Low power GNSS receiver network for remote space weather observations

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Abstract

The poleward section of the auroral oval is an active site of magnetosphere-ionosphere coupling as it envelopes the boundary between open and closed magnetic field regions. Ionospheric dynamics in this region thus represent a projection of the region of energy transfer into the geospace system. However, observations of this region are challenging owing to logistical difficulties involved in deploying sensors to remote regions with little human infrastructure. Proposed is a concept for a dense low-power autonomous space weather observing network to explore ionospheric dynamics in this boundary region. The concept exploits the infrastructure of the Alaskan deployment of the Earthscope seismic network, the Alaskan Transport Array (ATA). A concept study would involve adding low-power GNSS receivers manufactured by Septentrio to approximately 40 stations in Northern Alaska. The importance of ionospheric science in the region, the project concept, and preliminary investigations are discussed.

Introduction

Northern Alaska embodies the nightside open-closed magnetic field boundary, a critical region in the magnetosphere-ionosphere-thermosphere (M-I-T) system. The auroral poleward boundary encompasses the ionospheric projection of the nightside open-closed boundary where intense auroral activity and plasma transport occur. The impacts on the I-T system at the auroral poleward boundary include:

1. Precipitation of plasma sheet particles due to magnetotail reconnection, the auroral acceleration region, and dispersive Alfven waves resulting in aurora and ionospheric density enhancements (e.g., poleward boundary intensifications, Alfvenic aurora) (Figure 1).
2. Transport of polar cap patch density into the nightside auroral oval and interaction with nightside aurora (Figure 2, 4)
3. Modulation of convective transport due to rapid changes in magnetospheric topology (Figure 1, 2)
4. Generation and propagation of traveling ionospheric disturbances (TIDs) (Figure 4)

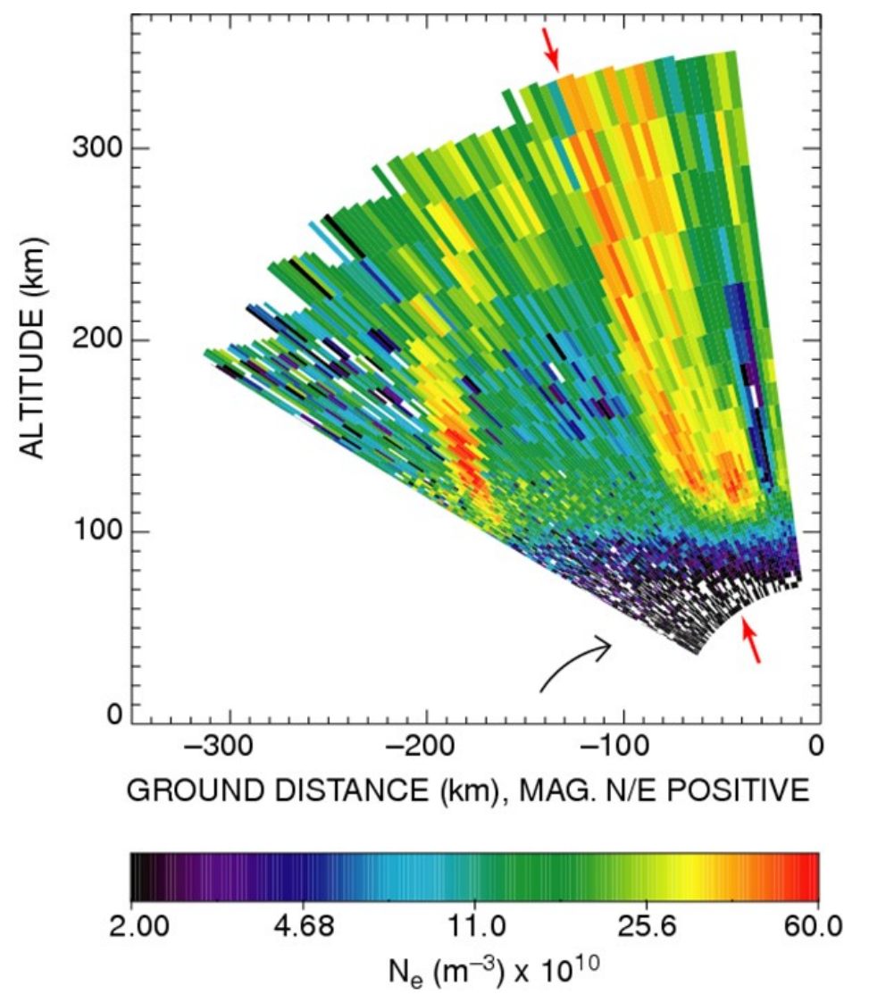

Figure 1. Ionospheric density structures produced by Alfvenic electron acceleration near the poleward auroral boundary [Semeter et al., 2005]

