

Analysis and Modeling of Mid-Latitude Decameter-Scale Plasma Wave Irregularities Utilizing GPS and Radar Observations

A. Eltrass¹, W. A. Scales¹, J. Erickson², J. M. Ruohoniemi¹, J. B. H. Baker¹

¹Virginia Tech, USA.

²MIT Haystack Observatory, USA.

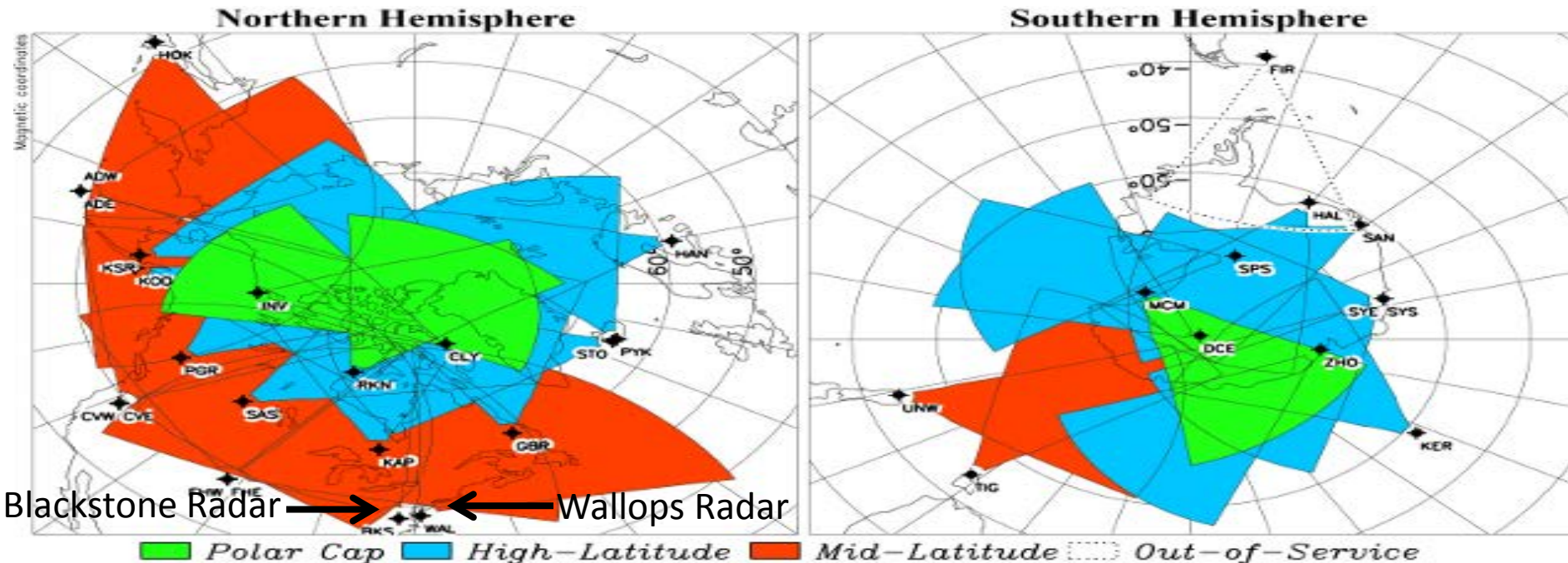
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Outline

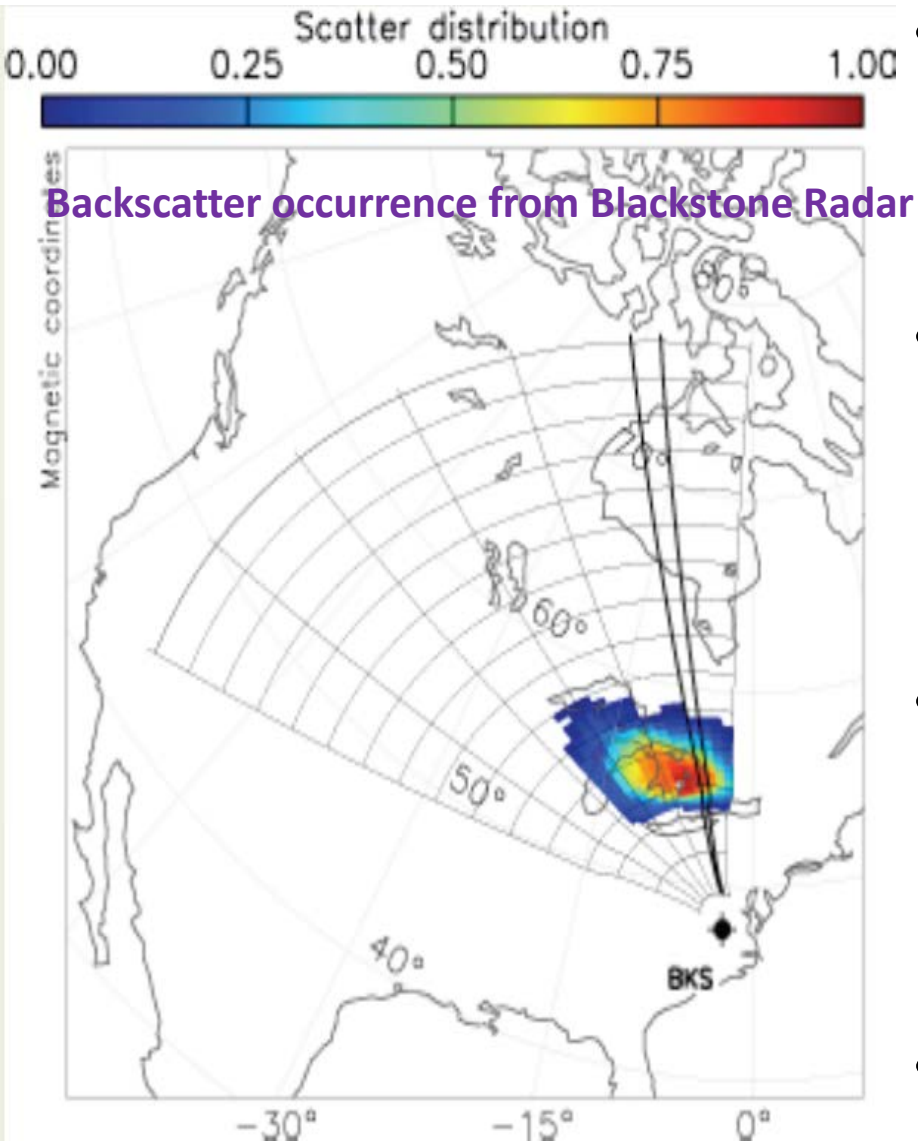
- Introduction
- Mid-Latitude Plasma Instabilities
- Experimental Radar Observations
- Computational Modeling
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Introduction

- Ionospheric irregularities are small-scale structures in the ionospheric plasma density caused by plasma instability processes. Their scale sizes range from thousands of kilometers down to a few centimeters.
- **SuperDARN** is a chain of HF radars that look into the Earth's upper atmosphere beginning at mid-latitudes and ending at the polar regions through the observation of decameter-scale ionospheric irregularities in the E- and F-regions.
- **Research Areas Advanced by SuperDARN:**
Plasma instabilities and turbulence, Plasma motion in the ionosphere, coupling to the magnetosphere and solar wind, Space Weather,.....etc.



