GNSS and the Ionosphere

What's in Store for the Next Solar Maximum?

Anna B.O. Jensen and Cathryn Mitchell

"HERE COMES THE SUN / HERE COMES THE SUN / AND I SAY / IT'S ALL RIGHT."
Is it? Of course, George Harrison was referring to the welcome return of the sun after a long dreary English winter. But can GNSS users sing the same refrain?

The signals from global navigation satellites must transit the ionosphere on their way to receivers on or near the Earth's surface. The passage exacts a toll in the form of an added delay of the pseudorandom-noise-code signals and an advance of the phase of the signals' carriers, due to the presence of the ionosphere's free electrons. These perturbations must be ameliorated in some way to achieve high accuracy in GNSS positioning, navigation, and timing applications.

Where do the ionosphere's electrons come from? For the most part, they are valence electrons, stripped from upper atmosphere atoms and molecules by the extreme ultraviolet light continuously emitted by the sun. On the Earth's night-side, the electrons and the ionized atoms and molecules tend to recombine. This ionization and recombination process, along with the interactions of the particles with the Earth's magnetic field, governs the density of the electrons at a particular location and time. The ionosphere is also affected by the solar wind, and its associated magnetic field, but the cocoon established by the Earth's magnetic field (the magnetosphere) tends to deflect the solar wind so that it usually has little influence on the ionosphere.

INNOVATION INSIGHTS
with Richard Langley

The sun can become disturbed, with occasional violent outbursts.

Normally, the sun is quiescent: its electromagnetic and particle radiation is fairly constant, and its effects on the ionosphere benign. The delay in GNSS code observations and the advance in phase observations can be readily estimated and removed from the observations using a variety of models and methods. However, the sun can become disturbed, giving rise to occasional violent outbursts with large increases in electromagnetic and particle radiation. These outbursts can radically change the distribution of the electrons in the ionosphere, reducing the effectives of some amelioration methods. The electron density variability can become so rapid that a GNSS receiver can lose lock on satellite signals. And an increase in the sun's radio emissions can become so large as to drown out GNSS signals on the sunlight side of the Earth.

Although the sun can become disturbed at any time, solar activity is correlated with the approximately 11-year cycle of spots on the sun's surface. We are just coming out of a minimum in the solar cycle and headed for the next maximum, predicted to occur around the middle of 2013. How significantly will GNSS users be affected? In this month's column, two ionosphere experts tell us what might be in store.

GNSS satellite signals are affected by the space environment and the Earth's atmosphere as they travel from satellites at an altitude of about 20,000 kilometers above the surface of the Earth to receivers located at, or close to, the surface.

In the upper part of the Earth's atmosphere, the ionosphere, which is located from about 80 to 1,000 kilometers above the surface of the Earth, satellite signals are affected by the free electrons stripped from atoms and molecules by ionization. The signals are refracted by this plasma, which changes their speed of travel. The effect is mainly a function of the number of free electrons present, the electron density.

In the lower parts of Earth's atmosphere, in the troposphere and the stratosphere — where the atoms and molecules are electrically neutral — the satellite signals experience additional refraction. Here the effect is a function of pressure, temperature, and humidity. The effect of the troposphere and stratosphere is often just referred to as the "tropospheric effect" in GNSS positioning as it is in the troposphere where most of the neutral atmosphere refraction occurs.

The ionospheric and tropospheric effects on satellite signals must be accounted for in the GNSS positioning process in order to obtain reliable and accurate position solutions. In this article, we look at the ionospheric effect on satellite signals. Although the variation in signal speed is the largest direct ionospheric effect on the GNSS satellite signals, scintillation is another important effect. Scintillation occurs when irregularities in the electron density of the ionosphere cause rapid changes in the phase and amplitude of the transmitted signals. These changes might cause a GNSS receiver to lose lock on a satellite signal. This means in practice that satellite signals are lost, or signal tracking can be rather difficult, during scintillation events. However, we restrict our article to the subject of the propagation speed of the signals and do not consider scintillation further.

