JOURNAL OF GEOSPACE SCIENCE

Vol. 6 No. 2 (2026)

E-ISSN : 2413-6093
https://jogss.org

Assessing the Impact of Geomagnetic Storms on the Earth's Ionosphere and Satellite Communication Systems

Elena Maren Voss
Centre for Ionospheric and Satellite Systems Research Northbridge International Institute of Technology, Oslo, Norway

ABSTRACT

Geomagnetic storms disturb the ionosphere through interacting electric fields, particle precipitation, thermospheric heating, and changes in atmospheric composition. Their consequences for satellite services depend on the structure of the disturbed plasma and the design of the receiving system, rather than on magnetic storm intensity alone. This narrative review examines the physical pathways linking solar wind energy input to electron density redistribution, radio propagation errors, scintillation, and communication interruptions. It integrates established ionospheric research, published storm observations, and operational space weather guidance while distinguishing measured findings from analytical illustrations. Particular attention is given to differences between large-scale total electron content variations and small-scale irregularities, because these disturbances require different monitoring and mitigation strategies. An original graph applies the first-order dispersive delay equation to hypothetical electron content values at representative navigation and communication frequencies. The calculation demonstrates frequency sensitivity without claiming to reproduce a particular storm. The review argues that resilience requires coordinated environmental monitoring, suitable receiver tracking, frequency and route diversity, and application-specific integrity checks. Remaining challenges include sparse observations over oceans, imperfect forecasts of irregularities, and limited access to receiver performance records. Improved assessment should connect local plasma conditions to measurable service outcomes and explicitly account for uncertainty.

KEYWORDS

Geomagnetic storms, Ionospheric disturbances, Satellite communications, Total electron content, Ionospheric scintillation

1. Introduction

Satellite communication and navigation services depend on radio signals crossing a variable ionized environment surrounding Earth. The ionosphere supports long-distance radio propagation, but it also introduces delays, changes polarization, and creates rapid signal fluctuations. Under disturbed conditions, these effects can interfere with the availability and reliability of services used in transport,

surveying, telecommunications, emergency response, and scientific observation. Understanding storm effects therefore requires a connection between space plasma physics and the practical performance of radio systems.A geomagnetic storm develops when solar wind conditions transfer substantial energy and momentum into the magnetosphere. Coronal mass ejections and interacting solar wind streams can produce such conditions, although their geoeffectiveness depends on magnetic orientation, speed, duration, and the preceding state of the near-Earth environment. The resulting disturbance is transmitted into the upper atmosphere through multiple pathways. The ionosphere consequently responds as part of a coupled system whose behavior varies across latitude, longitude, altitude, season, and local time (Schunk & Nagy, 2009).The central assessment problem is that no single environmental indicator describes every operational consequence. A strong global magnetic disturbance does not establish that all satellite links are impaired. Similarly, high total electron content does not necessarily imply severe scintillation. A smooth electron distribution can produce substantial dispersive delay while remaining comparatively easy to track. A smaller amount of highly structured plasma can create rapid phase changes that challenge carrier tracking. Service risk must therefore be evaluated at the spatial and temporal scales relevant to the affected system.This article presents a narrative review rather than an original observational experiment or systematic meta-analysis. Its purpose is to explain mechanisms, compare diagnostic approaches, and develop a practical framework for assessing consequences. The nine thematic sections connect storm development to plasma variability, propagation physics, navigation performance, communication vulnerability, published case evidence, monitoring, and mitigation. An analytical graph provides a reproducible example of frequency dependence. The argument throughout is that credible impact assessment requires environmental evidence, receiver behavior, and operational context to be examined together.

Solar Drivers and Magnetosphere Ionosphere Coupling:

