Trimble IonoGuard

Protecting RTK GNSS from ionospheric disturbances

Contents

Overview

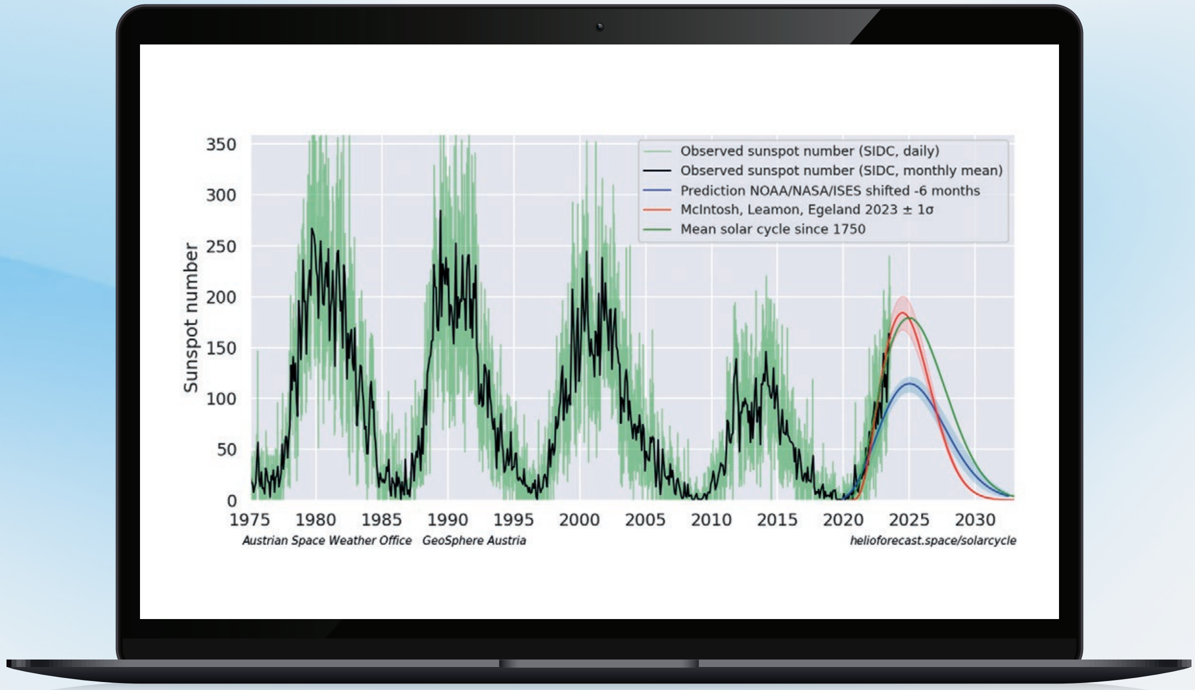
Solar activity peaks every 11 years with the next maximum predicted in 2025. This has a direct impact on delays and stability of GNSS signals and can have a negative impact on precision positioning. This paper identifies the challenge to GNSS users and manufacturers and how Trimble IonoGuard™ technology is mitigating the effects in Trimble ProPoint® GNSS technology enabled receivers.

Introduction

High precision GNSS users operating around equatorial and high latitude regions are familiar with position degradation from ionospheric disturbances. The last solar cycle, which peaked in 2014, was a relatively mild cycle compared to the recent historical record. Understanding that the follow on cycles may not be as moderate or geographically constrained, Trimble embarked on a data collection and development exercise early in the current cycle to ensure hardware and software was ready to maximize customers' productivity. The result is Trimble IonoGuard technology.

We will take a look at how the ionosphere affects GNSS positioning and how Trimble IonoGuard is being used in the field today to optimize accuracy, availability and integrity in critical applications.

What are *ionospheric disturbances* and how do they affect GNSS?



Solar Cycle

Sunspots are temporary areas of the sun, caused by active magnetic flux reducing convection. The more sunspots, the more areas with magnetic activity. These areas can eject particles which add to the solar wind and may be carried to Earth. As more particles hit earth, the layer of atmosphere known as the ionosphere becomes more charged, and the GNSS signal delay resulting from the ionosphere increases. The Sun's magnetic field flips once every 11 years and sunspot activity is correlated with this 11-year cycle. It is difficult to predict the magnitude of the solar cycle. Early models predicted that the maximum in 2025 would be similar to the previous. See the NOAA model above. However, new models and measurements indicate a cycle more similar to the cycle which peaked around 2002.

