# Ionospheric Scintillations

## How Irregularities in Electron Density Perturb Satellite Navigation Systems

The Satellite-Based Augmentation Systems Ionospheric Working Group

**THE IONOSPHERE.** I first became aware of its existence when I was 14. I had received a shortwave radio kit for Christmas and after a couple of days of soldering and stringing a temporary antenna around my bedroom, joined the many other "geeks" of my generation in the fascinating (and educational) hobby of shortwave listening. I avidly read *Popular Electronics* and *Electronics Illustrated* to learn how shortwave broadcasting worked and even attempted to follow a course on radio-wave propagation offered by a hobbyist program on Radio Nederland. Later on, a graduate course in planetary atmospheres improved my understanding.

The propagation of shortwave (also known as high frequency or HF) signals depends on the ionosphere. Transmitted signals are refracted or bent as they experience the increasing density of the free electrons that make up the ionosphere. Effectively, the signals are "bounced" off the ionosphere to reach their destination.

**INNOVATION INSIGHTS**
with Richard Langley

Scintillations can bedevil GNSS.

At higher frequencies, such as those used by GPS and the other global navigation satellite systems (GNSS), radio signals pass through the ionosphere but the medium takes a toll. The principal effect is a delay in the arrival of the modulated component of the signal (from which pseudorange measurements are made) and an advance in the phase of the signal's carrier (affecting the carrier-phase measurements). The spatial and temporal variability of the ionosphere is not predictable with much accuracy (especially when disturbed by space weather events), so neither is the delay/advance effect. However, the ionosphere is a dispersive medium, which means that by combining measurements on two transmitted GNSS satellite frequencies, the effect can be almost entirely removed. Similarly, a dual-frequency ground-based monitoring network can map the effect in real time and transmit accurate corrections to single-frequency GNSS users. This is the approach followed by the satellite-based augmentation systems such as the Federal Aviation Administration's Wide Area Augmentation System.

But there is another ionospheric effect that can bedevil GNSS: scintillations. Scintillations are rapid fluctuations in the amplitude and phase of radio signals caused by small-scale irregularities in the ionosphere. When sufficiently strong, scintillations can result in the strength of a received signal dropping below the threshold required for acquisition or tracking or in causing problems for the receiver's phase lock loop resulting in many cycle slips.

In this month's column, the international Satellite-Based Augmentation Systems Ionospheric Working Group presents an abridged version of their recently completed white paper on the effect of ionospheric scintillations on GNSS and the associated augmentation systems.

The ionosphere is a highly variable and complex physical system. It is produced by ionizing radiation from the sun and controlled by chemical interactions and transport by diffusion and neutral wind. Generally, the region between 250 and 400 kilometers above the Earth's surface, known as the F-region of the ionosphere, contains the greatest concentration of free electrons. At times, the F-region of the ionosphere becomes disturbed, and small-scale irregularities develop. When sufficiently intense, these irregularities scatter radio waves and generate rapid fluctuations (or scintillation) in the amplitude and phase of radio signals. Amplitude scintillation, or short-term fading, can be so severe that signal levels drop below a GPS receiver's lock threshold, requiring the receiver to attempt reacquisition of the satellite signal. Phase scintillation, characterized by rapid carrier-phase changes, can produce cycle slips and sometimes challenge a receiver's ability to hold lock on a signal. The impacts of scintillation cannot be mitigated by the same dual-frequency technique that is effective at mitigating the ionospheric delay. For these reasons, ionospheric scintillation is one of the most potentially significant threats for GPS and other global navigation satellite systems (GNSS).

Scintillation activity is most severe and frequent in and around the equatorial regions, particularly in the hours just after sunset. In high latitude regions, scintillation is frequent but less severe in magnitude than that of the equatorial regions. Scintillation is rarely experienced in the mid-latitude regions. However, it can limit dual-frequency GNSS operation during intense magnetic storm periods when the geophysical environment is temporarily altered and high latitude phenomena are extended into the mid-latitudes. To determine the impact of scintillation on GNSS systems, it is important to clearly understand the location, magnitude and frequency of occurrence of scintillation effects.

