A Propagation Model for Geolocating Ionospheric Irregularities along Radio Occultation Ray-Paths

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***Abstract*—We have developed a new propagation modeling technique for characterizing and geolocating ionospheric irregularities using radio occultation observations of amplitude scintillation. The approach taken is to solve an inverse problem for the propagation of radio waves through a phase changing screen. Referred to as Irregularity Parameter Estimation (IPE), this inverse technique infers the irregularity turbulence strength, spectral index, and Fresnel frequency from measurements of amplitude scintillation. A geometric model for the effective velocity at which the radio occultation ray path scans through the irregularity region is used to map the Fresnel frequency to Fresnel spatial scale, which yields the distance from the receiver to the irregularities. We demonstrate the approach by geolocating irregularities observed by the CORISS instrument onboard the C/NOFS satellite.**

I. INTRODUCTION

Radio occultations (RO) with Global Navigation Satellite System (GNSS) signals have been widely used for the remote sensing of tropospheric parameters and to provide ionospheric electron density profiles for the purpose of improving terrestrial and space weather forecasts. Radio occultations have also been used to investigate the morphology of irregularities that cause radio wave scintillation. Space based monitoring of ionospheric irregularities is advantageous because it can be performed continuously and globally, including over ocean regions not easily monitored with ground based instruments. Nevertheless, the radio propagation path of an occultation through the ionosphere can be very long (up to several thousand km), such that it can be challenging to infer the geographic location and spatial extent of the irregularities from the scintillations they produce. Unlike RO retrievals of slant TEC which are dominated by the contribution from close to the tangent point, scintillations can be generated by irregularities distributed anywhere along the propagation path between transmitting and receiving satellites.

Irregularity Parameter Estimation (IPE) is an inverse radio propagation technique in which the statistical characteristics of ionospheric irregularities are extracted from the time-series of amplitude scintillations they produce [1]-[3]. These statistical characteristics may include the turbulence strength, spectral index, irregularity drift, and anisotropy ratio. We have modified the technique to provide an estimate of the mean distance to the irregularities responsible for producing scintillations along radio-occultation (RO) ray-paths.

Previous applications of the IPE technique have been to scintillation data from beacon satellites. For this space-to-ground propagation geometry it is possible to make a reasonable *a-priori* estimate of the distance, d_s, to the irregularities from the receiver. The Fresnel scale $\rho_F = (d_s/k)^{1/2}$, which also depends on the free-space wavenumber of the signal k, is therefore known as well. Conversely, for the case of space-to-space propagation the Fresnel scale is not known in advance. To apply IPE for this geometry, we first express the fitting function in a form that does not depend on a-priori knowledge of ρ_F but instead on a quantity we can measure directly.

Carrano and Rino [3] presented a 2D model for the spectral density function (SDF) of intensity fluctuations in the receiver plane following propagation of a plane wave through a thin phase-changing screen. Substitution of the dimensionless wavenumber $\mu=(2\pi f/V_{eff})\rho_F$, into their equation (10) yields a model for the temporal spectrum of intensity scintillation $I(f)$ in terms of the phase spectral index p, universal scattering strength U, and ratio of the effective scan velocity V_{eff} to ρ_F:

$$I(f;U,p,V_{eff}/\rho_F)=\int_0^\infty \exp\left[-\gamma\left(\eta,2\pi f\frac{\rho_F}{V_{eff}};U,p\right)\right]\cos\left(2\pi f\frac{\rho_F}{V_{eff}}\eta\right)d\eta$$

The functional form of the structure interaction function γ appearing in the equation above, which depends implicitly on U and p, is given in equation (12) of that paper. We use this model to fit the temporal SDF of the measured intensity fluctuations in the log-log domain using a non-linear least squares fitting technique. Of the resulting fit parameters, for our purpose of geolocating the irregularities, we need only the ratio V_{eff}/ρ_F. This ratio can be shown to be the angular frequency at which the Fresnel scale ρ_F is manifest in the temporal SDF.

II. DISCUSSION

We illustrate the technique with an example: an occultation of the C/NOFS satellite with GPS PRN09 on day 113 of 2011. Fig. 1 shows the measured SNR for this event. Dotted vertical lines show the period of interest we selected for analysis. Fig. 2 shows the measured (black) and fitted model intensity SDFs (red), along with the parameters inferred from the least squares fit. The angular Fresnel frequency inferred from the fit was $V_{eff}/\rho_F = 1.2$ Hz.

