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A Study on the Statistical Analysis of the Geomagnetic Storm of January 2021 and its Effect on the Ionosphere.

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Abstract

The twenty fifth solar cycle is in progress and is it expected in peak in 2025. More and more geomagnetic storms will be expected in the coming period. During a geomagnetic storm event a lot of energy is deposited in the magnetosphere and eventually in the ionosphere. In this paper we present the results of a minor geomagnetic storm that occurred on January 25, 2021. The solar wind data and geomagnetic data for the storm are studied. Significant changes in the solar and geomagnetic parameters were observed in association with the storm. All the parameters are statistically analysed to extract the storm time behaviour and also study the process of ionospheric magnetosphere coupling during the storm. For this we have selected taken the average of ten quiet days and statistical comparison with the disturbed days has been done.

***Key word:-** Geomagnetic Storm, Kp Index, ap Index, Proton Density, Wind Speed.*

Introduction

In his 1600 A.D. work De Magnete, William Gilbert postulated that Earth functions as a powerful magnet (Gilbert 1600). As a result, geomagnetism emerged as a promising scientific field for enhancing ship navigation, but it had not received much attention at that time. The magnetic field declination chart, initially created by Edmund Halley in the early 1700s, is unmatched in its accuracy and usefulness. We credit Alexander von Humboldt with discovering the magnetic storm phenomenon. In May 1806, he embarked on a journey and diligently recorded the local magnetic declination in Berlin every half hour from midnight to dawn until June 1807. On the evening of December 21, 1806, the aurora borealis, often known as the northern lights, manifested in the sky. Von Humboldt saw six hours of strong magnetic deflections. He saw that the aurora and magnetic disturbances ceased to exist when the sun rose. Based on these observations, Von Humboldt deduced a correlation between the magnetic disturbances on Earth and the auroras in the Arctic. In 1808, von Humboldt dubbed the phenomenon a "Magnetische Ungewitter," which translates to a magnetic storm. After a significant period of time, the worldwide network of magnetic observatories, which von Humboldt had contributed to establishing, confirmed the occurrence of these "magnetic storms" throughout the entire planet. In 1997, Schröder did research on geological storms. Geomagnetic storms are intense disruptions of the magnetosphere that result in a rapid transfer of solar wind energy into Earth's space environment. The fluctuations in the solar wind primarily cause these storms, significantly influencing the currents, plasmas, and fields of the Earth's magnetosphere. Geomagnetic storms are caused by long periods of solar wind activity that last several hours. The dayside of the magnetosphere experiences a southward orientation of the solar wind's magnetic field, which differs from Earth's magnetic field. These conditions facilitate the conversion of solar wind energy into Earth's magnetosphere. Solar coronal mass ejections (CMEs), in which solar plasma weighing around one billion tons and including an imbedded magnetic field reaches Earth, are associated with the most potent tempests that form under these circumstances. Researchers have documented certain exceptionally intense storms that arrive within just 18 hours, despite coronal mass ejections (CMEs) typically taking several days to reach Earth. Solar wind disturbances, such as high-speed solar wind streams, can trigger geomagnetic storms (HSS). High-speed streams (HSSs) collide with the slower solar wind in front of them to form co-rotating interaction regions (CIRs). Geomagnetic storms, although less severe than CME storms, have the potential to transfer a greater amount of energy into the Earth's magnetosphere over extended durations. These storms are frequently linked to the Earth by location.

In addition, storms induce modifications in the radiation belts, ionosphere, and magnetosphere, while also generating heating in the ionosphere and the higher region of the atmosphere called the thermosphere. A ring of westward current creates magnetic disturbances on Earth as it circles the planet in space. Traditionally, we have substituted this current with the DST index to quantify the intensity of geomagnetic storms. Furthermore, the magnetosphere generates field-aligned currents that connect to powerful currents in the auroral ionosphere. These currents closely follow the path of the magnetic field. Auroral electrojets, often referred to as auroral currents, cause significant magnetic disturbances. Kp is the index used to quantify the disruption in Earth's magnetic field caused by the combined effect of various electric currents and the resulting magnetic deviations. The Geomagnetic Storm (G-Scale) is one of the three NOAA Space Weather Scales. This specific index determines the space weather that has the potential to disrupt Earth's systems. Storm-related energetic particles and ionosphere currents contribute to an increase in heat in the upper atmosphere, resulting in a denser and more uneven distribution. This, in turn, leads to an increase in drag on satellites in low Earth orbit. In addition, localized heating can cause large changes in the density of the ionosphere, which can change radio signals' paths and possibly make GPS location data less accurate. Storms can be awe-inspiring when they exhibit auroras, but they can also interfere with navigational systems such as GNSS and cause dangerous geomagnetic-induced currents (GICs) in pipelines and the electrical grid.

Used parameters:

In order to aid in our investigation of the nature of geomagnetic storms, we have selected these parameters for the statistical analysis.

- **Kp Index**
- **ap Index**
- **The Interplanetary Magnetic Field IMF (Bz)**
- **Proton Density**
- **Temperature**
- **Wind Speed**

K- index : The K index is a quasi-logarithmic measure of the range of geomagnetic disturbance at a geomagnetic observatory in a three-hourly UT interval (00–03, 03–06,..., 21–24) that ranges in increments of 1 from 0 to 9.K-variation is another term for geomagnetic disturbance. K-variation, also known as geomagnetic activity or disturbance, was originally thought to be the result of "solar particle radiation" and predates the discovery of the solar wind. The following definition is applied by Siebert (1971) and Siebert and Meyer (1996): "K-variations are all irregular disturbances of the geomagnetic field caused within the 3 h interval concerned by solar particle radiation."

Kp is also utilized for data selection in geomagnetic field modelling and other geomagnetic investigations, where it is frequently employed in conjunction with other indices. Additionally, the monthly International Quiet and Disturbed Days—a commodity we obtain from Kp—are crucial for data selection.Since its launch more than 70 years ago, Kp has established itself as a significant and trustworthy index. While the Kp-like am index incorporates this information, Kp does not reflect the universal time (UT) dependent variation of geomagnetic disturbance. ACE and DSCOVR satellite measurements of solar wind parameters at L1 or solar wind parameters plus solar X-ray flux are typically the basis for predictions of Kp.

Kp-Index: - The Kp-index is the global geomagnetic activity index that is based on 3-hour measurements from ground-based magnetometers around the world.

- The K-index is a scale which quantifies disturbances in the horizontal component of Earth's magnetic field with an integer in the range 0–9.
- 1 -- being calm
- 5 or more indicating -- A geomagnetic storm.

This planetary index is designed to measure solar particle radiation by its magnetic effects.

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This defines the strength of the Northern Light Activity for a certain time

ap-Index: - The 3-hourly a**p** (equivalent range) index is derived from the Kp index as follows

Kp = 0o 0+ 1- 1o 1+ 2- 2o 2+ 3- 3o 3+ 4- 4o 4+

ap = 0 2 3 4 5 6 7 9 12 15 18 22 27 32

Kp = 5- 5o 5+ 6- 6o 6+ 7- 7o 7+ 8- 8o 8+ 9- 9o

ap = 39 48 56 67 80 94 111 132 154 179 207 236 300 400

Each individual, three-hourly Kp index is converted to an equivalent amplitude three-hourly a_{kp} index.

The Interplanetary Magnetic Field IMF (Bz): - Solar wind–Earth magnetosphere interactions are strongly affected by the interplanetary magnetic field (IMF). Three components along distinct axes make up the interplanetary magnetic field, which is a vector variable: Bx, By, and Bz. The ecliptic is parallel to two of these components, Bx and by. When it comes to auroral activity and similar phenomena, the Bx and By components don't matter. Solar wind oscillations and other disturbances produce the orthogonal to the ecliptic Bz value. Solar wind magnetic field strengths are typically only a few nano-Teslas. But if it goes over 10 nT, geomagnetic activity may be on the horizon. The northward-oriented part of the solar wind's magnetic field is represented by the Bz parameter.

Proton Density:-To find the density of the solar wind in grams/cc we have to do a two-step calculation. The wind usually has a particle density of about 5 particles/cc,Since these particles are typically protons (each with a mass of 1.6 x 10-24 gm),The density is then 5 x (1.6 x 10-24 gm)/cc so that

D = 1.28 x 10-23 gm/cc.

Temperature: - Solar flares possess the capacity to release substantial amounts of energy into the Earth's atmosphere. However, the majority of this energy is either absorbed by the planet's magnetic field or dissipates as heat from the thermosphere. The temperature within a solar flare can surpass 100 million Kelvin, equivalent to 18 million Fahrenheit. The temperature at the core of the Sun reaches a scorching 27 million degrees Fahrenheit, making it a point of reference.

The lower atmospheric layers already receive an insignificant amount of heat from visible and ultraviolet light, therefore the amount of heat that radiates to them from a solar flare is tiny in comparison to the usual heat exchange.

Solar Wind Speed: - The ejected plasma travels through interplanetary space at speeds between 10 and 2,000 km/s, or about 6 and 1,200 miles/s, and reaches Earth in about 21 hours. Coronal mass ejections and solar flares are common outcomes of solar radiation storms, which happen when large-scale magnetic eruptions accelerate charged particles in the solar environment to extremely high speeds. Protons, with a speed that is just a fraction of a light speed, are the most important subatomic particles. The sun constantly emits plasma, mainly consisting of protons and electrons, known as the solar wind. Different regions of the sun produce solar wind, which can be quite strong or very weak. Coronal holes produce solar wind that travels at speeds of 500 to 800 kilometers per second. Because the sun's north and south poles have large coronal holes, high latitudes experience fast solar wind. The slow-speed wind, with a velocity of about 400 kilometers per second, is the most common type of solar wind within the equatorial plane, where the Earth and other planets spin. When winds reach high speeds, they trigger geomagnetic storms; when winds are low, calm space weather is the result.