In the following, we review characteristics of the ionospheric effect on GNSS satellite signals as well as the predictions of increased ionospheric activity for the coming years and the consequences for GNSS users.

Signals

The ionosphere as a whole is electrically neutral, but it contains a significant number of free electrons and ions. The negatively charged free electrons affect the electromagnetic satellite signals in various ways. Most important is the signal delay affecting code (pseudorange) measurements, also called the "ionospheric delay" (and the associated advance of carrier-phase measurements), which is caused by a change in the refractive index along the signal path. The refractive index changes continuously as a function of the composition of the transmission media all the way from the satellites to the GNSS receivers.

For the majority of the signal path — that is, from the satellite at an altitude of about 20,000 kilometers down to approximately 1,000 kilometers above the surface of the Earth — the change in the refractive index is usually sufficiently small to ignore when the GNSS satellite signals are used for positioning at the surface of the Earth (although, at times, the region above the ionosphere — the plasmasphere — can affect GNSS signals). We therefore use the approximation that the first part of the signal path is in a vacuum where the propagation of GNSS satellite signals is not affected.

Then, when the signals enter the ionosphere, we must consider the signal delay, and even though the density of electrons is largest at an altitude around 300 kilometers, we must consider the total number of electrons experienced by a satellite signal all the way through the ionosphere.

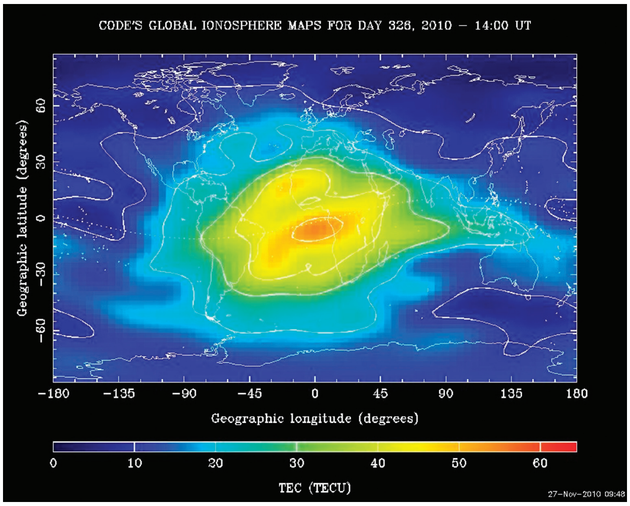
The size of the so-called first order effect of the signal delay, d, given in meters, can be modeled by the expression in Equation (1),

$$d = \frac{40.3}{f^2} TEC \qquad (1)$$

where f is the GNSS signal frequency, for instance 1.57542×10^9 Hz for the GPS L1 frequency. The constant 40.3 is derived from the values of the electron charge, the electron mass, and the permittivity of free space. Finally, TEC is an abbreviation for total electron content and this value is given by integrating the number of free electrons along the signal path in a cross section of one square meter.

It turns out that the "delay" affecting carrier-phase measurements has exactly the same magnitude as the signal delay but is negative. In other words, the phase is advanced.

In practice, for single-frequency receivers, it is not possible to obtain the actual number of electrons along the signal path for every satellite signal, and we therefore need other models to predict or estimate the electron density or the signal delay.



▲ **FIGURE 1** Global ionosphere map for November 22, 2010, at 14:00 UTC. Map generated by CODE, University of Bern.

A large number of models and methods for estimating the ionospheric signal delay have been developed. A comparison of some of them is given in a paper by Allain and Mitchell (see Further Reading). The most widely used model is probably the Klobuchar model, named after John Klobuchar, its developer. Coefficients for the Klobuchar model are determined by the GPS control segment and distributed with the GPS navigation message to GPS receivers where the coefficients are inserted into the model equation and used by receivers for estimation of the signal delay caused by the ionosphere.

Dispersion. The ionosphere is dispersive for radio waves, which means that the GNSS ionospheric signal delay is a function of the frequency of the signal. If pseudorange measurements from more than one frequency are available, for instance from dual-frequency GPS receivers, this can be used for enhanced modeling of the ionospheric effect by using combinations of the measurements made on both frequencies.

