Monitoring Space Weather with GNSS Networks: Expanding GNSS networks into Northern Alaska and Northwestern Canada

Anthea J Coster, *MIT Haystack Observatory*
Susan Skone, *University of Calgary*
Donald Hampton, *University of Alaska*
Eric Donovan, *University of Calgary*

BIOGRAPHIES

Anthea Coster, Ph.D. is an Assistant Director and principal research scientist at MIT Haystack Observatory. Her research interests include space weather, ionospheric and atmospheric coupling, and GNSS positioning and measurement accuracy. She received her PhD from Rice University in 1983. Contact her at ajc@haystack.mit.edu.

Susan Skone, Ph.D., is the Associate Vice President of Research and a Professor in Geomatics Engineering, Schulich School of Engineering, at the University of Calgary. She has a background in space physics and conducts research in ionospheric and tropospheric effects on GNSS. She has developed licensed software for mitigation of atmospheric effects on marine and aviation systems and is the recipient of several international awards for her work.

Donald Hampton, Ph.D. is an is an Associate Research Faculty member at the Geophysical Institute at the University of Alaska, Fairbanks, and Optical Science Manager at Poker Flat Research Range. His specialty is auroral dynamics and energy deposition in the upper atmosphere and ionosphere. At Poker Flat he maintains an array of all-sky cameras and spectrograph across northern Alaska, and is the PI of the Geophysical Institute Magnetometer Array. He has a PhD in Physics from the University of Alaska Fairbanks. His contact is dhampton@alaska.edu.

Eric Donovan, Ph.D., is a Professor (Department of Physics and Astronomy) and Associate Dean Research and Graduate Education, Faculty of Science, University of Calgary. He specializes in auroral ionosphere and magnetosphere physics with a focus on using optical, radar, and riometer data to remote sense magnetospheric dynamics. His group deploys, operates, and recovers data from All-Sky-Imager arrays located in Canada. He leads the RISR-C incoherent scatter radar at Resolute Bay, Canada, and the TREx ground-based ionospheric sensing network. He served as Chair of the Geospace Environment Modeling (GEM) program (2013-2015) in the United States National Science Foundation (NSF) Division of Atmospheric and Geospace Sciences and currently serves in the European Space Agency's SWARM's mission advisory group.

ABSTRACT

In October 2015, The White House Office of Science and Technology Policy (OSTP) released a National Space Weather Strategy and an accompanying National Space Weather Action Plan aimed at improving the United State's ability to prepare, avoid, mitigate, respond to, and recover from the potentially devastating impacts of space weather. The primary phenomena that produce space weather impacts on the global navigation satellite system (GNSS) include: the introduction of large gradients in the ionospheric total electron content (TEC); the rapid variation of a signal's amplitude and/or phase (scintillation); and/or the sudden increase in background L-band noise. These phenomena have the potential to severely impact users of GNSS services, and at minimum, require that users, specifically those with high accuracy requirements, be aware of current space weather conditions. Among the major deficiencies in the current network of GNSS receivers are the lack of GNSS monitors in the auroral regions of Canada and Alaska, specifically those that can provide near-real time access to total electron content (TEC) and scintillation. To rectify some of these deficiencies there is a new plan to install an additional thirty-five GNSS receivers in Northern Alaska and northwestern Canada (Northern Alberta, Saskatchewan, and Manitoba). Key advances of this plan will be: 1) the incorporation GLONASS total electron content data, along with GPS

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measurements, into global TEC maps; 2) the development of a real-time (or near real-time) capability of TEC measurements, and 3) the development of software that triggers the collection of the high-rate scintillation data across the sensor network. High-rate GNSS data are required for detailed analysis of scintillation during active time periods. As a pathfinder, a single GNSS receiver was installed in Venetie Alaska, recording high-rate data from multiple satellite constellations. We will provide specific case examples of high-latitude phenomena impacted by space weather and discuss our experiences with the additional receiver in Venetie, AK during time periods of moderately severe space weather events. We will summarize by providing a detailed plan for our deployment of additional receivers.

INTRODUCTION

Space weather can have serious adverse effects on the advanced technology that our society depends on, e.g. satellite communications, GNSS positioning and timing, power grids. The primary sources of space weather are solar flares and coronal mass ejections (CMEs), both initiated on the Sun. Solar flares produce sudden bursts of radiation while CME's are associated with bursts of plasma, embedded with magnetic field structures, that travel in the solar wind before interacting with the Earth's magnetosphere. Energy and radiation from these events can harm astronauts, damage electronics on spacecraft, and impact GNSS precision, tracking, and acquisition. The geospace response to these changes includes impacts on the radiation belts, multiple large-scale and small-scale changes in the ionosphere, and production of intense geomagnetically-induced currents. To better protect against space weather, there is a recognized need for improved forecasts, better environmental specifications, and more durable infrastructure. Improved monitoring and modelling of space weather have been identified as critical components of initiatives designed to better protect infrastructure and the national economy during time periods of large space weather events.