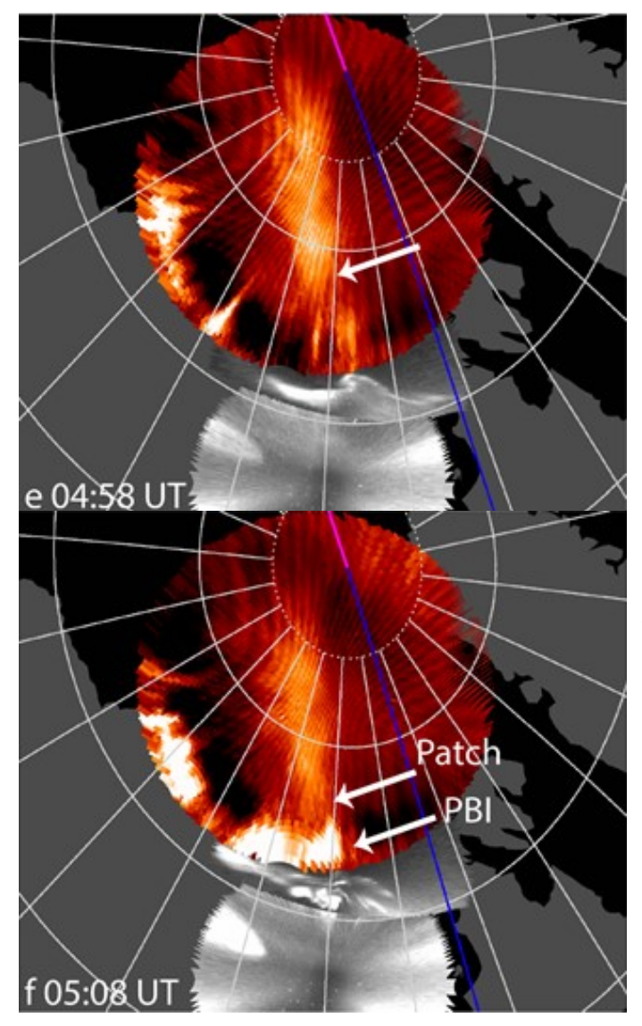

Figure 2. Snapshots of THEMIS and Resolute Bay ASI data during the 25 February 2008 substorm showing a polar cap patch triggering a poleward boundary intensification [Nishimura et al., 2011]

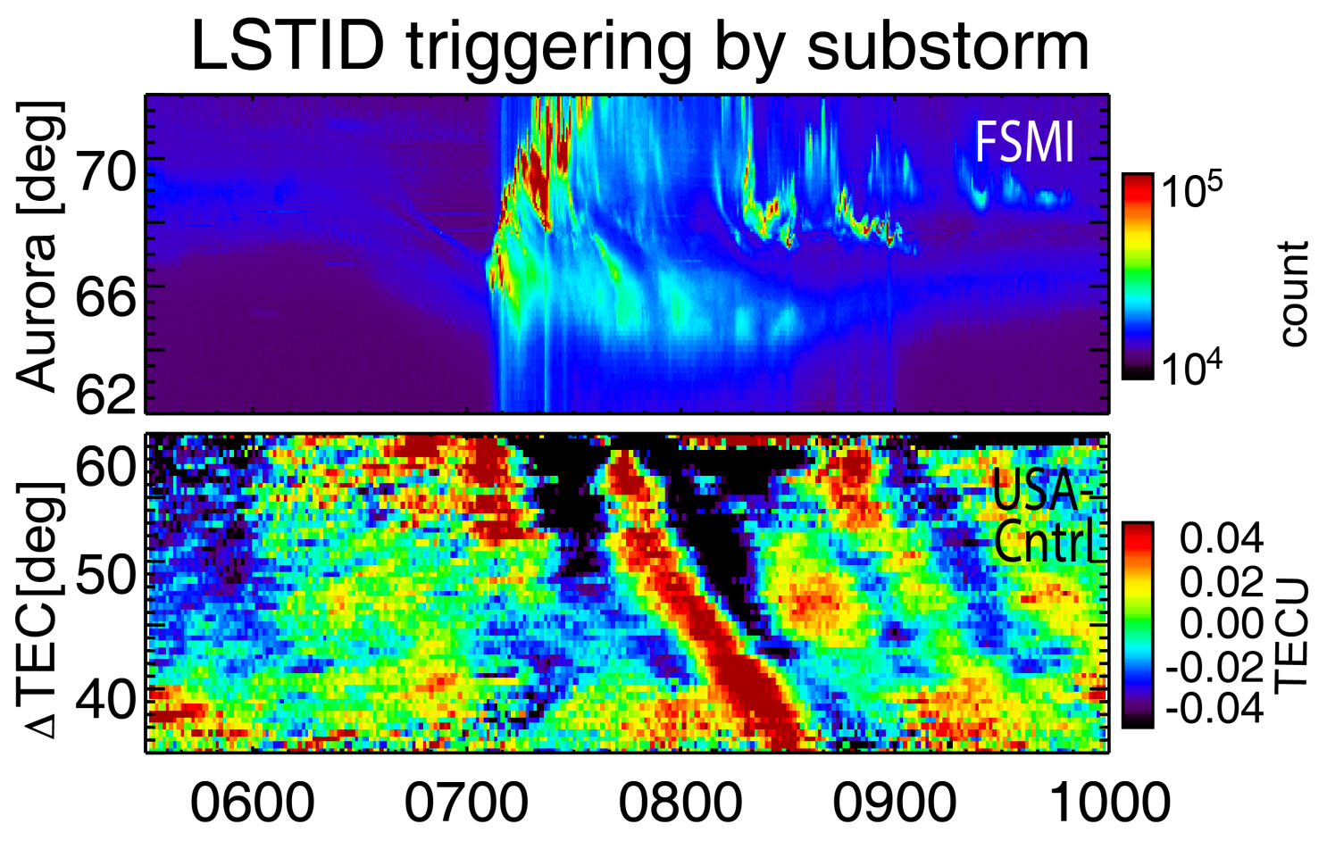

Figure 3. Allsky imagers and ΔTEC keograms for selected stations during the 26 March 2014 substorm showing LSTIDs initiated by the substorm [Lyons et al., 2019]

The specific role of M-I coupling processes in structuring the ionosphere has been the subject of many investigations (e.g., [Lockwood et al., 2005] [Oksavik et al., 2004]), but disentangling the relative importance of the mechanisms and establishing the net effect on the I-T state remain major observational challenges. This gap in scientific understanding readily translates to observational requirements. Global Navigation Satellite System (GNSS) receiver networks have proven to be a highly effective tool for observing M-I-T system dynamics. The GPS TEC map in Figure 4 shows important features such as a polar cap patch passing through northern Alaska, but observations are severely limited due to the low density of available receivers.

