Kp 8 (n=3) had the lowest Bz minimum values (mean -27.57 nT, median -24.68 nT) but the highest Bz maximum values (mean 24.74 nT, median 26.04 nT). CMEs associated with the storms of Kp 6 (n=11) had the highest Bz minimum values (mean -12.79 nT, median -11.13 nT), but the lowest Bz maximum values (mean 10.09 nT, median 10.35 nT). CMEs associated with the storms of Kp 8 had the highest Bt minimum values (mean 7.09, median 7.33) and the highest Bt maximum values (mean 36.29 nT, median 35.10 nT). Whereas, CMEs associated with the storms of Kp 6 had the lowest Bt minimum values (mean 4.66 nT, median 5.41 nT) and Bt maximum values (mean 16.73 nT, median 15.72 nT).

In terms of the range, CMEs associated with storms of Kp 8 showed the highest range of Bz (mean 52.31 nT, median 50.72 nT) and Bt values (mean 29.20 nT, median 27.77 nT), whereas CMEs associated with storms of Kp 6 showed the lowest range of Bz (mean 22.88 nT, median 20.28 nT) and Bt values (mean 12.07 nT, median 12.16 nT).

The duration for which the Bz values stayed >0, 0 to -10, -10 to -20, or <-20 nT during the duration of the entire storm was also determined to explore its relationship with the intensity of the geomagnetic storm. Figure 3 shows a comparison of the average duration (expressed as percentage of total duration) for which the Bz values stayed >0, 0 to -10, -10 to -20, or <-20 nT for the Geomagnetic Storms of Kp 6, Kp 7, and Kp 8. The average duration for which the Bz values stayed >0 nT decreased with the severity of the storm, from 37% of the total duration of storms of Kp 6, to 24 % and 26% for Kp 7 and Kp 8 storms, respectively. For storms of Kp 6 and Kp 7, Bz values persisted between 0 to -10 nT for an average duration of 56% of the total

duration of the storm, whereas for storms of Kp 8, Bz values persisted between 0 to -10 nT for an average duration of only 31% of the total duration of the storm. The average duration for which the Bz values persist between -10 to -20 nT increased with the intensity of the storm, from 7% of the total duration of the storms of Kp 6, to 20 % for Kp 7 storms, to 35% for Kp 8 storms. Bz values of <-20 nT were only observed with storms of Kp 8 and persisted for an average of 8% of the total duration of the storm.

Monitoring Geomagnetic Storms in the Ionosphere with GPS Errors
Figure 4 shows the average deviation in WAAS-enabled and -disabled GPS readings of each locational component caused by storms of Kp indices 0 to 5. Our data indicated that for storms of Kp indices of 0 to 5, the average error between the WAAS-enabled and WAAS-disabled GPS readings were less than 0.00010 Decimal Degrees for both latitudue, and longitude, and 50 feet or less for elevation. No significant differences were observed in the GPS errors for storms of Kp indices <5 suggesting that storms of Kp indices ≤5 don't cause significant GPS errors.

DISCUSSION

This study consisted of two parts: analysis of the geomagnetic storms and measuring errors in GPS signals in relation to the Kp index of the storm.

Geomagnetic storms were analyzed to investigate the relationship between Kp-index and Bz, Bt values (minimum, maximum and range) during a geomagnetic storm and the duration for which Bz values are >0, 0 to -10, -10 to -20, <-20 nT. Since the negative turning of the interplanetary magnetic field component Bz is related to the strength (Kp-index) of geomagnetic storm (Klimas et al., 1991), we believe that the longer the Bz values are below zero, the higher the Kp index would be. Additionally, stronger storms will be caused by CMEs that exhibit a wider range in Bz and Bt values during the duration of the storm.

Our theories were supported by the results obtained. The storms of Kp 8 had the lowest Bz minimum but the highest Bz maximum values and therefore, the highest Bz range values. The storms of Kp 6 had the highest Bz minimum values but the lowest Bz maximum values and therefore, the lowest Bz range values (Figure 2). For relationship with Bt, CMEs associated with the storms of Kp 8 had the highest Bt minimum and maximum values as well as the highest Bt range values. Storms of Kp 6 had the lowest Bt minimum and maximum values as well as the lowest Bt range values (Figure 2). Our results showed that the strength of geomagnetic storm is related to the negative turning of the IMF component Bz; the greater the negative turning (Bz-minimum), the stronger the storm. The stronger storms exhibited higher Bz-maximum and Bt-maximum values, and a wider range of IMF components Bz and Bt.

