High-latitude GPS Scintillation from E Region Electron Density Gradient During the December 20-21, 2015 Geomagnetic Storm

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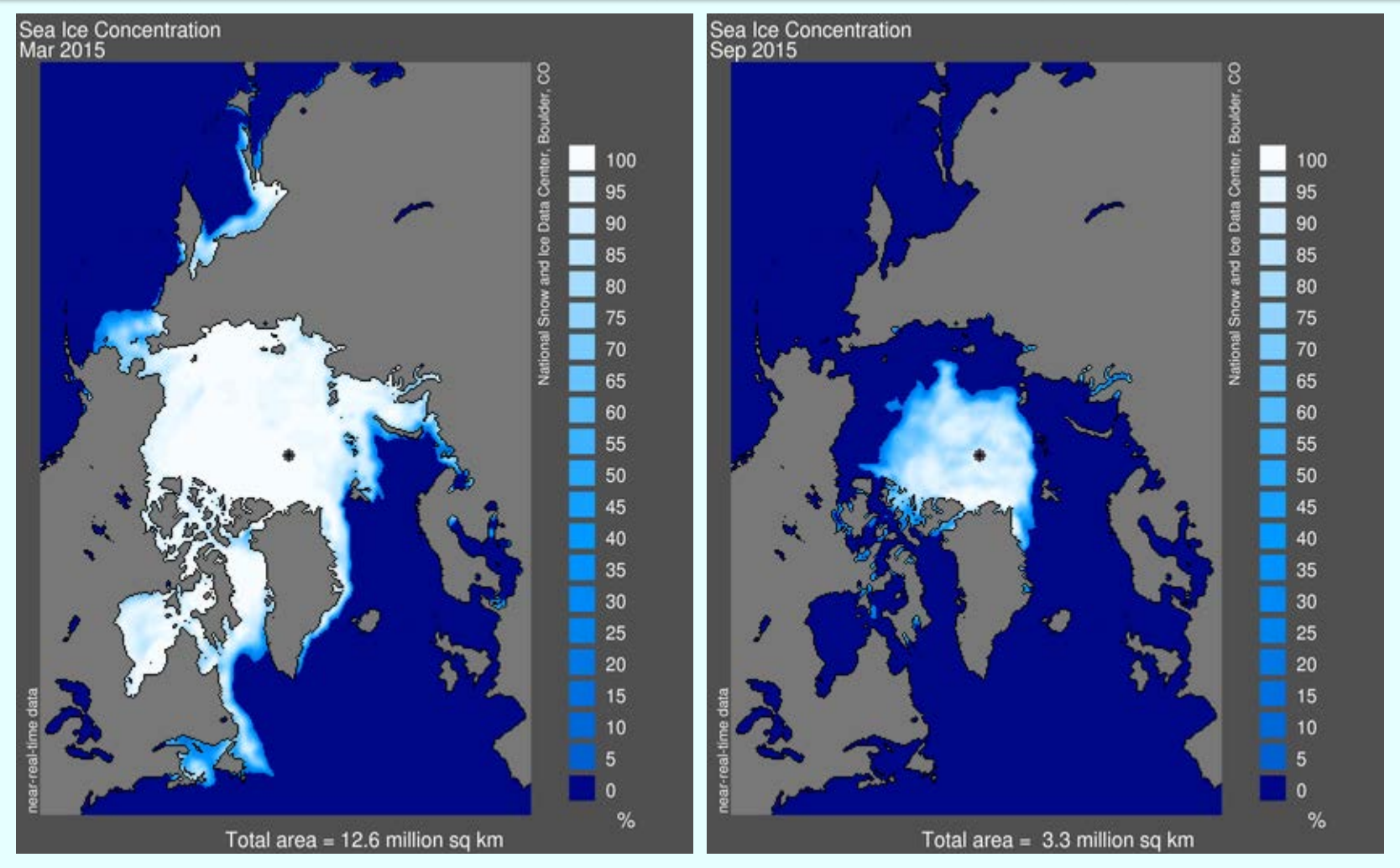
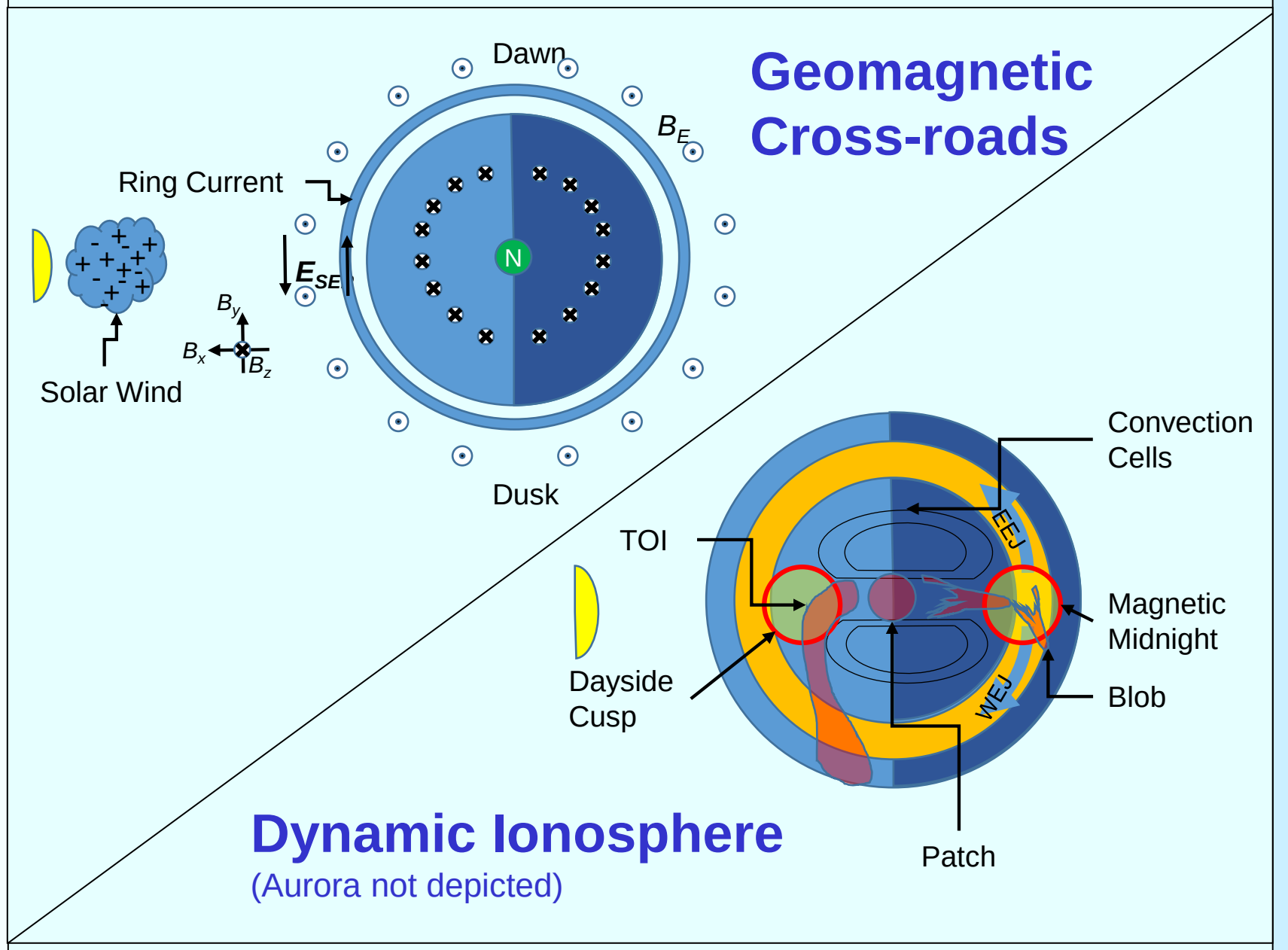
Motivation & Background



