Equatorial scintillation predictions from C/NOFS Planar Langmuir Probe electron density fluctuation data

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Abstract

Data from the Planar Langmuir Probe onboard Communication/ Navigation Outage Forecasting System will be combined with coherent scatter radar and scintillation measurements to analyze the performance of different propagation models of satellite signals. This work will characterize: (i) the prediction capability of a purely space-based phase-screen scintillation model in comparison with another that represents the variation of the irregularity strength along ray paths in detail; and (ii) how early in time it is possible to detect irregularity structures, estimate their temporal and spatial evolution and predict their effects on propagation through different ionospheric regions at later instants of time.

1. Introduction

Ionospheric scintillation exhibits extreme variability in space and time, significantly degrading both the performance and the availability of space-based communication and navigation systems. For their support at equatorial latitudes, short-term scintillation forecast systems based on real-time measurements may explore the facts that the irregularities are field-aligned, their motion is ordered, and their lifetime is relatively long [1]. One such support system, the Communication/Navigation Outage Forecasting System (C/NOFS) [2] is based on a non-geostationary equatorial satellite successfully launched in an elliptical orbit with *400-km* perigee, *850-km* apogee and orbital inclination of 13^o on 16 April 2008. Due to its orbital period, the satellite is able to track the evolution and motion of plasma bubbles at *90-min* intervals. Data from sensors on board the satellite drive an equatorial ionospheric model to forecast the onset of plasma instability and its evolution (plasma bubbles). A phase screen model is used to determine the magnitude of phase and intensity scintillation of satellite signals propagating through the turbulent medium and received on the ground. These calculations are validated by scintillation measurements performed using tri-band beacon transmissions (TBB) at *150 MHz, 400 MHz,* and *1067 MHz.*

As an independent testing tool of the above models, the authors [3] developed an algorithm for the propagation of satellite signals through a three-dimensional irregularity layer which solves a parabolic approximation to the wave equation, valid when partial reflections are negligible. The layer is subdivided into multiple statistically homogeneous and independent thin slabs, and the Huygens-Fresnel diffraction theory is repeatedly applied to each of them. The random electron density fluctuations inside each slab are characterized by a flexible model for their power spectral density, with shape parameters estimated from C/NOFS Planar Langmuir Probe (PLP) data and mean square electron density fluctuation estimated from signal-to-noise ratio *S/N* measurements by the São Luís (*2.57° S, 44.21° W,* dip angle *-2.70°*) coherent scatter radar operated by INPE within the corresponding sampled volume. Results from calculations were used to predict time variations of the scintillation index S_4 (standard deviation of $I/\langle I\rangle$, where I is the intensity of the received signal) at the L1 Global Positioning System (GPS) frequency (*1575.42 MHz*) and compared with corresponding measurements by the co-located São Luís scintillation monitor to assess the prediction capability of the formulation. One example of good agreement between S_4 calculations and measurements as functions of Universal Time is shown in the left-hand side of Figure 1 for the evening of 28 December 2001 and GPS satellite PRN 28, together with the elevations of the corresponding ray paths. In spite of the use of a climatological model to characterize the drift velocity of irregularity structures through the radar main beam, the time fluctuations of the calculated and measured S_4 values are reasonably well synchronized. It seems realistic to expect improved agreement from future calculations using

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simultaneously-measured drift velocities, unavailable for that study. The right-hand side of the same Figure displays a direct comparison between absolute values of *644* pairs of calculated and measured S_4 values associated with different GPS satellites with elevations above 55^o. It is observed that the resulting least-square trend line through the origin is very close to the ideal one ($y = x$) and that most of the points are evenly spread around it within the interval $0 < S_4 < 0.4$. The exceptions are the outlier ones around $S_{4meas} \approx 0.04$ with $S_{4calc} > 0.2$ and $S_{4calc} \approx 0.37$.