The basic expression for estimation of the ionospheric delay for dual frequency code-based positioning is shown in Equation (2),

$$d_{L1} = \frac{f_{L2}^2}{f_{L2}^2 - f_{L1}^2}(P_{L1} - P_{L2}) \qquad (2)$$

where d is the ionosphere delay, P denotes pseudorange, and f denotes frequency. The subscript notation $L1$ and $L2$ refers to the GPS L1 and L2 frequencies, respectively.

For high-accuracy carrier-phase-based positioning, an ionosphere-free combination of carrier-phase observations of the L1 and L2 frequencies is often used to reduce the effect of the ionospheric phase advance in the positioning process.

Estimating the ionosphere delay with Equation (2) for code observations or utilizing the ionosphere-free combination of the phase observations compensates for the first order ionospheric effect. This is the major part of the effect, but higher order effects are present, and the size of the residual higher order effects is increased (up to some centimeters) when the ionospheric activity is increasing.

For high-accuracy applications, the difference in the time of transmission and reception of the satellite signals of the various frequencies also must be considered as the signals on various frequencies are not transmitted from the satellites (nor received at a GNSS receiver) at exactly the same time epochs. These differences are normally referred to as the satellite and receiver differential code biases.

It is important also to note in this context that the noise level on the pseudorange corrected for the ionosphere and on the ionosphere-free carrier-phase observation is increased compared to using the pure single-frequency observations for positioning, but nevertheless these first-order approaches are used successfully in most software and receiver firmware for dual-frequency positioning.

Further developments of ionosphere-free combinations will evolve in the future as the new GPS L5 frequency and the new Galileo and GLONASS frequencies become fully available for multi-frequency ionosphere-free combinations. These more advanced combinations have the potential to further reduce the residual effect of the ionospheric delay in the positioning process.

Summing up, the GNSS signal delay caused by the ionosphere is a function of the electron density of the ionosphere. But what is driving the variation in electron density, and how do we know if it is changing?

Solar Activity and Sunspots

Equation (1) shows that the ionospheric signal delay is a direct function of the total electron content. The number of free electrons in the ionosphere is not constant; it varies significantly with time and space. The number of free electrons is driven by the ionization and recombination processes of the ionosphere, and these processes are in turn driven mainly by extreme ultraviolet radiation from the sun. Radiation from other cosmic sources also has an influence but it is minor compared to the effect of the solar radiation. There are also significant short-term (minutes to hours) changes caused by wave activity from the neutral atmosphere. The ionosphere itself is embedded in the neutral atmosphere — at these altitudes this is known as the thermosphere. The thermosphere is in constant movement due to waves and tides that are generated *in situ* or ascending from the underlying atmosphere. This thermosphere activity affects the ionosphere and causes some of the short-term variability in the electron density. However, the term "ionospheric activity" generally refers to the variability in electron density as driven by solar activity.

The fact that ionospheric activity is mainly driven by solar activity implies that the temporal variation of the electron content of the ionosphere follows a daily cycle, with the largest TEC values in the early afternoon local time, when the effect of the solar radiation has reached a maximum. Consequently, we see the lowest activity late at night just before sunrise.

There is also a geographic variability in the electron content with the highest electron density in the equatorial region and the lowest density in the high latitude regions. The latter, however, is affected by a larger variability, correlated with auroral activity.

The geographic variation of TEC is illustrated with a global ionosphere map from the Center for Orbit Determination in Europe (CODE) shown in **FIGURE 1**. Global ionosphere maps are generated at CODE on a daily basis, and the maps are available on the CODE website (see Further Reading).

