New Cyberinfrastructure for GNSS Ionospheric Scintillation and Total Electron Content Parameters

Anthea Coster, MIT Haystack Observatory, Susan Skone, University of Calgary, Donald Hampton, University of Alaska, Fairbanks, Eric Donovan, University of Calgary, Allan Weatherwax, Merrimack College

Biography

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.

Allan Weatherwax, **Ph. D.,** is the Provost and a Professor of Physics at Merrimack College. An internationally recognized teaching-scholar, he has spent two decades contributing to fundamental research in space plasma physics, geophysics and space weather. He has conducted research in the polar-regions since the 1990s and has served as principal investigator on numerous NSF and NASA grants. Weatherwax holds a doctorate in physics from Dartmouth.

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ABSTRACT

The Monitors for Alaskan and Canadian Auroral Weather in Space (MACAWS) project was launched this year. Its goal is to install an additional thirty-five GNSS scintillation receivers in Northern Alaska and northwestern Canada (Northern Alberta, Saskatchewan, and Manitoba). Key advances will be: 1) the incorporation GLONASS total electron content data, along with GPS 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. Separately, a portable weather system will be deployed with these units to estimate the precipitable water vapor measured by the GNSS units. The high-rate GNSS data is required for detailed analysis of scintillation during geomagnetically active time periods. These data will be input into the National Science Foundation's Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) Madrigal database. Madrigal is a robust, World Wide Web based system capable of managing and serving archival and real-time data, in a variety of formats, from a wide range of upper atmospheric science instruments. Plans are now being made to develop built-in tools to merge different datasets within Madrigal, in order to enable to quicker monitoring of space weather events. In the past, SUPERDARN convection data has been overlaid onto GNSS TEC maps showing the formation of the tongue of ionization (TOI) that flows over the polar cap. With the new scintillation data sets available, the values of the scintillation parameters can be denoted on these maps and studied for their correlation with ionospheric gradients and their relationship to the TOI. Another example is the use of GNSS TEC data in the tracking of the energetic particle precipitation boundary during substorms. By overlaying, the TEC data onto optical imaging data from the Transition Region Explorer (TREx) – A Ground-Based Sensor Web for Space Weather Research, the correlation of GNSS TEC to substorm behavior can be studied. These new products will enable a better understanding of physical mechanisms behind space weather disturbances.

INTRODUCTION

The Monitors for Alaskan and Canadian Auroral Weather in Space (MACAWS) project is deploying 35 GNSS receivers to high latitude regions in Northern Canada and northwestern Alaska. The goal of this project is to improve the monitoring of space weather in the important high latitude regions; regions that are currently lacking dense networks of atmospheric sensors. By observing the dynamics and structure of the high latitude ionosphere, insight can be gained into the role of near-earth geophysical processes. A high density of GNSS receivers is required to capture the multi-scale phenomena occuring in this active region, and currently both northern Alaska and Canada are particularly lacking in coverage.

In the high latitudes, there two main regions, the polar cap and the auroral oval, in which important magnetospheric-ionospheric processes occur and initiate space weather. These regions are not fixed in space but rather have boundaries that evolve due to changing conditions in the interplanetary magnetic field and the solar wind. The driving magnetospheric dynamics occur across multiple scales and map primarily to the auroral oval on closed field lines and to the polar cap on open field lines. What results are variations of ionospheric parameters, such as total electron content (TEC), on multiple temporal and spatial scales. Observations in these regions can provide information on the background space weather conditions. For example, observing the size of the polar cap can be used as a gauge of the amount of coupling between the solar wind, the magnetosphere, and the ionosphere. Ionospheric phenomena of interest for GNSS applications include the aurora, polar patches, and storm enhanced density and its associated tongue of ionization. The two primary issues for GNSS users are phase scintillation and sudden jumps in range measurements due to abrupt changes in TEC. Scintillation is produced by ionospheric irregularities that form in response to solar and geomagnetic events. In the high latitudes, they are primarily related to polar cap patches and the tongue of ionization (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 [1], [2], [3]. Large changes in TEC have been observed associated with aurora and have been reported [4], [5]. The MACAWS 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 illustrates the tongue of ionization, polar cap patches, and auroral signatures observed in GNSS TEC polar maps.

