GPS and Radar Data Analysis of Midlatitude Ionospheric Plasma Wave Irregularities

W. A. Scales*, A. Eltrass†, J. M. Ruohoniemi*, J. B. H. Baker*, and P. J. Erickson‡
*The Bradley Department of Electrical and Computer Engineering
Virginia Tech, Virginia, USA
†The Department of Electrical Engineering
Faculty of Engineering, Alexandria University, Alexandria, Egypt
‡Haystack Observatory
Massachusetts Institute of Technology, Westford, Massachusetts, USA

***Abstract*—Recent studies reveal that midlatitude ionospheric irregularities are less understood due to lack of models and observations that can explain the characteristics of the observed wave structures. In this paper, the Temperature Gradient Instability (TGI) and the Gradient Drift Instability (GDI) are analyzed as the cause of the midlatitude irregularities. Based on co-located experimental observations by the Blackstone SuperDARN radar and the Millstone Hill Incoherent Scatter Radar (ISR), a time series for the growth rate of both TGI and GDI is calculated for observations in the sub-auroral ionosphere. Multiple GPS data sets are recorded and analyzed to monitor the amplitude scintillations and to obtain the spectral characteristics of irregularities producing ionospheric scintillations. The GPS spectral indices of the spectra observed on the ground are computed and found to be consistent with both TGI and GDI simulations and previous in-situ satellite measurements during disturbed periods. The alignment between experimental, theoretical, and computational results of this study suggests that turbulent cascade processes of TGI and GDI may cause the midlatitude GPS scintillations during disturbed times.**

I. INTRODUCTION

Ionospheric irregularities are small-scale structures in the plasma density created by various plasma instabilities. The storm-time ionospheric irregularities at midlatitudes are sufficiently strong to cause signal power fluctuations, known as ionospheric scintillation, in transionospheric satellite transmissions such as the Global Position System (GPS) [1]. This raises the importance of knowing the cause and distribution of these ionospheric plasma irregularities to maintain the performance of satellite-ground data transmission. The midlatitude Super Dual Auroral Radar Network (SuperDARN) radars frequently observe decameter-scale irregularities in the nightside sub-auroral ionosphere, however, the mechanism responsible for the growth of such irregularities has not yet been established. Although the Temperature Gradient Instability (TGI) and the Gradient Drift Instability (GDI) are strong candidates for generating the observed midlatitude irregularities, the exact role of these plasma instabilities in generating the sub-auroral irregularities is still unknown.

The aim of this work is to model and analyze the observed ionospheric structures at midlatitudes through the coordination between the SuperDARN HF radars, Incoherent Scatter Radars (ISRs), and GPS receivers under various sets of geomagnetic conditions. This can be achieved by determining the role of the TGI and GDI in the generation of these ionospheric irregularities. Also, the potential impact of the midlatitude ionospheric irregularities on GPS signals is investigated utilizing modeling and observations.

II. THEORY AND COMPUTATIONAL MODELING

The TGI derives its free energy from the opposed temperature and density gradients in the F-region in the plane perpendicular to the magnetic field [2]. The TGI kinetic electrostatic dispersion relation has been solved with full kinetic effects for Landau damping, finite gyro-radius, temperature anisotropy, and electron collisions [3]. The TGI wave frequency and growth rate are calculated at 300 km altitude in a region of opposed temperature and density gradients relevant to SuperDARN observations. The GDI is an interchange instability process that is known to cause irregularities in the F-region ionosphere [4]. The GDI kinetic dispersion relation based on [4] is used here to allow the study of GDI for short wavelengths (decameter-scale waves of SuperDARN observations).

The nonlinear evolution of the TGI is investigated utilizing gyro-kinetic Particle-In-Cell (PIC) simulation techniques with Monte Carlo collisions [2]. The spatial power spectra of the density fluctuations associated with the TGI are computed and the 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 the previous numerical simulations of GDI [5], showing that the spectral indices of TGI and GDI density irregularities are of the order 2.

III. EXPERIMENTAL RADAR OBSERVATIONS

During the night of 10-11 October 2014 (active geomagnetic conditions with $3 < K_p \leq 4$), the Blackstone SuperDARN radar and Millstone Hill ISR were running colocated observations of sub-auroral ionospheric irregularities [6]. Figure 1 shows the backscatter power and line-of-sight Doppler velocity observed by the Blackstone SuperDARN radar along beam 13.

