INVESTIGATION OF THE IMPACT OF GEOMAGNETIC STORM ON IONOSPHERIC SCINTILLATION

BY

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CERTIFICATION

This is to certify that the project work was carried out and reported by **OLASUNKAMI TOHEEB ABOLAJI** with matric number **ND/23/SLT/PT/0594** in the department of Science Laboratory Technology [SLT] Institute of Applied science [IAS], Physics Option and has been read and approved as meeting the requirement for the award of National Diploma [ND].

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DEDICATION

We dedicate this Project to Almighty GOD, the giver of knowledge and to our parents.

ACKNOWLEGEMENT

We are highly grateful to **ALMIGHTY GOD** who in his infinite mercy has showered his blessings and favour upon us throughout the course.

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ABSTRACT

During the geomagnetic storms of 1 October 2002 and 22 January 2004, strong ionospheric scintillations on the GPS L1 band were observed at Wuhan station (30.6°N, 114.4°E; magnetic dip 45.8°), located near the northern crest of the Equatorial Ionospheric Anomaly (EIA). The observed intense scintillation events were closely associated with the main phases of the storms and coincided with a marked enhancement of the EIA. Additionally, both large- and small-scale ionospheric irregularities were detected during the post-midnight hours, indicating sustained ionospheric instability. These findings suggest that storm-time modifications in the eastward equatorial electric field play a significant role in generating and sustaining ionospheric irregularities. The results contribute to a deeper understanding of space weather impacts on low-latitude ionospheric dynamics and emphasize the importance of continuous monitoring for the mitigation of GPS signal degradation during geomagnetic disturbances.

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CHAPTER ONE

1.1 The Sun

At first, nothing well, not quite. The sun, earth, and solar system didn't exist billions of years ago. The galaxy was a vast cloud of gas and dust. The cloud has enough hydrogen atoms for gravity to draw them together abo ut 5 billion years ago. The cloud got denser as it shrank. Before long, the speed of the atoms caused this clou d to glow. When the cloud became sufficiently heated, the hydrogen atoms' protons and electrons flew apart. When two protons collided, they fused, or adhered to one another, to form helium atoms. Fusion is the term f or this procedure. Fusion also creates energy in the form of heat and light. This energy made the called to en large, while the gravity was pulling to hold the atoms together. Finally, the forces balanced and the sun was formed. With the sun at the center, our solar system formed. Over millions of years, the leftover gas and dus t formed the nine planets, and a variety of moons asteroids, comets, and meteors.

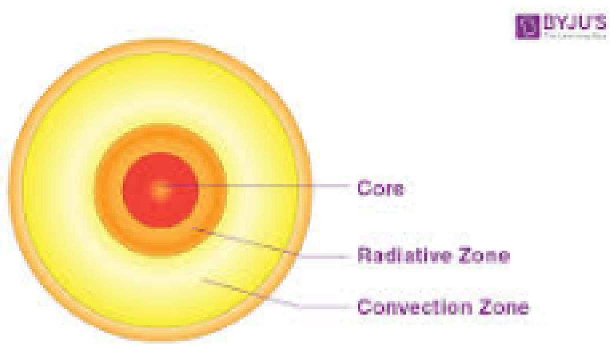
The temperature can reach as high as 27 million degrees fahrenheit. The core's gas is about one hundred t imes denser than most metal. Since the core is this dense, it is hard for rats to leave. When gamma rays are rel eased by fusion, they continue to collided with other atoms. Due to this, it takes the gamma rays almost thirty thousand years to reach the sun's surface. This means that the light that we receive on earth was created thou sands years ago.

The Sun is by far the largest object in the solar system. It contains more than 99.8% of the total mass o f the solar system (Jupiter contains most of the rest). It is often said that the sun is an "ordinary" star. That's true in the sense that there are many others similar to it. But there are many smaller stars than larger ones; the sun is in the top 10% by mass. The median size in our galaxy is probably less than half the mass of the sun.

