Characterizing Ionospheric Disturbances for Space Weather Hazard Mitigation

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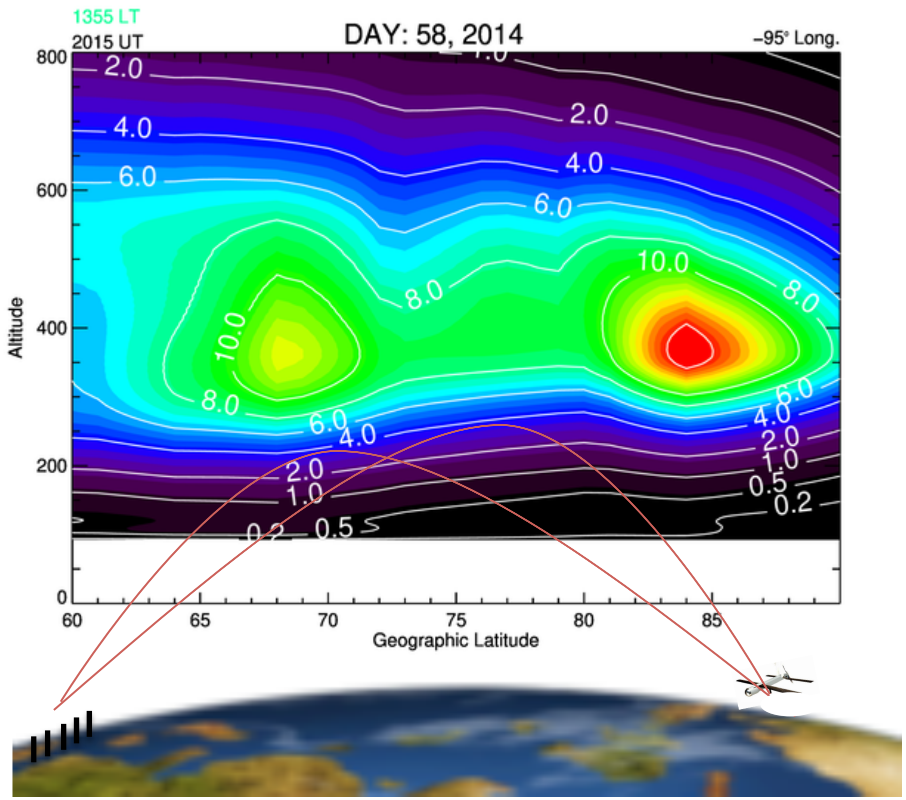