Ionosphere

The ionosphere is an ionized layer of the upper atmosphere that has a large number of electrically charged atoms and molecules, which cause a delay in the GNSS signals passing through it. The ionosphere varies over time, with significant differences between night and day, when the solar energy source is present. The impact on radio waves is dependent on frequency. The delay is inversely proportional to the square of the frequency, as a result L1 (at a higher frequency) has less delay than L2. A common metric describing the ionosphere is TEC or Total Electron Content. This is the total number of electrons integrated between two points, e.g., from the receiver to the satellite in a straight line. The units are electrons per meter squared; with the frequency of a signal, this can be converted to an equivalent signa delay.

The delay through the ionosphere is not fixed and will change based on the time of day, year, and location. The elevation angle between the receiver and satellite also impacts the magnitude of the delay. A high-elevation signal will take the shortest path through the ionospheric layer of the atmosphere as the path is perpendicular to the ionosphere. A low elevation signal will pass through the ionosphere at an angle and thus experience a much higher delay. In the absence of a geomagnetic storm, the ionosphere is correlated with solar activity and hence the peak delay is in the early afternoon, with a lower delay overnight.

Equatorial Effects

During the evening hours around the geomagnetic equator, plasma rises in the ionosphere. This can lead to instability within the ionosphere and result in scintillation. This is an effect where the GNSS signals are impacted by varying electron densities in the ionosphere, which can result in very rapid phase and amplitude change, leading to poor tracking, complete loss of lock, and/or carrier phase cycle slips. When the instability occurs, it may be limited to certain regions or bubbles of the ionosphere and thus only a subset of satellites may be affected. In South America, where many of our agriculture and mining customers operate, scintillation occurs an hour or two after sunset and will typically last for 4-5 hours. It also follows an annual cycle with most disturbance between September and March and severity dependent on the 11 year solar cycle.

Polar Effects

Sunspots can eject material from the sun that travels a few 100 km/s to a few 1,000 km/s. This phenomenon is called Coronal Mass Ejection. If the material is ejected with an Earth-bound trajectory, it will typically take a few days to reach Earth. Due to the Earth's magnetic field, it tends to travel to the poles, where it can significantly impact the ionosphere at either pole. In addition to impacting GNSS performance, this can sometimes be observed as the Northern (or Southern) lights, a phenomenon referred to as aurora borealis (or aurora australis). During more intense storms, the Northern lights can extend to the continental US, and the impact on the ionosphere can affect GNSS signals at lower latitudes.

While a loss of lock and cycle slips can occur in the polar region, data typically shows less severe amplitude scintillation compared to the equatorial regions, with limited cycle slips and less disruption.

Global Effects

Although most noticeable disturbances occur around the geomagnetic equator and northern latitudes, we have also observed an increase in the ionospheric delay measurement globally as we approach the solar cycle maximum. While dual and triple frequency techniques are leveraged to mitigate these effects by using an ionospheric free combination, this also increases measurement and position noise. With the potential for large solar storms to cause disruptions in mid-latitude operations, ionospheric protection has become a critical global requirement for GNSS receivers.

Impact on GNSS Operations

As mentioned above, ionospheric disturbance can lead to poor signal tracking and in some cases complete loss of lock on the GNSS satellite. Disturbances can also be localized, resulting in RTK algorithms experiencing difficulty when base and rover measurements are affected differently. The agriculture and mining industries are the largest RTK user base that experience disruptions from high ionospheric activity. These operations depend on the availability of centimeter level positions. Machines cannot operate safely or effectively if the accuracy is determined to be outside the threshold limits. Productivity is reduced and the economic impact can be substantial.