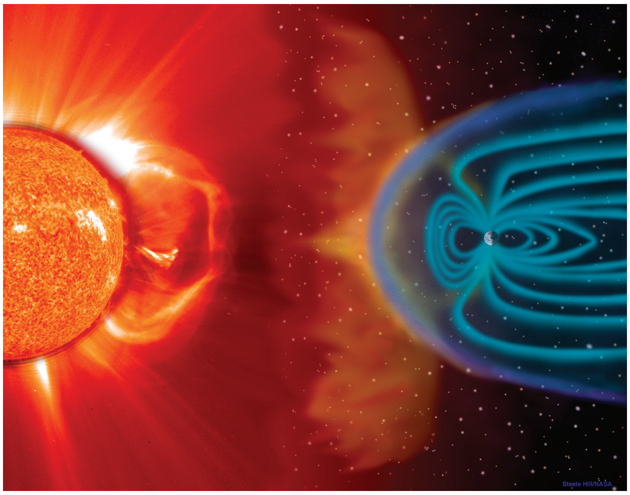
The TEC is provided in TEC units (TECU), where one TECU equals 10^{16} electrons per meter squared.

The sun also emits a constant flow of charged particles called the solar wind. The particles, mostly electrons and protons with energies between about 10 and 100 kilo-electron-volts, travel at an average speed of about 450 kilometers per second, but varying from 200 to 900 kilometers per second depending on solar activity. Although the Earth's magnetosphere deflects most of the solar wind, the interplanetary magnetic field, which is associated with the solar wind, can cause disturbances in the geomagnetic field. When this happens, particles of the solar wind enter the geomagnetic field and cause increased ionization in the ionosphere. The solar wind therefore also has a large influence on the variability of ionospheric activity. Also, sudden eruptions of the sun such as solar flares and coronal mass ejections (CMEs) cause increased ionization and thereby a larger ionospheric variability.

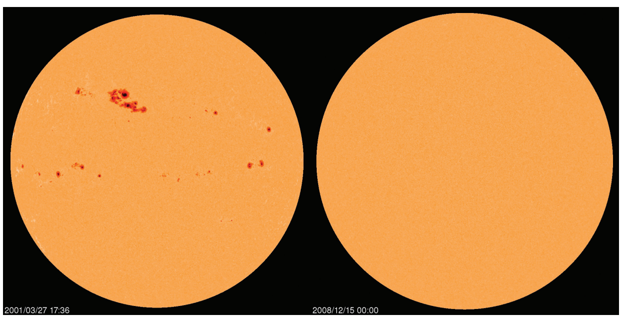
FIGURE 2 shows a CME blast and subsequent impact at the Earth.

Solar activity and the quantity of emissions from the sun are highly correlated with the number of sunspots on its surface. A sunspot looks like a dark spot because the temperature in a sunspot is lower than that in its surroundings. The generation of sunspots is not well understood, but it is related to anomalies in the solar magnetic field. What is well known, however, is the history of the number of sunspots, because these have been observed since the early 1600s.

The number of sunspots generally follows a cycle of about 11 years. During the last few years (2007–2009), we have experienced a time period with a low number of sunspots. In fact, there were many days in a row without any



▲ **FIGURE 2** Coronal mass ejection (CME) and subsequent impact at the Earth. The left part of the illustration is composed of an image from NASA's Solar Dynamics Observatory spacecraft superimposed on an image from the Solar and Heliospheric Observatory spacecraft jointly operated by NASA and the European Space Agency. The CME cloud arrives at the Earth about two to four days later and is shown being mostly deflected around the Earth's magnetosphere. The blue paths emanating from the Earth's poles represent some of its magnetic field lines. (Image courtesy of NASA's Goddard Space Flight Center.)



▲ **FIGURE 3** Images of the sun taken by the Solar and Heliospheric Observatory spacecraft. On the left is an image taken on March 27, 2001, at the peak of the last sunspot cycle. The daily sunspot count was 241. On the right is an image taken on December 15, 2008, near the minimum of the last sunspot cycle, showing no sunspots.

sunspots visible (see **FIGURE 3**). During the next three to four years, the number of sunspots is expected to increase, and this will be followed by a decrease until we reach a new period of low solar activity in 2019–2020.