Data Analysis

In order to analyze the data, we first determine which days in January are quit and disturbed. We then record the values of all the parameters for these days across several sources. Subsequently, we examined the values of these parameters and obtained the anticipated outcome, taking into account our hypothesis.

International Quiet Days (IQD's) are the days where the geomagnetic variations are a minimum in each month.

International Disturbed Days (IDD's) are 5 days in each month where the geomagnetic variations are maximum.

Identify **10 quiet days** of months of January 2021 and plot the above data

Identify **5 disturbed days** of months of January 2021 and plot the above data

The classification of days is relative only to the month of calculation.

QuietDays:-
02.01.2021,03.01.2021,04.01.2021,08.01.2021,09.01.2021,14.01.2021,

17.01.2021,21.01.2021,30.01.2021,31.01.2021

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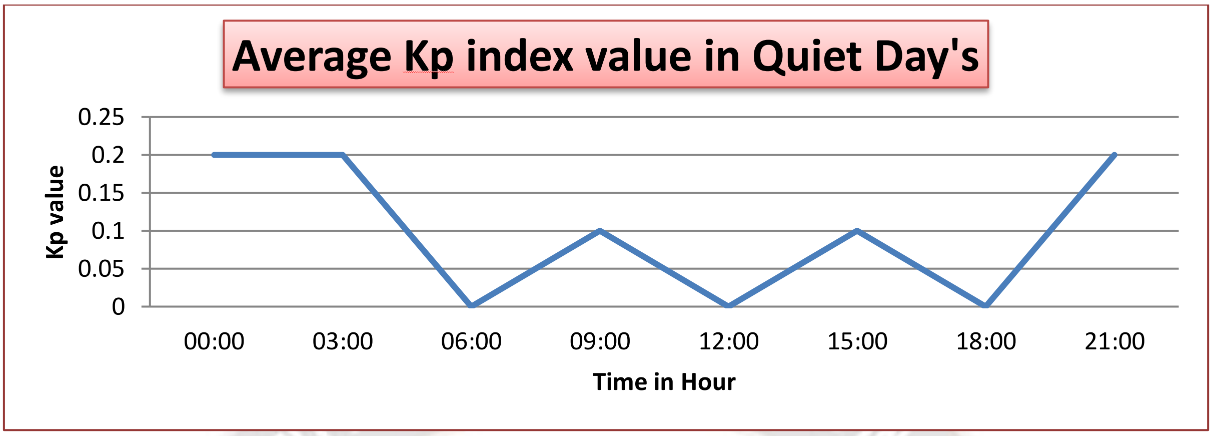
DisturbedDays:- **Kp index value Analysis**
06.01.2021,11.01.2021,25.01.2021,26.01.2021,27.01.2021

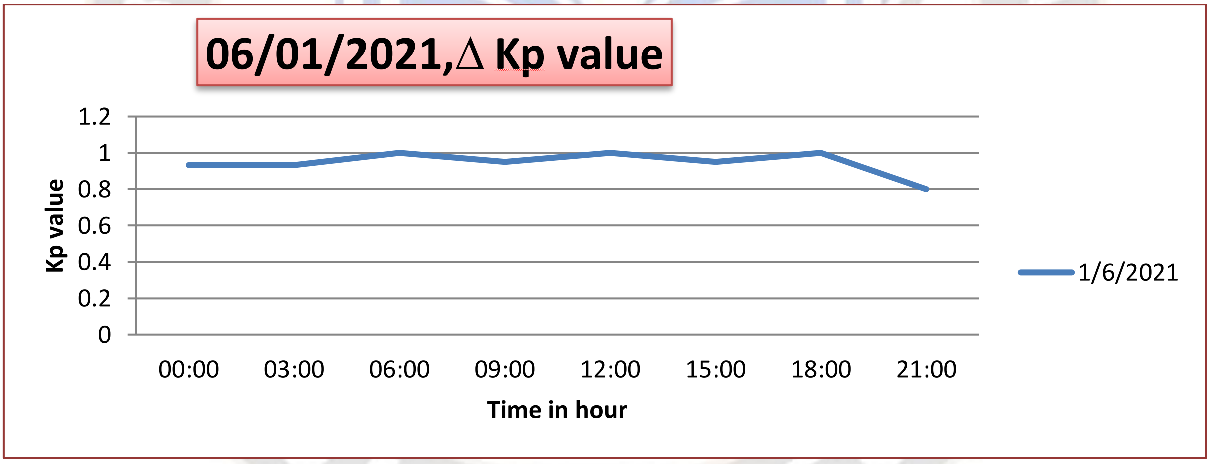


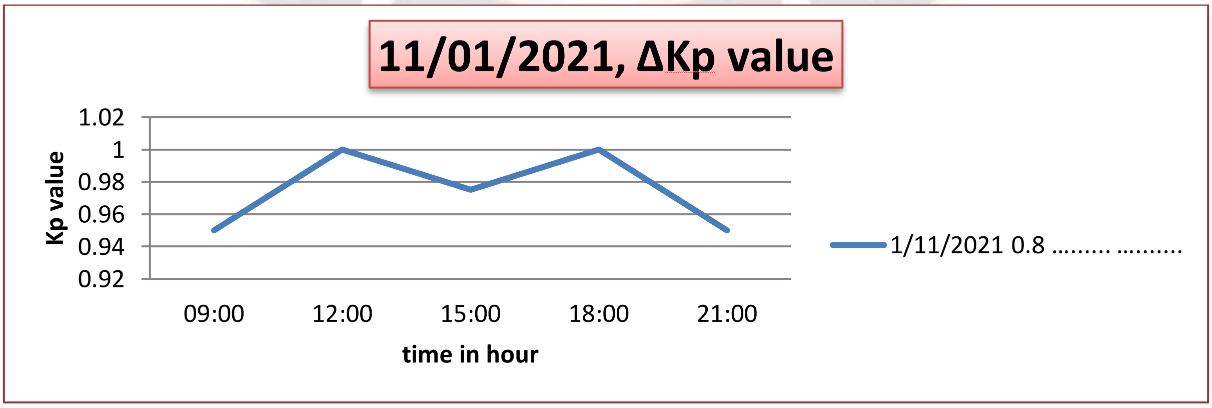
ΔKp= Kp(D)-Kp(Q)/Kp(D)

