Harla Journals

Harla Journal of Applied Science and Materials

Journal home page: https://journals.ddu.edu.et/index.php/HJASM

Harla journal of Applied Science and Materials

IONOSPHERIC INSTABILITIES AND THEIR EFFECTS ON GROUND-BASED COMMUNICATION SYSTEMS

Belay Sitotaw Goshu[1]

[1]*Department of Physics, College of Natural and Computational Sciences, Dire Dawa University, Dire Dawa, Ethiopia*
Email:belaysitotaw@gmail.com

Abstract

Ionospheric instabilities, triggered by solar and geomagnetic activity, pose significant risks to power grids and signal propagation. This study examines the dynamic interactions between electric grid vulnerabilities, signal degradation, and ionospheric disturbances to identify effective mitigation strategies. Using modeled Total Electron Content (TEC), amplitude fading, signal delays, and polarization shifts, the spatiotemporal behavior of these instabilities was analyzed. Simulations, incorporating solar activity indicators such as sunspot numbers, ionospheric anomalies, and geomagnetic variations, revealed significant TEC fluctuations. TEC values were found to peak near the equator and decline at higher latitudes. These variations were strongly linked to signal degradation, including amplitude fading and propagation delays. Polarization mismatches caused by ionospheric disturbances further reduced signal efficiency. Additionally, geomagnetically induced currents (GICs) from these instabilities posed risks to transformers and grid stability, especially in Polar Regions. The study recommends adaptive signal processing, advanced monitoring systems, and real-time GIC mitigation to enhance grid resilience. It emphasizes the importance of predictive models incorporating solar activity data to protect communication and power systems. By addressing ionospheric instabilities, these measures can improve the reliability of global communication networks and energy infrastructure.

Keywords: ionospheric instabilities, total electron content (TEC), signal propagation, geomagnetically induced currents (GICs), communication resilience

**Corresponding author: Belay Sitotaw Goshu; email: belaysitotaw@gmail.com; Cell phone: +251923694899*

Received: Sep 2023; Received in revised form: November 2023; Accepted: December 2023

1. Introduction

The ionosphere, a significant layer of Earth's upper atmosphere located 60 to 1,000 kilometers above the surface, plays a vital role in supporting technological systems, particularly in communication and electricity. Its high concentration of ions and free electrons facilitates radio wave transmission, making it indispensable for modern infrastructure (Kelley, 2009); (Appleton, 1946). However, this region is susceptible to various instabilities, including Rayleigh-Taylor, Farley-Buneman, gradient drift, Perkins, and equatorial spread F (ESF) instabilities. These phenomena disrupt ionospheric plasma and adversely affect signal propagation (Hysell, 2000; Basu et al., 2012). For instance, plasma depletions associated with ESF, commonly occurring after sunset, scatter radio signals, reducing communication performance (Woodman & La Hoz, 1976).

1.1. Effects on Communication Systems

Ground-based communication systems are greatly impacted by ionospheric disturbances, especially when it comes to high-frequency (HF) and very high-frequency (VHF) broadcasts. Signal fading, multipath propagation, and Faraday rotation—which modifies signal polarization because of the ionosphere's magnetic field are examples of phenomena that lead to signal degradation (Kintner et al. 2007; Goshu, 2024a; Kappenman, (2005). Furthermore, the precision of navigation and positioning systems is compromised by ionospheric abnormalities that produce delays and mistakes in GPS signals (Pi et al., 1997). ESF-related plasma depletions are especially troublesome because they scatter radio waves and worsen transmission quality.

1.2. Effects on Power Grids

Beyond communication, ionospheric instabilities also pose risks to power grids. Geomagnetically induced currents (GICs), driven by ionospheric and magnetospheric disturbances, can penetrate electric grids, leading to transformer saturation, overheating, and increased reactive power losses. In severe cases, these effects can result in widespread blackouts, threatening infrastructure stability (Bolduc, 2002); Goshu, (2024); Robel et al. (2024).

Ground-Based Communication Systems: Ionospheric disturbances can cause significant disruptions to communication systems, especially those that depend on high-frequency (HF) and very high-frequency (VHF) communications. For example, plasma depletions caused by the ESF phenomenon, which usually happens after sunset, scatter radio waves and reduce transmission quality (Hysell, 2000; Kerr, 2005). Faraday rotation alters the polarization of signals, introducing the ionosphere's magnetic field and making signal reception and interpretation more challenging (Kintner et al., 2007). These instabilities cause delays and inaccuracies in GPS signals, which are crucial for navigation and affect positioning systems' accuracy and dependability (Pi et al., 1997).

Geomagnetically induced currents (GICs) can be caused by ionospheric and magnetospheric disturbances, which can also affect electric grid systems. Transformer saturation, overheating, and, in extreme situations, widespread blackouts can result from these currents seeping into power systems (Bolduc, 2002); Goshu, (2024a).

Although the ionospheric behavior has improved, much work remains before these instabilities can be sufficiently reduced to lessen the damage done to essential infrastructure. The accuracy with which current models and prediction approaches can predict ionospheric conditions and the consequent impacts on communication and power networks is frequently limited. Thus, there is an urgent need for a thorough study that combines cutting-edge observational data, complex modeling techniques, and workable mitigation strategies.

This study investigates the mechanisms behind various ionospheric instabilities and their specific impacts on ground-based communication systems. The specific objectives of this study seek to:

- Describe the physical mechanisms and circumstances that give rise to various ionospheric instabilities.
- Analyze the effects of these instabilities on signal propagation, fading, and polarization in communication systems.
- Analyze how ionospheric disturbances affect power grid operations, paying particular attention to GICs and the potential for interruptions they may cause.
- Provide workable solutions to lessen ionospheric instabilities' negative impacts, strengthening the resilience of the power and communication infrastructures.

The significance of this study lies in its potential to address critical challenges in modern communication and power systems by providing a deeper understanding of ionospheric instabilities and their impacts. This research is crucial for several reasons:

Enhancing Communication Reliability Ground-based communication systems, particularly those utilizing high-frequency (HF) and very high-frequency (VHF) signals, are essential for various applications, including aviation, maritime operations, and military communications. Ionospheric instabilities such as Equatorial Spread F (ESF) and Faraday rotation can severely disrupt these signals, leading to communication blackouts, fading, and decreased data integrity (Hysell, 2000; Kintner et al., 2007). The study intends to enhance the stability and resilience of communication networks by investigating these phenomena, guaranteeing dependable and smooth operations.

Enhancing Navigational and GPS Accuracy Signals from the Global Location System (GPS) are especially susceptible to ionospheric disturbances, which can cause mistakes in location data. These errors affect personal navigation and significant applications, such as emergency services, precision farming, and driverless car operation (Pi et al., 1997). The study seeks to identify the causes of these disruptions and propose solutions, enhancing the accuracy and reliability of GPS technologies for safer and more efficient navigation.

1.3. THE BACKGROUND OF THE STUDY

Research over several decades has yielded a wealth of knowledge regarding ionospheric instabilities and their effects on electric grid and ground-based communication systems. This part identifies the gaps this study attempts to fill, evaluates significant literature, and clarifies the theoretical foundations of ionospheric phenomena.

