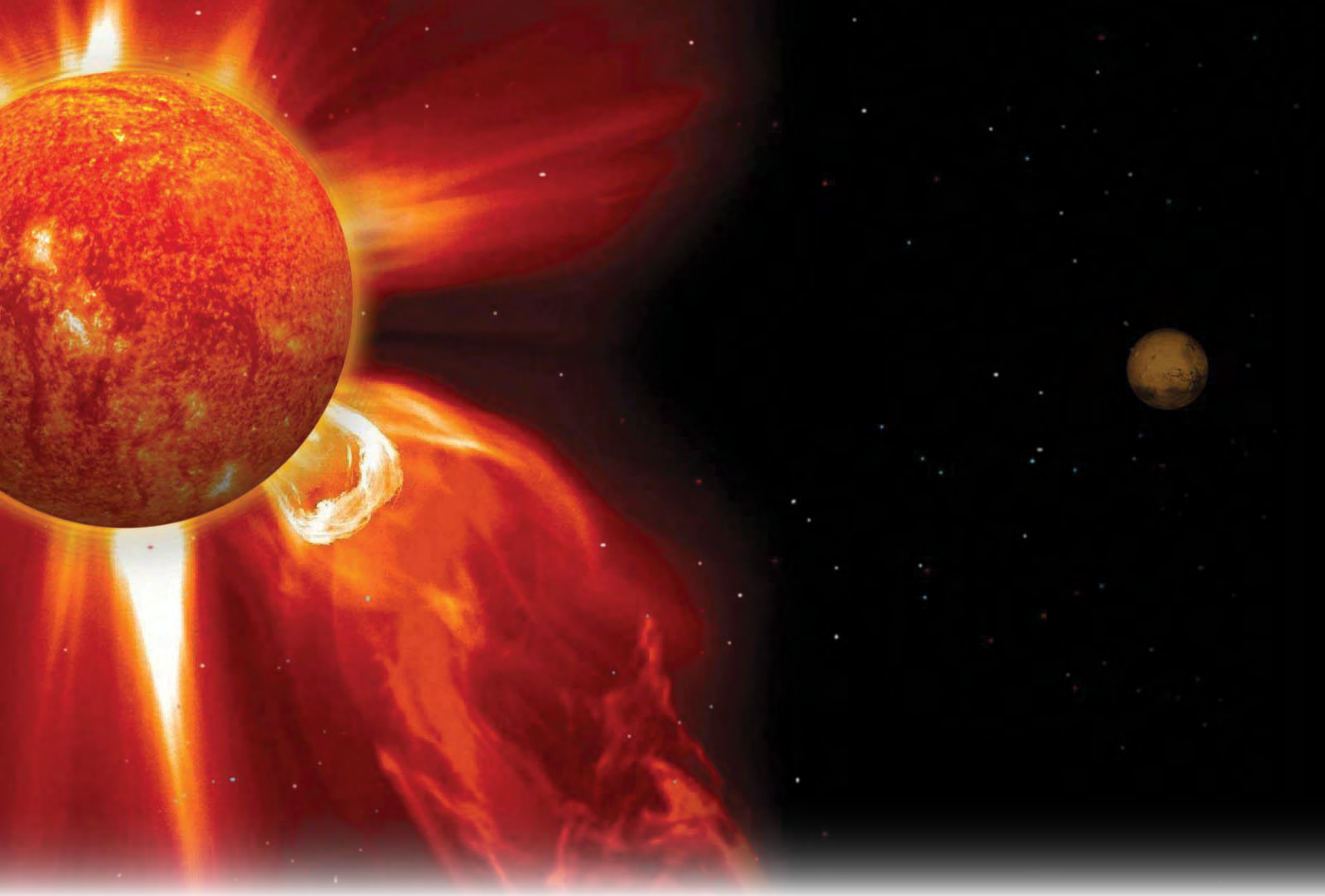

SPACE WEATHER EFFECTS ON GNSS:

Ionospheric Scintillation and Geomagnetic Storms

SPIRENT Communications

SPACE WEATHER EFFECTS ON GNSS: Ionospheric Scintillation and Geomagnetic Storms

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Abstract

Except for the precise application of GNSS orbit and clock products, the ionosphere is the largest naturally occurring error source in point positioning.

Ionospheric dynamics are highly dependent on solar activity or space weather such as solar flares, solar energetic particles and coronal mass ejections (which can cause geomagnetic storms).

On a regular, highly variable basis, space weather in the ionosphere causes signal scintillation, the diffraction and refraction of the signals as those signals propagate through electron density gradients in the ionosphere, ionospheric dispersion or both (geomagnetic storm effects). Signal scintillation/dispersion is highly dynamic and its properties vary depending on time of day, geomagnetic (not geographic) location and, especially, space weather (or solar activity).

The following whitepaper provides a summary of the space weather phenomena, its effects on the ionosphere and the subsequent impact on GNSS as well as a few examples of major space weather events and consequences in history. Understanding space weather phenomena is a critical foundation to effectively and accurately evaluating and mitigating ionospheric signal scintillation/dispersion events.

SPACE WEATHER EFFECTS ON GNSS: Ionospheric Scintillation and Geomagnetic Storms

CHAPTER 1:

The Space Weather Phenomena

Under the broadest definition, space weather[1] is all of the dynamic conditions in the Earth's outer space environment, including events on the sun, in the solar wind, in near-Earth space and in the upper atmosphere, which can affect space-borne and ground-based technological systems.