Where

Kp(D)=Kp index value in disturbed day's

Kp(Q)= Kp index value in quiet day's





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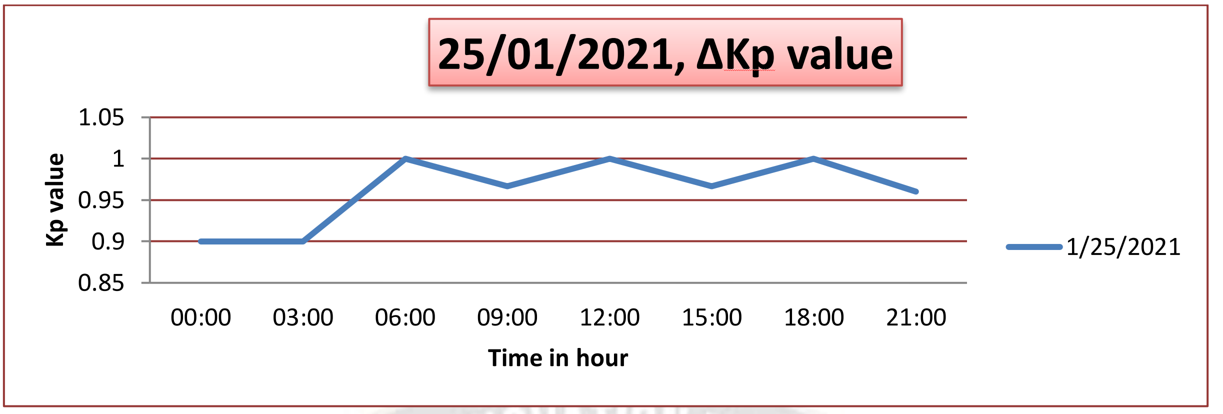
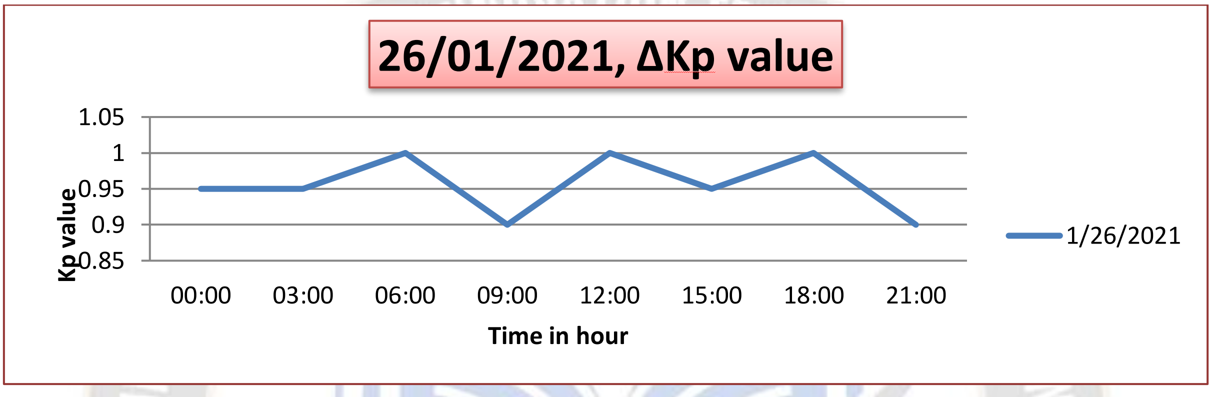
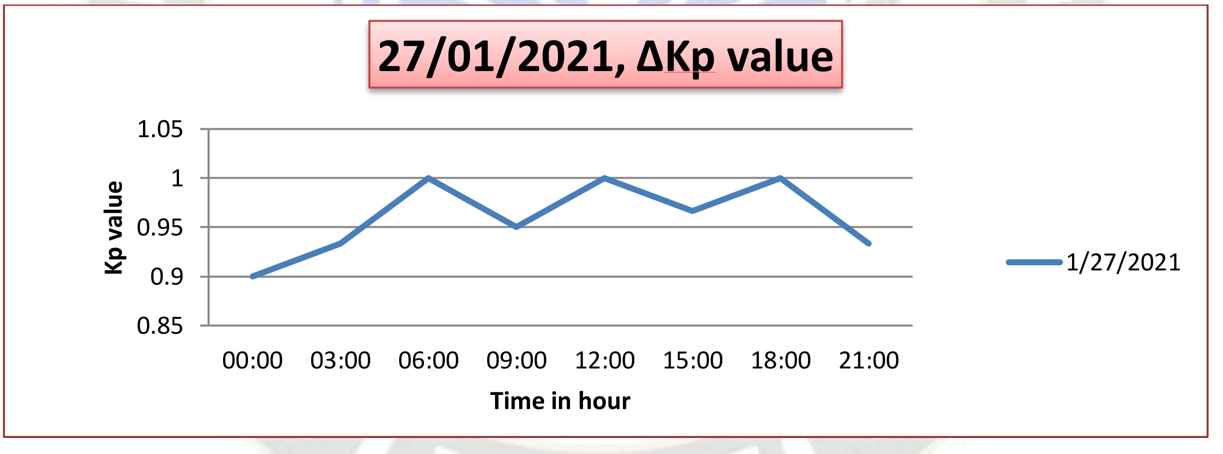
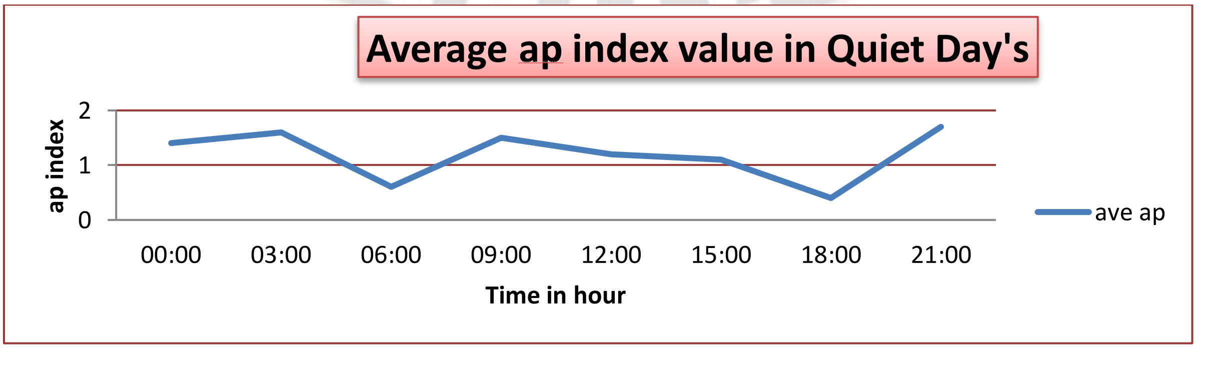






ap index value Analysis



Δap= ap(D)-ap(Q)/ap(D)

Where

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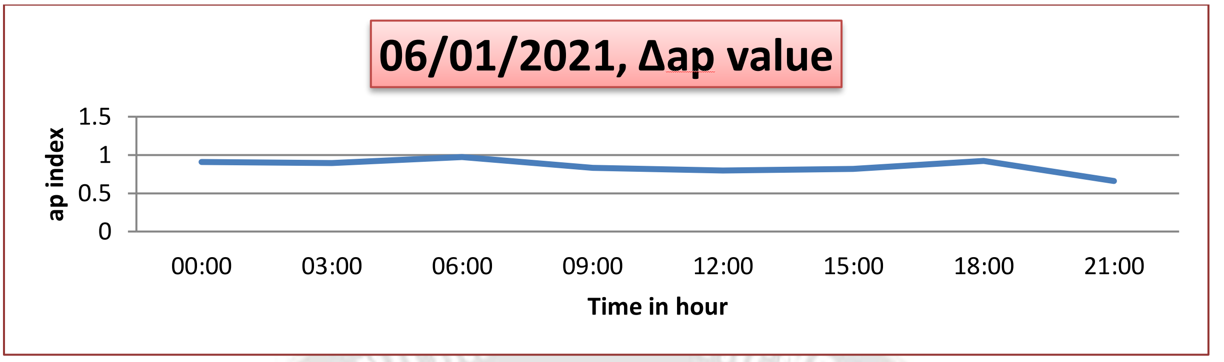
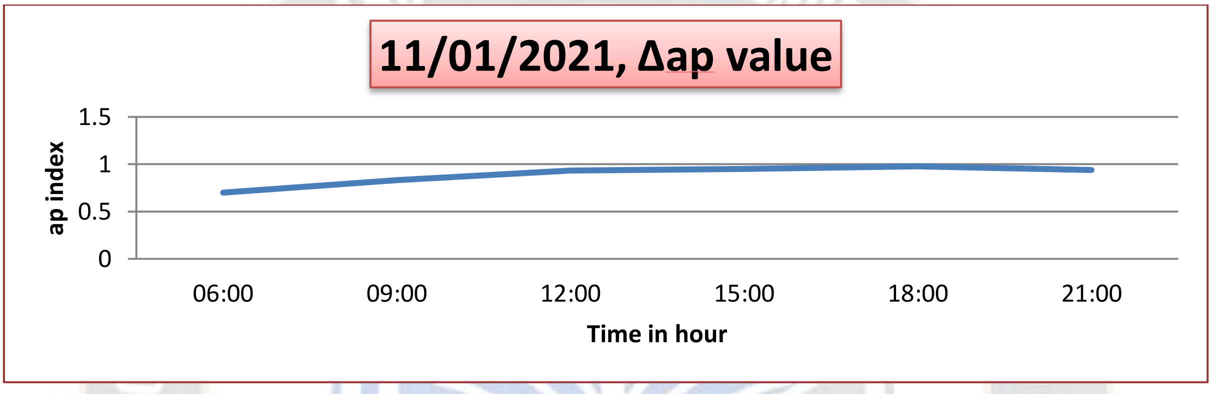
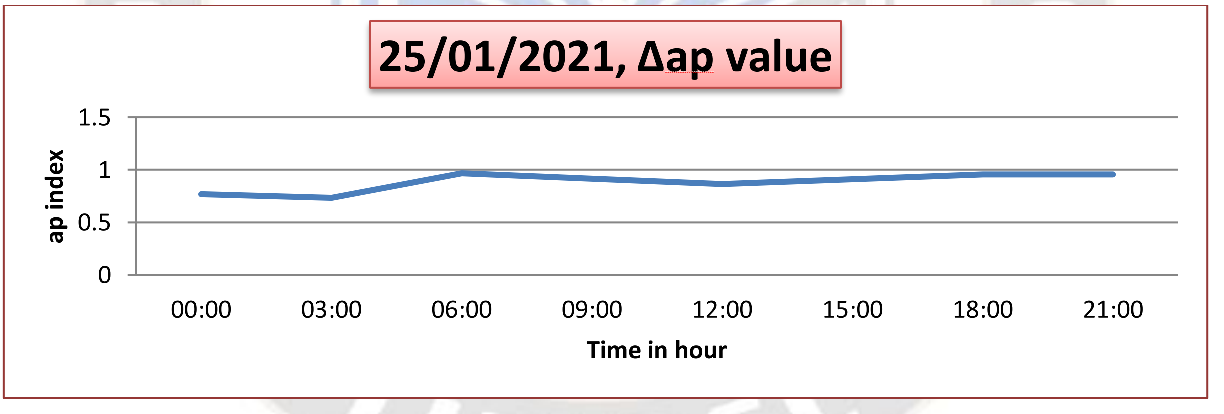
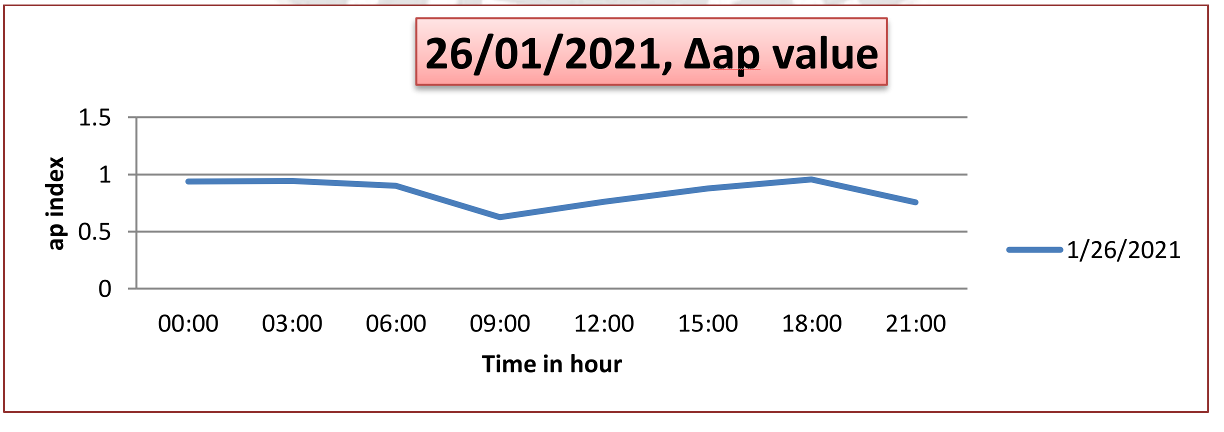
ap(D)=ap index value in disturbed day's

