Correlation Between GPS Error Signals and Geomagnetic Activity in the Ionosphere

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PURPOSE

The purpose of this investigation was to learn more about the correlation between GPS errors and geomagnetic activity in the ionosphere. Additionally, it was to investigate the specifics of this correlation, and find out exactly what values and measurements in the GPS system are affected and involved.

HYPOTHESIS

If the strength of geomagnetic activity increases, then number of GPS errors will also increase.

Rationale: Geomagnetic disturbances affect the ionosphere, and the ionosphere also happens to be where GPS signals travel through. Thus, if there are more disturbances then the GPS satellites are negatively affected even more, causing more GPS errors, and finally resulting in a possible positive linear relationship between the two variables.

REVIEW OF LITERATURE

Correlation between geomagnetic disturbances in the ionosphere and GPS errors

Aviation. Mining. Agriculture. Marine. Recreation. These are just a few of the industries that utilize GPS systems on a daily basis. (What Are GPS Systems Used For, n.d).For example, in aviation pilots use GPS data to obtain three dimensional or 4-dimensional data (Houston, n.d). Additionally, GPS data is used to help determine a plane's exact location on land, air or sea; speed; time etc. GPS systems are very multi-purposeful and are vital to many industries. However, these systems get faulty from time to time. One of the sources of error could possibly be due to solar disturbances affecting the Earth's magnetic field, causing geomagnetic disturbance/storms in the ionosphere.

The GPS is made up of three segments or parts: space segment, the control segment, and the user segment. The space segment consists of the worldwide network of 32 satellites that transmits radio signals into Earth's orbit. Every satellite releases signals to the receivers. The receivers then determine the location based on how long it took for the signal to reach. This is able to occur in part due to the extremely precise atomic clocks that a GPS satellite has. More specifically, an atomic clock is a clock that keeps time according to the vibrations of an atom, (Rouse, n.d). Once a GPS receiver determines how far it is from at least 3 satellites, it can determine the location based on a process called trilateration. Sometimes a 4th satellite is needed as well to determine altitude. Trilateration pinpoints the specific location. By determining the location with one satellite a "circle"(range) with many possible locations points is determined.

By having at least two more satellites, this range narrows down the potential location points and eventually the receiver will know the exact location, (How Does the GPS Work, n.d). The receiver also must take into consideration any decreases in the signal's speed caused by the ionosphere and the troposphere (propagation delays). The control segment is made up of a Master Station, monitor stations, and backup ground antennas. Located at the Schriever Air Force Base in Colorado Springs, CO, the Master Station is responsible for the management and control of the transmission sites. The monitor stations are in charge of checking the exact altitude, speed, position, and health of the 32 satellites in orbit. The control system uses measurements from these monitor stations to predict the behavior of each satellite. Lastly, there are 4 ground antennas that oversee and track the satellites from one end to the other. The user segment just consists of the GPS receiver, which allows one to utilize the GPS (Satellite Navigation-GPS-How It Works, 2015).

The Federal Aviation Administration (FAA) developed and implemented the Wide Area Augmentation System (WAAS) to supplement and correct the Global Positioning System (GPS) in hopes of improving accuracy, availability, and precision. WAAS is a correction system that spans only over North America. It has 38 ground-based reference stations, 3 Wide-Area Master stations, and 3 geostationary WAAS satellites (How WAAS Works, n.d). First, GPS satellite signals are received at the many Wide Area Reference (WRS) stations. The WRS stations are precisely surveyed in order to detect any GPS errors signals. This information accumulated by the WRS is then forwarded to the WAAS Master Station (WMS). At the WMS, the WAAS augmentation messages are generated, which has information that allows GPS receivers to remove errors in GPS signals, therefore improving accuracy. These augmentation messages are sent from the WAAS Master Station to the 2 geostationary satellites. The augmentation messages are then broadcasted on a GPS like a symbol. Then, the GPS/WAAS receiver processes the WAAS augmentation message and factors it into determining the position (Satellite Navigation-WAAS-How It Works, 2015).

