Weathering the Storm—GNSS and the Solar Maximum

Next Generation GNSS Ionospheric Scintillation and TEC Monitoring

NovAtel White Paper—March 2012

Overview

This paper addresses the concerns caused by the impending solar maximum, including a discussion of how disturbances due to magnetic and ionospheric storms disrupt radio signals and impact Global Navigation Satellite Systems (GNSS) receiver operations. The paper briefly covers the basics of the solar maximum and how NovAtel's new GPStation-6™ GNSS Ionospheric Scintillation and TEC Monitor (GISTM) receiver is designed to monitor the ionosphere during periods of maximum solar activity.

Introduction

Concern regarding the impact of ionospheric activity on GNSS operations during the solar maximum is not new to the GNSS community. Ionospheric errors caused by increased solar activity can degrade position accuracy, measurement quality, signal integrity, and in severe cases, cause a complete loss of lock for some GNSS signals. The ability to measure and monitor ionospheric activity is critical to assess GNSS signal quality and performance, especially during periods of increased ionospheric disturbance.

GNSS provides an excellent means to globally and continuously measure ionospheric activity. NovAtel's GPStation-6 GISTM receiver delivers specialized ionospheric monitoring capabilities, allowing system integrators to deploy enhanced monitoring solutions in advance of the solar maximum. This new product design is based on the mature and field proven GSV4004B GISTM receiver. The GPStation-6 incorporates NovAtel's multi-constellation, multi-frequency OEM628™ GNSS measurement engine and an ultra-low noise Oven Controlled Crystal Oscillator (OCXO).

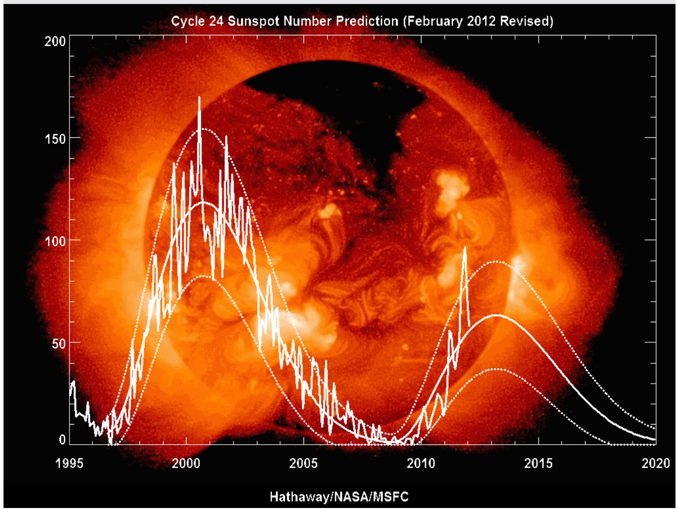
Solar Activity and GNSS Measurements

Solar Activity and the Ionosphere

Ionospheric activity is influenced by the periodic cycles of solar activity, the Earth's tilt/orbit (annual), the Earth's rotation (daily), as well as interaction with the Earth's magnetic field.

Periodic changes in solar activity directly affect the amount of solar irradiation received on earth. The solar cycle averages a period of 11 years, although cycles as short as 9 and as long as 14 years have been observed. Approximately every 11 years, the sun enters a period of increased activity called the solar maximum. The next solar maximum is expected to peak sometime between January and May 2013 (see **Figure 1**).

Figure 1 Sunspot Number Prediction[1]

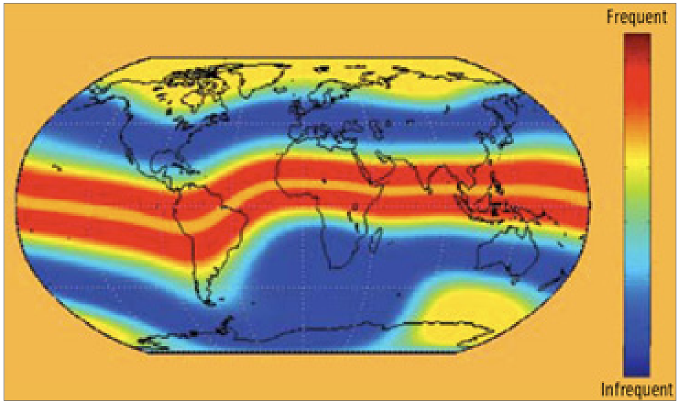


The solar maximum is associated with maximal solar flares (of powerful X types) and Coronal Mass Ejections (CME) that cause geomagnetic storms or temporary intense disturbances of the Earth's magnetosphere. The sun is already entering a period of increased activity, which is supported by recent reports from the space weather community regarding observed solar events.[2]