Our goal is to describe the need for better space weather coverage in the Arctic polar and auroral regions. Currently the GNSS arrays in Alaska have been primarily deployed by groups concerned with plate motion and earthquake prediction, as well as oil exploration. The northern part of Alaska lacks a dense network of GNSS receivers, although this is the area where the majority of space weather events begin in the ionosphere over the Northwestern United States. As part of the project Monitors for Alaskan and Canadian Auroral Weather in Space (MACAWS) project, we are proposing to deploy an additional thirty-five GNSS receivers in Northern Alaska and northwestern Canada (Northern Alberta, Saskatchewan, and Manitoba). MACAWS is planned as a sensor web network that provides both real-time and historical GNSS total electron content (TEC), differential TEC, and scintillation data products. The scintillation information is designed to monitor cm-scale irregularities observed at L-band frequencies. Real-time TEC measurements are a requirement for space weather monitoring, or now-casting. MACAWS data will be available to all who request it. Detailed TEC, differential TEC, and scintillation data will be available through the NSF-funded CEDAR Madrigal online database. For each of the new sites, scintillation indices will be overlaid onto the local TEC maps. Finally, real-time TEC values will be made publicly available for streaming, as will the high-rate scintillation data.

The proposed MACAWS sensor web provides significant new capabilities currently unavailable from an instrument provided by a vendor: the merging of GPS and GLONASS TEC observations into a unified North American TEC map; the development and deployment of triggering algorithms to collect the high-rate GNSS scintillation data during highly dynamic time periods; and the distribution of real-time (RT) TEC data to users. The receivers are to be installed at strategic geographic locations to provide unprecedented spatial and temporal coverage of ionospheric phenomena arising from near-earth magnetosphere processes, in particular auroral arcs associated with substorms, pulsating aurora, polar cap patches, tongue of ionization events. Figure 1 shows the planned receiver sites.

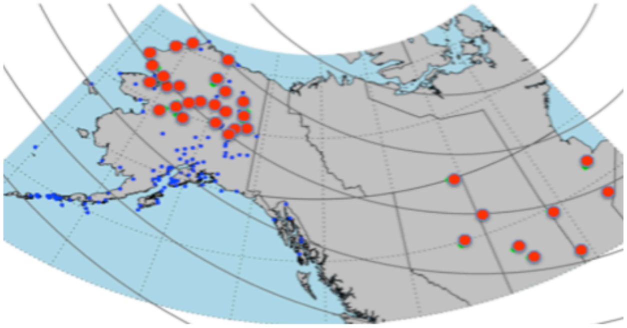


Figure 1. The red points in Alaska show the planned GNSS receiver sites. These sites are to be located at existing schools in Alaska, taking advantage of existing infrastructure. The blue points show the location of the existing Plate Boundary Observatory GPS receiver sites. Over Canada are shown 10 University of Calgary Transition Region Explorer (TREx) sites that will also host these new GNSS receivers.

This regional network of receivers will enable researchers to reach the broad science goal of understanding how the high latitude thermosphere-ionosphere system responds to energy inputs from above and below. In conjunction with existing instrumentation – including the SuperDARN radars, the Poker Flat Incoherent Scatter Radar, and ground based optics, as well as NASA satellite missions and sounding rockets and NSF CubeSat opportunities – this network will become part of an effective regional-scale synoptic geospace observatory. Measurements from the array will, directly or in conjunction with other instruments and models, address science topics as diverse as ion-neutral coupling in the high-latitude thermosphere, the impacts on the ionosphere of the dynamics of the lower atmosphere, and sources of high-latitude gravity (buoyancy waves).

The MACAWS array will contribute directly to space weather monitoring and to studies of operational space weather impacts with its real-time TEC data product and its summary of scintillation statistics and high-rate scintillation data in the auroral and polar regions. Many of the processes that lead to irregularity formation in this region are not well understood [Sahr and Fejer, 1996], yet these irregularities can have major effects on radio wave propagation. Plasma structuring and regions of plasma irregularities are frequently observed in the high-latitude regions. On the operational side, there is a lack of in-depth understanding of scintillation effects on GNSS tracking. This has relevance to the FAA's Wide Area Augmentation System (WAAS), which is currently operational in Alaska and much of the Canadian region. One of the goals of the MACAWS project is to collect high-rate GNSS data during time periods of disturbances for later in-depth analysis. The next sections of this paper provide a brief description of space weather effects at high latitudes, followed by an in-depth analysis of an auroral break-up event with a newly installed GNSS receiver at Venetie, AK, and then concluding with a summary.

SPACE WEATHER EFFECTS AT HIGH LATITUDES

The high latitude ionosphere is a projection of approximately 10^{15} million cubic km (40,000 times the Earth's volume) of solar-magnetosphere driven processes in the near-earth space environment (Figure 2). In the high-latitude ionosphere the irregularities forming in response to solar and geomagnetic events are related to polar cap patches (in the polar ionosphere) and particle precipitation (in both auroral and polar ionospheres). The propagation of GNSS signals through these irregularities is affected by large TEC fluctuations and (primarily) phase scintillation [Pi et al., 1997; Kintner et al., 2007; Ghafoori and Skone, 2012].

