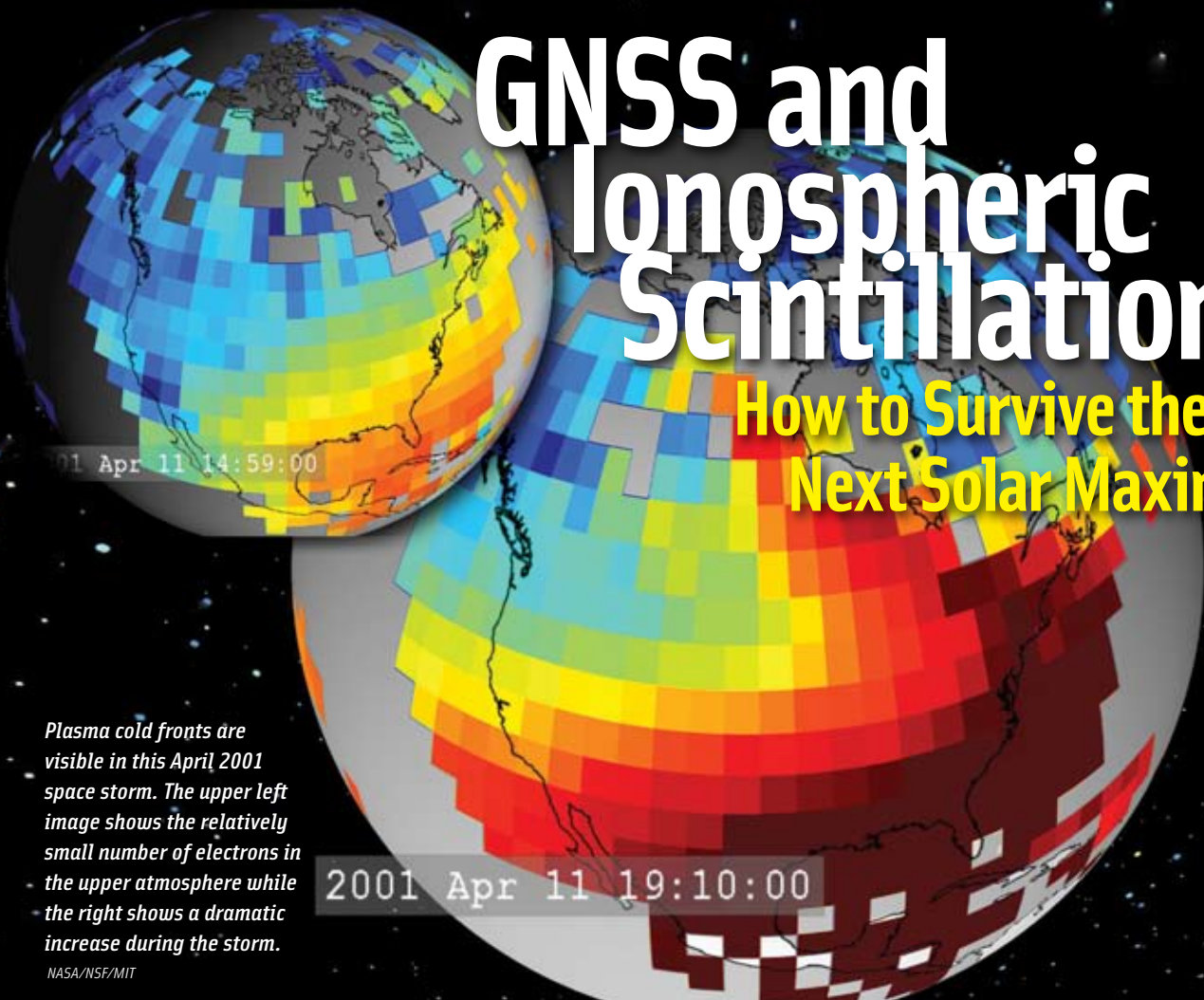# GNSS and Ionospheric Scintillation

How to Survive the Next Solar Maximum

Plasma cold fronts are visible in this April 2001 space storm. The upper left image shows the relatively small number of electrons in the upper atmosphere while the right shows a dramatic increase during the storm.

NASA/NSF/MIT

Eleven years marks only one iteration of the cycle of solar activity, but it represents several generations of GNSS receiver design. So, as the next high point of sunspots arrives in 2013 much of the installed base of GPS equipment will have been untested in the environment of intense ionospheric scintillation that accompanies the solar maximum. Scientists at Cornell University have developed a model of this scintillation to help evaluate the performance of GNSS user equipment in the face of potential disruption.

