

**ASSESSING THE IMPACT OF SEVERE SPACE WEATHER ON
SATELLITE POSITIONING AND NAVIGATION**

BY

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DECLARATION

I Adriko Norbert Bakole hereby declare that the above research work is owned by me under the supervision of Dr. Andima Geoffrey. This work has never before been submitted to a university or any other higher educational institution for the purpose of attaining a degree or any other credential.



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APPROVAL

This research work is submitted as a partial fulfillment for the award of Bachelor of science education of Busitema University, with the approval of my academic supervisor.

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DEDICATION

I would like to dedicate this research to my Father Mr. Bakole Lonzino and my mother Andiru Julliet and Chebet Joan and for their continued support, motivation, prayers and financial assistance towards the project and me.

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At the forefront, I want to thank the almighty God for life and the gift of being able to carry out the research and for the ability to explore science through my research work.

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ACRONYMS AND ABBREVIATIONS

Dst	Disturbance storm time
DOP	Dilution of precision
GDOP	Geometric dilution of precision
HDOP	Horizontal dilution of precision
VDOP	Vertical dilution of precision
TDOP	Time dilution of precision
PDOP	Position dilution of precision
GNSS	Global navigation satellite system
WAAS	Wide area augmentation system
GPS	Global positioning system
SBAS	Satellite based Augmentation system
MSAS	Multi-functional satellite augmentation system
SWPC	Space weather prediction center
NOAA	National Oceanic and Atmospheric Administration

ABSTRACT

The accuracy and dependability of the Global Positioning System (GPS) can be severely impacted by severe space weather occurrences. This work explores the measurement of GPS variability during such situations using the Dilution of Precision (DOP) metric. The diurnal fluctuation of DOP under quiet space weather conditions was determined by analyzing GPS data collected during a selected severe space weather event. According to findings, there was no noticeable increase in DOP values during the severe space weather event, which suggests that the sources where I obtained the data did not register the geomagnetic storm event. Throughout the event, the pattern of diurnal fluctuation is also disturbed. The results show that DOP is a useful tool for evaluating GPS variability and emphasize the significance of taking space weather effects into account when evaluating GPS performance. The findings of this study have consequences for GPS users and operators, especially in situations when high accuracy and reliability such as navigation, precision agriculture, and emergency response.

CHAPTER ONE: INTRODUCTION

The Global Positioning System (GPS) has become an essential technology for modern navigation, communication, and precision applications. With its widespread use, the impact of space weather on GPS performance has become a growing concern. Severe space weather events, such as solar flares and geomagnetic storms, can cause significant disruptions to GPS signals, leading to decreased accuracy and reliability (Demyanov & Yasyukevich, 2021). These disruptions can have critical effects on various applications, including navigation, precision agriculture, emergency response, and military operations.

The Dilution of Precision (DOP) metric, which measures the geometric dilution of GPS satellite signals, has shown promise in assessing GPS variability. However, its application in severe space weather events has not been thoroughly investigated.

This research aimed to address this knowledge gap by analyzing the use of DOP in determining GPS variability during severe space weather events. Specifically, this study sought to explore the relationship between DOP and doing so, this research aimed to contribute to the development of more accurate and reliable GPS systems, applications that rely on GPS technology.

STATEMENT OF THE PROBLEM

Extreme space weather phenomena, such as geomagnetic storms, can significantly disrupt the Earth's ionosphere, leading to changes in ionospheric density and electron content. These disturbances cause elevated noise, signal delays, and inaccuracies in the propagation of GPS signals. One of the key challenges is scintillation, which involves abrupt variations in the amplitude and phase of GPS signals as they travel through the ionosphere. These variations have the potential to reduce GPS accuracy, especially in areas near the equator and poles where ionospheric activity is more intense. As a result, the quality of signals that GNSS receivers receive is lowered, which reduces accuracy and dependability. During large geomagnetic storms, the cycle slip threshold model, which is based on the ionospheric disturbance index ROTI, is used to mitigate the rate of false detection of cycle slip in GNSS PPP. However, the problem remains unresolved. Therefore, this research aims to enrich understanding of the impact of

severe space weather on satellite positioning and navigation. Additionally, it seeks to improve forecasting methods for these events to inform better mitigation techniques.

AIM OF THE STUDY

Assessing the impact of severe space weather on positioning and navigation.

OBJECTIVES

1. To identify a severe space weather event.
2. To determine the diurnal variation of dilution of precision (DOP).
3. To determine the variation of dilution of precision during a severe space weather event.

SCOPE

This research is expected to take around 4-6 months with about 1 to 10 years data collection scope which is highly dependent on the availability of GPS and space weather data. The data types are pseudorange data and navigation data. The required space weather data are solar flux and geomagnetic indices i.e. Dst with data resolution of 1-30 seconds depending on the data source and quality.

This data will be obtained from Busitema University Nagongera campus satellite receiver located above and the internet respectively.



Figure 1: Map showing GPS station that was used in this study, indicated by the blue circle.

This research will investigate the influence of severe space weather events on GPS positioning accuracy, employing the metric to quantify errors. The study will concentrate on a recent solar cycle with readily available space weather data i.e. Solar Cycle 24: 2008. Data analysis will target well-documented severe space weather events within this timeframe, such as the March 2015 storm.

The results of this research can add to the body of information previously available about how severe space weather affects positioning and navigation. They can also provide data for forecasting, raise awareness and readiness, and enhance GPS accuracy and dependability.

CHAPTER TWO: LITERATURE REVIEW

2.1: INTRODUCTION TO SPACE WEATHER

2.1.1: Definition and Overview

Space weather refers to the environmental conditions in space as influenced by the Sun and the solar wind, which can impact the Earth and its technological systems (Schwenn, 2006). Space weather encompasses various phenomena, including: solar flares, coronal mass ejections, geomagnetic storms, solar wind.

2.1.1.1: Solar Flares: intense radiation flares that result from sunspot-related magnetic energy releases. They have the ability to release ultraviolet and X-ray radiation that can interfere with radio transmissions and navigational signals by impacting the upper atmosphere of the Earth.

2.1.1.2: Coronal Mass Ejections (CMEs): Large expulsions of plasma and magnetic field from the Sun's corona. When directed toward Earth, CMEs can cause significant geomagnetic storms by interacting with the Earth's magnetosphere.

2.1.1.3: Geomagnetic Storms: Disturbances in the Earth's magnetic field caused by enhanced solar wind conditions, often resulting from CMEs or high-speed solar wind streams. These storms can affect satellite operations, navigation systems, and power grids.

2.1.1.4: Solar Wind: A stream of charged particles (primarily electrons and protons) released from the upper atmosphere of the Sun, known as the corona. The solar wind's interaction with the Earth's magnetic field can cause variations in space weather conditions.