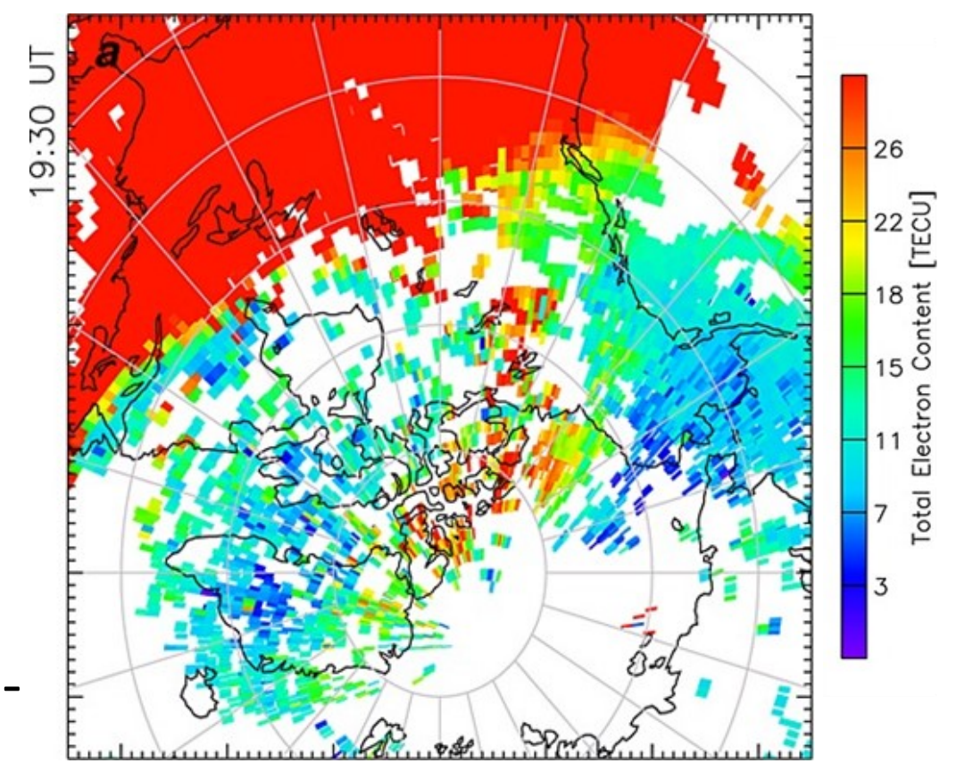

Figure 4. GPS TEC map showing a polar cap patch [Thomas et al., 2013]. The magnetic noon is at the top. Note the sparse sampling over Northern Alaska.

Objectives

We propose to deploy a dense GNSS network in northern Alaska where few instruments exist, but important M-I coupling processes occur. The proposed solution will take advantage of the existing EarthScope network and will impact scientific investigation in the following areas:

1. Ionospheric modification by dynamic precipitation along the auroral poleward boundary
2. Evolution of polar cap density structures entering the nightside auroral oval.
3. Generation of TIDs via polar vortex dynamics, stratospheric warming events, and storm-time thermospheric forcing.

Methodology/Instrumentation

The EarthScope Transportable Array (TA) is a network of 400 seismic stations that has been systematically migrated across the United States since 2007 [Freymueller et al., 2011]. The TA is currently concentrated in Alaska, where 195 autonomous stations are deployed with nominal 85-km spacing across the entire state and into the Yukon region (Figure 5). We developed a partnership with the NSF Earthscope to form a plan to deploy GNSS receivers by taking advantage of their heritage – logistics, permitting, power systems, telemetry). The proposed project duration is four years.

Figure 6 shows the pierce points of the existing (blue) and proposed (red) receivers. The proposed receivers will provide a dense coverage in northern Alaska. The magnetic field inclination in Alaska varies from ~70˚ to ~80˚ across the state. GPS satellites reach the magnetic zenith in central Alaska; GLONASS satellites reach the magnetic zenith up to the northern coast. Inclusion of GPS and GLONASS measurements allows TEC samples to be obtained in an approximately field-aligned direction simultaneously from all receivers for high elevation satellite passes.

