Ground-based VLF Remote Sensing and the October 10-11 G4 Storm

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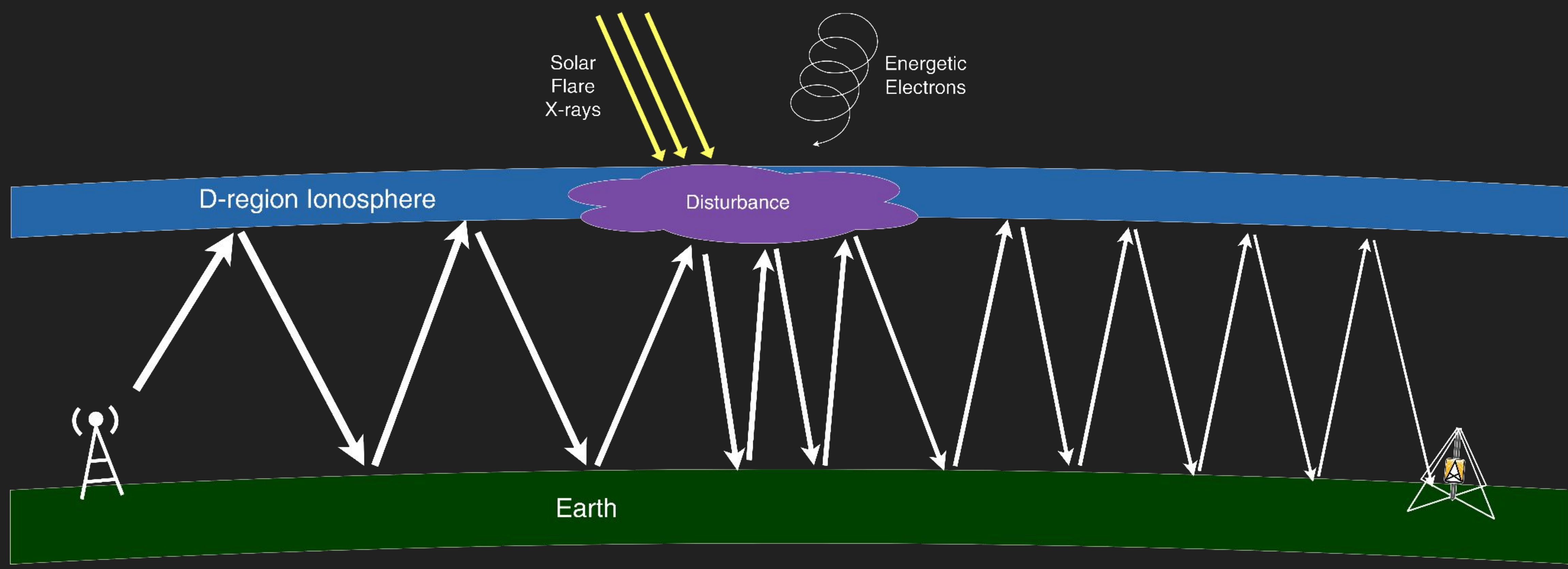
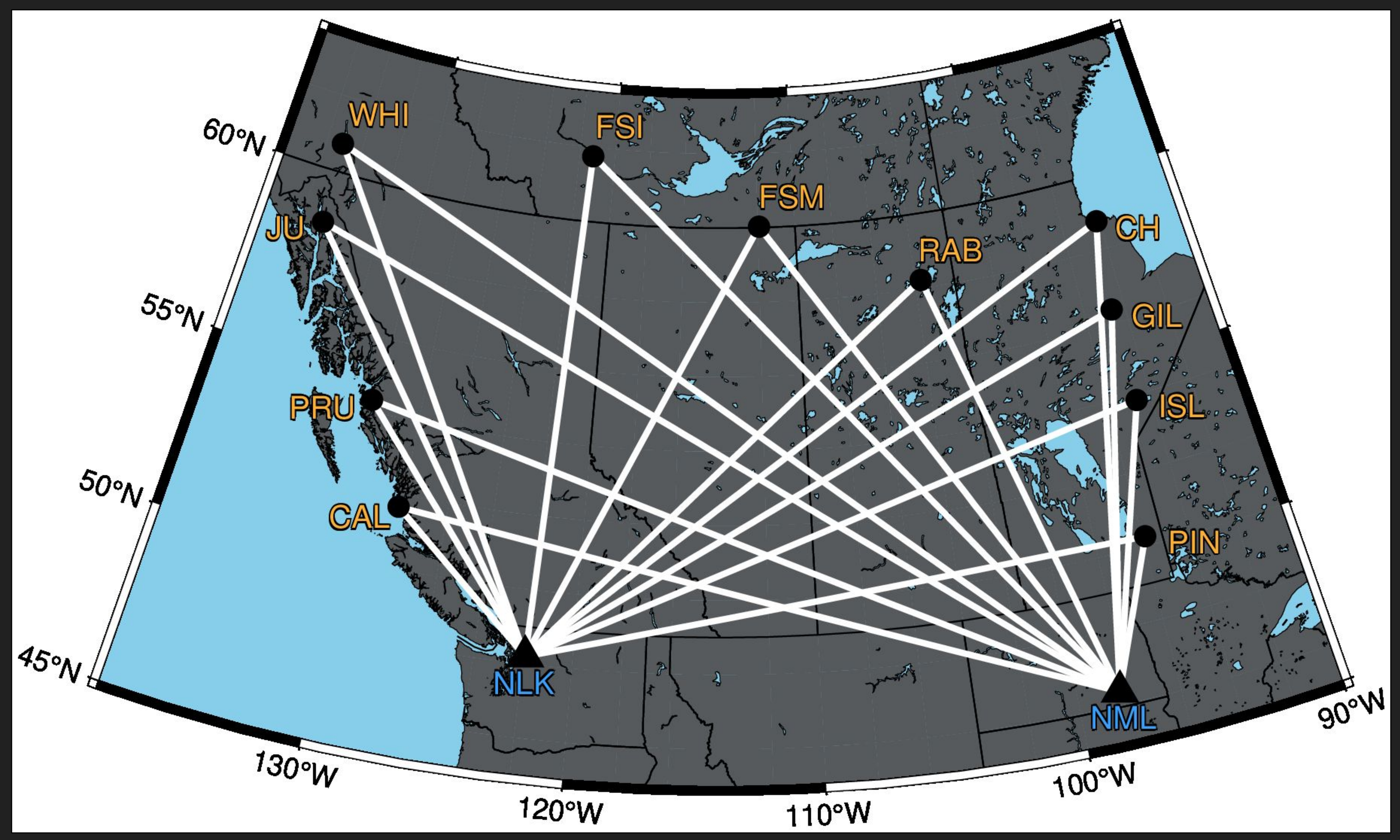