Importance of high-latitude ionosphere:

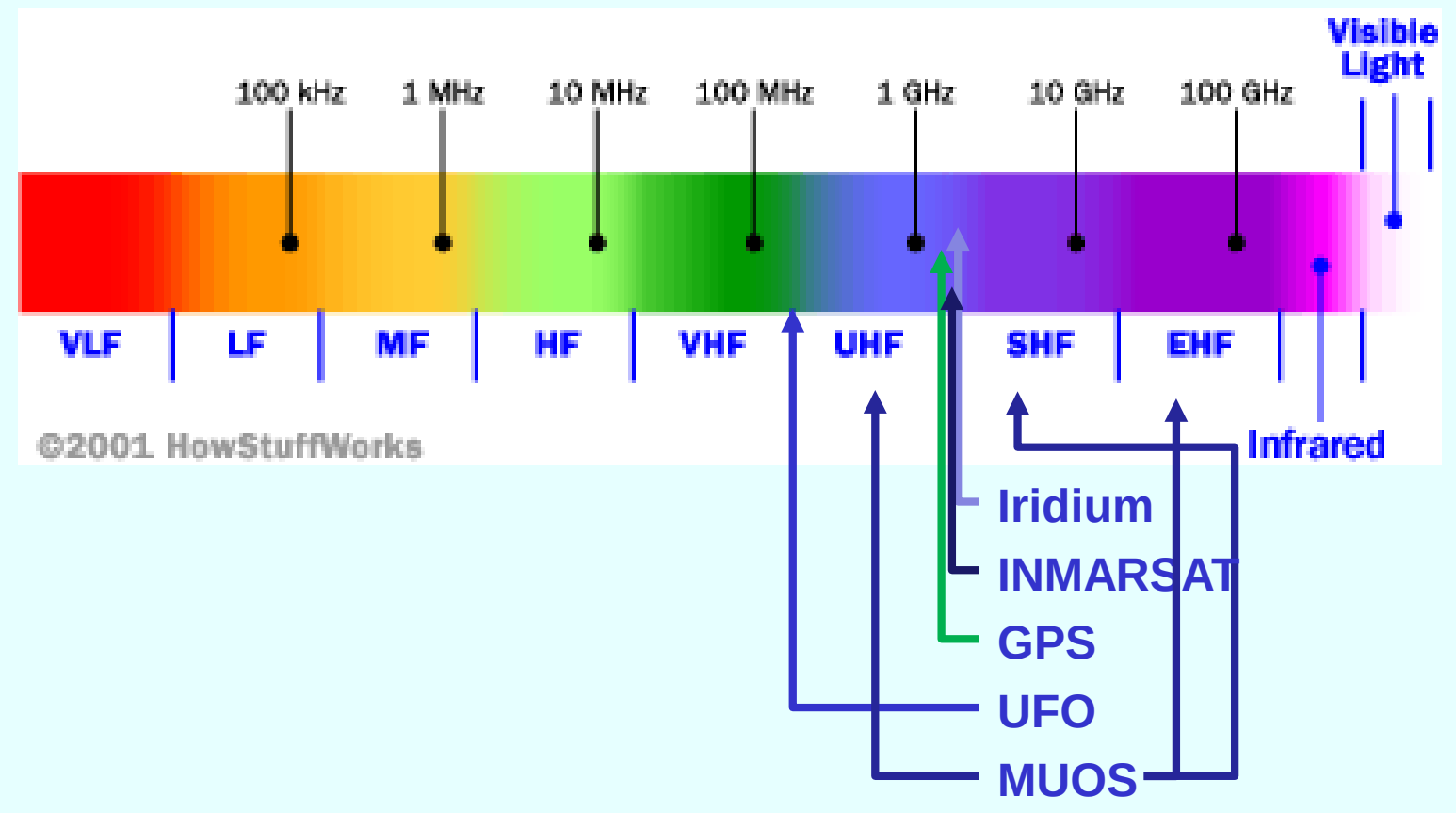
- Over 6 million square kilometers of trafficable ocean in the Arctic at summer's close (shown above).
- The high-latitudes are the geomagnetic cross-roads for the interaction of the Sun-Earth system, hosting a dynamic ionosphere.



Scintillation due to ionospheric structures can be the single greatest GPS vulnerability in the high-latitudes.

- Introduces positioning errors on the order of meters to decameters
- Potentially causes loss of or inability to maintain GPS receiver-satellite lock
- Ionospheric structural scales
  - Spatial: decameters to hundreds of kilometers
  - Temporal: seconds or less

Civilian and military communications systems operate in the same band as GPS, including some in very close proximity to GPS (shown below)