The primary source of space weather is solar activity, which follows an approximately 11-year cycle known as the solar cycle (Gorney, 1990). Key sources and causes include:

Sunspots: Temporary phenomena on the Sun's photosphere that appear as spots darker than the surrounding areas. They are regions of intense magnetic activity and are often the origin points for solar flares and CMEs.

Solar Flares: Result from the release of magnetic energy stored in the Sun's atmosphere. The energy release accelerates particles to high velocities, emitting radiation across the electromagnetic spectrum.

Coronal Mass Ejections (CMEs): Arise from the Sun's corona, where magnetic field lines become twisted and then reconfigure, releasing large amounts of plasma and magnetic fields into space.

High-Speed Solar Wind Streams: Emanate from coronal holes, which are regions where the Sun's magnetic field is open to interplanetary space, allowing solar wind to escape at higher speeds.

2.1.2: EFFECTS ON EARTH

Space weather has a variety of impacts on Earth, particularly on technological systems. Some of the key effects include:

2.1.2.1: Satellite Operations: Increased radiation from solar flares and geomagnetic storms can damage satellite electronics and cause disruptions in satellite communications and navigation signals.

2.1.2.2: Global Navigation Satellite Systems (GNSS): Geomagnetic storms can cause ionospheric disturbances, leading to errors in GNSS signals and reduced accuracy in positioning and navigation services.

2.1.2.3: Power Grids: Geomagnetic storms can induce electric currents in power lines, potentially causing voltage instability, transformer damage, and even large-scale power outages.

2.1.2.4: Aviation: Increased radiation levels at high altitudes during solar events can pose risks to passengers and crew on high-latitude flights. Communication and navigation systems can also be affected.

2.1.2.4: Communication Systems: High-frequency radio communications can be disrupted by increased ionization in the Earth's atmosphere, particularly during solar flares and geomagnetic storms.

2.2: GEOMAGNETIC STORMS

The Earth's magnetic field is disturbed by solar wind variations, especially those brought on by solar flares or coronal mass ejections (CMEs). These disruptions are known as geomagnetic

storms (Webb, 1995). These storms happen when the Earth's magnetosphere interacts with the solar wind's increased electric field, leading to a large-scale energy transfer.

2.2.1: CLASSIFICATION

According to Loewe and Prolss (1997), geomagnetic storms can be classified as moderate, intense, severe and extreme.

Moderate: May cause voltage corrections in power grids. Aurora borealis visible at lower latitudes. Dst range ($-100\text{nT} < \text{Dst} \leq -50\text{nT}$) (Parashar et al., 2011).

Intense: Can cause power grid fluctuations and transformer damage. Strong aurora displays possible at mid-latitudes. Dst range ($-200\text{ nT} < \text{Dst} \leq -100\text{nT}$) (Parashar et al., 2011).

Severe: may cause widespread power outages and satellite disruption. Severe aurora displays down to low latitudes Dst range ($-350\text{ nT} < \text{Dst} \leq -200\text{ nT}$) (Parashar et al., 2011).

Extreme (Great): Can cause large scale power blackouts and damage to infrastructure. Aurora visible even near the equator. Dst range ($\text{Dst} \leq -350\text{ nT}$) (Parashar et al., 2011).

2.2.2: HISTORICAL EVENTS

The most powerful geomagnetic storm ever recorded, the **Carrington Event (1859)**, was brought on by a large CME. Strong electric currents were induced, resulting in the failure of telegraph systems throughout Europe and North America, and it also produced auroras that could be seen as far south as the Caribbean(Pierce, 2016).

The 1989 Quebec Blackout: A severe geomagnetic storm induced by a CME that caused a nine-hour blackout in Quebec, Canada. The storm disrupted power transmission due to geomagnetically induced currents (GICs), which overwhelmed the grid's capacity and led to equipment failure.

2.3: GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

Global Navigation Satellite Systems (GNSS) are a group of satellite-based systems that provide global positioning, navigation, and timing information(Grewal, 2011). These systems are essential for a wide range of applications, from everyday navigation to complex scientific research and military operations. The most well-known GNSS include:

2.3.1: Global Positioning System (GPS): Operated by the United States, GPS was the first fully operational GNSS and remains the most widely used.

2.3.2: GLONASS: Developed by Russia, GLONASS is similar to GPS in functionality and is designed to provide alternative and complementary coverage.

2.3.3: Galileo: Managed by the European Union, Galileo aims to provide high-precision positioning services globally and is interoperable with other GNSS.

2.3.4: BeiDou: Operated by China, BeiDou offers global coverage and has been rapidly expanding its constellation to provide enhanced accuracy and reliability.

2.3.5: IMPACT OF SPACE WEATHER ON GNSS

2.3.5.1: Signal Degradation

Space weather, particularly geomagnetic storms and solar activities, can significantly impact GNSS signals. These effects primarily arise from disturbances in the Earth's ionosphere and magnetosphere, which alter the propagation of satellite signals. Key phenomena include:

2.3.5.2: Ionospheric Scintillation: This refers to rapid variations in the amplitude and phase of GNSS signals caused by small-scale irregularities in the ionosphere. These irregularities scatter the satellite signals, leading to fluctuations that can degrade signal quality and cause data loss.

2.3.5.3: Signal Attenuation: Increased levels of solar radiation, especially during solar flares, can enhance the ionization in the ionosphere, causing higher signal absorption and attenuation. This weakens the signal strength received by GNSS users, impacting the accuracy and reliability of positioning information. (Russell et al., 1974)

2.3.5.4: Geomagnetic Storms: These storms, triggered by solar wind and Coronal Mass Ejections (CMEs) interacting with the Earth's magnetic field, can cause significant disturbances in the ionosphere. These disturbances can lead to increased positioning errors and, in severe cases, complete loss of GNSS signal lock.

2.3.5.5: Positioning Errors: Research has shown that during periods of high geomagnetic activity, the accuracy of GNSS positioning can degrade substantially (Sikirica et al., 2021). For instance, studies have documented positioning errors increasing by several meters during intense geomagnetic storms, affecting both civilian and military GNSS applications. (Spivak et al., 2021)

2.3.5.6: Operational Disruptions: Several studies have focused on the operational disruptions caused by space weather events. For example, the report on the temporary loss of GNSS signal lock and increased time-to-first-fix (TTFF) during ionospheric disturbances (Isoz, 2015). These disruptions can be critical for applications requiring continuous and precise positioning, such as aviation and maritime navigation.