ap(Q)= ap index value in quiet day's









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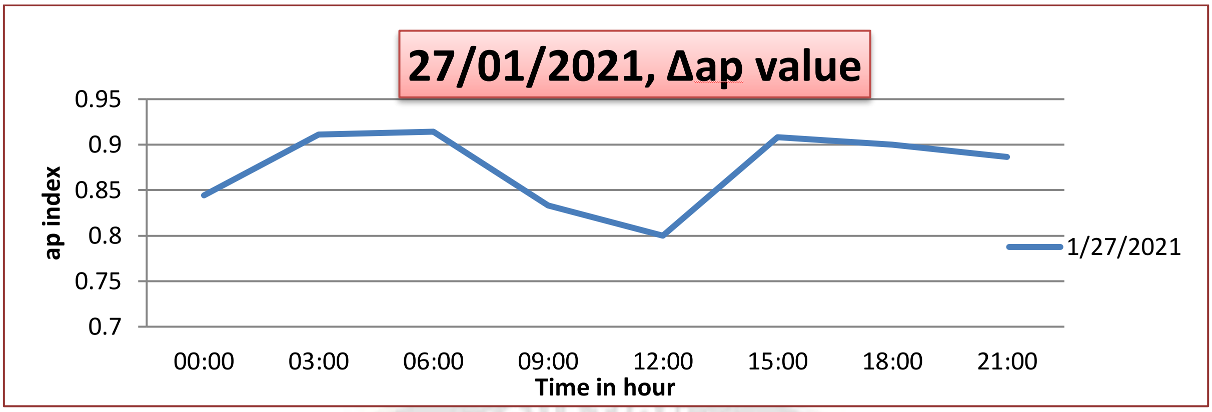
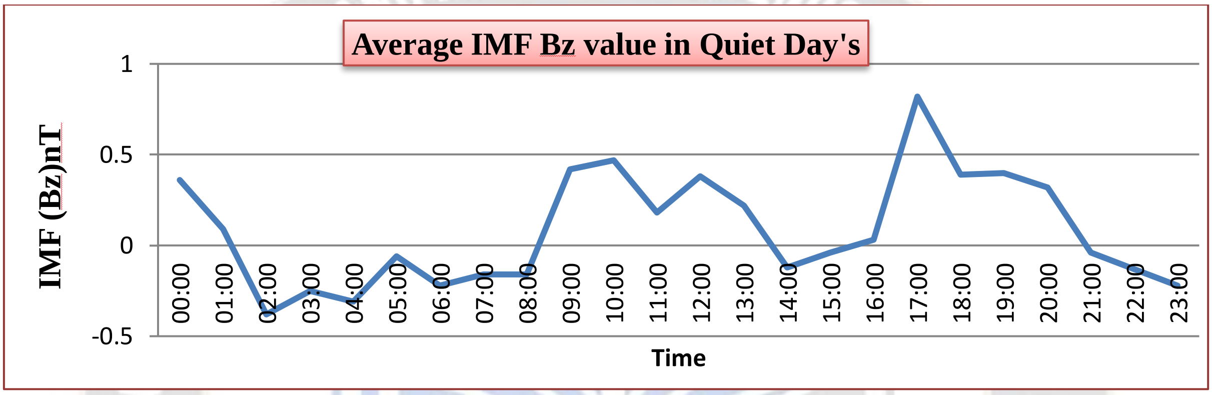
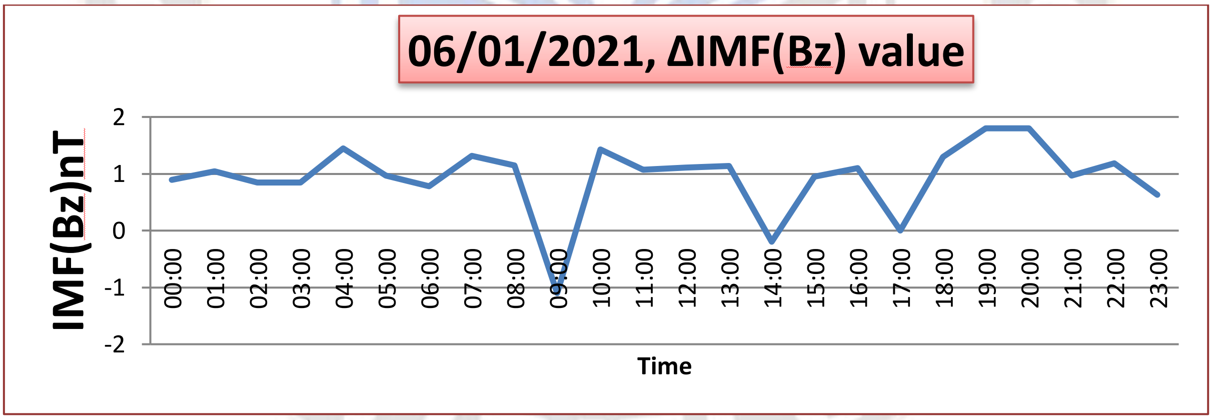
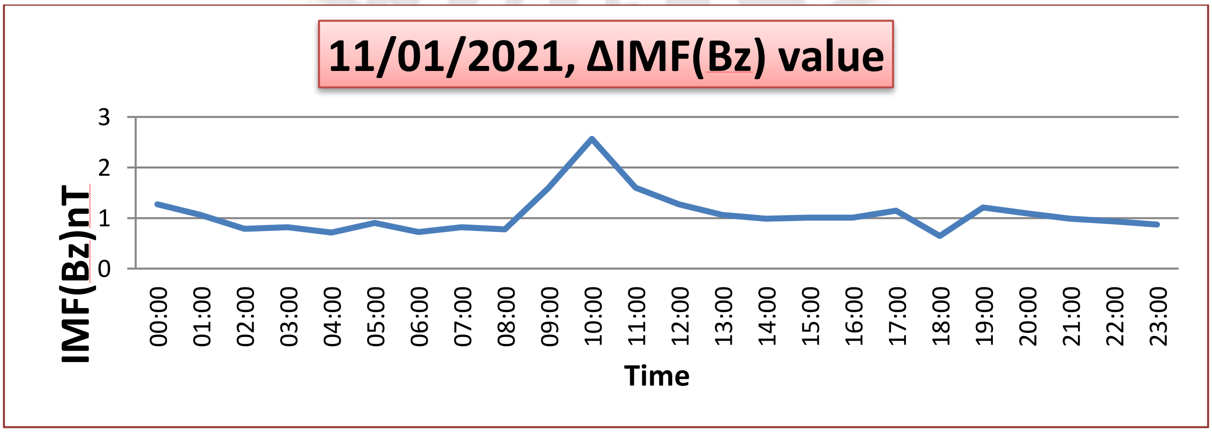