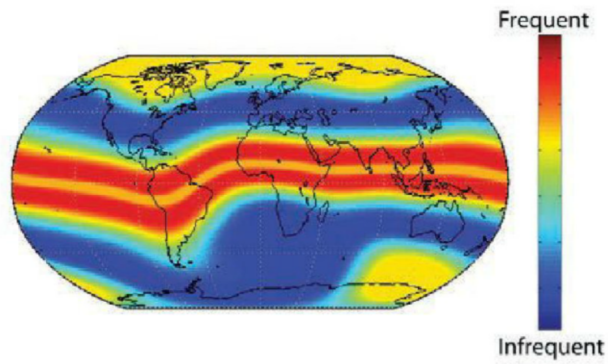
This article describes scintillation and illustrates its potential effects on GNSS. It is based on a white paper put together by the international Satellite-Based Augmentation Systems (SBAS) Ionospheric Working Group (see Further Reading).

## Scintillation Phenomena

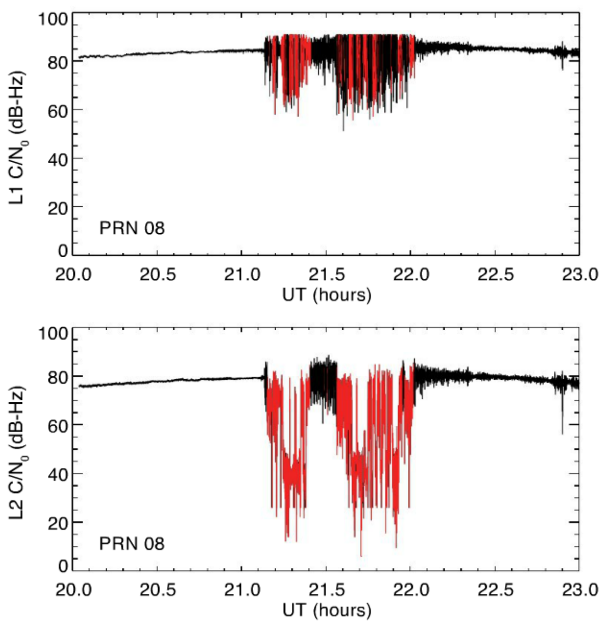
Fortunately, many of the important characteristics of scintillation are already well known.

**Worldwide Characteristics.** Many studies have shown that scintillation activity varies with operating frequency, geographic location, local time, season, magnetic activity, and the 11-year solar cycle. **FIGURE 1** shows a map indicating how scintillation activity varies with geographic location. The Earth's magnetic field has a major influence on the occurrence of scintillation and regions of the globe with similar scintillation characteristics are aligned with the magnetic poles and associated magnetic equator. The regions located approximately 15° north and south of the magnetic equator (shown in red) are referred to as the equatorial anomaly. These regions experience the most significant activity including deep signal fades that can cause a GNSS receiver to briefly lose track of one or more satellite signals. Less intense fades are experienced near the magnetic equator (shown as a narrow yellow band in between the two red bands) and also in regions immediately to the north and south of the anomaly regions. Scintillation is more intense in the anomaly regions than at the magnetic equator because of a special situation that occurs in the equatorial ionosphere. The combination of electric and magnetic fields about the Earth cause free electrons to be lifted vertically and then diffuse northward and southward. This action reduces the ionization directly over the magnetic equator and increases the ionization over the anomaly regions. The word "anomaly" signifies that although the sun shines above the equator, the ionization attains its maximum density away from the equator.

Low-latitude scintillation is seasonally dependent and is limited to local nighttime hours. The high-latitude region can also encounter significant signal fades. Here scintillation may also accompany the more familiar ionospheric effect of the *aurora borealis* (or *aurora australis* near the southern magnetic pole) and also localized regions of enhanced ionization referred to as polar patches. The occurrence of scintillation at auroral latitudes is strongly dependent on geomagnetic activity levels, but can occur in all seasons and is not limited to local nighttime hours. In the mid-latitude regions, scintillation activity is rare, occurring only in response to extreme levels of ionospheric storms. During these periods, the active aurora expands both poleward and equatorward, exposing the mid-latitude region to scintillation activity. In all regions, increased solar activity amplifies scintillation frequency and intensity. Scintillation effects are also a function of operating frequency, with lower signal frequencies experiencing more significant scintillation effects.