The average duration for which the Bz values remained positive (>0 nT) decreased with the intensity of the storm. The average duration for which the Bz values remained < -10 nT increased with the severity of the storm. In other words, the longer the Bz values are below -10 nT, the higher the Kp index would be. These results further support the argument that the strength of geomagnetic storm is related to the negative turning of the IMF component Bz.

However, only three storms of Kp 8 were analyzed in this study, whereas 11 storms each for Kp 6 and Kp 7 were analyzed. No other geomagnetic storms were recorded for the time-range that was analyzed. Additionally, no storms of Kp 9 have been recorded for the current solar cycle. Better statistics could be obtained when analyzing periods of more and stronger geomagnetic storms.

The other purpose of this study was to determine whether the magnitude of GPS errors can be used as a reliable indicator of Geomagnetic Storm activity. Our theory was that magnitude of errors in the GPS signals will be higher (or lower) for the Geomagnetic Storms with higher (or lower) Kp-index. This idea was refuted by the results obtained. No significant differences in the GPS errors were observed for the geomagnetic storms of Kp indices 0 through 5 (Figure 4). Our results suggest that storms of Kp indices ≤5 don't cause significant GPS errors. These results might be true for less-severe storms; however, there were several limitations in this study. Storms >Kp 5 and the associated GPS errors were not observed for the duration of this study, and GPS readings at only one location and one time per day were measured.

CONCLUSIONS

In conclusion, our results support the argument that the strength of a geomagnetic storm is related to the negative turning of the IMF Bz component. The greater the negative turning (Bz-minimum) of the IMF, the stronger the geomagnetic storm will be. Furthermore, the longer the Bz values are below -10 nT, the higher the Kp index of the geomagnetic storm would be. Our results also showed that the stronger geomagnetic storms are associated with higher Bz-maximum and Bt-maximum values, as well as a wider range of IMF components Bz and Bt. Our results suggest that storms of Kp indices ≤5 don't cause significant GPS errors; however, more measurements, including those during the period of higher geomagnetic activity (Kp index >5) are required to study the relationship between GPS error signal and geomagnetic storm activity.

ACKNOWLEDGEMENTS

REFERENCES:

- About GPS. (n.d.). Retrieved Feb. 25, 2016 from http://www8.garmin.com/aboutGPS/
- Andonov, B., Muhtarov, P., Kutiev, I. (2004). Analogue model, relating Kp index to solar wind parameters. Journal of Atmospheric and Solar-Terrestrial Physics , 66, 927–932
- INTEGRATED SPACE WEATHER ANALYSIS SYSTEM (iSWA). (n.d.). Retrieved Nov. 15, 2015, from http://iswa.gsfc.nasa.gov/iswa/iSWA.html
- Klimas, A., Baker, D., Roberts, D. (1991). Linear prediction filters for linear and nonlinear modeled geomagnetic activity. Geophysical Research Letters 18 (8), 1635–1638.
- Marhavilas, P.K. (2004). The Space Environment and its impact on human activity. CSEG Recorder, 29 (10). Available from: http://csegrecorder.com/articles/view/the-space-environment-and-its-impact-on-human-activity
- Muhtarov, P., Andonov, B. (2000). Improved relationship between the IMF component Bz and Kp index. Bulgarian Geophysical Journal 26 (1–4), 165–172.
- Planetary K-Index, NOAA Space Weather Prediction Center. (n.d.). Retrieved from http://www.swpc.noaa.gov/products/planetary-k-index
- Space Weather Database of Notification, Knowledge, and Information (DONKI). (n.d.). Retrieved Nov. 15, 2015 from http://kauai.ccmc.gsfc.nasa.gov/DONKI/

GST 2015-06-22 (Kp-Index 8)

Storm Duration			
	From	**To**	**Total Minutes**
Date; Time	June 22, 2015; 17:33	June 23, 2015; 13:23	**1190**

Storm Duration vs. Bz values				
	>0 nT	**0 nT to -10 nT**	**-10 nT to -20 nT**	**< -20 nT**
Minutes	381	149	451	209
% of total duration	32%	13%	38%	18%

Bz, Bt values (Min, Max & Range)			
	Minimum	**Maximum**	**Range**
Bz (nT)	-37.45	30.86	68.31
Bt (nT)	4.01	38.71	34.7

Table 1. The Bz and Bt magnetic field components of the CME for the June 22, 2015 Geomagnetic Storm of Kp-Index 8. LEFT: Tables on the Left hand sideshow the total storm duration; and Minimum, Maximum and Range values for Bz and Bt components. **RIGHT:** This table shows the duration (in minutes and % of total duration) for which Bz values stayed >0, 0 to -10, -10 to -20, or <-20 nT.