Certain conditions in space affect Earth and its technological systems such as the GPS. One of the major causes of this is due to the behavior of the Sun and the nature of the Earth's magnetic field. "As the sun approaches its solar maximum—the peak of intensity in the sun's cycle—solar flares and associated coronal mass ejections occur more frequently. These eruptions on the sun launch charged particles into space, called solar wind" (Geomagnetic Disturbances, n.d., [Online]). Solar flares are sudden events of increased brightness from the Sun and are giant bursts of X-ray energy. These occur more often than CMEs (coronal mass ejections) and it only takes 8 minutes to reach Earth because they travel at the speed of light in all directions. CMEs are bursts of solar wind and are not always associated with solar flares. The Earth's magnetic field protects Earth and the satellites, such as the GPS systems, from the solar wind. Thus, when there is too much solar wind released, and when CME's occur, a temporary disturbance happens and, if it gets big enough, a geomagnetic storm occurs, (Redd., n.d). The ionosphere is where all the radio signals are transmitted, including the GPS systems. So when these solar winds interfere and CME's get too big and interfere with the ionosphere, there is trouble in transmitting signals so GPS errors occur. WAAS is used to correct these errors. The K-index is used to measure geomagnetic storms. The "K-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. It is derived from the maximum fluctuations of horizontal components observed on a magnetometer during a three-hour interval" (Planetary K-index, n.d., [Online]). Another way to measure geomagnetic storms is through the Dst index, which measures the westward current around the Earth, and in turn, produces magnetic disturbances on the ground. In general, geomagnetic storms are categorized from a scale of G1 to G5, with G1 being minor and G5 being extreme.

The geomagnetic storms appear on Earth as the commonly known Aurora Borealis. During intense geomagnetic storms the Aurora Borealis, or also known as the northern lights, are amplified and can be viewed from a longer distance than usual (Writer, n.d). Geomagnetic storms can lead to changes in the radiations belts, such as the Van Allen radiation Belt surrounding Earth. These storms can sometimes compress the magnetosphere and that compression brings the particles in the belt inwards. These particles are very energetic and they are then put in a place where they usually are not seen. When this occurs, the particle intensity goes up and stays high, which can be very harmful to satellites in that certain region. There are currently two Van Allen probes in space further investigating this issue and topic (Garner, 2016).

The ionosphere is the layer of Earth's atmosphere, which overlaps the mesosphere, thermosphere, and exosphere that has a high concentration of ions and electrons and is able to reflect radio signals and waves (Ionosphere, 2015). It lies 42 to 621 miles above Earth, and the ionosphere is very important because it influences and takes part in the reaction between the satellites and Earth. The ionosphere grows and shrinks depending on how much energy it exerts from the Sun. The ionosphere is where all Sun and Earth reactions happen. "The ionosphere and the ground produce a "waveguide" through which radio signals can bounce and make their way around the curved Earth" (The Earth's Ionosphere, n.d. [Online]). The ionosphere consists of three main components, the D, F, and E regions. These regions are broken down based on the most frequent wavelength of solar radiation absorbed in a specific region. The D region is the lowest in altitude and absorbs energetic radiation. The E region absorbs soft x-rays. Lastly, the F region, the highest in altitude, absorbs extreme ultraviolet radiation (Ionospheric Layers: D, E, F, F1, F2, Regions, n.d).

GPS's are used almost daily by civilians, government officials, and many other industries. Geomagnetic storms in the ionosphere happen to be one of the major disruptions in the GPS process. If the number of GPS errors increases, then most likely the intensity of geomagnetic storms might have also increased. This is because geomagnetic disturbances occur in and affect the ionosphere, and the ionosphere is also where the satellite signals are transmitted. Therefore, since the geomagnetic disturbances negatively affect the ionosphere and everything in it, the amount of GPS errors will increase as there are more geomagnetic disturbances. Finding the specific correlation between GPS errors and geomagnetic storms will boost one's understanding on this topic and can possibly lead to the complete removal of errors in the first place.

MATERIALS

- GPS that has the ability for WAAS to be turned on and off
- The internet in order to access the K-index
- Notebook paper or Microsoft Excel to record data

PROCEDURE

1. Buy GPS that has the feature to turn WAAS on and off (the Garmin nuvi).

2. Find a permanent safe location to keep GPS and all measurements will be taken here.

3. Turn GPS on at 12AM, and turn off WAAS. Record the elevation, longitude, and latitude measurements in a table.

4. Then turn on the WAAS and record the elevation, longitude, and latitude, measurements in another table.

5. Calculate the error between each measurement with WAAS on and off, by subtracting the with WAAS measurement from the measurement without WAAS and record this value in a separate table.