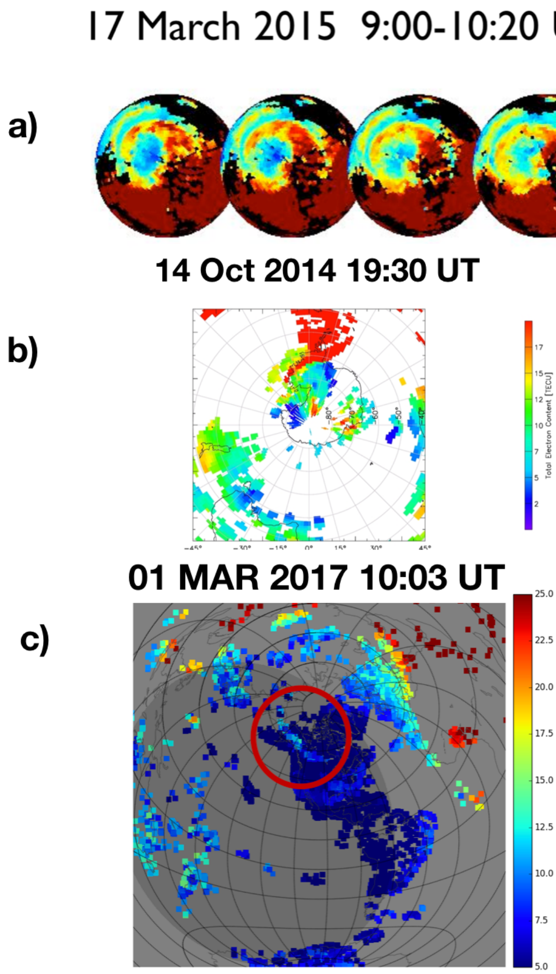

Figure 1 illustrates (a) tongue of ionization events, (b) polar cap patches, and (c) auroral signatures observed in GNSS TEC polar maps.

THE CURRENT MACAWS PROJECT

The first 15 of MACWS units have been shipped to Canada and Alaska, and an additional unit has been sent to the Arecibo Observatory in Puerto Rico. These units are set up to provide real-time and near real-time total electron content (TEC) and scintillation data from multi-constellations (EGNOS, GLONASS, GPS, and others].

Figure 2 shows one of the MACAWS units. Christine Alcade, a student from Merrimack College, along with Eryl Derome of MIT Haystack (not shown), have been responsible for assembling and testing the MACAWS units. These units will be hosted at locations indicated by red circles on the map of Alaska and Northwestern Canada in Figure 2. Each unit consists of a Septentrio PolaRx5S GNSS receiver with a PolaNT B3/E6 choke ring antenna and a weather station fabricated at MIT Haystack Observatory. These are connected (Figure 2) to an Intel NUC mini PC which collects and stores the GNSS and weather data. The PC is running an Ubuntu Linux OS and utilizes the Septentrio utilities as well as python scripts to acquire and process data. The typical total power consumption during operations can be about 20W.