	Bz Minimum			Bz Maximum			Bz Range		
	Kp 6 (n=11)	**Kp 7 (n=11)**	**Kp 8 (n=3)**	**Kp 6 (n=11)**	**Kp 7 (n=11)**	**Kp 8 (n=3)**	**Kp 6 (n=11)**	**Kp 7 (n=11)**	**Kp 8 (n=3)**
Minimum	-22.80	-20.86	-37.45	4.53	1.90	17.32	13.17	14.25	37.89
25% Percentile	-15.19	-19.15	-37.45	6.34	8.50	17.32	17.47	24.00	37.89
Median	-11.13	-16.99	-24.68	10.35	12.81	26.04	20.28	30.28	50.72
75% Percentile	-8.79	-15.50	-20.57	12.41	15.50	30.86	30.62	33.24	68.31
Maximum	-7.91	-12.28	-20.57	19.03	19.99	30.86	39.81	36.98	68.31
Mean	-12.79	-16.88	-27.57	10.09	12.12	24.74	22.88	29.00	52.31
Std. Deviation	4.83	2.81	8.80	4.83	5.18	6.86	8.36	6.59	15.27

	Bt Minimum			Bt Maximum			Bt Range		
	Kp 6 (n=11)	**Kp 7 (n=11)**	**Kp 8 (n=3)**	**Kp 6 (n=11)**	**Kp 7 (n=11)**	**Kp 8 (n=3)**	**Kp 6 (n=11)**	**Kp 7 (n=11)**	**Kp 8 (n=3)**
Minimum	1.92	0.12	4.01	9.16	13.33	35.07	4.63	4.45	25.14
25% Percentile	3.56	1.88	4.01	14.50	18.39	35.07	9.04	10.53	25.14
Median	5.41	6.90	7.33	15.72	21.59	35.10	12.16	14.45	27.77
75% Percentile	5.56	8.88	9.93	20.60	22.84	38.71	15.04	19.85	34.70
Maximum	7.47	14.12	9.93	23.47	26.30	38.71	18.06	22.40	34.70
Mean	4.66	6.15	7.09	16.73	20.99	36.29	12.07	14.84	29.20
Std. Deviation	1.68	4.12	2.97	4.20	3.41	2.09	3.73	5.61	4.94