Storm development begins outside the ionosphere, where changing solar wind conditions compress and reorganize the magnetosphere. Sustained southward interplanetary magnetic field can favor magnetic reconnection at the dayside boundary, enabling enhanced coupling. Energy is stored and redistributed through magnetospheric currents, plasma transport, and magnetic field reconfiguration. These processes alter the electric fields and particle populations that connect to the high-latitude atmosphere. The ionospheric response is consequently mediated by the magnetosphere rather than determined solely by the brightness of a solar eruption.Electric currents flowing along magnetic field lines connect magnetospheric processes to ionospheric current systems. Enhanced convection moves plasma across the polar regions, while particle precipitation modifies ionization and conductivity. Energy deposited through collisions between charged particles and neutrals heats the upper atmosphere. This Joule heating is especially important because it changes the neutral background in which ionospheric chemistry and transport occur. A complete causal account must therefore follow both charged and neutral components rather than treating the ionosphere as an isolated layer.Prompt changes in electric fields may reach lower latitudes relatively quickly. Their effects depend on local time and the evolving shielding of magnetospheric convection. Disturbance dynamo fields develop through a different pathway: storm-driven neutral winds modify the atmospheric dynamo and subsequently alter electric fields. Blanc and Richmond (1980) established the physical basis for this delayed electrodynamic response. For interpretation, the distinction matters because apparently similar plasma movements can arise at different stages of a storm and can persist after the original external forcing weakens.Magnetic indices provide useful context but represent different parts of the disturbance. Kp summarizes planetary activity over three-hour intervals, whereas Dst characterizes a low-latitude magnetic disturbance strongly influenced by the ring current. Neither directly measures the irregularities intersected by an individual satellite signal. An operator should therefore use these indices as triggers for closer examination rather than as universal outage predictors. Local observations and solar wind histories are needed to determine whether a particular region is experiencing rapid forcing, delayed atmospheric adjustment, or recovery.A further distinction concerns solar flares and geomagnetic storms. Flare radiation can reach Earth and

change ionization before a solar wind disturbance arrives. Energetic particle precipitation can also affect polar propagation through pathways that differ from F-region redistribution. These phenomena may occur within the same broader solar event, but their timing and physical mechanisms are not interchangeable. Assigning every radio anomaly to the magnetic storm obscures causation and weakens the selection of mitigation measures.

Electron Density Redistribution and Thermospheric Feedback:

The ionosphere contains regions with different dominant chemistry, collision rates, and transport behavior. The F region is particularly important for satellite signal delay because it often contains a substantial part of the integrated electron population. Electron density there reflects competition among production, chemical loss, vertical motion, horizontal redistribution, and exchange with the topside ionosphere and plasmasphere. Storms disturb this balance through simultaneous changes in electric fields and the neutral atmosphere. Consequently, both increases and decreases in electron density can develop within the same event.A positive ionospheric response denotes electron density or total electron content above a suitable quiet reference, while a negative response denotes a reduction. These descriptions identify the direction of change rather than a complete explanation. Uplift can move plasma into regions where chemical loss is slower, allowing enhanced densities to persist under favorable illumination. Changes in composition may instead increase loss and reduce F-region density. Buonsanto (1999) reviews these competing processes and the difficulty of separating them using a single measurement type.Thermospheric heating creates pressure gradients and circulation changes that transport composition disturbances beyond their initial source regions. Fuller-Rowell et al. (1994) showed through coupled modeling that neutral winds and composition are central to interpreting storm evolution. Their work supports a broader inference for assessment: plasma anomalies observed far from the auroral zone can result from atmospheric redistribution as well as direct electric forcing. The geographic extent and persistence of the disturbance therefore depend partly on the atmosphere's preceding state and its subsequent circulation.At low latitudes, changes in vertical electric drift can reshape the equatorial ionization anomaly. Plasma lifted near the magnetic equator can move along field lines and change the location or strength of anomaly crests. At middle latitudes, storm-enhanced density structures can introduce sharp gradients along selected paths. At high latitudes, convection can transport dense plasma through the cusp and polar cap. These spatial patterns matter because a terminal does not experience a global average; it samples the plasma lying along its instantaneous lines of sight.Recovery is likewise an active physical phase rather than an immediate return to normality. Neutral composition, winds, plasma refilling, and electric fields can relax at different rates. A decline in a global magnetic index can therefore precede the disappearance of operationally important ionospheric structure. Impact studies should extend their observation windows beyond the main phase and compare recovery behavior with matched quiet conditions. Otherwise, late disruptions may be missed or incorrectly classified as unrelated anomalies.