A few space weather cause/effect scenarios include:

- Solar Flares: Strong x-rays degrade/block high-frequency radio waves used for radio communication (similar to jamming).
- Solar Energetic Particles (energetic protons): Particles penetrate satellite electronics and cause electrical failure. These energetic particles also block radio communications at high latitudes (precipitation).
- Coronal Mass Ejections (CMEs): Can cause geomagnetic storms on Earth when interacting with the geomagnetic field, eroding of the upper ionosphere (compress magnetic field) and inducing extra currents in the ground that can degrade power grid operations and degrade GNSS accuracy.

While the impact of space weather (e.g., solar flares, CMEs) is strongly related to 11-year solar activity cycle,

major space events can occur at any time. Radio blackout storms, solar radiation storms and geomagnetic storms are the commonly seen 'effect' of solar flares, solar energetic particle events and CMEs, respectively (i.e. the causes).

Space weather causes/effects manifest within the ionosphere.

THE IONOSPHERE

The ionosphere, that layer of atmosphere that extends vertically from about 70 km to 1000 km above the Earth, is an electrically neutral plasma of ions and free electrons mainly caused by the ionization of the neutral atmosphere by solar UV radiation. The polar regions also experience particle precipitation, which contributes to the ionosphere.

Ionospheric activity is dependent on solar activity, time of day, location on Earth and seasons.

The ionosphere is the largest naturally occurring error source in point positioning (after the application of precise GNSS orbit and clock products). The impact of the ionosphere on radio communication is dependent on two tightly coupled factors: signal frequency and ionospheric conditions (electronic density variations).

During geomagnetic storms (caused by CMEs) and other energetic particle events, the ionosphere experiences increased particle precipitation at high latitudes and an expansion of the aurorae equatorward. The impact of particle participation is strong enough that the bulk ionosphere increases in the mid-latitudes, causing ionospheric signal scintillation or the rapid fluctuation of signal amplitude and phase of an electromagnetic signal.

As an analogy, daily ionospheric scintillation might be compared to regular or normal rainfall occurrences, while a geomagnetic storm is a specific weather event like a hurricane on Earth.

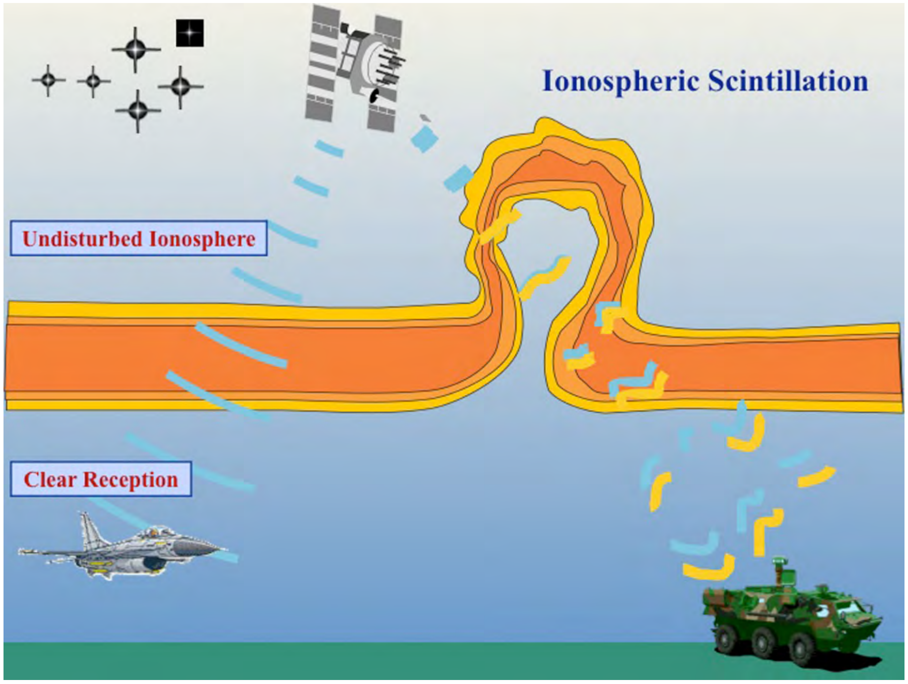

FIGURE 1: Ionospheric scintillation *(courtesy of NASA)*

In essence, ionospheric dynamics—and thus signal scintillation—are caused by space weather.

SIGNAL SCINTILLATION

Signal scintillation, the diffraction and refraction of signals as they propagate through electron density gradients in the ionosphere, is highly dynamic and its properties vary depending on time of day, geomagnetic (not geographic) location and solar activity.

Scintillation is not event-specific, but instead is a daily issue. Different mechanisms contribute to signal scintillation in different regions. For example:

- Equatorial regions—all equatorial regions experience scintillation caused by plasma bubbles, commonly from post sunset until dawn
- High latitudes—polar cusp/precipitation with scintillation throughout the day (slight increase at night time)

In addition, there are some regionally-based propagation idiosyncrasies. For instance, peculiarities in ionospheric conditions are commonly observed over Brazil due to local physical conditions. In Brazil, the scintillation 'season' is observed from September to March from 20:00-00:00 hours, with maximum in December (summer).