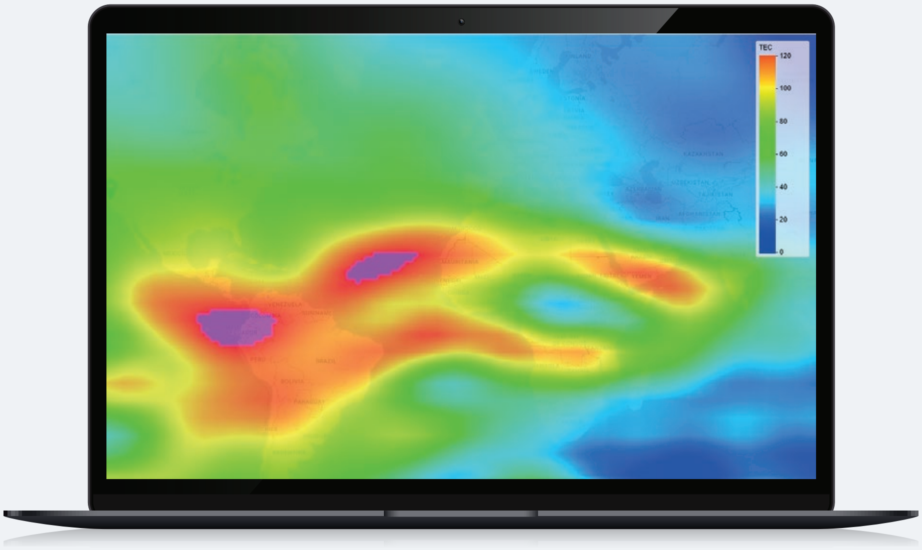
What is Trimble doing about it?

During the last three solar cycle peaks dating back to the early 1990's, Trimble customers have experienced issues with carrier phase GNSS positioning.

Each cycle has resulted in focused research and development to improve receiver tracking and processing algorithms. With the number of GNSS users more than doubling every cycle, significant effort had to be made to ensure that technology was in place to minimize disruption during future cycles.

GNSS Planning Online Tool

During peaks of solar activity, where certain portions of the ionosphere are excited, higher signal delays will occur. While ionospheric activity may typically occur at key times throughout the day, such as midday or dusk, that is not always the case. Trimble has setup a global ionospheric measurement network, which via the GNSS Planning Online (gnssplanning.com) tool allows users to plan ahead and avoid working during times where there is higher probability of disturbance.



Above is an example of a map of TEC from the planning tool.

An ionospheric index value for a given location and time is also provided. This is a value on a scale of zero to 10 indicating ionospheric level derived from measured TEC and scintillation.

Data Collection

To devise effective ionospheric mitigation methods in GNSS RTK receivers, Trimble engineers require data gathered from areas where the issue is prevalent. Trimble R&D facilities are generally concentrated in mid latitudes where disturbance is low. Collecting code and carrier measurements in addition to raw radio frequency (RF) data for all GNSS frequencies during high periods of solar activity is a logistically difficult exercise. In previous solar cycles, Trimble constructed specialized RF recorders that were bulky and necessitated frequent replacement of storage media. Fortunately, contemporary recorders are significantly smaller and have the ability to capture extended data periods directly on their internal storage.

Trimble installed both online continuously operating receivers and RF recorders at multiple equatorial and high latitude locations. The recorders captured large amounts of regular seasonal ionospheric activity in addition to during some major solar storm events. This data provided the basis for R&D development. Signal processing techniques and RTK algorithms are tuned using replayed data. Updated firmware is then loaded into onsite receivers for real time evaluation.

Trimble IonoGuard

Ionospheric mitigation features have been included and improved in Trimble receivers over the last three solar cycles. To ensure preparation for the current and future solar maximums, the data collection exercise was leveraged to develop next generation Trimble IonoGuard technology.

Signal Processing Mitigation

During ionospheric storms, there can be significant frequency-dependent differences in the phase and group delay through the ionosphere. It is therefore important for the receiver not to be dependent on any one frequency for operation. Trimble's GNSS signal processing has been updated to track signals independently. The exception to this is the L2 code measurement on GPS satellites launched before 2005. Unlike the newer L2C signals, these require L1 to assist tracking. To account for this, IonoGuard adjusts the signal processing on these channels during ionospheric events to minimize tracking error.

RTK algorithms rely on carrier phase measurements from all frequencies. During extreme ionospheric events, the receiver can lose lock on the carrier for brief periods, often for just a few seconds. Phase tracking algorithm improvements with IonoGuard technology has reduced the time taken to recover carrier phase tracking and minimize potential disturbances. ProPoint is also agnostic to the signals tracked, e.g. it can operate with any combination of triple, dual, or single frequency measurements.

Trimble ProPoint RTK Mitigation

Trimble IonoGuard has been tightly integrated into the Trimble ProPoint RTK engine. Optimum performance is achieved when IonoGuard is enabled at both the base and rover receivers. With IonoGuard enabled at the base station, ionospheric information for each satellite is transmitted via CMRx or RTCM MSM protocols to rover receivers. IonoGuard rover receivers utilize this information together with their own ionospheric measurements to optimize the computed positions.