Total Electron Content and Dispersive Radio Propagation:

Total electron content, commonly abbreviated TEC, is the integral of electron density along a specified path. One TEC unit corresponds to ten to the sixteenth electrons per square metre. Vertical TEC describes an approximately vertical column, whereas slant TEC describes a satellite-to-receiver path and is usually more directly relevant to the received signal. Converting between them requires assumptions about geometry and electron density distribution. These assumptions become consequential when the disturbed ionosphere contains strong horizontal gradients or substantial vertical restructuring.For a sufficiently high radio frequency, the first-order ionospheric group path delay can be approximated by the expression $I = 40.3 \times TEC / f^2$, where I is in metres, TEC is in electrons per square metre, and f is in hertz. The corresponding time delay is I divided by the speed of light. The code observable experiences a positive group delay, while the carrier phase has an advance of equal first-order magnitude when expressed as range. Higher-order magnetized plasma effects and measurement biases require separate treatment for demanding applications.The equation explains why lower-frequency satellite services

generally require greater attention to dispersive delay. Doubling frequency reduces the first-order term by a factor of four for the same electron content. However, this scaling does not describe every propagation impairment. It does not calculate scintillation, signal power, receiver tracking failure, or atmospheric attenuation. The graph in this article is therefore an analytical sensitivity illustration. Its selected TEC values are hypothetical path integrals rather than measurements of a named geomagnetic storm.At an assumed slant TEC of 100 TEC units, the calculated first-order delay is approximately 16.24 metres at 1.57542 GHz and 26.74 metres at 1.22760 GHz. At 4 GHz, the corresponding value is approximately 2.52 metres. These values describe individual propagation terms before correction. They are not direct predictions of position error or communication outage. A positioning solution combines multiple observables, satellite geometry, estimation methods, and corrections, while a communication link has its own timing and tracking requirements.

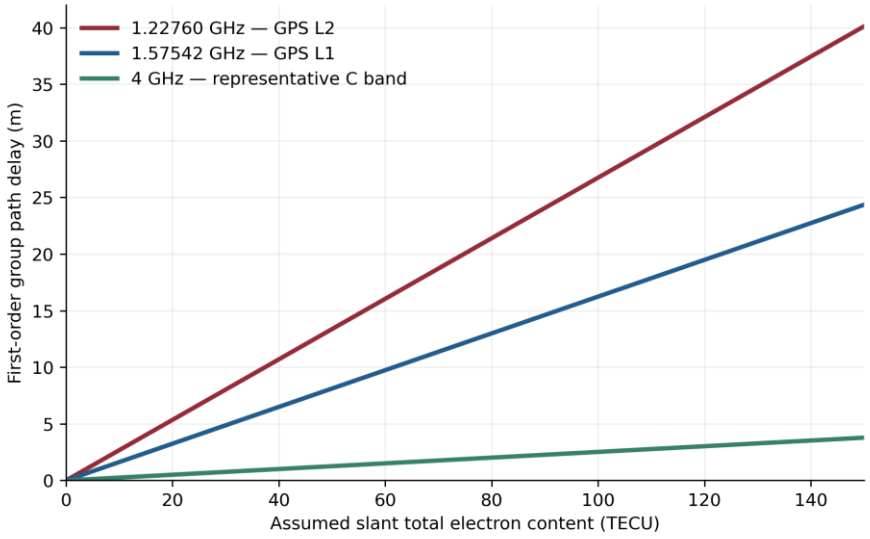


Figure 1 Calculated first-order group path delay at three frequencies. Values use I = 40.3 × TEC / f² and hypothetical slant TEC from zero to 150 TECU. This is an analytical illustration, not observed storm data.

The present review does not estimate an average worldwide outage rate, rank commercial receivers, or calculate economic losses. The selected literature provides mechanisms and examples rather than a statistically representative inventory of all service incidents. Its conclusions are strongest when applied to the design of an assessment framework. Quantitative operational thresholds require additional event data, explicit system specifications, and independent validation under the conditions in which the intended service will operate.Mendillo (2006) emphasizes the value of TEC for describing storm patterns, but integrated content alone cannot specify the distribution of all irregularity scales. Operational interpretation should therefore distinguish bulk delay, spatial gradients, and rapid temporal variation. A large delay that changes smoothly may be correctable, whereas a steep gradient can undermine interpolation from reference stations. The most useful TEC product is one whose sampling, latency, uncertainty, and spatial support match the intended application.