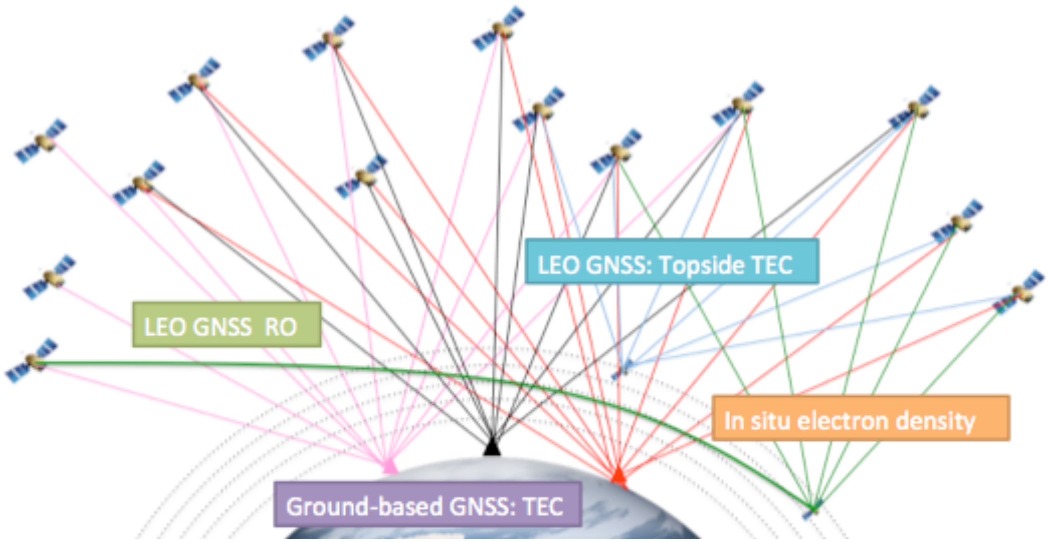
Abstract

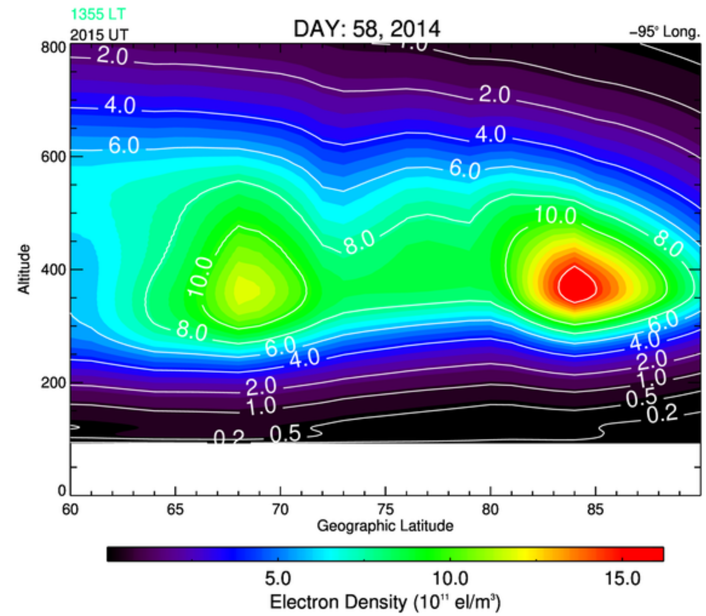
We present space weather monitoring for ground-based and space-based RF systems. Our ionosphere modeling capabilities include a data-driven approach to estimate the three-dimensional temporally evolving electron density distributions over regional spatial scales.

We focus on a recent study assimilating imaging riometer observations to provide D-region specification and estimation of key space weather parameters for HF applications.

Potential outcomes include new approaches in space situational awareness and monitoring of space environmental conditions with improved anomaly resolution (distinguishing artificial from natural hazards) and informed mitigation.

Ionospheric Tomographic Imaging





Ionosphere is assumed to consist of discrete layers or voxels, each defined by a single value of electron density.

Typical observations ingested in tomography approach include slant path total electron content (TEC) from ground and space-based GNSS receivers. Additional observations include in situ plasma/electron density from low-earth orbiters. Model outputs are typically electron density E- to F-region (100 km to 800 km).

Ionospheric Data Assimilation Four Dimensional (IDA4D)

For each observation *i*, the estimate of the observation inside IDA4D is given by

$$y_i = H_{i,k}\, x_k$$

where y_i is the estimate of the observation, x_k is the current estimate of electron density at grid point *k*, and $H_{i,k}$ is the "geometry matrix" that carries the information connecting electron density to observations, and a sum over all k is implied. Once we have the geometry matrix we generate the current model estimate.

$$\vec{x_a} = \vec{x_f} + \tilde{P}_f \tilde{H}^T [\tilde{H}\tilde{P}_f\tilde{H}^T + \tilde{R}]^{-1} (\vec{y} - \tilde{H}\vec{x_f})$$

where *f* denotes forecast values and the data and model forecast error covariances are given by $\tilde{R}$ and $\tilde{P}_f$, respectively.

The performance of most global tomographic imaging and data assimilation algorithms is dependent on the amount and distribution of input observations. The bottom-side ionosphere, with sparse observability and low values of electron density, is particularly difficult to image.

References

Bust, G.S, T.W. Garner, and T. L. Gaussiran II, Ionospheric Data Assimilation Three Dimensional (IDA3D): A Global, Multi-Sensor, Electron Density Specification Algorithm, *J. Geophys. Research*,109, A11312, doi:10.1029/2003JA010234, 2004.