Mid-Latitude Ionospheric Irregularities

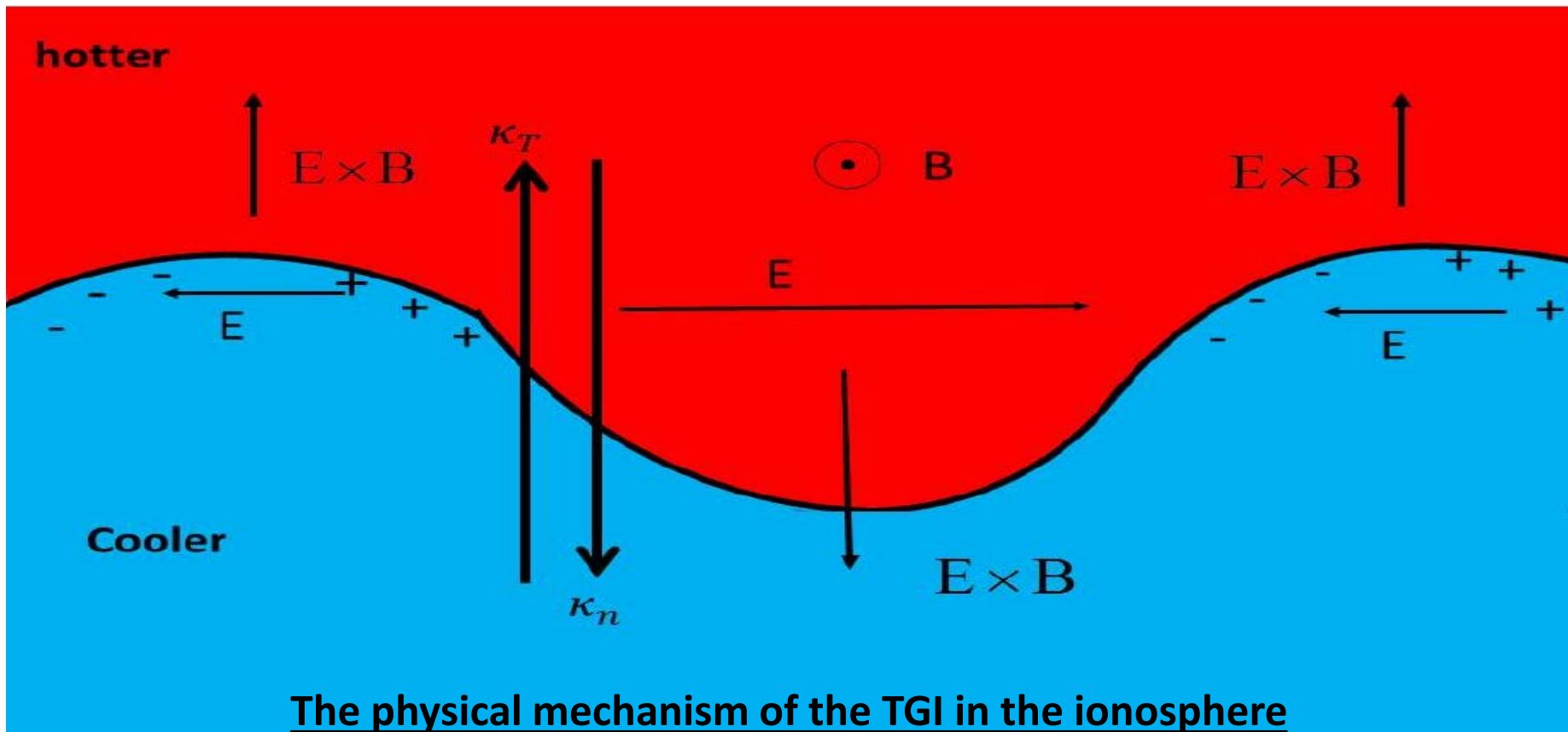


- Recent studies reveal that the mid-latitude region is more complicated than previously thought, as it includes many different scales of wave-like structures.
- The mid-latitude SuperDARN radars frequently observe decameter-scale irregularities in the nightside sub-auroral ionosphere during quiet and disturbed geomagnetic periods.
- Despite their high occurrence rate and large geographical spread, **the plasma instability mechanism responsible for the growth of these irregularities is still largely unknown.**
- Kintner et al. [2007] and Keskinen et al. [2004] suggested that the **TGI** in association with the **GDI** could be responsible for generating the mid-latitude irregularities that cause **GPS scintillations**.

Temperature Gradient Instability (TGI)

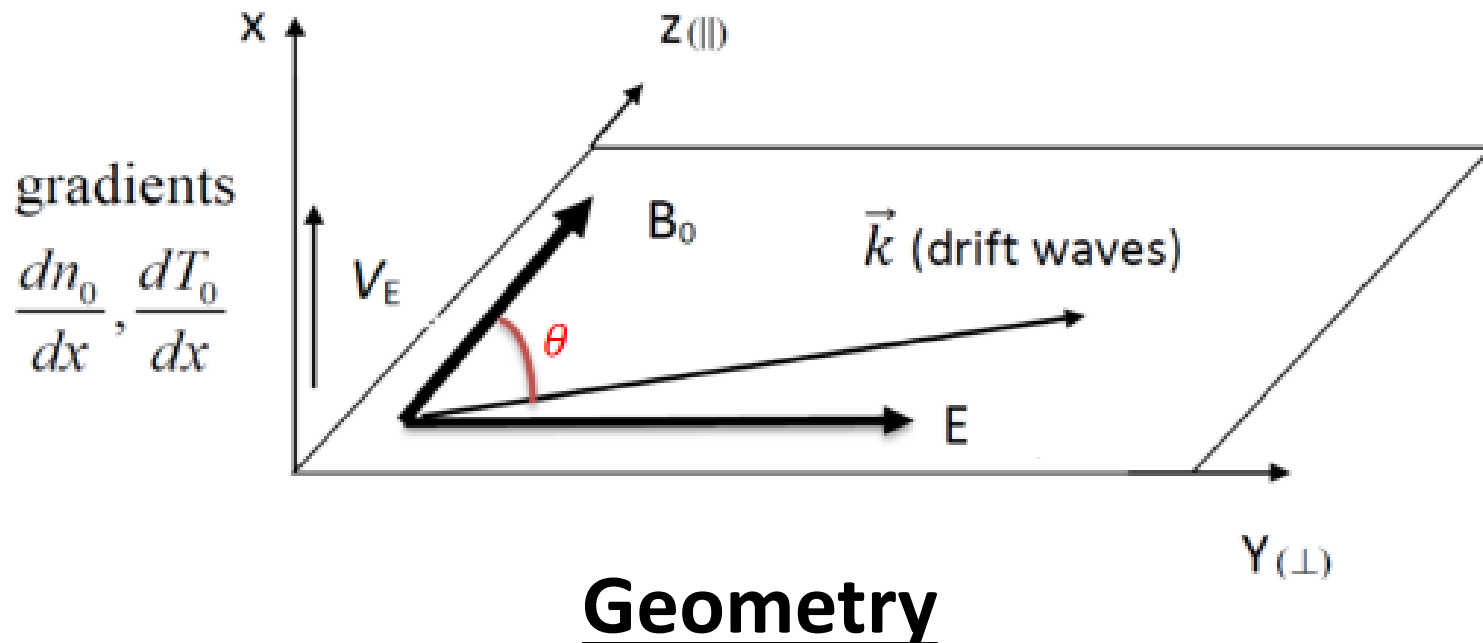
(Eltrass et al., JGR, 2014)

- The TGI is a form of universal instability and an example of collisional drift wave instabilities.
- The TGI is generated in plasmas with opposed temperature and density gradients in the F-region in the plane perpendicular to the magnetic field.
- The TGI may exist at either long wavelengths ($\lambda \gg 15\text{m}$) or short wavelengths ($\lambda \leq 15\text{m}$).

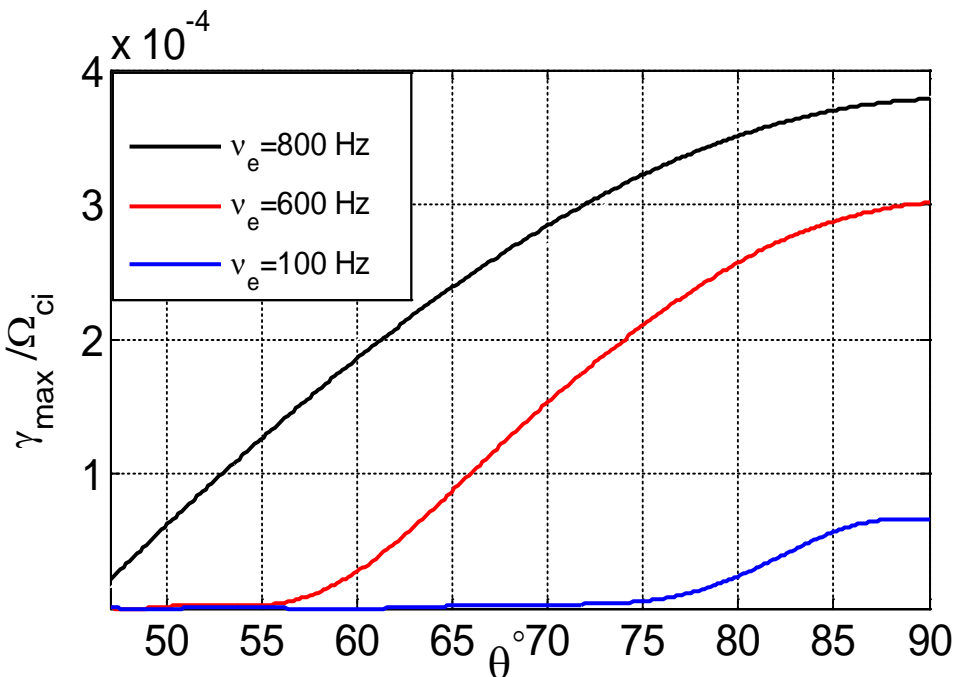
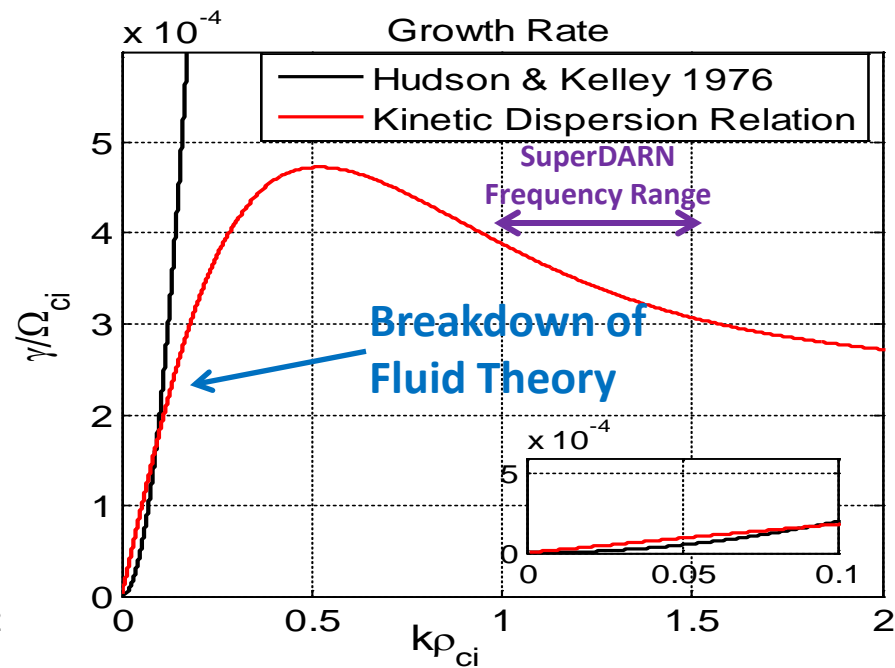
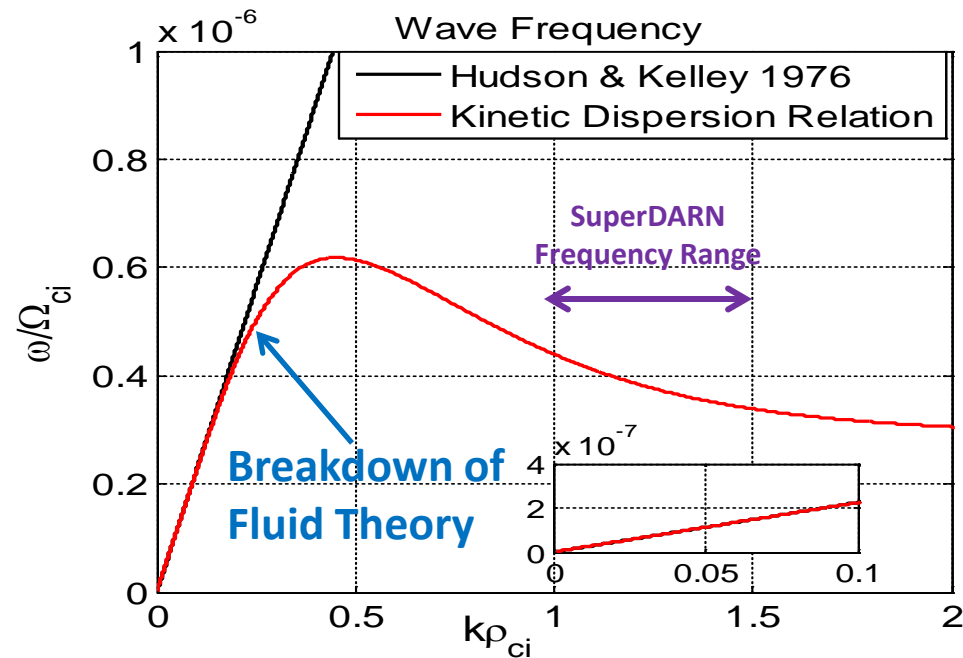