6. Record qualitative data, such as the current weather condition, to possibly find any trends, and also record the actual temperature during that time, all in another table in the notebook.

7. Go on the internet and record the K-index value; note any geomagnetic storms.

8. Turn off GPS.

9. Come back at 6PM.

10. Turn on GPS and turn off WAAS. Record the elevation, longitude, and latitude measurements in a table.

11.Then turn on the WAAS and record the elevation, longitude, and latitude, measurements in another table.

12. Calculate the error between each measurement with WAAS on and off, by subtracting the with WAAS measurement from the measurement without WAAS and record this value in a separate table.

13. Record qualitative data, such as the current weather condition, to possibly find any trends, and also record the actual temperature during that time, all in another table in the notebook.

14. Go on the internet and record the K-index value; note any geomagnetic storms.

15 . Turn off GPS.

16. Repeat steps 3-15 every day ideally for at least 2 weeks.

VARIABLES

Independent Variable: Geomagnetic disturbances/activity in the ionosphere (measured by the K-index value. The higher the K-index value the more geomagnetic disturbances there are in the ionosphere).

Dependent Variable: GPS errors as determined by WAAS (WAAS is a system put into many GPSs and it is more accurate, so the difference between the WAAS on measurement and the WAAS off measurement is the error signal).

Constant Variable: the place where the measurement (bedroom) is taken, and the type of GPS (Garmin nuvi)

Comparison Group: The amount of GPS errors when the K-index is 0 compared to when it is not.

RESULTS

Table 1 shows the 3 measurements (elevation, longitude and latitude) taken at the certain date and time without WAAS enabled.