▲ **FIGURE 1** Global occurrence characteristics of scintillation. (Figure courtesy of P. Kintner)

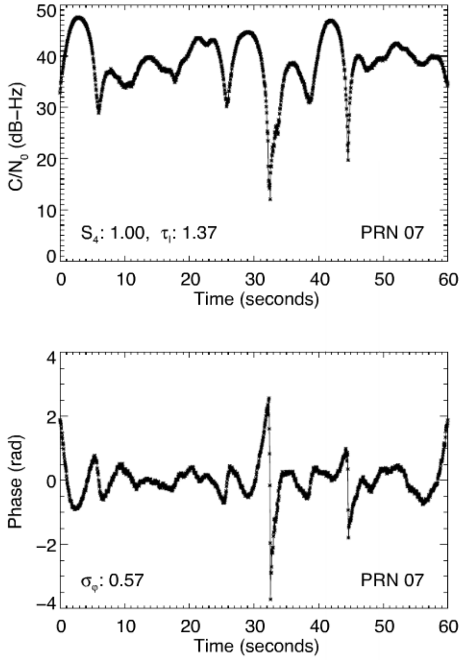



▲ **FIGURE 2** Fading of the L1 and L2 Signals from one GPS satellite recorded from Ascension Island on March 16, 2002. Absolute power levels are arbitrary. (Figure courtesy of C. Carrano)

**Scintillation Activity.** Scintillation may accompany ionospheric behavior that causes changes in the measured range between the receiver and the satellite. Such delay effects are not discussed in detail here but are well covered in the literature and in a previous white paper by our group (see Further Reading, available online).

Amplitude scintillation can create deep signal fades that interfere with a user's ability to receive GNSS signals. During scintillation, the ionosphere does not absorb the signal. Instead, irregularities in the index of refraction scatter the signal in random directions about the principal propagation direction. As the signal continues to propagate down to the ground, small changes in the distance of propagation along the scattered ray paths cause the signal to interfere with itself, alternately attenuating or reinforcing the signal measured by the user. The average received power is unchanged, as brief, deep fades are followed by longer, shallower enhancements.

Phase scintillation describes rapid fluctuations in the




▲ **FIGURE 3** Intensity (top) and phase scintillations (bottom) of the GPS L1 signal recorded from Ascension Island on March 12, 2002. (Figure courtesy of C. Carrano)

observed carrier phase obtained from the receiver's phase lock loop. These same irregularities can cause increased phase noise, cycle slips, and even loss of lock if the phase fluctuations are too rapid for the receiver to track.

**Equatorial and Low Latitude Scintillations.** As illustrated in Figure 1, the regions of greatest concern are the equatorial anomaly regions. In these regions, scintillation can occur abruptly after sunset, with rapid and deep fading lasting up to several hours. As the night progresses, scintillation may become more sporadic with intervals of shallow fading. **FIGURE 2** illustrates the scintillation effect with an example of intense fading of the L1 and L2 GPS signals observed in 2002, near a peak of solar activity. The observations were made at Ascension Island located in the South Atlantic Ocean under a region that has exhibited some of the most intense scintillation activity worldwide. The receiver that collected this data was one that employs a semi-codeless technique to track the L2 signal. Scintillation was observed on both the L1 and L2 frequencies with 20 dB fading on L1 and nearly 60 dB on L2 (the actual level of L2 fading is subject to uncertainty due to the limitations of semi-codeless tracking). This level of fading caused the receiver to lose lock on this signal multiple times. Signal fluctuations depicted in red indicate data samples that failed internal quality control checks and were thereby excluded from the receiver's calculation of position. The dilution of precision (DOP), which is a measure of how pseudorange errors translate to user position errors, increased each time this occurred. In addition to the increase in DOP, elevated ranging errors are observed along the individual satellite links during scintillation.