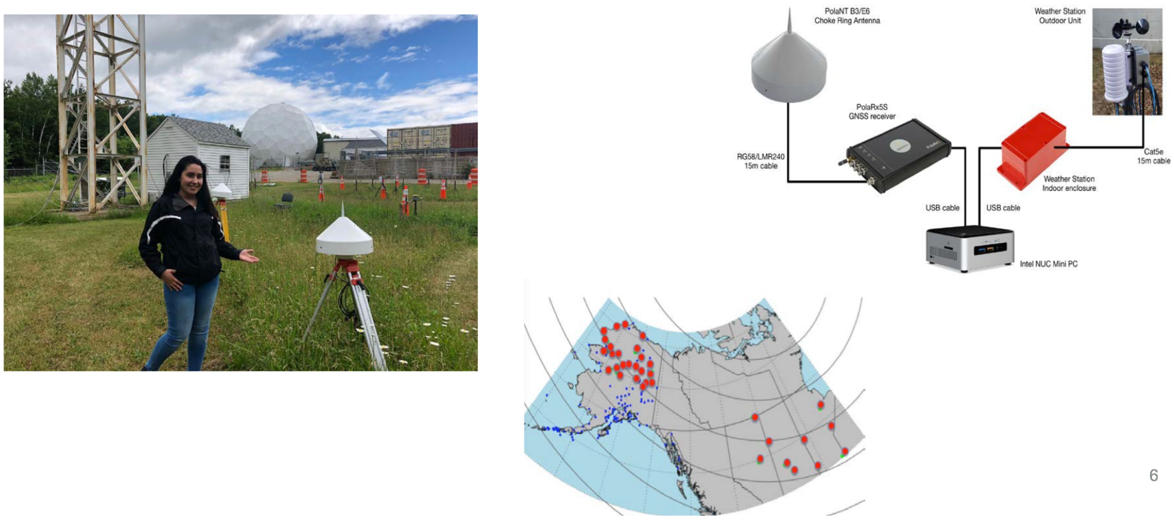

Figure 2. Illustration of current MACAWS receiver and potential locations across Canada and Alaska.

The three main innovations of the current MACAWS installation are: the incorporation of all GNSS signals, the real-time or near real-time access to the data, and the sensor web. Figure 3 shows the difference in monitoring scintillation with the GPS constellation only versus all constellations. This data was collected during a magnetic substorm event on 2 March 2017 in Venetie Alaska as an auroral arc was moving overhead. The GNSS receiver was monitoring phase scintillation on all satellites in view. The scintillation data is overlaid onto an image of the aurora from an all-sky camera. The large white line across the images is the aurora expanding. The larger red circles indicate larger values of scintillation, whereas the smaller green and red circles indicate little to no scintillation. The additional information provided by the other constellations clearly delineates the relationship between observed aurora and the scintillation.

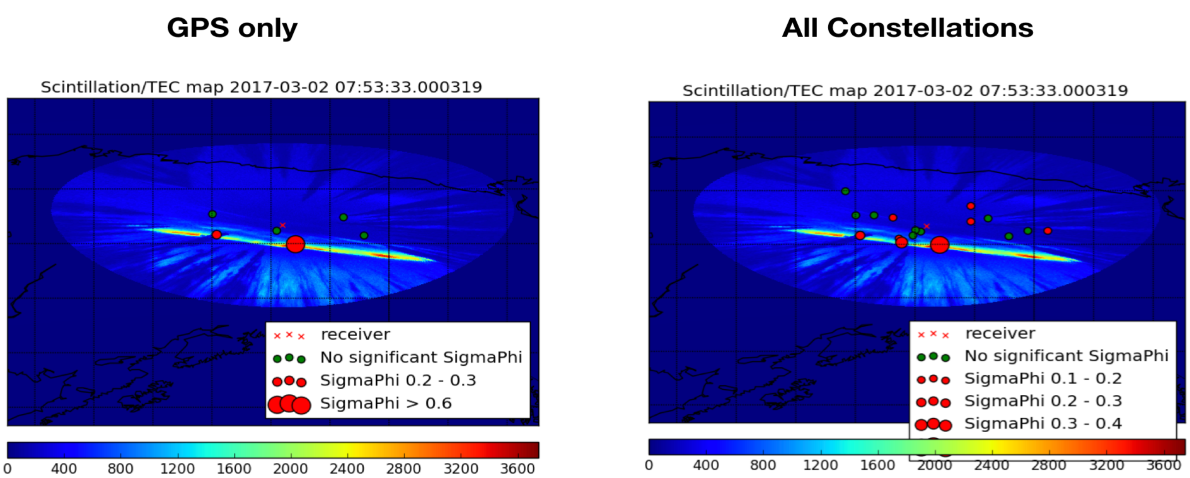

Figure 3. Illustration of the advantage of incorporating all GNSS signals versus GPS alone.