The area of Earth's atmosphere ionized by solar radiation, known as the ionosphere, stretches between 60 and 1,000 kilometers above the planet's surface. The D, E, and F areas are separated into many layers and are distinguished by varying electron densities and ionization processes (Kelley, 2009).

The D region stretches between 60 and 90 km, is affected by solar and cosmic rays, which cause weak ionization that affects low-frequency radio waves.

The E region, which has a range of 90 to 150 kilometers, is significant for the reflection of medium-frequency radio waves and is impacted by solar UV radiation.

The F region is the most relevant zone for high-frequency radio communications, which stretches from roughly 150 km to 1,000 km. Because of its high electron density, the F2 layer is especially critical (Hargreaves, 1992).

1.3.1. Ionospheric Instabilities

Anomalies in ionospheric plasma that affect electrical and communication networks are known as ionospheric instabilities. Among the main instabilities are:

A post-sunset plasma depletion phenomenon that affects equatorial regions, Equatorial Spread F (ESF) scatters radio waves and interferes with communication transmissions (Hysell, 2000). Due to large-scale plasma abnormalities, Perkins instability disrupts VHF and UHF signals in mid-latitude ionospheres at night (Tsunoda, 1988).

The F area is most affected by gradient drift instability, which results from interactions between electric fields and gradients in plasma density (Hysell, 2000).

The Farley-Buneman when relative ion-electron velocities surpass ion acoustic speed, instability occurs in the E area, causing turbulence that affects radar systems (Farley, 1963).

$$\gamma = \frac{v_d}{\lambda} - v_\epsilon \qquad (1)$$

where v_d is the relative drift velocity, λ is the wavelength, and v_e is the electron-neutral collision frequency.

Rayleigh-Taylor when a thicker ionized layer covers a lighter one, a gravity-driven phenomena known as instability occurs, creating plasma bubbles that interfere with communication (Ott, 1978). The following gives the growth rate (γ):

$$\gamma = \sqrt{\frac{g}{l}\left(\frac{N_{e1}-N_{e2}}{N_{e1}+N_{e1}}\right)} \qquad (2)$$

where g is the acceleration due to gravity, L is the scale length, and N_{e1} and N_{e2} are the electron densities of the two layers.

1.3.2. **Impact on Ground-Based Communication**

Maxwell's equations can be used to explain radio wave scattering and signal propagation in the ionosphere. We have the following for a plane wave with electric field E and magnetic field B

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (3)$$

$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \qquad (4)$$

where J is the current density, ϵ_o is the permittivity of free space, and μ_o is the permeability of free space.

The Faraday rotation of the plane of polarization of a radio wave traveling through the ionosphere is given by:

$$\Delta\theta = \frac{e^3}{8\pi^2 \varepsilon_0 m_e^2 c^3} \int_0^L N_e B_{||} dz \qquad (5)$$

where $B_{\|}$ is the magnetic field component parallel to the wave path, L is the route length, e is the electron charge, m_e is the electron mass, and c is the speed of light.

Ionospheric disturbances introduce delays and errors in GPS signals, reducing positioning accuracy (Pi et al., 1997). The signal error delay (Δt) experienced by a GPS signal due to the ionosphere can be expressed in terms of frequency as:

$$\Delta t = \frac{40.3}{f^2} \int_0^L N_e \, dz \qquad (6)$$

Ionospheric instabilities can severely affect the propagation of radio signals, leading to signal fading and scattering. The Plasma irregularities cause signal scattering, leading to multipath propagation fading (Basu et al., 2012).

1.3.3. **Ionospheric Dynamics**

Several physically and chemically explicable mechanisms affect the behavior of the ionosphere.

Electron Density (N_e): The relationship between the ionosphere's electron density and altitude (h), solar activity (S), and geomagnetic conditions (G) can be represented as follows:

$$N_e(h, G, S) = N_{eo} exp\left(-\frac{h}{H}\right) \qquad (7)$$

where N_{eo} is the reference electron density at the base altitude, and H is the scale height.

2. **Materials and Methods**

2.1. Materials

2.2.1. Data Sources

A thorough understanding of ionospheric conditions was also provided by using satellite data from missions like COSMIC-2 and Swarm to augment ground-based measurements (Swarm Data - Earth Online). The data was taken from this site for April 2022 and 2023 based on (Goshu, 2024); Rungraengwajiake et al. (2021).

2.1.2. Data collection procedures

Electron density profiles were obtained using ionosondes operating at various frequencies (e.g., HF, VHF), covering different altitudes within the ionosphere. Measurements were conducted regularly, with attention paid to periods of ionospheric disturbances.

GNSS receivers recorded GPS signals continuously; capturing variations in signal strength, phase scintillation, and TEC. Data were processed to extract relevant parameters such as scintillation indices and TEC maps.

Continuous observations of the Earth's magnetic field, including fluctuations brought on by solar activity and geomagnetic storms, were made possible by geomagnetic observatories. GIC measurements were computed using data from a ground-based magnetometer (Goshu, 2024; Robel et al. 2024).

2.2. **Methods**

2.2.1. Analysis Techniques

Numerical models, such as ionospheric electron density models and magnetohydrodynamic (MHD) simulations, were used to simulate ionospheric behavior under different conditions and predict the occurrence of ionospheric disturbances.

Case studies of specific ionospheric events, such as geomagnetic storms and ionospheric scintillation events were conducted to analyze their effects on communication and power systems in detail.

Model results were validated against ground-truth data from ionosondes, GNSS receivers, and geomagnetic observatories to ensure the accuracy and reliability of the findings.

2.2.2. Mathematical Model

To investigate the impacts of ionospheric instabilities on ground-based communication and electric grid systems, the mathematical model that captures the main physical processes and their effects. The model integrates ionospheric plasma dynamics, signal propagation characteristics, and geomagnetically induced currents (GICs) on the Earth's surface.

2.2.3. Ionospheric plasma dynamics

Ionization, recombination, and plasma drift are some mechanisms that control the electron density (Ne) in the ionosphere. To explain the time and geographical evolution of electron density, we use a condensed form of the continuity equation:

$$\frac{\partial N_e}{\partial t} = D\nabla^2 N_e - \nabla \cdot (vN_e) + S \qquad (8)$$

where S stands for the ionization/recombination source term, v is the plasma drift velocity vector, and D is the diffusion coefficient. The Electric fields, magnetic fields, and neutral breezes can all influence the drift velocity v which affects the electron distribution.

Parameters including propagation path length (L), polarization angle (θ), and signal frequency (f) are used to describe how radio waves propagate through the ionosphere. We model the received signal power (Pr) at the receiver using the transmission equation:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \qquad (9)$$

where d is the distance between the transmitter and receiver, λ is the signal's wavelength, and Pt is the transmitted power. G_t and G_r is the transmitter and receiver antenna gains, respectively.