Scintillation is also a problem at mid-latitude locations during geomagnetic storms. For example, satellite tracking problems typically occur around equatorial and polar regions, which will subsequently degrade initialization and positioning performance.

The effect of scintillation on space-borne and ground-based technological systems such as GNSS is multi-fold.

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CHAPTER 2:

Impact on GNSS

The space weather effects on GNSS occur due to three distinct phenomena:

1. Ionospheric dispersion—i.e. the group delay/phase advance
2. Ionospheric scintillation
3. Geomagnetic storm effects—combination of enhanced dispersion effects and scintillation

The following details each of these phenomena and the subsequent effects.

IONOSPHERIC DISPERSION

GNSS signals have to pass through the ionosphere causing the modulation of a GNSS signal to be delayed in proportion to the electron density (note that speed of propagation through the ionosphere is referred to as the group velocity). The same condition causes an equivalent RF carrier phase advancement.

In general, ionospheric effects are stronger as frequency decreases. Keep in mind that the ionosphere is a dispersive medium: n = c/v and n is frequency dependent, which means code and carrier signals travel with different velocities (a).

GNSS signals experience a group delay along with an equal carrier phase advance (b):

IONOSPHERIC SCINTILLATION

During a scintillation event, scintillation strengths are a function of frequency. Amplitude scintillation is generally measured by the S4 index—the normalized standard deviation of the received power:

$$S_4 \propto \frac{1}{f^{(1.5)}}$$

The S4 relationship breaks down during a very strong scintillation event.

Phase scintillation is measured by σ_φ (sigma-phi), the standard deviation of the signal's carrier phase:

$$\sigma_\varphi \propto \frac{1}{f}$$

In equatorial regions, GNSS signals experience mainly diffraction conditions:

- Amplitude scintillation causing deep signal fades.
- Very strong scintillation conditions accompanied by phase scintillation.

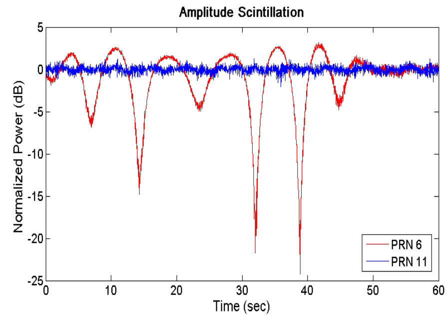


FIGURE 2: Amplitude scintillation

At high latitudes (polar regions), the primary cause of scintillation is signal refraction dominated by phase scintillation.

In summary, scintillating GNSS signals disrupt a receiver's tracking ability, leading to loss of signal lock, causing degraded accuracy, availability and reliability. Scintillating GNSS signals are a safety critical concern for operations such as aviation and PPP applications.

GEOMAGNETIC STORMS

Geomagnetic storms, which can last from a few hours to a week, can also increase electronic density in the ionosphere and cause delays.

Effectively a combination of enhanced ionospheric dispersion and scintillation conditions, these storms can result in widespread degradation of PNT solution accuracy and reliability for an extended period of time and create jamming-like effects if accompanied by Radio Blackout Storms.

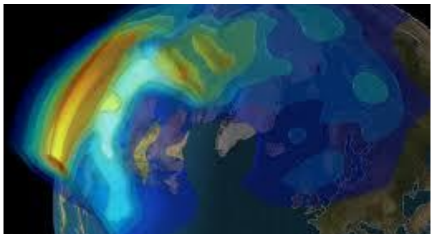
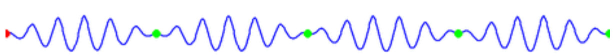


FIGURE 3: Electron density reconstruction during geomagnetic storm

a.



$$n_{carrier} = 1 - \frac{40.3 n_e}{f^2}; \qquad n_{nav+code} = 1 + \frac{40.3 n_e}{f^2}$$

$$v = \frac{c}{n}; \qquad v_{carrier} = \frac{c}{1 - \frac{40.3 n_e}{f^2}}; \qquad v_{nav+code} = \frac{c}{1 + \frac{40.3 n_e}{f^2}}$$

$$\Rightarrow \quad v_{carrier} = -v_{nav+code}$$

b.

$$r_{iono} = \int_{User}^{SV} (n-1)\,dl \quad \Rightarrow \quad \boxed{sTEC = \int_{User}^{SV} n_e\,dl}$$

CHAPTER 3:
Historical Events

CASE STUDY 1:
BRAZILIAN LONGITUDINAL IRREGULARITIES

In a 2007 paper, space research scientists studied the characteristics of the ionospheric irregularities over Brazilian longitudinal Sector[2] as well as recommendations for mitigation.

In this region, the authors noted that plasma instability processes in the post-sunset equatorial ionosphere generate plasma depleted regions/bubbles that vary in size from centimeters to kilometers. Subsequently, radio phase and amplitude signals passing through these irregularities undergo significant fluctuations that can cause degradation in the GPS navigational accuracy and tracking performance.

The authors studied storm-triggered GPS scintillations from two events—the magnetic storm of April 10-13, 2001 and the magnetic storm of November 20–22, 2003.

The magnetic storm of April 2001 caused strong GPS scintillation outside of the irregularities season in Brazilian sector.

