# RETURN OF A GNSS VILLAIN: the ionosphere strikes again

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Every 11 years or so, the activity on the Sun reaches a peak. During this solar maximum, which can extend to several years either side of the actual peak, the Earth gets hammered by intense space weather.

When storms of particles spat out from the Sun smash into the Earth's atmosphere, the results can be spectacular. They are responsible for breathtakingly beautiful events like the dancing curtains of light known as the aurora (northern and southern lights). But they can also be equally vicious, causing widespread electrical power blackouts and disrupting navigation and communication systems worldwide.

In regards to global navigation satellite system (GNSS) observations, the ionosphere is still our biggest villain. The ionosphere is part of the Earth's upper atmosphere and continues to be the single most important error-source affecting GNSS observations.

This article describes the ionosphere and how it is influenced by space weather. It goes on to discuss the likely effects of the approaching solar maximum (expected to occur in early 2013) on GNSS surveys in Australia. We conclude with the good news that Australian GNSS users should be alert, but not alarmed.

## Sunspot number

Sunspots are caused by complex processes within the Sun. Simply put, they are pimples on the Sun's face that come and go within a few hours to many years. Sunspots appear darker than their surrounding area because they are cooler than the average temperature of the solar surface.

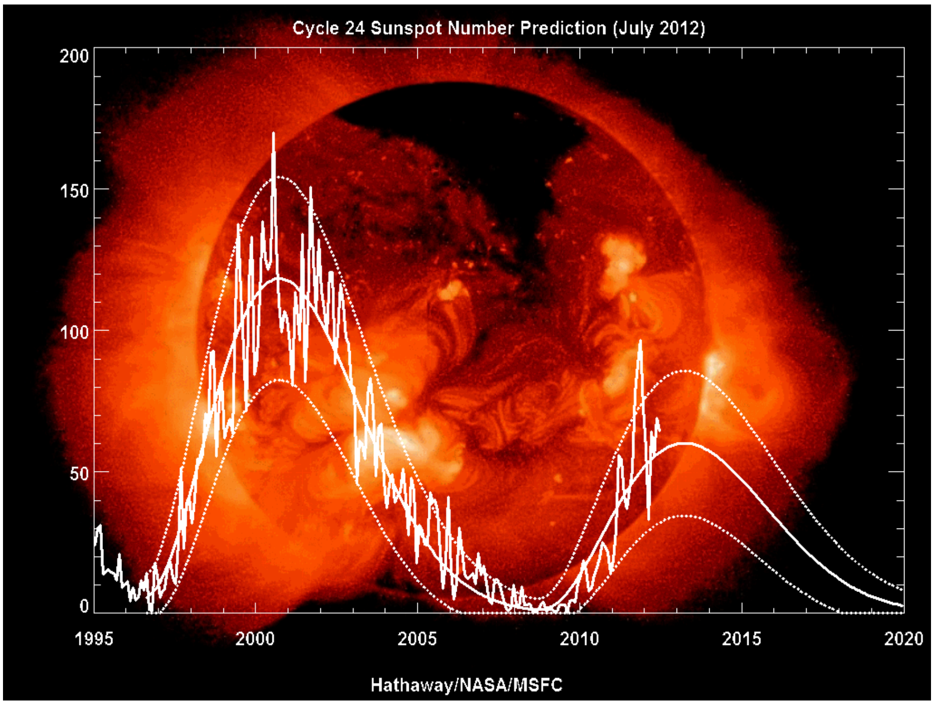
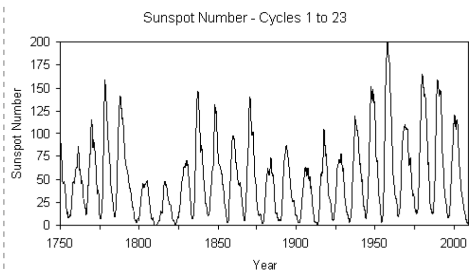



**Figure 1 (right): Variation of the solar cycle over the last 260 years, illustrated by the smoothed sunspot number (IPS). Note the distinct maximum every 11 years or so.**

**Figure 2 (above): Monthly and smoothed sunspot number for solar cycles 23 and 24, including prediction (NASA).**




Therefore they can easily be observed.

To quantify the abundance of these spots, an index called the sunspot number was introduced about 400 years ago. It has been used to consistently and continuously monitor sunspots for the last 260 years. The sunspot number is calculated from the number of individual sunspots and sunspot groups visible on the Sun, with due consideration of differences between observers and observatories.

Before we go on, let's clarify a few terms associated with solar activity. Solar flares are sudden bursts in the intensity of solar radiation. The solar wind is composed of particles charged with high energy that are emitted from the Sun. Coronal holes are low density regions around the Sun and the primary source of the solar wind.