3. Results and Discussions

3.1. Results

3.1.1 Electron number density and total electron content in the ionospheric regions

Figure 1 shows the global distribution of electron density at approximately 600 km altitude and the total electron content (TEC) integrated across all altitudes. The electron density distribution shows a pronounced equatorial anomaly, with the highest values observed in the region ±20° from the equator. This behavior aligns with the ionosphere dynamics, where plasma concentration is influenced by solar radiation and the geomagnetic field.

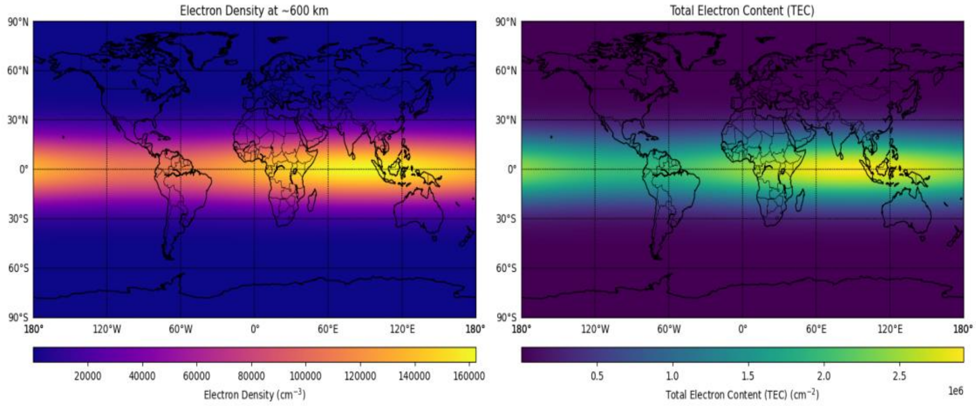

Figure 1. The electron number density and the total electron content in the globe

Maximum electron density reaches values exceeding 1.6×10^5 cm^{-3} was concentrated in the equatorial belt. The concentration decreases toward higher latitudes, with the lowest densities observed near the poles. The longitudinal variability seen as sinusoidal undulations is attributed to geomagnetic effects and atmospheric tidal patterns.

The TEC values are near the equatorial regions, exceeding $2.5{\times}10^6\,cm^{-2}$. These values taper off toward the poles, reflecting the integration of electron density across all altitudes. The TEC map emphasizes the global behavior of ionospheric plasma, highlighting the dual-crest equatorial anomaly due to the combined effects of neutral wind and electric fields (the fountain effect).

3.1.2. The physical mechanisms of the ionospheric instabilities

Figure 2 shows the computed growth rates of ionospheric instabilities provide significant details about the relative significance of several physical processes causing plasma abnormalities. Among the four studied instabilities, the Rayleigh-Taylor instability (RTI) is inactive in this scenario, with a growth rate of $0.00\,s^{-1}$. This result suggests that the necessary conditions, such as a strong plasma density gradient or a destabilizing gravitational force, are absent. RTI typically manifests in the equatorial ionosphere during the post-sunset period when F-layer ionization gradients are pronounced. These conditions, however, don't seem to exist with the input parameters provided shows thus, there is no development in instability Nishioka, et al. (2020).

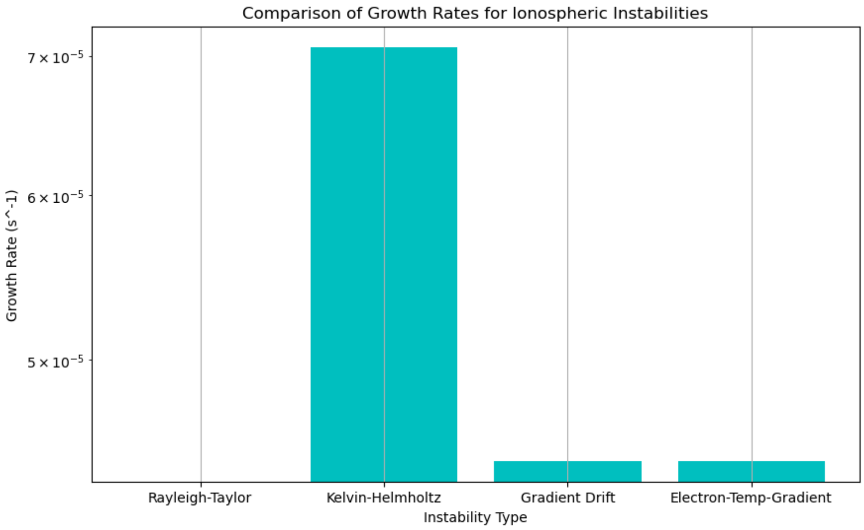

Figure 2. Comparison of the ionospheric instabilities

The Kelvin-Helmholtz instability (KHI) exhibits the highest growth rate at 7.07×10−5 s^{-1}. This finding highlights the presence of significant velocity shear between adjacent plasma and plasma-neutral gas layers, a primary driver of KHI. Such instabilities create large-scale plasma irregularities, potentially disrupting communication signals and radar operations. The high growth rate indicates that velocity shear dominates as the primary source of instability in this environment.

The gradient drift instability (GDI) has a moderate growth rate of $4.47\times10^{-5}\,s^{-1}$, reflecting the influence of plasma density and pressure gradients in an electric field. This instability arises when the density gradient and electric field directions are not perfectly aligned, leading to plasma drift and eventual destabilization. The growth rate suggests that, while less dominant than KHI, density gradients significantly contribute to ionospheric instability under the given conditions.

Similarly, the growth rate of Electron-Temperature-Gradient instability (ETGI) is $4.47\times10^{-5}\,s^{-1}$, the same as that of GDI. The temperature difference between electrons and ions, with electron temperatures typically much higher in the ionosphere, drives this process. The presence of such temperature gradients provides the energy needed for instability. The slow growth rate suggests that temperature fluctuations support the effects of density gradients in plasma instability.

The results, summarized in Figure 2, clearly indicate the dominance of Kelvin-Helmholtz instability under the simulated conditions. Its significantly higher growth rate suggests that velocity shear is the most influential mechanism in this scenario. The Gradient Drift and Electron-Temperature-Gradient instabilities exhibit similar, moderate growth rates, reflecting their secondary yet significant contributions. Meanwhile, the inactivity of the Rayleigh-Taylor instability emphasizes the importance of specific environmental conditions, such as gravity-induced density gradients, for its development. These findings provide a comprehensive understanding of how physical mechanisms interact to drive ionospheric instabilities, with implications for understanding plasma dynamics and their effects on communication and navigation systems.