Real-time or near real-time TEC estimation from GNSS data is not necessarily an innovation. GNSS data has been processed in real-time for TEC measurements since the early 1990's [6]. However, the number of receivers with real-time data transmission is limited. Having this dense network over this relatively small area will play an important part of the sensor web development.

The development of a *sensor web* is required to accomplish the goals of the MACAWS project. A sensor web is a dynamic, adaptable, and autonomous network of sensors. Using Artificial Intelligence (AI), a sensor web reacts in real time to information from its instruments, invoking information sharing and autonomous decision making, feedback, and control. This capability provides a combination of greatly enhanced information content in the overall data and/or vastly improved resource efficiency. Research into sensor webs is rapidly expanding; they are emerging as the primary viable path forward for large-scale (Big Data) Earth observing systems. In the MACAWS project, working with the University of Calgary, significant effort will be expended toward the development of these capabilities. A simple example of efficiency, is the triggering of high rate GNSS data collection if it is known that a scintillation event is imminent.

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 4 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. In partnership with IBM, TREx also implements a multi-spectal sensor web to autonomously control and coordinate sensor behavior in response to evolving space weather conditions across the observational region. The MACAWS project will take advantage of the larger network of TREx instrumentation and work closely with UCalgary scientists to develop this sensor web.

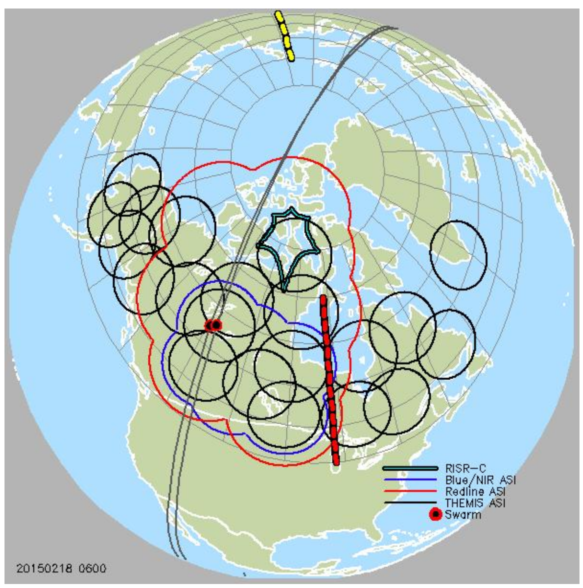

Figure 4. University of Calgary's Filds of view from its all-sky imagers, from the UCalgary Incoherent Scatter Radar.

The combined TREx and MACAWS networks provide one of the most comprehensive multi-scale observations of the aurora and other high latitude phenomena ever obtained. This is the first sensor web in the world for space weather and space science applications.

FUTURE MACAWS SENSORS

In addition to current MACAWS sensors to be deployed, we are trying to fund the development for low-power GNSS units to operate with the MAHALI boxes developed for an earlier project [7]. Mahali was originally was designed as a low-power system to enable its deployment to challenging environments. The original data acquisition system was designed to run on 3 W of power. The micro-computer, an Intel Edison board, provided a high performance, dual-core CPU and a single core micro-controller in a low power package. The Renogy solar panels used were rated at 100 W and 12 amp lithium-iron-phosphate (LiFePO4) batteries were used to store the power collected by the solar panels. Due to the seasonally low solar illumination available at the Alaska location, power-saving features were implemented to support the powering down of the GPS receivers outside of our 'preferred' operational windows. In addition, our Wi-Fi radios were set to remain powered off for nine minutes out of every ten when not otherwise in use as a power conservation measure. A total of 16 Mahali boxes and 16 solar panels were built, supporting 4 different types of GPS/GNSS receivers: CASES, Novatel GPS Station 6, Novatel GSV4004, and Trimble NetR9 receivers. The approximate cost per Mahali enclosure, solar panel and frame was $1,450.00 completely built. This includes everything except the GPS receiver and antenna. Figure 1 shows a Mahali unit deployed at one of the Alaskan sites.

