Geomagnetic Storms:

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

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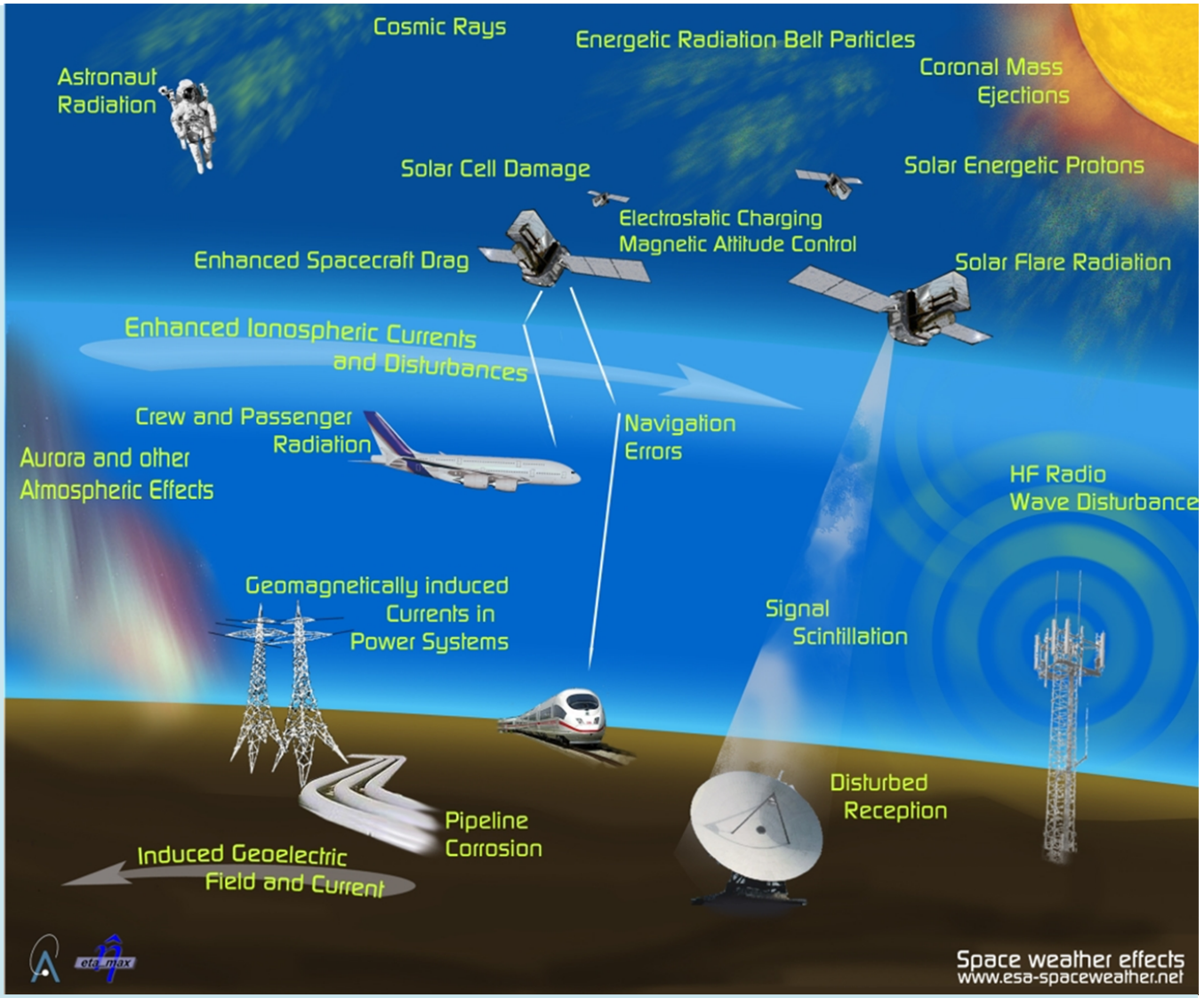
What is a Geomagnetic Storm?

- **A geomagnetic storm** is a temporary disturbance of the Earth's magnetosphere that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth.
  - Caused by Coronal Mass Ejections (CMEs) and High Speed solar-wind Streams from the Coronal Holes (CH-HSS)
- **How are Geomagnetic Storms measured?**
  - K-index: quantifies disturbances in the horizontal component of Earth's magnetic field, observed on a magnetometer during a three-hour interval. **Planetary K index (Kp-index)** is the mean of twelve observing stations.
  - Kp-levels range from 0 to 9. Kp-Levels of >5 are considered geomagnetic storms.
  - The higher the Kp, the stronger the geomagnetic storm, & higher the interaction.