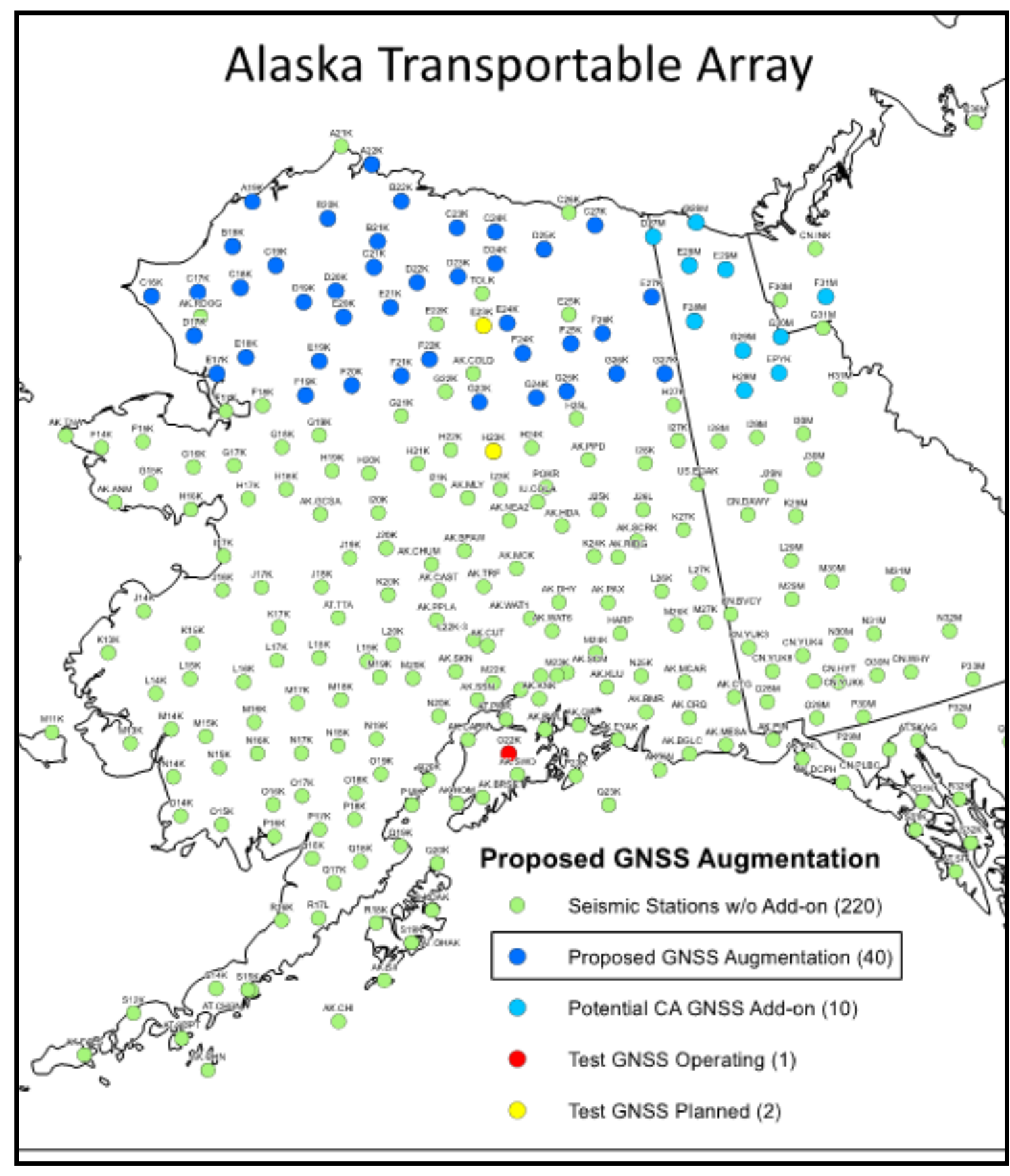

Figure 5. Map of currently operating Alaska Transportable Array stations shown as circles. The 40 stations proposed to have GNSS installations are dark blue.