Figure 4 shows the scintillation indices S4 for six different satellites and at the equatorial station of São Luís, Maranhão, Brazil. The storm commenced at 13:43 UT on April 11, 2001 and the Dst reached its largest negative incursion at about 24 UT (21 LT) in the night 11/12, when eastward magnetospheric electric field penetrated to magnetic equator. Large scintillations observed at GPS amplitude signals were triggered in the night 11/12 for the satellites 6, 10, 21, 23 and 25 and were intensified for the satellite 26.

In 2003, the disturbance dynamo westward zonal electric fields that occurred during the magnetic storm reached low latitudes, reducing the plasma upward drift during day and downward drift during night. In this way, the prereversal vertical drift peak is inhibited/reduced in amplitude and, as a result, the ionospheric irregularity generation is weakened or inhibited.

Figure 5 shows the S4 scintillation index over São José dos Campos for eight GPS satellites from November 19–22. The storm energy deposition occurred during the day and at low lat-

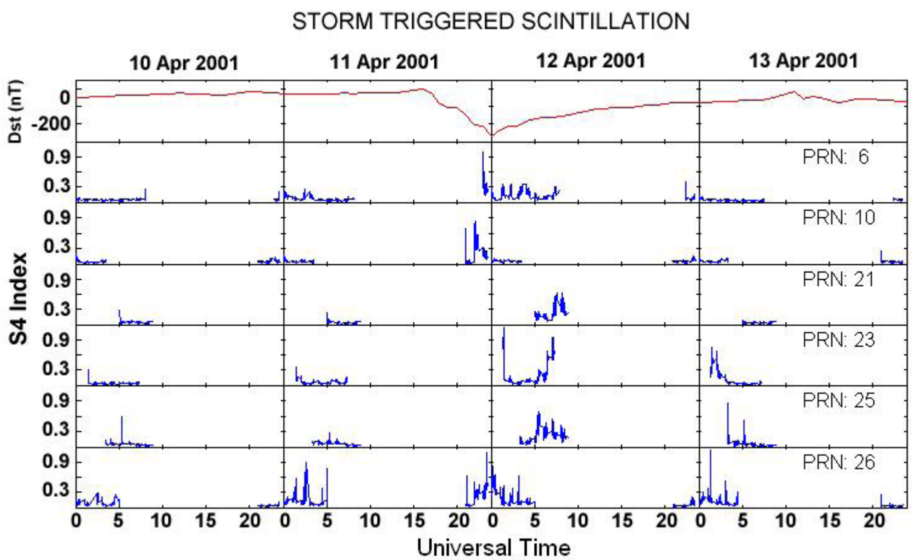


FIGURE 4: Storm triggered GPS scintillations from the April 11, 2001 magnetic storm *(courtesy PaulaEtAl_2007)*

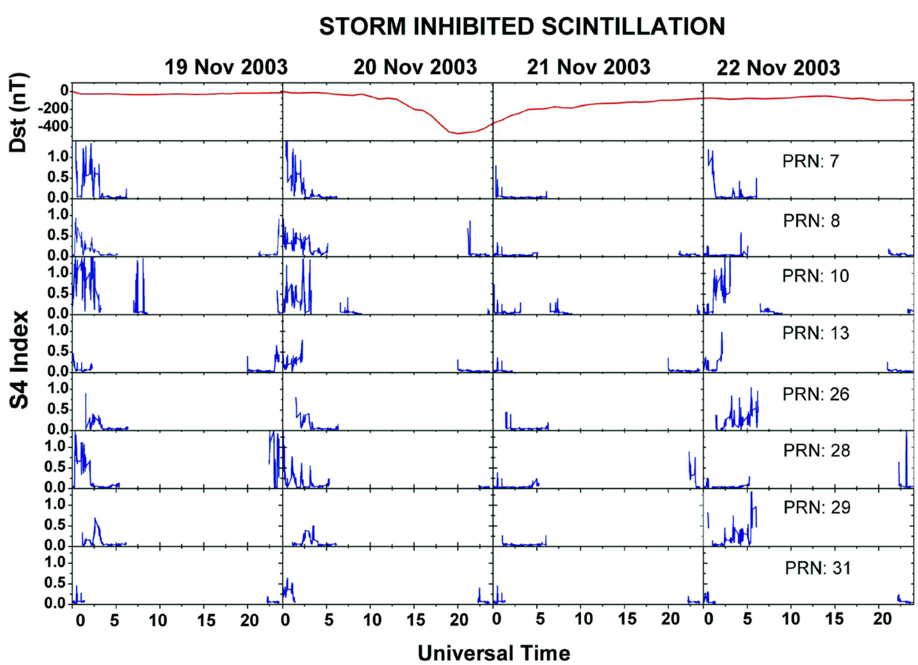


FIGURE 5: Westward electric field GPS scintillation from Nov. 20-22, 2003 magnetic storm[2]

itudes during the post sunset hours inhibiting the prereversal electric field enhancement and the subsequent irregularity development. Scientists also observed strong GPS scintillations during the nights of November 18/19 and 19/20 previous to the SSC and in the night of 21/22 during the storm recovery phase.