Although the driving force behind ionospheric activity is the sun, the Earth also plays an important role. The tilt of the Earth's rotational axis, with respect to the sun, results in annual cycles (seasonal). The Earth's rotation results in daily cycles. Finally, the Earth's magnetic field results in an uneven distribution of electrical charge throughout the ionosphere. Geographical differences in ionospheric effect are a result of these complex interacting factors (see **Figure 2**). The polar (at auroral latitudes) and equatorial regions (±20° of the geomagnetic equator) are most significantly affected by the ionospheric irregularities.

During these solar events, the ionosphere can cause severe disruptions to radio signal propagation in satellite communications and navigation systems, as well as radio astronomy. Such disruptions are expected to increase in regularity and severity during the imminent solar maximum.

Figure 2 Global Frequency of Ionospheric Irregularities[3]



GNSS Ionospheric Effects

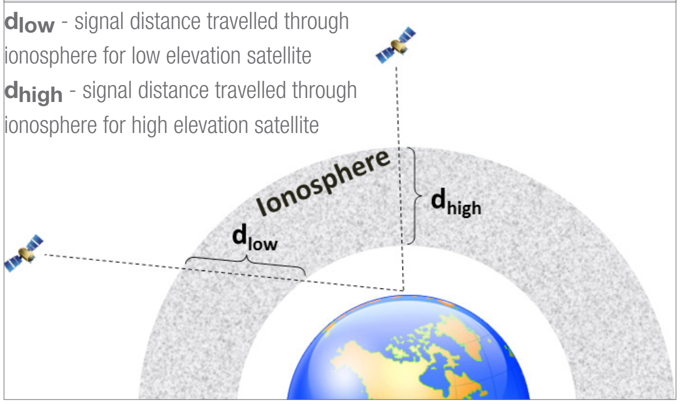
Total Electron Content (TEC)

TEC is the total number of electrons present along a path, between two points, and is measured in TEC units (1 $TEC_U = 10^{16}$ electrons/m^2).

TEC is a measure of the amount of electric charge present in the ionosphere, fueled directly by the sun's energy. The ionospheric charge builds when the sun's rays hit the upper atmosphere (TEC build up). The charge dissipates when the ionosphere is not exposed to the sun (TEC discharge). This results in a daily TEC cycle.

The ionosphere is a dispersive medium extending between 50 km and 1000 km above the Earth's surface. The ionosphere has a high concentration of electrically charged atoms or molecules (ions) formed primarily by solar radiation ionization. As a GNSS signal passes through these charged particles the signal is delayed. The magnitude of the ionospheric delay is a function of the refractive index of the ionosphere in the path of the GNSS signal. The refractive index is a function of frequency and TEC. The TEC will vary depending on the latitude of the receiver, the time of the day, the season and the level of solar activity. Given that TEC is a Line Of Sight (LOS) measurement, the path through the ionosphere is longer for satellites at lower elevations than for satellites at higher elevations. Effective TEC generally increases as the elevation of a satellite decreases and vice versa (see **Figure 3**).

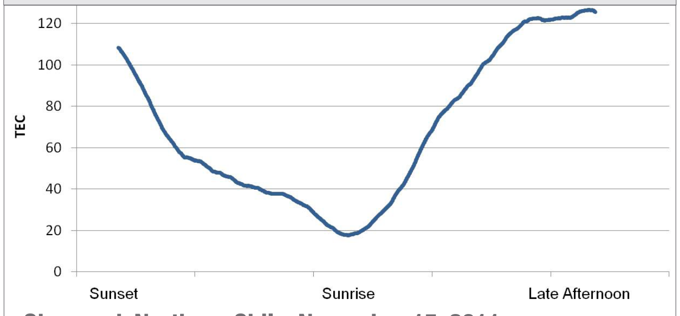
Figure 3 TEC and Geometry



The GNSS ranging code and carrier are affected differently as the signal interacts with the free electrons, along its transmission path through the ionosphere. Specialized GNSS applications make use of the carrier phase ranging measurements from GNSS signals to obtain precise positioning. However, the propagation of the satellite signal through the ionosphere affects the carrier measurement differently from the code measurement by advancing the carrier wave (by increasing the phase velocity), while retarding the carrier modulation (by reducing the group velocity). As a result, the range obtained from the integrated carrier phase is shortened while the measurement obtained from the code ranging is lengthened.