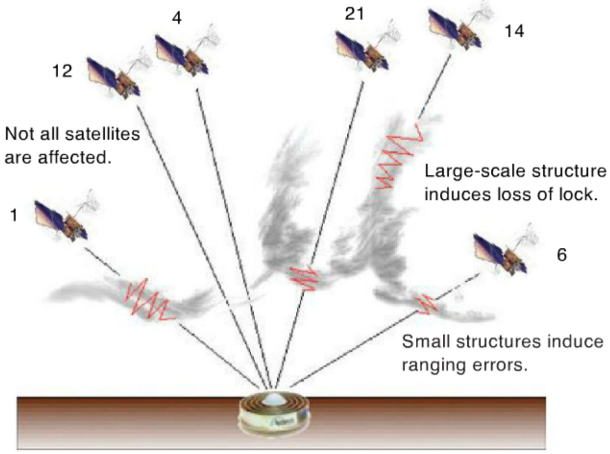
**FIGURE 3** illustrates the relationship between amplitude and phase scintillations, also using measurements from Ascension Island. As shown in the figure, the most rapid phase changes are typically associated with the deepest signal fades (as the signal descends into the noise). Labeled on these plots are various statistics of the scintillating GPS signal: S4 is the scintillation intensity index that measures the relative magnitude of amplitude fluctuations, $\tau_I$ is the intensity decorrelation time, which characterizes the rate of signal fading, and $\sigma_\varphi$ is the phase scintillation index, which measures the magnitude of carrier-phase fluctuations.

The ionospheric irregularities that cause scintillation vary greatly in spatial extent and drift with the background plasma at speeds of 50 to 150 meters per second. They are characterized by a patchy pattern as illustrated by the schematic shown in **FIGURE 4**. The patches of irregularities cause scintillation to start and stop several times per night, as the patches move through the ray paths of the individual GPS satellite signals. In the equatorial region, large-scale irregularity patches can be as large as several hundred kilometers in the east-west direction and many times that in the north-south direction. The large-scale irregularity patches contain small-scale irregularities, as small as 1 meter, which produce scintillation. Figure 4 is an illustration of how these structures can impact GNSS positioning. Large-scale structures, such as that shown traversed by the signal from PRN 14, can also cause significant variation in ionospheric delay and a loss of lock on a signal. Smaller structures, such as those shown traversed by PRNs 1, 21, and 6, are less likely to cause loss of the signal, but still can affect the integrity of the signal by producing ranging errors. Finally, due to the patchy nature of irregularity structures, PRNs 12 and 4 could remain unaffected as shown. Since GNSS navigation solutions require valid ranging measurements to at least four satellites, the loss of a sufficiently large number of satellite links has the potential to adversely affect system performance.

**FIGURE 5** illustrates the local time variation of scintillations. As can be seen, GPS scintillations generally occur shortly after sunset and may persist until just after local midnight. After midnight, the level of ionization in the ionosphere is generally too low to support scintillation at GNSS frequencies. This plot has been obtained by cumulating, then averaging, all scintillation events at one location over one year corresponding to low solar activity. For a high solar activity year, the same local time behavior is expected, with a higher level of scintillations.

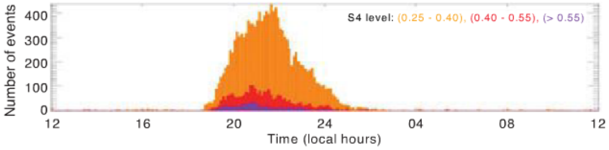
**FIGURE 6** (top panel) shows the variation of the monthly occurrence of scintillation during the pre-midnight hours at Ascension Island. The scintillation data was acquired by the use of Inmarsat geostationary satellite transmissions at 1537 MHz (near the GNSS L1 band). The scintillation occurrence is illustrated for three levels of signal fading, namely, > 20 dB (red), > 10 dB (yellow), and > 6 dB (green). The bottom panel shows the monthly sunspot number, which correlates with solar activity and indicates that the study was performed during the years 1991 to 2000, extending from the peak of solar cycle 22 to the peak of solar cycle 23. Note that there is an increase in scintillation activity during the solar maximum periods, and there exists a consistent seasonal variation that shows the presence of scintillation in all seasons except the May-July period. This seasonal pattern is observed from South American longitudes through Africa to the Near East. Contrary to this, in the Pacific sector, scintillations are observed in all seasons except the November-January period. Since the frequency of 1537 MHz is close to the L1 frequencies of GPS and other GNSS including GLONASS and Galileo, we may use Figure 6 to anticipate the variation of GNSS scintillation as a function of season and solar cycle. Indeed, in the equatorial region during the upcoming solar maximum period in 2012-2013, we should expect GNSS receivers to experience signal fades exceeding 20 dB, twenty percent of the time between sunset and midnight during the equinoctial periods.