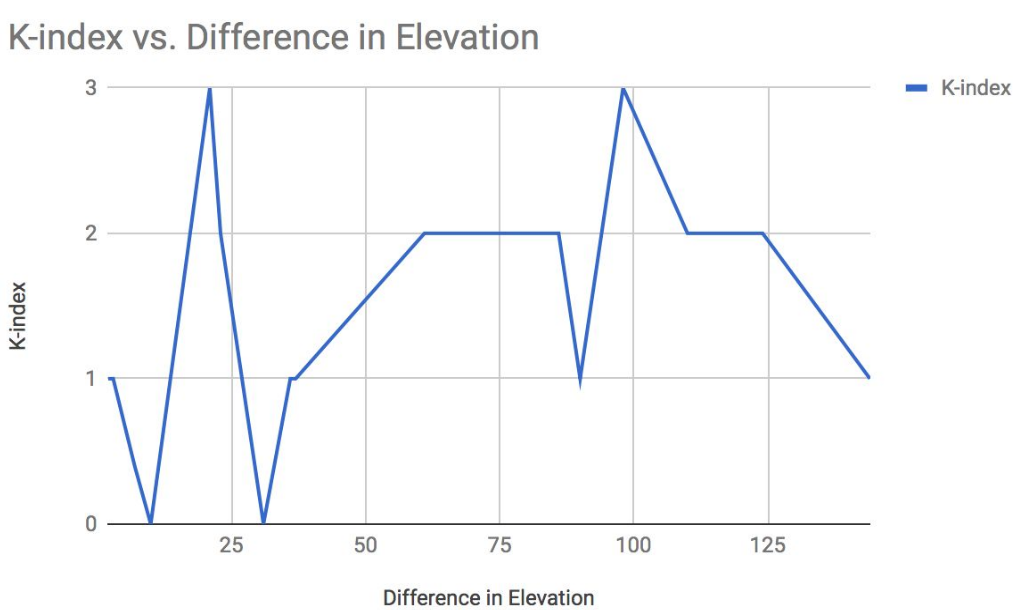
Measurement Values without WAAS

Date	Time	Elevation without WAAS	Longitude without WAAS	Latitude without WAAS
12/28/17	12:00 AM	945 ft	W088º04.944'	N42º02.555'
12/28/17	6:00 PM	848 ft	W088º04.944'	N42º02.567'
12/29	12:00 AM	893 ft	W088º04.946'	N42º02.560'
12/29/17	6:00 PM	704 ft	W088º04.952'	N42º02.560'
12/30/17	12:00 AM	843 ft	W088º04.948'	N42º02.543'
12/30/17	6:00 PM	952 ft	W088º04.944'	N42º02.565'
12/31/17	12:00 AM	669 ft	W088º04.951'	N42º02.548'
12/31/17	9:30 PM	846 ft	W088º04.938'	N42º02.568'
1/1/18	12:00 AM	887 ft	W088º04.940'	N42º02.566'
1/1/18	11:00 PM	853 ft	W088º04.950'	N42º02.576'
1/2/18	12:00 AM	848 ft	W088º04.945'	N42º02.565'
1/8/18	12:00 AM	782 ft	W088º 04.941'	N42º02.562
1/8/18	10:00 PM	759 ft	W088º04.938'	N42º02.571'
1/9/18	12:00 AM	785 ft	W088º04.947'	N42º02.569'
1/10/18	12:45 AM	924 ft	W 088º04.961'	N42º02.570'
1/17/18	1:00 AM	805 ft	W 088º04.941'	N42º02.564'
1/18/18	1:00 AM	948 ft	W088º04.951'	N42º02.574'
1/20/18	3:00 AM	818 ft	W088º04.942'	N42º02.566'
1/24/18	12:00 AM	824 ft	W088º04.944'	N42º02.565'
1/26/18	1:30 AM	827 ft	W088º04.950'	N42º02.571'

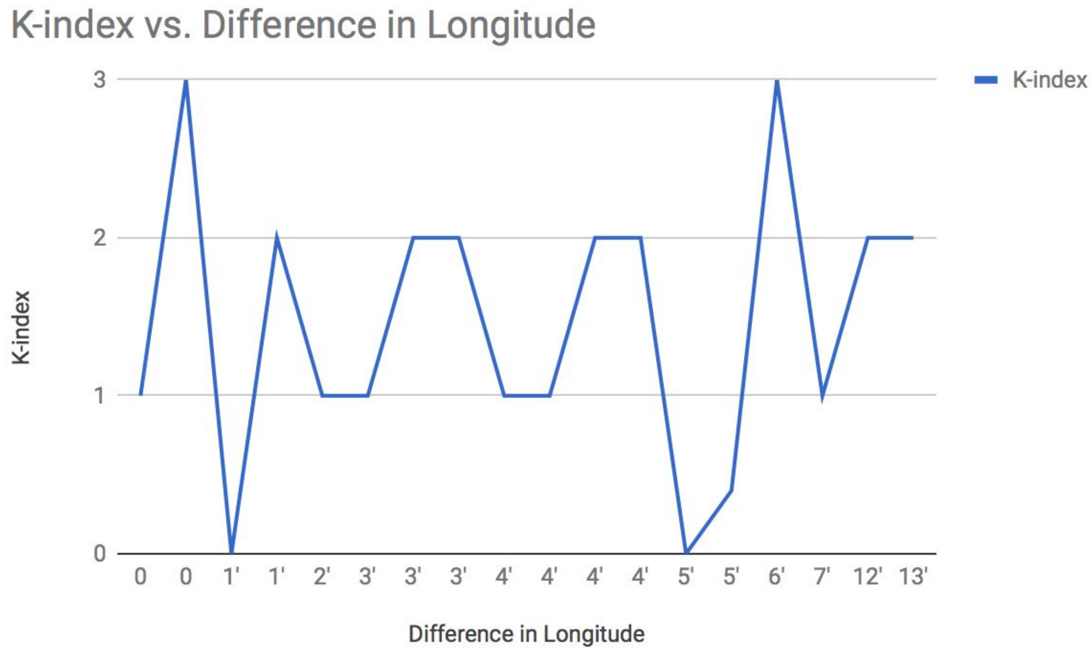
Table 2 shows the 3 measurements (elevation, longitude and latitude) taken at the certain date and time with WAAS enabled.