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The sun has its own seasons, and the stormy season will soon be upon us. Every 11 years, the sun enters a period of increased activity called the solar maximum.

During this period, the far ultraviolet (FUV) portion of the solar spectrum intensifies, making our ionosphere denser and thicker. Frequent solar flares eject up to 10 billion tons of plasma at speeds approaching 1,000 miles per second. Flare-generated, high-energy protons and x-rays reach the earth nearly instantly.

Flare-generated, high-energy electrons will produce intense broadband bursts of radio waves from HF to above the L-band. Called the sunspot cycle, this period of activity is the result of a solar dynamo in which electric currents and magnetic fields are built up in the outer layer of the sun and then destroyed in energetic outbursts.

The next sunspot maximum is currently predicted to arrive in May 2013 and to be a relatively weak maximum in terms of sunspot count — a prediction that would normally trigger sighs

of relief. However, many of the most intense solar outbursts have occurred during below-average solar cycles.

The approaching solar maximum will produce magnetic storms, ionospheric storms, and disruptions to radio signals, including the Global Positioning System and other GNSSs, that directly affect our technical infrastructure. In some cases, solar radio bursts will directly interfere with GNSS signals; in other cases, ionospheric and magnetic storms will disrupt radio signals from satellites.

These conditions will fully test for the first time much of the GPS technology installed since the last solar maximum in 2001. During the height of the previous solar cycle, some users of GPS signals were surprised that their receivers were vulnerable — especially the more precise receivers using carrier phase tracking techniques.
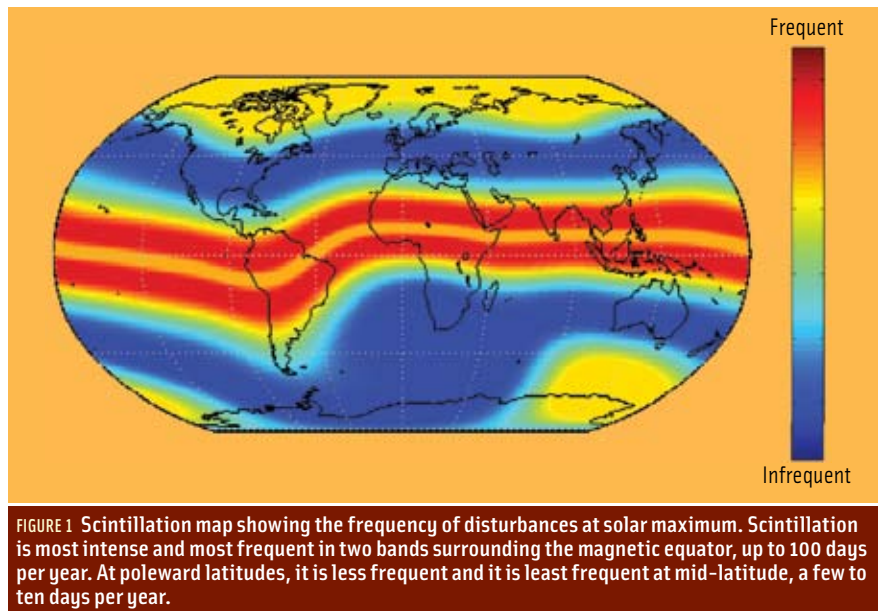
For the casual user of GNSS technology in the United States or Europe, who can tolerate an outage of several minutes at most a few times a year, scintillation is not a concern. Other users should be aware that scintillation will affect their receiver operation. (For an example of comparative results from the previous solar cycle, see the article by K. M. Groves et alia in the Additional Resources section near the end of this article.)

In this article we will review the subject of ionospheric scintillation and suggest a method for evaluating GPS receivers before the next solar maximum arrives in 2013.

Scintillation Effects

Ionospheric scintillation, which is produced by ionospheric irregularities, affects GPS signals in two ways, broadly classified as *refraction* and *diffraction*. Both types of effects originate in the group delay and phase advance that a GPS signal experiences as it interacts with free electrons along its transmission path.