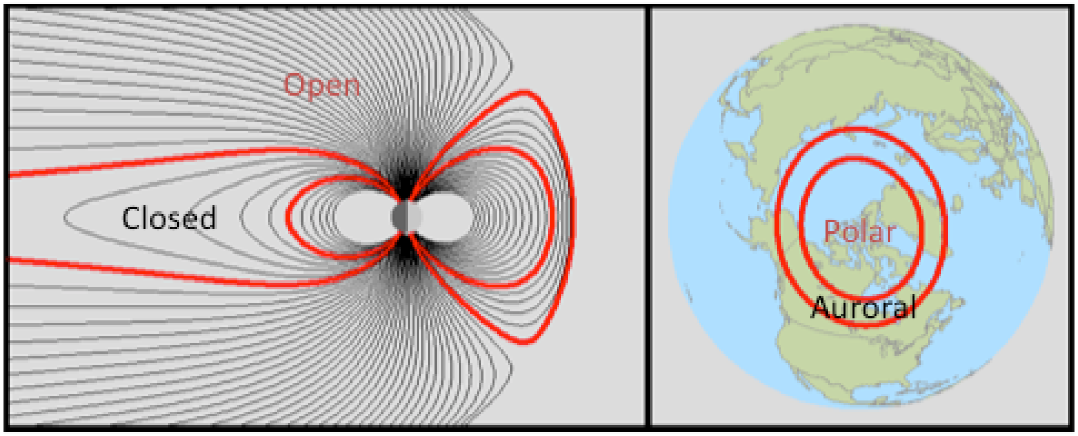


Figure 2. Boundaries of magnetospheric regions (left) mapping to ionospheric regions (right).

By observing dynamics and structure of the high latitude ionosphere, insight can be gained into the role of near-earth physical processes and key space weather parameters can be determined to characterize impact of specific phenomena on GNSS users. The driving magnetospheric dynamics occur across multiple scales on closed (primarily mapping to auroral oval) and open (primarily mapping to polar cap) magnetic field lines resulting in variations of ionospheric parameters with latitude and local time. Ionospheric phenomena of interest for GNSS applications include the aurora, polar patches, and storm enhanced density – all readily observed in ionospheric electron density measurements, auroral emissions, and radio and magnetic field measurements. A high density of GNSS receivers is required to capture the multi-scale phenomena occuring in this active region. Northern Alaska is particularly lacking in coverage.

Example – Auroral Arcs

Aurora are observed as high-latitude optical emissions caused by the precipitation of energetic particles from the magnetosphere into the ionosphere. Auroral arcs or discrete aurora are typically observed as bright bands of fine structure aligned east-west. With recent advances in imaging technology the physical morphology of aurora has been studied more clearly from micro to macroscopic sizes using digital all sky imagers [Donovan et al., 2006; Mende et al., 2008] and correlated with impact on GNSS signals and applications.

Figure 3 shows auroral image data from a UCalgary all-sky imager [Donovan et al., 2006; Mende et al., 2008] in northern Alberta (~61 deg. geo. mag. lat.). Spatial resolution of this 256 pixel wide image is ~1 km at zenith assuming the aurora at an altitude of 110 km. The complementary GPS data were obtained from a nearby Canadian High Arctic Ionospheric Network (CHAIN) commercial GPS scintillation receiver. The GPS signals provide opportunity to study evolution and impact of large-scale phenomena like aurora. Phase and amplitude scintillation indices provide information about plasma variations in the ionosphere propagation medium; the indices σ_Φ and S_4 are standard deviation of phase and normalized detrended signal intensity, respectively. When such measurements are combined with auroral images, a greater understanding of the causal physical phenomena can be gained – with the potential to develop space weather warning tools.

In this example, surface mining operations for natural resource extraction were disrupted due to discontinuities in GPS precise positioning services during auroral activity. Figure 4 shows the percentage of ambiguity resets for local GPS carrier phase observations. The GPS observations are degraded for signals propagating through the edges of quickly evolving auroral arcs. The carrier phase residuals during the period of auroral activity are at decimeter-level compared with centimeter-level during periods of minimal ionospheric activity.

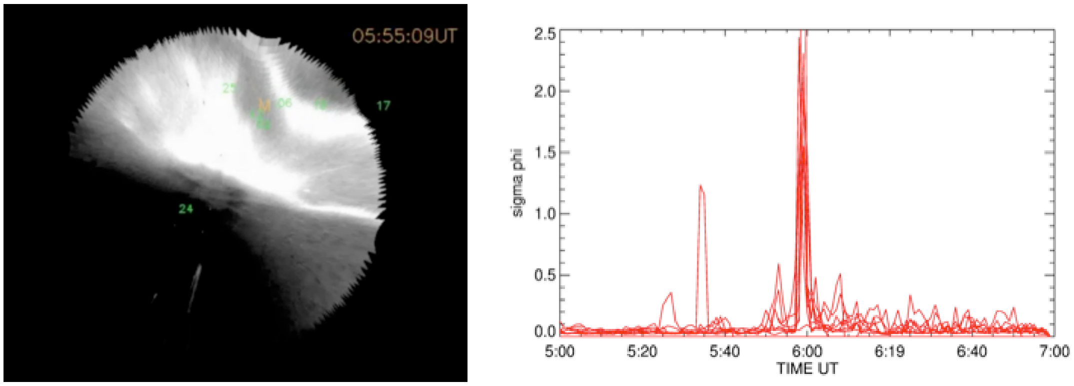


Figure 3. Auroral image (left) at 5:55 UT, 2 March 2017, from all-sky imager at Athabasca. GPS PRN numbers (in green) show locations of signal ionospheric pierce points. Corresponding phase scintillation indices (right) for all satellites in view 5:00-7:00 UT.