Acknowledgements

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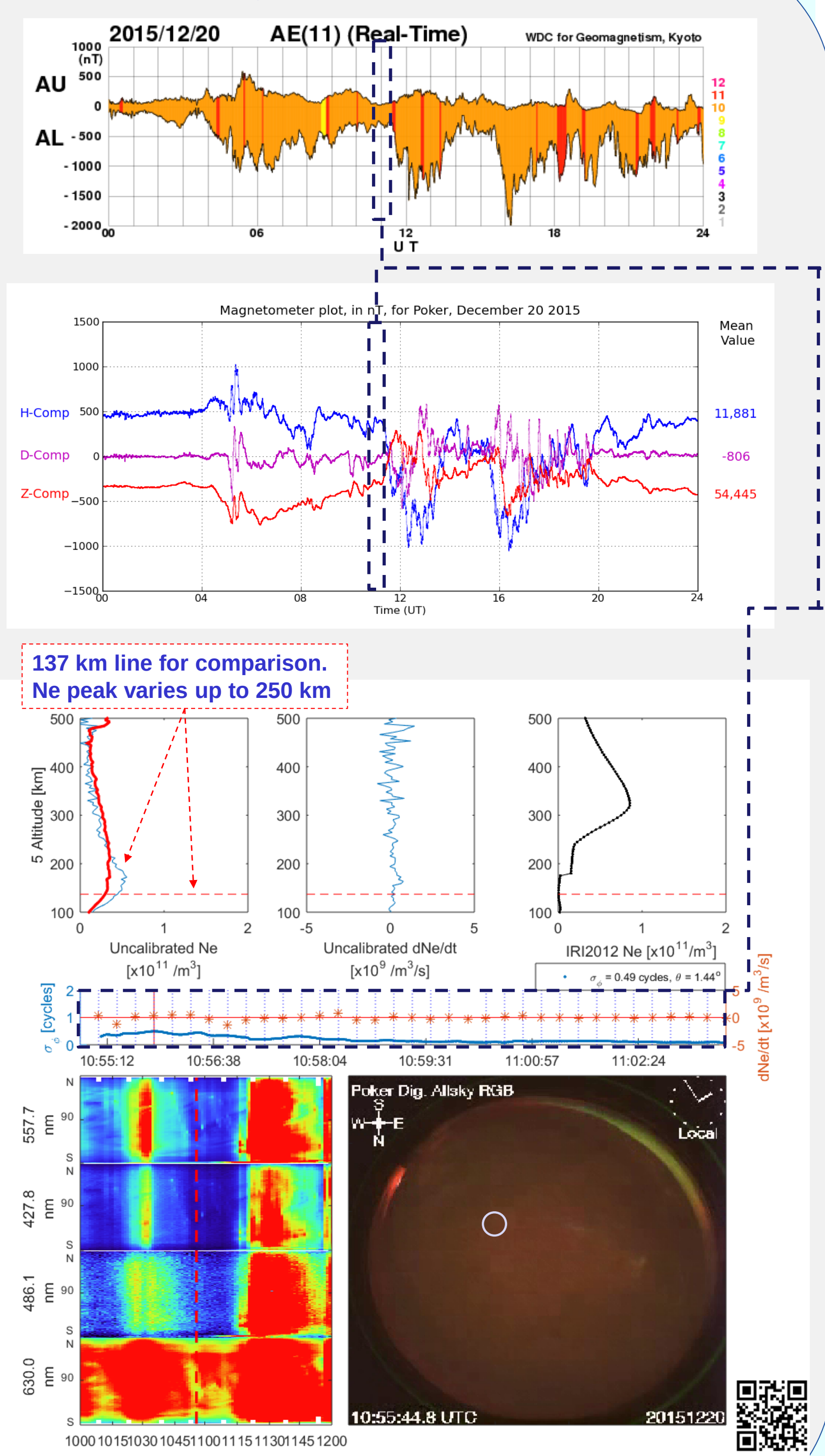
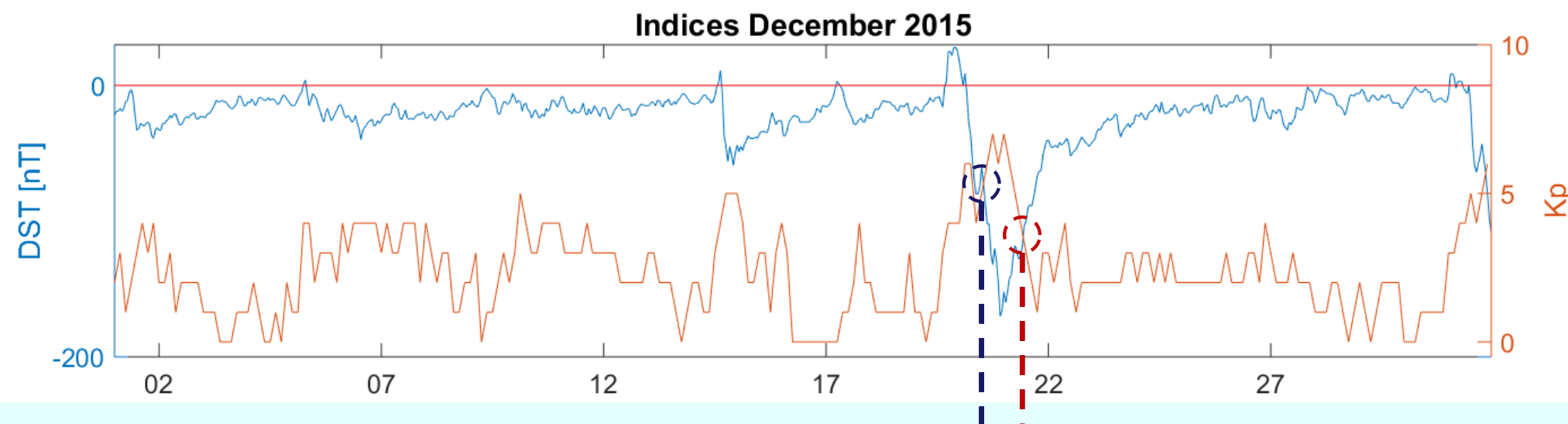
- The Poker Flat Incoherent Scatter Radar (PFISR) is operated by SRI International on behalf of the US National Science Foundation under NSF Cooperative Agreement AGS-1133009. Data retrieved from the Open Madrigal Web (http://cedar.openmadrigal.org/)
- Atmospheric & Space Technology Research Associates (ASTRA): GPS Scintillation, IDA4D data
- Optical imagery data was provided by Don Hampton at the Geophysical Institute and Poker Flat Research Range
- DST, Kp, AE and AL Indices downloaded from WDC for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/201303/index.html)
- GPS Visibility data computed through the use of B.K. Bradley's Sidera v1.1
- Colorado Center for Astrodynamics Research (CCAR)
- For more information on this project please contact Diana Loucks: loucksd@colorado.edu

