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Inverse Modeling of Ionospheric Irregularities Observed using GPS Scintillations at Poker Flat, AK

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Abstract

Scintillations in the Global Navigation Satellite System (GNSS) signals are rapid variations in their amplitude and phase resulting from electron density irregularities in the ionosphere, can be used to study the ionospheric irregularities. We utilize Global Positioning System (GPS) scintillation measurements from scintillation auroral GPS array (SAGA) at the Poker Flat Research Range (PFRR) (*Datta-Barua et al.*, 2015), Alaska on 8 December 2013 in conjunction with ancillary multi-instrument observations combined with physical parameters derived from a forward propagation model, and an inverse method to achieve an improved understanding of the physics of the irregularities and the processes that may produce them.

1 Introduction

Understanding how Geospace responds to solar and heliospheric variations is one of the major objectives of the space science community. A better characterization of the plasma irregularities, especially in the high latitude ionosphere, that are triggered by geomagnetic activity, will assist in understanding the large and small scale dynamics produced due to coupling of solar wind, magnetosphere and ionosphere.

High latitude electron density irregularities produce short-lived Global Positioning System (GPS) scintillations and make it challenging to characterize them using scintillation studies (*Aarons*, 1997; *Basu et al.*, 2002). Moreover, solar wind and magnetospheric plasmas are connected to the auroral regions of the ionosphere through complex magnetosphere-ionosphere coupling mechanisms. High latitude irregularities are therefore a result of different systems interacting with each other.

2 SIGMA Model

Intermediate (0.1-10 km) to medium scale (10-100 km) irregularities (*Kelley et al.*, 1982) are more likely the sources of GPS phase scintillations that are predominantly observed at high latitudes (*Basu et al.*, 1998; *Mitchell et al.*, 2005; *Kinrade et al.*, 2012; *Deshpande et al.*, 2012). In spite of availability of so many high latitude observations, there haven't been many attempts in characterizing these plasma structures using inverse modeling. A newly developed forward propagation model Satellite-beacon Ionospheric-scintillation Global Model of the upper Atmosphere (SIGMA) (*Deshpande et al.*, 2014) fills the gap by facilitating characterization of irregularities with an inverse method (*Deshpande et al.*, 2016). Inside SIGMA the satellite signal is propagated to the ground through an irregularity modeled as multiple phase screens. An inverse method that uses SIGMA helps identify physical parameters associated with an irregularity such as the background number density, altitude of the irregularity, spectral characteristics such as the spectral index and drift velocity magnitude and direction. With an ability of doing these runs with different seed plasma instability, this exercise would enable us to learn about the underlying mechanisms, magnetospheric-ionospheric coupling effects on the irregularity generation, and perhaps also identify the causes of prevalent phase scintillations at high latitudes.

The study of ionospheric scintillations of radio signals involves the problem of electromagnetic (EM) wave propagation in random media. A variable angle of incidence from a satellite, the geometry of magnetic field lines at high latitude regions and inhomogeneity in the random media of irregularities makes GPS scintillation modeling challenging. These issues are addressed by SIGMA. The power and phase time series obtained from SIGMA as a function of time is similar to the phase scintillation observations from a GPS receiver recorded as fluctuations with respect to time.

3 8 December 2013 Event

A geomagnetic storm on 8 December 2013, produced elevated GPS scintillation activity at SAGA receivers as shown in Figure 1. This period corresponded to high AE index activity as well as a Kp index of 6 (Reference: World Data Center for Geomagnetism, Kyoto website http://wdc.kugi.kyoto-u.ac.jp/). This event also occurred during a PFISR Ion-Neutral Observations of the Thermosphere (PINOT) campaign (*Makarevich and Bristow*, 2014).

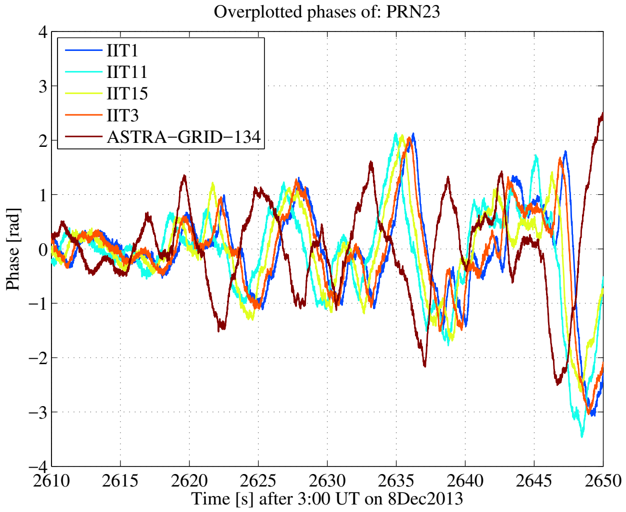

Figure 1. Filtered, detrended 100 Hz phase GPS measurements from the SAGA receivers from 03:43:30 to 03:44:10 UT on 8 December 2013.