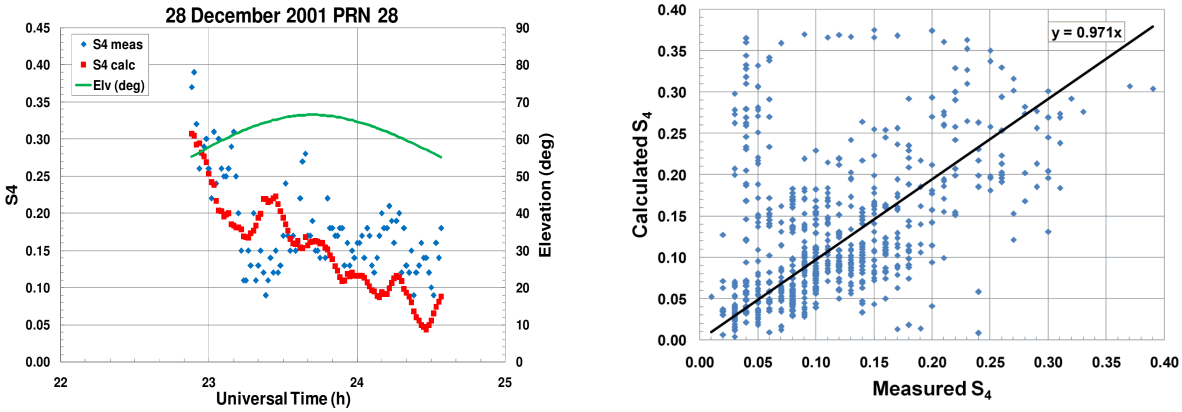

Figure 1. The left plot shows one example of good agreement between S_4 calculations and measurements as functions of Universal Time, in combination with the elevation of the corresponding GPS satellite. The right plot compares *644* pairs of calculated and measured S_4 values associated with GPS satellites with elevations above 55^o and the corresponding least-square trend line through the origin.

2. Summary

Due to extended solar minimum conditions, relatively few simultaneous data sets associated with strong irregularities have been collected since April 2008. The increasing solar flux promises to improve the quality and intensity of both C/NOFS satellite data and ground-based measurements appropriate for scintillation algorithm development and validation under all the expected operational conditions.

The present modeling effort will continue to explore coherent scatter range-time-intensity (RTI) radar and L1 GPS data collected at the INPE São Luís Observatory. However, it is well known that L1 scintillation is relatively weak in the equatorial region, even during solar maximum conditions. Therefore, the proposed work will focus on scintillation measurements at *250 MHz* by the Scintillation Network Decision Aid (SCINDA) receivers and at the three frequencies by the TBB receiver located at this site. It will also explore the expanding scintillation monitoring network observed in Figure 2 [4]. Particular attention will be paid to stations located as closely as possible to the equatorial anomaly crests but within ± 13^o from the geographic equator. These stations should observe stronger scintillation during high-elevation passes of the C/NOFS satellite. The corresponding data will be used in two complementary investigations.

The first study will identify high-elevation passes of the satellite over São Luís and compare results from scintillation index S_4 measurements by the TBB receiver at its three operation frequencies with predictions by: (i) the model briefly described in the previous section [3]; and (ii) a purely space-based phase-screen scintillation model [5],[6]. The second model will use a properly scaled version of electron density fluctuations directly measured by the Planar Langmuir Probe on board the C/NOFS satellite to represent the random phase of the screen. Estimation of the thickness of the irregularity layer for this model will be performed with basis on São Luís coherent scatter radar data or by using simpler surrogate models (for example, distributions following background electron-density height profiles). Note that both scintillation models will be applied to short batches of in situ C/NOFS PLP data associated with an instant of time to represent propagation along the corresponding ray path and their results will be compared with the simultaneous TBB receiver measurements. The main missing information in the calculations is the variation of the irregularity strength along the ray path. While the previous model (i) represents this variation through a mapping of *S/N* measurements by the São Luís coherent scatter onto mean square electron density fluctuations [3], this representation will be performed by the space-based phase-screen model (ii) in an approximate fashion (to keep its independence from ground-based data). Therefore, the results from this comparative study, which are not adversely affected by time and west-to-east evolution of irregularity structures, will characterize the prediction capability of the space-based model, being important to relate each set of measured and calculated S_4 values to the position of the C/NOFS satellite with respect to those of intense irregularities, displayed by corresponding RTI maps from the INPE São Luís Observatory.