The number of free electrons is usually expressed as *total electron content (TEC)*, which is the number of free electrons in a rectangular solid with a one-square-meter cross section extending from the receiver to the satellite. By

FIGURE 1 Scintillation map showing the frequency of disturbances at solar maximum. Scintillation is most intense and most frequent in two bands surrounding the magnetic equator, up to 100 days per year. At poleward latitudes, it is less frequent and it is least frequent at mid-latitude, a few to ten days per year.

a quirk of physical fate, the product of the group velocity and phase velocity of the GPS signals is equal to the speed of light squared. So, if the TEC increases, the group velocity slows down and the phase velocity speeds up to keep their product a constant.

A slower group velocity produces ranging errors while a faster phase velocity causes unexpected phase shifts. If the phase shifts are rapid enough, they can challenge the tracking loops in GPS receivers' phase lock loops. We refer to variations in group delay and phase advance caused by large-scale variations in electron density as signal refraction.

The second effect, signal diffraction, is more complicated. When ionospheric irregularities form at scale lengths of about 400 meters, they begin to scatter GPS signals; so, the radio wave reaches the receiver through multiple paths. The GPS signals on each path will add in a phase-wise sense, causing fluctuations in the signal amplitude and phase. The same process occurs with light and can be seen in the fuzzy image passing through jet exhaust from a commercial airliner.

Both refractive and diffractive effects are called scintillation. Unfortunately, diffractive scintillation can seriously challenge GPS receivers, causing signal power fades exceeding 30 dB-Hz and fast phase variations.

Who Should Be Concerned?

The upcoming solar maximum does not affect all regions of the earth equally, and the physics behind the space weather in different regions is dramatically different. The dense and thick ionosphere arising during the next solar maximum will slow electromagnetic waves, including GPS signals, at all latitudes.

At high latitudes, the northern lights will disrupt GPS signals. At tropical latitudes, the ionosphere will create its own storms, now made more intense by the denser, thicker ionosphere. Even at mid-latitudes, the ionosphere will experience storms driven by solar flares and magnetic storms.

Storms in the ionosphere present an additional danger to GPS signals when they create irregularities. Fortunately, decades of studying satellite signals in these locations — recently including GPS signals — has left a clear picture of the ionospheric climate. **Figure 1** illustrates where scintillation will most frequently impact GNSS signals.

The greatest danger to satellite signals is at tropical latitudes where ionospheric storms typically form after sunset and last for several hours. During the day, solar heating causes the ionosphere to rise near the equator and then fall under its own weight down magnetic field lines to form two bands of enhanced density on either side of the geomagnetic equa-

tor, as shown in Figure 1. After sunset, an electromagnetic form of the Rayleigh-Taylor instability (upside down water class) forms. The heavy ionosphere supported by horizontal magnetic field lines can suddenly erupt with bubbles, hundreds of kilometers across, that violently surge upward at many hundreds of meters per second, leaving behind an ionosphere filled with irregularities.

This behavior has a seasonal component, being most intense at the equinoxes, but it departs from this pattern in the South American sector where the geomagnetic equator deviates sharply from the geographic equator. The pattern can also be disrupted by magnetic storms, which can generate tropical ionospheric storms after midnight or thrust ionospheric content poleward into midlatitudes. Because the ionosphere is the densest and the thickest in two bands surrounding the magnetic equator, as shown in Figure 1, this is where scintillation is most intense.

At high latitudes, the threat to GPS comes during magnetic storms in which blobs of ionosphere from the dayside are swept over the polar cap onto the nightside. During the last solar maximum, magnetic storms were observed to fatten the ionosphere over the dayside United States and then carry blobs of it over the North Pole and polar cap into Europe.

These blobs form irregularities that cause GPS signals to scintillate and pose significant concern for GPS users at high latitudes. In addition to these effects, individual auroral arcs can cause rapid phase variations or even diffractive scintillation.

At mid-latitudes, the threat comes during magnetic storms when sharp ionospheric gradients are formed. These gradients threaten augmentation systems directly and sometimes they form irregularities that cause GPS signals to scintillate.

Unfortunately, we know very little about this threat because during the last solar maximum very few resources were applied to understanding scintillation at mid-latitudes. Despite the low level of ionospheric activity at mid-latitudes implied in Figure 1, one should not assume that no activity exists there.

What Is Scintillation?

Scintillation is a form of space-based multipath. Instead of radio waves reflecting from nearby surfaces and then adding at the antenna, a planar radio wave strikes a volume of irregularities, and then emerges as a surface of nearly constant amplitude but variable phase. The variable phase is introduced by the varying TEC along different signal paths.