Table 2. The Bz and Bt magnetic field components (in nT) of the 25 Geomagnetic Storms analyzed in this study. The table shows the Mean, Median and other statistics of the Minimum, Maximum and Range of Bz and Bt values distributed by Kp-index 6, 7, or 8.
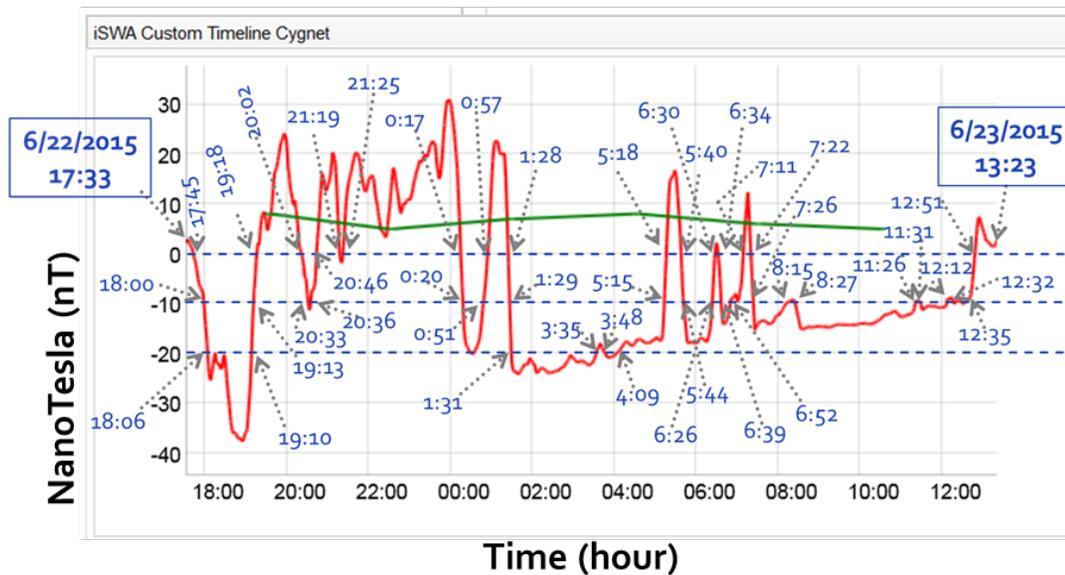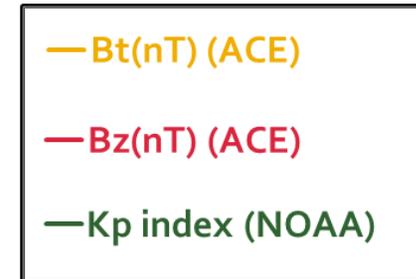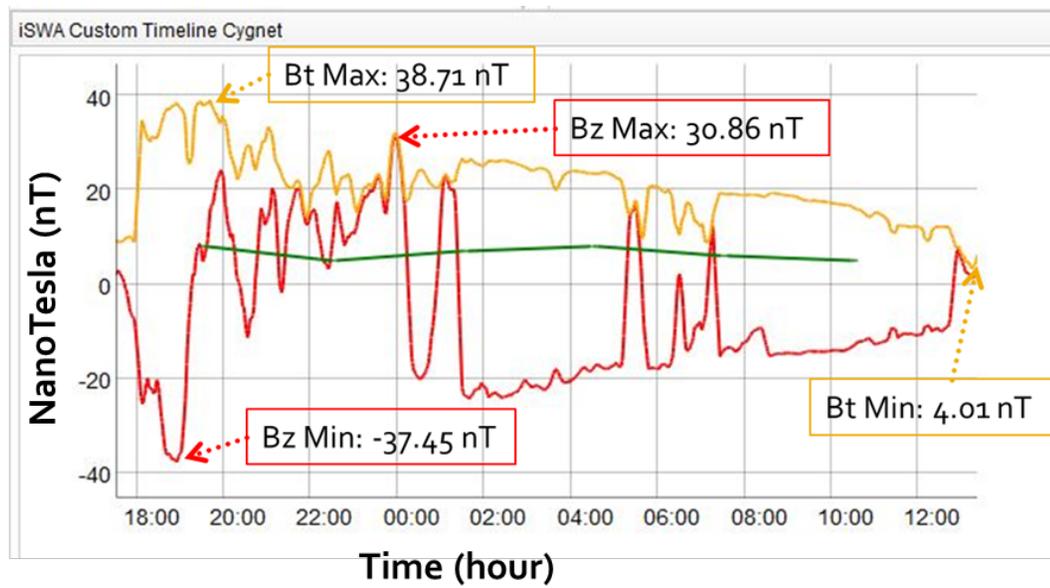
Figure 1. The Bz and Bt magnetic field components of the CME for the June 22, 2015 Geomagnetic Storm of Kp-Index 8. Top: The graph depicts maximum and minimum