## Solar cycle

The solar cycle tracks the Sun's activity and is characterised by the sunspot number. It has an average length of about 11 years, although individual cycles can be between 9 and 14 years long. Due to its large day-to-day variability, the sunspot number is averaged over a month. If smoothed over a 13-month period, it effectively charts the progress of the solar cycle (see Figure 1).

At present, we are more than three years into the current solar cycle (cycle 24). The solar maximum is predicted to occur in early 2013. Fortunately, this maximum will be a lot smaller than the previous peak in 2000. In fact, it will be the smallest in about 100 years. This is great news for GNSS users!

Figure 2. illustrates the monthly and the smoothed sunspot number for the previous solar cycle 23 (with its maximum in 2000) and the current solar cycle 24. It also includes a prediction for the remainder of the cycle. Note that activity tends to remain high for several years around the solar maximum.

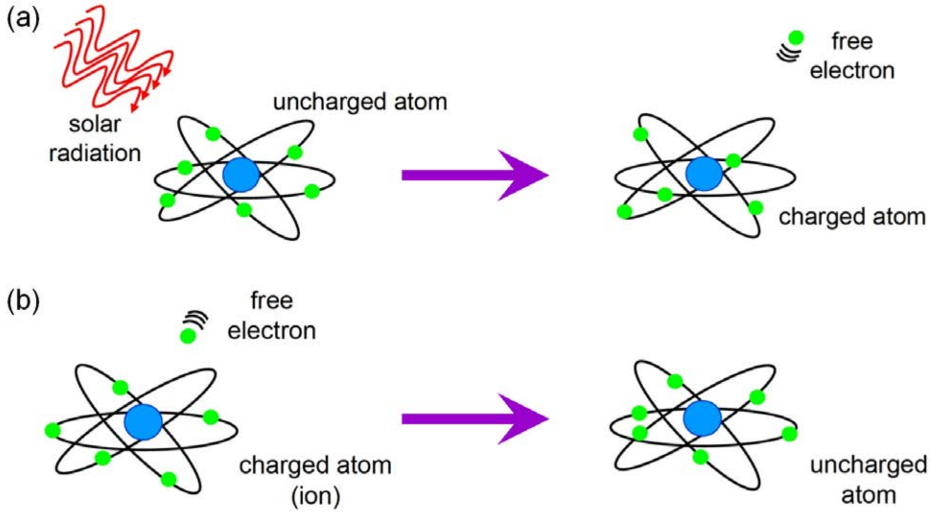



**Figure 3. Ionisation through (a) production and (b) loss of free electrons in the ionosphere (IPS).**

## Ionosphere

The ionosphere is a band of the Earth's upper atmosphere located about 50-1,000 km above the surface. Most of the ionosphere is electrically neutral. However, ionisation occurs when solar radiation strikes. This supports the flow of electric currents, which in turn affects the propagation of radio waves (including GNSS signals) travelling through the ionosphere.

Figure 3. illustrates the principle of ionisation. Free (negatively charged) electrons are 'produced' when solar radiation collides with uncharged atoms and molecules, leaving behind positively charged atoms (i.e. ions). This only takes place

during daylight hours because it relies on solar radiation. On the other hand, a 'loss' of free electrons in the ionosphere occurs when a free electron combines with an ion to form a neutral particle. This happens continually, both day and night.

The free electrons present in the ionosphere affect the propagation of radio waves. At frequencies of up to about 30 MHz, the ionosphere acts almost like a mirror. It reflects the path travelled by a terrestrial radio wave back towards the Earth, allowing long-distance radio communication ('over the horizon' via 'skips and hops').

At higher frequencies, such as those used by GNSS, radio waves pass right through the ionosphere. However, in the ionosphere the speed of the GNSS signal deviates from the speed of light. As a result, measured pseudoranges are 'too long' compared to the geometric distance between satellite and receiver, while carrier-phase observations are 'too short'. This is known as the ionospheric delay.

The ionosphere is a dispersive medium for microwaves. This means that its refractivity (or the ionospheric delay) depends on the frequency of the propagating GNSS signal. Therefore, we can use measurements on multiple frequencies to account for most of the ionospheric effect on GNSS observations.

For short baselines (<10 km), we generally assume that the ionospheric delay is the same for both GNSS receivers. Consequently, it is eliminated by differencing the measurements taken at both ends. But this assumption is not always true, particularly in periods of high solar activity, because there are additional disturbances we have to deal with.

## TEC

The effect of the ionosphere on GNSS signal propagation is a function of the frequency of the signal and the total electron content (TEC) along the signal path. The TEC is basically a measure of the free electron density contained in a 1m$^2$ column stretching through the ionosphere, along the signal path between satellite and receiver.