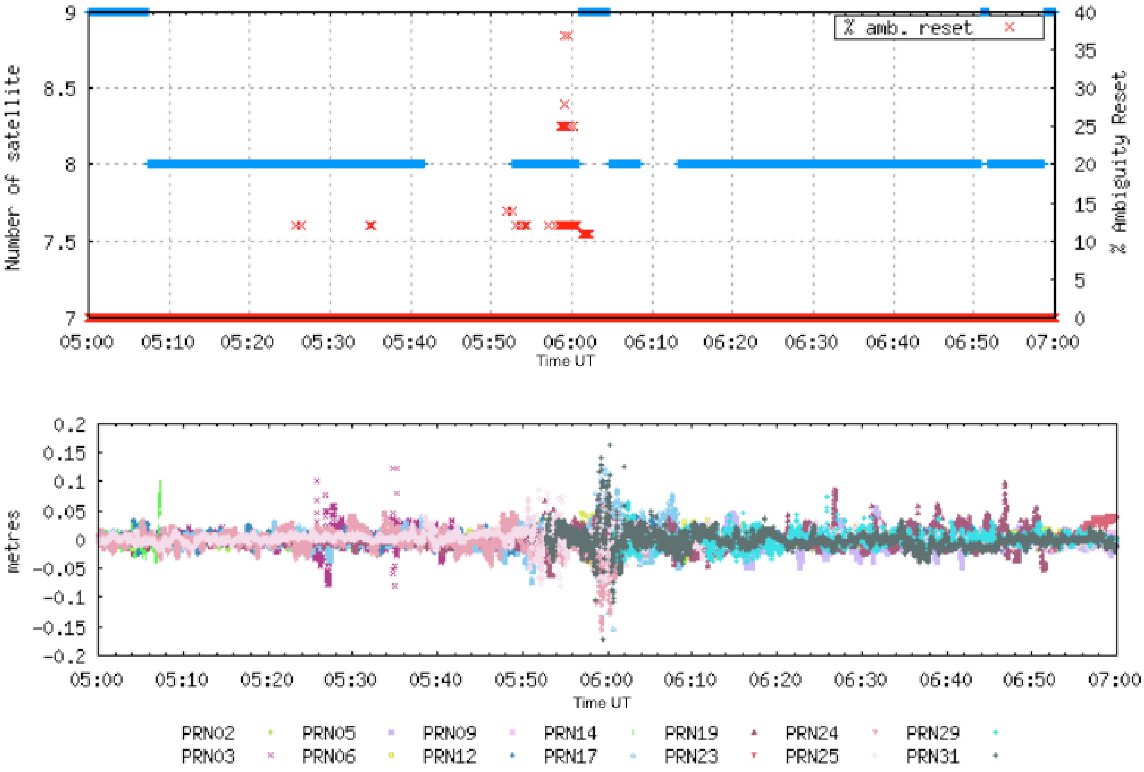


Figure 4. Number of satellites (blue) and percentage of carrier phase ambiguity resets (red) on 2 March 2017 (top plot) and GPS carrier phase residuals (bottom plot). Results generated using Natural Resources Canada precise point positioning tool.

Example – Polar Cap Patches

Polar cap plasma patches are regions or islands of high-density plasma within the high-latitude region. They have important practical consequences for technological systems because of their impacts on high-latitude ionospheric radio propagation. A standard definition of these patches is areas where the peak density is at least a factor of 2 greater (sometimes 10 times) than background density [Weber et al., 1984]. It is known that the convection electric field in the dayside cusp region is crucial for the formation of polar cap patches. Some of the patches are formed when storm enhanced density plumes are entrained into the cusp region and then enter the polar cap. If this plume of ionization is continuous, it is termed a tongue-of-ionization (TOI). If it is not continuous, it can be cut up into polar cap patches, depending on the shape and spatial coverage of the high-density region [e.g., Foster et al., 2005; Moen et al., 2013; David et al., 2016]. After formation, the patches drift anti-sunward at the convection speed and can be used as tracers of convection flows. They can persist for hours. Polar cap patches are an important plasma source for both the polar cap and the nightside ionosphere. Within the patches, electrons undergo recombination with O2+ producing excited oxygen atoms (O1D), leading to the 630 nm red line airglow. Various formation mechanisms of patches have been proposed and nicely reviewed in Carlson, 2012. These mechanisms include: (1) time-dependent reconnection and pulsating soft electron precipitation; (2) sudden expansion and contraction of the convection pattern; (3) Interplanentary magnetic field y-component (dawn-to-dusk) direction changes; and (4) enhanced recombination within high-speed convection flows creating low-density regions. There is evidence for each mechanism, but the question of which one is responsible for the majority of the patches remains unanswered.