**High Latitude Scintillation.** At high latitudes, the ionosphere is controlled by complex processes arising from the interaction of the Earth's magnetic field with the solar wind and the interplanetary magnetic field. The central polar region (higher than 75° magnetic latitude) is surrounded by a ring of increased ionospheric activity called the auroral oval. At night, energetic particles, trapped by magnetic field lines, are precipitated into the auroral oval and irregularities of electron density are formed that cause scintillation of satellite signals. A limited region in the dayside oval, centered closely around the direction to the sun, often receives irregular ionization from mid-latitudes. As such, scintillation of satellite signals is also encountered in the dayside oval, near this region called the cusp.

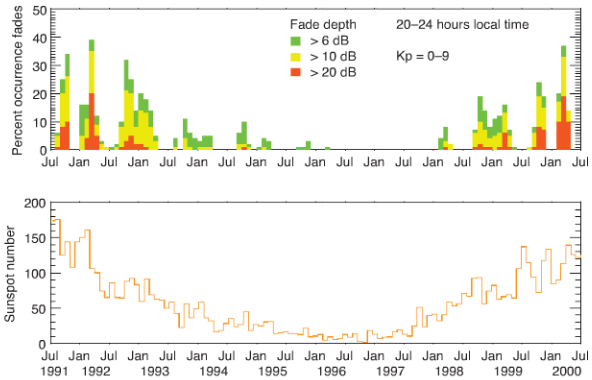



▲ **FIGURE 4** Schematic of the varying effects of scintillation on GPS.

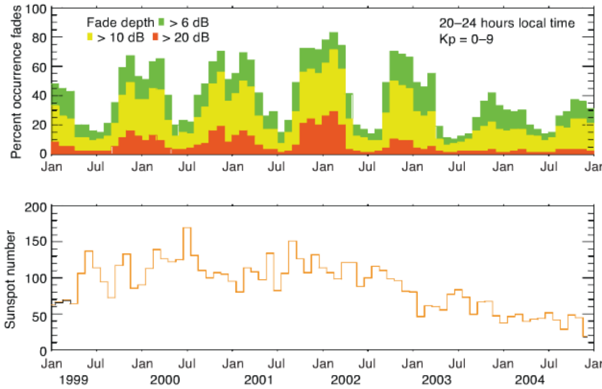
When the interplanetary magnetic field is aligned oppositely to the Earth's magnetic field, ionization from the mid-latitude ionosphere enters the polar cap through the cusp and polar cap patches of enhanced ionization are formed. The polar cap patches develop irregularities as they convect from the dayside cusp through the polar cap to the night-side oval. During local winter, there is no solar radiation to ionize the atmosphere




▲ **FIGURE 5** Local time distribution of scintillation events from June 2006 to July 2007 (in 6 minute intervals). (Figure courtesy of Y. Béniguel)




▲ **FIGURE 6** Frequency of occurrence of scintillation fading depths at Ascension Island versus season and solar activity levels. (Figure courtesy of P. Doherty)




▲ **FIGURE 7** Variation of 244-MHz scintillations at Thule, Greenland with season and solar cycle. (Figure courtesy of P. Doherty)

over the polar cap but the convected ionization from the mid-latitudes forms the polar ionosphere. The structured polar cap patches can cause intense satellite scintillation at very high and ultra-high frequencies. However, the ionization density at high latitudes is less than that in the equatorial region and, as such, GPS receivers, for example, encounter only about 10 dB scintillations in contrast to 20-30 dB scintillations in the equatorial region.

**FIGURE 7** shows the seasonal and solar cycle variation of 244-MHz scintillations in the central polar cap at Thule, Greenland. The data was recorded from a satellite that could be viewed at high elevation angles from Thule. It shows that scintillation increases during the solar maximum period and that there is a consistent seasonal variation with minimum activity during the local summer when the presence of solar radiation for about 24 hours per day smoothes out the irregularities.

The irregularities move at speeds up to ten times larger in the polar regions as compared to the equatorial region. This means that larger sized structures in the polar ionosphere can create phase scintillation and that the magnitude of the phase scintillation can be much stronger. Large and rapid phase variations at high latitudes will cause a Doppler frequency shift in the GNSS signals which may exceed the phase lock loop bandwidth, resulting in a loss of lock and an outage in GNSS receivers.