IMF (Bz) value Analysis







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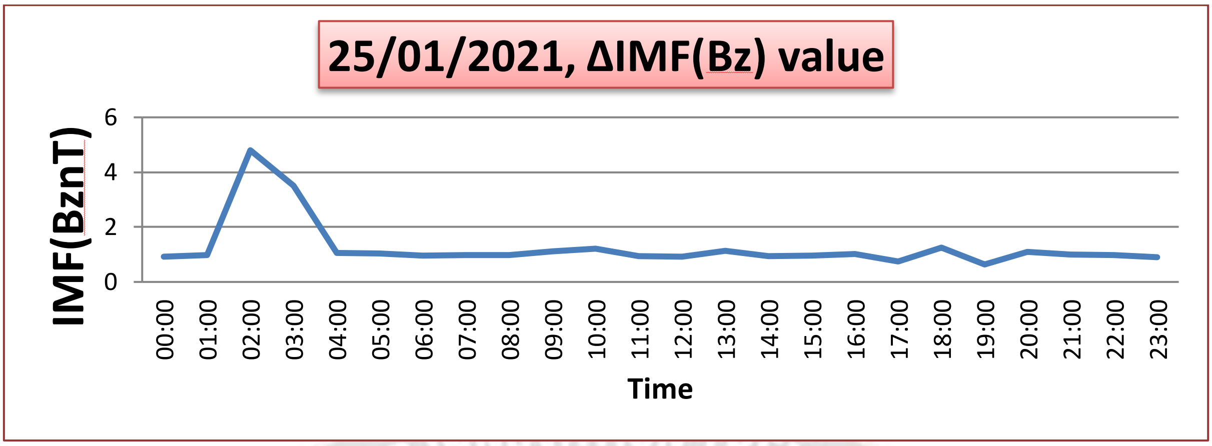
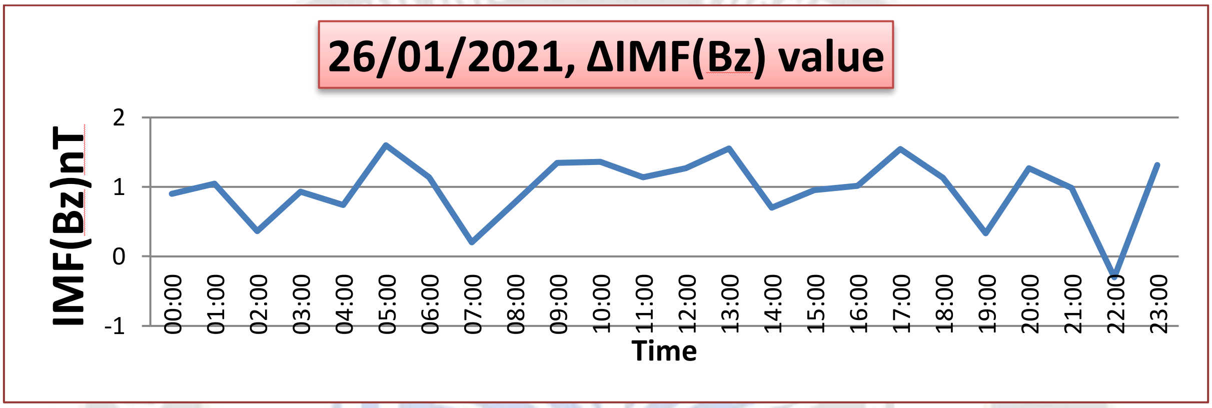
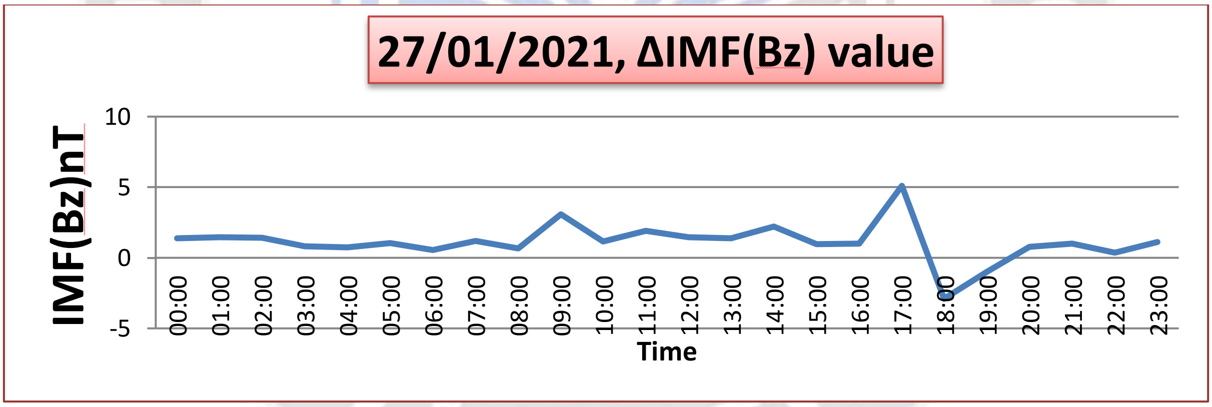
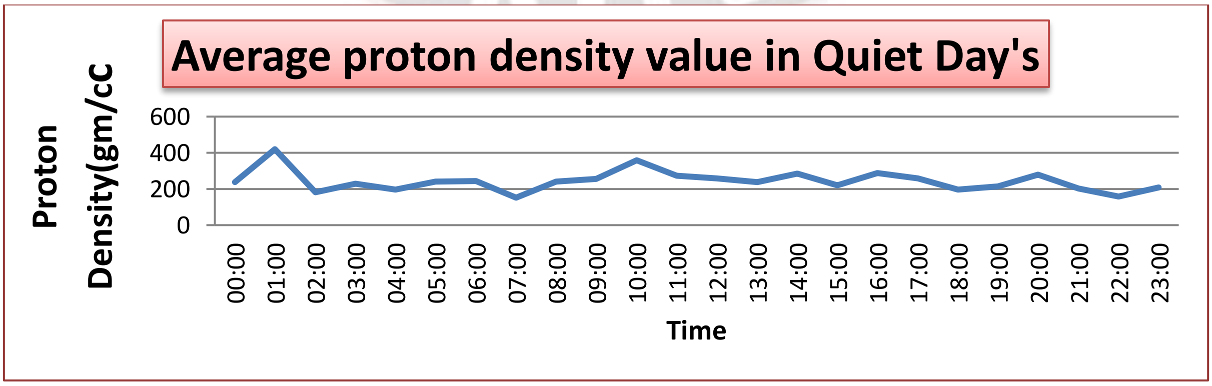






Proton Density value Analysis



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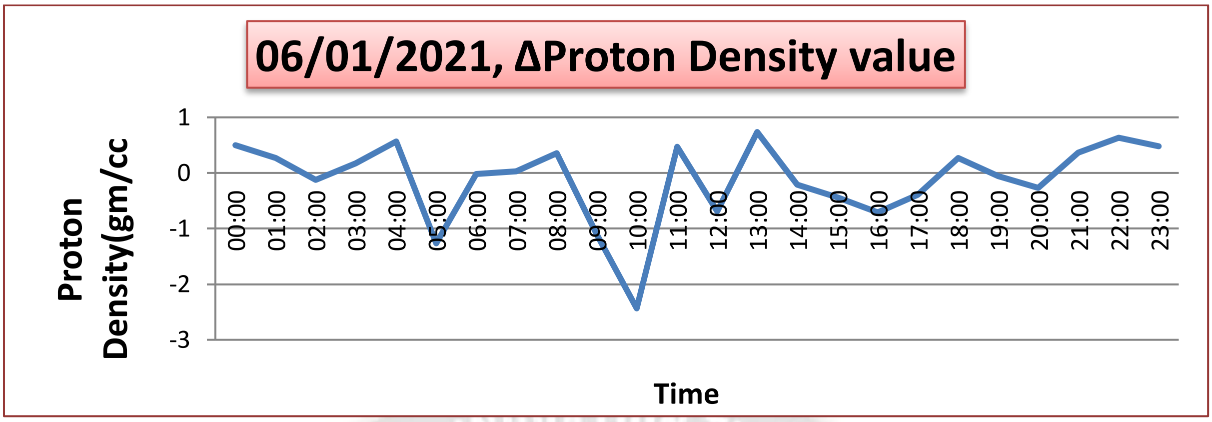