In order to determine the physical mechanisms responsible for the observed ionospheric irregularities during this event,

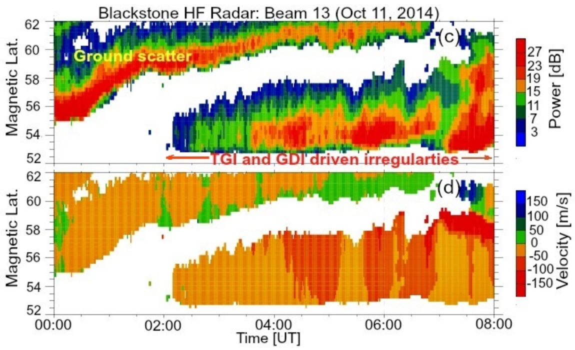

Fig. 1: Backscatter power and line-of-sight Doppler velocity measured along beam 13 of the Blackstone SuperDARN radar on the night of October 10-11, 2014.

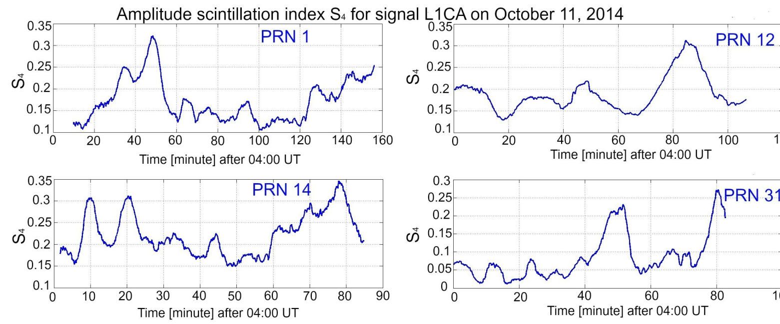

Fig. 2: S_4 measurements for four different GPS satellites in view during the night of 10-11 October 2014.

data from the Millstone Hill ISR are used. For this experiment, overhead measurements were obtained with the 68 m zenith-pointing antenna and oblique measurements were obtained with the 46 m steerable dish. The electron density and temperature gradients are calculated in the direction perpendicular to the magnetic field B in the topside F region by estimating the vertical gradients along the zenith direction and the horizontal gradients and adding the two projections in the direction perpendicular to B.

Millstone Hill and SuperDARN measurements provide all the information needed to calculate the TGI and GDI growth rates. The growth rate calculations are consistent with TGI and GDI driven irregularities during the event under consideration.

IV. GPS Measurements

Ionospheric GPS scintillation measurements are recorded at Virginia Tech to monitor the amplitude scintillations at midlatitudes under various sets of geomagnetic and seasonal conditions. The amplitude scintillation index S_4 is used to estimate the intensity of the observed scintillation [7]. During the night of 10-11 October, S_4 indices reached a peak value of approximately 0.35, indicating scintillation activity. Figure 2 shows the S_4 index for four different satellites in view during this night. These four satellites were chosen because they exhibited the largest S_4 indices. For some nights with $K_p = 5$ or more, S_4 indices reached values up to ~ 0.6, revealing strong scintillation activity.

The scintillation measurements are also analyzed to obtain the spectral characteristics of irregularities producing ionospheric scintillations at midlatitudes. The power spectral index for the irregularities at 04:50 UT on October 11, 2014 is calculated and found to be 2.8. The in-situ irregularity spectral index n can be related to the ground spectral index p by $n = p - 1$ [8]. In the range of S_4 between 0.2 and 0.5, the average p is 2.6, which is comparable to the midlatitude measured in-situ irregularity spectral index minus one [9].

V. Conclusions

This work has investigated the TGI and GDI as the cause of midlatitude ionospheric irregularities observed by the SuperDARN radars during disturbed geomagnetic conditions. The GPS scintillation data are analyzed to obtain the spectral characteristics of midlatitude irregularities producing GPS scintillations. Both modeling and GPS spectral analysis are consistent with previous in-situ satellite measurements during disturbed periods, showing that the spectral index of midlatitude density irregularities with scale sizes less than 1 km are of the order 2. The spectral calculations suggest that initially TGI or/and GDI irregularities are generated at large scale size (km-scale) and the dissipation of the energy associated with these irregularities occurs by generating smaller and smaller (decameter-scale) irregularities. The scintillation results along with radar observations suggest that the observed decameter-scale irregularities that cause SuperDARN backscatter, coexist with kilometer-scale irregularities that cause L-band scintillations. Further insight requires the coordination between in-situ satellite measurements, ground radar observations, and GPS data at midlatitudes.

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