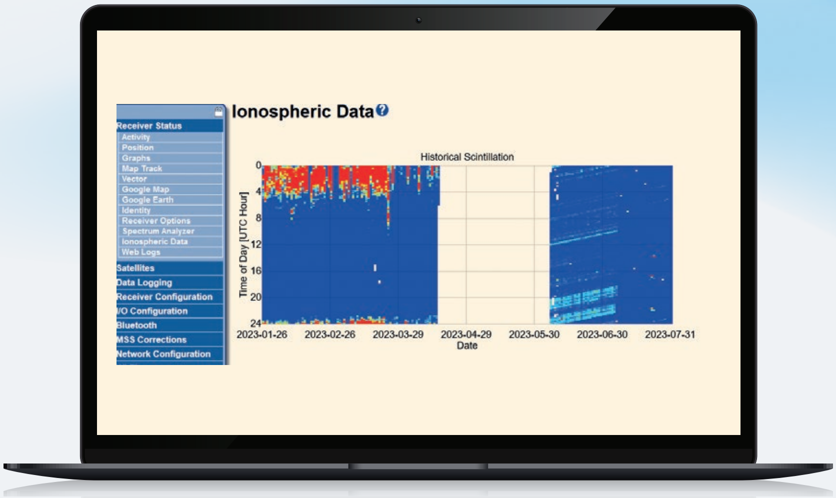
If IonoGuard is not enabled at the base receiver then an IonoGuard rover will analyze the standard base messages and determine if ionospheric adjustments are necessary. These adjustments are then used to improve positioning performance. This method is not as rigorous as having the more detailed ionospheric information sent from the base but can assist when using a non Trimble ProPoint receiver or 3rd party base receiver.

Customer Diagnostics

Troubleshooting issues in high precision positioning systems can be an expensive endeavor. Multipath, jamming and other factors can cause similar outcomes as ionosphere disturbances and therefore it is important to pinpoint the problem accurately and rapidly. With the introduction of Trimble IonoGuard, an additional traffic light system has been added to the receiver web interface. A green, yellow, orange or red icon indicates the level of ionosphere disturbance that the RTK base station is experiencing on each satellite. The rover receiver shows this same information using the received IonoGuard base messages.

SV	Type	Elev. [°]	Azim. [°]	L1-C/No [dBHz]	L1	L2-C/No [dBHz]	L2	L5-C/No [dBHz]	L5	Iono	IODE	URA [m]	Type
3	GPS	86.46	258.86	51.2	CA	51.2	CM+CL	54.3	I+Q		34	2	IIF
4	GPS	53.38	307.68	47.2/49.3	CA/BOC	49.3	CM+CL	51.3	I+Q		112	2	III
6	GPS	13.12	318.35	39.4	CA	42.4	CM+CL	46.5	I+Q		126	2	IIF
9	GPS	26.53	288.58	44.1	CA	44.4	CM+CL	49.1	I+Q		107	2	IIF
16	GPS	31.73	130.18	43.5	CA	30.7	E	-	-		116	2	IIR
26	GPS	40.05	90.11	44.6	CA	47.2	CM+CL	51.4	I+Q		120	2	IIF
31	GPS	42.66	46.71	48.2	CA	43.2	CM+CL	-	-		190	2	IIR-M

If IonoGuard messages are not being received from the base, then the circle symbols are replaced by squares and the rover's calculation of base ionosphere activity is indicated.



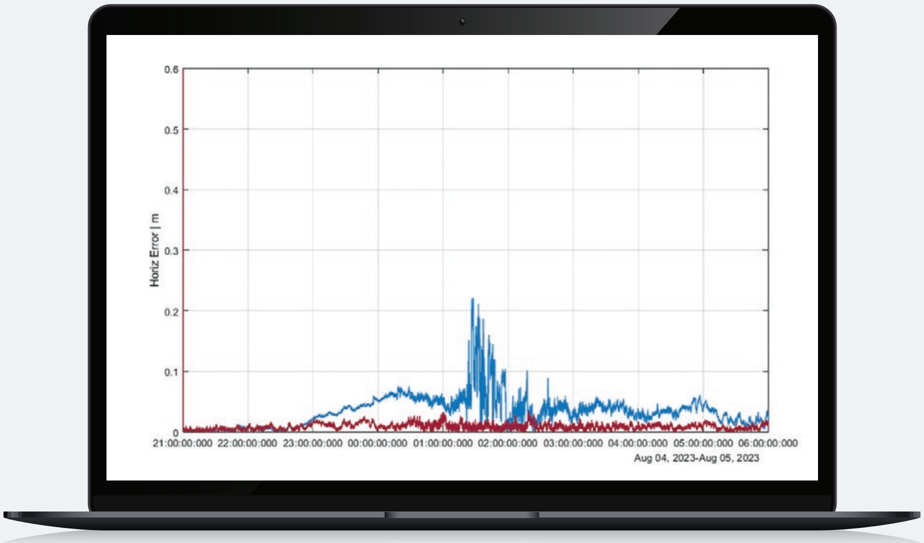
▲ A history of base ionospheric activity is also available on the base web interface.