Figure 5. Example MAHALI box for GNSS deployment in challenging environments

We would like to develop this scheme with additional battery and solar power, and incoporate a new low power GNSS receiver and an Iridium modem into the package so that these units work truly off the grid.

EXAMPLE OF SPACE WEATHER EVENT

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. 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). [Coster et al., 2017] reported earlier on phase scintillation observations related to this substorm. The observed phase scintillation also increased suddenly.

Here we report on the abrupt increase of approximately 10 TEC units (more than 1.5 m of range delay at L1) due to this auroral arc and its associated precipitation. Shown in Figure 6 are the measured vertical TEC from all GNSS satellites. The top plot represents the Venetie measurements and the bottom plot shows the Poker Flat measurements. Both locations show an approximate increase of about 10 TEC close to 10 UT, when visible aurora were noted at both locations. The enhancement in TEC is slightly earlier at the Poker Flat location.

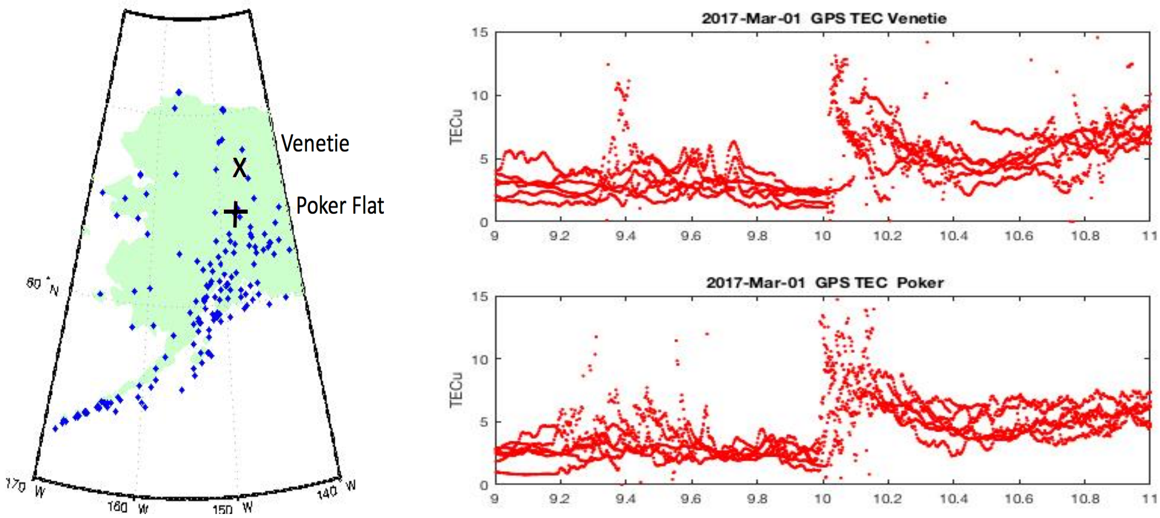

Figure 6. On the left is a map of Alaska showing both the Venetie and Poker Flat locations. On the right, are plots of the measured vertical TEC as a function of time at both the Venetie (top) and Poker Flat (bottom) locations.