TGI Linear Kinetic Theory

- This is an extension of past work of the magnetospheric fluid model of Hudson and Kelley [1976] appropriate for long wavelengths ($\lambda \gg 15\text{m}$).
- The observations discussed in this work examine wavelengths of around 10-15 m, which is where kinetic effects begin to play a role and the fluid theory loses validity. Hence, in this regime a kinetic model is required.
- The TGI electrostatic dispersion relation has been extended for the first time into the kinetic regime appropriate for SuperDARN radar frequencies by including Landau damping, finite gyro-radius effects, and electron collisions.



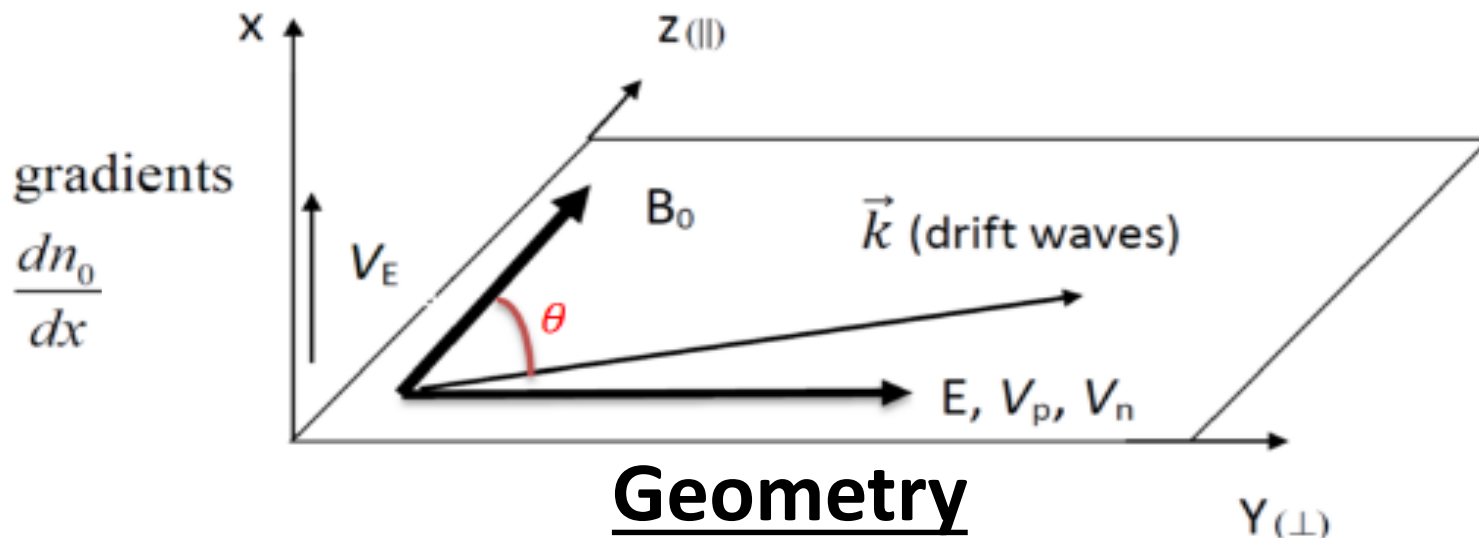
Parametric Investigation of TGI at Altitude 300 km



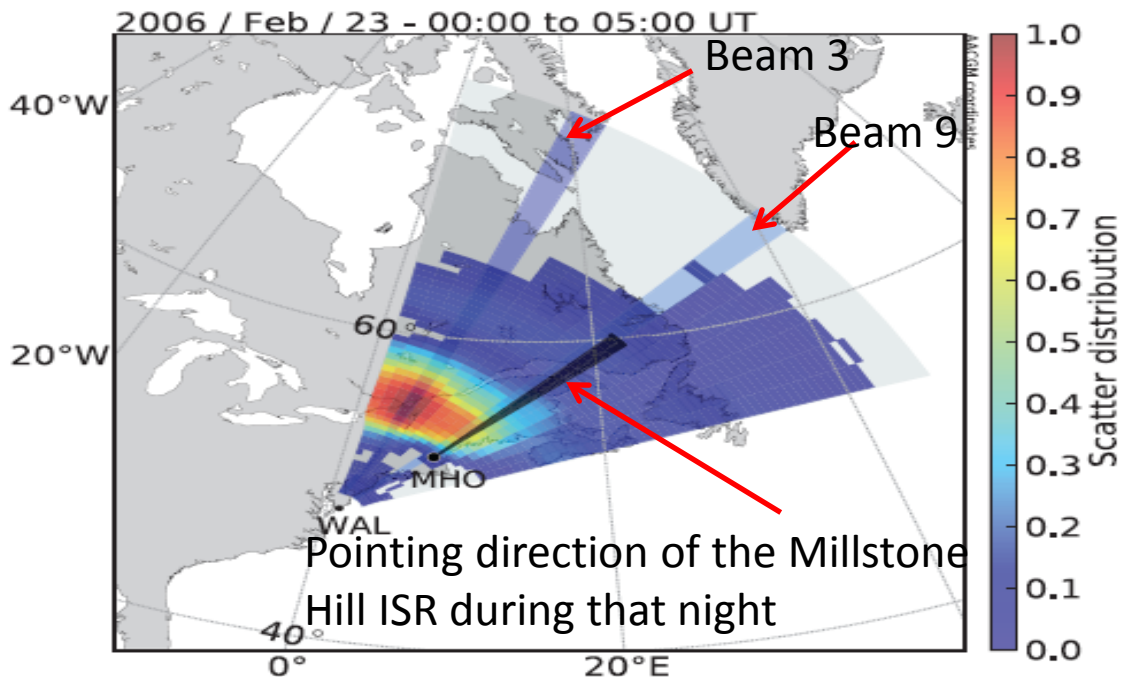
- The results of both fluid and kinetic theories have reasonable agreement for long wavelengths $k_{\perp}\rho_{ci} \ll 1$ ($\lambda \gg 15\text{m}$). However, the fluid theory breaks down for short wavelengths $k_{\perp}\rho_{ci} \geq 1$ ($\lambda \leq 15\text{m}$).
- It can be noted that the TGI resistive drift waves can propagate at a relatively large angle off-perpendicular to the magnetic field and contribute to the irregularities.