Figure 2 illustrates this process. The ionosphere can be thought of as a relatively thin phase-changing shell at 350 kilometers altitude. As GPS radio waves propagate through irregularities in the ionosphere, they experience different values of TEC. Consequently, when the radio waves emerge from an irregularity slab, the phase along the wavefront varies.

At this point the amplitude of the wave is still unchanged. However, as the wave continues propagating downward, the waves emerging from different points along the bottom of the ionosphere begin to add and, depending on the relative phases, the signal amplitudes may either increase or fade. When the signals reach us, power fades may be deeper than 30 decibels.

These fades should be thought of as a spatial phenomenon with a characteristic scale length called the Fresnel length, given by $\sqrt{2\lambda d}$ where λ is the wavelength (e.g., 19 centimeters at L1) and d is the distance from the receiver to the scattering volume. A typical Fresnel length for the GPS L1 signal is 400 meters, but this varies with elevation and the altitude of the scattering volume.

The temporal behavior of scintillation fades comes from motion of the ionosphere, motion of the GPS signal puncture point along the ionosphere, and motion of the receiver.

A common situation for scintillation in the tropics is for the ionosphere to be moving from west to east at about 100

meters per second (m/s) and for the GPS signal puncture point to be also mostly moving from west to east at a few tens of m/s but with some geometries producing motion in excess of 100 m/s. Such behavior typically produces fade scale times of half a second to substantially longer than a few seconds.

The motion of a GPS receiver can substantially modify this result, especially at aircraft speeds. In the tropics where the magnetic field is mostly horizontal, the scintillation pattern is greatly extended in the north-south direction like a picket fence.

Figure 3 shows an example of two GPS signals recorded simultaneously: one that is experiencing scintillation with fades exceeding 30 dB-Hz (PRN 7) and one that is not experiencing scintillation (PRN 8). This is real data taken in Brazil during the most recent solar maximum and is typical of what GPS receivers will see during the next solar maximum in the tropics.

Most L1CA GPS receivers or civilian L1P(Y)/L2P(Y) GPS receivers will stop tracking for signals with C/N_0 below 25-30 dB-Hz and, for the conditions illustrated in Figure 3, they will likely stop tracking for tens of seconds or longer.

In addition to signal amplitude fading during scintillation, the signal phase also varies but in a more subtle way. Obviously, as TEC changes along the wave path, the signal phase will change as a refractive process substantially independent of the diffractive amplitude scintillation and the Fresnel length. However, the signal phase also changes as a result of the same diffractive process that drives amplitude fading.

Figure 4 shows an example of a GPS software receiver responding to severe scintillation. This is a magnified look at scintillation and shows only ten seconds of data. The circled areas in the upper panel show the largest fades during this period; associated with these large fades are half-cycle phase jumps shown in the lower panel. Often this produces a cycle slip or, worse yet, total carrier tracking loss with the GPS receiver.