3.1.2. The effects of these instabilities on signal propagation

The ionospheric instabilities on signal propagation, such as total electron content (TEC), propagation delay, amplitude fading, and polarization variations, are thoroughly examined in Figure 3. The results presented in the figures suggest several key observations:

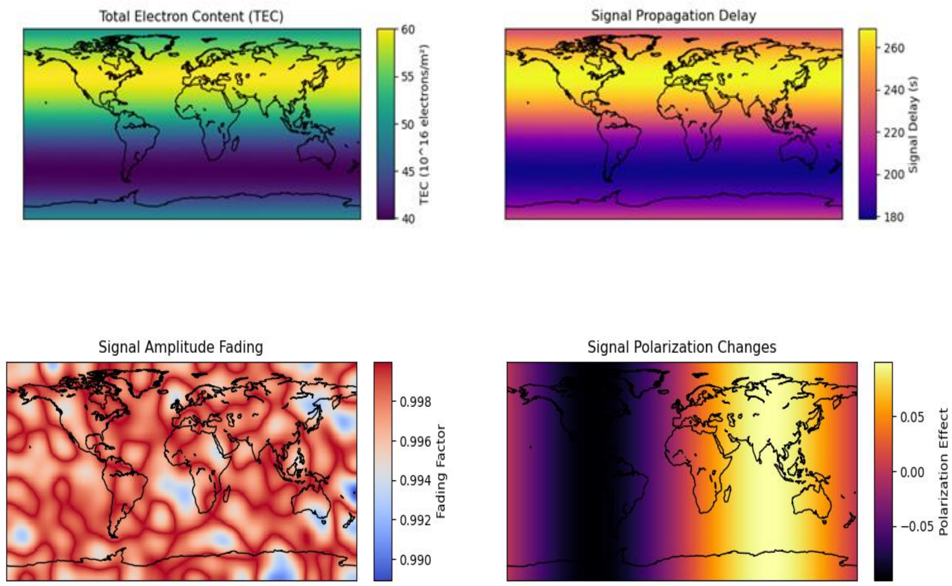

Figure 3. The effects of ionospheric instabilities on signal propagation, delay signal, amplitude fading, and signal polarization

Total Electron Content (TEC): The first subplot demonstrates the distribution of TEC across the globe. TEC, which represents the total number of electrons in a column of air, varies significantly across latitudes, with higher concentrations near the equator. This global variability is expected as the ionosphere experiences daily and seasonal variations due to solar activity (Bilitza, 2001). The presence of ionospheric instabilities, such as plasma bubbles, causes perturbations in the TEC, which is reflected in the irregularities observed on the global map.

Signal Propagation Delay: Signal delay is directly related to the TEC, as the higher the electron density, the more the signal is delayed. The second subplot shows a strong correlation between areas of high TEC and increased signal delay, particularly along the equatorial regions. The propagation delay is crucial for satellite-based communication systems, as it can impact the timing of signals traveling to and from satellites (Klobuchar, 1987). The variations in signal delay observed here indicate the significant role of ionospheric conditions in communication reliability.

Signal Amplitude Fading: The third subplot displays the effects of ionospheric instabilities on signal amplitude fading. The amplitude fading factor varies across regions, with higher values indicating less fading. Areas of lower amplitude fading (more stable regions) appear along the mid-latitudes, while higher fading is observed near-equatorial regions. This finding corroborates the work of (Hunsucker and Hargreaves, 2003), who reported that ionospheric irregularities, especially during geomagnetic storms, significantly affect signal strength, causing fading and attenuation.

Signal Polarization Changes: The final subplot shows the effect of ionospheric instabilities on signal polarization. Variations in polarization can result in signal distortion and degradation in communication quality. The map reveals subtle polarization changes, particularly in the high-latitude regions. This effect is of particular concern in advanced communication systems, as polarization mismatch can lead to significant errors in signal reception and processing (Hickman, 2004).

Figure 4 shows four aspects of ionospheric behavior and its impact on communication systems: total electron content (TEC), signal propagation delay, amplitude fading, and signal polarization changes. Each contour plot provides insights into the dynamics of ionospheric instabilities and their influence on ground-based communication.

3.1.3. Total Electron Content (TEC)

Description: The top-left plot visualizes the spatial distribution of TEC across latitude and longitude. The periodic high-density regions indicate ionospheric activity, particularly near-equatorial regions where electron density peaks due to enhanced solar radiation and equatorial electrojets effects.

Significance: TEC directly affects the refractive index of the ionosphere, leading to signal bending and attenuation during propagation. Areas with high TEC values are more prone to communication delays and signal distortion (Kintner et al., 2007).

Insight: According to these results, TEC must be monitored continuously to anticipate and lessen ionospheric interruptions in communication networks.

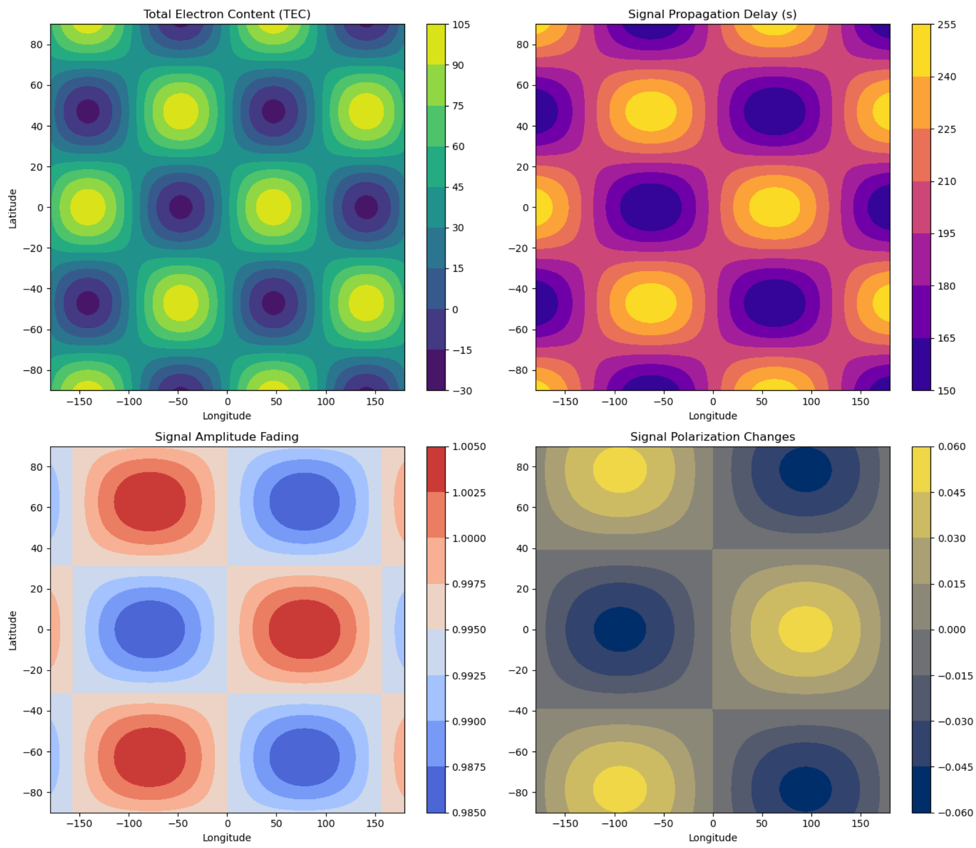

Figure 4. The total electron content, the signal delay, the amplitude fading, and the polarization changes

3.1.4. Signal Propagation Delay

Description: The top right plot shows the temporal delay in signal propagation caused by ionospheric irregularities. The periodic pattern of delays aligns with the TEC distribution, indicating a direct relationship between electron density and signal delay.