The Sun is personified in many mythologies: the Greeks called it Helios and the Romans called it sol. The Sun is, at present, about 70% hydrogen and 27% helium by mass everything else (" metals") amounts to less than 2%. This changes slowly over time as the sun converts hydrogen to helium in its core. The outer layers of the sun exhibit differential rotation: at the equator the surface rotates once every 25.4 days; near the poles it's as much as 36 days. This odd behavior is due to the fact that the sun is not a solid body like the Earth. Similar effects are seen in the gas planets. The differential rotation extends considerably down into the interior of the sun but the core of the sun rotates as a solid body. Conditions at the sun's core (approximately in the inner 25% of it's radius) are extreme. The temperature is 15.6 million kelvin and the pressure is 250 billion atmosphere. At the center of the core the sun's density is more than 150 times that of water

1.2 Internal Structure Of the earth

The diagram below depicts the sun's structure, including the inner core, radiative core, convectional shell, photosphere, chromosphere, and corona, which are then detailed.



Internal Structure of the Sun

Figure 1.1: The structure of the sun

The surface of the sun, called the photosphere, is at a temperature of about **5800** k. Sunspot are "cool" regions, only **3800 K** (they look dark only by comparison with the surrounding regions). Sunspot can be very large, as much as **50,000** km in diameter.sunspot caused by complicated and not very well understood interactions with the sun magnetic field.

A small region known as the chromosphere lies above the photosphere. The highly rarefied region above the chromosphere, called the corona, extend millions of kilometers into space but is visible only during a total solar eclipse (left). Temperatures in the corona are over **1,000,000 K**. It just happens that the moon and the sun appear the same size in the sky as viewed from the earth. And the moon orbits the Earth in approximately the same plane as the Earth orbit around the sun sometimes the moon comes directly between the Earth and the sun. This is called solar eclipse ; if the alignment is slightly imperfect then the moon covers only part of the sun's disk and the event is called partial eclipse.

When it lines up perfectly the entire solar disk is blocked and it is called total eclipse of the sun. Partial eclipse are visible over a wide area of the Earth but the region from which a total eclipse is visible, called the path of totality, is very narrow, just a few kilometers (though it is usually thousands of kilometers long). Eclipse of the sun happen once or twice a year. If you stay home, you are likely to see a partial eclipse several times per decade.

But since the path of totality is so small it is very unlikely that it will cross you home. So people often travel half way around the world just to see total solar eclipse. To stand in the shadow of the moon is an awesome experience. For few precious minutes it gets.

CHAPTER TWO: LITERATURE REVIEW

2.1 Review of Related Literature

Basu et al. (1981) made significant contributions to understanding the relationship between geomagnetic storms and ionospheric scintillation. Their study, one of the early systematic investigations into storm-time effects on the ionosphere, utilized ground-based radio wave observations to analyze how plasma irregularities evolve under disturbed magnetic conditions. They found that the occurrence of ionospheric scintillation is highly sensitive to magnetic storm phases, particularly the main and recovery phases when energy input from the solar wind is elevated.

The methodology employed by Basu and his colleagues involved monitoring Very High Frequency (VHF) signal fluctuations from satellites over equatorial and low-latitude regions. They recorded the S4 index (amplitude scintillation) and $\sigma\varphi$ index (phase scintillation) under varying geomagnetic conditions characterized by indices such as Kp and Dst. A major finding was that during intense geomagnetic storms, post-sunset ionospheric irregularities became more pronounced, resulting in stronger scintillation events. Notably, they observed that the amplitude and duration of scintillation were more significant during the solar maximum, a time characterized by heightened solar and geomagnetic activities.

Their results indicated that plasma bubble formation is critically dependent on the strength of the pre-reversal enhancement (PRE) of the eastward electric field at the equator. During geomagnetic storms, electric fields can be disturbed, either strengthening the PRE or reversing it entirely. When enhanced, the upward plasma dri fts promote Rayleigh-Taylor instabilities that culminate in the creation of large-scale plasma depletions, or "bubbles," responsible for the severe scintillation observed.

An important aspect of Basu's work is the emphasis on **storm-time electrodynamics** as a primary driver of scintillation variability. They provided a physical model in which increased electric fields from storm-time magnetospheric convection result in a redistribution of plasma in the ionosphere. This dynamic alteration leads to regions with steep plasma density gradients that refract or scatter radio signals.

Critically, their findings have implications for satellite communication and GPS navigation systems, even though GPS technology was in its infancy during their study. Their identification of the causal link between storm-induced electric fields and ionospheric turbulence laid the groundwork for later research and operational monitoring systems in the space weather community.