4 Inverse Modeling Results for the Event

For an inverse modeling run, there are eight unknown input parameters: the outer scale, spectral index, density fluctuation ΔN, axial ratio, height and thickness of the scattering layer, plasma drift velocity, and number of layers N_l. For SIGMA inverse modeling, along with GPS observations from one of the SAGA receivers, number density estimate from PFISR, altitude of irregularity estimated from collocated all sky imagers and drift velocity derived using correlation properties of the spaced receiver array (*Bust et al.*, 2013; *Su et al.*, 2017) were used. We use all these estimates and the inverse method using SIGMA to find the best fit (using least squares or the chi-square test) of the simulated power spectral density (PSD) to the observed PSD. The input parameters pertaining to the best fit represent the characteristics of the irregularity responsible for those scintillations.

An estimate of PFISR electron density N_e from the beam closest to the SAGA array was found to be $1 \times e^{11}$ electrons/m^3. An estimate of altitude of the irregularity was obtained to be 500 km using Rytov's solution. Drift velocity was derived to be 1200 m/s with 150° measured counterclockwise from Geographic East. With these as starting inputs, SIGMA inverse modeling was performed to solve for the input parameters for the best fit, namely, thickness, altitude, drift velocity vector and spectral index. A thickness L_{Th} of 100 km, ionospheric height of 500 km, spectral index of 2, background number density $2 \times e^{11}$ electrons/m^3, and a drift velocity 1000 m/s and 130° measured counterclockwise from Geographic East. This implies that they are F-region structures.

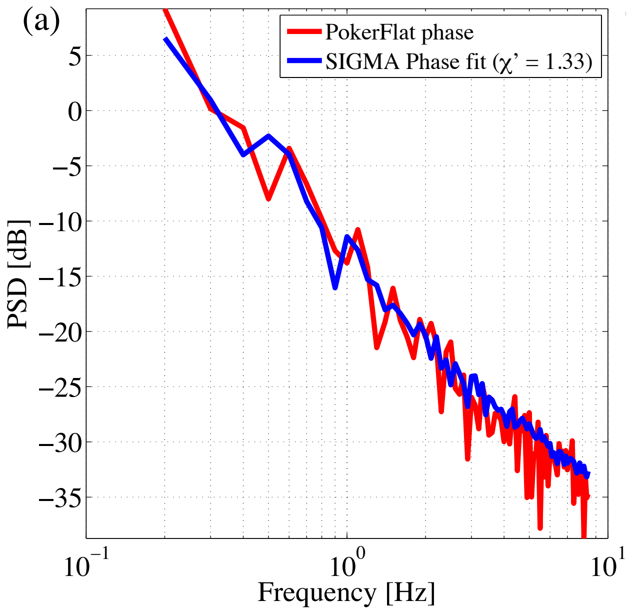

Figure 2. Comparisons of PSD of the observed phase from Poker Flat with those of the best fit found using SIGMA. χ' value close to 1 indicates a good fit of the modeled and observed data.

5 Conclusion

GPS scintillation measurements from SAGA, Poker Flat, Alaska, USA during an geomagnetically disturbed time on 8 December 2013 were utilized in conjunction with SIGMA model, and an inverse method to achieve an improved understanding of the physics of the underlying irregularities. The structures were found to be about 100 km thick and at F region altitude. These could be polar propagating patch or F-region soft precipitation. As can be confirmed using ISR data, in fact, it is the soft F-region precipitation triggered by the geomagnetic storm. We see scintillations that imply intermediate scale structuring on the order of a kilometer. This inverse method study was performed over a very limited range of input parameters but it still gives promising results with estimates close to the output of the Rytov method which is more established theoretical analysis tool. SIGMA can be expanded to work with multiple receivers and can be used to understand the effects of irregularity on the signal itself as well as its two dimensional snapshots. Electron number density has been obtained using a spectral model for this current work. However, the number density distribution can be obtained from a set of different plasma instabilities to find whether the underlying instability is gradient drift or velocity shear or Kelvin-Helmholtz, to name a few.