The Brazilian region is unique in that ionospheric irregularities occur at varying times. They occur predominantly from September to March, thought they can occur at any epoch of the year during magnetic storms, with the increase in solar flux values, in the sunset–midnight local time sector during magnetically quiet period and extend to the midnight-sunrise sector during some magnetic storms. They are suppressed during magnetic storms with main phase occurring during daylight, and several hours prior to sunset, causing the disturbance dynamo electric fields to reach the equatorial latitudes and leading to the inhibition of the prereversal electric field and they can also be triggered or intensified during any season when magnetic storm main phase, and therefore eastward electric field penetration to equatorial latitudes coincides with the prereversal electric field enhancement peak hours.

Ionospheric irregularities can affect the GPS positioning and navigation due to losses of lock during strong scintillations, what increase the GDOP and decrease the number of available GPS satellites. To mitigate these effects, it is suggested to increase the number of available satellites (Galileo), to decrease the bandwidth of the GPS receivers, to implement real time scintillation detectors as a warning system and to select carefully the positioning of the geostationary SBAS satellites.

To mitigate ionospheric scintillation effects over the Space Based Augmentation System (SBAS), increase the number of available satellites, build more robust GPS receivers decreasing the bandwidth of receivers and/or implement real time scintillation detectors to flag areas where large error in the GNSS system could occur. According to the authors, it's also helpful to carefully select the geostationary SBAS satellite locations with adequate longitudinal separation

The authors noted: "Ionospheric irregularities present large day-to-day variabilities and they depend on local time, season, solar cycle activity and magnetic activity, so many aspects of their generation and evolution still remain to be clarified and more in-situ and remote measurements need to be performed."

CASE STUDY 2: IONOSPHERIC SCINTILLATIONS AND AVIATION

In 2012, researchers studied the impacts of ionospheric scintillations on GPS receivers intended for equatorial aviation applications for the solar maximum year of 2002 (March 5–19, 2002)[3] as a way to improve modeling and simulations and to improve aviation GPS receiver architecture. During this time, scientists observed deep signal fades, which led to navigation outages (fewer than four satellites) during most nights of the event.

As part of the equatorial aviation study, the Akala, et.al. study team analyzed GPS data acquired at Ascension Island during the Air Force Research Laboratory (AFRL) campaign of the 2002 solar event.

For the purposes of this whitepaper, make note of the ionospheric irregularities that cause the carrier-to-noise density ratio (C/No) values of satellites to fluctuate rapidly. Equatorial ionospheric scintillation reduces the number of satellites that are available for a receiver to calculate a navigation solution, leading to poor dilution of precisions and positioning accuracy and deep signal fades (>20 dB-Hz), and subsequently, navigation outages. As the authors note, the extent of these modulations on a satellites signal depends largely on whether the signals from the satellites traverse a patch of ionospheric irregularities in the sky or not.

During the 2002 event, up to five or more satellites signals were scintillating at times, many of them strong. The outages were generally localized between 2100 and 2300 UT of the nights with durations ranging from 1s to 50s. On the most active night, six outages were observed and while most were less than 10s in duration, one outage lasted for 25s and two longer outages lasted for 50s each.

During the active night, most of the satellites' signals experienced scintillation. Ionospheric irregularities modulated the C/No, leading to incursions in excess of 20 dB–Hz at times.

Figures 6a–6b show the C/No of the satellites in view of the receiver during the less active night and a worst data of the active night respectively, at a time window of 180 s. The choice of a 180 s time window was informed by the interest to observe the signal characteristics of each satellite during a short time period, especially near a navigation outage.