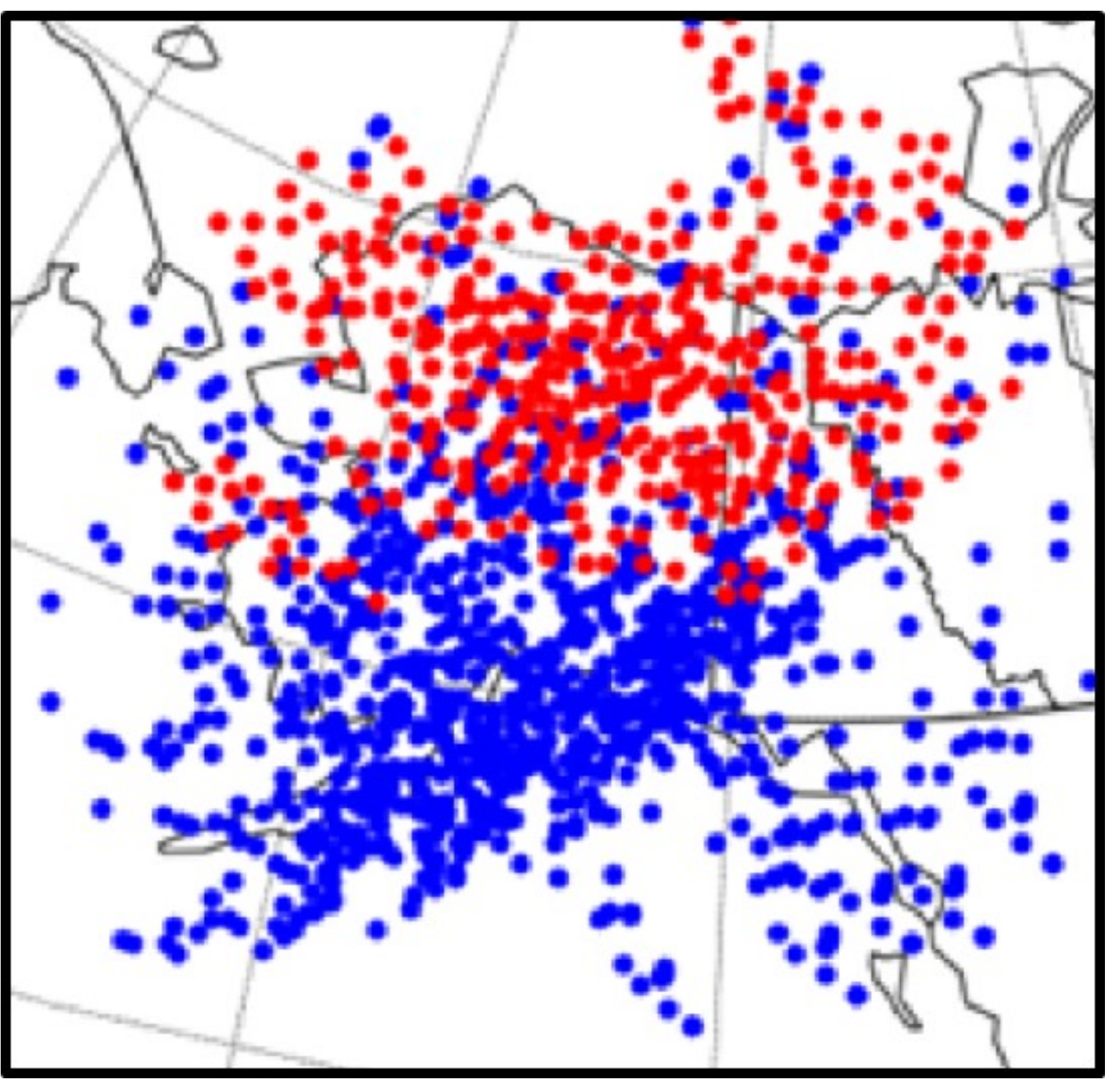

Figure 6. The net sampling pattern enabled by the combined receiver set, represented as 350-km ionospheric pierce points for all visible satellites above 30^o elevation angle for a typical interval.

Figure 7 shows the TEC and auroral evolution during a geomagnetic substorm using Alaskan auroral all-sky cameras and TEC samples from currently available GNSS receivers. Figure 8a and 7b show poleward boundary dynamics during polar cap inflation period. Figure 8c shows the north-south auroral streamers after the expansion-phase onset. Figure 7d shows the `Alfvenic' structures appearing to the north during substorm recovery. The TEC response in southern Alaska can be seen in detail, but it is heavily undersampled in the northern region. Despite that most intense and dynamic aurora occurs near the poleward boundary of the auroral oval, only a few pierce points in Figure 7c intersect TEC enhancements related to the auroral streamers. Additionally, there are very few common volume observations within the field of view of PFISR shown by the white hexagonal region in Figure 7a referenced to 400 km. Figure 8 shows the time series data for the same event. Above 67˚ latitude, TEC data becomes noisy, and above 70˚, TEC data is too sparse to plot.