Gradient Drift Instability (GDI)

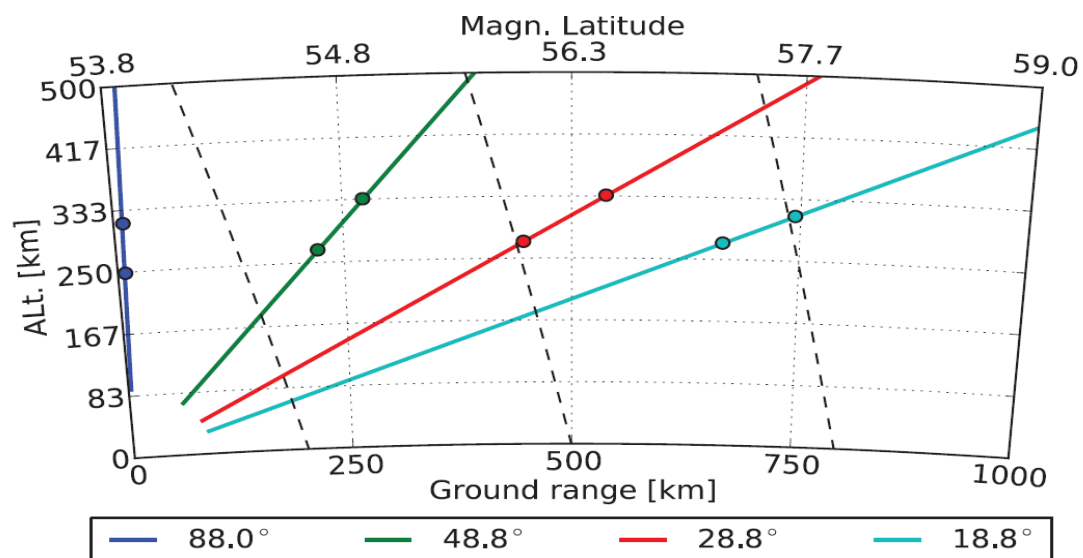
- The GDI is driven by Pederson and density drifts in a collisional plasma and is thought to be an important mechanism for generating high-latitude ionospheric irregularities at decameter-scales.
- When a force acts on a volume of plasma with density enhancement and a disturbance occurs, a charge separation can take place causing a small polarization electric field which, due to the presence of a magnetic field, increases the disturbance, thus producing the instability.
- Previous theoretical studies have considered the generation of GDI irregularities in the F-region for large-scale (>1 km in wavelength) but there are no sufficient details about the generation of GDI at small spatial scales [Kelley, 2009].



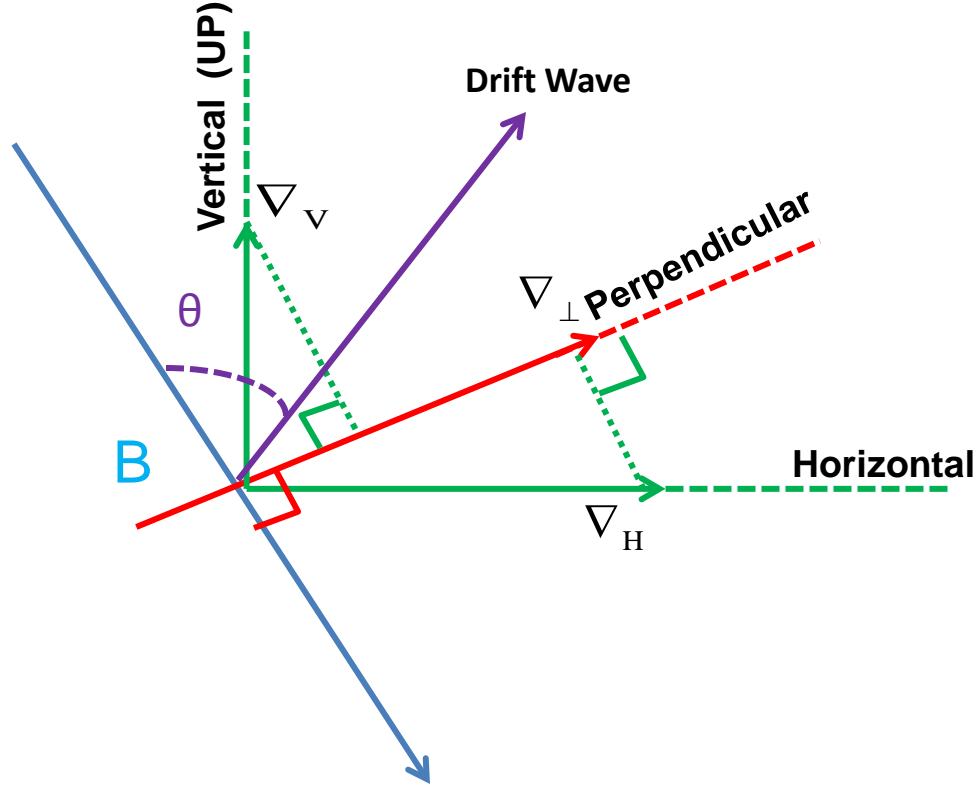
Experimental Radar Observations



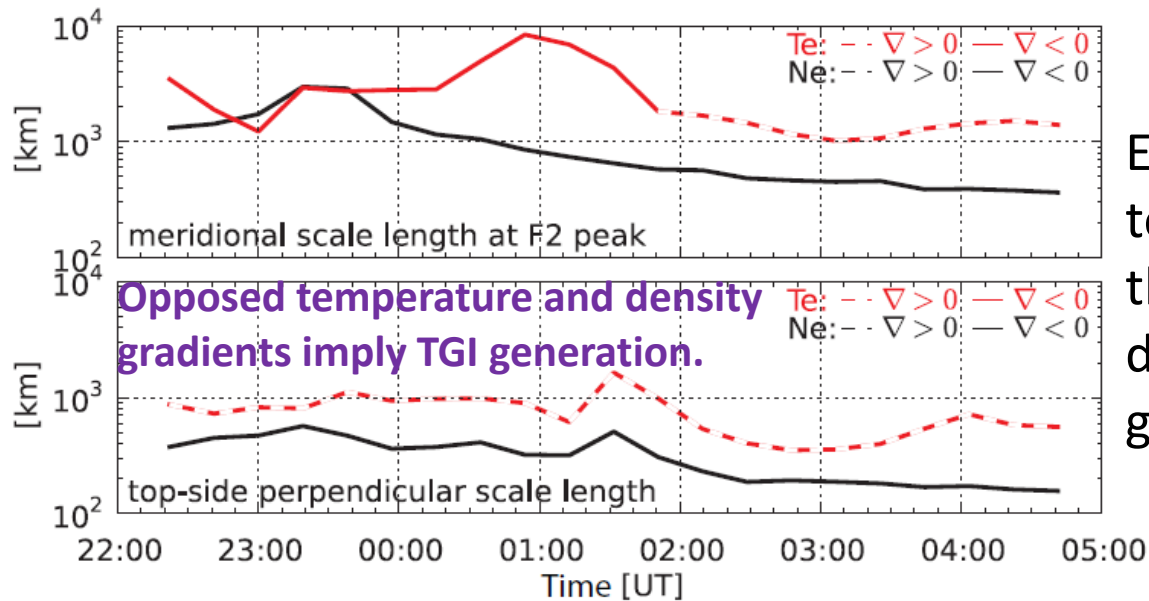
SuperDARN backscatter distribution between 00:00 and 05:00 UT on the night of February 22-23, 2006. Beams 3 and 9 of the Wallops (WAL) SuperDARN radar.



Millstone Hill pointing directions during the February 22-23, 2006 experiment. The colored dots with black edges represent the extreme positions of hmF2 (The F2 layer peak).