Results

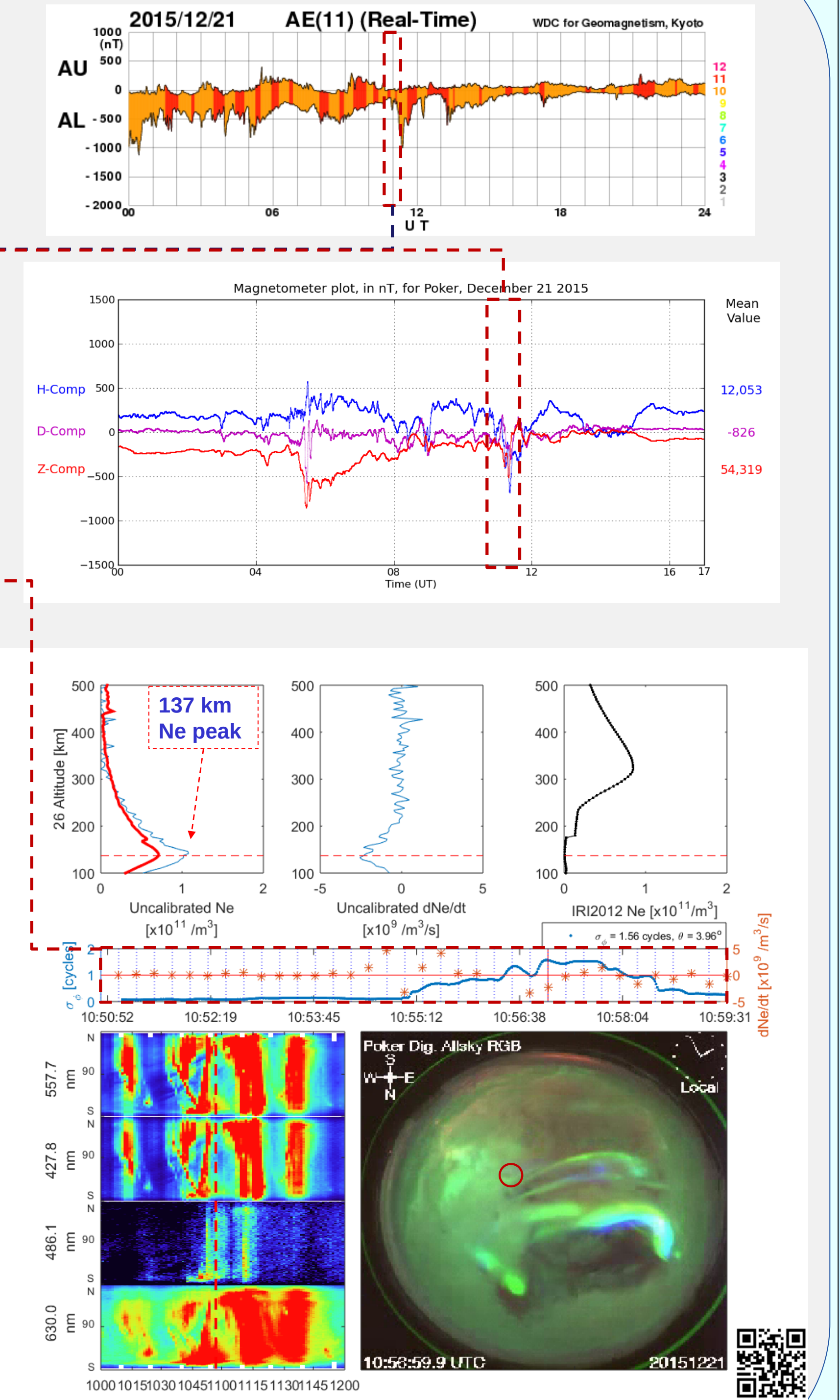
Data was taken on the Poker Flat Incoherent Scatter Radar (PFISR) field aligned beam (64157), for approximately ten minutes each day, 14-22 December 2015 as part of a pilot experiment. Times were chosen that correlated with ephemeris that predicted for PRN 12 to align with the field aligned beam. Serendipitously, a geomagnetic storm occurred on the 20th of December with a recovery phase that began at midnight on the 21st and lasted several more days. Two scintillation events were detected during the PFISR experiment windows, one on each of the 20th and 21st of December, the latter being the stronger of the two. A summary of those two events is presented here.

Geomagnetic Storm Main Phase





Geomagnetic Storm Recovery

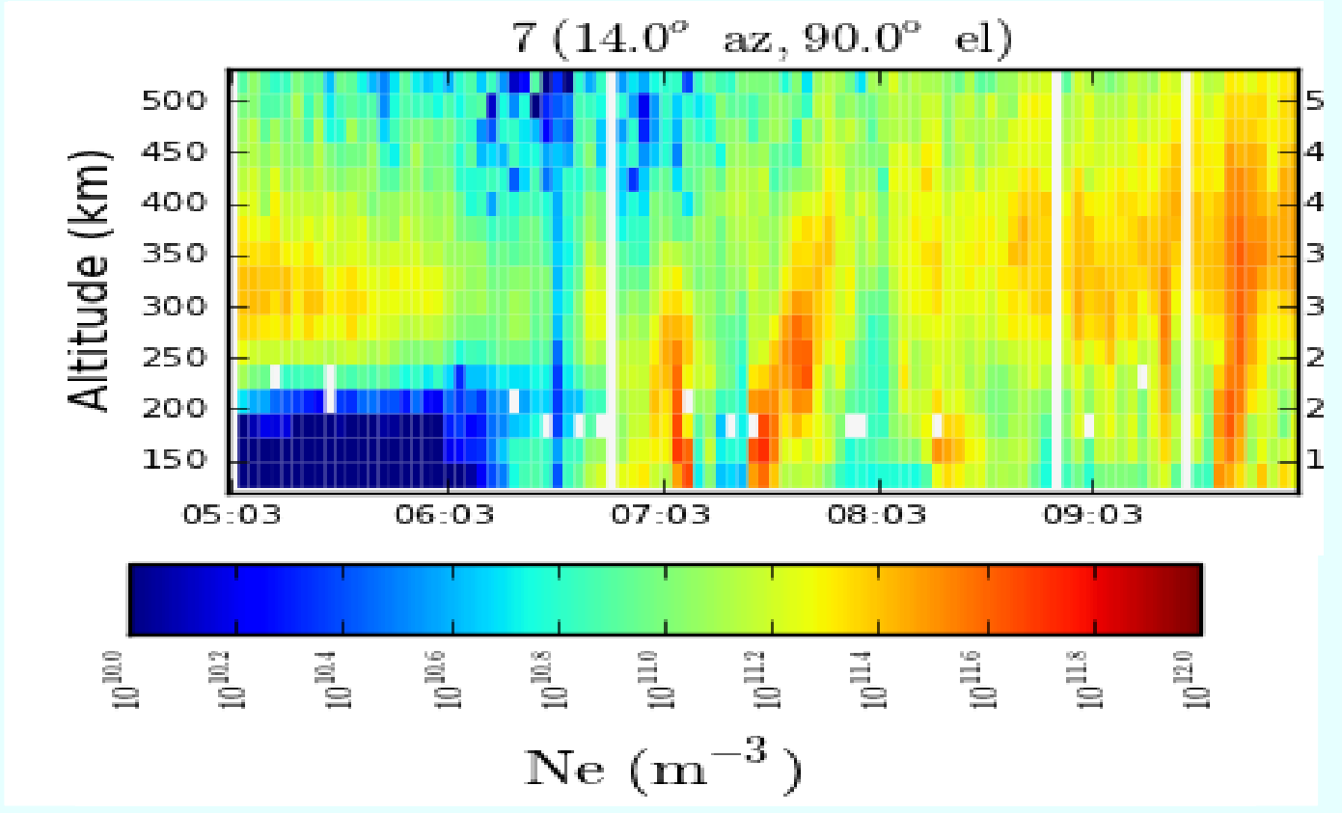


20 DEC 2015	Event Parameters	21 DEC 2015
-60 nT (falling)	DST (event minimum -170 nT)	-105 nT (rising)
5 (rising)	Kp (event max 7)	4 (falling)
Limited Activity	Auroral Indices	Limited Activity
Disturbed	Local magnetometer	Disturbed
1055 UT/1059 UT	Start/End (Approximate)	1055 UT/1100 UT
0.49 cycles	Peak σ_Φ detected (PRN 12)	1.56 cycles
Peak Ne varies between 150km & 250km altitude with a moderate temporal gradient	Radar results	Peak Ne occurs near 137 km with a strong temporal gradient
Limited	Auroral Activity	Strong
	Emissions detected	
Limited if any	557.7 nm	Strong
Strong	630.0 nm	Moderate

Clearly both E and F region gradients linked to GPS scintillation were detected. In the case analyzed here, the most intense scintillation above Poker Flat is caused predominately by E region gradients.