Continuously increasing GPS TEC coverage in the polar cap has allowed for the tracing of the movement of the patches using TEC observations (see Figure 6 from Zhang et al., 2013). SuperDARN convection patterns have been overlaid onto TEC values provided by the MIT Haystack Madrigal database [Thomas, 2011]. In Figure 5, white indicates regions of no data. In addition, image processing was used to minimize the gaps in data coverage. The MACAWS data will improve the ability to trace the movement of the patches across the polar cap as shown in Figure 6. When combined with other measurements, such as SuperDARN, magnetometers, ASIs, and ISR data, a more complete picture of the physical processes responsible for these processes can be found.

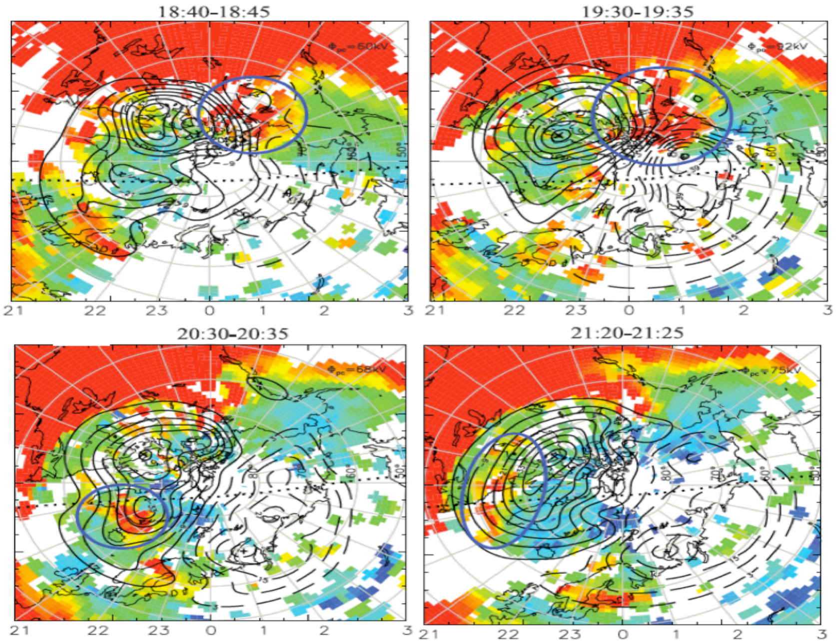


Figure 5. SuperDARN convection patterns overlaid onto GPS TEC, showing the movement of polar cap patches across the pole [Zhang et al., 2013].

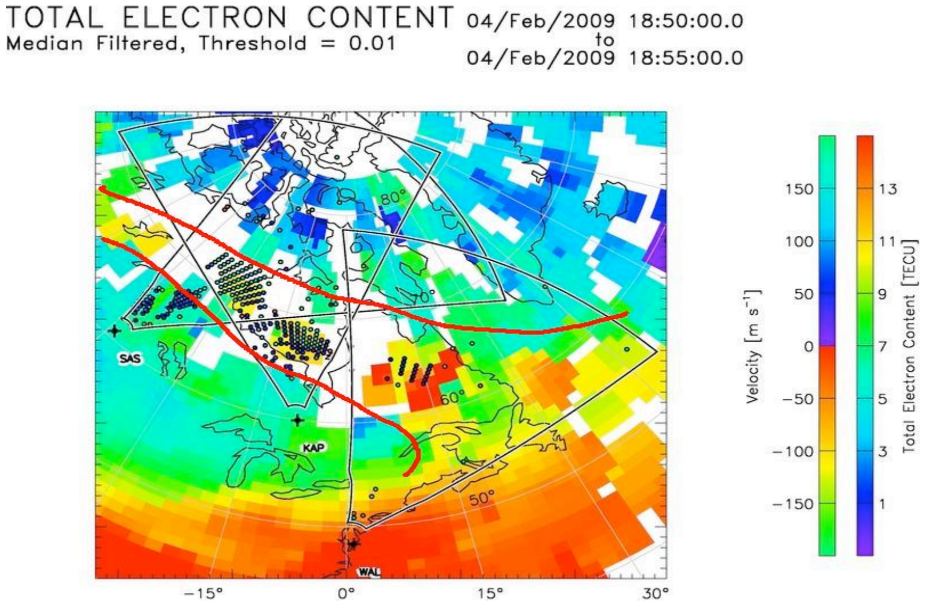


Figure 6. Irregularity features shown in black observed by the mid-latitude SuperDARN radars within the SED plume feature (indicated by red line). The white areas indicate regions of no TEC data.

Observing Networks

Canada and Alaska are situated under large extents of the auroral and polar high latitudes, providing extensive opportunity to remotely sense these ionospheric regions. The evolution of ground-based observing capabilities over the past decade has been transformative. For example, the University of Calgary currently leads the Transition Region Explorer (TREx), the world's foremost auroral imaging facility for remote sensing the near-earth space environment. Shown in Figure 7 are the fields of view of all-sky imagers (Blue/NIR, Redline, and THEMIS), and that of the UCalgary Incoherent Scatter Radar (ISR) at Resolute Bay (RISR-C). Additional ground-based assets include GNSS receivers and scintillation monitors, VLF receivers, photometers, and magnetometers. This amounts to more than 60 instruments (a hardware investment of more than 30M USD) observing ionospheric precipitation, electric currents, plasma waves and convection simultaneously.

