INTRODUCTION

The arrival of the solar maximum is of interest as extreme solar events pose risks to the operation of certain types of infrastructure, such as power grids, communications satellites, and spacecraft tracking and control systems. The frequency and intensity of disruptive events increase during the years around the solar maximum, although extreme events are unpredictable and may occur at any time.

GNSS users face several challenges. Any given solar event can potentially impact a user’s specific region of operation. If local ionospheric disturbances occur and users employ traditional RTK techniques, positioning performance and productivity can suffer.

The Trimble® Pivot™ platform provides proven infrastructure solutions today that enable users and operators to counter the effects of the ionosphere, view and analyze ionospheric conditions, and monitor positioning accuracy to verify system performance.

THE SOLAR CHALLENGE

Extreme ultraviolet radiation from the sun frees electrons from molecules in the upper atmosphere, creating the ionosphere. The density of free electrons grows during daylight hours and drops after sunset. Daily peak levels also follow seasonal cycles with higher intensities occurring around the equinoxes and larger long-term variations that track the sunspot cycle, which on average lasts about 11 years.

Instabilities in magnetic fields near sunspots may result in a burst of radiation called a solar flare and/or a huge burst of ions from the corona, referred to as a coronal mass ejection (CME). These events disturb the earth’s ionosphere, causing variations in satellite signal delays that can degrade GNSS survey positioning performance with effects varying across the earth.

The frequency and intensity of solar flares generally track the solar cycle with elevated levels and disruptive events for many months before and after...
the nominal solar maximum, currently predicted for late 2013. However, powerful events may occur at any time. In fact, a solar flare in December 2006 caused a 10 minute outage for most GPS receivers on the sunlit side of the earth.

Single-frequency differential techniques suffer first as the difference in free electron levels between a reference station and roving site increases. Dual and multi-frequency techniques use combinations of the code and carrier phase that eliminate the ionospheric delay but require ambiguity initialization using combinations still impacted by the ionospheric delay. Consequently, longer RTK initialization times, reduced initialization reliability, and lower accuracy result even if traditional dual-frequency techniques are used.

Instabilities in the ionosphere near the equator or near the poles during geomagnetic storms create multiple paths for satellite signals. Interference from multiple signal paths creates variations in carrier phase and signal strength referred to as scintillations. The effects depend on the location of ionospheric interference sources relative to signal paths. Receiver tracking loops can tolerate low levels of scintillation, but as levels increase, weaker signals from low elevation satellites may no longer be tracked. Higher elevation satellites are impacted when scintillation reaches extreme levels.

Solar events and the resulting ionospheric dynamics create a number of challenges for GNSS survey users. Firstly, if traditional single baseline techniques are used, reliability and accuracy can suffer. Secondly, the impact of any given solar event on the ionosphere in the region of operation is unpredictable. Finally, the impact of elevated levels in the regional ionosphere on GNSS survey positioning varies depending on the exact nature of disturbances. Methods are needed to –

- mitigate the effects of the ionosphere,
- monitor ionospheric levels and activity where a user works, and
- monitor positioning performance to verify accuracy levels and detect conditions of outlying performance.

**SOLUTION: TRIMBLE PIVOT PLATFORM**

The Trimble Pivot platform for software applications is the framework on which the solutions discussed here operate. The Pivot platform provides a system architecture that ensures reliable operation and allows customers to pick and choose the exact functionality required in the form of apps that operate on a common foundation.

Figure 1 (see overleaf) shows the Pivot platform application hierarchy, which is described in greater detail in the *Trimble Pivot Platform Technical Note*. 
Shared components may be updated at any time, and new apps may be added as needed to expand system functionality. The combination of modularity, scalability, and apps specifically designed to mitigate and monitor ionospheric errors provides a complete solution for maximizing productivity in the face of challenges due to solar events.

**SOLUTION: PIVOT NETWORK MODELED RTK**

Network RTK models the errors in satellite signals and produces RTK corrections for users with most ionospheric and geometric errors removed. This reduces initialization times and enables users to reliably obtain high-accuracy position solutions during a wide range of ionospheric conditions.