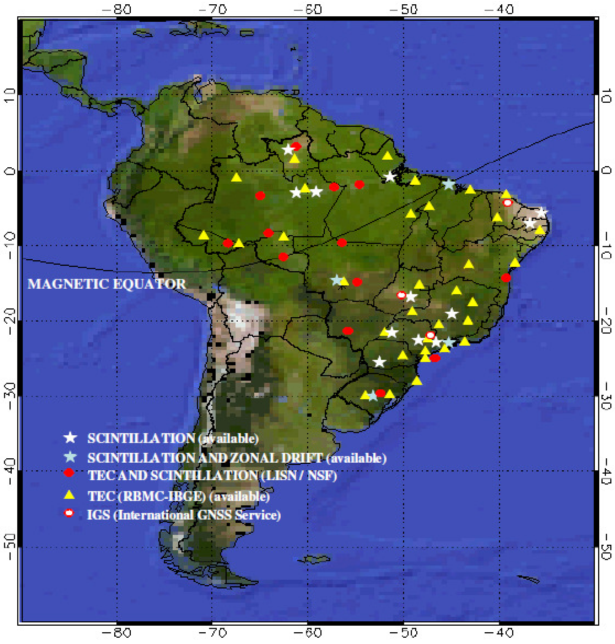

Figure 2. Network of monitoring stations in the Brazilian territory.

The second study will assume that, due to the fast velocity (approximately *7.5 km/s*) of the C/NOFS satellite, the PLP data provides a near-instantaneous and high-resolution snapshot of the irregularity structures that drift along the geomagnetic west-to-east direction with a relatively slow velocity, typically in the range from *80 m/s* to *150 m/s*. It will use PLP data in combination with mapping of measured electron density fluctuations along field lines defined by the International Geomagnetic Reference Field (IGRF-11) to create an extended phase screen that drifts as described over selected ground stations during long periods of time. The intended calculations will assume drift velocities for the phase screen which are consistent with climatological models or, preferably, simultaneous space- or ground-based measurements [5],[6]. The evolution of the irregularities may also consider decay, characterized by a diffusion process with a constant coefficient. At equally-spaced and short time intervals, the position of the phase screen with respect to each station (with structures adjusted for diffusion), as well as the azimuths and elevations of ray paths from the station to tracked satellites will be updated. The spaced-based scintillation model (ii) will then be applied to the local phase screen centered at each ray path to estimate the corresponding scintillation index S_4. At the São Luís Observatory, these procedures can also use model (i) and both results will be compared with measurements by the GPS scintillation monitor and the *250-MHz* SCINDA receivers. At stations near the crests of the equatorial anomaly, only the results from model (ii) will be compared with measurements by the local GPS receiver. Therefore, through a comparison between calculations and measurements from all stations, the results from this study will indicate how early in time it is possible to detect irregularity structures, estimate their combined temporal and spatial evolution using a simplified model and predict their effects on the propagation of satellite signals through different ionospheric regions at later instants of time.

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4. References

1. S. Basu, K. M. Groves, and Su. Basu, and P. J. Sultan, “Specification and Forecasting of Scintillations in Communication/Navigation Links: Current Status and Future Plans,” *Journal of Atmospheric and Solar-Terrestrial Physics*, **64**(16), November 2002, pp. 1745-1754.

2. O. de La Beaujardière, and the C/NOFS Science Definition Team, “C/NOFS: a Mission to Forecast Scintillation,” *Journal of Atmospheric and Solar-Terrestrial Physics*, **66**(17), November 2004, pp.1573-1591.

3. E. Costa, E. R. de Paula, L. F. C. Rezende, K. M. Groves, and P. A. Roddy, Equatorial Scintillation Calculations Based on Coherent Scatter Radar and C/NOFS Data, accepted for publication in *Radio Science*, December 2010.

4. E. R. de Paula, M. T. A. H. Muella, L. F. C. de Rezende, I. J. Kantor, K. S. Correa, P. M. de Siqueira, A. Dutra, and C. Guedes, Ionospheric Effects Over GNSS, Galileo Networking Meeting, INPE, São José dos Campos, SP, Brazil, November 2009.

5. E. Costa and S. Basu, “A Radio Wave Scattering Algorithm and Irregularity Model for Scintillation Predictions,” *Radio Science*, **37**(3), doi:10.1029/2001RS002498, June 2002, pp. 18.1-18.13.

6. E. Costa, M. J. Starks, K. M. Groves, S. Basu, and R. E. Sheehan, Application of a Radio Wave Scattering Algorithm to Satellite in Situ Electron Density Fluctuation Data for Equatorial Scintillation Predictions, *Proceedings of the International Beacon Satellite Symposium (BSS 2004, CD-ROM)*, Trieste, Italy, October 2004.