We call the relationship between a deep fade and a half-cycle phase jump
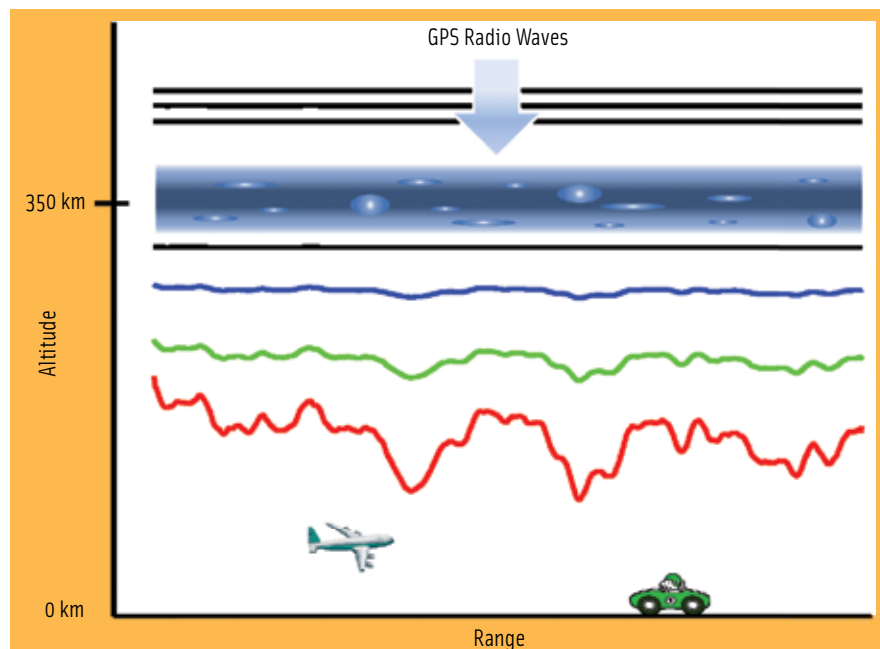
FIGURE 2 Radio wave propagation through a disturbed ionosphere. The horizontal curves represent signal amplitude. Irregularities in the ionosphere introduce phase shifts that become amplitude perturbations as the wave propagates below the ionosphere.
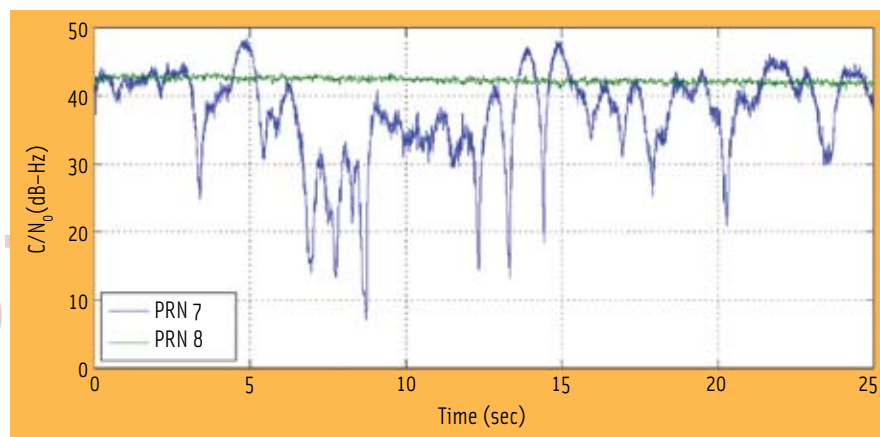
FIGURE 3 Two examples of GPS carrier-to-noise ratios for a non-scintillating satellite signal (PRN 7) and for a scintillating satellite signal (PRN 8).

a *canonical fade* because this relationship is maintained for every deep fade we have analyzed.

The reason for the half-cycle phase jump is remarkably simple. A deep fade occurs when the magnitude of the direct signal and the interfering signal resulting from multiple paths are nearly equal and have opposite phase. That is, if we sum the direct signal and the interfering signal as two vectors with the tail of the interfering signal at the head of the direct signal, then a deep fade results when the interfering signal head passes

close to the tail of the direct signal.

At this point the resultant vector, from the sum, quickly becomes very small and then points in the opposite direction, which is a half-cycle phase shift.

Frequently we are asked, "What causes a GPS receiver to stop tracking during scintillation: amplitude fades or phase variations?" The answer is "yes," because the fastest phase variations occur during the deepest fades. Very few, if any, GPS receivers will correctly track these deep fades without cycle slips.
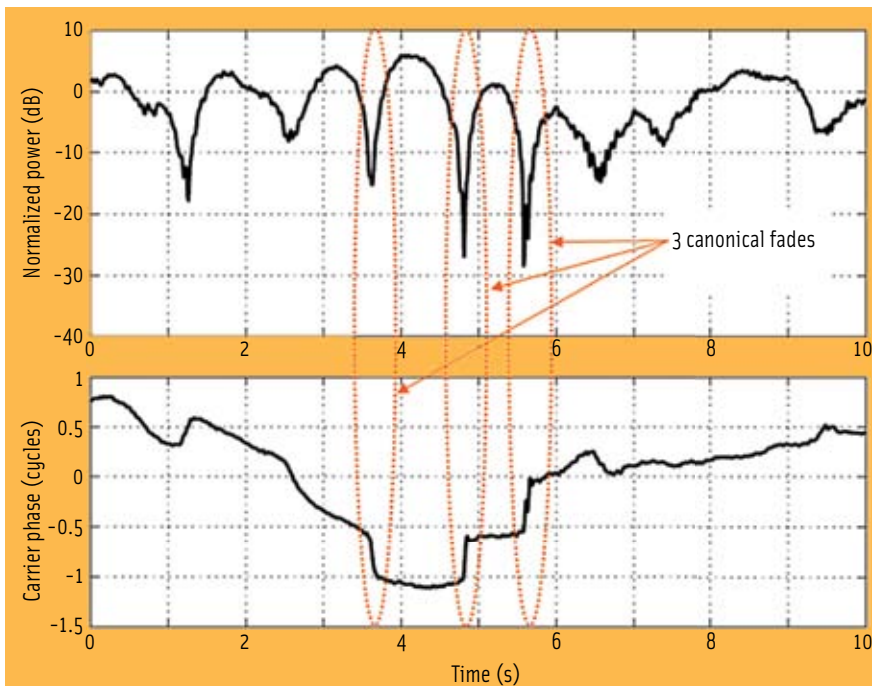
FIGURE 4 **Examples of deep fades and their relation to signal phase. At the maximum in fade, a half-cycle phase jump occurs. These are called canonical fades.**