Specific geomagnetic storms, such as the Halloween Storms of 2003 and the St. Patrick's Day Storm of 2015, have been extensively studied (Mridula et al., 2022). These events provided valuable data on the scale and nature of GNSS signal degradation. Findings indicate that during these storms, users experienced substantial degradation in signal quality, increased positioning errors, and, in some cases, total service outages. Research has also explored various strategies to mitigate the impact of space weather on GNSS. These include developing advanced algorithms for signal processing, integrating GNSS with other navigation systems, and using real-time ionospheric correction models to improve positioning accuracy during space weather events. (Sreeja, 2016)

2.4: DILUTION OF PRECISION (DOP)

Dilution of Precision (DOP) is a measure used in GNSS to describe the impact of satellite geometry on the accuracy of position estimates. It quantifies how errors in satellite signal measurements translate into errors in the user's position calculation (Milbert, 2008). Lower DOP values indicate better satellite geometry and, consequently, more accurate positioning. The DOP is significant because even with precise satellite signals, poor geometry can degrade positioning accuracy, making it a critical factor in GNSS performance.

2.4.1: TYPES OF DOP

There are several types of DOP, each focusing on different aspects of positioning accuracy:

2.4.1.1: GDOP (Geometric Dilution of Precision): Represents the overall DOP, combining both position and time dilation. It provides a general indication of the quality of the satellite configuration.

2.4.1.2: PDOP (Position Dilution of Precision): Specifically measures the effect of satellite geometry on three-dimensional position accuracy (latitude, longitude, and altitude). Lower PDOP values signify better positional accuracy.

2.4.1.3: HDOP (Horizontal Dilution of Precision): Refers to the impact of satellite geometry on horizontal position accuracy (latitude and longitude). This is particularly important for applications requiring precise 2D location information, such as map navigation.

2.4.1.4: VDOP (Vertical Dilution of Precision): Indicates the effect on vertical position accuracy (altitude). VDOP is crucial for applications like aviation and surveying, where altitude accuracy is essential.

2.4.1.5: TDOP (Time Dilution of Precision): Represents the impact of satellite geometry on time accuracy. Accurate timing is vital for synchronization in various applications, including telecommunications and network operations.

2.4.2: FACTORS INFLUENCING DOP

Several factors influence DOP values, impacting the accuracy of GNSS positioning:

2.4.2.1: Satellite Geometry: The relative positions of the satellites in the sky play a crucial role. Widely spaced satellites (both in azimuth and elevation) provide better geometry and lower DOP values, enhancing positioning accuracy. Conversely, closely spaced satellites lead to higher DOP values and reduced accuracy.

2.4.2.2: Number of Satellites: More satellites generally improve DOP by providing better geometric diversity. A larger constellation allows for selecting satellites with optimal spacing, reducing DOP and improving accuracy.

2.4.2.3: Signal Quality: The strength and clarity of the satellite signals affect DOP. Stronger, clearer signals ensure more accurate distance measurements, thereby improving DOP. Signal obstructions, multipath effects, and atmospheric conditions can degrade signal quality, increasing DOP.

2.4.2.4: Atmospheric Conditions: The ionosphere and troposphere can affect signal propagation, introducing errors that influence DOP. Variations in atmospheric conditions, such as ionospheric scintillation or tropospheric delays, can alter signal paths, impacting the accuracy of satellite positioning and thus the DOP.

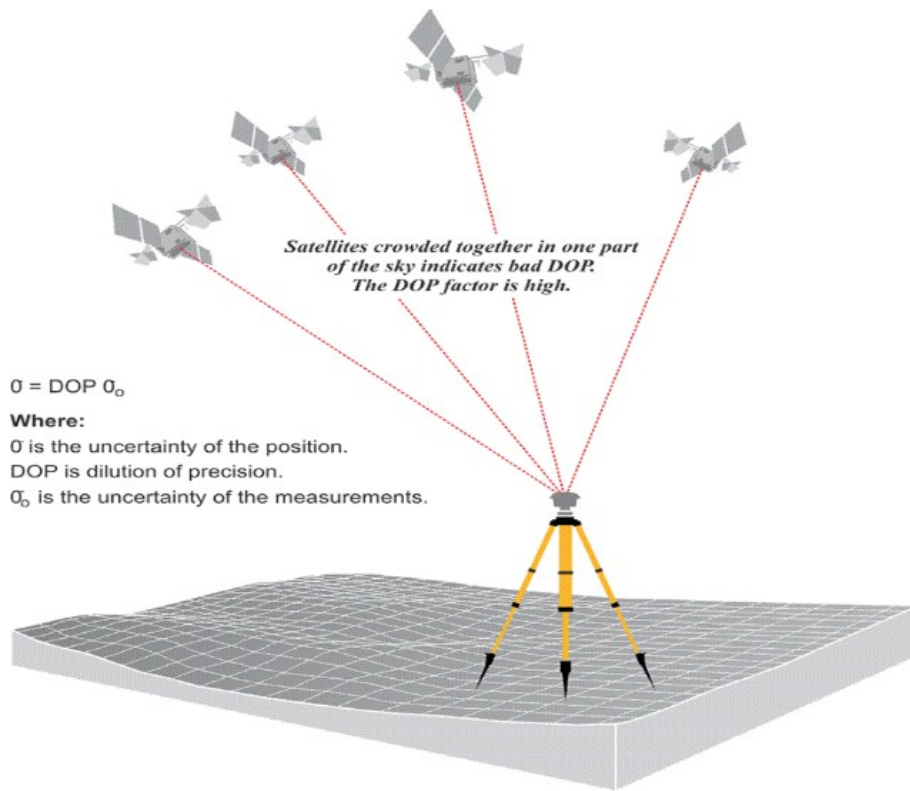


Figure 2: Bad DOP (The Space Segment: Dilution of Precision | GEOG 862:GPS and GNSS for Geospatial Professionals, n.d.)

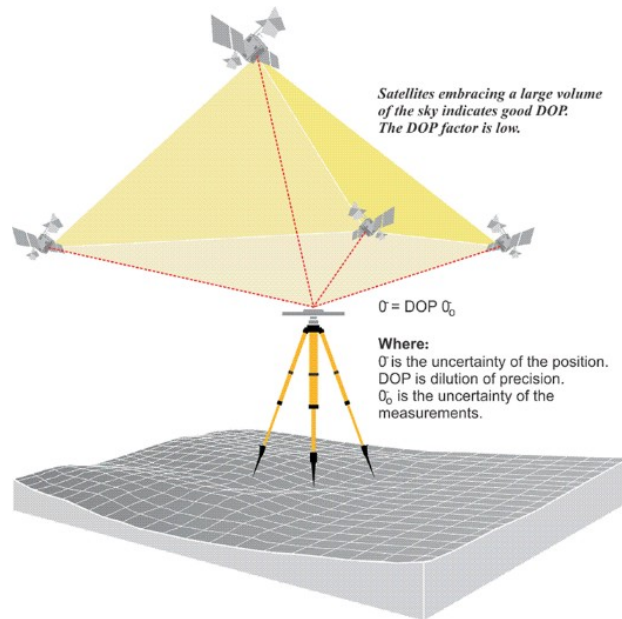


Figure 3: Good DOP (The Space Segment: Dilution of Precision | GEOG 862: GPS and GNSS for Geospatial Professionals, n.d.)