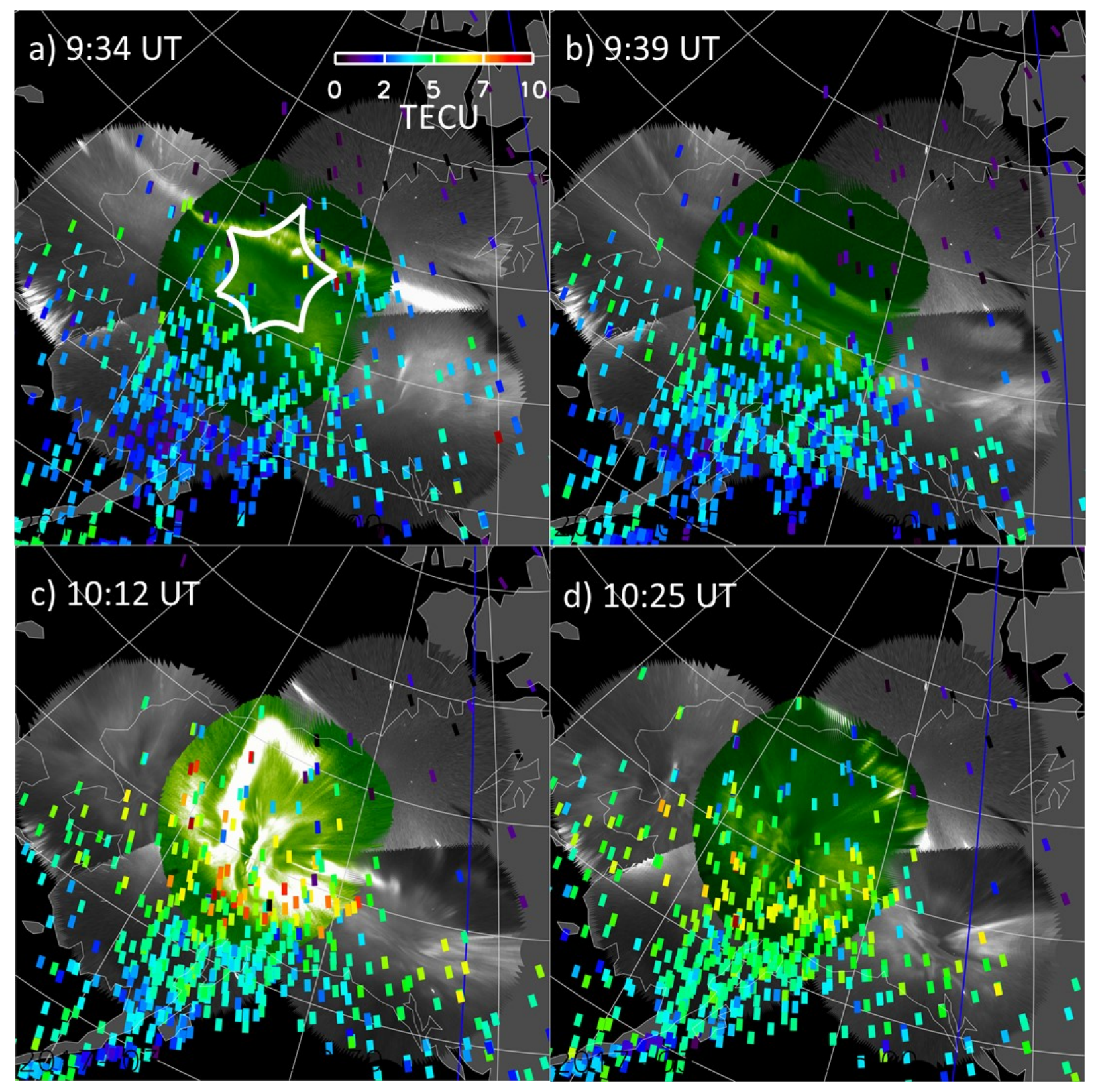

Figure 7. 2 March 2017 geomagnetic substorm imaged by Alaskan auroral all-sky cameras and TEC from the existing receivers. The 400-km field of view of PFISR is indicated in the left-hand panel.

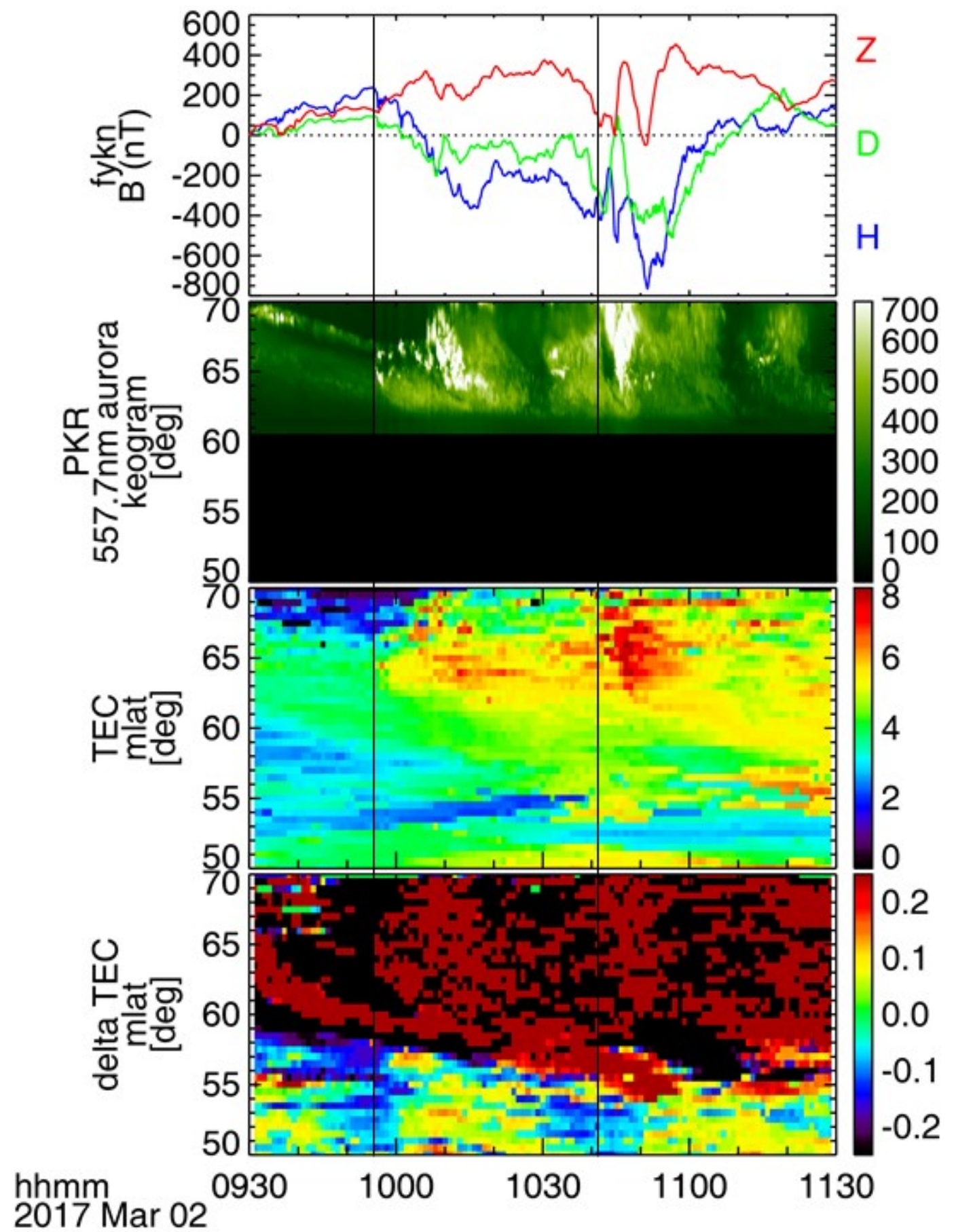

Figure 8. Time series magnetometer, all-sky camera, and TEC data of 2 March 2017 geomagnetic substorm

Initial Work

Each site has global broad-band connectivity, efficient photovoltaic/battery power systems, and new low-power sensors and antennas. The average station power is 5.8 W. The Xeos Resolute Polar with the Septentrio AsteRx-m2 was chosen for its ability to operate in remote polar climates in Northern Alaska with low power consumption. Specifics of the Xeos Resolute Polar are listed in Table 1. As a prototype, one Resolute Polar is deployed as part of ATA station O22K as shown in Figure 9.