Why should we care?

Effects of Space Weather:

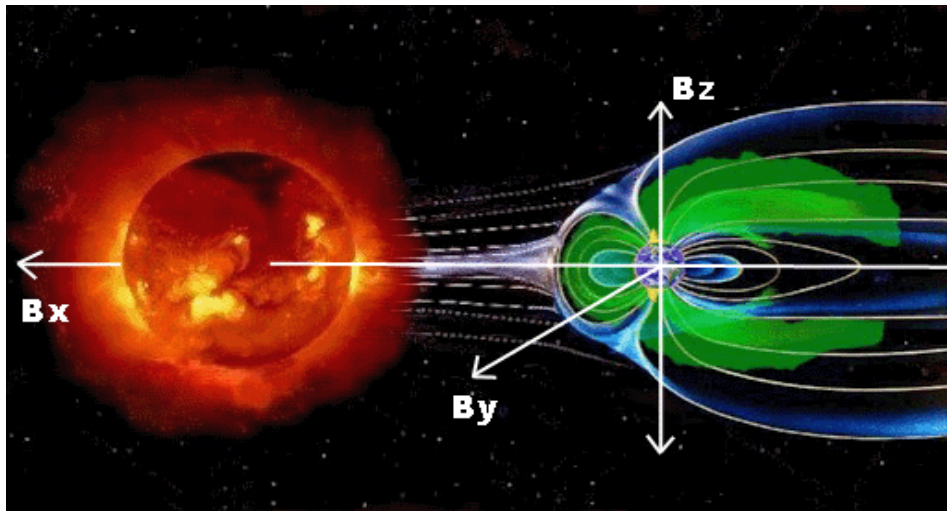
- Damage to spacecraft electronics
- Radiation exposure to astronauts and crew and passengers in flight
- Navigation Errors
- Disruptions in High Frequency communications affecting trans-oceanic and trans-polar aviation routes
- Electric power grid disruptions and localized power outages
- Disturbances to electronic systems
- Induced Effects in submarine cables



Main systems affected when space weather disturbances take place (Source: ESA website)

Do all CMEs have the same effect on Earth?

- The interplanetary magnetic field (IMF) plays a huge role in how the solar wind interacts with Earth's magnetosphere
  - **in particular, the north-south direction, or 'Bz' component.**
- When the Bz component is **positive (north):** little effect on the Earth
- When the Bz component is **negative (south)**: it opposes the direction of the Earth's magnetic field – on the day side.
  - **An interaction between the two magnetic fields will occur, allowing the energy from the solar wind to enter the Earth's protective shield – the magnetosphere.**



Interaction of the Interplanetary Magnetic Field with Earth's Magnetosphere.
Source:
http://www.spaceweatherlive.com/en/help/the-interplanetary-magnetic-field-imf

Hypothesis & Testable Questions

For Relationship between Geomagnetic Storms and the IMF

➢ **Testable questions:**

1. How is Kp-index related to Bz and Bt values (minimum, maximum and range) during the geomagnetic storm?
2. How is Kp-index related to the duration for which Bz values are >0, 0 to -10, -10 to -20, <-20 nT?