Plasma Irregularities and Ionospheric Scintillation:

Scintillation consists of rapid variations in signal amplitude and phase caused by propagation through structured plasma. Irregular electron density creates fluctuations in refractive index, and scattered signal components interfere at the receiver. The resulting behavior depends on irregularity scales, propagation geometry, wavelength, and relative motion. Kintner et al. (2007) explain why these propagation effects must be considered together with receiver tracking behavior. A signal that remains present in a physical sense may still become unusable if its fluctuations exceed the capabilities of the tracking system.Amplitude scintillation is commonly represented by the S4 index, based on normalized intensity variability over a defined interval. Phase scintillation is often represented by the standard deviation of

detrended carrier phase. Neither index is meaningful without information about sampling, detrending, noise correction, and observation geometry. At high latitudes especially, an inappropriate detrending method can mix large-scale refractive variation with the fluctuations of interest. Comparisons between stations should therefore use compatible processing or explicitly account for differences in the underlying definitions.Low-latitude irregularities frequently involve the development of equatorial plasma depletions after sunset, but storms do not enhance this activity in every circumstance. Changes in electric fields and winds can favor growth or suppress it depending on timing and background conditions. High-latitude disturbances involve different configurations, including auroral structures, polar patches, and their boundaries. An equatorial risk model cannot simply be transferred to the polar region because the relevant drivers, geometries, and characteristic motion differ.The distinction between large-scale structure and small-scale irregularity has practical consequences for forecasting. A regional TEC map may resolve a density enhancement while smoothing over the structure responsible for rapid fading. Conversely, a scintillation receiver samples selected satellite paths and may not represent the entire surrounding area. Combining measurements can improve interpretation, but the observations must be aligned in time and space. Apparent disagreement between instruments may reflect different sampling scales rather than an error in either instrument.A robust operational threshold should be linked to an observed consequence such as repeated cycle slips, loss of carrier tracking, or increased packet errors. Universal scintillation thresholds can conceal differences between antennas, receivers, modulation schemes, and application requirements. The same environment may be tolerable for one service and disruptive for another. This makes co-recorded environmental measurements and engineering telemetry especially valuable: they help identify which plasma characteristics actually exceed the system's operating margin.

Consequences for Satellite Navigation and Timing:

Global navigation satellite systems estimate position and time from signals whose propagation must be modeled accurately. Storm-time ionospheric delay introduces errors when the model or correction does not represent the actual path. Dual-frequency combinations can remove the dominant first-order dispersive term, which is a major advantage over reliance on a single frequency. Nevertheless, correcting a measurement requires that the relevant signals remain trackable. Dual-frequency capability consequently reduces one error mechanism without guaranteeing uninterrupted observations during severe irregularity-driven fading.Carrier-phase applications are particularly sensitive to discontinuities. A cycle slip changes the inferred phase history and can require ambiguity repair or reinitialization. Precise point positioning and differential methods may then lose accuracy or require additional convergence time. Astafyeva et al. (2014) provide observational evidence linking disturbed ionospheric conditions with degraded GPS measurement quality. Their findings support the need to distinguish between an available signal, a valid observable, and a positioning solution meeting the required accuracy and integrity standards.Reference networks and augmentation services face a related spatial problem. Corrections calculated at one station are most useful when nearby users experience sufficiently similar conditions. A steep or rapidly evolving ionospheric gradient can violate this assumption. For safety-sensitive navigation, the critical concern is whether the correction uncertainty is bounded reliably and whether a warning arrives in time. Reduced availability may be an appropriate protective response when the system cannot guarantee its integrity requirements, even if some position estimates remain numerically plausible.Timing services depend on the same propagation environment but have distinct operational tolerances. A timing receiver may continue providing a stable output through short disruptions if it has suitable holdover capability. The quality of that holdover depends on the local oscillator and the duration of lost or rejected satellite observations. A communication network can therefore experience timing stress even when its own radio traffic uses frequencies relatively insensitive to ionospheric delay. Assessment must include dependencies on navigation timing within the wider service architecture.Multi-constellation reception increases the number of potentially usable satellites and can improve geometric redundancy. Its benefit is conditional because nearby lines of sight may

cross the same disturbed plasma region. More satellites also create additional opportunities to detect inconsistency between observations. The engineering objective should be dependable measurement selection and calibrated uncertainty, not merely maximizing satellite count. Application-specific tests are needed to determine how long the system can tolerate degraded tracking, biased corrections, or interrupted initialization.