values of Bz and Bt components. **Bottom:** The graph shows how the duration, for which Bz values stayed >0, 0 to -10, -10 to -20, or <-20 nT, was calculated. [nT = nanotesla]
**Source:** iSWA ACE Magnetic Field cygnet, iSWA tool; http://iswa.gsfc.nasa.gov/iswa/iSWA.html
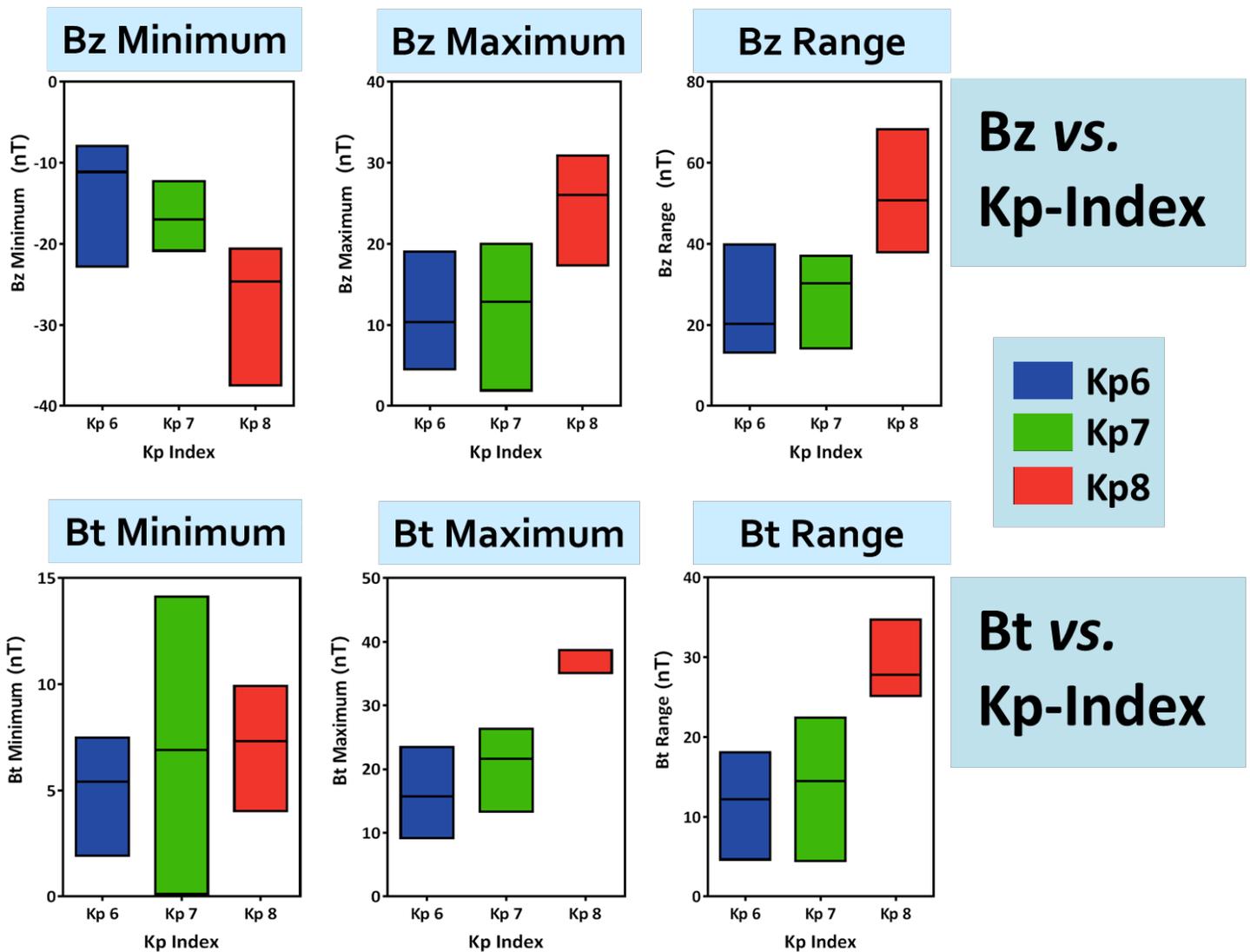
Figure 2. Comparison of Bz and Bt values (minimum, maximum and range) of all CMEs distributed by Kp-index 6, 7, or 8. Floating bars indicate minimum to maximum values; line at median values.
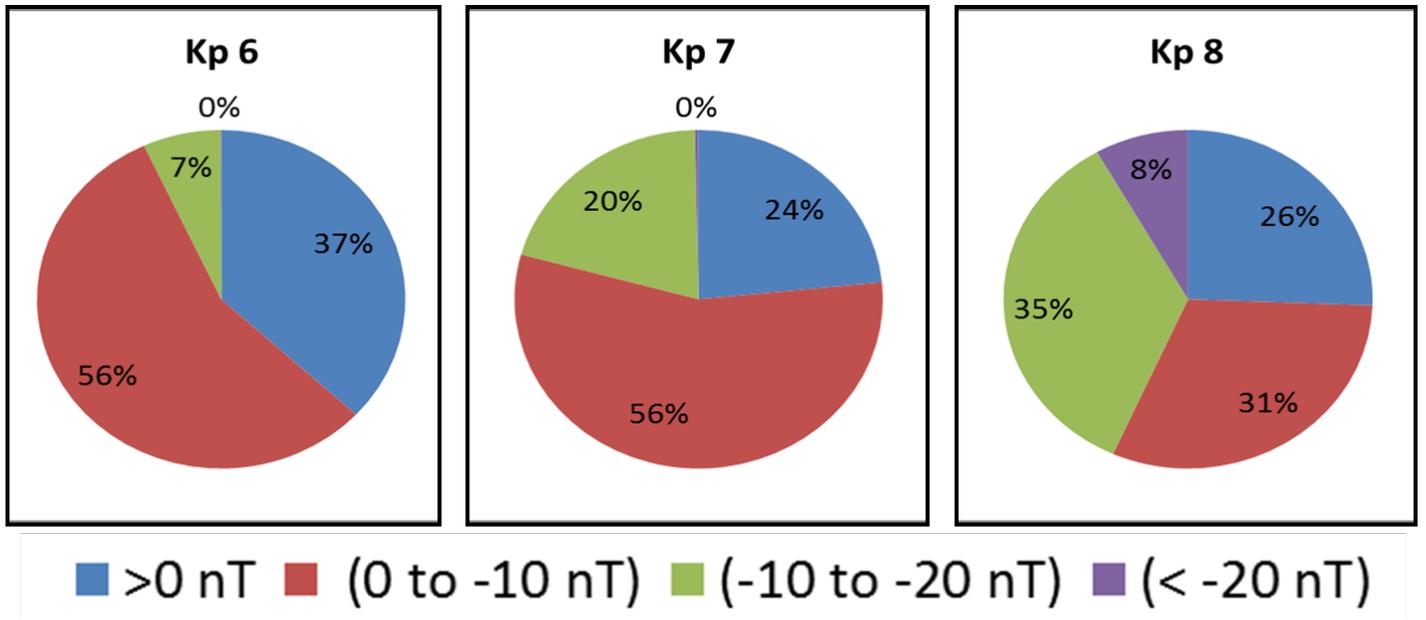