So, what can be done? The first step to designing more robust receivers is to have a simulation that tests how receivers respond to scintillation.

Cornell Scintillation Model

We can model ionospheric scintillation in many ways. One obvious approach is to evaluate the performance of GPS receivers in the field and stay there until satisfied, if ever.

Another obvious approach is to record the entire GPS bandwidth during scintillation and then play back the recordings into receiver tracking loops. The disadvantages of this approach include the possibility that the recordings may not be representative, the fact that the recordings are probably not statistically stationary, and the fact that most receivers do not allow direct access to their tracking loops. An alternative is to create scintillation from a first-principles phase screen model and apply it to a GPS signal simulator. However, these models are neither well developed nor theoretically mature for strong scintillation.

We have chosen instead to create a statistical model and then to com-

pare the results of the statistical model with empirical data gathered from GPS receivers and from the WIDEBAND satellite project. The complete analysis used to validate the Cornell scintillation model can be found in the article by T. Humphreys et alia (2009a) listed in the Additional Resources section.

We begin by representing the GPS signal as $z(t) = \bar{z} + \xi(t)$ where $\bar{z}$ represents the complex direct signal, which is assumed to be independent of time for this discussion, and $\xi(t)$ represents the complex contribution from signals scattered in the ionosphere. Our problem then reduces to a statistical description of $\xi(t)$, sometimes called the fading process.

With this approach, scintillation is described by the amplitude distribution of $z(t)$ defined as $p(\alpha)$ where $\alpha = |z(t)|$ is the signal amplitude, and by the autocorrelation function of $\xi(t)$, which is given by

$$R_\xi(\tau) = \frac{1}{2} E\left[\xi^*(t)\xi(t+\tau)\right]$$

We find that the description for $p(\alpha)$ that best fits the empirical data is a zero-mean, complex Gaussian distribution for $\xi(t)$, implying that $\alpha(t)$ obeys a

Rice distribution. Scintillation intensity is described by the S_4 index, which is defined as

$$S_4^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$

and $I = \alpha^2$ is the signal intensity. The S_4 index can be directly related to the Rician K parameter, which specifies the amplitude distribution.

The temporal behavior of $z(t)$ is specified through the autocorrelation function $R_\xi(\tau)$. To approach this specification, we start with the power spectrum of $\xi(t)$, which is related to $R_\xi(\tau)$ through the Fourier transform.

For moderately intense to intense scintillation, the scintillation power spectrum looks like complex-valued white noise passing through a low pass filter. Hence, $R_\xi(\tau)$ is specified in the frequency domain with a second-order Butterworth filter the input of which is complex-valued white noise. The filter's cutoff frequency can be related to the decorrelation time τ_0, the time τ at which $R_\xi(\tau)/R_\xi(0)$ equals e^{-1}.

The scintillation model is then specified in three steps, as shown in **Figure 5**. First, complex white noise, $n(t)$, passes through a low pass filter whose cutoff frequency is defined by τ_0. The scintillation intensity is determined by specifying a constant component $\tilde{\bar{z}}$, where a larger $\tilde{\bar{z}}$ corresponds to smaller S_4. The filtered white noise and $\tilde{\bar{z}}$ are then summed, and this result is normalized by the mean amplitude of $z(t)$.

This model was validated in a software test bed specially created to study the effects of scintillation on GPS receivers. The tracking loop configuration most extensively tested was a 10-hertz third-order loop with a pre-detection interval of 10 milliseconds and a decision-directed, four-quadrant arctangent phase detector, although the results were not particularly sensitive to the tracking loop configuration.