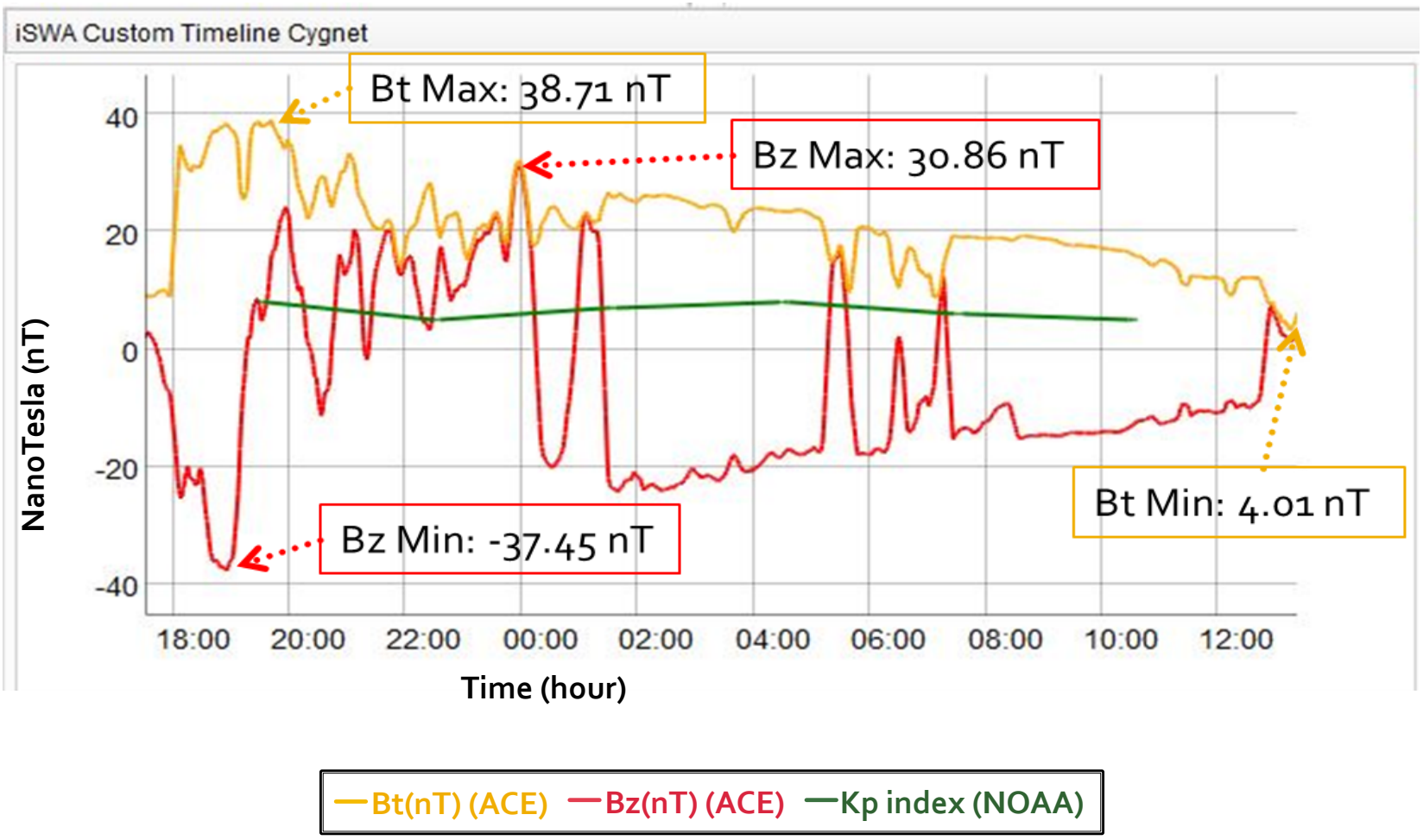
- **Hypothesis:** The negative turning of the interplanetary magnetic field component Bz is related to the strength (Kp-index) of geomagnetic storm. The longer the Bz values are below zero, the higher the Kp index would be.