2.5: DIURNAL VARIATION OF DOP

Diurnal variation of DOP refers to the predictable changes in DOP values over the course of a day. These variations are primarily influenced by the movement of GNSS satellites relative to the Earth, which rotates on its axis once every 24 hours. Literature on diurnal patterns of DOP indicates that these variations are cyclic and can be attributed to several factors including Satellite constellation, Earth's rotation, influence of ionosphere, ionospheric activity, diurnal effects on ionospheric delays and ionospheric scintillation.

2.5.1: Satellite Constellation: As the Earth rotates, the relative positions of GNSS satellites change. This movement affects the geometry of the satellite constellation as seen from any given point on Earth, leading to fluctuations in DOP values. Typically, there are periods during the day when satellite geometry is more favorable, resulting in lower DOP values and better positioning accuracy. Conversely, there are times when the geometry is less favorable, leading to higher DOP values and reduced accuracy. (Specht et al., 2015)

2.5.2: Earth's Rotation: The rotation of the Earth causes different satellites to come into view and move out of view at different times. This rotation, combined with the orbital paths of the satellites, means that the DOP values at any specific location on Earth will vary predictably throughout the day. Research shows that these diurnal patterns are location-dependent, with some areas experiencing more pronounced variations than others. (Steenburgh et al., 2008)

2.5.3: Ionospheric Activity: The ionosphere's density and composition vary throughout the day due to solar radiation. During the daytime, increased solar activity leads to higher ionization levels, which can cause more significant delays and distortions in GNSS signals. These ionospheric effects are typically more pronounced near the equator and during periods of high solar activity. (*Ionosphere* | NOAA / NWS Space Weather Prediction Center, n.d.)

2.5.4: Diurnal Effects on Ionospheric Delays: At sunrise, ionospheric density starts to increase, reaching its peak around noon, and then gradually decreases towards the evening. These changes can introduce errors in the GNSS signals, which contribute to variations in positioning accuracy and, consequently, in DOP values. During nighttime, ionospheric activity is lower, often resulting in more stable and lower DOP values. (Su et al., 2019)

2.5.5: Ionospheric Scintillation: This phenomenon, characterized by rapid fluctuations in signal amplitude and phase, is more likely to occur during certain times of the day and under specific conditions, such as near the magnetic equator and during periods of high solar activity. Scintillation can severely affect GNSS signal quality, leading to increased DOP values and degraded positioning accuracy.(Steenburgh et al., 2008)

2.6: SEVERE SPACE WEATHER EVENTS AND DOP

Severe space weather events, such as geomagnetic storms, have a significant impact on the DOP in GNSS. These events can cause substantial degradation in GNSS signal quality, leading to increased DOP values and reduced positioning accuracy. During severe space weather conditions, ionospheric disturbances become more pronounced, causing delays and errors in signal transmission that directly affect the geometry of satellite signals received by GNSS users.

2.6.1: CASE STUDIES

2.6.1.1: Halloween Storms (October-November 2003): The Halloween Storms are among the most studied geomagnetic storms, known for their severe impact on GNSS performance. During these events, GNSS users experienced substantial increases in DOP values, especially in the polar and equatorial regions. Reports indicated that positioning errors grew by several meters, significantly affecting navigation and timing applications.

2.6.1.2: St. Patrick's Day Storm (March 2015): Another notable geomagnetic storm, the St. Patrick's Day Storm, caused widespread GNSS disruptions. Studies documented that the DOP values increased sharply during the storm, leading to degraded positioning accuracy. This event highlighted the vulnerability of GNSS to sudden and intense space weather phenomena, with DOP values increasing by factors of two to three in some instances.

2.6.2: MECHANISMS

Severe space weather impacts GNSS and DOP through several mechanisms:

2.6.2.1: Increased Ionospheric Disturbance: Geomagnetic storms energize particles in the Earth's magnetosphere, which then collide with the ionosphere, increasing its density and causing irregularities. These irregularities lead to delays and phase shifts in GNSS signals, resulting in higher DOP values. The more turbulent the ionosphere, the more severe the impact on signal propagation and positioning accuracy.

2.6.2.2: Satellite Signal Disruption: Space weather events can also cause direct disruptions to satellite signals. For example, solar flares emit intense bursts of electromagnetic radiation that can interfere with GNSS signals, causing temporary outages or signal degradation. This disruption can lead to loss of satellite lock, increased DOP, and errors in positioning calculations.

2.6.2.3: Scintillation Effects: During severe space weather, ionospheric scintillation—rapid changes in signal amplitude and phase—becomes more prevalent. Scintillation can cause signal fading and increased noise, making it difficult for GNSS receivers to maintain accurate signal tracking. This results in higher DOP values and reduced reliability of the positioning information.

2.7: MITIGATION AND ADAPTATION STRATEGIES

2.7.1: Technological Solutions

To mitigate the impact of space weather on GNSS, several technological solutions have been developed and proposed. These solutions aim to enhance the robustness and reliability of GNSS systems during adverse space weather conditions. They include improved algorithms, augmentation systems, Dual-Frequency receivers, real-time ionospheric models.

2.7.1.1: Improved Algorithms: Advanced signal processing algorithms can help mitigate the effects of ionospheric disturbances on GNSS signals. These algorithms improve the accuracy of position calculations by filtering out noise and correcting for errors induced by space weather.

2.7.1.2: Augmentation Systems: Augmentation systems like the Wide Area Augmentation System (WAAS) and Satellite-Based Augmentation Systems (SBAS) provide additional corrections to GNSS signals(Choy et al., 2017). These systems use a network of ground reference stations to monitor GNSS signals and calculate corrections that are broadcast to users, enhancing accuracy and reliability. WAAS: Operated by the United States, WAAS improves the accuracy, integrity, and availability of GPS by providing real-time corrections for ionospheric disturbances and other errors(EL-ARINI et al., 1994). SBAS: Similar to WAAS, SBAS includes systems like the European Geostationary Navigation Overlay Service (EGNOS) and the Japanese Multi-functional Satellite Augmentation System (MSAS). These systems enhance GNSS performance by offering corrections and integrity information(Choy et al., 2017).

2.7.1.3: Dual-Frequency Receivers: Using dual-frequency GNSS receivers can help mitigate the impact of ionospheric delays. By comparing signals from two different frequencies, these receivers can more accurately estimate and correct for ionospheric errors, reducing the overall impact on positioning accuracy.