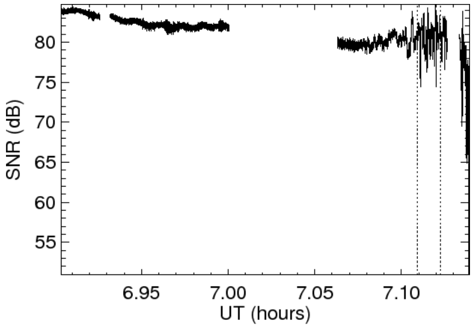

Fig. 1. Signal to noise ratio (SNR) for a C/NOFS occultation with PRN09 that occurred on day 113 of 2011.

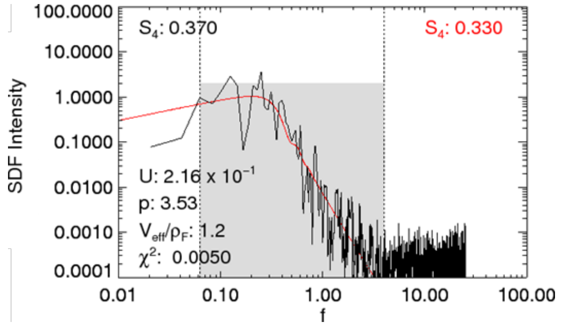

Fig. 2. Measured (black curve) and model (red curve) spectral density functions (SDF) of signal intensity fluctuations.

Next we use the scintillation theory developed by Rino [4], which we generalized for the radio occultation geometry, to estimate the effective scan velocity in terms of the known transmitter and receiver velocities, the propagation direction, and the magnetic field direction. We selected a central ray-path (corresponding to the midpoint of the period of interest) and computed the ratio V_{eff}/ρ_F for the central ray as a function of distance from the C/NOFS satellite (Fig. 3). This IPE prediction is shown in Fig. 3 with a horizontal dashed line. The intersection of the solid curve and dashed line gives an estimate for the distance to the irregularity region, $d_s = 3075$ km. Using the known geometry of the central ray, this distance translates to a scattering region located at (0.4°N, 275.1°E, and 246 km). Note that this analysis predicts the irregularity region to be located roughly 9 degrees westward of the tangent point.

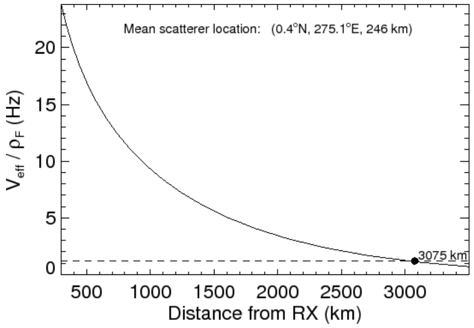

Fig. 3. Angular Fresnel frequency V_{eff} / ρ_F along the central ray as a function of distance from the C/NOFS satellite.

Fig. 4 shows the path of the central ray and the locations of the C/NOFS satellite, tangent point, and scattering region. Also shown in the figure are the *in-situ* density measurements from PLP probe onboard C/NOFS, which show evidence of an equatorial plasma bubble located at approximately the same longitude as the scattering region predicted by IPE.

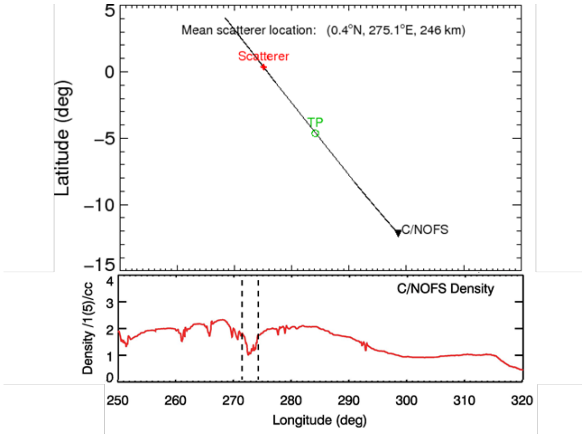

Fig. 4. Top: central ray and locations of the C/NOFS satellite, tangent point (TP), and scattering region. Bottom: in-situ density measurements from PLP probe on C/NOFS.

III. CONCLUSIONS

More work is needed to validate this modeling approach, using a large number of occultation events with a wide range of propagation geometries. With the upcoming launch of the COSMIC II constellation of low-inclination satellites, we anticipate that the current technique will contribute to the development of enhanced ionospheric specification products for the low-latitude region.

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