Scan the QR code in the lower right corner of each figure to watch a video over the entire time interval.

Radar Operations



Normal operations of the Poker Flat Incoherent Scatter Radar (PFISR) provide for 3D coverage with a temporal resolution of 1-3 minutes depending on the number of beams used.* The integration period per beam is approximately 15 seconds, and the radar switches sequentially through a series of beams for a single epoch (a representative electron density profile for a single beam is shown above). In order to improve the temporal and spatial resolution, a single beam was chosen and operated for a 10 minute interval. To determine the electron density at each altitude from the integrated radar returns, the equation:

$$N_e = \frac{2R^2 P_r}{P_t \tau_p K_{sys}}$$

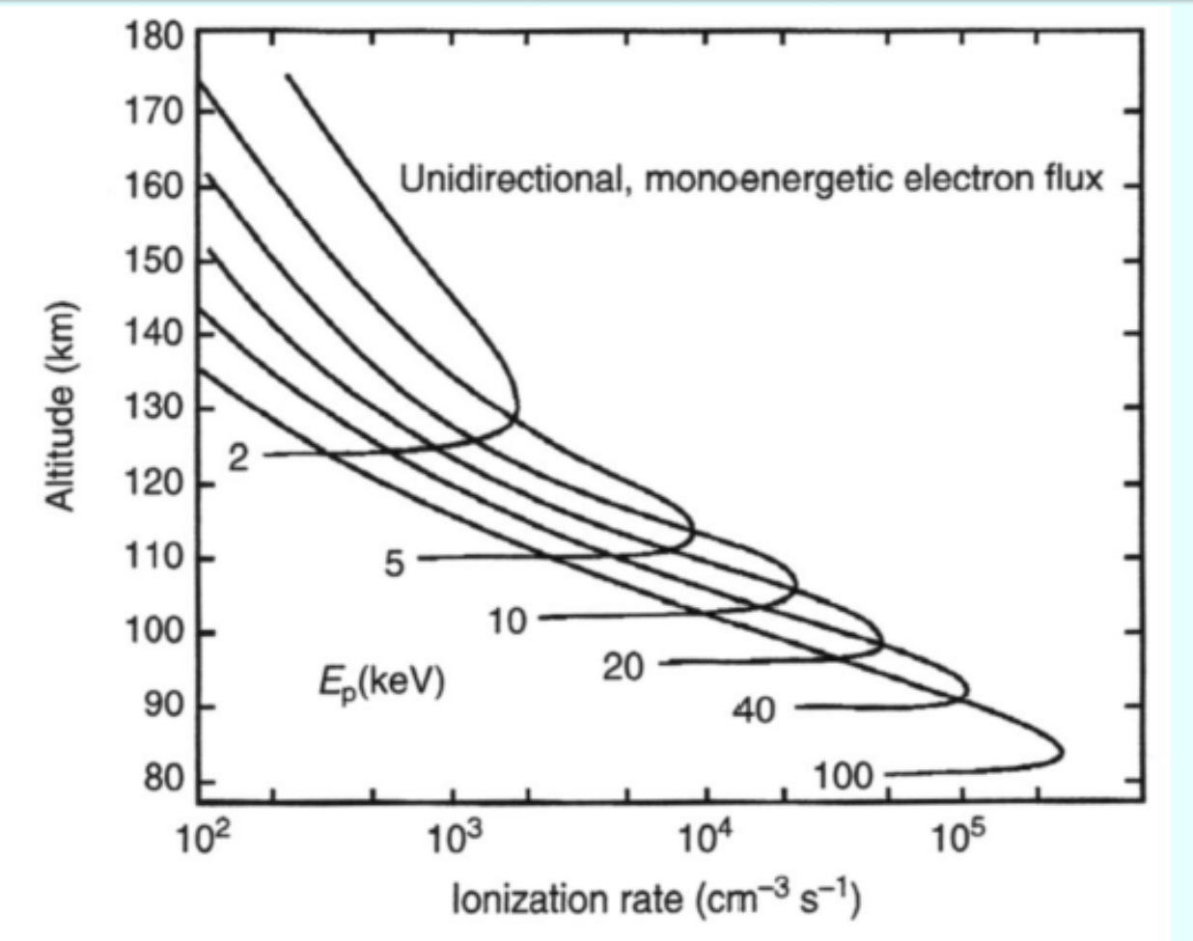
was applied.

Here R is the range [m], P_t and P_r are transmit and receive power [W], respectively, τ_p is the pulse length [s], and K_{sys} the system constant [m^5/s]. Note, it is assumed that the electron and ion temperatures are equal, and effects associated with the Debye length and Bragg scattering are neglected. An additional calibration, the plasma line fit, is performed to finalize the returns at PFISR. Since it is the gradient in Ne that is important in this study the plasma line calibration step can be omitted.