2.7.1.4: Real-Time Ionospheric Models: Integrating real-time ionospheric models with GNSS systems allows for dynamic corrections based on current space weather conditions. These models can provide updates on ionospheric activity, enabling more accurate adjustments to GNSS signal processing.

2.7.2: Operational Procedures

Operational procedures and best practices can help GNSS users adapt to and mitigate the effects of space weather. These procedures involve utilizing available forecasting services and implementing real-time monitoring techniques. They include, forecasting services, real-time monitoring, best practices for critical applications and adaptive planning.

2.7.2.1: Forecasting Services: Space weather forecasting services provide valuable information about upcoming geomagnetic storms and ionospheric disturbances. GNSS users can subscribe to these services to receive alerts and updates, allowing them to plan and adjust their operations accordingly. Organizations like the NOAA Space Weather Prediction Center (SWPC) offer comprehensive space weather forecasts and warnings.

2.7.2.2: Real-Time Monitoring: Implementing real-time monitoring of GNSS performance and space weather conditions can help users quickly detect and respond to anomalies. By continuously assessing the quality of GNSS signals and DOP values, users can identify periods of increased space weather activity and take corrective actions, such as switching to alternative navigation methods or adjusting operational plans.

2.7.2.3: Best Practices for Critical Applications: For critical applications such as aviation and maritime navigation, it is essential to have contingency plans in place. This includes having backup navigation systems, conducting regular training for dealing with GNSS outages, and establishing standard operating procedures for periods of severe space weather.

2.7.2.4: Adaptive Planning: Organizations relying on GNSS for operations can develop adaptive plans that consider space weather impacts. This involves scheduling critical tasks during periods of expected low space weather activity and being flexible to reschedule when forecasts predict severe conditions.

CHAPTER THREE: METHODS

This chapter will describe all the data type and sources that were used for obtaining the data and possibly explaining it step by step for analysis of the data obtained.

3.1: DATA SOURCE AND DATA ANALYSIS

The Dst data was obtained from the WDC Kyoto and OMNIWeb sites which is downloaded into a notepad format by setting certain criteria like the date and the format of the data to be downloaded. The navigation data was accessible from the Busitema University Nagongera Campus satellite receiver. The Ephemeris data was downloaded from <https://earth-info.nga.mil> which is obtained by selecting the date range and choosing the EOPP data type i.e. GPS ephemeris centre of mass.

Observation files for DOP calculation were downloaded from NASA website <https://cdis.nasa.gov/archive/gnss/data/daily/2023/001/23o> by specifying the exact data type from GNSS and setting the geomagnetic storm days and the year it occurred.

The GPS data is downloaded from public archives and the Nagongera satellite receiver during selected space weather events and quiet period.

This data was saved using a text editor (notepad) and then imported in to MATLAB programming language for plotting the Dst graphs.

Downloaded observation data and navigation data from the above websites is also imported into MATLAB to plot the various daily DOP types.

Implement DOP calculations e.g. PDOP, HDOP, VDOP, GDOP) to quantify GPS positioning accuracy and geometry.

3.2: DOP CALCULATION

Satellite navigation depends on accurate range measurements in order to determine the position of the user. Because the receiver clock is generally not synchronized with GPS system time, the range measurements are erroneous and are therefore called pseudoranges. A pseudorange is thus:

$$PR_i = \sqrt{(X - X_i)^2 + (Y - Y_i)^2 + (Z - Z_i)^2} + ct_B + \text{random error}$$

Where: PR_i is the pseudorange to the i^{th} satellite (m) (X, Y, Z) is the unknown three dimensional user position, (X_i, Y_i, Z_i) is the known three dimensional satellite position (m), t_B is the unknown receiver clock offset (s), c is the speed of light (m/s)

Because there are four unknowns, at least four measurements are required to solve for X,Y,Z and t_B . Because the pseudorange equations are nonlinear, the system must be linearized in order to derive a linear relationship between pseudorange errors and position errors. If we linearize the GPS pseudo-ranges by using a first order Taylor Series expansion, we obtain a linear equation of the form:

$$\begin{pmatrix} \delta P R_1 \\ \delta P R_2 \\ \delta P R_3 \\ \delta P R_4 \end{pmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & 1 \\ h_{21} & h_{22} & h_{23} & 1 \\ h_{31} & h_{32} & h_{33} & 1 \\ h_{41} & h_{42} & h_{43} & 1 \end{bmatrix} \begin{pmatrix} \delta X \\ \delta Y \\ \delta Z \\ c t_B \end{pmatrix}$$

Where the h_{mn} elements represent direction cosines to each of the satellites.

In general, this equation can be written as:

$$\delta Y = H\delta\beta$$

Thus, a receiver modifies initial estimate of β using $\delta\beta$ and iterates until convergence is achieved.

The column of ones in H shows that the receiver clock offset (ct_B) biases each pseudorange measurement by exactly the same amount. In practice, there may be interchannel biases that affect each measurement differently. However, great care is taken by receiver manufacturers to calibrate these effects.

The GPS satellite geometry relates position errors to range measurement errors. Considering equation 1 with m pseudorange measurements. Then δY is an $m \times 1$ vector, H is an $m \times 4$ matrix, and as usual $\delta\beta$ is a 4×1 vector. If we think of $\delta\beta$ as a zero-mean vector containing the errors in the estimated user state, then we are interested in the statistics of $\delta\beta$ because that will characterize the expected position errors. Using the generalized inverse of H, we find the covariance of $\delta\beta$

$$C_X = (H^{G^T} H^G)^{-1} \sigma_\rho^2 = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{x\delta t_u} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & \sigma_{y\delta t_u} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & \sigma_{z\delta t_u} \\ \sigma_{x\delta t_u} & \sigma_{y\delta t_u} & \sigma_{z\delta t_u} & \sigma_{\delta t_u}^2 \end{bmatrix} \quad GDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_{\delta t_u}^2}}{\sigma_{UERE}}$$

$$(H^{G^T} H^G)^{-1} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & D_{14} \\ D_{21} & D_{22} & D_{23} & D_{24} \\ D_{31} & D_{32} & D_{33} & D_{34} \\ D_{41} & D_{42} & D_{43} & D_{44} \end{bmatrix} \quad GDOP = \sqrt{D_{11} + D_{22} + D_{33} + D_{44}}$$

$$\text{Similarly, } PDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}}{\sigma_{UERE}}$$

$$HDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2}}{\sigma_{UERE}}$$

$$VDOP = \frac{\sqrt{\sigma_z^2}}{\sigma_{UERE}}$$

$$TDOP = \frac{\sqrt{\sigma_{\delta t_u}^2}}{\sigma_{UERE}}$$

Specified observation data and navigation data for march, 2015 which registered a geomagnetic storm are downloaded and similarly loaded into MATLAB for calculation of DOP and plotting the various DOP graphs for the geomagnetic storm even. This data is for the four days of the occurrence of the geomagnetic storm

The data is analyzed and the DOP values compared for during geomagnetic storm days and quiet periods (Normal days).