Figure 3. Comparison of the average duration (% of total duration) for which Bz values stayed >0, 0 to -10, -10 to -20, or <-20 nT, for the Geomagnetic Storms of Kp 6 (n=11), Kp 7 (n=11), and Kp 8 (n =3), respectively.
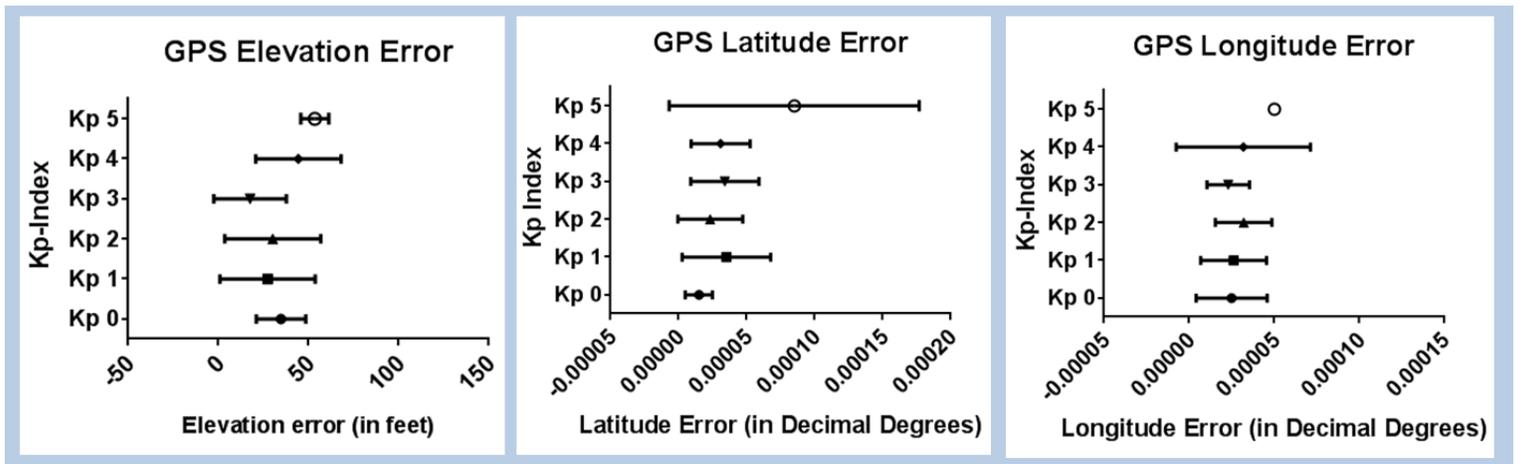
Figure 4. Magnitude of errors in the GPS signals vs. Kp-index. The graphs show Mean values with Standard Deviation. Data was obtained for 63 days from Nov. 2015 to Jan 2016. Kp-0 (4 days), Kp 1 (21 days), Kp 2 (15 days), Kp 3 (10 days), Kp 4 (11 days), and Kp 5 (2 days).