Numerous investigations of time series of sunspot numbers have been carried out, and even though the cycles generally last 11 years, cycles of 9 and 13 years' duration have been observed. Also, the cycles vary with respect to the maximum number of sunspots observed during a cycle, and various "cycles of cycles" appear to be present with respect to the strength of the sunspot cycles. For instance, a cycle with a period of about 420 years has been identified in the historic listings of sunspot numbers combined with other observations contributing to the knowledge of solar activity. A very low number of sunspots was observed for a number of years between 1645 and 1715 when the sun was especially calm. This period is often referred to as the Maunder Minimum after the solar astronomer Edward W. Maunder. If the theory of the 420-year cycle is correct, then we will see a period with lower solar activity and fewer sunspot numbers by the end of this century.

But let's turn our attention to the previous and current sunspot cycles referred to as cycles number 23 and 24 (The 1755–1766 cycle is traditionally numbered "1."). A new cycle begins with the first observed high-latitude, reversed-polarity sunspot. Reversed polarity means a sunspot with opposite magnetic polarity compared to sunspots from the previous solar cycle. Sunspots from the new and previous cycles initially coexist. Eventually, only the new-cycle sunspots are present. Cycle 24 began on January 4, 2008, when the first reversed-polarity sunspot appeared.

Analyses of observations of solar activity show that the density of the solar wind increases with increasing sunspot number. Also, with a large sunspot number, solar flares and CMEs happen more frequently. Ionospheric storm activity is more common when the sunspot number is high, and this activity increases the variability in ionospheric delays. This all adds up to an increased number of free electrons in the ionosphere and a larger variability, which provides a larger and more variable signal delay for all types of GNSS-based positioning, navigation, and timing during periods with high sunspot numbers.

We know that the sunspot number is expected to increase during the next three to four years. What can be expected and what can we do to minimize the effects of the increased ionospheric activity on positioning, navigation, and timing applications?

The Last Solar High

As mentioned earlier, the current solar cycle is referred to as cycle 24. During the last solar cycle, cycle 23, the GNSS community was alert and aware of what could happen, and therefore many events were observed and analyzed. Among the most well-known events is a sequence of storms during October and November 2003, commonly referred to as the Halloween Storms. The most extreme was the storm on October 30, 2003, which resulted from a CME on October 29 at 20:49 UTC, which subsequently impacted Earth's magnetic field at 16:20 UTC on October 30 and produced a great geomagnetic storm, which lasted for many hours.

Effects on GPS positioning of this storm have been documented by the GNSS research group of the Royal Observatory of Belgium, where kinematic analyses of data from 36 GNSS stations in Europe showed position errors of more than 10 centimeters in the horizontal and up to 26 centimeters in the vertical between 21:00 and 22:00 UTC on October 30. The position errors were largest for locations in northern Europe including Sweden and Norway. The data analysis was carried out using high-quality carrier-phase data, and the processing was based on using an ionosphere-free linear combination of observations from the L1 and L2 frequencies, whereby the first-order effect of the ionosphere is removed from the results. The position errors are thus caused by mainly higher order ionospheric effects.

For navigation-grade GPS positioning, a U.S. National Atmospheric and Oceanic Administration technical memorandum (see Further Reading) reported that the Wide Area Augmentation System (WAAS) vertical error limit of 50 meters was exceeded for a period of about 11 hours on October 30, 2003. This means that, in practice, WAAS was not available for precision aircraft approaches during that time. The European Geostationary Navigation Overlay Service (EGNOS) was not transmitting during the storm, but simulations carried out later by ESA showed that the boundary regions of the EGNOS coverage area would have been especially affected by a reduction in service availability of about 20–60 percent during that day. The simulations also showed, however, that in the center of the EGNOS coverage area (in the vicinity of northern Italy), the effect would have been much smaller with a reduction in service availability of only 5–6 percent over the day.