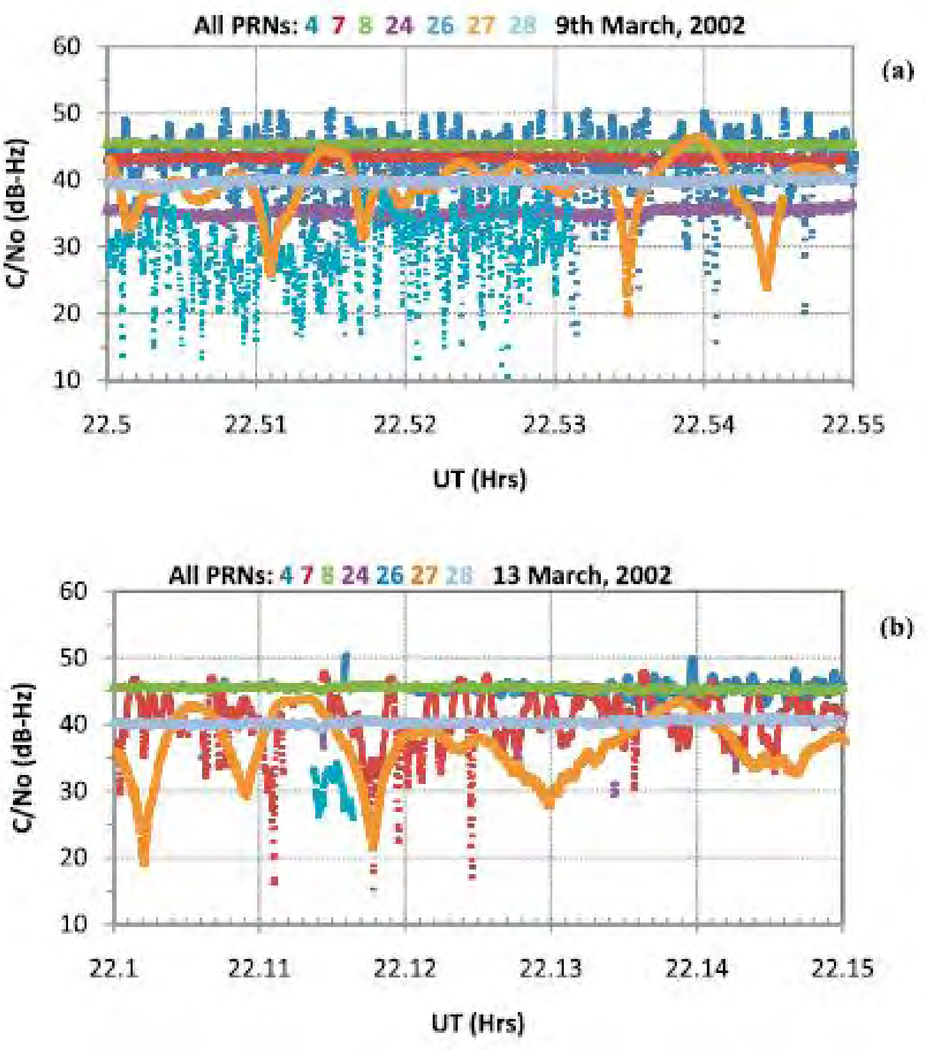


FIGURE 6: Carrier-to-noise density ratio for a 180s time window during (a) less active night and (b) active night[3]

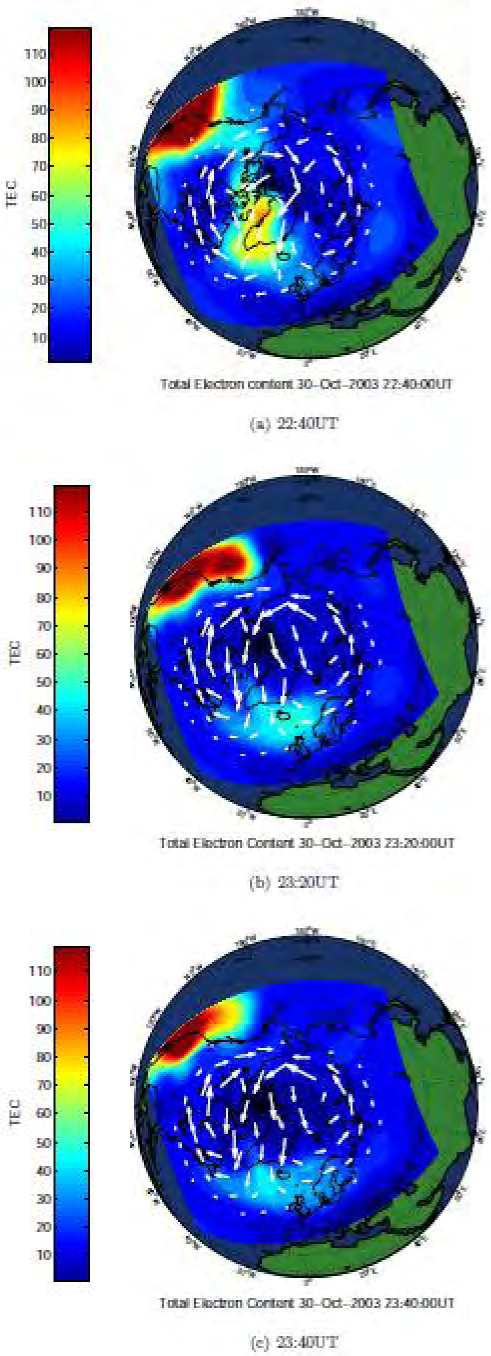
The authors noted, that while an international multi-constellation network will reduce the chances of ionospheric disturbances, they won't eliminate the challenge. They concluded, "Scintillation being a nature-made phenomenon may cover line of sight of most of the satellites if their tracking locations are in the region of scintillation in the sky. Moreover, SBAS satellites are geostationary satellites. This implies that they have a permanent IPP, and if they are covered by scintillation patches, until the patches move away, they will continue to suffer fading because they (geostationary satellites) are not moving. Applications of other augmentations such as GBAS and ABAS will be of significant advantage in enhancing aviation safety under these conditions."

CASE STUDY 3: THE HALLOWEEN 2003 STORM

During the Halloween Storms of 2003, flares from sun's magnetic field lines created coronal mass ejections that blasted billions of tons of electrified gas and subatomic particles into space between Oct. 19–Nov. 7. The event was one of the most intense geomagnetic disturbances ever recorded. Lasting more than three days, high-density plasma was uplifted in the dayside ionosphere and convected anti-sunward across the polar cap to European high latitudes, ultimately causing sever radio disturbances that forced aircraft to reroute, affected satellite systems and communications, and caused power outages in parts of the world.

In 2008, P. Yin, et.al.[4] sought to better understand high latitude plasma transport and the origin of electron density enhancements to support for future studies of high-latitude morphology and dynamics. The team used a multi-instrument approach to differentiate between density structures observed at the EISCAT (European Incoherent SCATter) Svalbard Radar (ESR), which occurred as a result of cross-polar transport, and those more likely to have been produced by in-situ soft particle precipitation.

The team presented data from the ESR and the EISCAT mainland UHF radar at Tromsø, that was recorded during the second night of this intense disturbance. As well, they used global dual frequency GPS measurements provided by the International GNSS Service (IGS) with a 4-D Multi-Instrumental Data Analysis System (MIDAS) tomographic algorithm to investigate the source of the high-density plasma observed by the two EISCAT radars.



