The International Beacon Satellite Symposium *BSS2010*
P. Doherty, M. Hernández-Pajares, J.M. Juan, J. Sanz and A. Aragon-Angel (Eds)
Campus Nord UPC, Barcelona, 2010

MULTIPLE PHASE SCREEN MODELING OF IONOSPHERIC SCINTILLATION ALONG RADIO OCCULTATION RAYPATHS

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Key words: radio occultation, equatorial ionosphere, scintillation, phase screen, C/NOFS

Abstract. We use the multiple phase screen method to simulate the forward-scatter of radio waves by electron density irregularities in the equatorial ionosphere during radio occultati n experiments. The simulated scattered signal is examined to assess the extent to which spectral analysis techniques can yield useful information about the structure and distribution of irregularities along the propagation path.

1 INTRODUCTION

Rapid fluctuations in the intensity and phase of radio occultation signals can indicate the presence of small scale electron density irregularities along the radio propagation path. Instruments onboard several low Earth orbiting satellites routinely collect radio occultation observations using signals transmitted by the GPS constellation of satellites, providing a rich source of information about the occurrence and morphology of ionospheric scintillation. Nevertheless, the relatively longer propagation path of a radio occultation signal through the ionosphere, as compared to through the lower neutral atmosphere, makes it challenging to determine the geographic location and horizontal extent of the ionospheric irregularities responsible for the scintillation. In this paper, we use the multiple phase screen method1,2 to simulate the forward-scatter of radio occultation signals by irregularities in the equatorial ionosphere, and explore spectral techniques for geolocating these irregularities along the radio occultation raypath. We validate the results of our phase screen simulations and analysis using radio occultation measurements from the CORISS instrument onboard the C/NOFS satellite.

2 METHODOLOGY

The phase screen simulations we perform employ a simple model for the statistical distribution of electron density fluctuations (N) in the equatorial ionosphere. We specify the background electron density as a Chapman layer. We assume a power-law form for the three-dimensional spectrum of electron density fluctuations with an outer scale, as proposed by Rino3. The amplitude of density fluctuations (RMS N) throughout the volume is assumed to scale with the background electron density. For simplicity, we assume the irregularities to be infinitely extended along the magnetic field direction so that a sequence of one-dimensional phase screens may be used to model propagation perpendicular to the magnetic field1. We note that while this assumption of perpendicular propagation may be suitable for radio occultation observations made by the C/NOFS satellite, since it orbits the equatorial zone in a low inclination orbit, it is not appropriate for occultation observations made by satellites with high orbital inclinations such as COSMIC, CHAMP, SAC-C, or PICOSat4.

3 SIMULATION RESULTS

Figure 1 shows a simulation of radio occultation forward-scatter through a layer of uniformly distributed irregularities. The phase in each screen (shown in red) is obtained via incoherent integration of the density fluctuations between adjacent vertical partitions of the volume (blue dashed lines). The signal intensity at the observation plane (middle panel) is computed by propagating through multiple phase screens oriented perpendicularly to the raypath. In this example, the scattering is strongest near the height of the F region peak, but also occurs at much lower apparent altitudes (when referenced to the tangent point) due to curvature effects. Since the scattering region is thick in this case, the intensity spectrum (right) exhibits a break scale but not the Fresnel nulls characteristic of weak scatter through a thin layer of irregularities5.

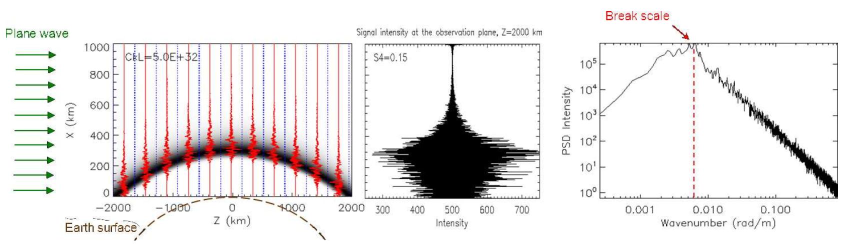

Figure 1: Simulation of radio occultation propagation through a layer of uniformly distributed irregularities.

We note that, as compared to the radio occultation case, a radio wave propagating from space to ground encounters a much thinner layer of irregularities and also propagates a shorter distance after traversing them down to the receiver. These effects cause the intensity and phase fluctuations of the received signal to be weaker for space-to-ground propagation than radio occultation propagation through the same uniform ionospheric medium. The occultation raypath encounters 20 times more TEC than along the vertical raypath, and the corresponding scintillation intensity index is 7.5 times greater (simulation results not shown).