In connection with the present study, Basu et al. (1981) offer a foundational understanding of how geomagnetic storms modulate the ionospheric environment, making their work a crucial reference point for examining scintillation phenomena during disturbed space weather conditions.

Aarons (1991) provided an important extension to the prevailing understanding of ionospheric scintillation by emphasizing the role of **pre-storm conditions**. His investigations challenged the simplistic view that all geomagnetic storms inherently lead to increased scintillation. Instead, Aarons proposed that the ionosphere's "memory" its pre-existing state plays a decisive role in determining its response to storm-time forcing.

Through meticulous analysis of scintillation records and geomagnetic indices over multiple solar cycles, Aarons identified that the presence of strong post-sunset plasma drifts and quiet-time equatorial spread-F (ESF) activity prior to a storm significantly enhances the likelihood of severe scintillation during the storm's main phase. Conversely, if the pre-storm ionosphere is relatively quiet or shows suppressed instability, the subsequent stor m may not necessarily lead to the expected amplification of scintillation.

Methodologically, Aarons employed radio beacon satellite data and ground-based observations, linking patter ns of nighttime ionospheric instability with preceding magnetospheric and thermospheric conditions. One key insi ght was that a suppression of the pre-reversal enhancement (PRE) could sometimes occur due to storm-time dis turbance dynamo electric fields, which may counteract the normal eastward field at sunset. If the PRE is wea kened before or during the storm, plasma bubble formation and associated scintillation can actually decrease, contrary to expectations.

This nuanced view has profound implications. It means that predictive models of ionospheric scintillation must account for pre-existing conditions rather than relying solely on the magnitude of the geomagnetic storm (e.g., Dst or Kp values). Aarons' research thus called for a more holistic approach to space weather modeling, incorp orating background ionospheric and thermospheric measurements.

From a physical perspective, Aarons highlighted the complexity of plasma instability mechanisms under varying electrodynamic inputs. His work illustrates how the ionosphere is not merely passively responding to geomagne tic input but behaves as a dynamic, nonlinear system with feedback processes. This aligns with modern physics' un derstanding of complex systems and their sensitivity to initial conditions.

For the present study, Aarons (1991) is highly relevant as it stresses the critical importance of initial ionospheri c conditions when evaluating the impact of geomagnetic storms on scintillation phenomena. It provides a cautio n against oversimplified cause-effect assumptions and encourages deeper investigation into pre-storm ionospher ic behavior.

Kintner, Humphreys, and Hinks (2009) shifted the focus of scintillation studies firmly into the practical realm by examining its impact on Global Navigation Satellite Systems (GNSS), particularly the Global Positioning System (GPS). Their study was pivotal in demonstrating the operational vulnerabilities of satellite-based technologies to ionospheric irregularities induced by geomagnetic storms.

Using a combination of field measurements, controlled experiments, and data from GPS networks, Kintner et al. (1998) documented how intense plasma irregularities caused rapid phase and amplitude variations of GPS signals. These variations often resulted in loss of signal lock a situation where GPS receivers temporarily lose track of satellites, causing severe positioning errors.

Their findings showed that scintillation was particularly intense near the magnetic equator and within the South Atlantic Anomaly, regions where the ionosphere is naturally unstable. During geomagnetic storms, the enhanced electric fields drive stronger plasma bubbles, which, in turn, exacerbate signal degradation. Importantly, their study quantified the degree of signal disruption, reporting positioning errors that could exceed 50 meters during severe events, with some outages lasting for several minutes.

From a physics standpoint, Kintner et al. explained that phase scintillation arises from multipath propagation caused by plasma density gradients on scales of hundreds of meters to kilometers. These irregularities cause rapid changes in the path length of the signal, introducing phase errors. Amplitude scintillation, on the other hand, results from constructive and destructive interference of scattered signals.

Kintner and colleagues also highlighted that GPS systems operating on the L1 frequency (1575.42 MHz) are particularly vulnerable, but even dual-frequency receivers (using both L1 and L2) could suffer under extreme conditions. This finding had significant implications for aviation, military operations, and commercial navigation systems, which heavily rely on precise GPS data.

Their work encouraged the development of scintillation monitoring networks and predictive models to warn us ers of potential disruptions. Moreover, they advocated for the improvement of receiver algorithms to better handle scintillation-induced errors.