Vulnerability of Satellite Communication Links:

Communication satellites use a range of frequency bands, waveforms, antenna configurations, and orbital geometries. Lower microwave frequencies are generally more exposed to ionospheric dispersive effects than substantially higher bands, but communication performance depends on more than propagation delay. Rapid fading and phase changes can challenge synchronization and demodulation. The relevant assessment variables include carrier-to-noise density, fade duration, phase dynamics, coding margin, and the tracking response of the terminal. NOAA's satellite communications guidance identifies severe scintillation as a potential source of link disruption (NOAA SWPC, n.d.-a).Faraday rotation provides an additional mechanism for systems using linear polarization. The rotation depends on electron content, the geomagnetic field projected along the path, and frequency. If the received polarization becomes poorly matched to the antenna, useful signal power can decline. System design can reduce susceptibility through appropriate polarization choices and compensation. This mechanism should be evaluated separately from scintillation because the diagnostic observations and engineering remedies differ, even though both originate in the ionized propagation medium.Geostationary links sample comparatively stable viewing directions, whereas low Earth orbit links change geometry rapidly and require frequent handovers. These differences affect how long a ray path remains within a disturbed region and how propagation variability interacts with terminal tracking. A constellation may provide alternative paths, but coordinated switching must account for whether those alternatives intersect the same irregularities. Route diversity is effective only when the alternative route provides sufficient environmental and infrastructure independence to reduce the relevant failure mode.Higher-frequency links require a balanced interpretation. Their first-order ionospheric delay is smaller, yet they can be strongly affected by lower-atmospheric conditions such as rain attenuation. A storm-time communication outage at such a terminal should therefore not be attributed automatically to the ionosphere. Weather records, terminal telemetry, network status, and space weather measurements should be compared. This attribution discipline prevents expenditure on remedies that address the wrong mechanism and helps establish whether several simultaneous environmental pressures are involved.Spacecraft charging, energetic particle damage, and increased drag can also disrupt satellite services during disturbed periods. These are important space weather hazards, but they are distinct from radio propagation through the ionosphere. Drag can influence orbit prediction and operations, while charging can affect spacecraft electronics. A credible incident report should identify which pathway is supported by evidence. Grouping all satellite anomalies under ionospheric interference prevents meaningful comparison between events and exaggerates what propagation monitoring can diagnose.

Published Storm Evidence and Comparative Interpretation:

Published case studies demonstrate that intense storms can produce extensive ionospheric restructuring, yet the observed patterns differ between events. Mannucci et al. (2005) investigated the October 2003 Halloween storms and documented a pronounced dayside response associated with strong interplanetary forcing. Their interpretation includes prompt electric-field effects and plasma uplift. The case establishes that storm coupling can reorganize electron content over broad regions. It does not establish that every point within those regions experiences identical scintillation or communication performance.Cross-event investigations are useful because isolated examples can overemphasize an unusual configuration. Astafyeva et al. (2014) connect storm disturbances to GPS tracking problems across events of different strength. The important lesson for application assessment is that magnetic intensity should be compared with direct measurements of signal behavior. A storm with a lower global index can still create a damaging local configuration if sharp gradients or irregularities develop along operationally important

paths. Conversely, a major storm can leave some systems functioning within their design margins.Comparative interpretation must account for observation bias. Dense receiver networks provide detailed information over some continental regions, while oceans and parts of the Southern Hemisphere remain less well observed. Reported disturbance maps therefore reflect both the actual plasma state and the distribution of available measurements. An absence of reported impairment is weaker evidence when monitoring is sparse. Studies should state station coverage, data gaps, quality control, and the criteria used to count failed or degraded observations.Quiet-time references also influence the apparent size of a storm effect. A monthly average, a nearby quiet day, and an empirical climatology can yield different anomaly estimates. Each choice has advantages, but none removes all variability associated with solar illumination, atmospheric waves, or ordinary day-to-day changes. Event comparison is more informative when authors report both absolute measurements and departures from a clearly defined baseline. Uncertainty in that baseline should be recognized rather than folded silently into a claimed storm response.Case evidence should ultimately support mechanism-specific conclusions. A TEC increase demonstrates altered integrated content; a scintillation record demonstrates rapid propagation variability under its processing definition; receiver logs establish tracking behavior. Connecting these observations strengthens causal interpretation when their timing and geometry agree. Without that connection, explanations remain plausible hypotheses. The review therefore favors qualified attribution over universal claims that a particular storm magnitude necessarily produces a specified level of satellite service disruption.