Correlate the changes in DoP with the severity of the space weather event using space weather data sources (e.g., NOAA's Space Weather Prediction Center).

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1: RESULTS

4.1.1: Identifying a geomagnetic storm.

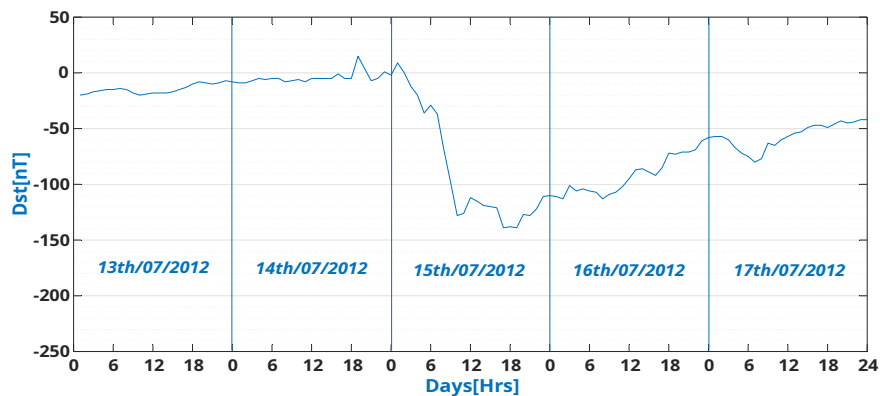


Figure 4: Shows a minor geomagnetic storm with Dst variation from OMNIWeb from 13th/07/2012 to 17th/07/2012

From 13th to 14th, Dst was stable and roughly zero. Then it increased by 15th July which marks the sudden storm commencement. The main phase of the storm was on 15th of July, 2012 and then the storm recovered from 16th/July/2012 to 17th/July/2012 which is called the recovery phase of the storm.

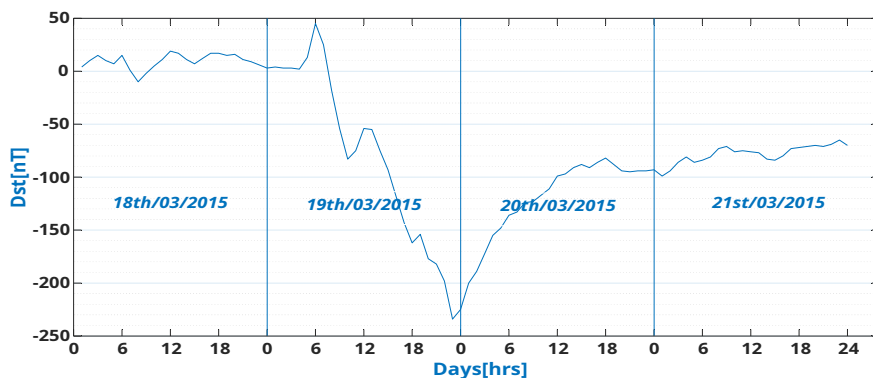


Figure 5: Shows a major Geomagnetic storm from OMNIWeb with Dst variation starting 18th/03/2015 to 21st/03/2015

The first day 18th shows a steady and stable Dst then on the 19th, there was a sudden storm commencement. The peak occurrence was in 12:00am in the night of 19th to the new day 20th/03/2015. The storm then starts its recovery phase from that day to the 21st and the days there forth.

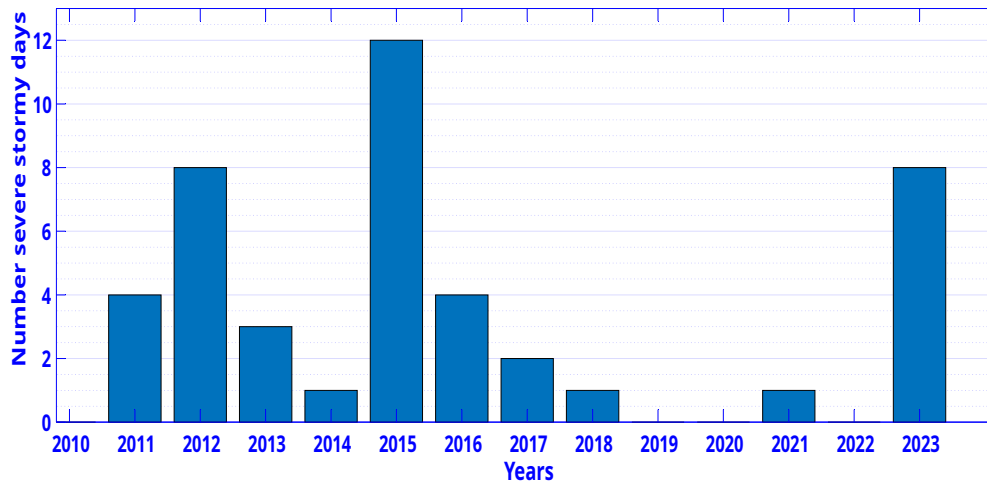


Figure 6: Shows a bar graph plotted for data downloaded from OMNIWeb services from the year 2010 to the year 2023 and shows the distribution of geomagnetic storms within the 11th solar cycle.

The years of 2010, 2019, 2020 and 2022 were seen not to have observed noticeable geomagnetic storms probably due to the low solar activity in those years. The years of 2011, 2013 and 2016 registered moderate geomagnetic events and the peak years i.e. 2012, 2015 and 2023 registered the most geomagnetic storm events. This graph shows geomagnetic storm distributions in the 11th solar year.

4.1.2: Diurnal Variation of Dilution of Precision.