Measurement Values with WAAS

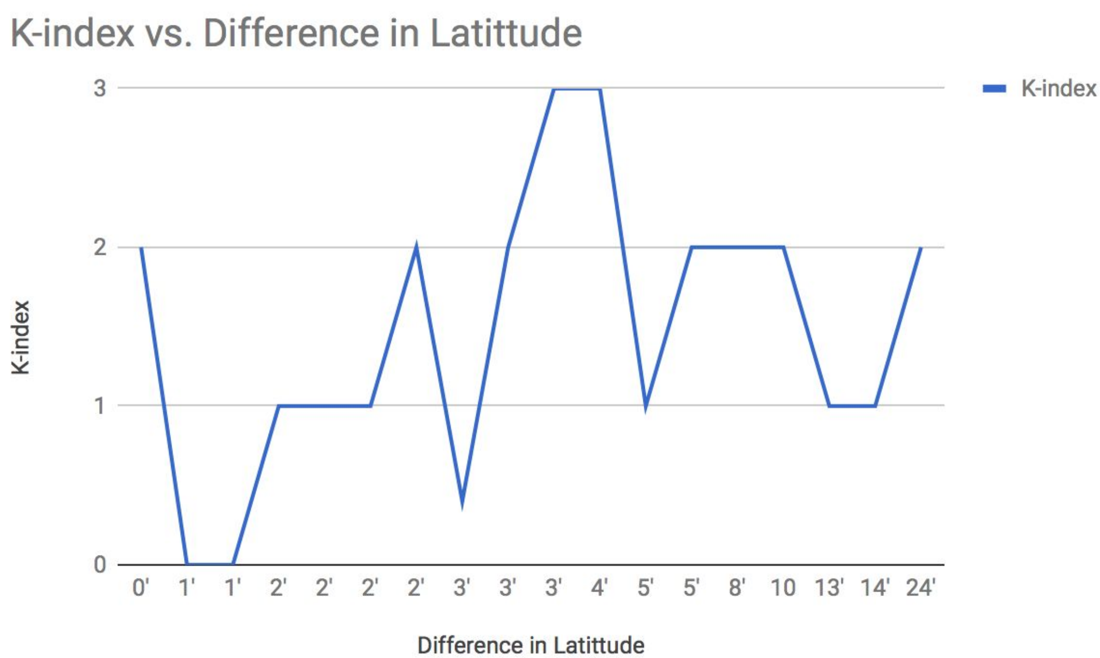
Date	Time	Elevation with WAAS	Longitude with WAAS	Latitude with WAAS
12/28/17	12:00 AM	835 ft	W088º04.941'	N42º02.568'
12/28/17	6:00 PM	812 ft	W088º04.944'	N42º02.569'
12/29	12:00 AM	771 ft	W088º04.942'	N42º02.570'
12/29/17	6:00 PM	828 ft	W088º04.949'	N42º02.561'
12/30/17	12:00 AM	846 ft	W088º04.564'	N42º02.944'
12/30/17	6:00 PM	808 ft	W088º04.946'	N42º02.567'
12/31/17	12:00 AM	779 ft	W088º04.954'	N42º02.572'
12/31/17	9:30 PM	785 ft	W088º04.942'	N42º02.565'
1/1/18	12:00 AM	789 ft	W088º04.946'	N42º02.562'
1/1/18	11:00 PM	816 ft	W088º04.943'	N42º02.571'
1/2/18	12:00 AM	934 ft	W088º04.933'	N42º02.573'
1/8/18	12:00 AM	775 ft	W088º 04.946'	N42º02.565'
1/8/18	10:00 PM	831 ft	W088º04.946'	N42º02.569'
1/9/18	12:00 AM	818 ft	W088º04.943'	N42º02.568'
1/10/18	12:45 AM	809 ft	W 088º04.948'	N42º02.568'
1/17/18	1:00 AM	803 ft	W 088º04.937'	N42º02.550'
1/18/18	1:00 AM	917 ft	W088º04.946'	N42º02.573'
1/20/18	3:00 AM	797 ft	W088º04.942'	N42º02.569'
1/24/18	12:00 AM	834 ft	W088º04.945'	N42º02.564'
1/26/18	1:30 AM	804 ft	W088º04.949'	N42º02.571'



Graph 1 compares the K-index value to the difference (error signal) in elevation(feet), over the course of the data. Although not linear, there are only two points where a difference was not detected.



Graph 2 compares the K index value to the difference (error signal) in longitude in minutes, over the course of the data. Although not linear, there are only two points where a difference was not detected.