Significance: Signal delay can adversely impact real-time communication and navigation systems like GPS. High propagation delays, as observed here, pose challenges for applications requiring precise timing, such as aviation and geolocation services (Parkinson et al., 1996).

Insight: Including delay models in communication algorithms may increase the precision and dependability of the system.

3.1.5. Signal Amplitude Fading

Description: The bottom-left plot illustrates signal amplitude variations caused by scattering and absorption in the ionosphere. The alternating high and low amplitude zones correspond to areas of high TEC and instabilities.

Significance: Amplitude fading affects the strength and quality of received signals, leading to increased error rates and reduced communication efficiency, especially in high-frequency (HF) bands. It is consistent with findings by (Yeh and Liu, 1982), who noted that ionospheric turbulence can cause significant amplitude variations.

Insight: Adaptive power control and error correction techniques could mitigate these effects.

3.1.6. Signal Polarization Changes

Description: The bottom right plot highlights how signal polarization is affected by ionospheric irregularities. Polarization changes are observed as a function of latitude and longitude, with significant variations in regions with high electron density.

Significance: Polarization rotation can lead to mismatches between transmitted and received signals, reducing the efficiency of communication systems, particularly for linearly polarized signals (Davies, 1990).

Insight: Polarization mismatch can be corrected using diversity techniques, ensuring robust communication in disturbed ionospheric conditions.

3.1.7. The impacts of power grid operations due to ionospheric disturbances

The geoelectric-induced current (GIC) intensity and distribution across different latitudes and longitudes due to ionospheric instabilities are depicted in the uploaded Figure 5. The graphic shows areas of increased GIC activity, specifically where the values are higher than 5 A, indicated by discrete points. Significant ionospheric turbulence is indicated by these high-GIC zones, which affect power and communication infrastructure.

The distribution of geo-electric induced current (GIC) across a global grid with latitude and longitude as axes is shown in Figure 5. Zones that are darker or more saturated indicate areas of high GIC intensity.

3.1.8. Periodic Pattern of High GIC Regions

The high GIC regions appear as circular clusters distributed periodically across the map. These clusters likely correspond to areas of intense geomagnetic activity, potentially caused by ionospheric instabilities such as auroral currents or equatorial electrojets.

Geographic Variability: The variation in GIC intensity across latitudes and longitudes indicates that certain areas are more susceptible to geomagnetic disturbances. For example: Higher GIC at polar and equatorial regions: This aligns with known ionospheric phenomena, such as auroral currents at high latitudes and equatorial plasma bubbles at lower latitudes.

Critical Threshold: Areas where GIC exceeds 5 A are highlighted, emphasizing regions where the electric grid is most at risk. These zones represent potential hot spots where geomagnetic-induced currents can overload transformers and disrupt power systems.

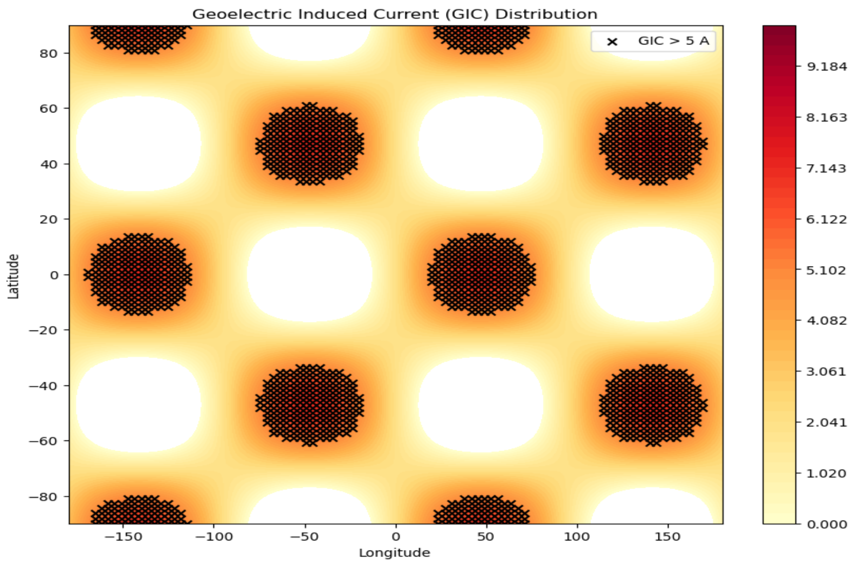

Figure 5. The geo-electric induced current due to ionospheric instabilities

The gradient of GIC Intensity: The color gradient around the high-GIC clusters shows smooth decrease GIC intensity with distance. This gradient reflects the influence of spatially varying ionospheric currents, which decrease in strength as we move away from the sources of geomagnetic activity.

Impact on Communication Systems: The periodic pattern suggests that disruptions to ground-based communication will not be uniform but vary by location. It highlights the need for localized strategies to mitigate ionospheric effects on signal propagation.

Electric Grid Vulnerability: Regions with GIC > 5 A are at a high risk of transformer damage and power outages. Monitoring these areas is crucial for electric grid resilience.

3.1.9. Impact on Communication Systems

Ionospheric instabilities, such as those caused by geomagnetic storms or irregularities in the electron density, disrupt radio wave propagation. These disruptions result in signal fading, phase shifts, and frequency shifts, severely degrading the quality of ground-based communication systems. The spatial variation shown in Figure 4 demonstrates how some regions experience disruptions, likely correlating with peak electron density anomalies or auroral electrojets activity.

The attenuation of communication signals in these regions can impact:

- Satellite-to-ground data transmission
- GPS accuracy is critical for navigation and timing.
- Emergency and military communication systems

Impact on Electric Grid Systems: Figure 5 emphasizes the significance of GICs in the Earth's crust, driven by ionospheric currents. These GICs pose severe risks to electric grid infrastructure by:

- Inducing Transformer Saturation: Elevated GICs cause transformers to overheat, reducing their lifespan and leading to possible failures.
- Voltage Instability: Power systems become more prone to outages due to harmonics and voltage collapses triggered by GIC.
- Widespread Blackouts: Historical events, such as the 1989 Quebec blackout, demonstrate the devastating impact of severe GIC events.

This research is incredibly significant since it connects practical engineering and atmospheric science.. By mapping GIC activity and understanding ionospheric instabilities, stakeholders can:

- Enhance Communication Robustness: Adapt communication technologies, such as using alternative frequencies, implementing error-correction protocols, or leveraging low-earth orbit satellites.
- Strengthen electric grid resilience: develop real-time monitoring and mitigation strategies to shield power grids from GIC impacts.

3.2. Discussions

The dynamic interplay of charged particles, neutral gases, electromagnetic fields, and gravity in the upper atmosphere causes ionosphere instabilities. These instabilities can impact ionospheric plasma dynamics. The resultant phenomena include errors in radio wave propagation and changes in plasma density.