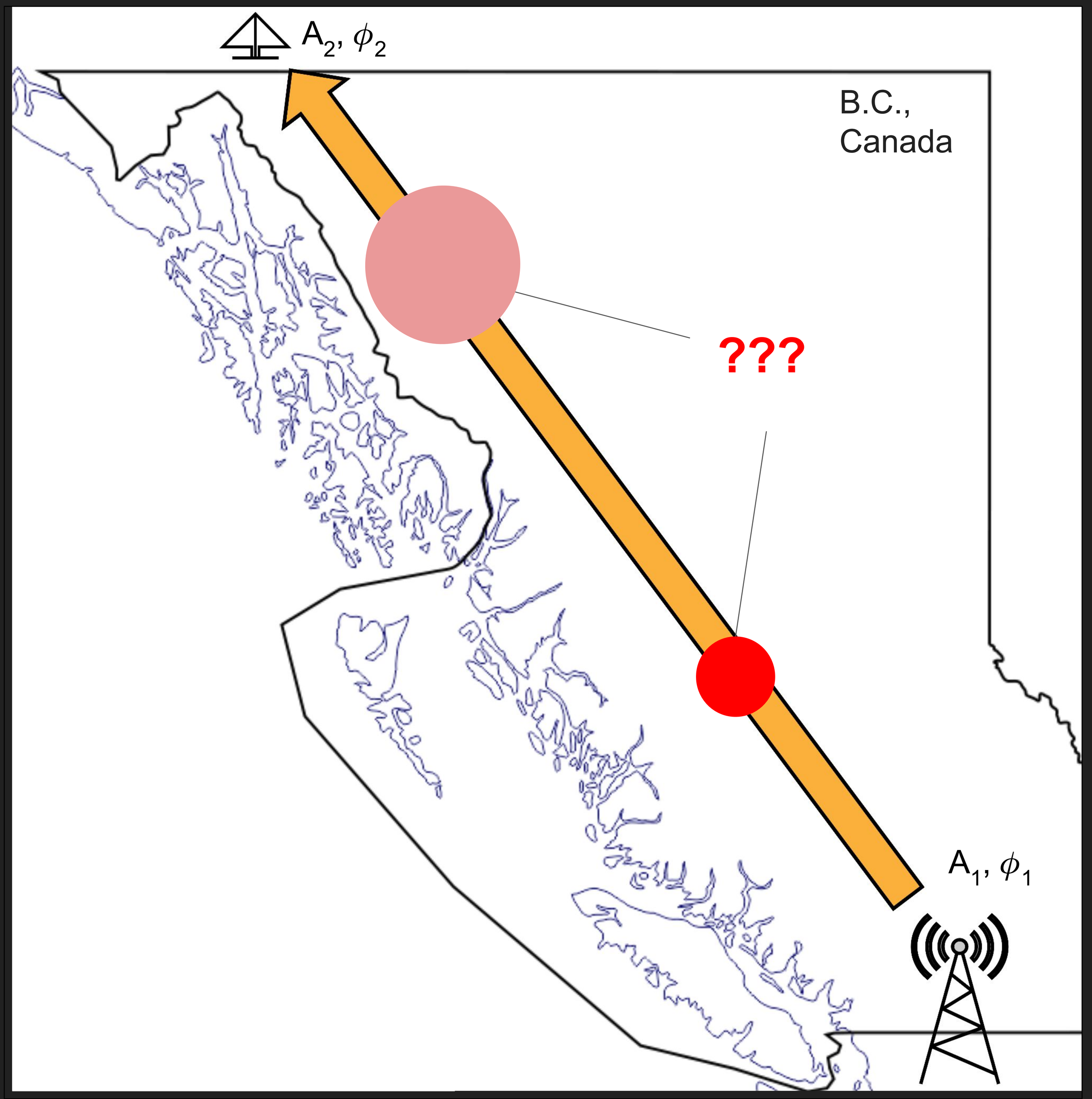
VLF Waves in the Earth-Ionosphere Waveguide