Figure 4 provides an example of average TEC fluctuations observed in Chile using NovAtel's GPStation-6. TEC discharge is observed between sunset and sunrise, when the local ionosphere is shielded from the sun by the earth. Similarly, TEC build up is observed between sunrise and sunset, when the sun is actively charging the local ionosphere. Twenty-four hour TEC patterns vary greatly depending on the amount of sun exposure at a given location.

Figure 4 Variation in Average TEC Values - Equatorial Region



Observed, Northern Chile, November 15, 2011

Ionospheric Scintillation

Ionospheric scintillation is a rapid temporal fluctuation in both amplitude and phase of a GNSS signal.

Localized ionospheric irregularities form when the local electron density differs significantly from the surrounding electron density. Such irregularities can cause both refraction and diffraction of radio signals. The refraction and diffraction effects cause group delay, phase advance and constructive/destructive interference of the GNSS signal as it interacts with free electrons in the ionosphere.

Refraction is the "bending" of the ray-path of GNSS signals, so the signal transmission path is longer than the LOS path, between the satellite and the receiver.

Diffraction is the "scattering" of radio signals in the ionosphere. Signal diffraction can cause amplitude scintillation and phase scintillation which can severely degrade GNSS receiver performance. Amplitude scintillation directly impacts the received signal quality (i.e., carrier-to-noise density ratio) at the GNSS receiver and subsequently degrades both pseudorange and carrier phase measurements. Amplitude scintillation as large as 30 dB can be sufficiently severe to cause signal fades which can force a loss of lock. Phase scintillation can stress the Phase Lock Loops (PLL) in a GNSS receiver and cause loss of phase lock, thereby impeding carrier phase measurements.

As a result of ionospheric scintillation (phase or amplitude), a GNSS receiver may be affected in any of the following ways:

- **Degraded pseudorange and carrier phase measurement**
- **Cycle slips and loss of phase lock**
- **Degraded navigation solution due to loss of multiple satellites for short periods**
- **Signal power fading and loss of lock**

Ionospheric scintillation near the equator is associated with the chaotic discharge of the ionospheric charge and is typically observed after sunset. Equatorial scintillation is generally observed, on both amplitude and phase, while polar scintillation is predominantly observed on the phase measurements alone. Although scintillation can be observed outside equatorial/polar regions, in equatorial/polar regions scintillation is generally more frequent and severe, particularly during a solar maximum.

Ionospheric Models and Corrections for GNSS Receivers

Single frequency GNSS receivers make use of ionospheric correction data broadcast as part of the GNSS navigation signal. The corrections are based on ionospheric models, such as Klobuchar (GPS) or NeQuick (Galileo). Although fairly effective during periods of moderate to low ionospheric activity, these models tend to poorly reflect the true state of the ionosphere during periods of high ionospheric activity or during severe ionospheric disturbances.

Improved ionospheric corrections are available from Satellite Based Augmentation Systems (SBAS), such as the United States Wide Area Augmentation Area (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), India's GPS-Aided GEO-Augmented Navigation (GAGAN) and Japan's MTSAT Space-based Augmentation System (MSAS). These augmentation systems provide ionospheric corrections called Grid Ionospheric Vertical Error (GIVE) at defined Ionospheric Grid Points (IGP). The IGP are vertices of regularly spaced grids covering the local coverage area of the SBAS system. Although an improvement for single frequency receivers, the corrections again poorly reflect the true state of the ionosphere during severe ionospheric disturbances. It should be noted that SBAS signals are also vulnerable to ionospheric effects.

Since ionospheric delay is frequency dependent, it can be removed in real-time in multi-frequency GNSS receivers, by combining multi-frequency (i.e., L1/L2) observations to form a new signal free from ionospheric effects. This ionosphere free combination is effective in removing first order ionospheric effects, in the order of 10's of metres, however, the impact of higher order ionospheric effects still remain. The higher order effects are becoming more relevant with the growth of precision GNSS applications (carrier phase positioning, RTK, PPP, etc.).