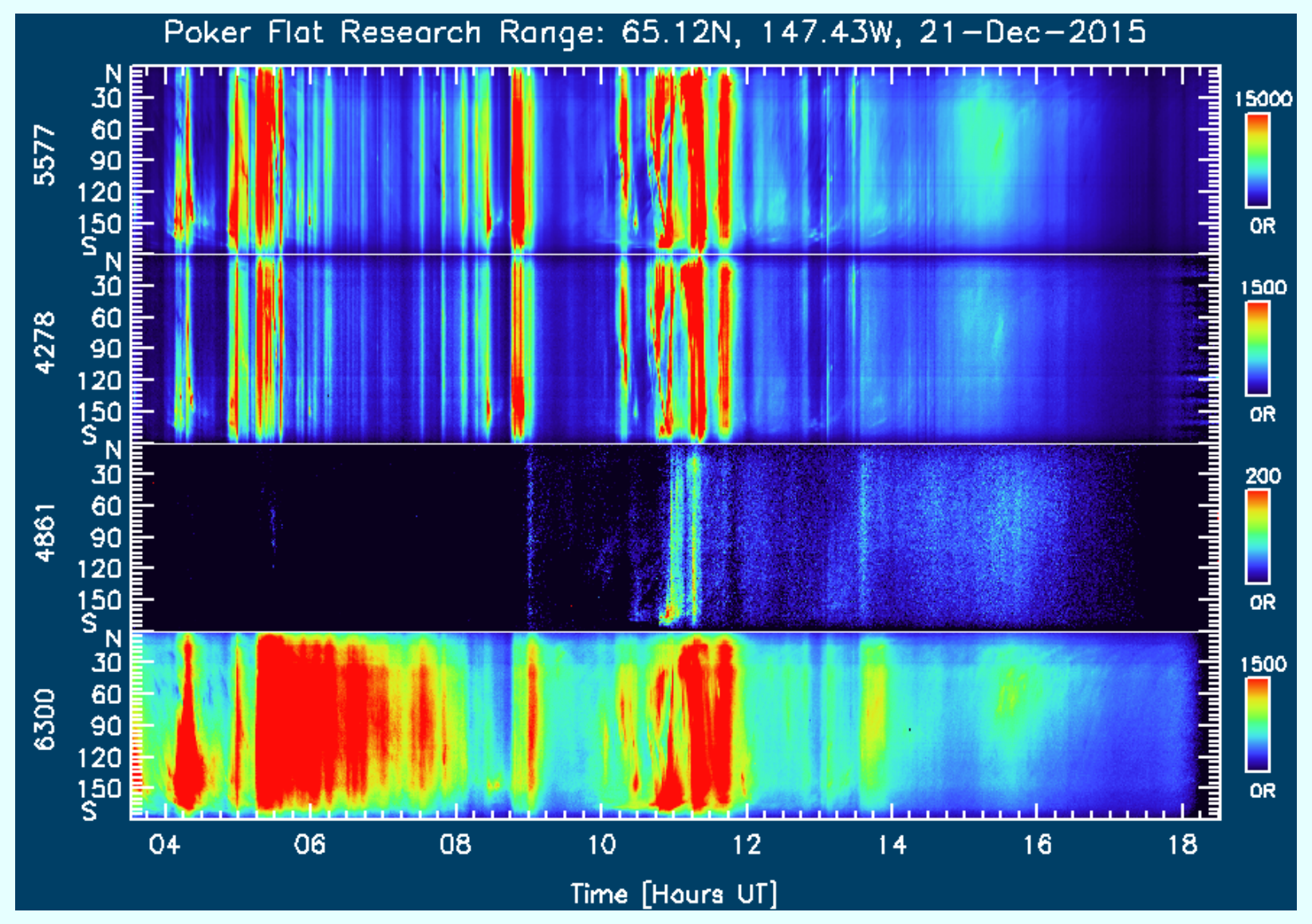
*Other specifications contributing to this cadence can be found at www.amisr.com.

Auroral Activity & Monitoring

Auroral activity lends itself to impact ionization of the ionosphere. The ionization occurs at lower altitudes for higher energy precipitating particles due to their ability to penetrate further into the atmosphere. Shown at right are particle energies and peak ionization rates at corresponding altitudes. Note the 2keV particles yield a peak ionization altitude near 130km.



Schunk & Nagy, *Ionospheres*, 2d Ed, 2009

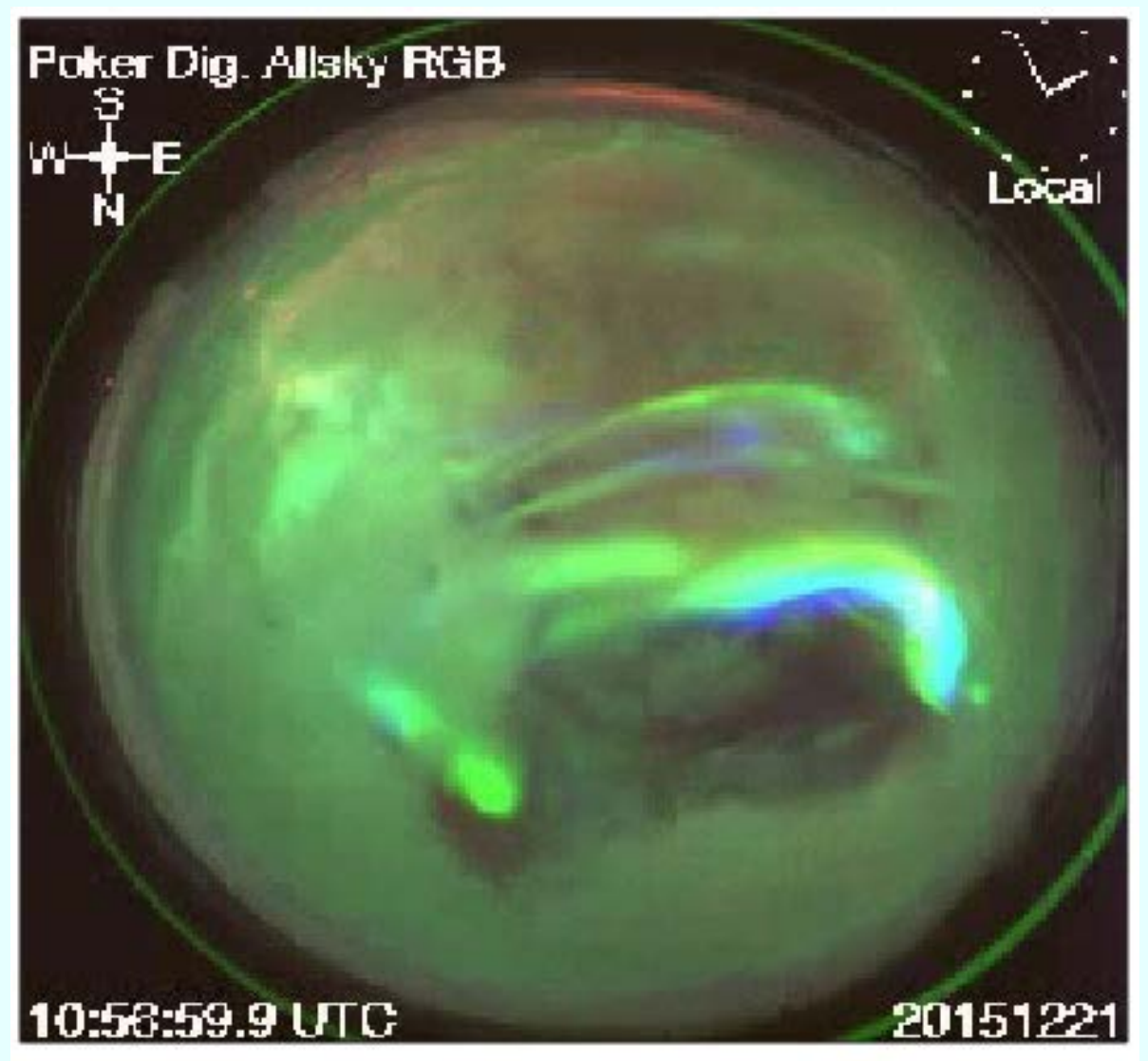


Shown above is a keogram representing North-South scans of emissions through zenith above the Poker Flat Research Range over time. Each line is described below:

- Top Panel: green (λ = 557.7 nm), visible down to ~ 100 km
  Atomic oxygen (O) emission (primarily E region)
- Second Panel: blue/violet (λ = 427.8 nm)
  Ionized molecular nitrogen (N2+) (band of emissions)
  Typically e⁻ energies ~ several to 10's keV
- Third Panel: blue-green (λ = 486.1 nm) Balmer line
  Ionized hydrogen (H⁺) due to collisions with neutrals
- Bottom Panel: red (λ = 630.0 nm)
  Atomic oxygen (O) forbidden transition emission
  Predominantly F region (>~ 180 km)

Show below is a consolidated image of the red, green and blue lines from the all-sky camera at Poker Flat Research Range. Note that

- the image is inverted (North is down), and that the date, local and Universal times are represented in each of the remaining corners
- the red and blue wavelengths have been artificially intensified for visibility in this image.



Future Work

Request PFISR experiments focusing on

- Max unambiguous range of 450 km
- Spatial resolution on the order of 5 km
- Temporal resolution on the order of 15 s.

Use emission intensities at multiple wavelengths to determine precipitating particle energies and confirm attributes of the detected electron density profiles

Use IDA to confirm/deny the presence of plasma patches and auroral blobs.

Compare the relative import of E and F region gradients to the intensity of GPS scintillation

References

Key References*

1. Jin, Moen, Miloch, *GPS Scintillation Effects*, 2014
2. Kintner, Ledvina, de Paula, *GPS & ionospheric scintillations, 2007*
3. Schunk & Nagy, *Ionospheres*, 2009
4. Semeter, et al, *Volumetric Imaging*, 2009

* Abbreviated, full list provided upon request

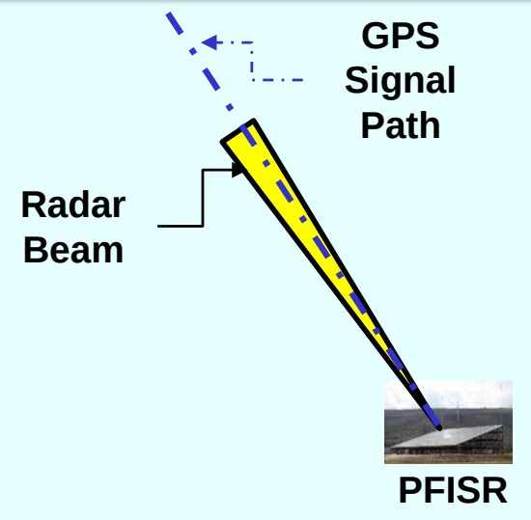
Problem Statement

Recent studies indicate ionospheric electron density gradients are responsible for GPS scintillation. There are two primary sources of high-latitude electron density gradients, which can occur separately or simultaneously:

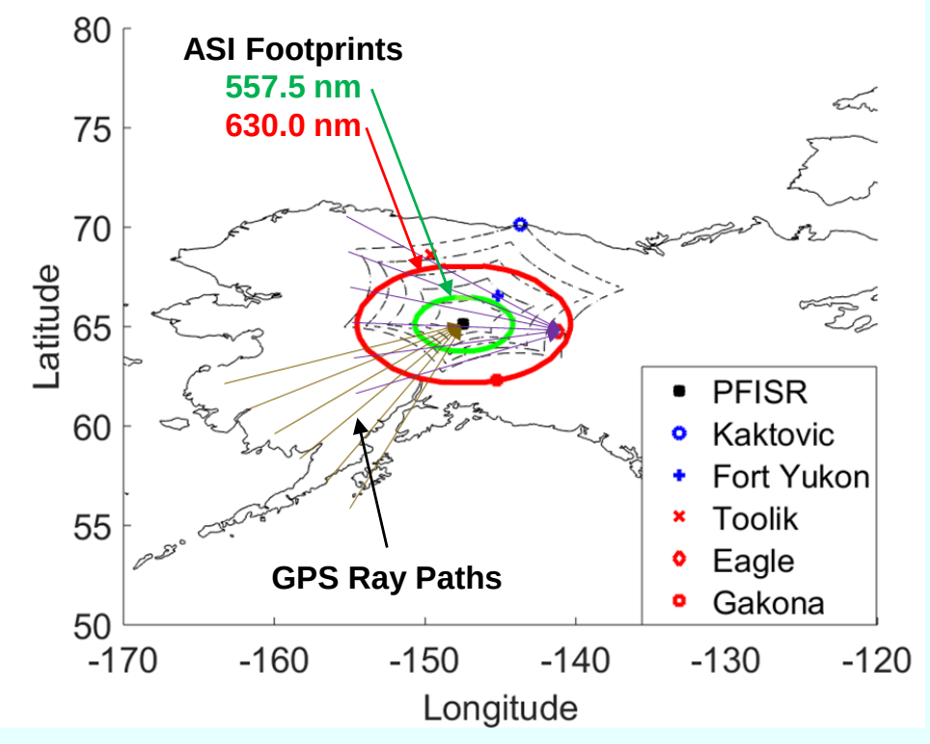
- F region: Plasma patches and auroral blobs
- E region: Discrete aurora

Can we detect E and/or F region irregularities that are the source of GPS scintillation using PFISR?

Methodology



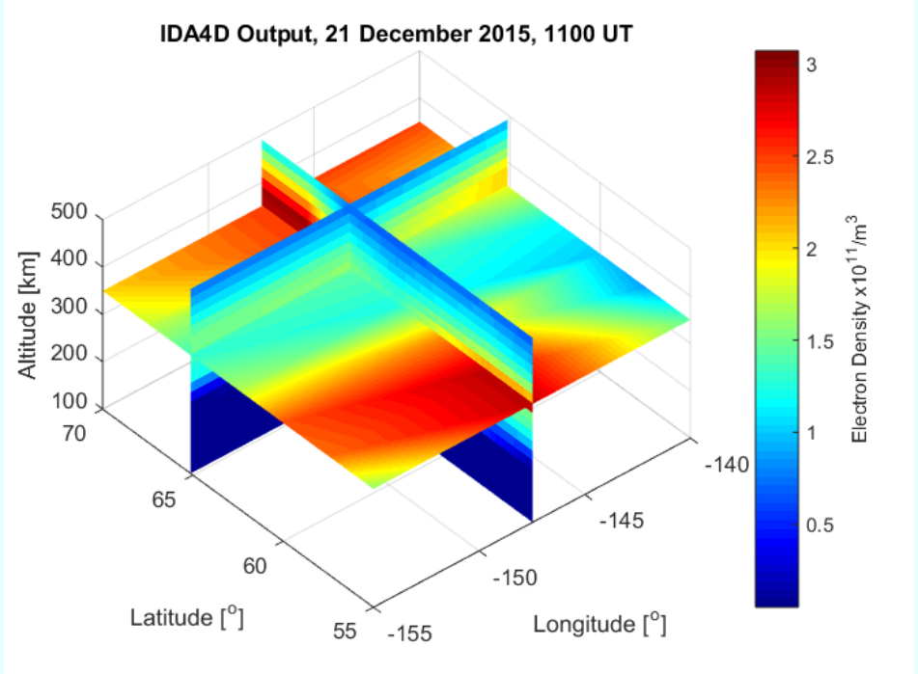
This research seeks to combine GPS scintillation data with incoherent scatter radar measurements of electron density in order to determine the temporal and spatial electron density gradient along the GPS ray path for a scintillation event.