Monitoring and Modeling for Impact Assessment:

An effective observing strategy combines complementary instruments. Ground-based GNSS networks provide extensive slant TEC measurements, ionosondes constrain bottomside electron density structure, and incoherent scatter radars can resolve plasma parameters and motion. Radio occultation supplies vertical information along selected satellite geometries, while in situ instruments sample local plasma conditions. No instrument captures the complete disturbed system. Integration is needed because storm processes span scales from global circulation to irregularities intersecting individual radio paths.Operational TEC products help translate observations into regional or global descriptions. NOAA's electron content resources illustrate the use of observational and modeled information for monitoring ionospheric conditions (NOAA NCEI, n.d.). For service assessment, product resolution must be compared with the relevant disturbance scales. A global map can be suitable for estimating broad delay patterns but insufficient for detecting the steepest gradients. Users should also examine latency and uncertainty, since a spatially accurate reconstruction received too late may have little operational value.Physics-based models represent the governing transport, chemistry, and coupling processes, while empirical models summarize patterns learned from observations. Data assimilation combines observations with a model and an explicit treatment of uncertainty. Scherliess et al. (2009) demonstrate the value of this approach for recovering ionospheric dynamics. For operational use, the challenge is to determine which aspects of the state are actually constrained by measurements and which remain strongly dependent on assumptions or poorly specified external forcing.Forecast evaluation should use independent events and avoid sharing closely related storm intervals between training and testing. A model that reproduces broad TEC patterns may still fail to predict rare tracking interruptions. Performance measures should therefore reflect the intended service: delay error, gradient exceedance, scintillation occurrence, loss-of-lock probability, or time to recovery. Probability calibration matters because operators act on confidence as well as the predicted magnitude. A useful forecast quantifies how often its stated likelihoods are realized.A reproducible assessment workflow begins with synchronized clocks and documented preprocessing. Receiver biases, multipath, satellite geometry, elevation masks, and missing data can imitate or distort environmental signatures. Environmental measurements should then be linked to engineering logs and tested against alternative explanations. Reporting the complete sequence from raw observations to service outcome makes the conclusion auditable. It also allows later studies to compare systems without assuming that identically named indices or failure counts were

calculated in the same way.

Mitigation Strategies and Future Research Priorities:

Resilience begins with a clear definition of acceptable degradation. A consumer messaging service, an aircraft navigation system, and a precision timing network have different requirements for continuity, accuracy, and warning. Engineering measures should therefore be matched to the consequence being controlled. Additional link margin can help with some fades, while robust tracking algorithms address selected phase dynamics. Neither approach automatically corrects stale ionospheric corrections or repairs a long interruption in a precision carrier-phase solution.Frequency diversity, multi-constellation reception, and geographically separated routes can reduce exposure when they provide sufficiently independent observations or paths. Adaptive coding and modulation can preserve communication under reduced signal quality, although throughput may decline. Receiver tracking settings may also be adjusted to disturbance conditions, subject to tradeoffs between noise rejection and dynamic response. The effects should be tested using representative signals and actual terminal behavior. A proposed mitigation is credible only when its benefit is demonstrated for the relevant failure mechanism.Operational preparation should connect forecasts to predefined actions. These may include closer monitoring, postponing particularly sensitive measurements, checking timing holdover, validating backup routes, and temporarily tightening integrity checks. NOAA's guidance on scintillation emphasizes its dependence on location and environmental conditions (NOAA SWPC, n.d.-b). This supports geographically targeted responses rather than blanket assumptions of global failure. Operators should also define recovery criteria so that normal operations resume on evidence of restored performance rather than on a single declining magnetic index.Research priorities include denser observations in underserved regions, better characterization of irregularity evolution, and improved sharing of anonymized receiver performance data. Environmental researchers often have detailed plasma measurements without access to application outcomes, while service providers possess failure records without sufficient environmental context. Joint studies could connect these records using common timing and geometry standards. Such collaboration would help distinguish correctable delay, tracking stress, infrastructure dependence, and unrelated equipment faults within the same disturbance interval.Future assessments should publish processing choices, uncertainty budgets, and negative results alongside notable disruptions. Open descriptions of successful operation during severe conditions are useful for identifying which designs provide resilience. Analytical examples, including the graph presented here, should remain clearly separated from observations. The most productive direction is a calibrated chain of evidence linking solar wind forcing to local plasma structure, radio observables, receiver response, and service consequences. That chain provides a stronger foundation for investment than storm classification alone.