We first tested the tracking loops on empirical signals from previous GPS experiments and from the WIDEBAND satellite project. From these empirical signals, we also calculated τ_0 and S_4,

created the synthetic model shown in Figure 5, and then applied the synthetic signal to the same tracking loops.

The results, as measured by phase noise (σ_ϕ) and number of cycle slips, agreed well. For one example with $S_4 = 1.0$, $\tau_o = 0.36$ s, and over a 265-second period, the empirical signal yielded $\sigma_\phi = 14.1°$ and 37 cycle slips whereas the synthetic signal yielded $\sigma_\phi = 15.0°\pm 0.5°$ and 41.6 ± 5.9 cycle slips.

Testing in software is efficient for evaluating the validity of our approach but is not particularly useful for testing GPS receivers existing in hardware. To achieve this latter goal, a signal simulator must be employed in a hardware-in-the-loop test, which we will describe next.

Implementation of the Model

To examine the effects of scintillation on GPS receivers, we first created a variety of complex scintillation histories (a
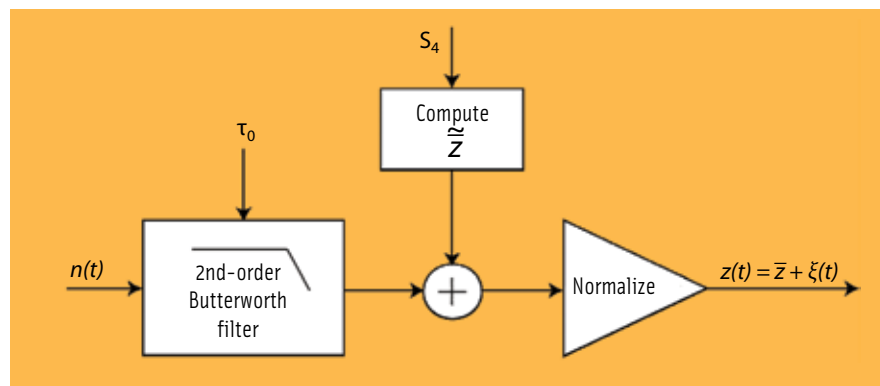
FIGURE 5 A schematic describing the Cornell Scintillation Model

sequence of varying signal amplitude and phase) with varying values of S_4 and τ_0 as signals to be investigated.

We used a GPS signal simulator for the signal source. This simulator allows us to specify the receiver location and dynamics, the satellites present and their orbits, and base signal power. Moreover, the simulator accepts modification to the signal amplitude and phase at 100

hertz, which is sufficient for even fast scintillation. Individual satellites can be controlled with different phase and amplitude time histories.

We first created a history with a unique S_4 and τ_o for each selected satellite and then combined these into a single file. The histories are then passed to another MATLAB function, along with time and pseudorandom noise (PRN)

numbers to create a formatted command file called a User Actions File.

The User Actions File is loaded into the simulator where it can be called for a specific scenario. This file automatically creates the changes in signal amplitude and phase.

We tested several histories of scintillation activity. Severe scintillation at GPS frequencies would be represented by $S_4 = 1.0$ and $\tau_o = 0.5$ s.

Figure 6 shows the phase response of a Cornell GRID (GPS Receiver Implemented on a DSP chip) to the phase and amplitude variations generated by the GPS simulator. In this case, we graphed the difference between the simulator signal phase and that measured by the GRID receiver with some correction for clock drifts. As clearly seen in Figure 6, many half-cycle phase slips are present, and each of these phase slips is associated with a canonical fade (a simultaneous deep amplitude fade and fast phase shift).

We chose a signal magnitude of 51.8 dB-Hz, and the GRID receiver was optimized for operating in a scintillating environment so that it would not lose track. Tests with commercial receivers produced results showing considerably more disruption to tracking.

We also tested the accuracy of navigation solutions as the number of satellites scintillating was increased. As expected, both geometrical dilution of precision (GDOP) and positioning errors increased with the number of scintillating satellites. This is an important test because frequently, multiple satellites — even all satellites in view — will scintillate during ionospheric storms in the tropics.

Designing Scintillation–Resistant GPS Receivers

GPS receivers can be designed to operate in scintillating environments, although we are not aware of any commercially available receivers optimized for this function. For example, if the receiver application does not require carrier phase tracking, a frequency lock loop (FLL) can be employed instead of a phase lock loop (PLL). The FLL is more robust than a PLL during scintillation.