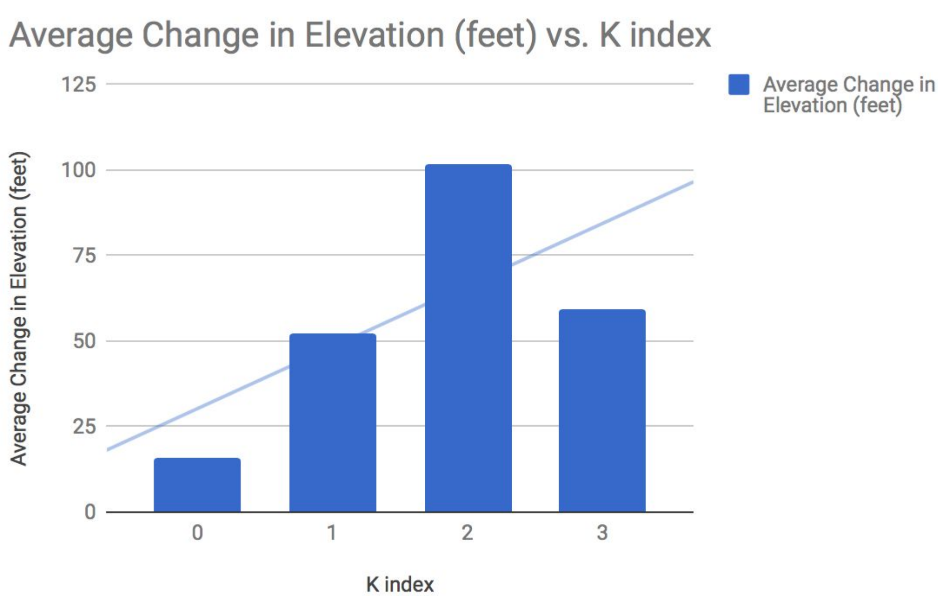
Graph 3 compares the K index value to the difference (error signal) in latitude in minutes, over the course of the data. Although not linear, there are only two points where a difference was not detected.

Table 3 shows all of the differences (error signals) from the data for each type of measurement and it's according K-index value.