Monitoring the Ionosphere using GNSS

Specialized GISTM Receivers

GNSS signals provide an excellent means for global and continuous ionospheric monitoring. With a specialized GNSS receiver it is possible to precisely measure TEC and ionospheric scintillation (amplitude and phase) for all GNSS signals in view simultaneously, covering many pierce points through the ionosphere. TEC is measured using combinations of multi-frequency GNSS signals (L1/L2/L5). For ionospheric scintillation observations, the industry standard measurement is S4 for amplitude variations and sigma-phi (σ_φ) for phase variations.

A special class of advanced GNSS receivers were developed specifically for this purpose, called GNSS Ionospheric Scintillation and TEC Monitor (GISTM) receivers. NovAtel GPStation-6™ GISTM receiver, built on more than a decade of GISTM receiver experience, provides TEC and ionospheric scintillation measurements for all current and planned GNSS signals.

Introducing the GPStation-6™

NovAtel's next-generation GPStation-6 GISTM receiver provides an expansion and modernization path for ionospheric monitoring programs in advance of the imminent solar maximum. The GPStation-6 is powered by NovAtel's multi-constellation, multi-frequency OEM628 GNSS receiver card. This state-of-the-art measurement engine provides 120 independent tracking channels and features advanced ionospheric monitoring capabilities. It tracks GPS L1/L2-P(Y)/L2C/L5, SBAS L1/L5, GLONASS L1/L2, Galileo E1/E5a/E5b/Alt-BOC and QZSS L1/L2/L5 (Compass ready). The enclosure houses a fully integrated, ultra-low phase noise OCXO to ensure high performance phase tracking measurements needed to generate phase scintillation observations.

The GPStation-6 design is based on the mature and field proven GSV4004B GPS L1/L2 GISTM receiver from GPS Silicon Valley. The design provides maximum backward compatibility to the GSV4004B, reducing the time and cost to perform field upgrades to the new GPStation-6 platform. The GPStation-6 was developed through a collaborative partnership with Dr. A.J. van Dierendonck, founder of GPS Silicon Valley. Dr. van Dierendonck will continue to work with NovAtel, offering decades of experience in GNSS and GISTM receiver design to ensure GPStation-6 customers have access to the best-in-class expertise.

How the GPStation-6 Works

Traditional GNSS receiver performance is degraded during ionospheric disturbances. The GNSS signal measurements generated by a traditional receiver do not allow for observation or characterization of how the ionospheric disturbance is affecting the tracked signals. One major limitation of a traditional GNSS receiver, when it comes to ionospheric measurements, is the high phase noise of the onboard Temperature Controlled Crystal Oscillator (TCXO). The GPStation-6 GISTM receiver removes this limitation by utilizing an ultra-stable, low phase noise OCXO. Using the high-quality 10 MHz reference signal generated by the OCXO, the OEM628 measurement engine is able to generate the precise phase measurements required to observe phase scintillation.

The GPStation-6 outputs a variety of signal measurements and statistics useful for characterizing the local ionospheric environment. The receiver independently samples the raw amplitude and phase of each tracked signal at a high rate (50 Hz) and outputs these raw measurements every second. Raw TEC measurements are also output every second. The raw measurements are also processed (detrended) within the GPStation-6 receiver to produce 60-second summary logs (scintillation, TEC). The summary logs contain measurement data (C/No, code-minus-carrier, lock time, etc.) and smoothed ionospheric measurements provide valuable insight into the ionospheric conditions for each signal tracked over the past minute.

The smoothed ionospheric measurements output in the summary logs include computations for:

- **S4 - amplitude scintillation index**
- **sigma-phi (σ_φ) - phase scintillation index**
- **TEC**

The amplitude scintillation index (S4) is dimensionless and is defined as the square root of the normalized variance of signal intensity over a defined period of time. Strong scintillation is typically associated with an S4 index of 0.6 or higher, where an S4 index of 0.3 or lower is associated with weak scintillation (conditions unlikely to have any noticeable impact on receiver performance).

The phase scintillation index (σ_φ) is the standard deviation of the received signal phase over a defined period of time, measured in radians or degrees. A phase scintillation index of 1 radian or higher is typically associated with strong scintillation.