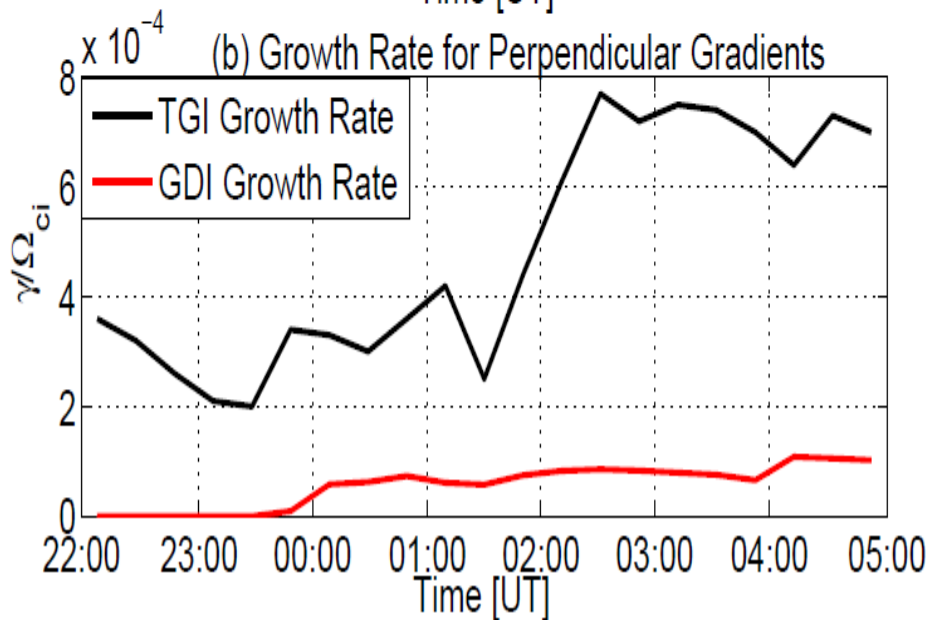
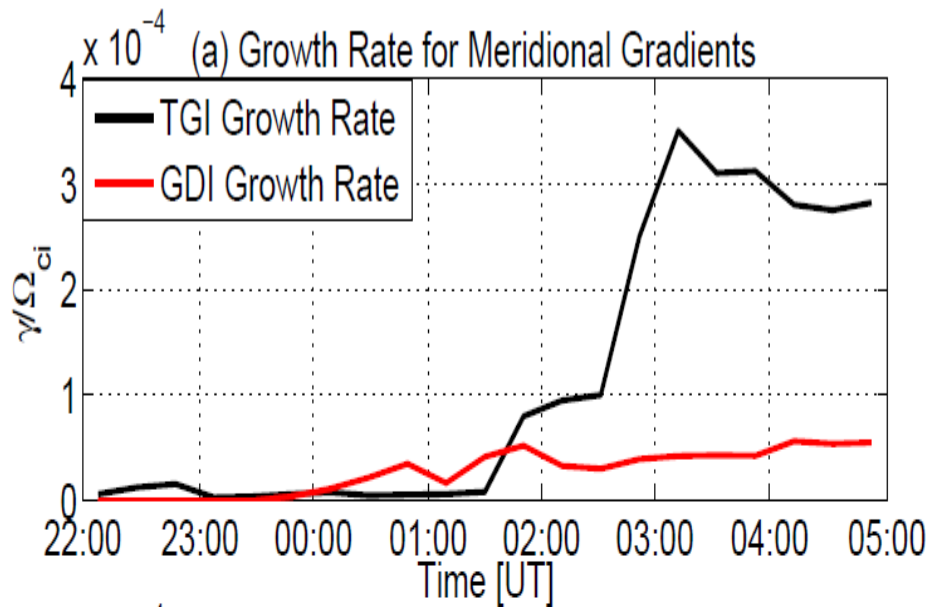


The TGI and GDI geometry in the mid-latitude ionosphere. The perpendicular temperature and density gradients are calculated as the sum of the projections of the horizontal and vertical gradients (∇_H and ∇_V , respectively).

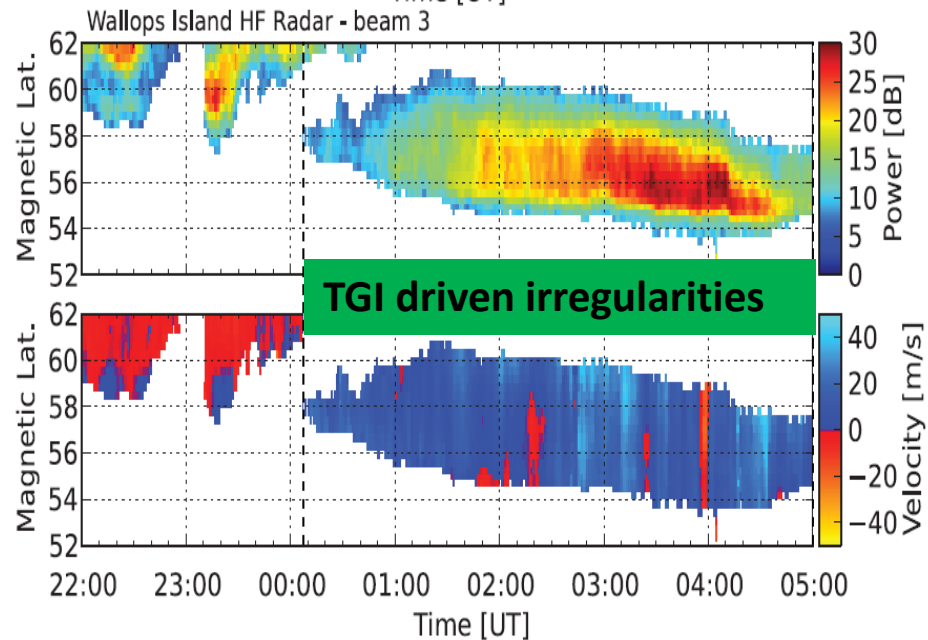
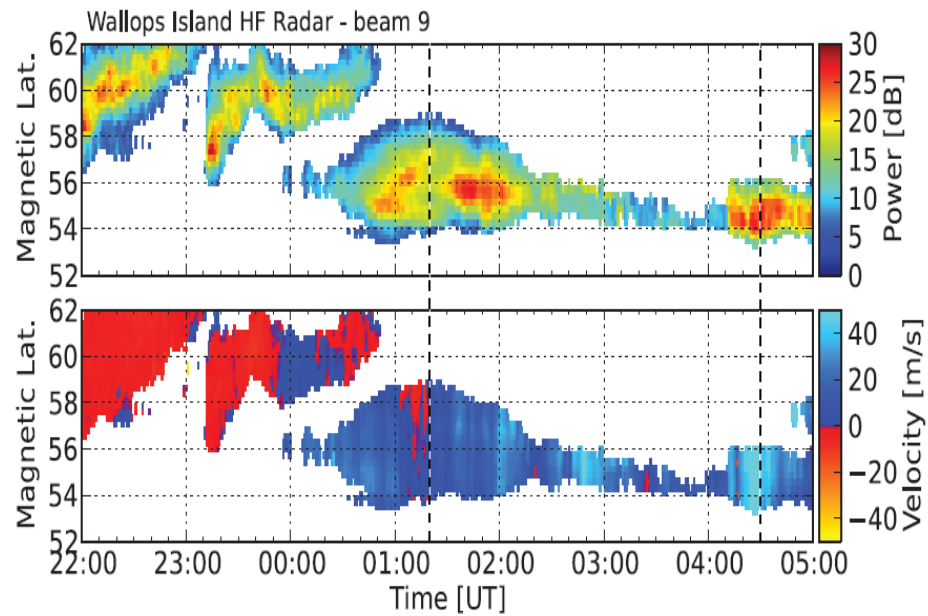


Electron density and electron temperature scale lengths along the meridional direction, and the direction perpendicular to the geomagnetic field B .

Opposed temperature and density gradients imply TGI generation.



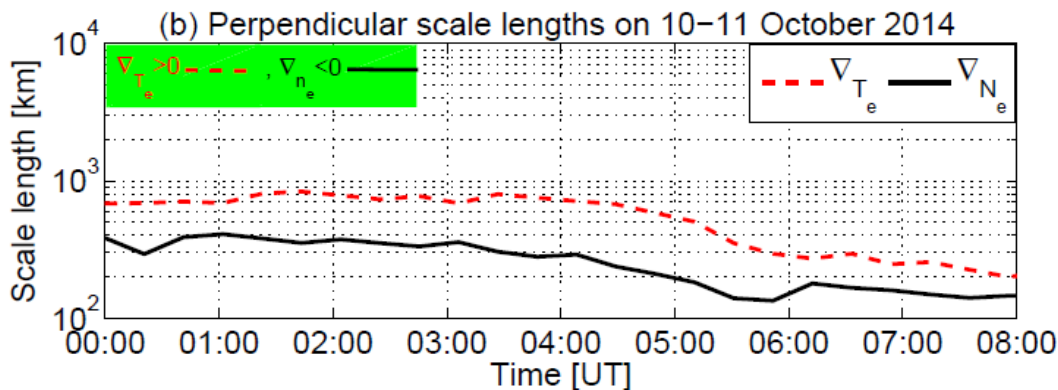
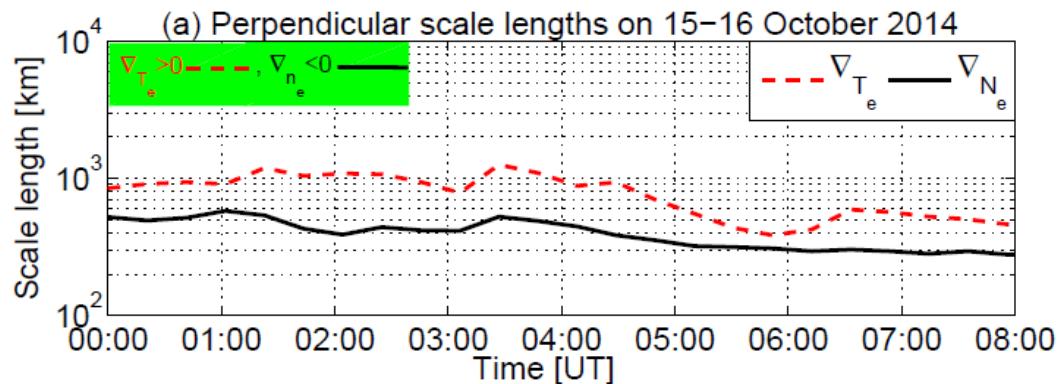
The time series of TGI and GDI growth rates for (a) meridional, (b) and perpendicular scale lengths.