Very Low Frequency (0-50 kHz) radio waves reflect off of the D-region ionosphere (55 to 90 km) to propagate within the Earth-Ionosphere waveguide with losses of ~2dB/Mm. **Measuring changes to these waves indicates the ionosphere has been disturbed.**

In the D-region, disturbances are generally caused either by energetic particle precipitation (EPP, generally electrons ~30+ keV) or by solar flare x-rays. Solar flares affect the entirety of the day-side Earth while EPP, guided by Earth's magnetic fields, affects smaller geographic regions at auroral and sub-auroral latitudes.



The Array for VLF Imaging of the D-region (AVID) shown with rx station codes in orange and tx codes in blue.

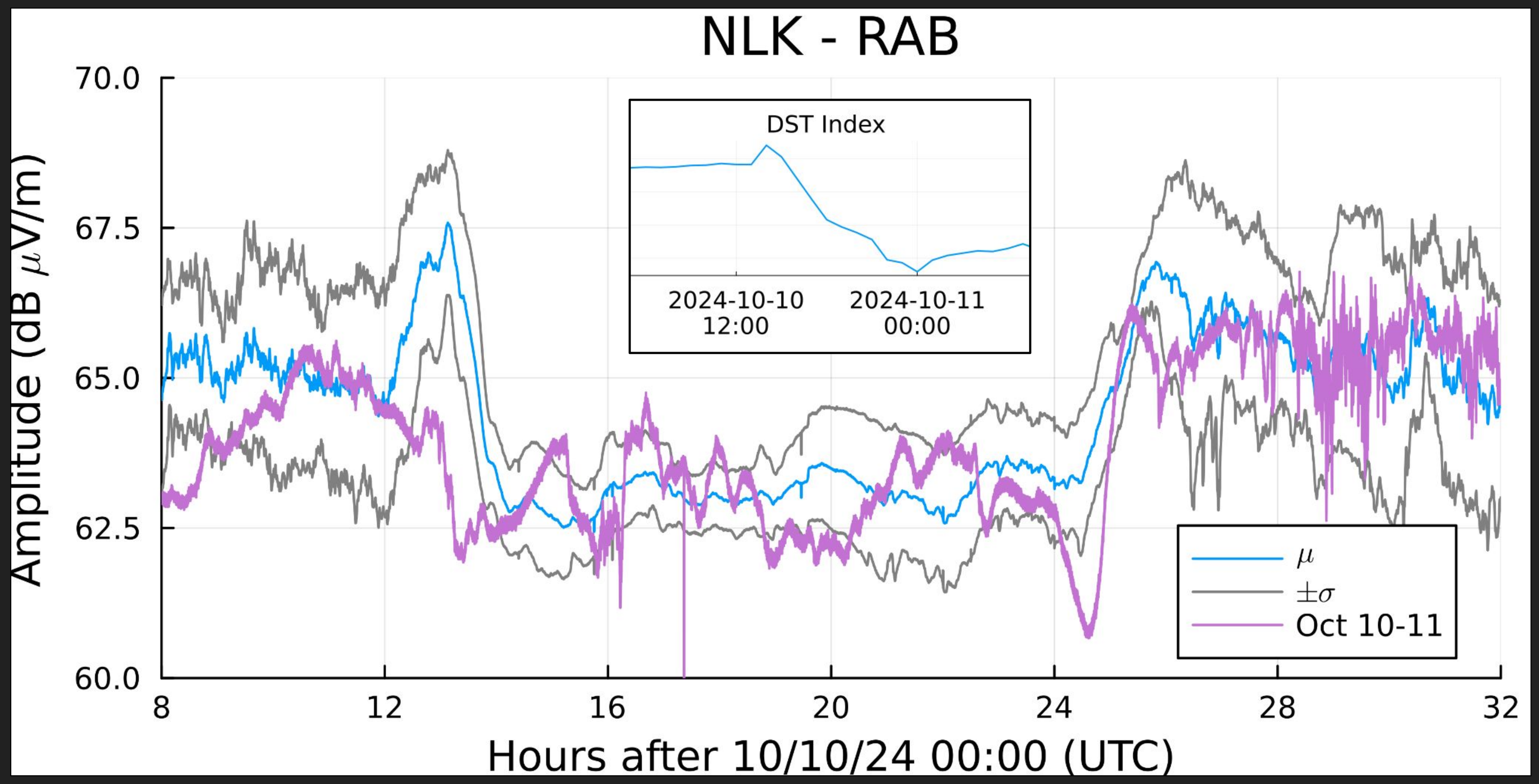


VLF measurements

A handful of naval transmitters (txs) operate in VLF frequencies for long-range communication. **These transmitters are "always-on", providing a constant diagnostic of the ionosphere** when measured.

Receivers (rxs) then can measure VLF wave amplitude (A) and phase (ϕ). When combined with propagation models, like the LongwaveModePropagator, average path characteristics can be determined. These measurements, however, are **path integrated**—for any given tx-rx pair, a disturbance can't be localized along the path without additional information.