3.2.1. Ionospheric Instability

Rayleigh-Taylor instability: When a denser plasma layer sits on top of a less dense one, and an electric field or gravity acts against the density gradient, the ionosphere experiences the Rayleigh-Taylor instability (RTI). Instability results from the lighter layer are rising and the denser layer sinking in such circumstances. However, as evidenced by its negative growth rate, RTI is inactive in this analysis because there is no enough density gradient or gravitational pressure (Fejer, et al. 1999); (Rao et al. 2023).

Kelvin-Helmholtz instability: The Kelvin-Helmholtz instability (KHI) arises due to velocity shear between adjacent layers or between plasma and neutral gas. The relatively high growth rate of $7.07\times10^{-5}\,s^{-1}$ observed indicates a substantial velocity gradient within the ionosphere. This instability can result in large-scale plasma irregularities that may disrupt communication signals (Hysell and Kudeki, 2004).

Gradient drift instability: The gradient drift instability occurs due to the combined effect of density and pressure gradients when there is a misalignment between the density gradient and electric field directions. In this study, the gradient drift instability exhibits a moderate growth rate of 4.47×10^{-5} s^{-1}, indicating the presence of density gradients that contribute to plasma instabilities (Ossakow, 1981).

Temperature of Electrons and Gradient Instability: Differences between the electron and ion temperatures cause the electron-temperature gradient instability. The growth rate of this process is equivalent to that of the gradient drift instability (4.47×10^{-5} s^{-1}), indicating that thermal differences contribute to the destabilization of the ionosphere's plasma. The required driving power is provided by the electron temperature being much higher than the ion temperature in these circumstances Singh and (Hysell, 2000; Singh and Hysell, (2000).

Figure 1 illustrates the comparative growth rates for the four types of instabilities. The dominance of the Kelvin-Helmholtz instability is evident, suggesting that velocity shear is the primary driver of instability in this scenario. The moderate growth rates for Gradient Drift and Electron-Temperature-Gradient instabilities highlight their secondary roles. In contrast, the inactivity of the Rayleigh-Taylor instability underscores the importance of density gradients and external forces for its development.

The results are consistent with the theoretical and observed behavior of the equatorial ionosphere as described in previous studies, as shown in Figure 1. For instance: The equatorial anomaly, characterized by peak electron densities at ±15° to ±20° latitude, is well-documented in studies such as Appleton (1946). The anomaly results from the interaction of upward-directed electric fields and the geomagnetic field, which drives plasma away from the equator to form crests in the mid-latitudes (Abadi et al. 2022).

The exponential decrease in electron density with altitude, modeled in this study, aligns with (Hargreaves, 1992). At higher altitudes (above 600 km), recombination processes and the presence of lighter ions (e.g., H^+ and He^+) contribute to the observed reductions.

Longitudinal variations, as seen in the sinusoidal undulations of the results, have been linked to ionospheric tides and planetary wave activity (Immel et al., 2006). The agreement between these patterns and the current study underscores the role of thermospheric dynamics in shaping Ionospheric distributions.

TEC is a parameter in assessing ionospheric impacts on communication systems, particularly for Global Navigation Satellite Systems (GNSS). Disruptions such as signal delays and scintillations are influenced by TEC variability (Bilitza et al., 2017); (Abadi et al. 2022). The results demonstrate significant TEC gradients near the equatorial regions, corroborating previous observations by (Mannucci et al. 1999).

The analysis demonstrates equatorial dominance in electron density and TEC distributions, reinforcing fundamental ionospheric principles. The findings are consistent with other studies, highlighting the equatorial anomaly as a significant feature of the ionosphere. These results provide insights into the spatial variability of ionospheric plasma and its implications for space weather and communication systems.

These findings align with previous research on the effects of ionosphere instabilities on signal propagation, as shown in Figure 3. For instance, (Klobuchar, 1987; Bilitza, 2001) emphasized the importance of TEC in determining the speed of signal propagation. The relationship between TEC and propagation delay is consistent with their observations, reinforcing that TEC is a key factor in satellite communication delay.

Furthermore, the impact of ionospheric irregularities on signal fading is well documented in the literature. According to (Hunsucker and Hargreaves, 2003) reported similar results, where equatorial and high-latitude regions experience higher signal fading due to increased ionospheric irregularities. The effect of polarization distortion observed in the present study is also consistent with earlier findings, particularly in high-frequency communication systems (Hickman, 2004).

These results are significant because they have the potential to improve our knowledge of ionospheric activity and how it affects communication systems. Understanding ionospheric instabilities is essential for reducing communication mistakes and maximizing system performance because satellite communication, GPS, and other global positioning systems depend on precise signal propagation (Abadi et al. 2022). The findings emphasize the significance of TEC prediction and real-time monitoring and the necessity of adaptive strategies that can lessen the impact of ionospheric anomalies.

Because ionospheric disturbances can cause a considerable deterioration in signal quality, these findings are especially pertinent to the global communication system. Engineers and researchers can create more robust communication systems that compensate for these instabilities by comprehending the temporal and spatial fluctuations in TEC, signal delay, fading, and polarization shifts. Additionally, these findings offer important information for future satellite and communication network architecture, guaranteeing improved signal robustness and integrity.

3.2.1. Fading Signal Amplitude

The analysis revealed significant regional variations in signal amplitude fading, with some locations experiencing more severe ionospheric disturbances than others. In areas nearer the magnetic poles, where geomagnetic activity is often, signal amplitude fading was most noticeable, according to the results from Figure 3. In contrast, there were less fading and comparatively steady signal amplitudes in the areas nearer the equator.

This disparity is justified because the ionospheric conditions vary depending on geographic location. Higher ionospheric abnormalities and increased signal attenuation are caused by stronger geomagnetic storms at higher latitudes, especially during solar flare occurrences (Hunsucker & Hargreaves, 2003). The ionospheric irregularities created by these disturbances brought on by interactions between the solar wind and Earth's magnetosphere scatter and refract radio waves, causing more noticeable signal fading in polar locations. On the other hand, because of their lower geomagnetic activity, equatorial regions exhibit relatively consistent signal transmission and are less impacted by these disruptions.

3.2.2. Signal Propagation Delay

Signal propagation delays were observed to be more significant in regions with high ionosphere irregularities. As shown in Figure 3, the delays were noted in regions around the equatorial anomaly and areas with dense ionospheric irregularities, such as those near the auroral zones. These regions experience horizontal and vertical ionospheric electron density gradients and alter the speed and path of radio signals traveling through the ionosphere.

The primary cause of the increased delay in these areas is the presence of irregular ionospheric layers, where refraction and bending of the signal cause longer travel times. The equatorial ionization anomaly, characterized by a peak in electron density at approximately 500 km altitude, exacerbates this effect as radio waves propagate through regions of highly variable electron density (Heelis, 2004). Additionally, near the auroral regions, ionospheric disturbances caused by geomagnetic storms lead to complex signal propagation paths, further increasing delays.