Materials & Methods

For Relationship between Geomagnetic Storms and the IMF

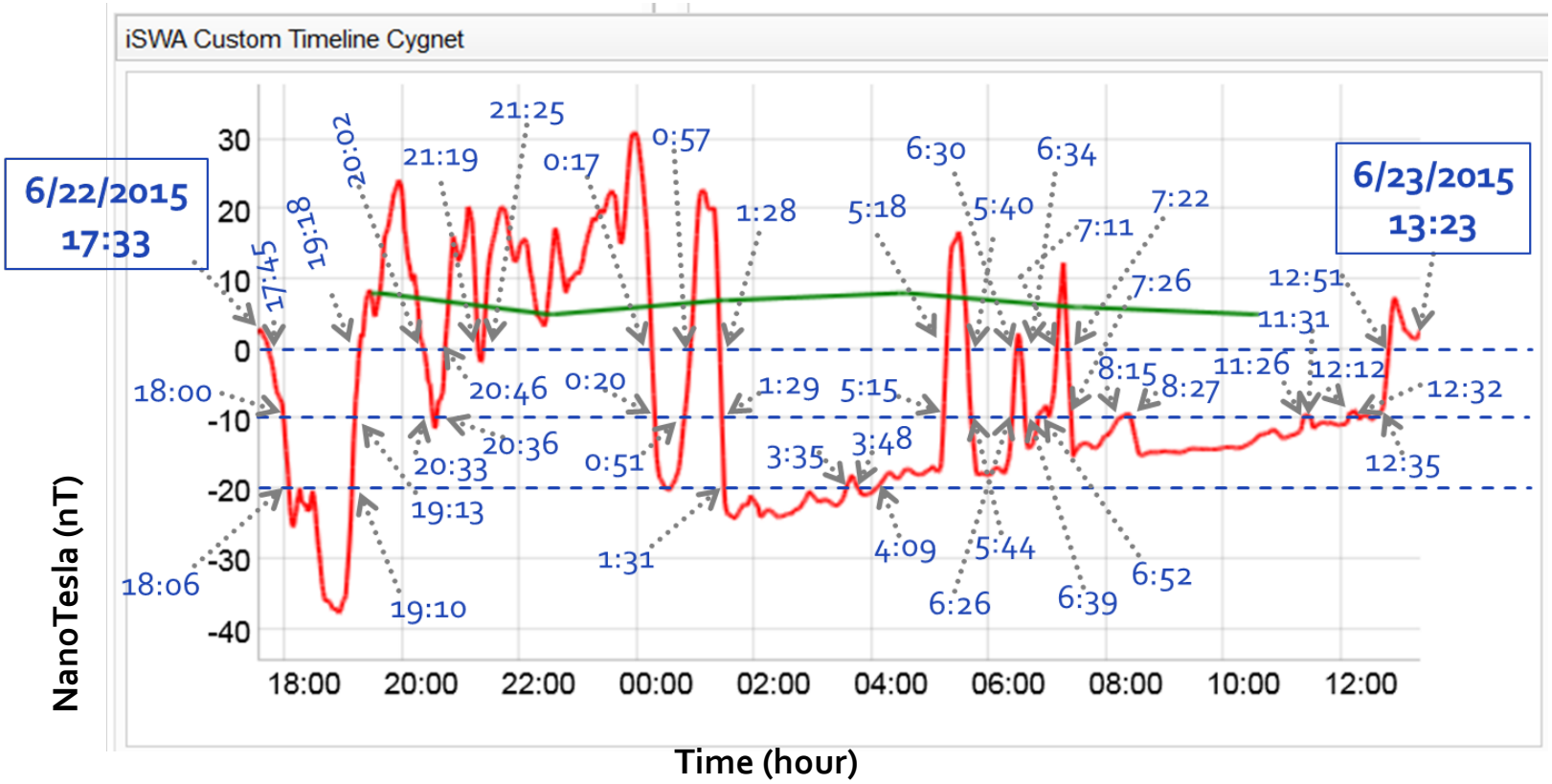
- **Databases:**
  - **Space Weather Database of Notification, Knowledge, and Information** (SW-DONKI; http://kauai.ccmc.gsfc.nasa.gov/DONKI/):
    - consists of CMEs and Geomagnetic Storms data from 2010 onwards
  - **Integrated Space Weather Analysis System (iSWA;** http://iswa.gsfc.nasa.gov/iswa/iSWA.html)
    - consists of cygnets depicting solar storms and other data from the satellites analyzing the sun (iSWA ACE Magnetic Field cygnet)
- **Selection:** Geomagnetic Storms Kp-index 6-8 (SW-DONKI database)

The Bz and Bt magnetic field components of the CME for the June 22, 2015 Geomagnetic Storm of Kp-Index 8



The graph depicts maximum and minimum values of Bz and Bt components. **Source:** iSWA ACE Magnetic Field cygnet, iSWA database; http://iswa.gsfc.nasa.gov/iswa/iSWA.html

The Bz and Bt magnetic field components of the CME for the June 22, 2015 Geomagnetic Storm of Kp-Index 8



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 database; http://iswa.gsfc.nasa.gov/iswa/iSWA.html

Results

Geomagnetic Storms and IMF

- Between Jan. 1, 2010 to Dec. 31, 2015, 63 Geomagnetic Storms (Kp index 6 to 8) are reported on the Space Weather Database Of Notifications, Knowledge, Information (SW DONKI) website.
- **In this study, 25 of the 63 geomagnetic storms were analyzed**