Bust, G.S., and C.N. Mitchell, The history, current state, and future directions of ionospheric imaging, *Rev. Geophys*, 46, RG1003, doi: 10.1029/2006RG000212, 2008.

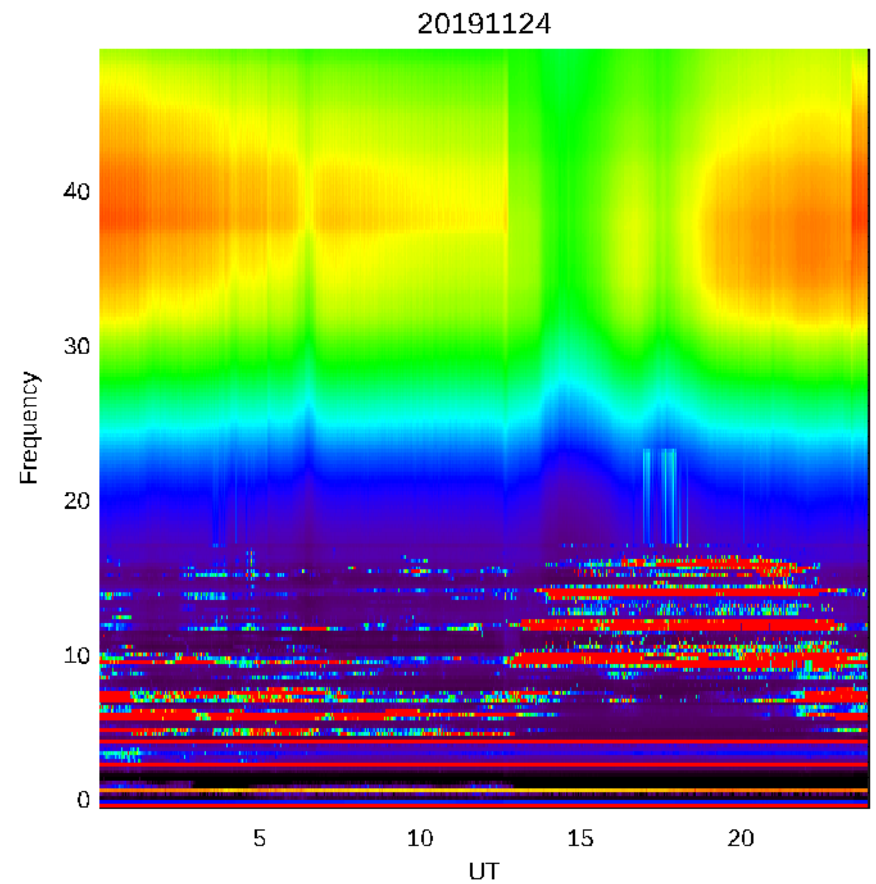
Bust, G. S. and S. Datta-Barua, Scientific Investigations Using IDA4D and EMPIRE, in Modeling the Ionosphere-Thermosphere System (eds J. Huba, R. Schunk and G. Khazanov), John Wiley & Sons, Ltd, Chichester, UK. doi: 10.1002/9781118704417.ch23, 2014.

Riometer Observations

Assimilation of riometer data allows estimation of D-region electron density.

For riometer data, only electron density grid cells intersected by the observation line-of-sight can contribute to the observation. The geometry matrix is given by the length of the path through the grid cell, multiplied by the electron collision frequency scaling factor:

$$H_{ik} = 0.046 \Delta s_{ik} \frac{\nu}{\nu^2+\omega^2}$$

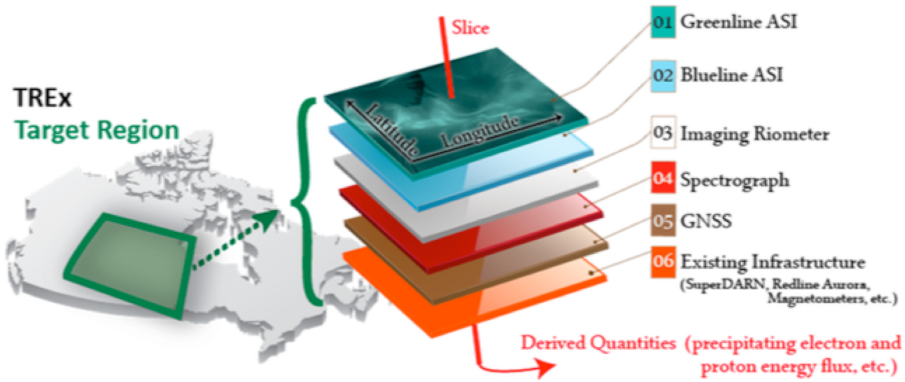


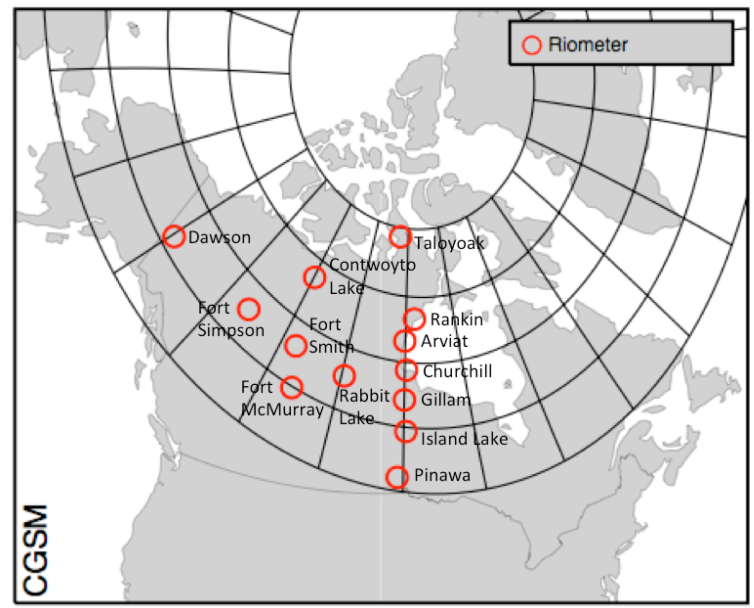
with ν the electron collision frequency in Hz, ω the angular frequency, and Δs_{ik} the length of the path through grid point k for measurement i. The electron collision frequency is modeled by obtaining electron and ion temperatures from the empirical model IRI and neutral densities from the empirical model MSIS.

IDA4D New Approach

We implement a new IDA4D approach using multi-instrument Canadian observations. Data are collected from both publicly available archives and our own space weather observing network TREx. We also introduce GNSS processing techniques using combined GPS+GLONASS observations for improved spatial resolution.

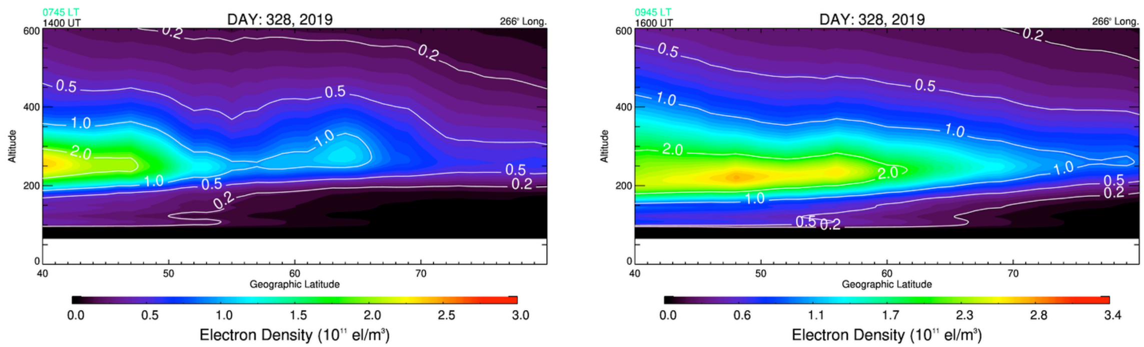
Two main observational types of data were ingested by IDA4D for this study: GNSS slant TEC; and absorption at 30 MHz from the Canadian Geospace Observatory Riometer Network (GO-RIO).