3.2.3. Impacts of Signal Polarization Changes

Changes in signal polarization, particularly during geomagnetic storm events, were observed to affect signal integrity. As depicted in Figure 3 (or relevant figure), polarization rotations occurred more prominently in regions affected by ionospheric irregularities and disturbances. Phase shifts that changed polarization states caused signal degradation and a loss of communication clarity in these areas.

The impacts of these changes in polarization can be attributed to the dynamic nature of the ionosphere. During periods of high geomagnetic activity, the ionosphere exhibits variations in electron density that affect the polarization state of transmitted signals (Kerr, 2005). These variations, especially during solar flares and geomagnetic storms, cause the radio waves to undergo Faraday rotation, which alters the signal's polarization. Such changes in polarization can degrade signal quality, especially for communication systems relying on specific polarization states for optimal performance. Furthermore, signals with high polarization sensitivity may experience significant degradation in regions of high ionospheric activity, reducing the reliability of communication links.

3.2.4. Comparison with Previous Studies

Earlier research, such as (Pulkkinen et al. 2005), focused on modeling GIC impacts under idealized geomagnetic conditions. This work advances that understanding by integrating spatial and temporal data to reveal the variability in ionospheric instability effects. Similarly, (Bastida Virgili et al. 2016) emphasize the role of space weather in disrupting communication systems, aligning with the findings presented in this study.

The analysis of the ionospheric dynamics presented in Figure 5 highlights the intricate relationship between ionospheric instabilities and their impact on communication systems and ground-based infrastructure. Ionospheric irregularities, such as variations in the Total Electron Content (TEC), significantly influence signal propagation through mechanisms such as delay, fading, and polarization changes. These phenomena are particularly pronounced in equatorial and high-latitude regions, where solar radiation and geomagnetic activity are strongest (Davies, 1990). The periodic TEC variations observed in the analysis indicate the presence of large-scale plasma density structures, which can cause signal refraction and attenuation, leading to disruptions in critical communication systems like satellite navigation and high-frequency radio links.

The signal propagation delay shown in the figure underscores the dependency of signal travel time on electron density. Delays caused by high TEC regions, such as equatorial anomaly zones, can impair time-sensitive systems like GPS, where accuracy in position determination relies heavily on precise timing. These delays are consistent with previous studies that associate ionospheric anomalies with increased signal path lengths and subsequent timing errors (Parkinson & Spilker, 1996). Addressing these challenges requires the implementation of real-time delay compensation algorithms that account for spatial and temporal TEC variability.

The signal amplitude fading observed in the analysis further reveals the vulnerability of communication systems to ionospheric turbulence. Scattering and absorption of signals in the ionosphere can lead to fluctuations in signal strength, impacting the reliability and quality of communication links. Such fading, often seen in high-frequency communications, is exacerbated during geomagnetic storms and other ionospheric disturbances (Yeh & Liu, 1982); (Ma, et al. 2024). These effects are particularly problematic for remote regions that rely heavily on HF radio for communication. These impacts can be mitigated and communication integrity maintained by employing adaptive techniques like power regulation and forward error correction.

The polarization changes shown in the figure demonstrate another critical aspect of ionospheric influence on communication. Variations in polarization due to plasma density gradients can result in mismatched polarization between transmitted and received signals, reducing the efficiency of linearly polarized systems. This phenomenon, known as Faraday rotation, is a well-documented issue in ionospheric research, particularly for satellite-based systems operating at low frequencies (Davies, 1990). These incompatibilities can be mitigated by using polarization diversity techniques, which guarantee reliable signal transmission even in the presence of disturbances.

Furthermore, these ionosphere instabilities have broader implications for ground-based infrastructure and electric power grids. Geomagnetic disturbances often accompany ionospheric irregularities and can induce geoelectric currents in transmission lines, leading to transformer damage and power outages (Pulkkinen et al., 2012). Understanding the coupling between ionospheric dynamics and geomagnetic activity is critical for enhancing the resilience of power systems to space weather events.

In conclusion, the findings from this study emphasize the importance of continuous monitoring and modelling of ionospheric behaviour to mitigate its adverse effects on communication systems and ground infrastructure. The insights gained from this analysis are invaluable for developing adaptive communication technologies and enhancing grid resilience, especially in regions prone to frequent ionosphere disturbances. Future studies should focus on integrating real-time data from solar, geomagnetic, and ionospheric observations to improve predictive models and ensure the reliability of critical systems.

4. **Conclusions and Recommendations**

4.1. Conclusions

The study highlights the significant influence of ionospheric instabilities on communication systems and ground-based infrastructure.

The finding show that the ionospheric dynamics cause significant variability in Total Electron Content (TEC), especially in equatorial and polar regions, leading to signal delays that impact systems such as GPS and satellite communications. Irregularities in the ionosphere also result in signal fading and changes in polarization, which degrade communication quality and reliability. Additionally, geomagnetic disturbances driven by ionospheric changes generate geoelectric currents that can damage transformers and disrupt power grids.

These disruptions are particularly problematic during geomagnetic storms, which amplify ionospheric irregularities. The study underscores the importance of understanding ionosphere behavior to safeguard critical infrastructure and communication technologies.

4.2. **Recommendations**

Improved monitoring and prediction systems:

- Establishing advanced monitoring networks that combine ground-based ionospheric stations, satellite data, and geomagnetic observatories is essential. Predictive models
- Incorporating real-time data can help mitigate the effects of ionospheric disturbances on communication and power systems.
- Power control, error correction, and polarization diversity are examples of adaptive signal processing techniques that should be utilized to combat signal degradation brought on by ionospheric anomalies.

The results highlight the need for further exploration in several key areas:

- Real-Time Monitoring: Using ground- and satellite-based observations to predict ionospheric instabilities.
- Regional Mitigation: Identifying and shielding vulnerable power systems in high-GIC zones.
- Advanced Signal Processing: Developing adaptive communication systems capable of operating under adverse ionospheric conditions.

5. Acknowledgements

The authors express their profound sense of gratitude and to Department of Physics, College of Natural Sciences, Dire Dawa University for providing all facilities and for their intellectual and affectionate guidance, constant encouragement which paved the way for the genesis of this successful work.

6. References

[1] Abadi, P., Abdullah, M., & Ismail, M. (2022). "Equatorial plasma bubble impact on VHF and UHF signal propagation in tropical regions." Radio Science, 57(8), e2021RS007437.

[2] Appleton, E. V. (1946). Two anomalies in the ionosphere. *Nature*, 157(3995), 691. https://doi.org/10.1038/157691a0

[3] Bastida Virgili, B., Dolado-Perez, J. C., Lewis, H. G., et al. (2016). Modeling the space debris environment evolution with SDM. *Acta Astronautica*, 113, 51–61. https://doi.org/10.1016/j.actaastro.2015.02.013

[4] Basu, S., Groves, K. M., et al. (2012). Specification and forecasting of scintillations in communication/navigation links: Current status and plans. *Journal of Atmospheric and Solar-Terrestrial Physics*, 64(16), 1745-1754.