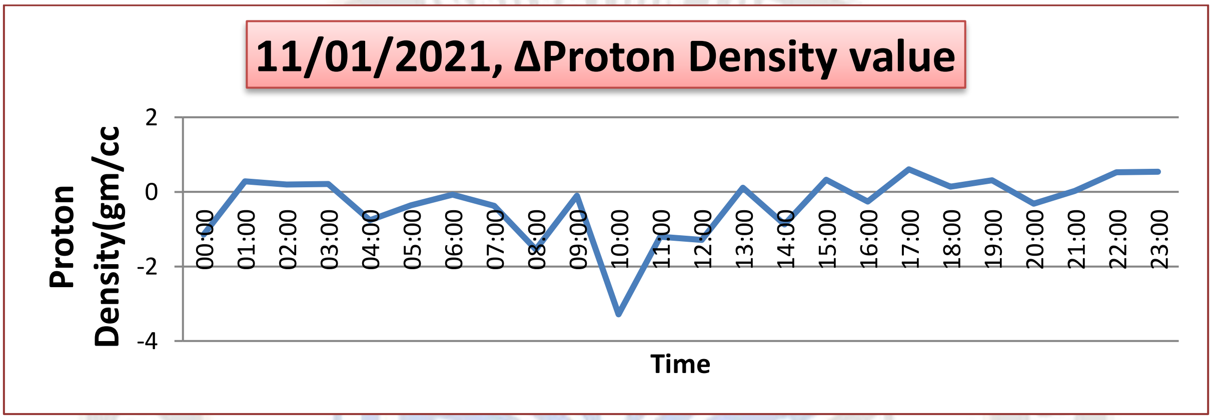

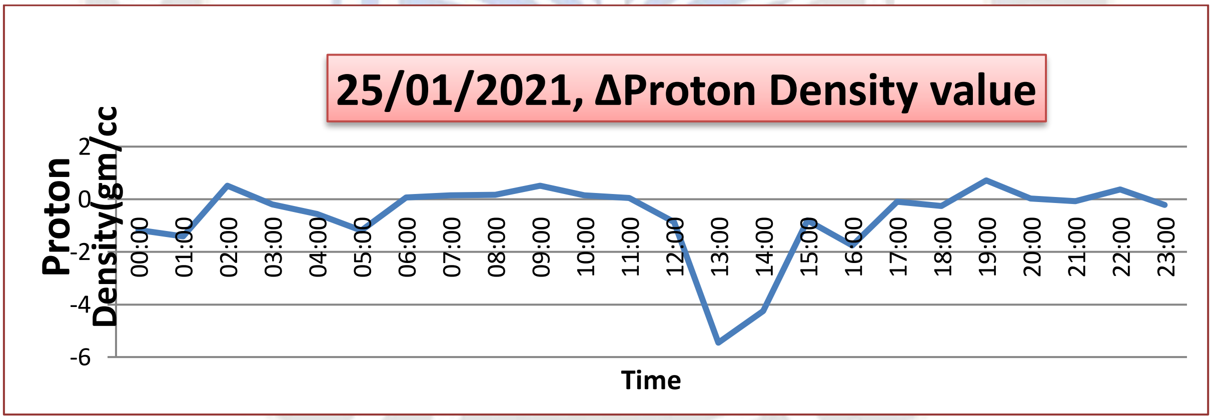

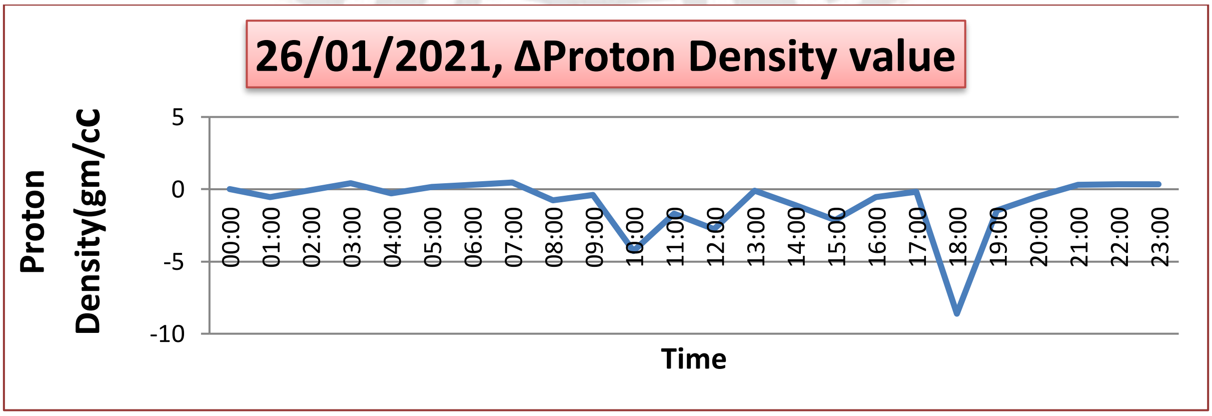

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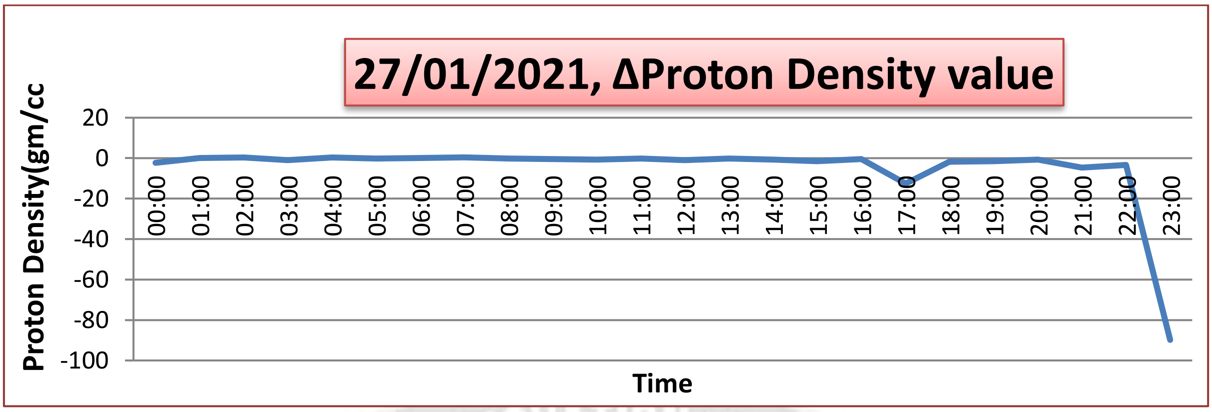
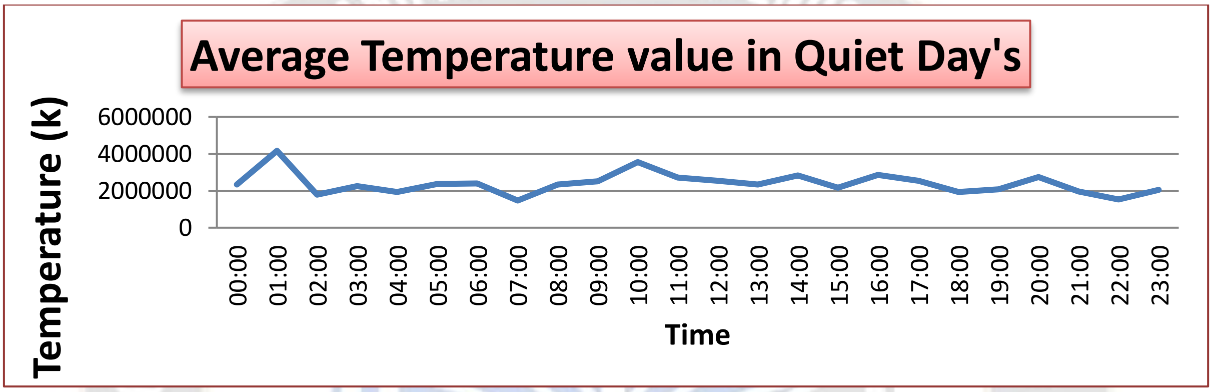
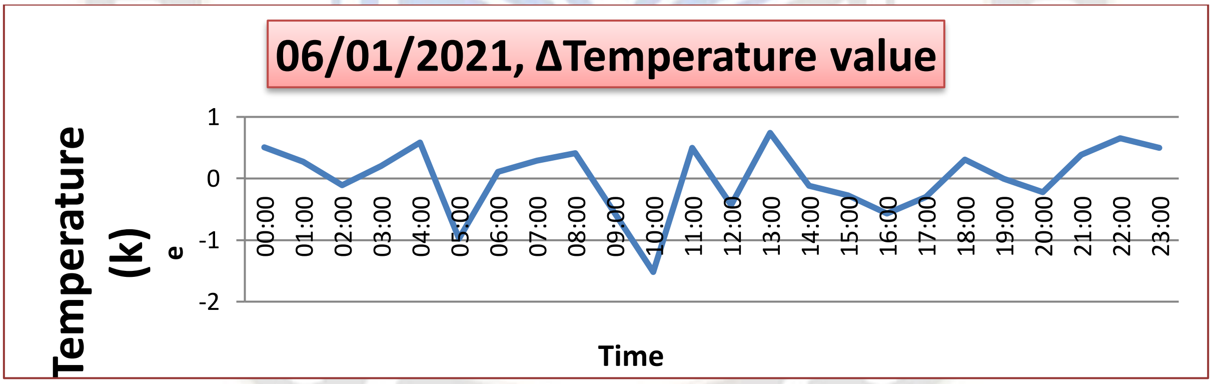
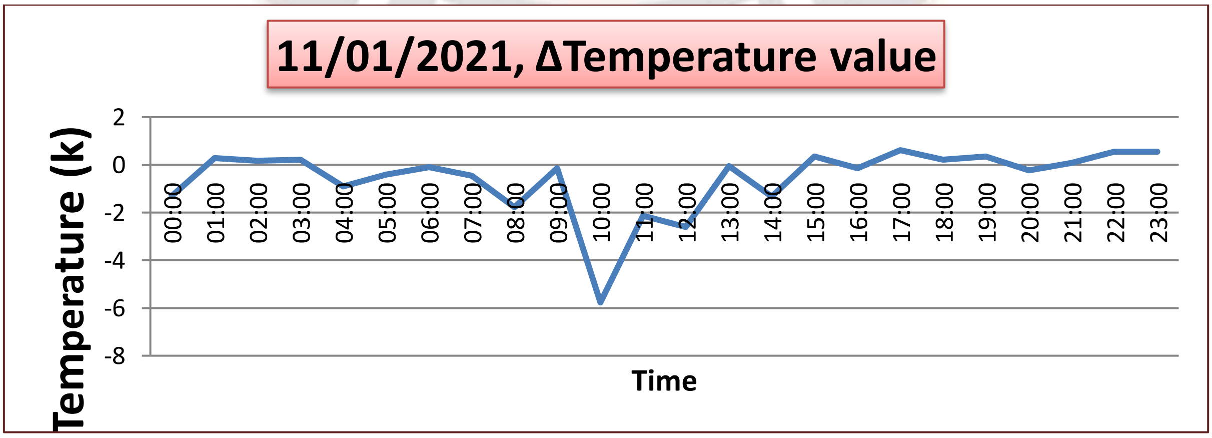