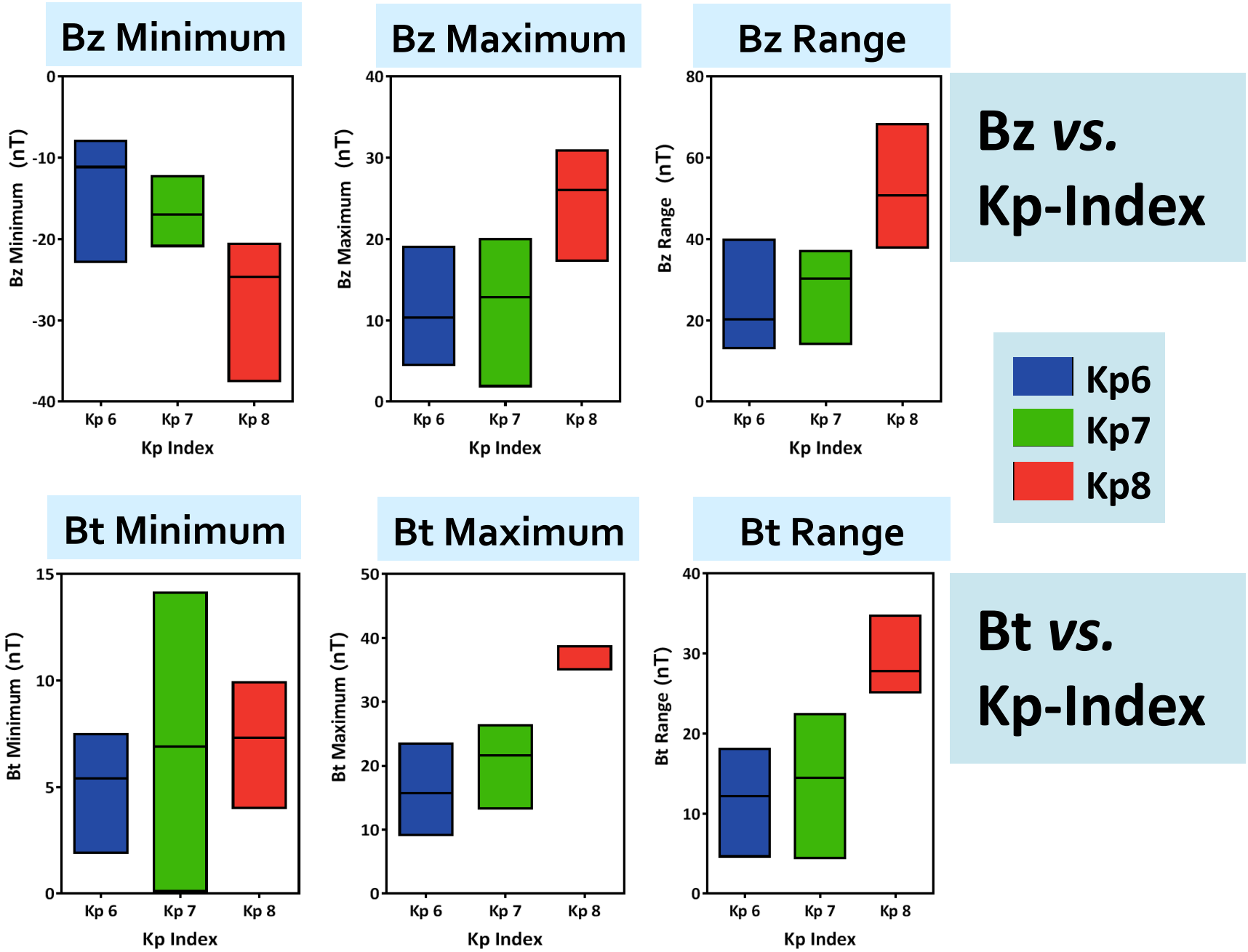
GSTs (by Kp index)	Total	No. Analyzed	% Analyzed
Kp 8	3	3	100%
Kp 7	11	11	100%
Kp 6	49	11	22%
	63	25	40%

Distribution of the geomagnetic storms by Kp index. The number of geomagnetic storms reported on SW DONKI website between Jan. 1, 2010 to Dec. 31, 2015 and those analyzed are indicated.