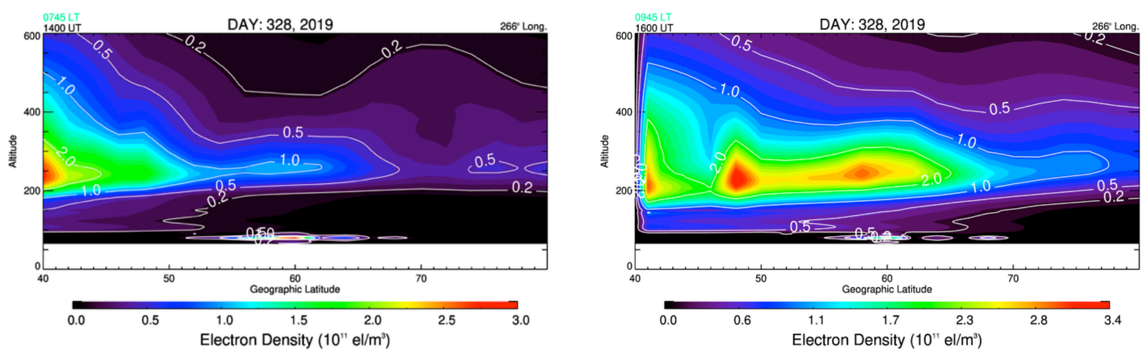


IDA4D: GNSS+Riometers

All multi-instrument data were collected and analysed for a one-month period October-November 2019. A dayside absorption event occurred November 24, 2019 due to a solar wind pressure pulse. Our case study focuses on this event. **We detected relative variations across the network in the riometer data related to D region enhancements.**

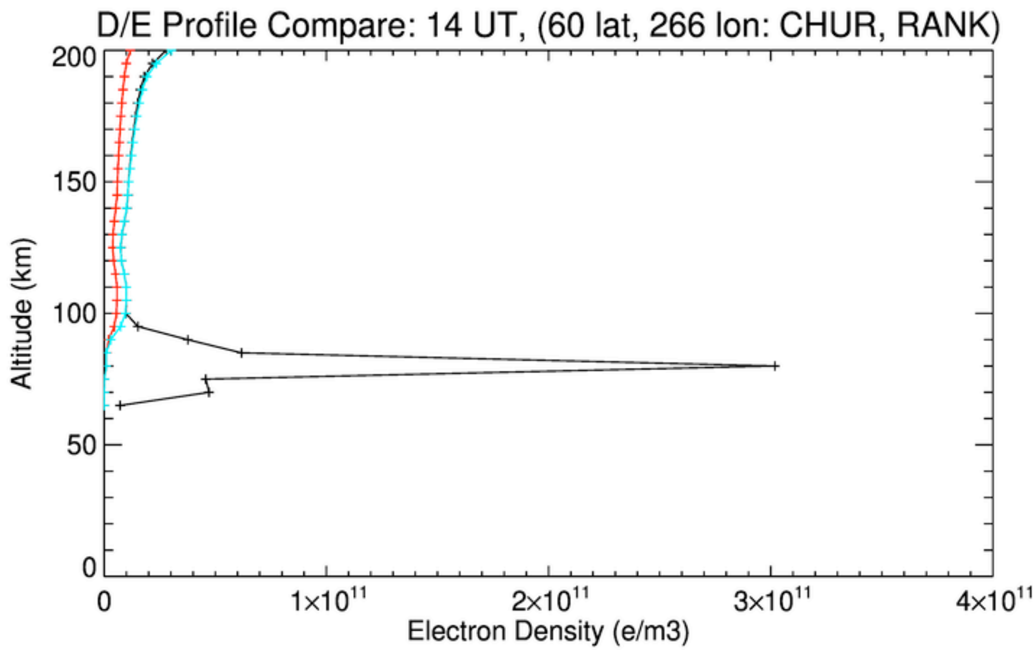


Slices from GNSS TEC observations ingested into IDA4D along constant 266 degrees longitude: 14 UT (left) and 16 UT (right) November 24, 2019.