TEC measurements are used to characterize ionospheric delay. The receiver generates code and carrier TEC measurements for each tracked satellite by differencing range measurements across the multiple frequencies broadcast by each satellite. The following signal pairs are used to generate the TEC measurements:

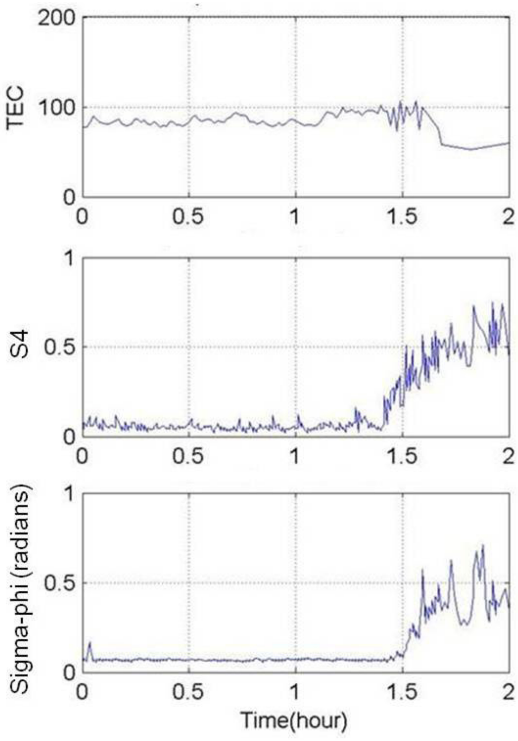
- **GPS L1/L2, L1/L5**
- **SBAS L1/L5**
- **GLONASS L1/L2**
- **Galileo E1/E5a**
- **QZSS L1/L2, L1/L5**

GPStation-6 Measurement Data

NovAtel has collected GPStation-6 data in both equatorial and northern latitudes during recent periods of increased ionospheric activity. These data collection efforts used a GPStation-6 in parallel with a GSV4004B in order to validate the measurements provided by the new product and demonstrate its extended capabilities.

Although extensive test results are not presented in this paper, the following figures illustrate the different ionospheric characteristics typically associated with the equatorial and auroral regions.

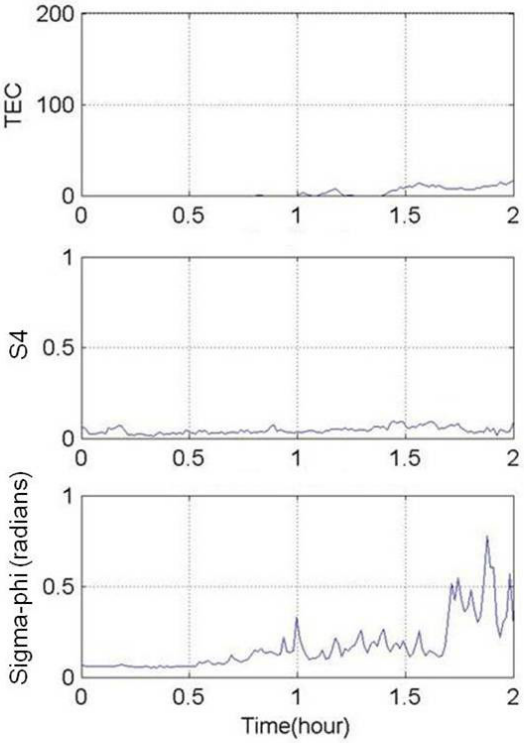
Figure 6 TEC, Amplitude and Phase Measurements - Equatorial



Data acquired by GPStation-6
Northern Chile - November 15, 2011

The GPStation-6 data presented in **Figure 6** was collected in Northern Chile on November 15, 2011. During the late evening hours (~02:00 to 04:00) a moderate ionospheric event was observed. Correlated amplitude and phase scintillations are observed, together with a sharp drop in TEC for the tracked signal. The TEC is also quite high, at around 100 TEC units. High TEC and correlated amplitude and phase scintillation are common to the equatorial region.

Figure 7 TEC, Amplitude and Phase Measurement - Auroral



Data acquired by GPStation-6
Calgary, Alberta, Canada - January 24, 2012

The GPStation-6 data presented in **Figure 7** was collected in Calgary on January 24, 2012. This data was collected in response to widespread reports of a solar flare event. Again, during the late evening hours (~02:00 to 04:00) a moderate ionospheric event was observed. The ionospheric disturbance affects only the phase measurement for the tracked signal, which is common to auroral observations. It should be noted that phase scintillation was only observed on low elevation satellites north of Calgary during the data collection period, suggesting the phase scintillations were indeed related to the solar event.