Such networks will provide the most comprehensive multi-scale observations of the aurora and other high latitude phenomena ever obtained. Scientific studies include multi-scale coupling of physical processes related to onset of auroral substorms and formation of polar patches, and the characterization of key ionospheric parameters for GNSS simulation tools and mitigation methods. In partnership with IBM, TREx also implements a sensor web to autonomously control and coordinate sensor behavior in response to evolving space weather conditions across the observational region. This is the first sensor web in the world for space weather and space science applications. UCalgary, UAlaska, and MIT Haystack are partners and collaborators in this research program.

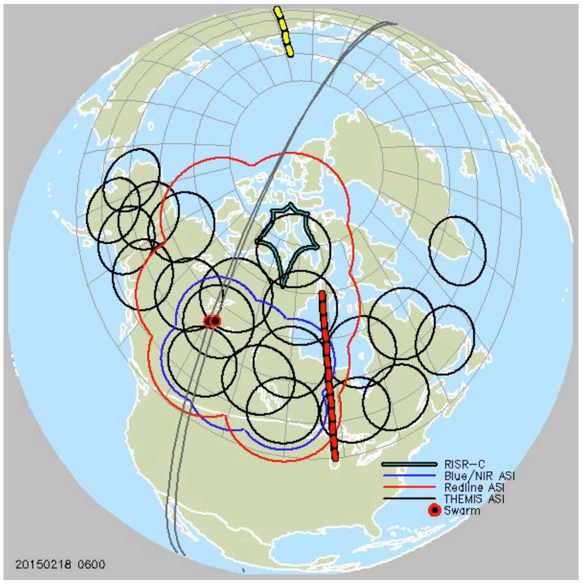


Figure 7. TREx ground-based network for ionosphere observation.

RESULTS FROM VENETIE, AK

As a pathfinder, a single GNSS receiver was installed in Venetie, Alaska, recording near real-time data from multiple satellite constellations this past February and March 2017. Venetie is located approximately 250 km north of Fairbanks, AK. A permanent site location has been identified in Venetie and the plans are to move it there in the near future. Here, we will describe one incident where the effects of space weather were observed during what is referred to as an as auroral substorm with large precipitation. At approximately 10 UT on 1 March 2017, a large brightening of aurora was observed visually over Venetie by a co-located UAF all-sky camera. This was part of an expansive phase of a magnetic substorm with discrete arcs. Figure 8 shows the magnetometer reading from near-by Fort Yukon. The H (north-south) magnetic field component is observed to decrease rapidly at 10 UT, which is a classic auroral substorm signature. During this time period, a large increase in the number of loss of locks on individual satellites were recorded (right after 10 UT almost 20 percent of satellites had measured loss of lock and ambiguities reset in the precise positioning solution). The observed phase scintillation also increased suddenly.

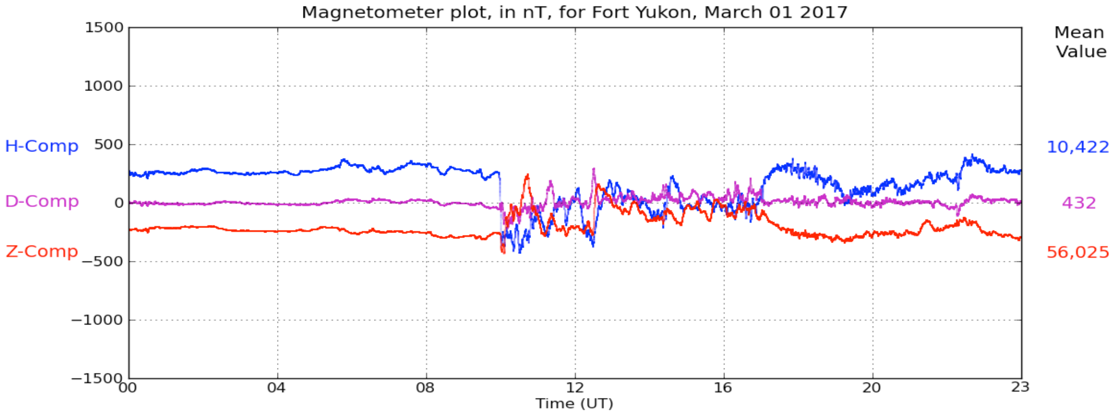


Figure 8. Magnetometer observations from Fort Yukon, AK

Figure 9. shows preliminary results from the GNSS receiver at Venetie during the 1 March 2017 disturbance. The photograph on the left was taken at approximately 10 UT. During the time period of aurora, the GNSS receiver at Venetie showed values of sigma phi exceeding the 0.6 threshold of severe scintillation, and, in addition, TEC values that fluctuated between 2 to 14 TEC units from 8 to 12 UT.