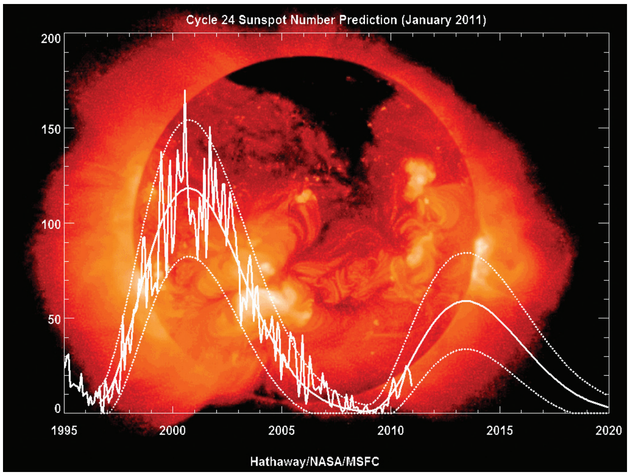
Such large storms are also often accompanied by displays of aurora (aurora borealis and aurora australis) at lower latitudes than normal. **FIGURE 4** shows full-sky aurora observed near Fredericton, New Brunswick, Canada (46 degrees north latitude) on October 31, 2003.

During a storm event on November 20, 2003, auroral activity was visible at mid-latitudes over most of North America as far south as Florida and in southern Europe including Italy and Greece.

Eruptions of the sun, often occurring in connection with high sunspot numbers, can have other effects besides the influence on GNSS-based positioning, navigation, and timing. Power-grid blackouts are known to have happened because of geomagnetic storms in connection with the sunspot peaks of both cycles 22 and 23 in 1989 and in 2003, respectively. For instance, the southern part of Sweden experienced a power blackout for several hours during the evening of October 30, 2003.

Also, orbiting satellites can experience problems with the increased radiation and solar wind density. Solar panels are, for instance, susceptible to increased aging. And many types of satellite communication can be affected by

▲ FIGURE 4 Photo of red and green auroras observed near Fredericton, New Brunswick, Canada (46 degrees north latitude) early on October 31, 2003. (Courtesy of Richard and Marg Langley.)



▲ FIGURE 5 Sunspot cycle 23 and predictions for cycle 24 from NASA's Marshall Space Flight Center.

increased ionospheric activity, not only GNSS satellite signals. Signals used for satellite phones, satellite TV, and so on can be affected.

Another phenomenon that can affect GNSS positioning is solar radio storms (also referred to as solar radio bursts) caused by events on the sun, often a solar flare, which creates radio waves that are emitted from the solar atmosphere and can propagate to the Earth where they cause an increased noise level in radio signals. Solar radio storms can cover a wide range of frequencies, including the frequencies used for GNSS. One such storm occurring on December 6, 2006, did affect GNSS positioning. With an increased noise level on the satellite signals, GNSS performance is reduced. If the noise level becomes too large, as a consequence of, for instance, a solar radio storm, GNSS receivers will lose lock on the GNSS signals, whereby positioning performance is further reduced or positioning might even be impossible. Solar radio storms are expected to happen more frequently during the peak of a solar cycle, but the event in December 2006 happened during a period with low solar activity, highlighting the fact that GNSS performance can be affected at any time, even when the sunspot number is low.

Predictions for the Next Solar High

Many predictions for the present solar cycle have been made. Because of the very long period with low solar activity during 2007–2009, some predictions expected a sudden outburst of activity and a very large cycle maximum, while other predictions foretold another increase in solar activity might not occur for many years.

However, with a general increase in the number of sunspots during 2010, it looks like we are now well into solar cycle number 24. Things can still change, but the current predictions say the maximum of the current solar cycle will be lower than the maximum of the last cycle encountered in 2001.

Predictions of sunspot numbers are based on history, logged information on sunspot numbers, and on observations of related geomagnetic activity.

The latest prediction for the current cycle as generated by NASA is shown in **FIGURE 5**.

The curves in Figure 5 show the observed smoothed sunspot number, with smoothing over a period of a year or so, and the predicted value for the remainder of cycle number 24. The dotted lines indicate the observed or expected range of the monthly-averaged sunspot numbers. The plot is updated every month as new data is obtained.