GPS ephemeris predictions were used to determine the PFISR beam parallel to a particular satellite signal's path. During the experiment, auroral activity was confirmed through the use of all-sky imagery measurements above PFRR.

For context, Ionospheric Data Assimilation Four-Dimensional (IDA4D) will be used. Inputs assimilated:

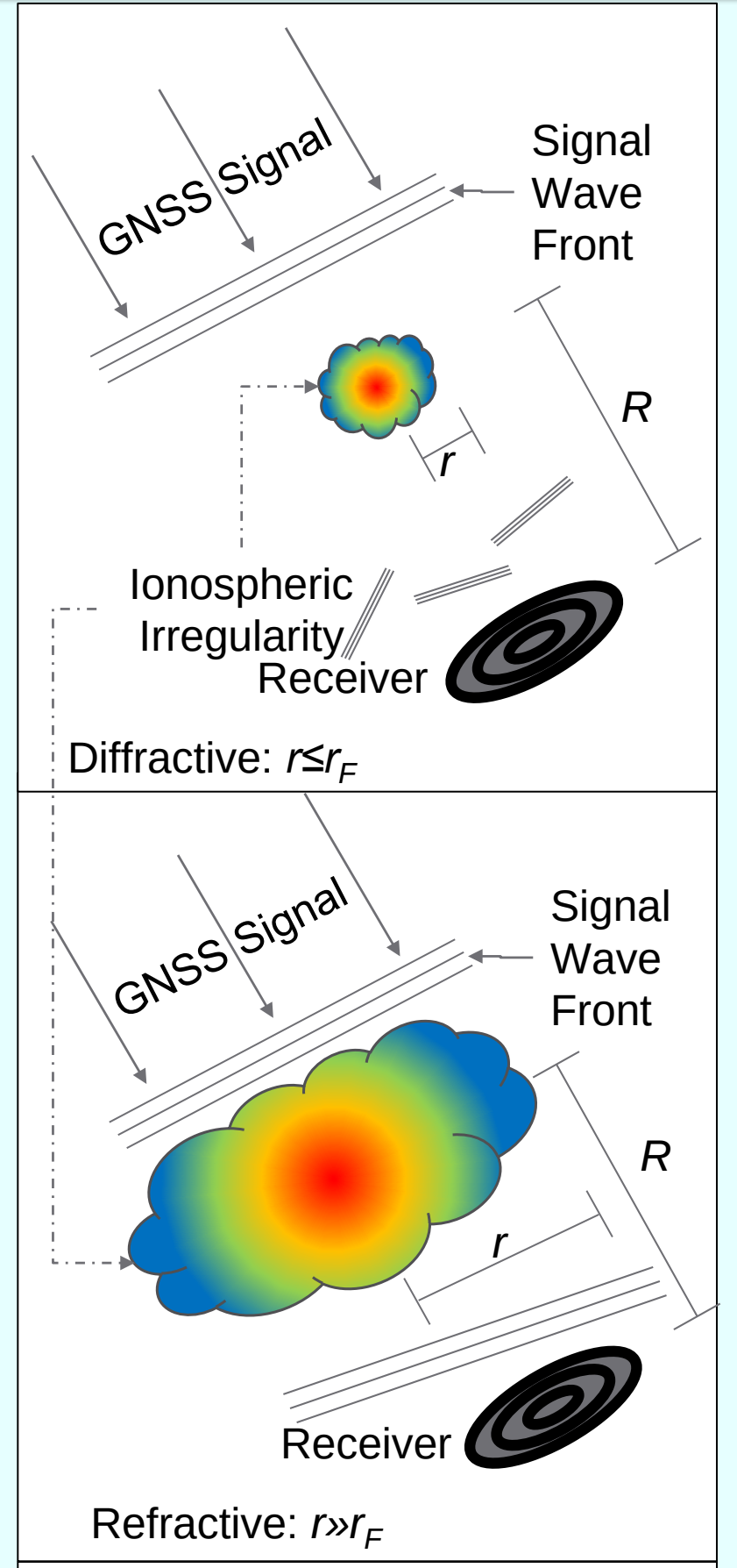
- GPS slant TEC derived from ground receivers, radio occultation, topside and beacon measurements
- IRI2012 background model



An example is shown at right with vertical slices along PFISR's lat/lon and a horizontal slice at an altitude of 350 km.

GPS Scintillation

Scintillation results from rapid variations in phase and/or amplitude of a signal at the receiver. Regions of increased electron density vary in size and the signals diffract around or refract through them. The cutoff between the two is determined by the Fresnel radius (r_F), depicted in the figures at right. A table of representative GPS frequencies and their associated Fresnel radii at 350km altitude is shown below.



GPS Civil Frequencies & Signals			
Carrier Label	Frequency [MHz]	Wavelength [m]	Fresnel Length [m]
L1	1575.42	~0.19	~365
L2	1227.60	~0.24	~413
L5	1176.45	~0.25	~422

Amplitude and phase scintillation are measured by the S_4 and phase scintillation (σ_Φ) indices, respectively. These are defined as shown at right. A variety of cutoffs for scintillation events exist across the literature. For this research, a scintillation event is defined as $\sigma_\Phi \geq 0.2$ cycles. In the high-latitudes, phase scintillation primarily dominates, even though amplitude scintillation has been known to occur. The S_4 index was not evaluated as part of this study.

Phase
σ_ϕ (100Hz)

- ***L3 = Geometry Free Observable***
- $\phi_i = \frac{\phi_g^{t_i} - \phi_g^{t_{i-1}}}{t_i - t_{i-1}}$
- $\sigma_\phi = \sqrt{\frac{1}{n}\sum(\bar{\phi} - \phi_i)^2}$

Amplitude
S_4

- **'…square root of normalized variance of signal intensity during a given time interval:'**
- $S_4 = \sqrt{\frac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2}}$