Trimble’s most advanced Network RTK product is the Trimble VRS³Net™ App, which delivers 1-2 cm horizontal performance throughout a network of GNSS reference stations with 50 km spacing. The VRS³Net App network processor continuously models ionospheric errors and geometric errors, such as orbit errors and tropospheric delays. The network operator has the option to select a standard ionospheric model for small networks or a new advanced model. The advanced model supports much larger networks with reduced processor overhead by using a federated filter architecture.

The SparseVRS App is a new option for Network RTK that delivers sub-decimeter (2 sigma) horizontal accuracies for inter-station spacing up to 120 km. The SparseVRS App supports the same ionospheric model options for small or large networks.

Using data from receivers providing the full set of GNSS observations, such as the Trimble NetR9™ reference receiver, allows the VRS³Net App and the SparseVRS App to deliver multi-system GNSS corrections. Providing modernized GPS and multi-system GNSS RTK corrections to users ensures robustness in the presence of rover site obstructions under normal conditions and also provides good positioning geometries even under moderate scintillation conditions.

The newly released Ionosphere App now enables computation of the Scintillation Index, which represents the level of scintillation activity on a scale of 0 to 10 (see below). A network operator can enable automatic editing of measurements exhibiting scintillations by setting a maximum threshold in the Scintillation Index Filter. Any measurements that exceed this value are omitted from real-time network processing and real-time correction output until the index returns to sub-threshold levels. Eliminating
measurements exhibiting scintillations can both improve the integrity of network processing and significantly improve rover positioning performance.

**SOLUTION: MONITOR THE IONOSPHERE**

Understanding the state of the ionosphere and its potential impact on GNSS precise positioning requires knowing the current free-electron density and how it varies across the network and over time. The Trimble Pivot platform offers a range of tools that allow you to evaluate several key parameters describing the state of the ionosphere. This information is available to network operators when the apps described below are installed. The same data can also be published to users through the Pivot Web interface or accessed using the new Pivot Field mobile app for smartphones and tablets.

The following are key parameters and indices that describe the state of the ionosphere:

**TEC** - GNSS signal delay is proportional to a measure called the total electron content, which is the total number of electrons encountered in a one square meter cross-section along the slant path from a satellite to the receiving antenna (STEC) or measured as STEC and converted to the direct vertical delay (VTEC). TEC is measured in TEC Units (TECU) with 1 TECU corresponding to 16.2 cm of delay at the L1 frequency (see Figure 2).

**Scintillation Index** – The Scintillation Index represents the level of detected scintillation activity on a scale of 0 to 10. The Scintillation Index is derived from the difference between the ionospheric delay observed in each epoch and the expected delay projected from the previous epoch. This residual is computed for each measurement from every satellite at every station and is used to create the summary scintillation index in the range 0 to 10.

**Iono Index** – This index combines the current TEC level and Scintillation Index into a single value summarizing the level of risk to GNSS positioning, also on a scale of 0 to 10.

**I95** – The I95 index is generated directly by the VRS2Net network processor and represents the network-wide state of ionospheric modeling. The I95 index is the 95th percentile of all ionospheric residuals across all stations over a period of one hour and is in units of PPM.
**IRIM** – The Ionospheric Residual Integrity Monitoring (IRIM) index is also generated by the network processor but on a station-by-station basis. It indicates by how much the ionospheric delay differs from a linear spatial variation. It is computed by differencing ionospheric delays measured at a station with the delays modeled with that station removed from the network. Reported values represent the 95th percentile of the weighted RMS residual values accumulated over a one hour period in units of meters. Network-wide IRIM values are also accumulated. (The Geometric Residual Monitoring index (**GRIM**) analogously represents the 95th percentile of geometric residuals.)

TEC provides a direct measure of the free electron density, usually presented as a color-mapped view as shown in Figure 2. The **I95** and **IRIM** indices are summary indicators for the variation of TEC over space within the network. The **Scintillation Index** depicts the time varying noise in the ionospheric delay, and the **Iono Index** represents combined space-time variations.

The following Pivot Apps provide tools that allow network operators and users to monitor and analyze the state of the ionosphere:

- **VRS Net App** – The network processor provides displays of the I95 index for the network and IRIM for each station and the full network. Hourly values are plotted over a period from one to seven days allowing you to detect trends and view elevated periods in context (see Figure 3 for an example display).