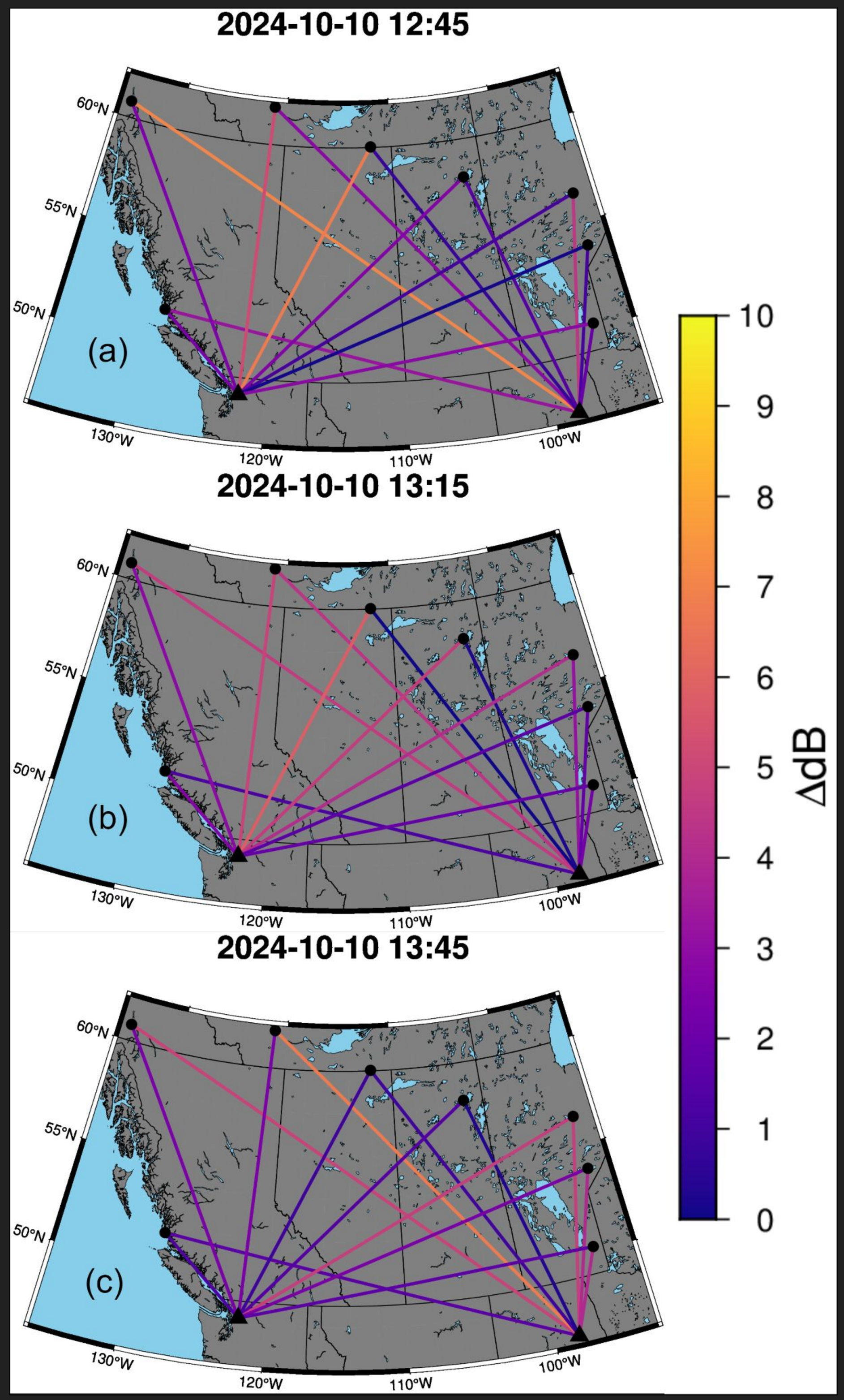
Building up an array of rxs such that multiple tx-rx paths overlap, gives extra information.