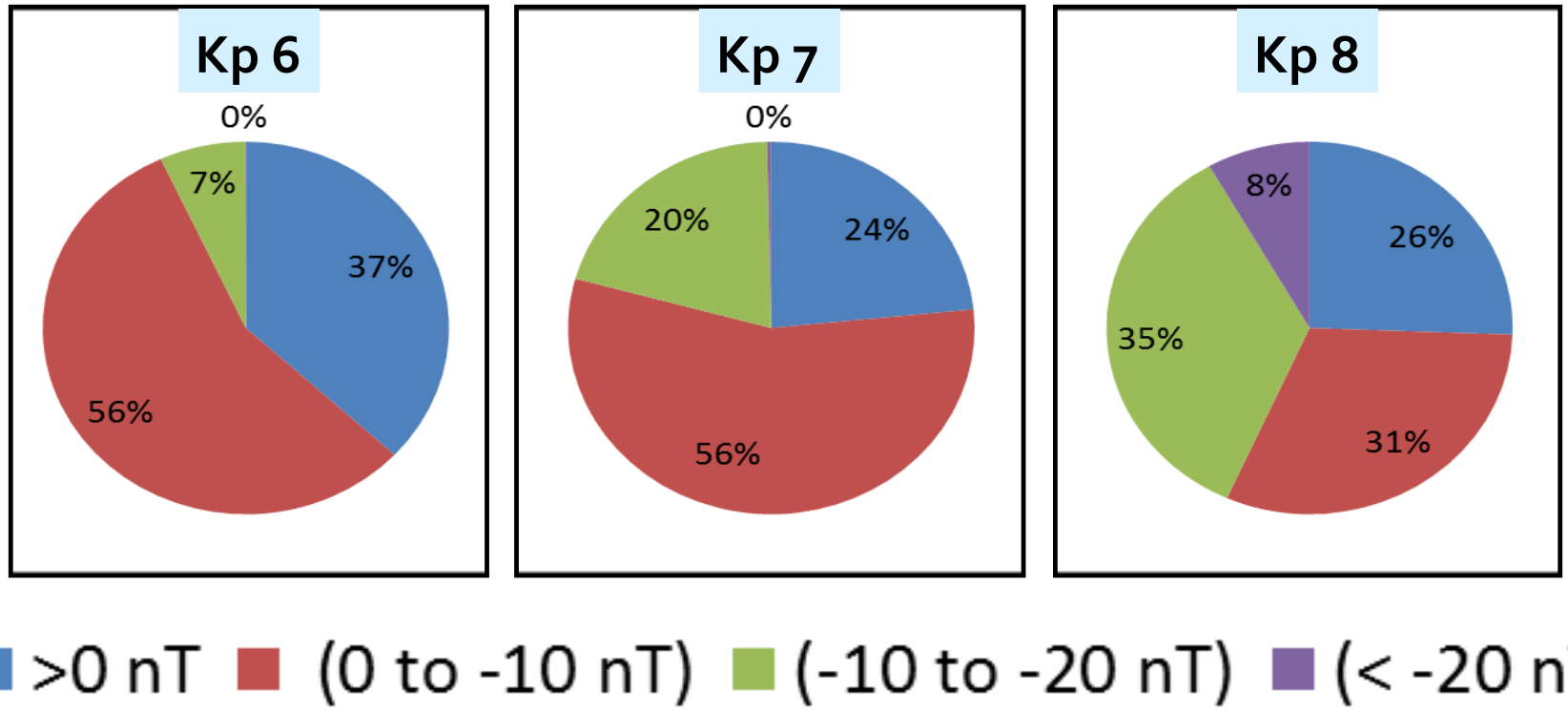
The Bz and Bt magnetic field components (in nT) of the 25 Geomagnetic Storms analyzed in this study

	Bz Minimum (nT)			Bz Maximum (nT)			Bz Range (nT)		
	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 (nT)			Bt Maximum (nT)			Bt Range (nT)		
	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



Floating bars indicate min. to max. values; line at median values



Pie Charts showing 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).

Hypothesis & Testable Question

For Monitoring Geomagnetic Storms with GPS

- **Testable question:**

  Can the magnitude of GPS error signal be used as a reliable indicator of Geomagnetic Storm activity?

  - **Hypothesis:** Magnitude of errors in the GPS signals will be higher (or lower) for the Geomagnetic Storms with higher (or lower) Kp-index.