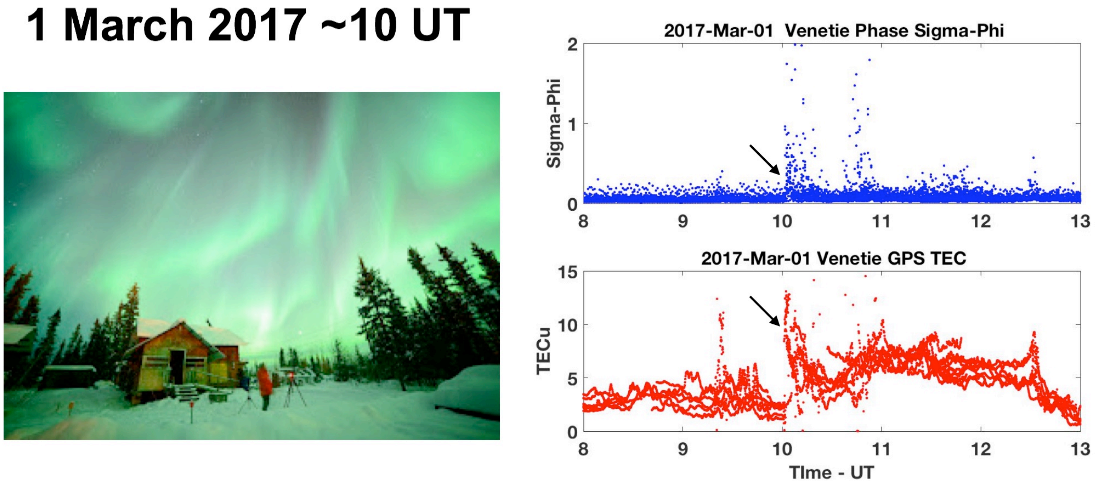
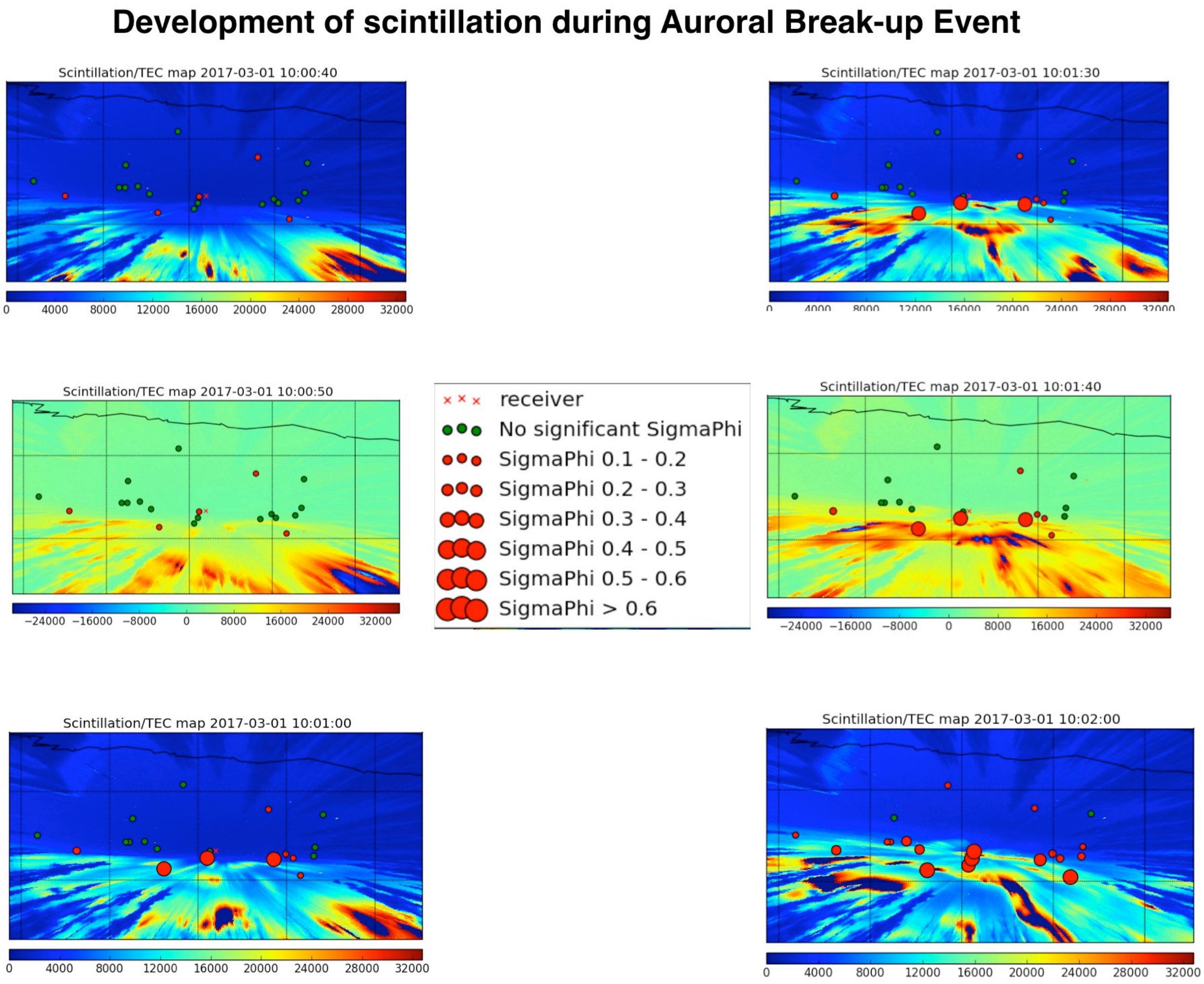


Figure 9. Observations of auroral activity of 1 March 2017 with the all-sky imager. Observations of sigma-phi and TEC measured by observed GPS satellites on 1 March 2017.