Temperature value Analysis







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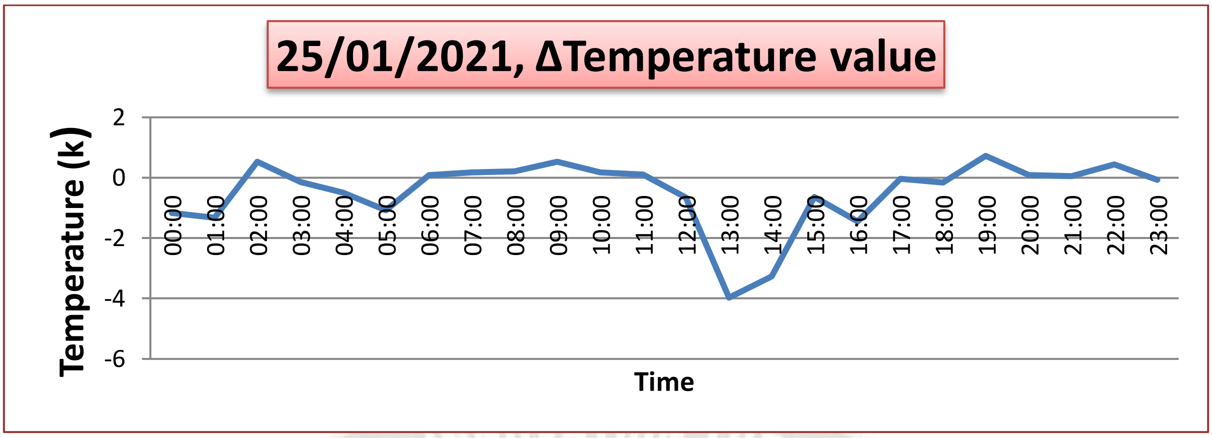
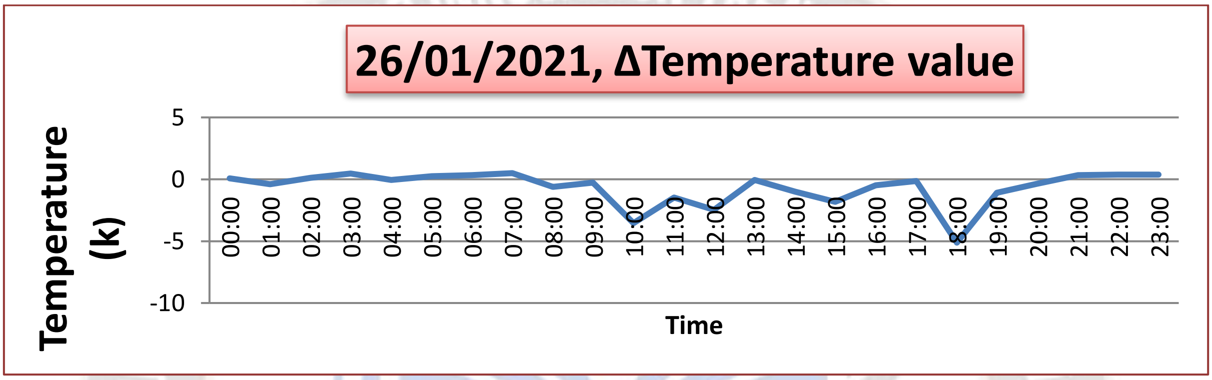
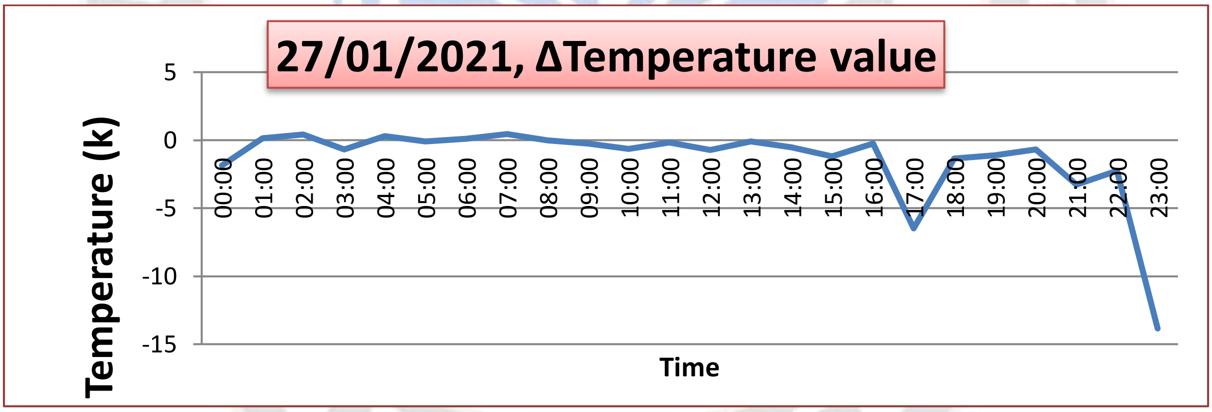
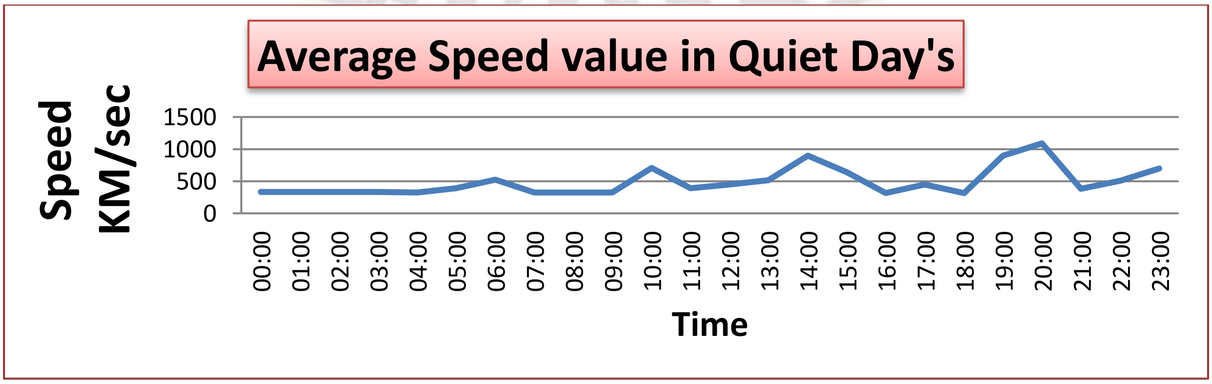






Speed value Analysis



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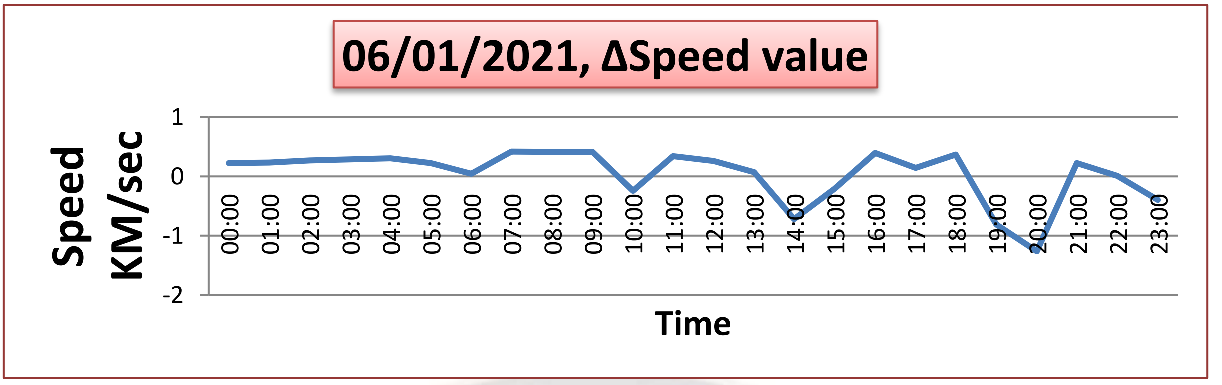