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References

Aarons, J. (1997), Global positioning system phase fluctuations at auroral latitudes, *Journal of Geophysical Research*, *102*, 17,219–17,232, doi:10.1029/97JA01118.

Basu, S., E. J. Weber, T. W. Bullett, M. J. Keskinen, E. MacKenzie, P. Doherty, R. Sheehan, H. Kuenzler, P. Ning, and J. Bongiolatti (1998), Characteristics of plasma structuring in the cusp/cleft region at Svalbard, *Radio Science*, *33*, 1885–1900, doi:10.1029/98RS01597.

Basu, S., K. M. Groves, S. Basu, and P. J. Sultan (2002), Specification and forecasting of scintillations in communication/navigation links: current status and future plans, *Journal of Atmospheric and Solar-Terrestrial Physics*, *64*, 1745–1754, doi:10.1016/S1364-6826(02)00124-4.

Bust, G., S. Datta-Barua, K. Deshpande, S. Bourand, S. Skone, and Y. Su (2013), Correlation properties of a 2-d array of high latitude scintillation receivers, in *Proceedings of the 26th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2013)*, pp. 2470–2479, Nashville, TN, September 2013.

Datta-Barua, S., Y. Su, K. Deshpande, D. Miladinovich, G. S. Bust, D. Hampton, and G. Crowley (2015), First light from a kilometer-baseline Scintillation Auroral GPS Array, *Geophysical Research Letters*, *42*(10), 3639–3646, doi:10.1002/2015GL063556, 2015GL063556.

Deshpande, K. B., G. S. Bust, C. R. Clauer, H. Kim, J. E. Macon, T. E. Humphreys, J. A. Bhatti, S. B. Musko, G. Crowley, and A. T. Weatherwax (2012), Initial GPS Scintillation results from CASES receiver at South Pole, Antarctica, *Radio Science*, *47*, RS5009, doi:10.1029/2012RS005061.

Deshpande, K. B., G. S. Bust, C. R. Clauer, C. L. Rino, and C. S. Carrano (2014), Satellite-beacon Ionospheric-scintillation Global Model of the upper Atmosphere (SIGMA) I: High latitude sensitivity study of the model parameters, *Journal of Geophysical Research (Space Physics)*, *119*, 4026–4043, doi:10.1002/2013JA019699.

Deshpande, K. B., G. S. Bust, C. R. Clauer, W. A. Scales, N. A. Frissell, J. M. Ruohoniemi, L. Spogli, C. Mitchell, and A. T. Weatherwax (2016), Satellite-beacon Ionospheric-scintillation Global Model of the upper Atmosphere (SIGMA) II: Inverse modeling with high-latitude observations to deduce irregularity physics, *Journal of Geophysical Research: Space Physics*, *121*(9), 9188–9203, doi:10.1002/2016JA022943, 2016JA022943.

Kelley, M. C., R. Pfaff, K. D. Baker, J. C. Ulwick, R. Livingston, C. Rino, and R. Tsunoda (1982), Simultaneous rocket probe and radar measurements of equatorial spread F - Transitional and short wavelength results, *Journal of Geophysical Research*, *87*, 1575–1588, doi:10.1029/JA087iA03p01575.

Kinrade, J., C. N. Mitchell, P. Yin, N. Smith, M. J. Jarvis, D. J. Maxfield, M. C. Rose, G. S. Bust, and A. T. Weatherwax (2012), Ionospheric scintillation over Antarctica during the storm of 5-6 April 2010, *Journal of Geophysical Research (Space Physics)*, *117*, A05304, doi:10.1029/2011JA017073.

Makarevich, R. A., and W. A. Bristow (2014), Coordinated radar observations of plasma wave characteristics in the auroral F region, *Annales Geophysicae*, *32*(7), 875–888, doi:10.5194/angeo-32-875-2014.

Mitchell, C. N., L. Alfonsi, G. De Franceschi, M. Lester, V. Romano, and A. W. Wernik (2005), GPS TEC and scintillation measurements from the polar ionosphere during the October 2003 storm, *Geophysical Research Letters*, *32*, L12S03, doi:10.1029/2004GL021644.

Su, Y., S. Datta-Barua, G. Bust, and K. Deshpande (2017), A GNSS Receiver Array Instrument for Distributed Sensing of Ionospheric Irregularities, *In preparation for submission to Radio Science*.