During major geomagnetic storms with southward IMF orientation, reconnection occurs between the magnetosphere and the solar wind, resulting in a large energy transfer through the open magnetic field into the polar ionosphere.

For our purposes, the study provides a comprehensive picture of total electron content (TEC) changes during this event.

For example, ***Figure 7*** shows the GPS TEC maps in the Northern Hemisphere on 30 October 2003 at certain times, reflecting the cross-polar movement of high density plasma. The TEC maps show that high-density plasma convecting from high latitude Canada toward the west of Greenland had drifted across Qaanaaq and covered much of southern Greenland by 22:40 UT (7a) and then weakened as it drifted equatorward into Europe ***(7b and 7c)***.

FIGURE 7: GPS ECT maps over the Northern Hemisphere at a) 22:40UT, b) 23:20 UT and c) 23:40 UT on 30 October 2003.[4]

CASE STUDY 4:
SPACE WEATHER EVENTS AND BUSINESS

The final case study[5] explored the direct impact of space weather on our lives and economies.

Probability data suggest a major geomagnetic storm affecting a large area of the globe is a 1 in 100-year event and therefore potentially at the extreme end of business continuity planning. The more frequent 1 in 10 year severe geomagnetic and solar radiation storms have serious enough impact and frequency to be considered by financial risk and business continuity professionals.

Disruptions to GNSS services may impact time stamping but can also affect commuter rail networks that rely on GNSS technology. Solar geomagnetic storms may cause flights to be disrupted, diverted or cancelled. Although firms cope with these service interruptions on a daily basis, it is important whenever possible to have advanced information for informed decision-making.

The report spotlights major space weather events that have occurred over the last 160 years and the technological consequences.

SEPTEMBER 2, 1859

On this date, British amateur astronomer Richard Carrington observed the dual occurence of a solar flare and a coronal mass ejection, which caused a geomagnetic storm on Earth. The event made some telegraph systems inoperable.

TABLE 1: 1859 Carrington flare, CME and geomagnetic storm *(courtesy of University College London[5])*

Flare intensity	X15 to X42 [1,2]
Coronal mass ejection transit time	17.5 hours
Geomagnetic storm intensity	Dst = - 850 nT[3]

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MARCH 13, 1989–QUEBEC

A geomagnetic storm caused by a coronal mass ejection on this date felt in Quebec over a period of about 30 hours.

The event affected 6 million people, caused a strong voltage fluctuations and ultimate shutdown (two minutes) to the Hydro-Quebec electric grid.

Flare intensity	X4.5[4]
Coronal mass ejection transit time	54 hours
Geomagnetic storm intensity	Dst = - 640 nT

TABLE 2: March 10, 1989 solar flare, CEM and geomagnetic storm. *(courtesy of University College London[5])*

HALLOWEEN STORMS 2003

(referenced in previous case study)

The sun produced a series of flares, coronal mass ejections and energetic particle events all at once. The effects were felt for several days. High-frequency communications blackout and risk of exposure to excessive particle radiation caused aircraft on high latitude routes to reduce altitude or to re-route and GNSS service was out for one hour on Oct. 29.

30th October 2003	
Flare intensity	X10 (flare occurred on 29th October)
Coronal mass ejection transit time	19 hours
Geomagnetic storm intensity	Kp 9
Radiation storm intensity	S3

TABLE 3: Solar activity and geomagnetic storm, Oct. 29, 2003. *(courtesy of University College London[5])*

JULY 2012— PERFECT STORM EVENT

On this date, the Sun produced a series of fast coronal mass ejections that were recorded by the STEREO Ahead solar observatory spacecraft. The data collected by the spacecraft showed that one of the coronal mass ejections had the highest speed and magnetic field strength ever measured at the distance of the Earth from the Sun.

Flare intensity	Not observed
Coronal mass ejection transit time	19 hours
Geomagnetic storm intensity	Dst = -600 nT to -1150 nT[8]

TABLE 5: July 2012 coronal mass ejection and estimated geomagnetic storm.

Technological impact on 29th October 2003			
Technological impact	Air traffic controllers reported minor to severe impact on HF communications[5]	Global Navigation Satellite System	Electricity network
Onset time		14:00 UTC on 29th October	None
Duration of disruption	26th October to 5th November	1 hour	None

TABLE 4: (Below) Impact of Oct. 29, 2003 storm *(courtesy of University College London[5])*

CHAPTER 4:

Challenges to Modeling Ionospheric Threats

The variability of ionospheric conditions makes modeling ionospheric threats to space-borne and ground-based technological systems a challenge.

Statistical models can provide the climate of ionospheric conditions. However, the ionosphere is highly dynamic and given to weather-like conditions that are not captured in statistical models.

The IRI model/MIDAS image comparison graphics and scintillation signature variability in Figure 8 and 9 reflect the difference in variability from the ionosphere modelling point of view (POV). In contrast, the scintillation signature variability shown in the images is the variability seen from the GPS receiver's point of view. demonstrate the challenge.

As Akala et al. reports in the Radio Science3 report, says, "…GPS receivers are usually designed and subjected to bench tests via modelling and simulations to ascertain their capabilities (Hegarty et al., 2001; Conker et al., 2003; Humphreys et al., 2009, 2010a, 2010b), but these testing strategies can give misleading results if the scintillation time histories … are not realistic."