Backscatter observed by the Wallops SuperDARN radar on 22-23 February 2006 from 22:00 to 05:00 UT in beams 9 and 3.

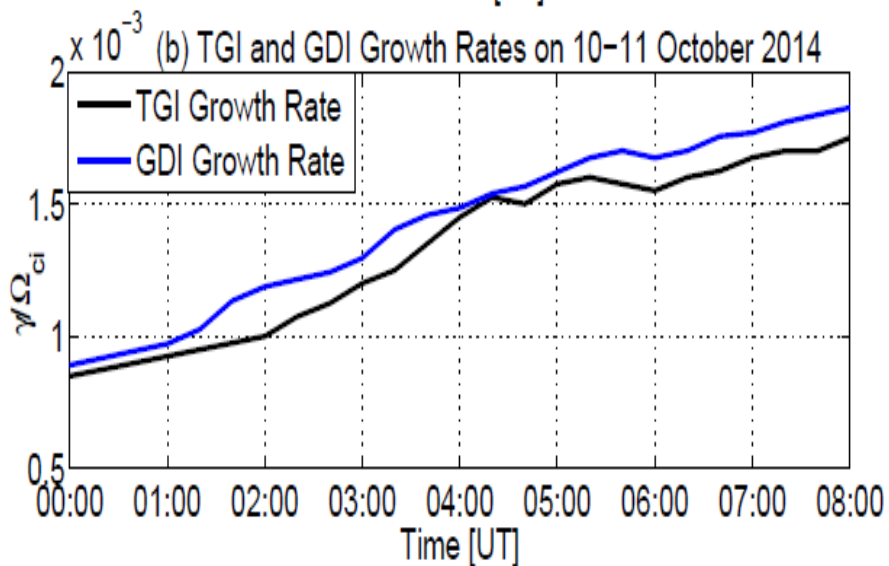
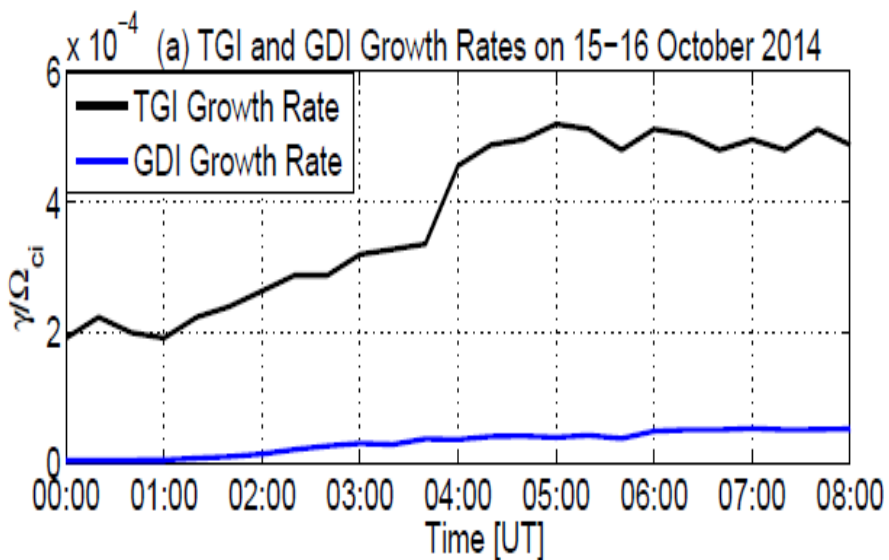
Quiet and Disturbed Time Plasma Wave Irregularities

- The disturbed-time ionospheric irregularities at mid-latitudes are sufficiently strong to cause signal power fluctuations in transionospheric satellite transmissions such as the GPS.
- The quiet- and disturbed-times plasma wave irregularities are compared by investigating co-located experimental observations by Blackstone SuperDARN radar, and the Millstone Hill ISR under various sets of geomagnetic conditions.

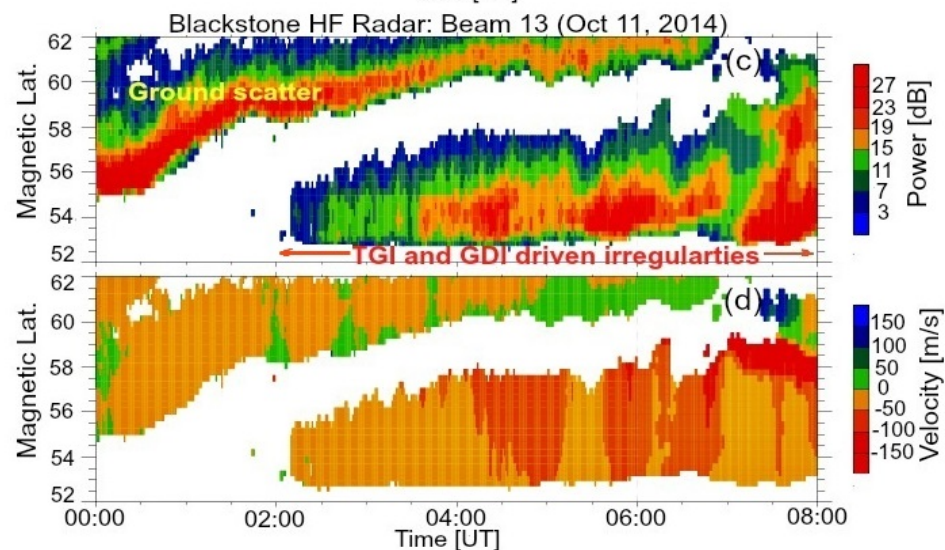
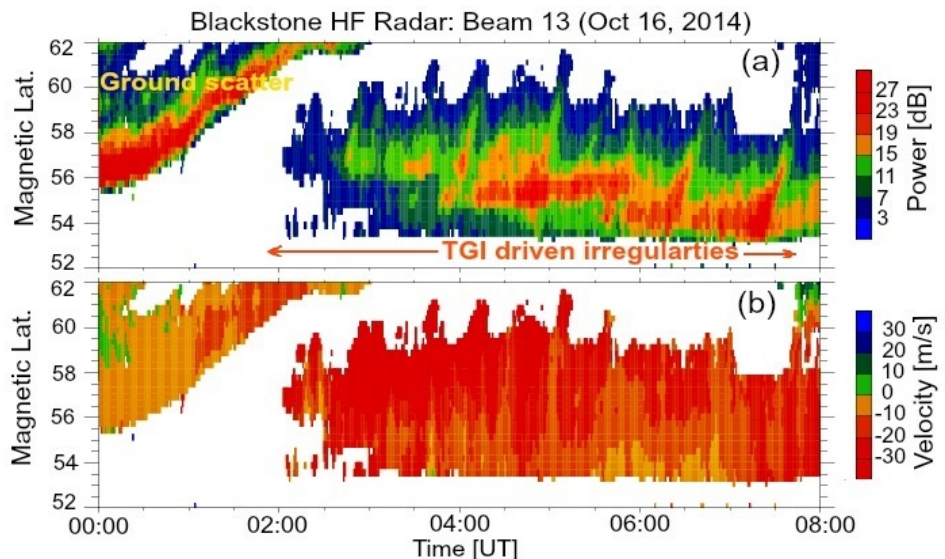


Electron density and electron temperature scale lengths along the direction perpendicular to the geomagnetic field B during the nights of (a) October 15-16 (quiet-time) and (b) October 10-11 (disturbed-time), 2014.

Quiet and Disturbed Time Growth Rate Comparison



The time series of TGI and GDI growth rates on the nights of (a) October 15-16 and (b) October 10-11, 2014.



Backscatter power and line-of-sight Doppler velocity measured along beam 13 of the Blackstone radar during the two events.

Computational Modeling

- While linear theory predicts the dominant wavelengths, it cannot fully describe the nonlinearly saturated behavior as observed by radars.
- Such nonlinear evolution, e.g., wave cascading, is most likely critical for ultimately determining the scale size of the irregularities observed by the radar observations.
- The physics associated with plasma instabilities can most effectively be investigated with plasma simulation models