![Figure 3: I95 index over 4-day period showing both hourly and day-to-day variations](image)

The **Atmosphere (Atmo) App** estimates TEC throughout the network for every satellite at every station. Values are logged to files at a user-defined interval for scientific applications. Both contour and color-mapped views of TEC provide a clear summary of current conditions. (This module may also be configured to compute zenith tropospheric delays and, with the addition of the Weather condition module, estimate integrated precipitable water vapor (**IPWV**).)

The **IonoSphere (Iono) App** (supported in Pivot platform version 2.5 and later), enables new features and provides centralized access to ionospheric information from all system modules, allowing rapid analysis of ionospheric conditions. It enables computation of the
Scintillation Index at each station and adds the Scintillation Index Filter that automatically disables data exhibiting scintillation noise at the individual satellite and station level. The Iono App provides both tabular views by station and surface map views of TEC and all indices described above along with a tabular view of the Scintillation Index for each station and every satellite observed at each station.

In addition to the apps available directly on the Pivot platform, Trimble now also provides apps for Android smartphones and tablets and the Apple iPhone and iPad. These apps are available free from Google Play and the Apple App Store.

The Mobile Communication App (supported in Pivot platform version 2.5 and later) enables login-based or anonymous access from smartphones and tablets to system resources via communications infrastructure provided by Trimble. The Mobile Communication App activates the modules within the Pivot platform and builds the workflow to ensure that information is delivered to the mobile apps (see Figure 4).

The Pivot Admin mobile app provides network operators with a view of the state of apps, servers, and Microsoft Windows services and includes controls to manage conditions that may arise, all from within the mobile device.

The Pivot Field mobile app may be used to access freely available data provided by worldwide Trimble tracking infrastructure, including global maps of TEC, the Scintillation Index and the combined Iono Index. A network operator installs the Mobile Communication App to make system data available to mobile users, either via login or anonymous access. Pivot Field users can then view the I95, IRIM, and GRIM indices for their network along with more detailed localized maps of TEC, the Scintillation Index, and the Iono Index from their mobile device (see Figure 5).
Note that access via the Pivot Field mobile app is directly useful to local users, but it is also possible to make data openly available. This allows a network operator to either promote network availability or publish information to an international audience of scientists and enthusiasts.

**SOLUTION: MONITOR RTK PERFORMANCE**

Positioning performance is the ultimate measure of any correction data. The Rover Integrity App provides several options for monitoring and evaluating the positioning performance of one or more rover receivers using system generated corrections. Continuous running position statistics are collected, and optional periodic resets can be triggered to evaluate initialization time and initialization reliability.

The **Rover Integrity** module receives RTK positions as GGA or GGK format NMEA strings and logs position performance data based on errors versus reference coordinates. One or more separate physical receivers supporting internal RTK processing may be used as the source of NMEA positions, or data from one or more reference stations can be processed using an RTK Engine module.

Performance is reported in tables showing the statistics of position errors and initialization times.

The **Position Chart** presents a time series of selected errors over an analysis time interval ranging from 30 minutes to 5 days. You may select Easting, Northing, Height, 2D (horizontal) or 3D errors and also select which rover(s) and solution type(s) (for example, float or fixed) are to be displayed (see Figure 6).

The **Position Scatter Plot** displays horizontal errors as a Northing vs. Easting scatter plot (see Figure 6).

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**Figure 5: Pivot Field mobile app view of the Iono Index**

**Figure 6: Rover Integrity Position Chart (left) and Position Scatter Chart (right) of horizontal (2D) performance**
The **Init Time Attempts** view presents initialization times for selected rovers vs. time.

The **Init Time Cumulative** view provides a summary of initialization statistics for all selected rovers in the form of a cumulative distribution function (CDF) plot.

**SUMMARY**

Under typical conditions, ionospheric delays represent the largest GNSS error source. Unpredictable events on the sun drive ionospheric behavior on earth that is often a challenge to productive, accurate precision survey applications. In the past, performance anomalies were sometimes attributed to atmospheric causes by assumption, but the tools described here allow you to clearly understand the state of the ionosphere and its effects on GNSS positioning. The Trimble Pivot platform, with its tools and wide range of apps, enables network operators to maximize user productivity and manage operations during the full spectrum of ionospheric activity.