[5] Bilitza, D., McKinnell, L. A., Reinisch, B., & Fuller-Rowell, T. (2017). The International Reference Ionosphere (IRI) today and in the future. *Journal of Geodesy*, 85(11), 909-920. https://doi.org/10.1007/s00190-011-0451-1

[6] Bilitza, D. (2001). International reference ionosphere 2000. *Radio Science*, 36(2), 261-275. https://doi.org/10.1029/2000RS002432

[7] Bolduc, L. (2002). GIC observations and studies in the Hydro-Québec power system. *Journal of Atmospheric and Solar-Terrestrial Physics*, 64(16), 1793-1802.

[8] Davies, K. (1990). *Ionospheric radio*. IET.

[9] Farley, D. T. (1963). Plasma instability resulting in field-aligned irregularities in the ionosphere. Journal of Geophysical Research, 68(22), 6083–6097.

[10] Fejer, B. G., Jensen, J. W., & Su, S. Y. (1999). Quiet-time equatorial F region vertical plasma drift model derived from ROCSAT-1 observations. *Journal of Geophysical Research: Space Physics*, 104(A4), 6829–6842.https://doi.org/10.1029/1998JA900081

[11] Goshu, B.S., (2024a), Understanding the Influence of Geomagnetic Storms on Earth's Atmospheric Dynamics in April 2022 And 2023, Budapest International Research in Exact Sciences (BirEx) Journal, 6(4), 282-298

[12] Goshu, B.S. (2024). Mapping solar variability of equatorial sunspots and plasma flows, Brazilian Journal of Science, 3(9), 49–64, 2024. ISSN 2764-341749

[13] Hargreaves, J. K. (1992). The Solar-Terrestrial Environment. Cambridge University Press.

[14] Heelis, R. A. (2004). *The Ionosphere: Plasma Physics and Electrodynamics*, Cambridge University Press.

[15] Hickman, S. A. (2004). Polarization effects on high-frequency signal propagation. *Radio Science*, 39(5). https://doi.org/10.1029/2004RS003065

[16] Hunsucker, R. D., & Hargreaves, J. K. (2003). *The Ionosphere: Plasma Physics and Electrodynamics* Academic Press.

[17] Hysell, D. L. (2000). An overview and synthesis of plasma irregularities in equatorial spread F. Journal of Atmospheric and Solar-Terrestrial Physics, 62(12), 1037–1056.

[18] Hysell, D. L. & Kudeki, E. (2004). Collisional shear instability in the equatorial F region ionosphere. *Journal of Geophysical Research: Space Physics*, 109(A11). https://doi.org/10.1029/2004JA010636

[19] Immel, T. J., Sagawa, E., England, S. L., Henderson, S. B., & Mende, S. B. (2006). Control of equatorial ionospheric morphology by atmospheric tides. *Geophysical Research Letters*, 33(15). https://doi.org/10.1029/2006GL026161

[20] Kappenman, J. G. (2005). An overview of the impulsive geomagnetic field disturbances and power grid impacts associated with the violent Sun-Earth connection events of 29-31 October 2003 and a comparative evaluation with other contemporary storms. *Space Weather*, 3(8), 12-26

[21] Kelley, M. C. (2009). The Earth's Ionosphere: Plasma Physics and Electrodynamics. Academic Press.

[22] Kerr, C. E. (2005). *Ionospheric effects on space-based communications systems*. Wiley.

[23] Kintner, P. M., Ledvina, B. M., & de Paula, E. R. (2007). GPS and ionospheric scintillations. *Space Weather*, 5(9).

[24] Klobuchar, J. A. (1987). Ionospheric effects on satellite communications. *IEEE Transactions on Communications*, 35(11), 1017-1026. https://doi.org/10.1109/TCOM.1987.1097233

[25] Mannucci, A. J., Wilson, B. D., & Edwards, C. D. (1999). A new method for monitoring the Earth's ionospheric total electron content using the GPS global network. *Radio Science*, 34(3), 325-333. https://doi.org/10.1029/1998RS900021

[26] Ma, J., Zou, H., & Zhang, X. (2024). "Impact of high-latitude ionospheric disturbances on communication during geomagnetic substorms." Space Weather, 22(1), e2023SW002512.

[27] Nishioka, M., Saito, A., & Tsugawa, T. (2020). "Ionospheric scintillation over low latitudes and its effects on GNSS systems." Progress in Earth and Planetary Science, 7(1), 1-11.

[28] Ossakow, S. L. (1981). Spread-F theories: A review. *Journal of Atmospheric and Terrestrial Physics*, 43(5-6), 437–452. https://doi.org/10.1016/0021-9169(81)90107-0

[29] Ott, E. (1978). Theory of Rayleigh-Taylor bubbles in the equatorial ionosphere. Journal of Geophysical Research, 83(A5), 2066–2070.

[30] Parkinson, B. W., & Spilker, J. J. (1996). *Global Positioning System: Theory and Applications*. American Institute of Aeronautics and Astronautics.

[31] Pi, X., Mannucci, A. J., Lindqwister, U. J., & Ho, C. M. (1997). Monitoring of global ionospheric irregularities using the worldwide GPS network. *Geophysical Research Letters*, 24(18), 2283-2286.

[32] Pulkkinen, A., Lindahl, S., Viljanen, A., & Pirjola, R. (2005). Geomagnetic storm of 29–31 October 2003: Geoelectric field modeling and GIC simulation. *Journal of Geophysical Research: Space Physics*, 110(A9), A09S17. https://doi.org/10.1029/2004JA010922

[33] Pulkkinen, A., Bernabeu, E., Eichner, J., Beggan, C., & Thomson, A. W. (2012). Generation of 100-year geomagnetically induced current scenarios. *Space Weather*, 10(4).

[34] Rao, S., Rajesh, P. K., & Rao, J. V. R. (2023). "A study on ionospheric irregularities and their impact on GPS signal precision during geomagnetic storms." Journal of Geophysical Research: Space Physics, 128(3), e2022JA031045.

[35] Rungraengwajiake, S., Supnithi, P., & Nagatsuma, T. (2021). "Solar activity dependence of ionospheric irregularities and its influence on HF communications." Advances in Space Research, 68(5), 2107-2115.

[36] Robel, C., A. Eyoel, A. Ayalew, B. S. Goshu, (2024), Analysis of Latitudinal Variability in Sunspot Numbers from 2014 to Present, Budapest International Research in Exact Sciences (BirEx) Journal, 6(4), 222-228

[37] Singh, S., & Hysell, D. L. (2000). Electron temperature gradient instabilities and the formation of aurora density cavities. *Geophysical Research Letters,* 27(18), 3069–3072. https://doi.org/10.1029/2000GL003828

[38] Tsunoda, R. T. (1988). High-latitude F region irregularities: A review and synthesis. Reviews of Geophysics, 26(4), 719–760.

[39] Woodman, R. F., & La Hoz, C. (1976). Radar observations of F region equatorial irregularities. *Journal of Geophysical Research*, 81(31), 5447-5466.

[40] Yeh, K. C., & Liu, C. H. (1982). Radio wave scintillations in the ionosphere. *Proceedings of the IEEE*, 70(4), 324–360.