GPStation-6 Benefits

Advanced Ionospheric Monitoring

TEC, S4 and σ_φ measurements provide unique insight into local ionosphere activity. This information can be processed in real-time to detect anomalies and monitor local ionosphere activity. The data can also be logged to a file and post-processed against suspected ionospheric events or to track long term ionospheric trends and behaviors. A GPStation-6 receiver can provide a single point perspective of local ionospheric activity, while a network of GPStation-6 receivers with central processing can enable detailed regional characterization of ionospheric activity and trends with redundancy.

Some examples of applications that could benefit from the GPStation-6 are:

- **Ionospheric research**
- **Space weather monitoring/prediction**
- **Local real-time ionosphere sensor**
- **Regional network of ionospheric sensors**

Backward Compatibility, Easy to Integrate

The GPStation-6 platform provides maximum compatibility to the GSV4004B. As such, existing systems using the GSV4004B can be upgraded to the new platform easily and at a lower cost. From a hardware perspective, the GPStation-6 enclosure is identical in size and supports the same power and communications cables from the first generation product. From a software and data processing perspective, the GPStation-6 will output the legacy L1/L2 logs specific to the GSV4004B so that existing processing software can still be used with minimal updates. Modernized communications and updated data logs/commands are included to simplify updades.

GPStation-6 setup is straightforward. The recommended antenna for most installations is NovAtel's triple frequency GPS-703-GGG Pinwheel™ antenna. Antenna and cable accessories are available from NovAtel so a complete hardware installation can be procured at the same time.

PC Utilities and Supporting Software

Included with the GPStation-6 receiver is a suite of PC utilities to support receiver configuration, data collection and post-processing. NovAtel Connect™ provides a graphical user interface for the GPStation-6 to confirm communications, signal tracking and receiver status. SLOG (scriptable logger) is a command line utility recommended for long term data collection activities. Data extraction utilities are provided to support post-processing analysis of the raw and summary files. C++ source code for GISTM log decoding is provided to support custom post-processing activities.

Commercial Off-the-Shelf Solution

The GPStation-6 receiver is manufactured at NovAtel's office in Calgary, Alberta, Canada. There are no export restrictions for this commercial off-the-shelf (COTS) product, making it easy to order and ensuring rapid delivery around the world.

The product is available with a variety of firmware models available depending on which GNSS signals are of primary interest in a region. The receiver can be quickly upgraded in the field as new constellations/signals become available.

GPStation-6 Feature Summary

- **Latest generation OEM6™ technology (OEM628 engine)**
  - **120 independent tracking channels**
  - **50 Hz raw measurement sampling rate**
  - **Advanced firmware for ionospheric monitoring**
- **Multi-constellation, modernized signal support**
  - **GPS, GLONASS, Galileo, SBAS, QZSS, COMPASS**
- **Integrated low phase noise OCXO**
- **USB communication**
- **Field-upgradeable FW**

Conclusion

GNSS technology is ubiquitous, relied upon by industries around the world to provide precise position and time. During periods of increased solar activity, such as the impending solar maximum, it is particularly important to monitor changes in the ionosphere to assess GNSS signal quality and performance.

NovAtel's GPStation-6 is a leading edge GISTM receiver designed to monitor GNSS disruptions caused by the solar maximum. By utilizing NovAtel's world class GNSS technology to detect and measure amplitude and phase scintillation, the GPStation-6 can be relied on to deliver high performance GNSS signal monitoring and characterization of ionospheric activity on a local or regional basis.

Incorporating NovAtel's multi-constellation, multi-frequency OEM628 GNSS receiver and an ultra-low noise OCXO, the GPStation-6 delivers unparalleled ionospheric scintillation and TEC monitoring. It is backward compatible with the proven GSV4004B receiver to minimize the time and cost of field upgrades.

About NovAtel, Inc.

NovAtel's GGNSS technology is inside many of the world's most innovative positioning applications. As the world's leading OEM GNSS supplier, NovAtel's collaboration on the GSV4004B GISTM receiver established the industry standard for using GNSS to monitor solar activity and its impact on satellite positioning.

End Notes

1 NASA/Goddard Space Flight Center

2 Paul M. Kintner, Jr., Cornell University, Todd Humphreys, The University of Texas at Austin, Joanna Hinks, Cornell University

3 Hathaway/NASA/MSFC