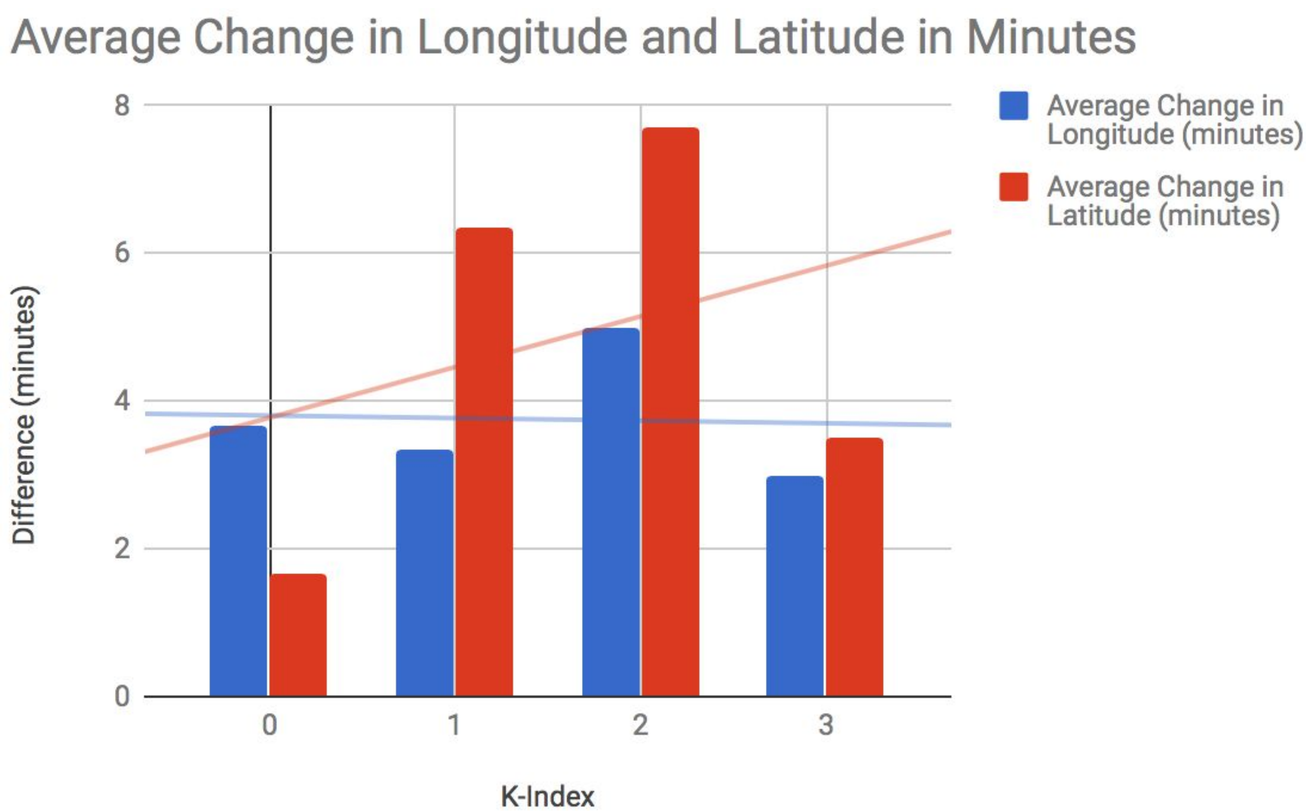
Difference in Measurement

Date	Time	Difference in Elevation (feet)	Difference in Longitude	Difference in Latitude	K-index Value
12/28/17	12:00 AM	90	3'	13'	1
12/28/17	6:00 PM	36	0	2'	1
12/29	12:00 AM	122	4'	10	2
12/29/17	6:00 PM	124	3'	5'	2
12/30/17	12:00 AM	3	4'	2'	1
12/30/17	6:00 PM	144	2'	2'	1
12/31/17	12:00 AM	110	3'	24'	2
12/31/17	9:30 PM	61	4'	3'	2
1/1/18	12:00 AM	98	6'	4'	3
1/1/18	11:00 PM	37	7'	5'	1
1/2/18	12:00 AM	86	12'	8'	2
1/8/18	12:00 AM	7	5'	3'	0.4
1/8/18	10:00 PM	72	8'	2'	2
1/9/18	12:00 AM	33	4'	1'	4
1/10/18	12:45 AM	115	13'	2'	2
1/17/18	1:00 AM	2	4'	14'	1
1/18/18	1:00 AM	31	5'	1'	0
1/20/18	3:00 AM	21	0	3'	3
1/24/18	12:00 AM	10	1'	1'	0
1/26/18	1:30 AM	23	1'	0'	2

Graph 4 shows the average differences (error signals) in elevation from the K-index values (measures geomagnetic activity; the higher the K-index value, the higher the geomagnetic disturbances/activity) present in this experiment.



Graph 5 shows the average differences (error signals) in longitude and latitude from the K-index values (measures geomagnetic activity; the higher the K-index value, the higher the geomagnetic disturbances/activity) present in this experiment.



Errors:

Some possible errors could of definitely occurred due to the times this data was being collected. As one can tell, there are many occasions where the times the data was collected did not follow the 12 AM, and 6PM schedule. The varied times may have prevented the most accurate results possible from being acquired.

Data Analysis:

Tables 1 and 2 show the elevation, longitude, latitude value with WAAS off and on respectively. Graphs 1, 2, 3 compare the difference in elevation, longitude, and latitude vs the K-index value, respectively. Table 3 shows all of the differences or GPS errors from the data for each type of measurement and its according K-index value. Graphs 4 and 5 show the average change in elevation and longitude/latitude respectively, associated with each K-index value over the course of the data.

CONCLUSION

The purpose of the research was to determine if there was a correlation between geomagnetic activity and GPS errors. It was hypothesized that as the strength of geomagnetic activity increases (as the K-index value increases), then the GPS errors would increase as well. The hypothesis was partially supported. There is a linear correlation in GPS errors in elevation and latitude when the K-index increased from 1 to 2, however the correlation does not continue as the K-index increases to a value of 3. The most likely explanation for this lack in trend is that the sample size when the K-index was 3 is less than that at the K-index of 0-2. The lack of enough data at the K-index value of 3 may explain why the trend fails to continue. However, the hypothesis is not supported for longitude as there does not seem to be a correlation in the data. Both of these statements can be supported by the trend lines seen on the graphs. Therefore, it can be concluded that there is a positive, linear correlation between geomagnetic activity in ionosphere and GPS errors in elevation and latitude but not in longitude.

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