Feature	Xeos Resolute Polar
Operating Temperature	-55˚ C to +60˚ C
Power Consumption	1.2 W Typical (12 V)
GNSS Signals	GPS L1, L2; Glonass L1, L2
Dimensions and Weight	6”x6”x3”, 2.8lbs
Communication	- Ethernet port for direct communication - Iridium modem for Iridium satellite communication

Table 1. Xeos Resolute Polar technical specifications [Alert Geomagnetics, 2018]

Figure 9. (left) The Xeos Resolute Polar unit pictured above was installed at the Alaska TA station O22K on 31 January 2019. (center) Alaska TA station O22K is an autonomous, telemetered station installed in Cooper Landing, Alaska. The GNSS antenna was added to the existing station mount (arrows), which holds the communications equipment and meteorological sensor. (right) hut interior showing electronics package.

ATA station O22K is co-located with UNAVCO station AC15 which operates a Trimble NetRS receiver. To evaluate Xeos Resolute Polar performance the differential phase-corrected slant TEC was calculated for both co-located receivers during quiet and weakly disturbed (AE index < 250 nT) ionospheric periods. An adjustment offset was needed to compare trends between the receivers since they were not synchronized together. Figure 10 and 11 show sample comparisons of phase-corrected TEC [Rideout, 2006] from the two receivers for quiet and weakly disturbed ionospheric periods, respectively. Both plots show good agreement and relatively similar signal variance indicating that the low-power sensors will provide reasonable TEC estimates.

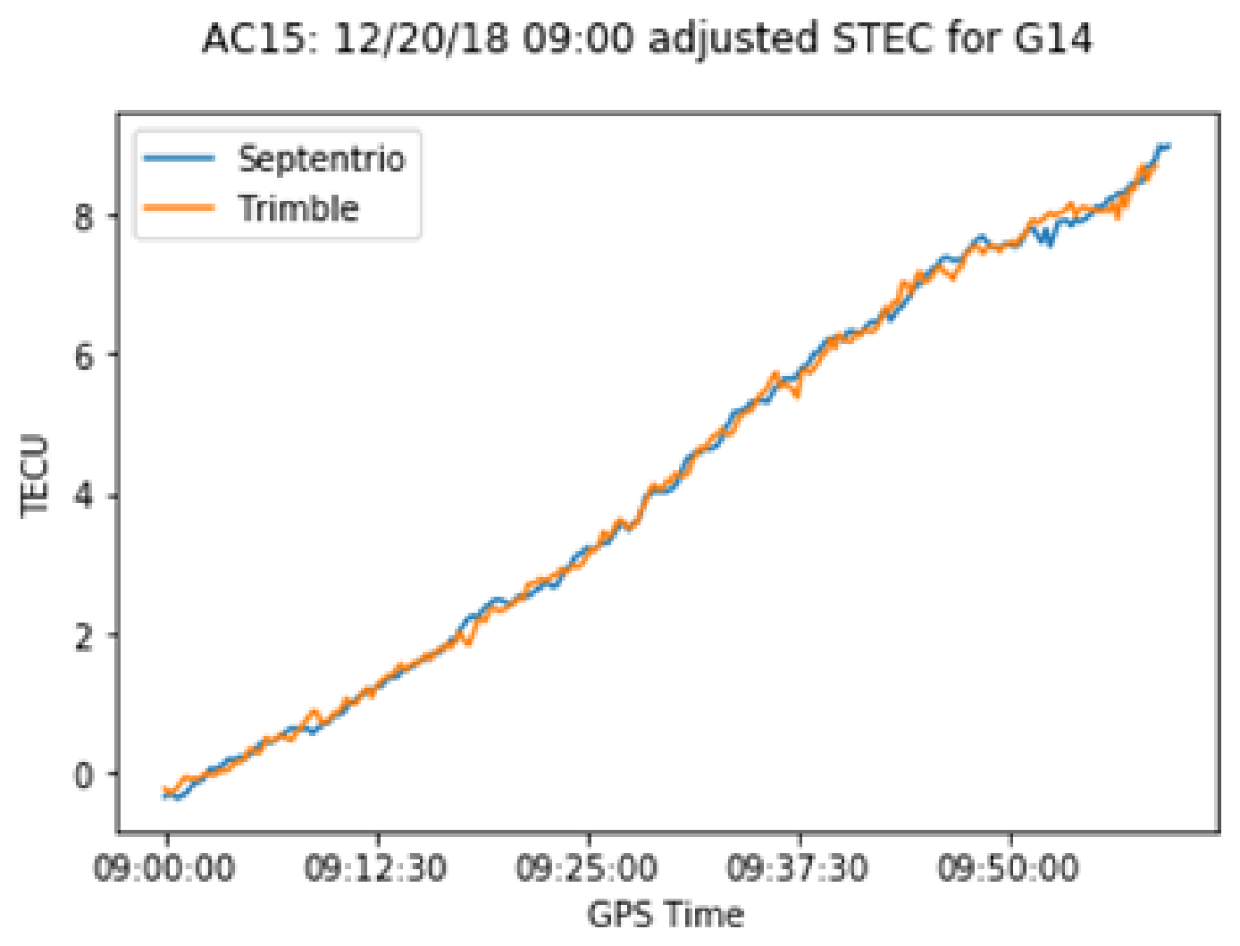

Figure 10. Comparison of phase-corrected TEC calculation for co-located Trimble NetRS and Xeos Resolute Polar for 20 December 2018 during quiet ionospheric period