As an example, on the night of November 7–8, 2004, there was a very large auroral event, known as a substorm. This event resulted in very bright aurora and, coincident with a particularly intense auroral arc, there were several disruptions to GPS monitoring over the region of Northern Scandinavia. In addition to intermittent losses of lock on several GPS receivers and to phase scintillation, there was a significant amplitude scintillation event. This event has been shown to be very closely associated with particle ionization at around 100 kilometers altitude during an auroral arc event. While it is known that substorms are common events, further studies are still required to see whether other similar events are problematic for GNSS operations at high latitudes.

## Scintillation Effects

We had mentioned earlier that the mid-latitude ionosphere is normally benign. However, during intense magnetic storms, the mid-latitude ionosphere can be strongly disturbed and satellite communication and GNSS navigation systems operating in this region can be very stressed. During such events, the auroral oval will extend towards the equator and the anomaly regions may extend towards the poles, extending the scintillation phenomena more typically associated with those regions into mid-latitudes.

An example of intense GPS scintillations measured at mid-latitudes (New York) is shown in **FIGURE 8**. This event was associated with the intense magnetic storm observed on September 26, 2001, during which the auroral region had expanded equatorward to encompass much of the continental U.S. This level of signal fading was sufficient to cause loss of lock on the L1 signal, which is relatively rare. The L2 signal can be much more susceptible to disruption due to scintillation during intense storms, both because the scintillation itself is stronger at lower frequencies and also because semi-codeless tracking techniques are less robust than direct correlation as previously mentioned.

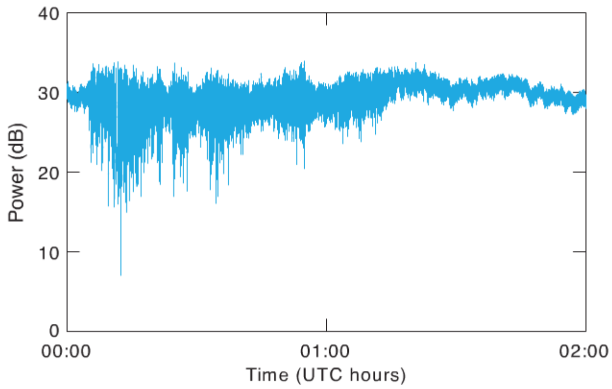
## Effects of Scintillation on GNSS and SBAS

Ionospheric scintillation affects users of GNSS in three important ways: it can degrade the quantity and quality of the user measurements; it can degrade the quantity and quality of reference station measurements; and, in the case of SBAS, it can disrupt the communication from SBAS GEOs to user receivers. As already discussed, scintillation can briefly prevent signals from being received, disrupt continuous tracking of these signals, or worsen the quality of the measurements by increasing noise and/or causing rapid phase variations. Further, it can interfere with the reception of data from the satellites, potentially leading to loss of use of the signals for extended periods. The net effect is that the system and the user may have fewer measurements, and those that remain may have larger errors. The influence of these effects depends upon the severity of the scintillation, how many components are affected, and how many remain.

**Effect on User Receivers.** Ionospheric scintillation can lead to loss of the GPS signals or increased noise on the remaining ones. Typically, the fade of the signal is for much less than one second, but it may take several seconds afterwards before the receiver resumes tracking and using the signal in its position estimate. Outages also affect the receiver's ability to smooth the range measurements to reduce noise. Using the carrier-phase measurements to smooth the code substantially reduces any noise introduced. When this smoothing is interrupted due to loss of lock caused by scintillation, or is performed with scintillating carrier-phase measurements, the range measurement error due to local multipath and thermal noise could be from three to 10 times larger. Additionally, scintillation adds high frequency fluctuations to the phase measurements further hampering noise reduction.

Most often scintillation will only affect one or two satellites causing occasional outages and some increase in noise. If many well-distributed signals are available to the user, then the loss of one or two will not significantly affect the user's overall performance and operations can continue. If the user has poor satellite coverage at the outset, then even modest scintillation levels may cause an interruption to their operation. When scintillation is very strong, then many satellites could be affected significantly. Even if the user has excellent satellite coverage, severe scintillation could interrupt service. Severe amplitude scintillation is rarely encountered outside of equatorial regions, although phase effects can be sufficiently severe at high latitudes to cause widespread losses of lock.