Materials & Methods

For Monitoring Geomagnetic Storms with GPS

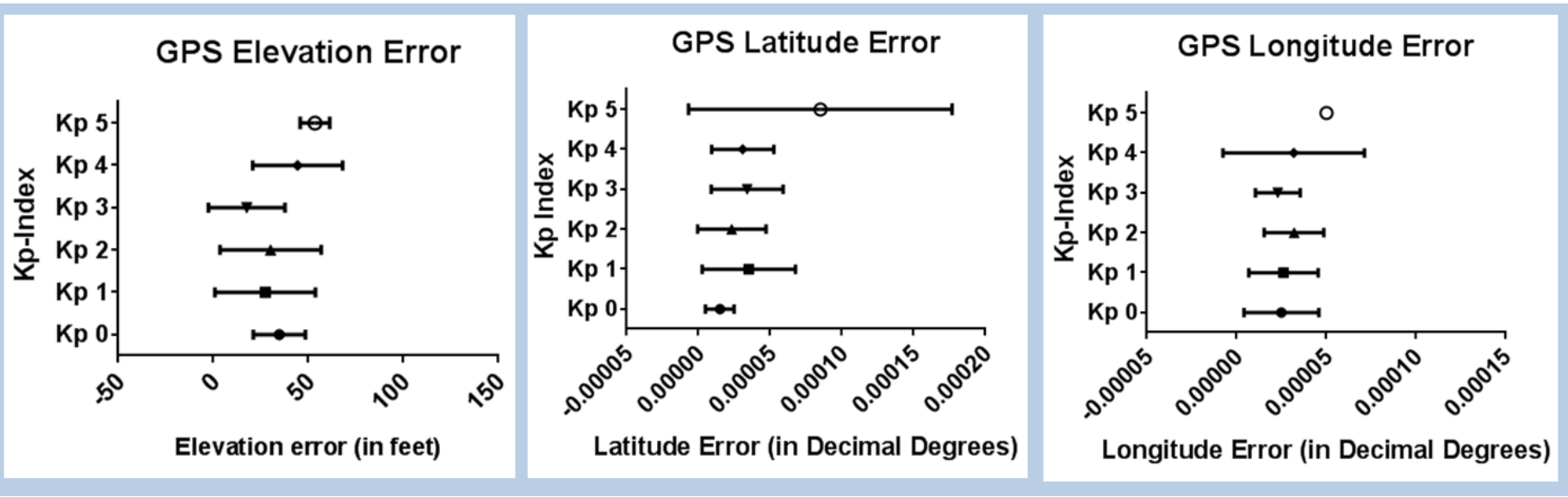
- **Observations:**
  - GPS readings obtained at fixed location and time
    - for over 60 days
    - **WAAS-Enabled** location data: lat., long. & elevation
    - **WAAS-disabled** location data: lat., long. & elevation
  - Recorded current Kp index from NOAA SWPC website http://www.swpc.noaa.gov/products/planetary-k-index
- **Magnitude of Error:**
  - Absolute value: |WAAS Enabled – WAAS disabled data|

Wide-Area Augmentation System capable Garmin nüvi 310 GPS

Source: *www.**garmin**.com*

Results

Magnitude of errors in the GPS signals vs. Kp-index



The graphs show Mean values with Standard Deviation. Data was obtained for 63 days in 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), Kp 5 (2 days).

Discussion & Analysis

- **The strength of geomagnetic storm is related to the negative turning of the interplanetary magnetic field component Bz**
  - **The greater the negative turning (Bz-Minimum), the stronger the storm**
  - The stronger storms also exhibited higher Bz-maximum and Bt-maximum values
  - The stronger storms exhibited a wider range of IMF components Bz and Bt
- **The longer the Bz values are below -10 nT, the higher the Kp index**
  - **Negative turning of Bz more than 10 nT:**
    Kp 6: 7% Kp 7: 20% Kp 8: 43% of total duration
- **For storms ≤ Kp 5, no trend or linear relationship was observed between magnitude of errors in the GPS signals and Kp-index**
  - Kp index >5 is a geomagnetic storm; Storms ≤Kp 5 don't cause GPS Errors

Acknowledgements

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- Thanks also to **Dr. Neel Savani** for suggesting this topic.

- This project was motivated by a talk given by NASA scientist **Dr. Alex Young** during the Sept. 26, 2015 Explore@NASAGoddard public event.