If the GPS application does require the carrier phase, we would recommend using a third-order PLL with a pre-detection interval of around 10 milliseconds and a bandwidth of around 10 hertz. These have been shown to be good values for tracking in the presence of scintillations (For test results, see the article by T. Humphreys et alia, 2009b, in the Additional Resources section.)

Another approach is to use designs that remove (wipe off) the navigation data bits. Because the phase change at the bottom of a deep fade approaches a half cycle, a regular squaring-type PLL cannot distinguish between a data bit transition and what might just be a scintillation-induced phase change.

As one might expect, the time between cycle slips can be greatly extended by wiping off the navigation data bits and allowing the PLL to do full-cycle (i.e., non-squaring-type) tracking. In this mode, the PLL knows that abrupt, half-cycle phase changes are noise, not signal.

A practical approach to data bit wiping is to continuously build a database holding the entire 12.5-minute super-

frame of each observable satellite's navigation message. Except during the first 20 seconds after an even-hour GPS time crossing (when the satellite ephemerides are refreshed), and during approximately-once-per-day-per-PRN almanac updates, the database should allow prediction of incoming data bits with better than 98 percent accuracy. The PLL can then be configured to draw on this database only when experiencing phase trauma. In clear space weather, the code can be configured to build up the data base.

The new, modernized signals also offer opportunities to design scintillation-robust receivers. For example, the new pilot (i.e., dataless) signals on L2 and L5 contain no data bit transitions; so, no data bit wiping is required. These signals are by design more scintillation-robust than L1 C/A.

One should also avoid the use of dual-frequency receivers that employ codeless, semicodeless, or z-tracking techniques for tracking the L2 signal. The L2 tracking loops of these receivers are particularly vulnerable to scintillation. As new GPS satellites transmitting the modernized signals are launched, replace the older L1 + L2P(Y) receivers with modern dual-frequency receivers (L1 + L2C or L1 + L5).

Finally, as a minimum, receivers should be designed to determine if they are being affected by scintillation. To do this, fast (50 hertz) amplitude or carrier-to-noise measurements and calculated S_4 should be available to the user. Without this capability, users will not be able to diagnose the presence of scintillation in their receiver operation and may confuse scintillation with other problems.

Summary
For most users of GPS receivers, space weather and scintillation will be at most a minor annoyance. However, there is a class of users that needs to be aware of scintillation effects on GPS receivers. If one depends on GPS signals to be truly continuously available with low dilution of precision, few or no cycle slips, and no loss of tracking, then scintillation is an issue.

For example carrier phase differential techniques that produce sub-decimeter accuracy are particularly vulnerable. This is especially true in the tropics, but scintillation at GPS frequencies can happen anywhere.

Also, if one is designing or making receivers for applications that depend on truly continuous operation, then a part of the design trade space should be consideration of scintillation. As for users in the market for GPS receivers, if they require truly continuous operations, then knowing how the receivers respond to a scintillating environment becomes a consideration, depending on when and where the receivers will be employed.

In this article we have offered a statistical approach that can be implemented in a hardware-in-the-loop test for evaluating GPS receiver operation in the presence of scintillations. This approach preserves the relationship between amplitude fades and phase fluctuations.

The MATLAB scripts used to develop the amplitude and phase scenarios from the Cornell Scintillation Model can be obtained at <gps.ece.cornell.edu> under the "Space Weather" link. Further information on how to apply the model using a GPS signal simulator can be found in the article by J. Hinks et alia cited in Additional Resources.

As new receivers are designed for modernized GPS signals and other GNSS signals, the Cornell scintillation model needs to be extended. For moderate scintillations, we know that scintillation fades on L1 and L2 are well correlated, with the fades being somewhat deeper on L2 because of its lower frequency. However, for more intense scintillation we expect the fades at the two frequencies to become more independent. We are currently researching exactly how this happens and modeling the result.

The Cornell Scintillation Model can still be employed to evaluate the tracking capability of single-frequency L1C/A receivers. During the past solar maximum, many users of GPS signals found that their receivers were vulnerable.

With the Cornell Scintillation Model, this need not happen again.

Manufacturers

A GSS7700 GPS simulator from **Spirent Communications**, Paignton, Devon, United Kingdom, was used as the signal source in evaluating the effects of scintillation on hardware receivers.

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Joanna C. Hinks is a Ph.D. student at Cornell University, studying mechanical and aerospace engineering. In addition to scintillation and its effects on GNSS, her research has been in satellite attitude and orbit determination and related estimation problems. **IG**