In Figure 10, we show the development of the scintillation over an 80 second time period following the onset of the auroral substorm. Prior to the expansion phase, no satellite in track was observing any scintillation. During and after the auroral expansion, sigma-phi measurements at or exceeding 0.3 were observed on 3 to 10 satellites as the expansion phase arcs crossed the GNSS pierce points at 110 km.

This simple case study shows the advantages of the proposed MACAWS array. By observing with multiple GNSS platforms the expanded number of pierce points better delineates the location of active auroral precipitation producing E-region ionization and enhanced ionospheric currents. An array of active real-time receivers will map help specify such active aurora over a wide range of solar disturbance since the array covers several degrees of latitude in the nominal auroral oval of Alaska and north-central Canada.


Development of scintillation during Auroral Break-up Event

Scintillation/TEC map 2017-03-01 10:00:40

Scintillation/TEC map 2017-03-01 10:01:30

Scintillation/TEC map 2017-03-01 10:00:50

Scintillation/TEC map 2017-03-01 10:01:40

Scintillation/TEC map 2017-03-01 10:01:00

Scintillation/TEC map 2017-03-01 10:02:00

Figure 10. These plots show the development of scintillation over a 80 sec time period during the expansion phase of the aurora.

The advantage of capturing these types of events in near real-time with high temporal and spatial evolution is that this provides the required data needed for prediction and now-casting models of scintillation.

SUMMARY

Space weather effects can have serious impacts on the global navigation satellite system (GNSS) including: the introduction of large gradients in the ionospheric total electron content (TEC); the rapid variation of a signal's amplitude and/or phase (scintillation); and/or the sudden increase in background L-band noise. The goal of this project is to deploy 35 GNSS receivers, 25 to sites in Alaska and 10 to sites in Canada. These locations were carefully chosen to maximize observations of auroral structures and impacts in the high-latitude regions of Northwestern Canada and Northern Alaska. In Figure 11, we illustrate the advantage of capturing the auroral substructures with the addition of these new GNSS receivers.

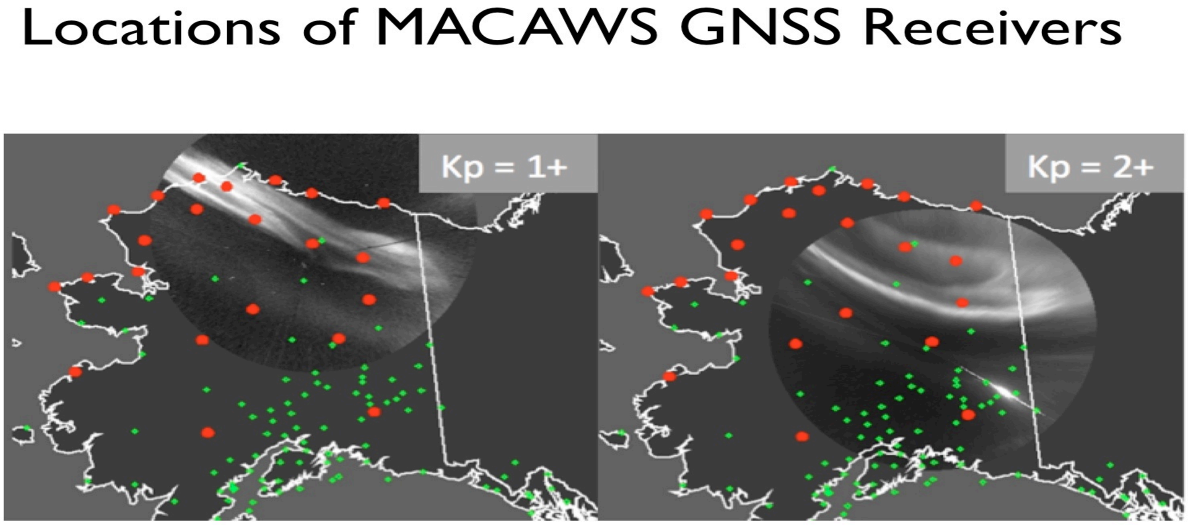


Figure 11. An example of how the proposed new locations are better suited at observing auroral events durine low to moderate geomagnetic disturbances.

In summary, the MACAWS project is a group of 35 GNSS receivers, connected into a sensor web, that provides for communication among the sensor network and to the Madrigal database. The output products of this sensor web will be:

1) Daily RINEX observation files with both GPS and GLONASS observations;
2) Daily summary scintillation L-band statistics files at a 1-minute cadence;
3) Triggering algorithms that start the collection of high-rate (50 to 100 Hz) scintillation data that can be pulled upon request;
4) Real-time observation files for TEC determination at a 1- to 5-minute cadence.

ACKNOWLEDGMENTS

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