**Effect on Reference Stations.** The SBAS reference stations consist of redundant GPS receivers at precisely surveyed locations. SBAS receivers need to track two frequencies in order to separate out ionospheric effects from other error sources. Currently these receivers use the GPS L1 C/A-code signal and apply semi-codeless techniques to track the L2 P(Y) signal. Semi-codeless tracking is not as robust as either L1 C/A or future civil L5 tracking. The L2 tracking loops require a much narrower bandwidth and are heavily aided with scaled-phase information from the L1 C/A tracking loops. The net effect is that L2 tracking is much more vulnerable to phase scintillation than L1 C/A, although, because of the very narrow bandwidth, L2 tracking may be less susceptible to




▲ **FIGURE 8** GPS scintillations observed at a mid-latitude location between 00:00 and 02:00 UT during the intense magnetic storm of September 26, 2001. (Figure courtesy of B. Ledvina)

amplitude scintillation. Because weaker phase scintillation is more common than stronger amplitude scintillation, the L2 signal will be lost more often than L1. The SBAS reference stations must have both L1 and L2 measurements in order to generate the corrections and confidence levels that are broadcast. Severe scintillation affecting a reference station could effectively prevent several, or even all, of its measurements from contributing to the overall generation of corrections and confidences. Access to the L5 signal will reduce this vulnerability. The codes are fully available, the signal structure design is more robust, and the broadcast power is increased. L5-capable receivers will suffer fewer outages than the current L2 semi-codeless ones, however strong amplitude scintillation will still cause disruptions. Strong phase scintillation may as well.

If scintillation only affects a few satellites at a single reference station, the net impact on user performance will likely be small and regional. However, if multiple reference stations are affected by scintillation simultaneously, there could be significant and widespread impact.

**Effect on Satellite Datalinks.** The satellites not only provide ranging information, but also data. When scintillation causes the loss of a signal it also can cause the loss or corruption of the data bits.

Each GPS satellite broadcasts its own ephemeris information, so the loss of data on an individual satellite affects only that satellite. A greater concern is the SBAS data transmissions on GEOs. This data stream contains required information for all satellites in view including required integrity information. If the data is corrupted, all signals may be affected and loss of positioning becomes much more likely.

**Mitigation Techniques.** There are several actions that SBAS service providers can take to lessen the impact of scintillation. Increasing the margin of performance is chief among them. The more satellites a user has before the onset of scintillations, the more likely he will retain performance during a scintillation event. In addition, having more satellites means that a user can tolerate more noise on their measurements. Therefore, incorporating as many satellites as possible is an effective means of mitigation. GNSS constellations in addition to GPS are being developed. Including their signals into the user position solution would extend the sky coverage and improve the performance under scintillation conditions. (See the white paper for other mitigation techniques.)

## Conclusions and Further Work

Ionospheric scintillations are by now a well-known phenomenon in the GNSS user community. In equatorial regions, ionospheric scintillations are a daily feature during solar maximum years. In auroral regions, ionospheric scintillations are not strongly linked to time of the day. In the mid-latitude regions, scintillations tend to be linked to ionospheric disturbances where strong total electron content gradients can be observed (ionospheric storms, strong traveling ionospheric disturbances, solar eclipses, and so on).

While the global climatic models of ionospheric scintillations can be considered satisfactory for predicting (on a statistical basis) the occurrence and intensity of scintillations, the validation of these models is suffering from the fact that at very intense levels of scintillation, even specially designed scintillation receivers are losing lock. Also, the development of models that can predict reliably the size of scintillation cells (regions of equal scintillation intensity), which allows establishing joint probabilities of losing more than one satellite simultaneously, is still ongoing.


## Acknowledgments

This article is based on the paper "Effect of Ionospheric Scintillations on GNSS — A White Paper" by the SBAS-IONO Working Group.


## Manufacturers

The data presented in Figure 2 was produced by an Ashtech, now **Ashtech S.A.S.** (*www.ashtech.com*) Z-XII GPS receiver. The data presented in Figure 5 was obtained from Javad, now **Javad GNSS** (*www.javad.com*) and **Topcon** (*www.topconpositioning.com*) Legacy GPS receivers and GPS Silicon Valley, now **Novatel** (*www.novatel.ca*) GSV4004 GPS scintillation receivers. The data presented in Figure 8 was obtained from a non-commercial receiver.

MORE ONLINE

### Further Reading

**For references related to this article, go to *gpsworld.com* and click on Richard Langley's Innovation.**

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