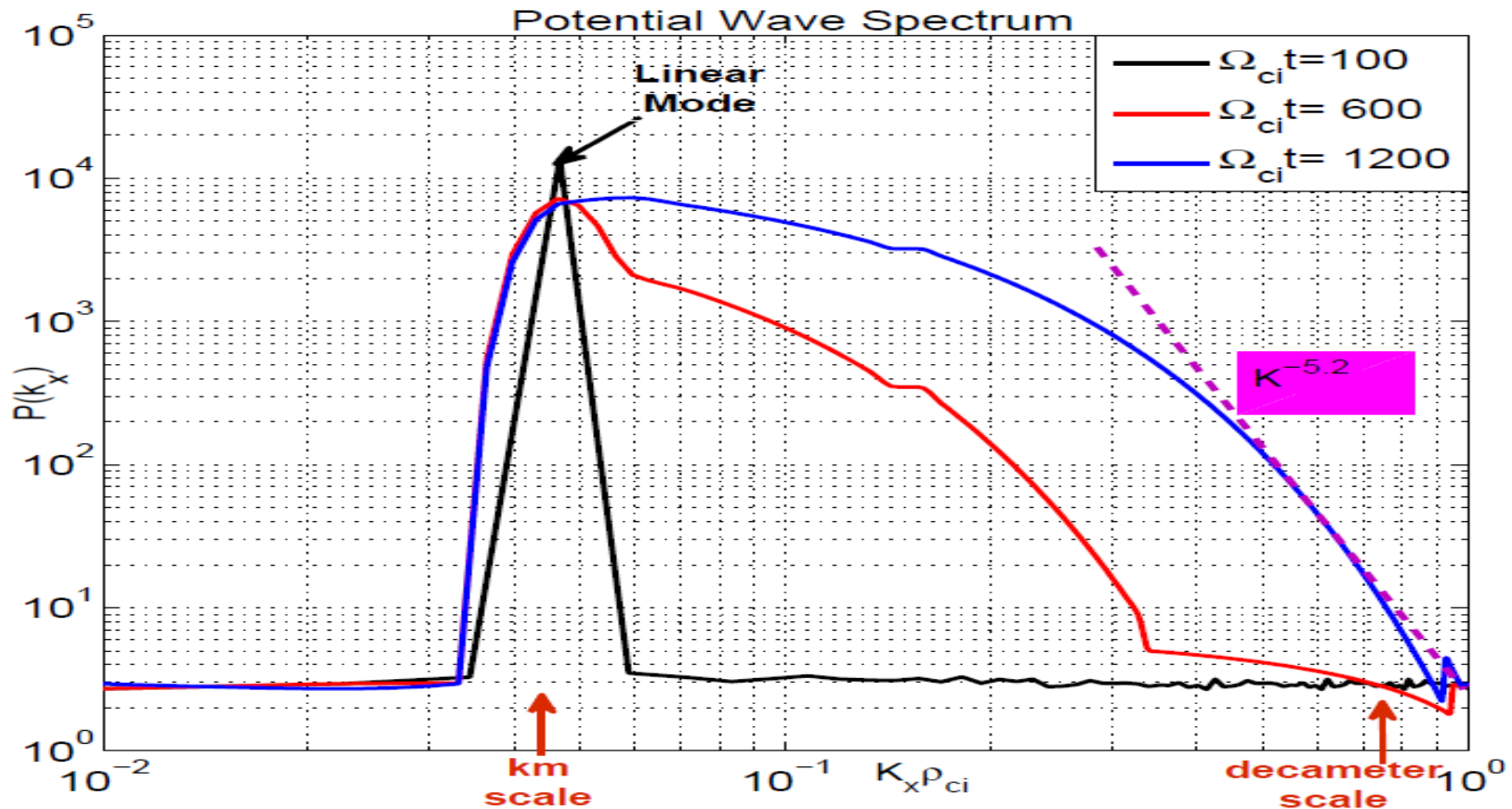
Gyro-kinetic Approach in Plasma Simulation

- Designed for investigating nonlinear kinetic effects associated with drift wave instabilities.
- Contains the nonlinearities corresponding to F-region irregularities.
- Appropriate for shallow density gradients (SuperDARN observations).
- Incorporates diamagnetic drifts (from both temperature and density gradients) to simulate replenishing gradients.
- This reflects the realistic experimental situation for SuperDARN observations, where the density and temperature gradients, which drive the TGI, tend to persist as a quasi-static profiles caused by the continuous replenishment of the plasma.

Simulation Results

(Eltrass and Scales, JGR, 2014)

- The spatial power spectra of the electrostatic potential and density fluctuations associated with the TGI are computed and found to be 5.2 ± 0.3 and 2.3 ± 0.2 , respectively.
- The wave number spectrum shows that the observed ionospheric irregularities by SuperDARN may be produced by turbulent cascade from km-scale primary TGI irregularity structures down to the observed decameter-scale irregularities (consistent with experimental results).

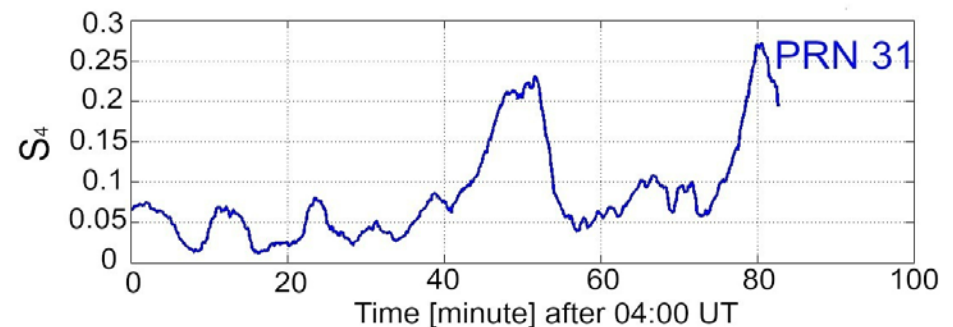
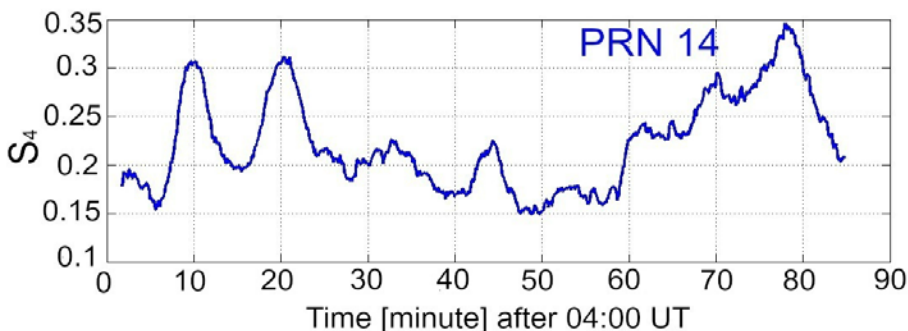
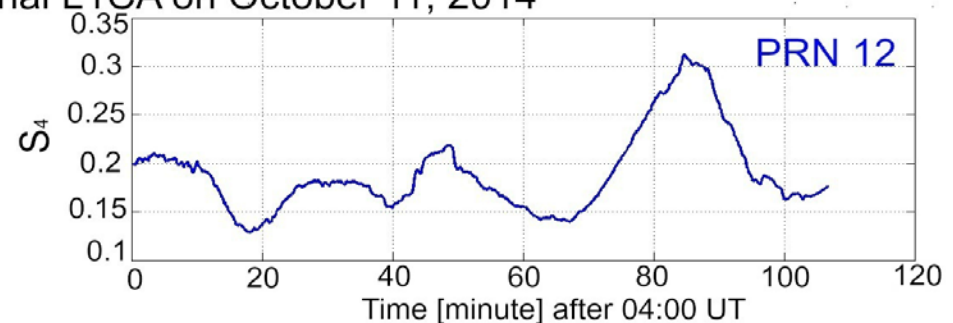
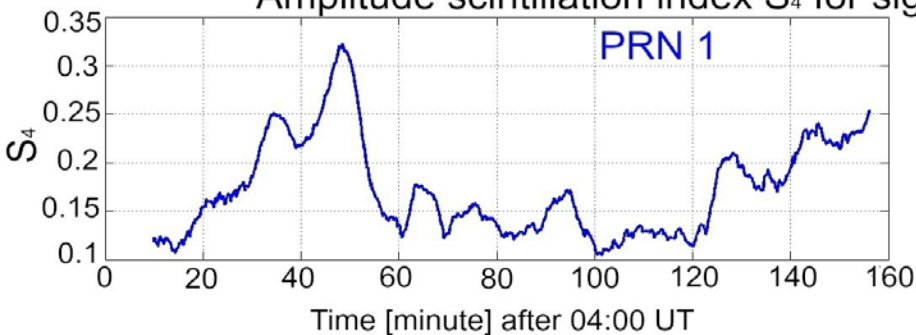


Potential Impact of Mid-Latitude Irregularities on GPS Signals

Scintillation Measurements

- The recorded GPS scintillation data are analyzed to monitor the amplitude and phase fluctuations of the GPS signals at mid-latitudes .
- During the night of 10-11 October, S_4 indices reached a peak value of approximately 0.35, indicating a scintillation activity.
- For some nights with $K_p = 5$ or more, S_4 indices reached values up to ~ 0.6 , revealing a strong scintillation activity.

Amplitude scintillation index S_4 for signal L1CA on October 11, 2014



Spectral Density Measurements at Mid-Latitudes

- As the radio signals pass through ionospheric irregularities, the spatial pattern of varying intensity is converted into temporal fluctuations or scintillations and recorded by the ground GPS receiver.

- The phase scintillation spectrum on ground can be expressed as [Rino, 1979a]:

$$S_{\varphi}(f) = Tf^{-p}$$

where T is the spectral strength of the PSD at 1 Hz, and p is the ground spectral index.