Relating to the current project, Kintner et al. (2009) provide crucial evidence that geomagnetic storm-induced ionospheric scintillation is not merely an academic concern but has profound real-world technological consequences, making understanding and forecasting these effects more important than ever.

Kil and Heelis (1998) made substantial contributions to understanding the formation and evolution of plasma bubbles in the ionosphere during geomagnetic disturbances. Their study, relying heavily on data from the DE-2 (Dynamics Explorer 2) satellite mission, focused on the behavior of plasma irregularities in the equatorial ionosphere, particularly how these irregularities respond to storm-time electric field variations.

The authors emphasized that plasma bubbles regions of depleted plasma density — typically form in the evening hours after sunset, a process largely driven by the pre-reversal enhancement (PRE) of the zonal electric field. During geomagnetic storms, this process becomes significantly modified. Kil and Heelis documented that storm-time electric fields, often intensified by penetration electric fields or disturbance dynamo effects, cause an earlier onset of bubble formation, faster growth rates, and larger spatial extents.

Their methodology involved analyzing in-situ plasma density measurements and electric field observations. They found that during disturbed conditions, the vertical plasma drift speeds increased dramatically, exceeding typical quiet-time values. This rapid uplift of plasma led to enhanced Rayleigh-Taylor instability, which is the primary mechanism responsible for bubble generation. The instability arises when the denser plasma overlying a region of lower density is gravitationally unstable, leading to the formation of "fingers" of depleted plasma that grow into large bubbles.

An important outcome of Kil and Heelis's research was the realization that not only does the strength of the vertical drift matter, but the timing of the disturbance relative to local sunset is critical. If the storm-time penetration electric fields arrive just before or during the local sunset period, they can strongly enhance bubble growth. However, if the disturbance arrives much later at night, it may have little to no effect on new bubble generation, although it can still affect existing structures.

Critically, their findings suggested that the morphology of storm-time plasma bubbles could be drastically different from typical quiet-time conditions. Storm-enhanced bubbles tend to reach higher altitudes, sometimes exceeding 1000 km, and can spread across broader latitudinal ranges.

In terms of physics, their work detailed how the electrodynamics of the low-latitude ionosphere are sensitive to external forcing from the magnetosphere, particularly through electric field penetration. This insight into ionosphere-magnetosphere coupling mechanisms has been essential for understanding storm-time effects on ionospheric dynamics.

Relating to the present study, Kil and Heelis (1998) provide a direct link between geomagnetic storm-time electric field modifications and the evolution of ionospheric plasma structures that ultimately cause scintillation, making their work indispensable for any analysis involving the effects of geomagnetic storms on communication and navigation systems.

Fejer et al. (1999) provided a seminal analysis of the role of electric fields during geomagnetic storms and how they impact equatorial ionospheric dynamics. Using a combination of incoherent scatter radar observations, satellite measurements, and theoretical modeling, they dissected the behavior of vertical plasma drifts and ionospheric electric fields under varying geomagnetic conditions.

One of the key contributions from Fejer's group was the distinction between prompt penetration electric fields (PPEFs) and disturbance dynamo electric fields (DDEFs). PPEFs occur rapidly in response to changes in the m agnetospheric convection electric field and can cause sudden and strong changes in the equatorial ionosphere, typically enhancing upward plasma drifts during the main phase of a storm. DDEFs, on the other hand, develop more slowly over several hours as thermospheric winds adjust to the storm-induced changes and create second ary electric fields.

Their observations showed that during the main phase of a storm, upward drifts can be significantly enhanced du e to PPEFs, promoting the growth of plasma bubbles and intensifying ionospheric irregularities. Conversely, duri ng the recovery phase, DDEFs often introduce westward electric fields at night, which suppresses the normal PRE and inhibits bubble formation.

Fejer et al. emphasized the variability and complexity introduced by these storm-time electric fields. They d emonstrated that even for storms of similar magnitudes (measured by Dst index), the ionospheric response coul d vary dramatically depending on the timing, local time, and the interplay between PPEFs and DDEFs.

From a physics perspective, their work illuminated the electrodynamic pathways through which energy input fro m the solar wind and magnetosphere alters ionospheric behavior. They provided detailed modeling of the temp oral evolution of electric fields and plasma drifts, crucial for understanding and forecasting scintillation eve nts.