Slices from GNSS TEC plus riometer observations ingested into IDA4D along constant 266 degrees longitude: 14 UT (left) and 16 UT (right) November 24, 2019.

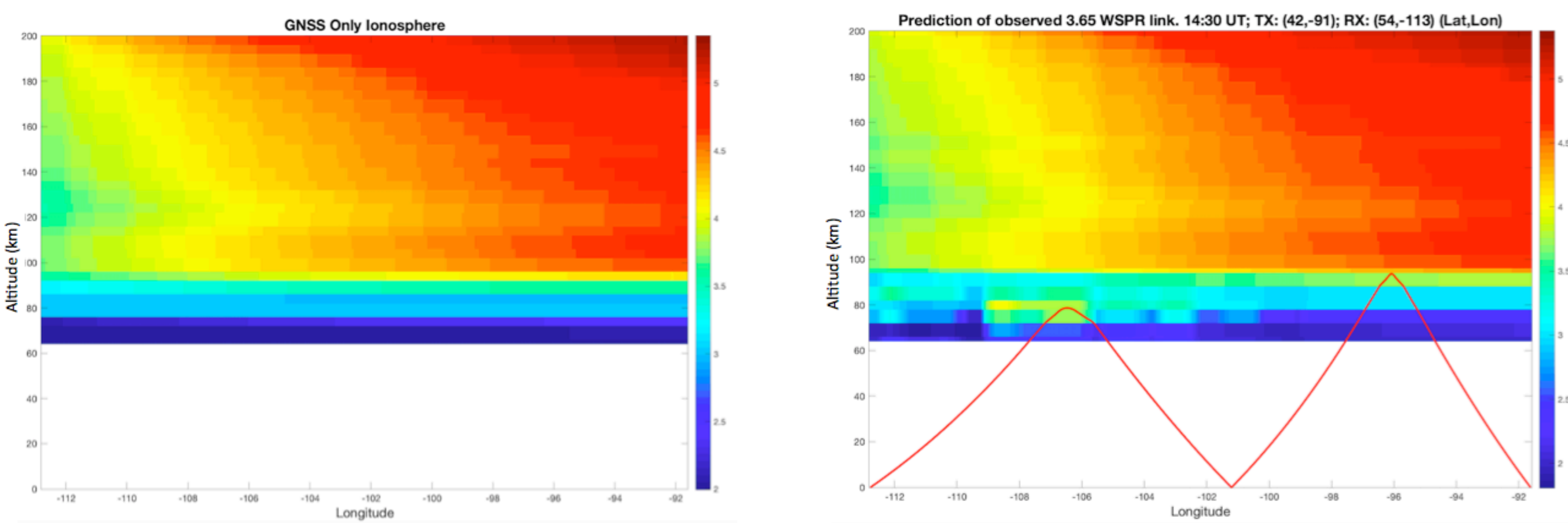
Electron Density Profile



Profile of electron density in D/E region for 14 UT November 24, 2019 at 60 degrees N latitude and 266 degrees longitude. The curves show IDA4D reconstruction using GNSS TEC with riometer data (black) and only GNSS TEC data (blue). The electron density profile for a default International Reference Ionosphere (IRI) model is shown for reference (red).

Validation: HF Propagation

An open WSPR (Weak Signal Propagation Reporter) link was observed at 14:42 UT November 24, 2019 between a transmitter (42 deg N latitude, 268 deg longitude) and a receiver located in Alberta, Canada (53.8 deg N latitude, 247.2 deg longitude). The frequency of propagation was 3.65 MHz. We model the HF propagation link for this case to demonstrate validity of the IDA4D approach using GNSS plus riometer data. HF ray-tracing is conducted for two ionosphere reconstructions: 1) IDA4D using only GNSS TEC data, and 2) IDA4D using GNSS TEC and riometer absorption data.



Electron density (log10 N_e in el/cm^3) along great circle propagation path for ionosphere reconstruction using IDA4D with GNSS (left) and GNSS+riometer (right). The 2-hop X-mode propagation path (shown in red) is predicted open and is consistent with WSPR observations.