The TEC is highly variable with time, season, and geographic location. The largest TEC values generally occur in the early afternoon, local time, when solar radiation has peaked. Consequently, we experience the lowest activity late at night, just before sunrise.

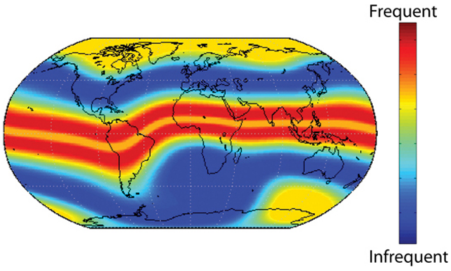



**Figure 4. Global occurrence of scintillations, which are most frequent and most intense in two bands on either side of the geomagnetic equator (P. Kintner).**

## Space weather phenomena

Several space weather phenomena affect the behaviour of the ionosphere (and therefore the ionospheric delay). These include scintillations, travelling ionospheric disturbances and ionospheric storms. The resulting effects on GNSS observations are much more severe during solar maximum periods.

Scintillations are rapid, short-term variations in the amplitude and phase of radio signals travelling through the ionosphere. These cause rapid changes in signal power, which makes it very difficult for a GNSS receiver to lock onto and keep tracking the signal.

Scintillations mainly occur along two bands on either side of the geomagnetic equator and in the polar regions (Figure 4). Those at the equator are moving 'blobs', one on either side, that chase sunset on a never-ending race around the Earth. If we imagined they left snail trails, then they would leave a band around the Earth every day. Most of Australia is usually spared from these effects.

Equatorial scintillations are caused by irregularities in the ionosphere following sunset. These generally occur from about one hour after sunset until midnight and should have disappeared by 03:00 local time. Polar scintillations, on the other hand, are mainly the result of geomagnetic storms that are associated with solar flares and coronal holes.

Travelling ionospheric disturbances (TID) are wave-like fluctuations in the electron density of the ionosphere. They propagate at various horizontal speeds and wavelengths of several hundred kilometres.

Large-scale TID (LSTID) are related to geomagnetic disturbances (e.g. caused by the aurora effect or ionospheric storms) and can travel large distances. They last for more than 1 hour and move faster than the speed of sound (i.e. in excess of 300 m/s or 1,080 km/h).

Medium-scale TID (MSTID) are caused by weather disturbances in the lower atmosphere, such as severe weather fronts and volcanic eruptions. They last for shorter time periods (10 minutes to 1 hour) and move at slower speeds of about 50-300 m/s. MSTID frequently occur in mid-latitudes (i.e. most of Australia), mainly during daytime in the winter months.

Ionospheric storms result from large energy input to the upper atmosphere associated with geomagnetic storms, which can last several days. The latter are large variations in the strength and direction of the Earth's magnetic field. These are caused by eruptions on the Sun that eject a mixture of particles into the solar wind.

The resulting disturbances in the geomagnetic field often cause disturbances in the ionosphere (through fluctuations in electron density) because both are linked in complex ways. This process can lead to strong scintillations and large rapid changes in the ionospheric delay for GNSS signals, at time periods of about one minute. Particularly for short-term GNSS observations, this can be of great concern.

## Modelling the ionosphere

As mentioned earlier, the effect of the ionosphere can be continuously measured by using dual-frequency GNSS observations and then modelled. How is this done?

We usually approximate the ionosphere by a very thin shell at a certain altitude (generally between 300 and 400 km). This single-layer approach is feasible because the majority of free electrons in the ionosphere are distributed at these altitudes.

However, such a 2-dimensional model is not ideal because it cannot provide a vertical profile of the ionosphere. Alternatively, more sophisticated 3-dimensional tomographic modelling (based on a medical imaging technique) can be used.

In any case, we then have two options in practice: we either predict the ionospheric delay, or use real-time mapping. The latter provides better accuracy but requires a sufficiently dense Continuously Operating Reference Station (CORS) network infrastructure to measure (and map) the TEC over the area of interest.

## Ionosphere maps

Ionosphere maps illustrate the TEC across a given area. Daily global ionosphere maps (GIM) based on a global

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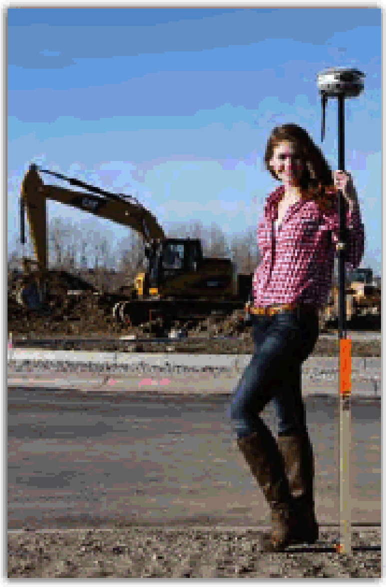

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CORS network are available from the International GNSS Service (IGS).