All ionospheric data is logged in the standard Trimble T04 raw data files which can help Trimble support teams further diagnose issues.

Real World Improvements

Continuously operating base and rover receivers in regions with high levels of ionosphere disturbance have been running with IonoGuard enabled. Comparison to firmware without IonoGuard can be made. During solar storm events the improvement in positional accuracy is particularly evident. Below are plots from Brazil, Peru, and Northern Sweden during a solar storm that occurred on August 5th 2023. The blue line is the horizontal positioning error in meters for firmware running without IonoGuard enabled. The red line represents the IonoGuard performance.

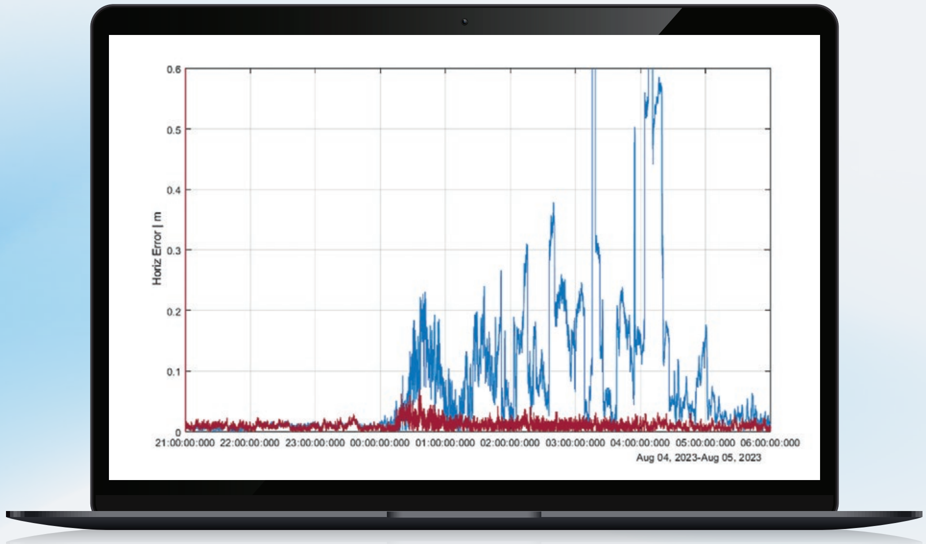
Brazil data



Horizontal position error with IonoGuard enabled

IonoGuard disabled

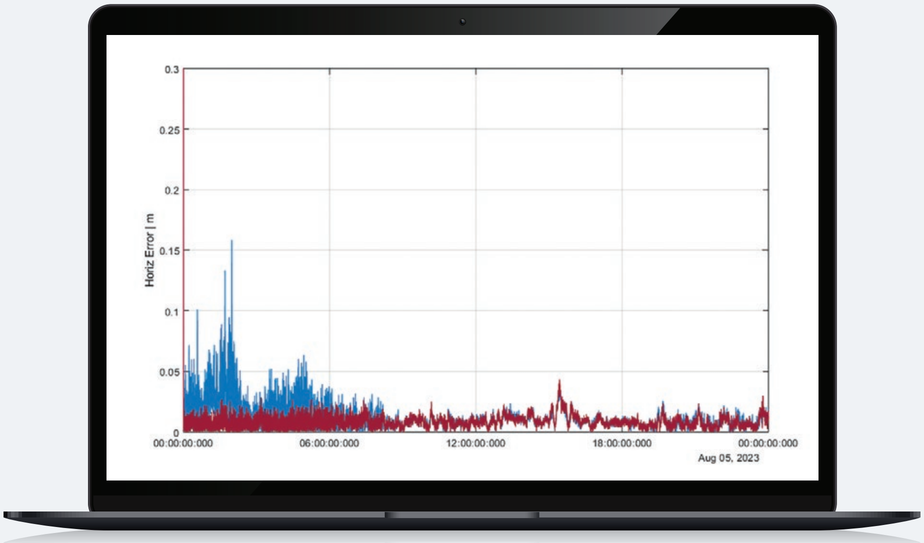
Peru data



Horizontal position error with IonoGuard enabled

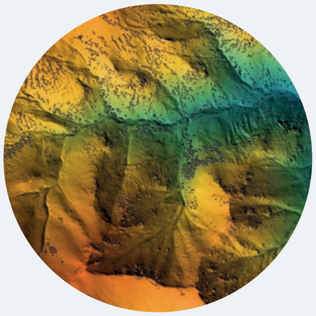
IonoGuard disabled

Sweden data

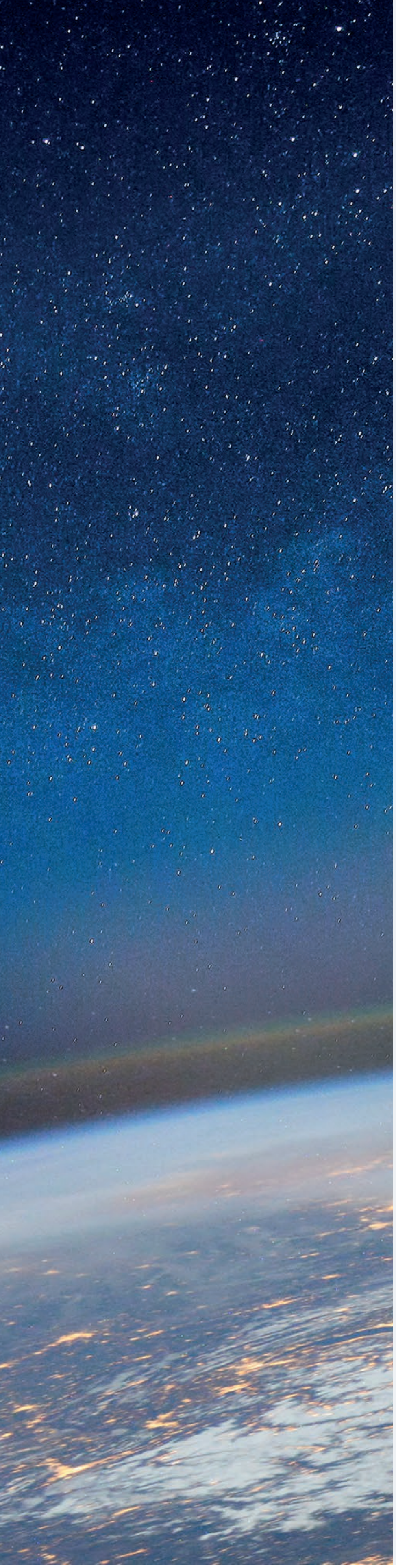


Horizontal position error with IonoGuard enabled

IonoGuard disabled



Similar results are achieved in terms of vertical accuracy. These results demonstrate that during high ionospheric activity, IonoGuard ensures that not only centimeter accuracy is continuously available but it is also at an acceptable level for mining, construction, agricultural and geospatial applications.



Conclusion

In equatorial and high latitude regions of the world, ionospheric disturbances are common with peak activity during solar storms and 11 year cycle maximums.

Industries with high operating costs such as mining and agriculture require centimeter level accuracy 24 hours per day. Unfortunately high precision GNSS is affected most by these disturbances and with increasing solar activity, the problem could become more global and expensive in nature.

Utilizing a global network of GNSS stations, Trimble's GNSS Planning Tool allows users to identify and plan around high ionospheric activity.

Trimble has taken further actions to ensure its customers GNSS accuracy and availability through the development of IonoGuard technology. An ongoing data collection campaign has provided GNSS and RF data to tune signal processing and RTK algorithms and deliver improved accuracy, availability and integrity. Diagnostic information indicating the real time level of ionosphere on each satellite together with historical data is presented in a user friendly graphical web interface.

IonoGuard technology in operation around the world has already shown significant improvements in positioning performance during the periods of high ionospheric activity. Users can feel confident that the superior performance of their ProPoint receivers has been further improved with the addition of IonoGuard ionospheric mitigation technology.