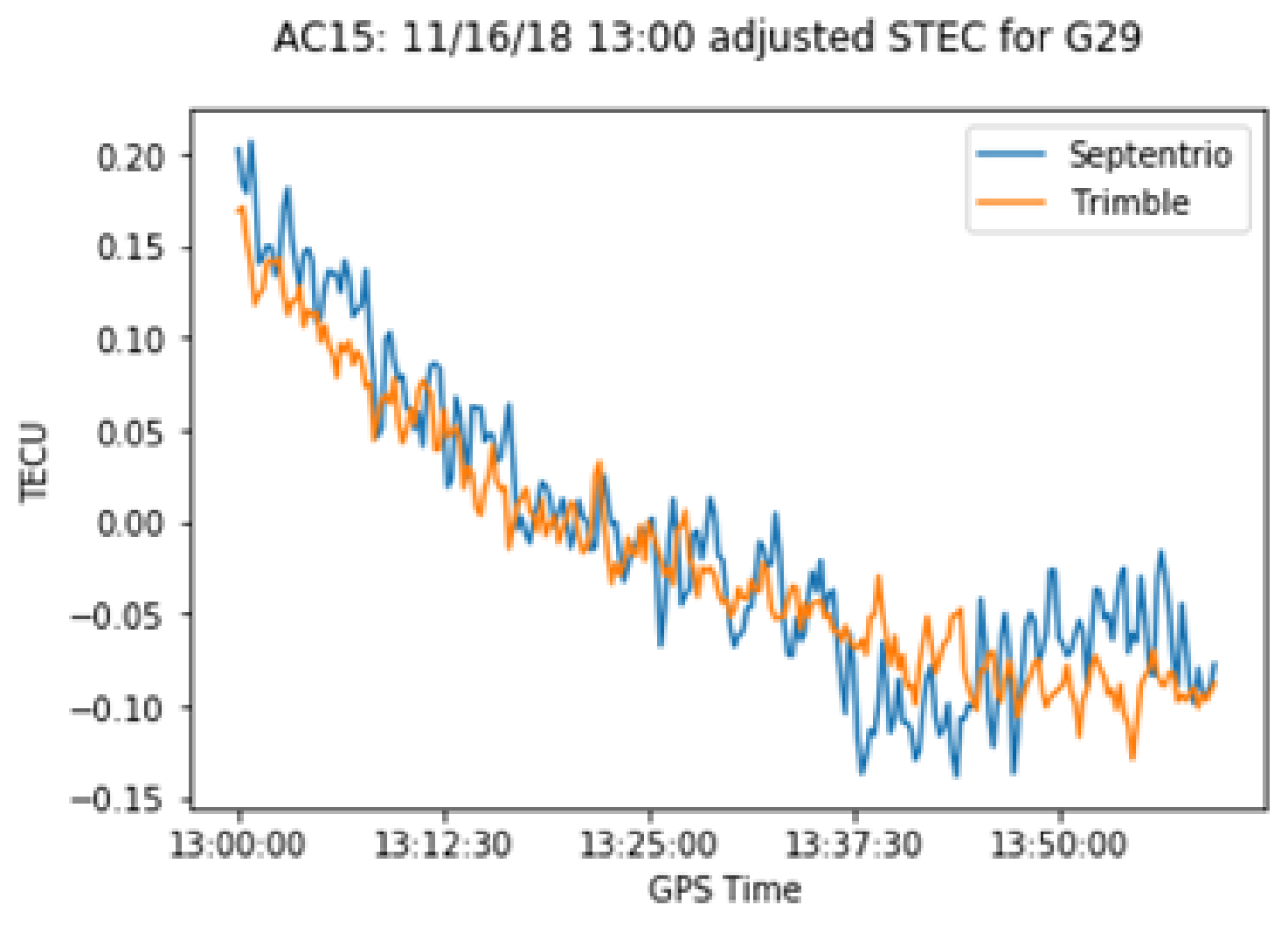

Figure 11. Comparison of phase-corrected TEC calculation for co-located Trimble NetRS and Xeos Resolute Polar for 16 November 2018 during weakly disturbed period

Conclusion

Substantial M-I-T dynamics are present near the auroral poleward boundary but are not adequately captured by the sparse GNSS sampling available with the current receiver network. Northern Alaska is the optimal location for proof-of-concept because a solution exists through collaborations with the NSF Earthscope seismic array project. GNSS receiver networks provide a flexible, cost-effective, multi-scale geospace diagnostic. The proposed deployment covers the poleward auroral oval and boundary in the evening sector, a critical region of the M-I-T system. The Xeos Resolute polar accurately measures TEC while providing a low-power alternative. Capturing the TEC variability at this location and synthesizing this information with measurements by state parameters from ISR and auroral imagery will provide new insight into the geospace system dynamics underlying space weather.