Summary:

Geomagnetic storms affect satellite services through a coupled sequence of magnetospheric forcing, ionospheric transport, thermospheric adjustment, and radio propagation changes. Their effects are geographically uneven and can continue into recovery. The review distinguishes integrated electron content, gradients, and small-scale irregularities because these properties create different engineering problems. Large-scale delay can often be estimated and corrected, while rapid fading and phase fluctuations may remove the observations required for correction. Communication and navigation systems consequently need different combinations of environmental monitoring and performance protection.The analytical graph shows the inverse-square dependence of first-order group path delay on frequency for explicitly hypothetical TEC values. It illustrates a physical relationship without claiming new storm measurements, predicting an outage, or equating path delay with positioning error. Published evidence supports the broader conclusion that service impacts depend on local plasma structure, viewing geometry, receiver capability, and operational requirements. Reliable assessment therefore combines global indices with path-specific observations, engineering telemetry, and uncertainty-aware models. Progress will depend on reproducible event comparisons, improved coverage, and tested mitigation

matched to particular failure mechanisms.

References:

Astafyeva, E., Yasyukevich, Y., Maksikov, A., & Zhivetiev, I. (2014). Geomagnetic storms, super-storms, and their impacts on GPS-based navigation systems. Space Weather, 12, 508–525. https://doi.org/10.1002/2014SW001072

Blanc, M., & Richmond, A. D. (1980). The ionospheric disturbance dynamo. Journal of Geophysical Research, 85(A4), 1669–1686. https://doi.org/10.1029/JA085iA04p01669

Buonsanto, M. J. (1999). Ionospheric storms—A review. Space Science Reviews, 88, 563–601. https://doi.org/10.1023/A:1005107532631

Fuller-Rowell, T. J., Codrescu, M. V., Moffett, R. J., & Quegan, S. (1994). Response of the thermosphere and ionosphere to geomagnetic storms. Journal of Geophysical Research, 99(A3), 3893–3914. https://doi.org/10.1029/93JA02015

Kintner, P. M., Jr., Ledvina, B. M., & de Paula, E. R. (2007). GPS and ionospheric scintillations. Space Weather, 5, S09003. https://doi.org/10.1029/2006SW000260

Mannucci, A. J., Tsurutani, B. T., Iijima, B. A., Komjathy, A., Saito, A., Gonzalez, W. D., Guarnieri, F. L., Kozyra, J. U., & Skoug, R. (2005). Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 "Halloween Storms". Geophysical Research Letters, 32, L12S02. https://doi.org/10.1029/2004GL021467

Mendillo, M. (2006). Storms in the ionosphere: Patterns and processes for total electron content. Reviews of Geophysics, 44, RG4001. https://doi.org/10.1029/2005RG000193

National Oceanic and Atmospheric Administration, National Centers for Environmental Information (NOAA NCEI). (n.d.). Total electron content (US-TEC and GloTEC). https://www.ncei.noaa.gov/products/space-weather/ionospheric-program/total-electron-content

National Oceanic and Atmospheric Administration, Space Weather Prediction Center (NOAA SWPC). (n.d.-a). Satellite communications. https://www.spaceweather.gov/impacts/satellite-communications

National Oceanic and Atmospheric Administration, Space Weather Prediction Center (NOAA SWPC). (n.d.-b). Ionospheric scintillation. https://www.swpc.noaa.gov/phenomena/ionospheric-scintillation

Scherliess, L., Thompson, D. C., & Schunk, R. W. (2009). Ionospheric dynamics and drivers obtained from a physics-based data assimilation model. Radio Science, 44, RS0A32. https://doi.org/10.1029/2008RS004068

Schunk, R. W., & Nagy, A. F. (2009). Ionospheres: Physics, plasma physics, and chemistry (2nd ed.). Cambridge University Press. https://www.cambridge.org/core/books/ionospheres/0C725C779F49AE7DF0C45BF5A350A003