Figure 2 shows a simulation of radio occultation propagation through a single plasma bubble, modeled by weighting the uniformly distributed layer of irregularities from the previous example by a Gaussian profile with a 100 km half-width. Because we have located the plasma bubble at the tangent point, the apparent altitude of the scattering is approximately the same as the altitude of the bubble. The distance (d) between the bubble and the receiver may be estimated from the intensity spectrum by measuring the wavenumber of the break scale, kF 2 , where kF = 2/(d)1/2 is the wavenumber of the 1st Fresnel zone radius. In general, the break scale may be difficult to measure precisely because the low frequency roll-off in the intensity spectrum may be relatively broad. Since the effective scattering layer is thin in this case, we can estimate the distance d precisely by indentifying the Fresnel nulls in the intensity spectrum, located at the wavenumbers kF n , n 1, 2, Even when the effective scattering layer is thin, however, these Fresnel nulls are only present when the scattering is weak.

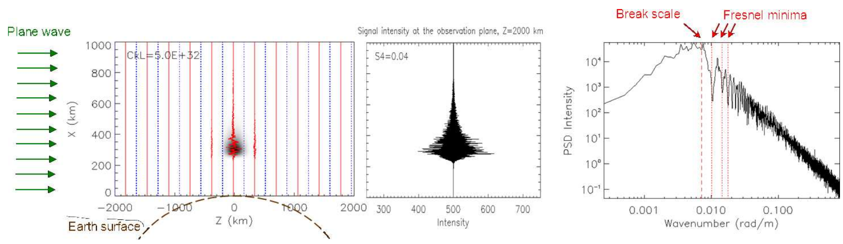

Figure 2: Simulation of radio occultation propagation through a single Gaussian plasma bubble.

Figure 3 shows a simulation of radio occultation propagation through multiple bubbles, produced by weighting the same uniformly distributed layer of irregularities by two Gaussian profiles each with a 100 km half-width. Since the irregularities are not located at the tangent point in this case, the apparent altitude of the scattering does not correspond to the actual attitudes of the bubbles. Instead, it is determined (approximately) by the projections of the bubbles onto the observation plane. In this simulation, where the wave penetrates multiple bubbles, the effective scattering layer is no longer thin and the Fresnel nulls in the intensity spectrum (right panel) are not as clear. The locations of the break scale (dashed line) and Fresnel nulls (dotted lines) corresponding to the distances from each bubble to the receiver are shown in the figure. Note that the break scale of the intensity spectrum corresponds to the distance from the first bubble to the receiver. In general, if there are multiple bubbles with the same turbulent intensity along the path, bubbles located farther from the receiver tend to dominate the scintillation spectra. This is not surprising, since the longer propagation distance traveled after the radio wave penetrates a more distant bubble creates greater opportunity for diffraction and generates stronger scattering.

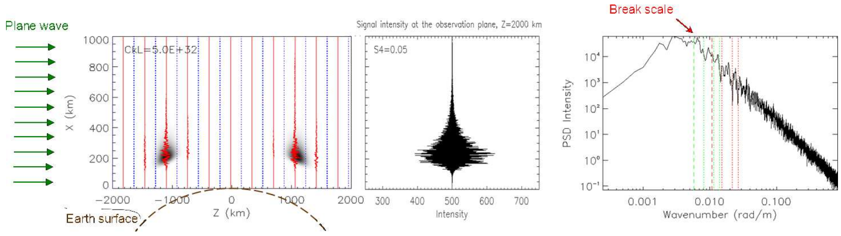

Figure 3: Simulation of radio occultation propagation through multiple Gaussian plasma bubbles.

4 DISCUSSION

A more complete simulation methodology for radio occultation propagation would account for the time-dependent geometry of the ionospheric penetration point along the line of sight between the transmitting and receiving antennas, relative to the plasma drift. Earlier works have shown that the angle of propagation with respect to the magnetic field has a pronounced effect on the intensity of radio occultation scintillation4. These geometrical issues must also be addressed in order to compare the temporal spectra observed in experiments with the spatial spectra produced by our simulations. We discuss these issues in the full paper, and demonstrate that simulation and spectral analysis can be used to characterize several important aspects of irregularity region structure. These include geolocation of the ionospheric irregularities along the propagation path, estimation of the effective scattering layer thickness, and possibly an indication of the presence of multiple bubbles in the region.

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