Storm Time vs. Quiet Days

To understand a disturbance along a tx-rx path, steady-state behavior must be known. For the October G4 storm a typical "quiet day" was constructed by averaging VLF measurements of ± 20 days outside of storm time. Then, we can compare storm time behavior to this quiet day.

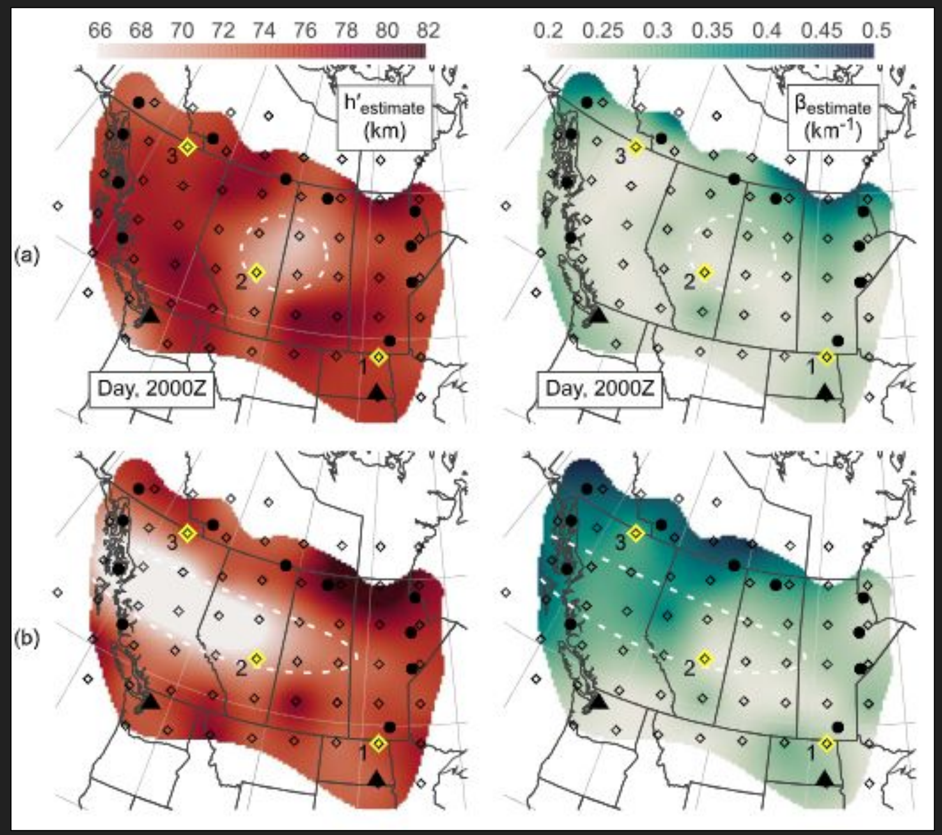
In the example above, during storm onset (12:30 to 14:30) we see a large deviation from the quiet day. In general, during storm onset, radiation belt electrons are being depleted and some are precipitating into the ionosphere. This large deviation may be a signature of precipitating electrons into the D-region.



Spatial Results

By looking at each path's difference from quiet day (Δ dB) we can get a sense of any spatial dynamics in the D-region ionosphere.

These three images on the right were taken 30 minutes apart during storm onset. They appear to show a localized disturbance in the central-Northwest portion of the array at 12:45 that broadens out and decreases in amplitude at 13:15 before re-localizing in the central-Southeast section of the map at 13:45.



Conclusions and Future Work

This shows an emerging ability to, over a mesoscale region, identify spatiotemporal dynamics in the D-region ionosphere. The next steps are to apply state estimation techniques combined with forward propagation modeling to quantitatively assess the characteristics of spatial disturbances in the D-region.