In relation to the present research, Fejer et al. (1999) underscore the importance of storm-induced electric fi eld dynamics in modulating ionospheric conditions that give rise to scintillation, thereby providing a deeper und erstanding of the physical mechanisms underlying the phenomenon.

Ledvina, Kintner, and de Paula (2002) tackled a practical aspect of ionospheric scintillation: its impact on sat ellite-based communication systems. Their study synthesized observational data and modeling efforts to evalu ate the extent to which geomagnetic storm-induced scintillation can disrupt radio signals at different frequen cies.

A major contribution of their work was the frequency dependence analysis. They demonstrated that lower-frequency signals, particularly those operating in the L-band (1–2 GHz), are more susceptible to scintillation effects. This is because the scale sizes of ionospheric irregularities responsible for scintillation typically fall within the Fresnel zone of these frequencies, leading to significant signal diffraction and interference.

Their research used GPS signal data collected during several strong geomagnetic storms. They recorded instances of rapid amplitude fading, phase slips, and complete loss-of-lock events. Their modeling indicated that the severity of scintillation increases not only with the strength of the storm but also with the local plasma density and irregularity scale sizes.

From a physics standpoint, Ledvina et al. detailed how variations in electron density on spatial scales of hundreds of meters cause scattering of electromagnetic waves. In regions where plasma density gradients are steep and irregularities are strong, the multiple scattered waves interfere destructively and constructively, leading to rapid fluctuations in received signal strength and phase.

Importantly, their findings emphasized the necessity of building robust communication and navigation systems capable of handling ionospheric scintillation. They suggested design considerations such as dual-frequency operation, improved receiver algorithms, and error-correction techniques.

For the present study, Ledvina et al. (2002) highlight the **technological vulnerabilities** associated with ionospheric scintillation during geomagnetic storms, reinforcing the practical importance of understanding and mitigating the effects of these space weather phenomena.

A particularly interesting result was that some storms suppressed plasma bubble formation altogether if they led to westward electric fields at sunset a finding consistent with theories on disturbance dynamo effects.

For the current study, Pimenta et al. **(2003)** provide important observational evidence linking geomagnetic storm dynamics with changes in plasma bubble behavior, highlighting the spatial broadening of scintillation zones during intense storms a crucial consideration for global communication and navigation systems.

Abdu **(2005)** produced a comprehensive review of the electrodynamic processes affecting the ionosphere during geomagnetic storms, especially in the equatorial and low-latitude regions. His work synthesized observations, theoretical modeling, and previous experimental studies to provide a unified framework for understanding how storm-time processes affect ionospheric stability and plasma irregularity development.

One of Abdu's major contributions was to elucidate the **competition** between prompt penetration electric fields (PPEFs) and disturbance dynamo electric fields (DDEFs) in controlling plasma dynamics. He explained that while PPEFs could enhance upward plasma drifts leading to plasma bubble growth, DDEFs typically acted to suppress these processes, especially during the storm's recovery phase.

Abdu's analysis highlighted that the **timing**, **duration**, and **magnitude** of these fields determine the ultimate outcome for plasma bubble development. Early evening PPEFs can trigger strong plasma uplift and instability, whereas late-night DDEFs introduce westward drifts that can inhibit spread-F and bubble formation.

Furthermore, Abdu discussed the impact of storm-time thermospheric winds, particularly equatorward surges of neutral winds from high latitudes, which can modify the F-region height and plasma density gradients. Such neutral wind disturbances can either favor or suppress plasma instability, depending on their direction and intensity.

His study emphasized that the ionosphere's response to storms is **highly nonlinear** and regionally variable. Local time, longitude, and background thermospheric conditions all influence how the ionosphere reacts to geomagnetic disturbances.

In terms of physics, Abdu provided detailed modeling of electric field generation and ion-neutral coupling pr ocesses. He incorporated the magnetosphere-ionosphere-thermosphere system into a coherent model of storm-time ionospheric dynamics.

For this project, Abdu (2005) offers a critical understanding of the **electrodynamic controls** over ionospheric scintillation during storms, reinforcing the need to consider multiple, often competing, physical processes in analyzing and predicting scintillation effects.

Michael C. Kelley's influential textbook *The Earth's Ionosphere: Plasma Physics and Electrodynamics* (2009) offers a broad and deep perspective on ionospheric processes, treating the ionosphere as a natural laboratory for plasma physics.