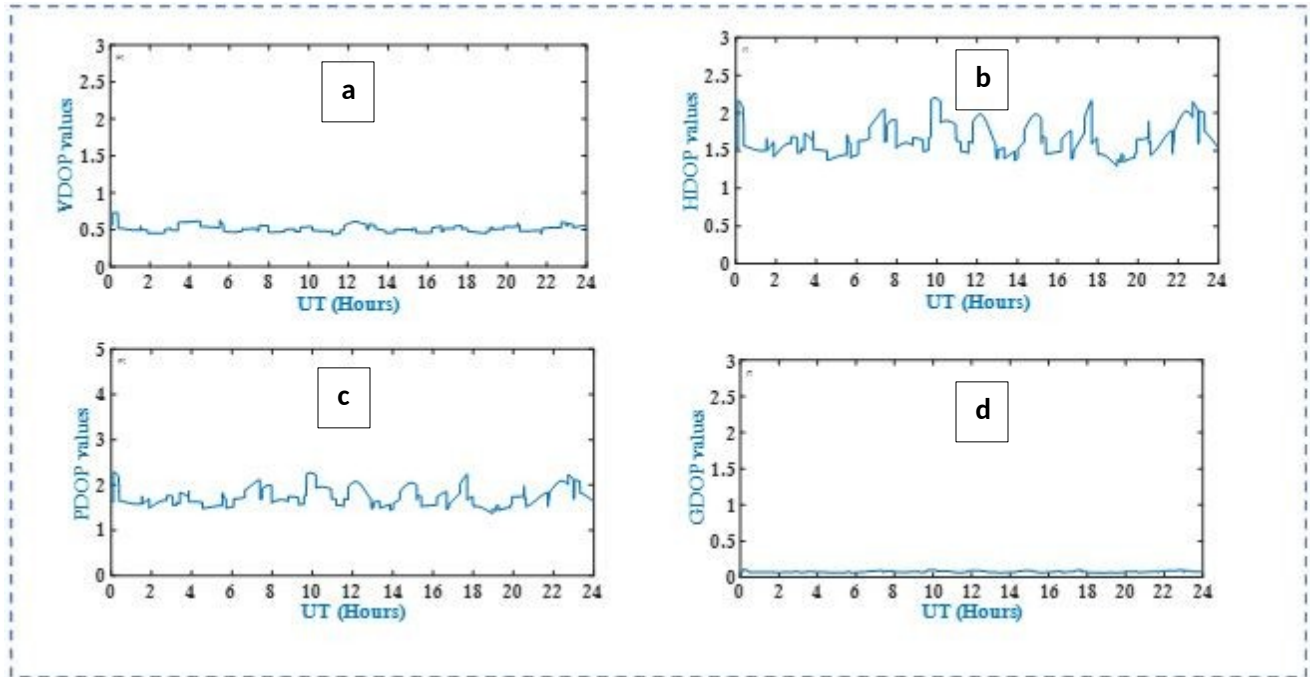


Figure 7: Shows the diurnal variation of Dilution of Precision for a selected day within a 24-hour window and the **a**, **b**, **c** and **d** above represent the Vertical, Horizontal, Positional and Geometric dilution of Precision plots against universal time

The graph **a** show an average vertical dilution of precision of around 0.5. The low variation of the VDOP throughout the day indicates that the satellite geometry is favorable for determining the height precisely. Graph **b** shows an average horizontal dilution of precision of 1.5 to 2.0, depicts that the satellite constellation is ideal for precise east-west and north-south measurements. Graph **c** shows an average dilution of precision of around 2 and lastly the graph **d** which represents the geometric dilution of precision which is around 0 which indicates a good satellite geometry with satellites clustered in wider area of the sky leading to smaller position errors.

4.1.3: Dilution of precision of the march, 2015 geomagnetic storm day.

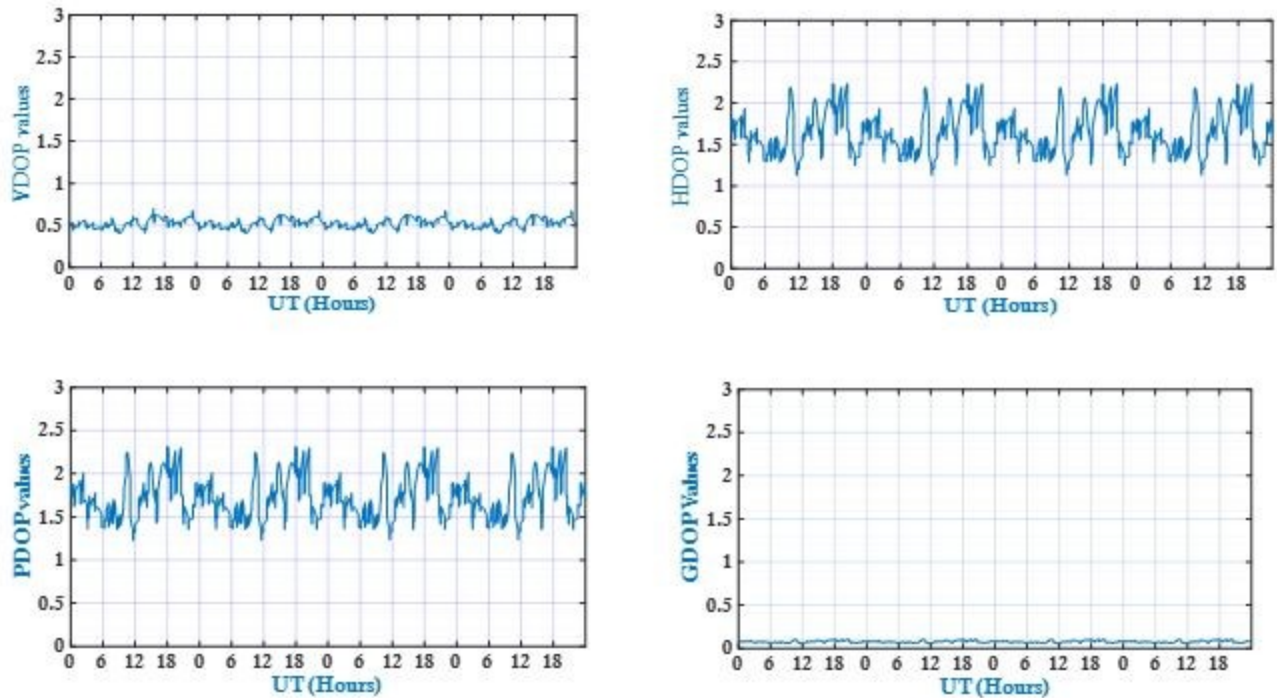


Figure 8: Shows the various Dilution of Precision metrics i.e. VDOP, HDOP, PDOP and GDOP plotted for the geomagnetic storm from 18th/03/2015 to 21st/03/2015.

The values of the VDOP and GDOP are noticeably similar to those obtained on a daily variation of DOP implying that there was no much change. The average value of the HDOP and PDOP was the same as that of the daily patterns though the where more fluctuations in the hourly variations of their DOP values.