This increase of ~10 TEC units was not expected, and cannot be verified by one instrument alone. The advantage of working with a network of various kinds of instrumentation is that there are additional corroborating measurements to confirm these results. In this case, the Poker Flat Incoherent Scatter Radar was operating and collecting measurements of electron density as a function of altitude along 11 different beam directions. PFISR is a two-dimensional phased array radar consisting of 4096 transmitting and receiving elements (see Figure 7). PFISR was built by SRI International on behalf of the National Science Foundation to conduct studies of the upper atmosphere and ionosphere in the auroral zone. The incoherent scatter radar technique of measuring the ionosphere is one of the most powerful sensors of ionospheric plasma. This technique can measure, as a function of altitude, electron density, electron temperature, ion temperature, plasma velocity, and can infer electric field strength, conductivity, current, neutral air temperature, and wind speed.

Figure 7. The Poker Flat Incoherent Scatter Radar in Alaska

We select only one beam out of the 11 beams of data collected. Shown in Figure 8 is the electron density as a function of altitude (vertical axis) and time (horizontal axis) in a beam with an elevation of 60 degrees and an azimuth of 20.5 degrees. Slightly below 10 UT there is a decrease in ionospheric plasma below 200 km. Just after 10 UT there is a large enhancement in the electron density from 100 to 220 km (seen in red). When converted to TEC units in the bottom plot, an increase in the TEC is measured at ~8 TEC, confirming the large jump in TEC as measured by the two GNSS receivers shown in Figure t.

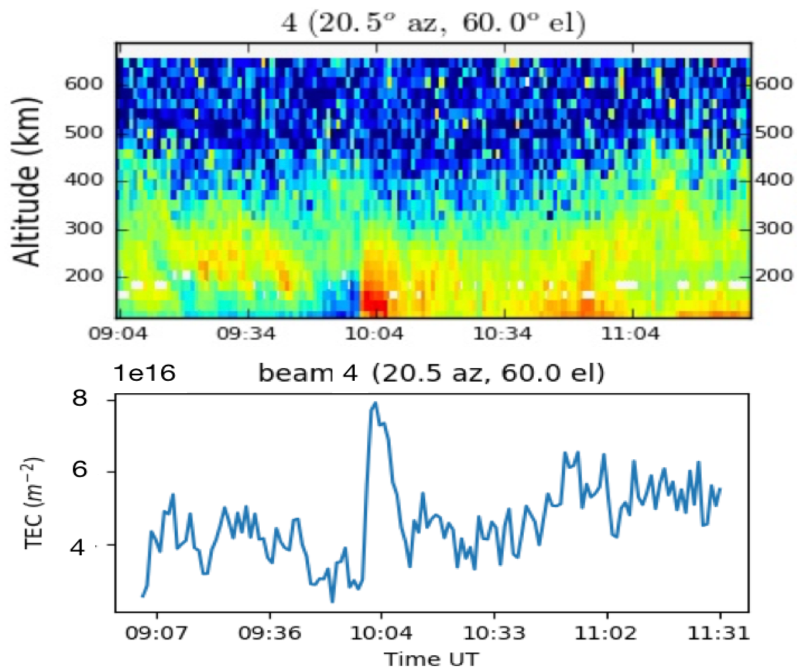

Figure 8. Observations from the Poker Flat Incoherent Scatter Radar of electron density as a function of altitude and time (top) and converted to TEC units as a function of time on 10 UT 1 March 2017.

SUMMARY

The MACAWS project has the aim of increasing coverage in north Alaska and northwestern Canada, areas where space weather events that impact the continental US are poorly covered. The advantage of using networks of ground-based instrumentation is that they allow multiple locations to be monitored simultaneously to capture system dynamics on a large scale. These networks can be utilized to monitor space weather events as they happen. But in addition, when these networks have been established for an extended period of time, the data can be examined for seasonal and solar cycle patterns as well as being available for random events, such as solar flares. In atmospheric science, continually operating ground-based networks provide the insight and validation required to understand global-scale processes such as the transport of energy during storm periods, and vertical coupling across different atmospheric regions, along with their associated global-scale variability. These networks of instrumentation play an ever increasing role in gathering the knowledge needed to unravel the system scale physics of the atmosphere.

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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