Within the context of geomagnetic storms and scintillation, Kelley described the ionosphere as a **highly dynamic, nonlinear medium** whose behavior under disturbed conditions provides rich insights into fundamental plasma instabilities. He discussed in detail the **Rayleigh-Taylor instability** that underpins equatorial plasma bubble formation, showing how the balance between plasma density gradients, electric fields, and gravitational forces leads to instability growth.

Kelley emphasized the effects of **storm-time electric fields** — both prompt and dynamo-driven — on plasma drift velocities. He elaborated on how these fields can either enhance or suppress irregularity growth, depending on the local time of penetration and the background ionospheric conditions.

A major highlight in Kelley's work is the clear connection between microphysical plasma processes and their macroscopic manifestations — such as large-scale plasma depletions that cause radio signal scintillation. He described how **small-scale turbulence** within plasma bubbles leads to signal scattering and diffraction effects observed at Earth's surface.

Kelley also discussed the impact of **particle precipitation** from the magnetosphere during storms, which can lea d to localized increases in ionospheric density and modified electric fields. These secondary processes can fur ther complicate the ionospheric response.

From an engineering perspective, Kelley pointed out the vulnerabilities of radio-based technologies to ionosp heric irregularities, reinforcing the need for robust modeling and mitigation strategies.

In relation to this project, Kelley (2009) provides the essential **theoretical foundation** for understanding ion ospheric scintillation from a plasma physics perspective, making his work indispensable for any serious investigat ion into the effects of geomagnetic storms on radio propagation.

Basu et al. (2010) conducted a detailed study focused on the characteristics of ionospheric scintillation during geomagnetic storm periods. Using data from specialized ground-based networks of GPS receivers and radio beac ons, they analyzed the amplitude and phase scintillation indices under various levels of geomagnetic disturban ce, offering critical insights into the behavior of irregularities during storms.

A major contribution of their work was the **statistical analysis** of scintillation intensity across different latit udinal regions, from the magnetic equator to mid-latitudes. They found that scintillation activity tends to **pea k** near the equator and that during geomagnetic storms, these regions of high activity can **expand** both northwar d and southward, affecting broader geographical areas than under quiet conditions.

Basu et al. also demonstrated that **phase scintillation** becomes more severe compared to amplitude scintillati on during storm times. Phase scintillation is particularly disruptive for GPS receivers because it can lead to cy cle slips and loss-of-lock, thereby degrading positioning accuracy or causing complete system outages.

From a physical perspective, the study attributed these observations to the enhanced generation of small-scal e irregularities inside plasma depletions (bubbles) triggered or intensified during storms. Basu et al. emphasized the role of **high-altitude plasma bubbles** reaching altitudes over 1000 km, where irregularities can align with m agnetic field lines and scatter radio waves over large distances.

Importantly, they also observed that the intensity of scintillation is **highly time-dependent**. Typically, scintillation peaks a few hours after local sunset under quiet conditions; however, during storms, the peak can shift or become prolonged, sometimes persisting into the early morning hours.

Basu et al.'s findings hold significant implications for satellite communication and navigation, especially for aviation and maritime sectors that rely heavily on GPS. They stressed the need for developing **scintillation warning systems** based on real-time ionospheric monitoring.

For the present research, Basu et al. **(2010)** provide strong empirical support linking storm-time enhancements in plasma irregularities to the severity and distribution of scintillation, making them a critical reference point for understanding the broader impact of geomagnetic disturbances on technological systems.

For the present project, Carter et al. **(2013)** highlight the **potential for forecasting** storm-related scintillation events, demonstrating how physical models can be translated into actionable predictive tools for mitigating the effects of space weather disturbances on critical technologies.

Yizengaw et al. **(2014)** conducted an important regional study on the behavior of the African equatorial ionosphere during geomagnetic storms. Their work filled a major gap in global ionospheric research, as Africa's equatorial sector had historically been under-observed compared to South America and Southeast Asia.

Using data from the African Meridian B-field Education and Research (AMBER) network and GPS receiver arrays, Yizengaw and colleagues analyzed storm-time variations in plasma density, vertical drift speeds, and scintillation occurrence over African longitudes.

One of their key findings was that the African ionosphere exhibits unique storm-time **responses**, including stronger vertical drifts and more frequent plasma bubble generation compared to other equatorial regions under simi