This section will delve into the key findings from the analysis of GPS data during a geomagnetic storm. Here's a breakdown of potential discussion points:

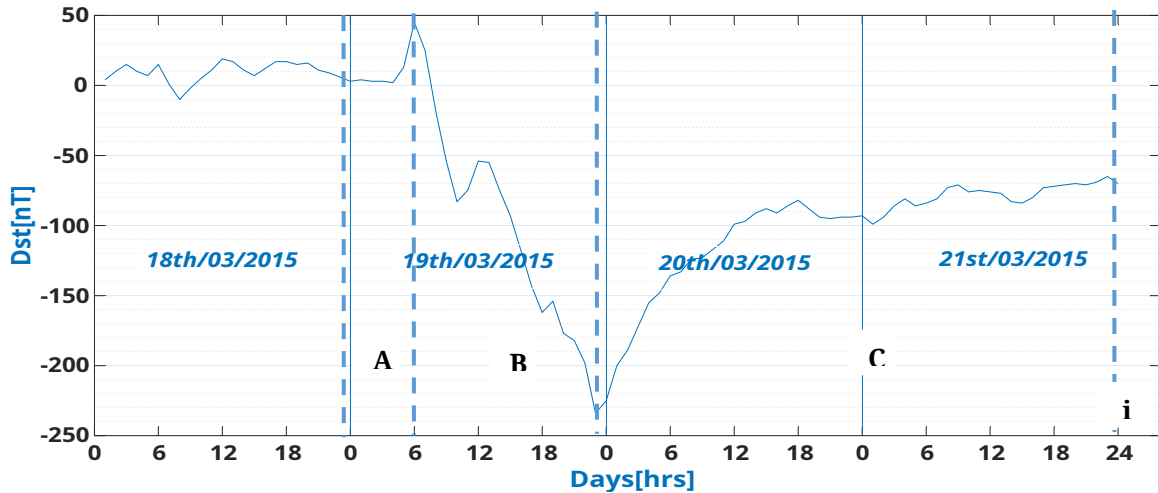


Figure 9: Shows the breakdown of the phases of the occurrence of the march, 2015 geomagnetic storm from 18th/03/2015 to 20th/03/2015.

Taking march 2015 which registered a geomagnetic storm of below -200nT. The geomagnetic storm took about 4 days for it to occur. A geomagnetic storm occurs in stages listed from A, B, and C.

A geomagnetic storm unfolds in several distinct phases, each characterized by specific changes in the Earth's magnetic field:

4.2.1: Initial Phase(A):

This phase begins with a coronal mass ejection (CME) or a high-speed solar wind stream erupting from the Sun. The ejected material travels towards Earth, taking several hours to days to arrive.

4.2.2: Main Phase(B):

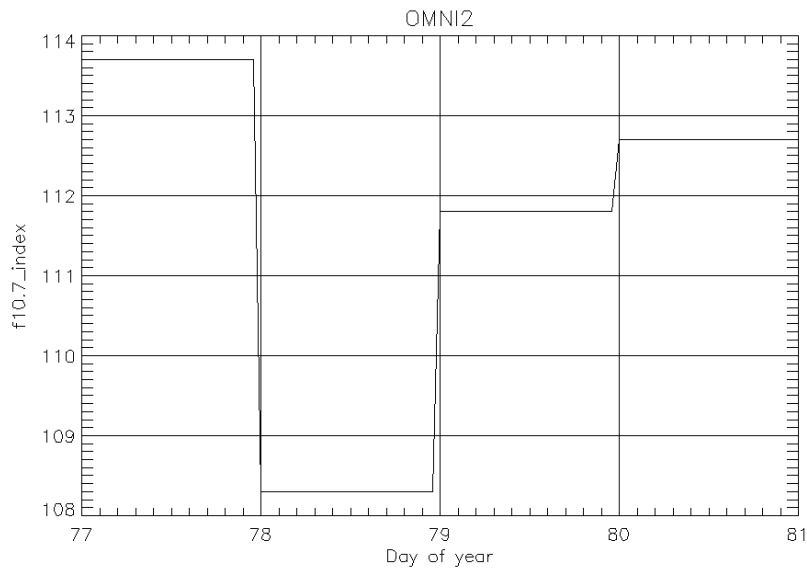
This is the most intense phase of the storm. Energy from the CME or solar wind is transferred to the magnetosphere, causing it to become agitated. This can trigger processes like Reconnection of magnetic field lines, allowing charged particles to enter the magnetosphere and Auroral displays at high latitudes (north and south poles) due to the influx of energetic particles. The intensity of the storm (measured by indices like Dst) peaks during this phase, which can last from hours to days.

4.2.3: Recovery Phase(C):

The magnetosphere gradually recovers its original shape as the pressure from the CME or solar wind stream subsides. The energetic particle influx weakens, and auroras become

less intense. The recovery can be slow, taking several days or even weeks depending on the severity of the storm.

The specific characteristics and duration of each phase can vary depending on the properties of the CME or solar wind stream.



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Figure 10: Shows the F10.7_index corresponding to the march, 2015 geomagnetic storm.

This figure shows a correspondence with the figure 28. This correspondence implied that as the geomagnetic storm occurred, the solar flux index increased which reflects the suns overall activity level with higher value indicating a more active sun.

4.2.4: Diurnal Variation of DOP under Normal Conditions:

4.2.5: Geomagnetic storm impact on DOP

In comparison to the diurnal variation pattern, there is no discernible change in the variation of any of the DOP types during the 2015 geomagnetic storm. This means that there were no appreciable variations in the DOP variation at the sites where the data was collected. This suggests that other places experienced the effects of the strong geomagnetic storms. There are typically two consequences of a geomagnetic storm: the positive storm effect and the negative storm effect.

4.2.5.1: Positive Effects

Although they are typically less common and significant than the negative impacts, space weather events can have some surprisingly beneficial benefits as well. Compared to the negative consequences, these favorable ones are less frequent. The Northern and Southern Lights, or auroras, and improvements to short-wave radio waves, which enable long-distance communication, are a couple of these beneficial events.

4.2.5.2: Negative Effects

Most consequences of space weather are bad and can interfere with a variety of human endeavors and systems. Disruption of electrical infrastructure, communication failures, damage to satellites, and health-related consequences are the main negative outcomes.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1: CONCLUSION

The only visible influence was on the daily pattern of DOP since the overall DOP of the severe space weather event (geomagnetic storm) did not rise above that of the diurnal rhythm. Since the geomagnetic storm fluctuation had little effect at the data collection point, the only conclusion is that there was a tiny geomagnetic storm that did not significantly alter the DOP. However, in order to advance GPS technology and boost location accuracy on Earth, as well as for aircraft operating in atmospheric conditions and integrating with space station communication systems, better technologies must be used. This has potential to change the global landscape of these position determining system like, GPS, GLONASS, Galileo, Beidou and the regional navigation satellite systems.

5.2: RECOMMENDATION

The above research has led me to recommend the following:

There is need to using multi-systems analysis of the GNSS constellations to see if specific storms are more or less susceptible to storm effects.

Use Differential GNSS technique to explore the effectiveness of DGPS techniques in mitigating storm-induced errors, especially for applications requiring high precision.

Public awareness. The public should be informed of geomagnetic storm events and limitations of GNSS during the geomagnetic storms, especially for users critical to infrastructure and safety. This should also include developing standardized protocols for reporting and analyzing GNSS data during geomagnetic storm days to enable early preparation.

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