Akala et al further noted that in field testing at Ascension Island during the solar maximum years of solar cycle 23, "Bishop et al. [1998], Groves et al. [2000] and Ganguly et al. [2004] observed receiver performance degradations that were much worse than those anticipated by the simulations … conducted prior to the campaign."

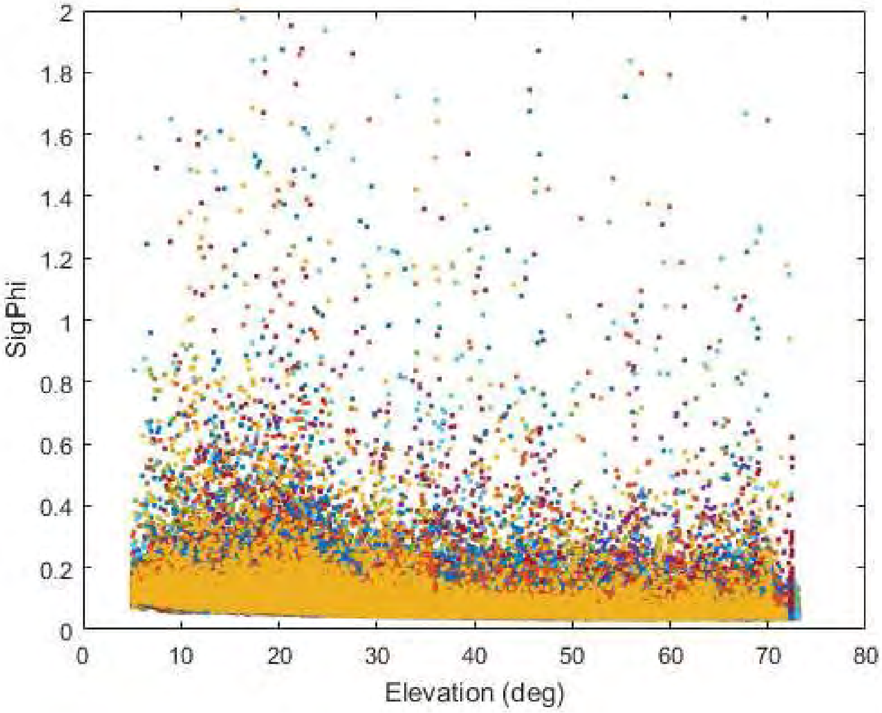

FIGURE 9: Cape Verde scintillation signature

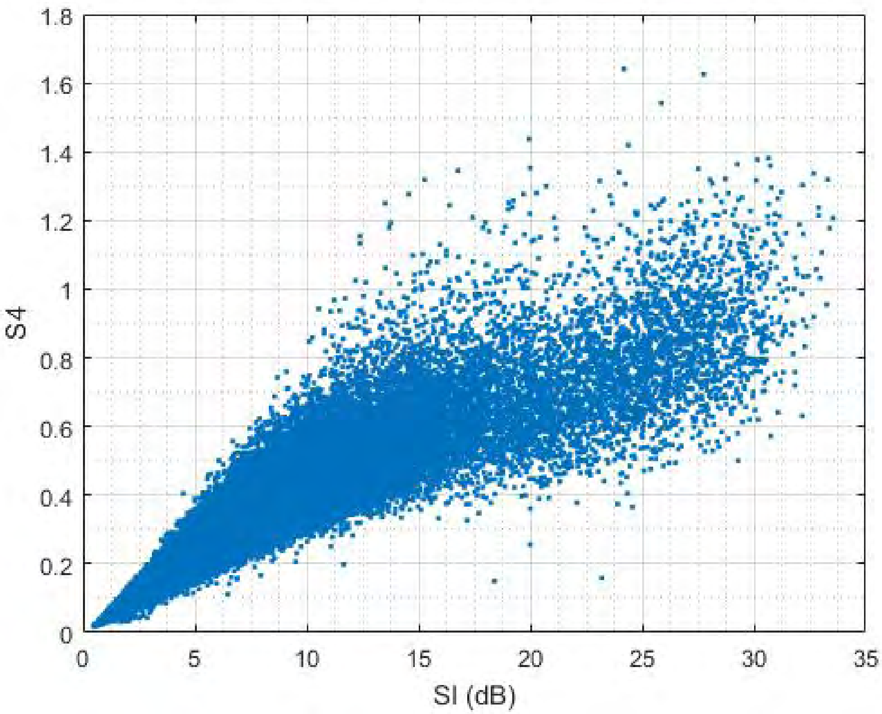

FIGURE 10: Tromso scintillation signature

"Although there is a growing realization that vulnerability arises not simply due to low-frequency and high-impact events, but also due to continuing degradation as a consequence of many smaller impacts, understanding the most severe event that might occur is crucial for disaster planning scenarios," noted Eastwood et al, in The Economic Impact of Space Weather, Risk Analysis, Vol 37. No. 2, 2017.

Despite the challenges, simulators can be used to effectively and accurately model ionospheric threats. Stay tuned for a follow-up whitepaper on this topic, which will reference to simulations used to model bulk ionospheric threats and scintillation scenarios.

ABOUT SPIRENT

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