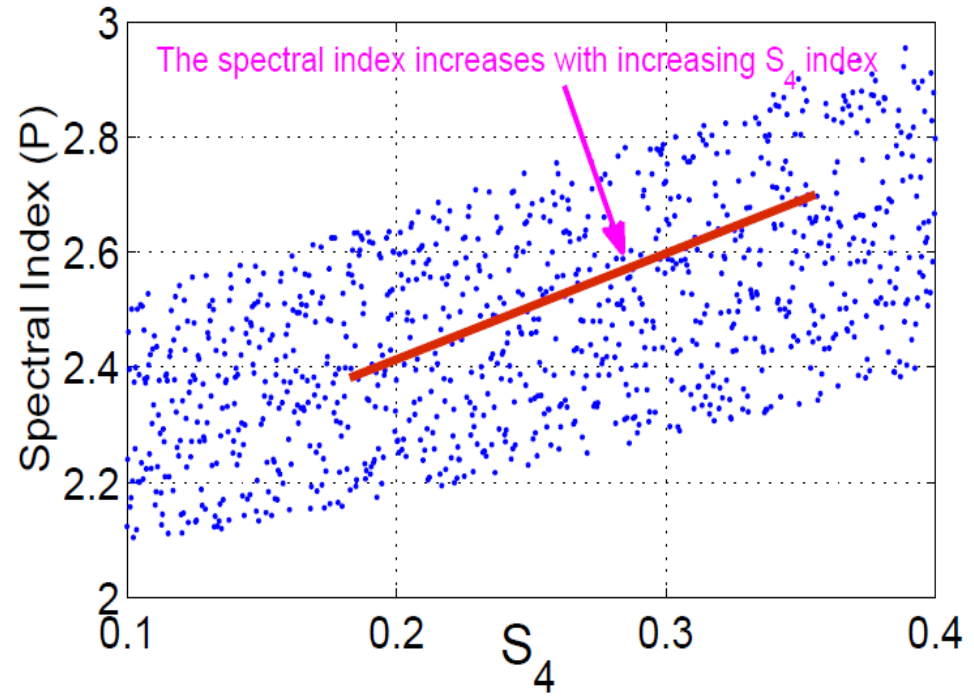
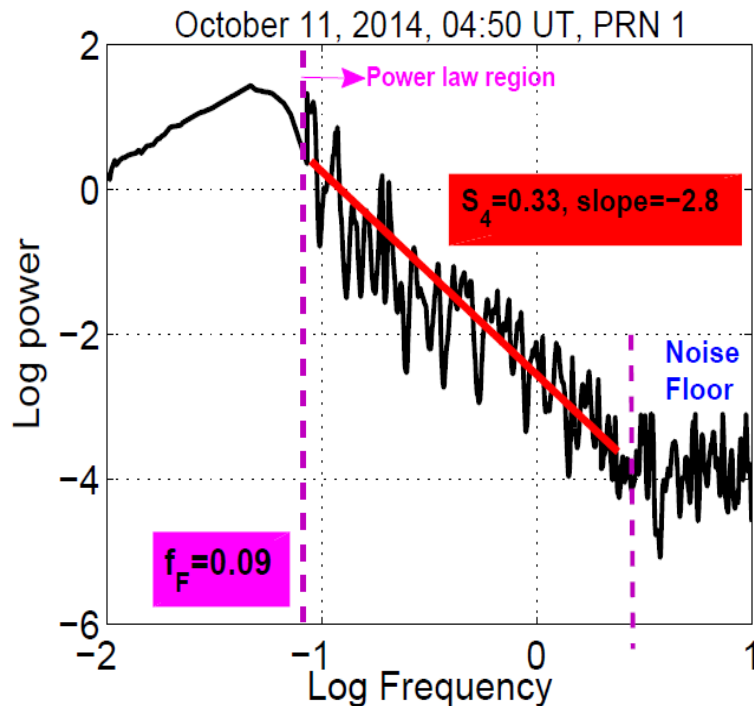
- The GPS ground power spectrum of radio waves scintillation can be related to the in-situ spatial spectrum of ionospheric irregularities by $n = p - 1$ [e.g., Bhattacharyya and Rastogi, 1985, 1991], where n is the in-situ irregularity spectral index.
- The amplitude scintillation spectrum follows the same relationship as the phase, however, it is attenuated after a cut-off frequency, known as the Fresnel frequency.

$$f_F = \frac{V_{rel}}{r_F} = \frac{V_{rel}}{\sqrt{2\lambda r}}$$

- Wernik et al. [1997] reported that the spectra of electron density fluctuations obey the power law quite well at high frequencies for weak to moderate scintillation.

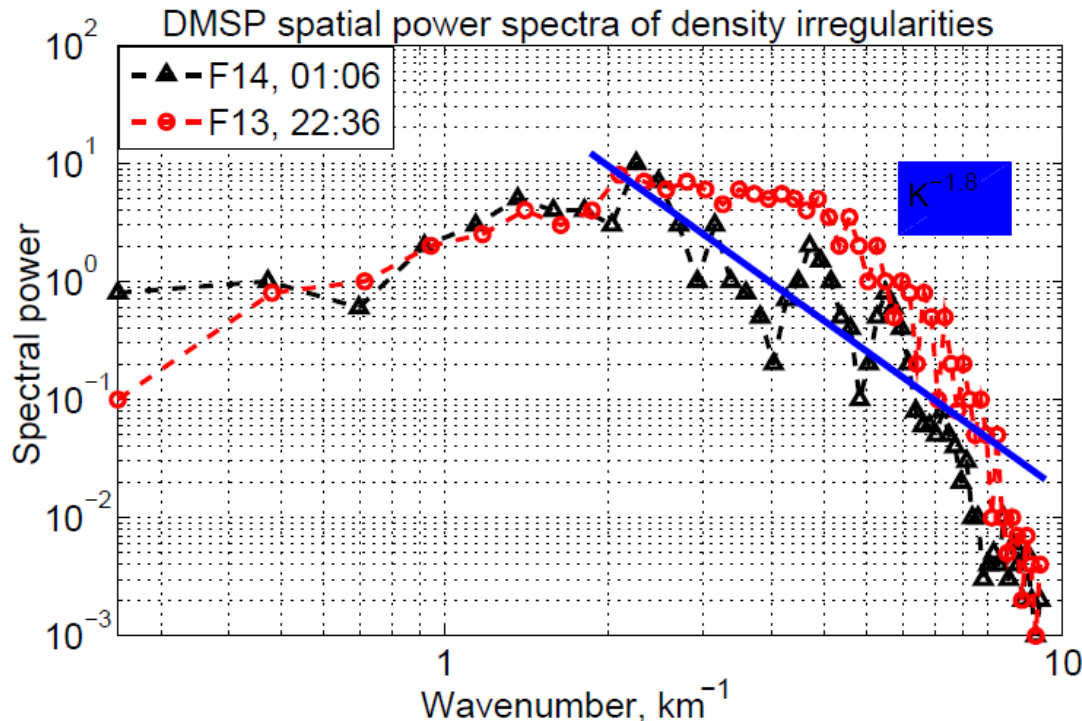
GPS Spectral Measurements

- The power spectra of amplitude scintillation at 04:50 UT on October 11, 2014 is computed to obtain the GPS spectral index.
- The GPS power spectral index for the irregularities is calculated and found to be 2.8.
- The GPS spectral index (p) is approximately related to the irregularity spectral index of TGI and GDI simulations (n) by $n = p - 1$.
- The statistical results indicate that the spectral index increases with S_4 indices for weak to moderate scintillation ($0.1 < S_4 \leq 0.4$).



Satellite In-Situ Spectral Measurements

- The satellite in-situ measurements of electron density fluctuations provide direct information about the structure of ionospheric irregularities that may cause scintillation of radio waves on transionospheric links.
- Using DMSP satellite data, Mishin and Blaunstein [2008] calculated the power spectral densities of mid-latitude irregularities as a function of spatial wave number during scintillation intervals on 26 September 2001.
- They showed that the power spectra of the density irregularities for scale sizes less than 1 km admit a power law characterization k^{-n} with a spectral index $n \sim 1.7-2$



The power spectra for the DMSP F13-14 measurements of density irregularities on 26 September 2001 [After Mishin and Blaunstein, 2008].

Summary and Conclusions

- This work has investigated the TGI and GDI as the cause of mid-latitude decameter-scale ionospheric irregularities during quiet and disturbed geomagnetic conditions by analyzing co-located observations by Blackstone SuperDARN radar, and the Millstone Hill ISR.
- The simulation results show wave cascading of TGI from kilometer scales into the decameter-scale regime of the radar observations.
- The spectra calculations of TGI lie in the same range of GDI numerical simulations, showing that the spectral index of TGI and GDI density irregularities are of the order 2.
- Both simulation results and GPS spectral analysis are consistent with previous in-situ satellite measurements during disturbed periods, showing that the spectral index of mid-latitude density irregularities are of the order 2.
- An interpretation of the spectral analysis is that TGI and GDI irregularities are initially generated at kilometer-scale, become unstable and dissipate their energy by generating smaller sized (decameter-scale) irregularities.
- The GPS scintillation results along with radar observations suggest that the observed decameter-scale irregularities that cause SuperDARN backscatter, co-exist with kilometer-scale irregularities that cause L-band scintillations.
- The reasonable agreement between experimental and computational results of this study suggests that **turbulent cascade processes of both TGI and GDI** may be responsible for the disturbed-time irregularities that cause GPS scintillations.