Unfortunately, this network is unevenly distributed with a much smaller number of sites located in the southern hemisphere. This results in less accurate ionosphere modelling in our part of the world.

GIM are invaluable for tracking the behaviour of the global ionosphere over time. But at this resolution they cannot reproduce local, short-lasting processes in the ionosphere.

To make matters worse, the temporal and spatial TEC variations over a local or regional area are very complex. It is a challenging task to precisely represent the varying behaviour of the ionosphere!

The Ionospheric Prediction Service (IPS), located in Sydney, produces regional ionosphere maps (RIM) for the Australasian region in near real-time (Figure 5.). These maps are available to users via the internet. Dark blue represents low TEC, while red indicates high TEC. The figure clearly shows that Australia is affected by changes in the electron density of the ionosphere.

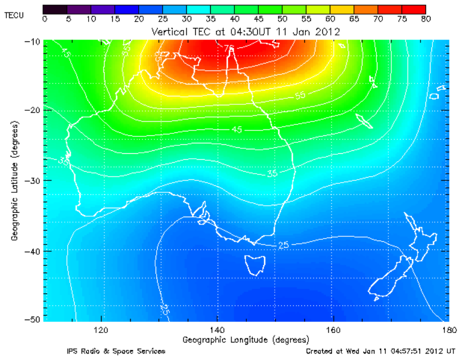


**Figure 5. Regional Ionosphere Map for Australia for 11 Jan 2012 at 04:30 UT or 15:30 AEDST (IPS).**

## Effects on GNSS surveys

During the solar maximum period, GNSS users can expect reduced positioning performance at times. The complexity of the ionosphere makes it very difficult to quantify the effects on GNSS positioning. As a rough guide, positioning quality may degrade by up to several centimetres for survey-grade equipment during ionospheric storm periods.

In general, we need to expect a higher noise level for both pseudorange and carrier-phase observations. For example, you may notice poorer Root Mean Square (RMS) or Coordinate Quality (CQ) values. Also, be prepared for a larger number of cycle slips and loss-of-lock occurrences. In regards to ambiguity resolution, it may take longer to fix ambiguities (i.e. longer initialisation times) and the success rate may be lower.

Importantly, ionospheric activity also affects the communication between a CORS network or a temporary base station and the user. This can lead to more frequent re-initialisations, a degradation in accuracy, and poorer coverage in the field because mobile phone connections and radio links will suffer at times.

Also note that the effect of ionospheric disturbances at the user end may differ significantly between receiver types, due to variations in receiver hardware, firmware and the algorithms employed.

## How to tackle the GNSS villain?

First of all, don't panic. The next solar maximum will be the smallest in 100 years, so mostly GNSS performance will be fine.

Connecting to a CORS network is the best guard against this GNSS villain. CORS networks can model and remove a large portion of the differential ionospheric errors. Network RTK provides a better reduction of these errors than single-base RTK (see *Position* 56, December 2011).

But remember that current ionospheric models cannot account for short-term changes, so there will always be a residual effect. This residual effect is larger during solar maximum periods. Unfortunately, the potential of new GNSS frequencies to help improve ionospheric modelling cannot be fully realised before the villain has retreated back to its lair for another 11 years or so.

Post-processing using Virtual RINEX data may become a valuable backup tool to infill pockets of RTK surveys affected by communication problems, while still employing short RTK-style observation times in the field.

Over the next few years, it would be wise to pay more attention to your rover, its real-time performance indicators and to include a few extra field checks. If possible, also increase observation times to obtain more measurements.

Those seeking the highest accuracy over the longest distances, such as the nation's geodesists who have started observations for the next geodetic datum, may consider observation sessions conducted between dusk and dawn during the summer months.

## Conclusion

GNSS signals travel about 20,000 km from the satellite to a receiver on the surface of the Earth. This takes less than 70 milliseconds. Towards the end of the journey, the signals must travel through the ionosphere.

The ionosphere is a very complex beast and continues to be the main error source for GNSS positioning. It is highly influenced by solar activity, which reaches a maximum approximately every 11 years. The next solar maximum is just around the corner, predicted to occur in early 2013.

GNSS users should be alert but not alarmed. The approaching solar maximum will be the smallest in about 100 years. We can expect GNSS positioning to continue to perform at current levels most of the time, with larger and more frequent glitches encountered in the field.

Most of Australia is located in the mid-latitude region. As a result, we will generally be spared from the most severe ionospheric disturbances. Nevertheless, GNSS users have to expect a reduction in positioning performance at times.

This means a larger number of cycle slips and loss-of-lock occurrences, a higher noise level, longer and more frequent re-initialisations and more intermittent communication problems. Consequently, GNSS users should pay particular attention to GNSS best practice and be more cautious over the next few years.

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