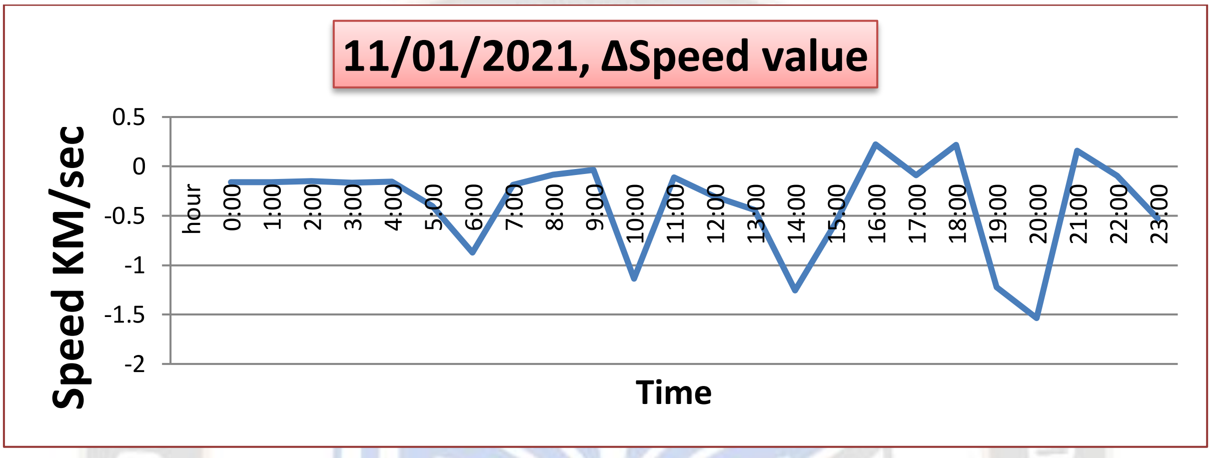

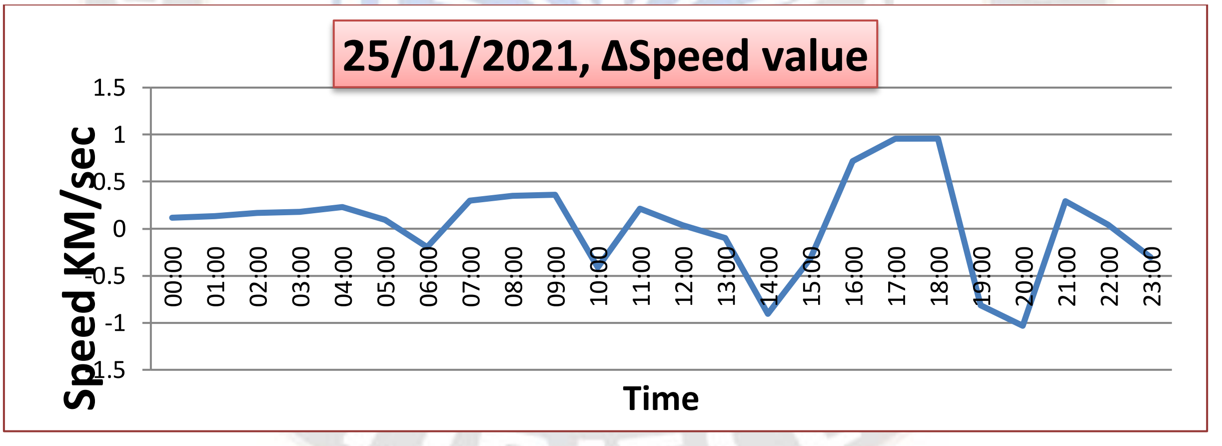

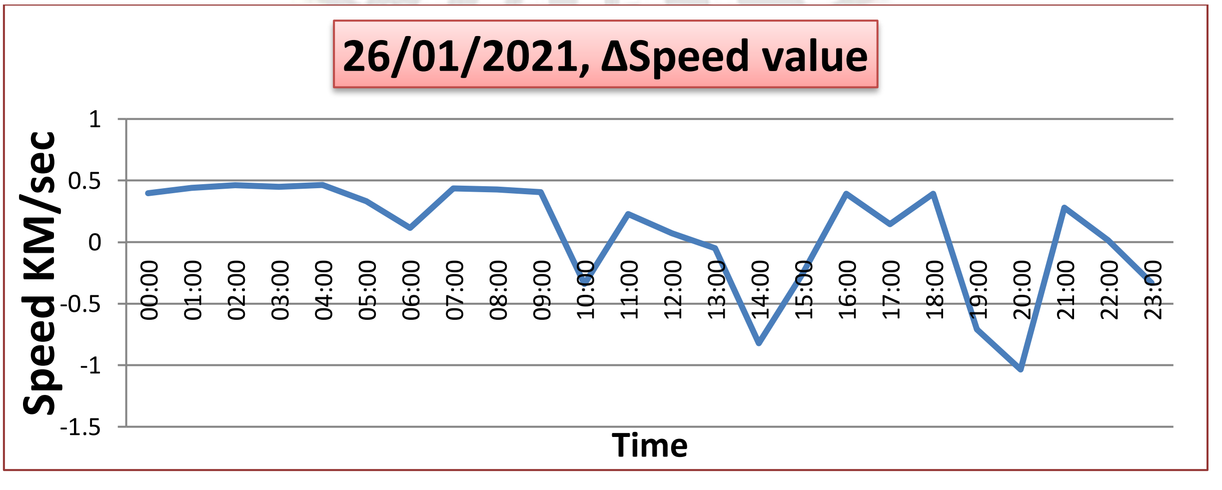

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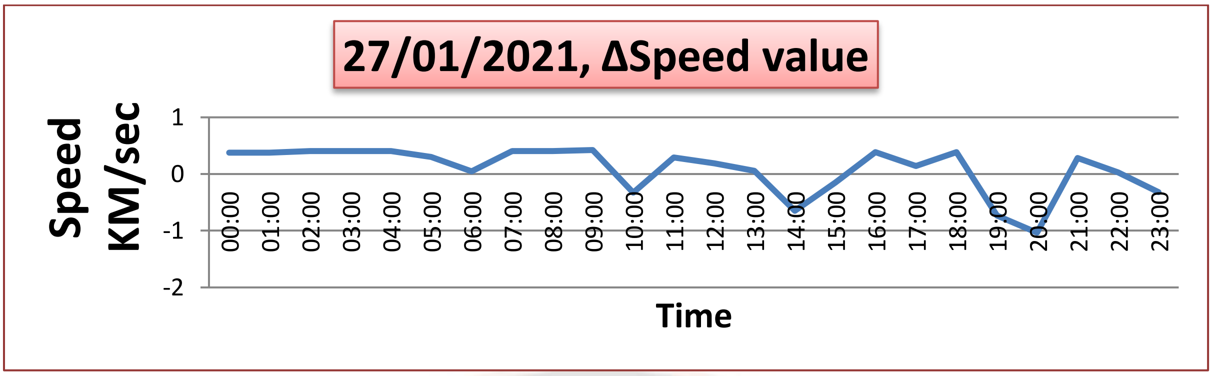

Result And Discussion

We present the results of a minor geomagnetic storm that occurred on January 25, 2021. For this we have selected taken the average of ten quiet days and statistical comparison with the disturbed days has been done.

The result from our analysis of different parameters are can understand by the table below.

S.No	**Parameters**	**Average of avg .value of parameter's during quiet day's**	**Difference in parameters Δ in %** **During disturbed day's 6,11,25,26,27 January 2021, respectively**
1	Kp	0.1	94%,94%,96%,95%,96%
2	ap	1.18	85%,85%,88%,84%,87%
3	IMF Bz(nT)	0.08nT	86%,107%,125%,97%,112%
4	Proton Density (gm/cc)	243.13 gm/cc	12%,34%64%,96%,508%
5	Temperature(K)	23 million K	1%,58%,47%,67%,142%
6	Speed(Km/s)	492 Km/s	4%,3%,4%,7%,8%

There is no cause for alarm regarding the temperature (23 million K) or the proton density (243.13 gm/cc), since the table indicates that the average values of Kp (0.1) and ap (1.18) during quiet days suggest a peaceful geomagnetic storm. Additionally, the IMF Bz value of 0.08 nT is below the 10 nT threshold, making it acceptable. During the geomagnetic storm, the velocity peaked at 492 kilometers per second. Typically, the solar wind moves at a speed of approximately 400 km/s. However, upon calculating the percentage difference between these traits, it becomes evident that they have undergone substantial changes. Amidst the turbulent period, these values evidently experienced a specific increment—96% in Kp and 88%–87% in AP. The IMF BZ value exceeded 100%, specifically reaching 125% on January 25th. On January 26, the temperature increased by 142%, and the proton density increased by 95%. The speed of the geomagnetic storm has remained relatively constant. These data suggest that the geomagnetic storm is intensified

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on days when it is disrupted and that it has an impact on the Earth's ionosphere.

The ionosphere is a region of the Earth's upper atmosphere that spans from 80 to around 600 kilometers in distance. Under these circumstances, solar energy, such as x-rays and extreme ultraviolet (EUV) radiation, ionizes atoms and molecules, resulting in the formation of an electron layer. The ionosphere plays an important role in reflecting and altering communication and navigational radio waves. Energetic charged particles and cosmic rays are additional sources of ionizing radiation that contribute to the ionosphere. Solar X-ray and extreme ultraviolet (EUV) radiation influence atmospheric atoms and molecules. The energy level (photon flux) at extreme ultraviolet (EUV) and x-ray wavelengths varies by approximately a factor of ten throughout the course of the eleven-year solar cycle. This causes fluctuations in the ionosphere's density. This causes fluctuations in the ionosphere's density. Geomagnetic storms, changes in the solar wind, flares, and other solar phenomena can alter the ionosphere's charge. The primary cause of ionization is solar irradiance, resulting in significantly lower levels of ionization on the night side of the Earth and the pole facing away from the sun compared to the day side and the pole facing towards the sun. However, this disparity can change considerably over different seasons.

Conclusion

The analysis of the minor geomagnetic storm that occurred on January 25, 2021, reveals significant variations in several key parameters when compared to quiet days. By examining the data collected during this period, we can draw several important conclusions regarding the impact of geomagnetic disturbances on the Earth's ionosphere and related atmospheric conditions.

1. **Kp and ap Indices**:
   - The Kp index, which measures the global geomagnetic activity, showed a substantial increase of up to 96% on disturbed days. This indicates heightened geomagnetic activity during the storm.
   - The ap index, which quantifies the overall planetary magnetic activity, similarly exhibited increases of 85% to 88%, further confirming the presence of significant geomagnetic disturbances.
2. **Interplanetary Magnetic Field (IMF) Bz**:
   - The IMF Bz component showed considerable variations, with increases reaching up to 125% on January 25th. Despite these fluctuations, the values remained below the critical 10 nT threshold, suggesting that while the storm was significant, it did not reach extreme levels.
3. **Proton Density and Temperature**:
   - Proton density experienced dramatic increases, particularly notable was the 508% rise on January 27th. Such a substantial change indicates a considerable influx of charged particles into the Earth's magnetosphere.
   - Temperature measurements also reflected significant increases, with a peak rise of 142% on January 26th. This suggests elevated energy levels within the Earth's atmospheric layers during the storm.
4. **Solar Wind Speed**:
   - The solar wind speed remained relatively stable, with only slight variations from 3% to 8%. The peak speed recorded was 492 km/s, which is above the average solar wind speed of approximately 400 km/s, but not excessively so.

Impact on the Ionosphere:

The ionosphere, spanning from 80 to around 600 kilometers above the Earth, plays a crucial role in communication and navigation by reflecting and altering radio waves. The data indicates that during the geomagnetic storm, the ionosphere was significantly affected:

- **Ionization Levels**: Increased solar energy, particularly in the form of X-rays and extreme ultraviolet (EUV) radiation, leads to higher levels of ionization. The data suggests that the geomagnetic storm caused fluctuations in the ionosphere's density, primarily due to increased ionizing radiation.
- **Communication and Navigation**: Changes in the ionosphere's charge density during geomagnetic storms can disrupt radio wave propagation, potentially affecting communication and navigation systems.
- **Seasonal and Diurnal Variations**: The ionosphere's response to solar irradiance varies between day and night and across different seasons. During the storm, the increased ionization on the day side and the pole facing the sun would have been more pronounced, highlighting the dynamic nature of the ionosphere.

The geomagnetic storm of January 25, 2021, while classified as minor, demonstrated significant impacts on various atmospheric and geomagnetic parameters. The substantial increases in the Kp and ap indices, proton density, and temperature, along with fluctuations in the IMF Bz component, underscore the storm's influence on the Earth's ionosphere.

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These findings illustrate the critical need for continuous monitoring and analysis of geomagnetic activity, as even minor storms can lead to significant changes in the ionosphere, affecting communication and navigation systems. Understanding these impacts is essential for mitigating the adverse effects of geomagnetic storms on modern technological infrastructure and ensuring the reliability of communication and navigation services.

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