The current prediction for cycle 24 gives a smoothed sunspot number maximum of about 59 in June/July of 2013. This peak is much lower than that of the previous cycle. We are currently two years into cycle 24 and the predicted size continues to fall. According to forecasters, predicting the behavior of a sunspot cycle is fairly reliable once the cycle is well under way (about three years after the minimum in sunspot number occurs). Prior to that time, the predictions are less reliable but nonetheless equally as important.

Even though the maximum of the current solar cycle is expected to be lower than the last peak, it is important for GNSS users to be aware of the effects to be expected during the coming years.

Consequences for GNSS Users

As discussed earlier in this article, GNSS users experience a general satellite signal delay caused by the ionosphere. This signal delay is always present but varies in size. The delay is generally well modeled by most receivers and software to an extent that makes GNSS useable for all of the purposes we know today.

During enhanced ionospheric activity, GNSS users can experience residual ionospheric effects, which can cause reduced positioning, navigation, and timing performance. In such cases, dual-frequency receivers might improve the situation because of the enhanced possibilities for handling the ionospheric effect with dual-frequency data.

During enhanced ionospheric or geomagnetic storm activity caused by sudden eruptions of the sun, increased ionospheric variability will occur. Apart from causing an increased ionospheric signal delay, and thereby increased residual effects in the positioning process, this will also cause increased scintillation effects. These might cause GNSS receivers to lose lock on some or all GNSS satellite signals, reducing performance of the GNSS receiver. In the few very worst cases, GNSS-based positioning, navigation, and timing might not be possible at all for a short interval of time during very high ionospheric activity.

These worst-case scenarios are more prone to happen close to the peak of a solar cycle, which we will meet next during 2013–2014.

However, it is worth noting that for the next peak of the solar cycle, we are much better prepared for the consequences than during the last cycle. GNSS software and receiver technology has been improved to better resist the challenges of increased ionospheric activity during this solar cycle. The improvements are based on experiences gained during the last solar cycles and are to the benefit of many GNSS users. For example, users of wide area augmentation systems such as WAAS and EGNOS have correction and integrity information available, which can be a great help in identifying time epochs when positioning and navigation solutions might not be trustable because of increased ionospheric activity. The integrity information is transmitted from geostationary satellites, and during time periods with extremely high ionospheric activity, the signals with integrity information might be disrupted. This should, however, be detected by the GNSS receiver, so warning messages will be displayed for navigators.

High-accuracy real-time kinematic (RTK) positioning is today often carried out with RTK correction data from a service provider generated using a network of reference stations. Here, indications of increased ionospheric activity can be detected by the software operated by the service provider, and warnings can be distributed to the RTK users.

Warning systems have been improved, and a number of sites on the Internet provide information on current and predicted ionospheric activity (see Further Reading).

Also, in the future, GNSS users will be able to benefit from the increased number of GNSS frequencies available. These frequencies open up opportunities for new and improved methods for correction of the ionospheric delay to the benefit of users who will experience more stable and reliable GNSS performance.

Summary and Conclusion

In this article we have reviewed the ionospheric effects on GNSS satellite signals, how these can be modeled and mitigated, and how they are related to solar activity and the number of sunspots. We have also described how sudden eruptions of the sun can cause increased ionospheric activity and how these events are often correlated with a high sunspot number. Some examples of consequences for GNSS users during the last solar high have been provided, and we have evaluated the predictions for the next solar high and possible consequences for GNSS users.

We are heading towards a period of increased solar activity. GNSS users must expect more disturbances compared to what we have seen for the last four to five years. The peak of the current solar cycle is expected to be lower than the last peak, and therefore consequences for GNSS users should also be less significant. Most of the time GNSS will work very well. But we will likely see a few days with major effects, and since the number of GNSS users is increasing, the overall consequences might also be more severe, not because the ionospheric activity is worse, but simply because more people will be affected.

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MORE ONLINE

Further Reading

For references related to this article, go to *gpsworld.com* and click on Richard Langley's Innovation under *Inside GPS World* in the left-hand navigation bar.

FURTHER READING

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