Evaluation of Ionospheric Scintillation in GNSS Radio Occultation Measurements and Simulations

Vinicius Ludwig-Barbosa1, Thomas Sievert1, Joel Rasch2, Anders Carlström3, Mats I. Pettersson1, and Viet T. Vu1

1Department of Mathematics and Natural Sciences, Blekinge Institute of Technology, Karlskrona, Sweden, 2Molflow, Gothenburg, Sweden, 3RUAG Space, Gothenburg, Sweden

Abstract Like any other system relying on transionospheric propagation, Global Navigation Satellite System (GNSS) Radio Occultation (GNSS-RO) is affected by ionospheric conditions during measurements. Regions of plasma irregularities in $F$ region create abrupt gradients in the distribution of ionized particles. Radio signals propagated through such regions suffer from constructive and destructive contributions in phase and amplitude, known as scintillations. Different approaches have been proposed in order to model and reproduce the wave propagation through ionospheric irregularities. We present simulations considering single-slope power law model of irregularities integrated with Multiple Phase Screen (MPS) propagation. In this work, the capability of the scintillation model to reproduce features in low-latitude MetOp measurements in the early hours of DOY 76, 2015 is evaluated. Power spectral density (PSD) analysis, scintillation index, decorrelation time, and standard deviation of neutral bending angle are considered in the comparison between the simulations and RO measurements. The results demonstrate the capability of the simulator to replicate an equivalent error contribution to the neutral bending angle measurement in cases of moderate to strong scintillation.

1. Introduction

Most of the satellite links providing telecommunication, navigation services or even remotely sensing the Earth’s atmosphere have their operations affected by the conditions in different atmospheric layers. In some applications, part of the signal propagation takes place in the ionosphere, which is composed of highly dynamic plasma of ionized particles (Kintner & Ledvina, 2005). The ionization is influenced by the solar radiation and, therefore, related to the solar cycle (number of sunspots), magnetic storms, seasons, geographical location, and daytime/nighttime (Aarons, 1982). The regions of depletion, that is, abrupt gradients in the electron density, are the results of ionospheric plasma redistribution. The propagation of radio signals, for example, Global Navigation Satellite System (GNSS) signals, is especially critical when passing through such regions, also known as electron plasma bubbles (EPBs). The gradient in electron density and its contribution in refractivity add random variation in the signal phase, hereafter scintillation, with potentially destructive and constructive effects in the signal. Eventually, clear signatures are also observed in the signal amplitude (Yeh & Liu, 1982).

In the context of remote sensing technique based on GNSS satellites, GNSS Radio Occultation (GNSS-RO) scans the Earth’s atmosphere from the ionosphere down to the troposphere in setting and rising directions defined by the trajectory of the Low-Earth Orbit (LEO) satellite (Kursinski et al., 1997). Since occultations rely on transionospheric propagation, the GNSS signal serves as a probe of the ionosphere. Data acquired in radio occultation measurements support the characterization of the ionosphere regarding the electron distribution in $F$ region and $E$ region (Vorob’ev et al., 1999) and the variability of the total electron content (TEC) during periods of solar minimum and maximum (Hocke et al., 2019). The ionosphere also imposes some complications in the usage of RO data. In the context of numerical weather prediction (NWP) and climatology, the bending angle in lower altitudes contains an undesirable bias due to the ionospheric propagation (Danzer et al., 2015; Syndergaard, 2000). Further, events related to space weather also contribute to the occurrence of scintillation in the GNSS signal (Hernandez-Pajares et al., 2011). The fluctuations observed in the complex signal have been investigated with the aid of log-amplitude and phase spectral analysis (Vorob’ev & Kan, 1999) as well as the relation between the occurrence of solar flares and the variation given in the excess phase (Gorbunov & Shmakov, 2014).
Some simulation work has been done using wave optics propagator (WOP) in order to provide better understanding of ionospheric scintillation during occultation events. Random irregularities were modeled to validate the detection of ionospheric scintillation in Global Positioning System (GPS)/MET radio occultation data (Sokolovskiy et al., 2002). Forward propagation and backpropagation simulations were performed to estimate the distance between LEO and the region with irregularities. The model confirmed the feasibility of detection and localization of irregularities in the F region. Sporadic clouds of ionized particles in E layer have also been investigated by using backpropagation and radio-holographic methods (Gorbunov et al., 2002), which allowed to solve the bending angle in multipath regions and indicated the presence of inhomogeneities in E region. In Zeng and Sokolovskiy (2010), the U-shaped signatures in the signal amplitude due to irregularities in E layer were replicated and compared to data of Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission. Cases involving sporadic E clouds with a tilted angle with respect to the wave propagation direction has been investigated using CHAMP data in high latitudes. Besides deriving the location and the tilt of the sporadic cloud, a technique to estimate the parameters of the internal gravity waves (IGWs) creating the tilt has been introduced in Gubenko et al. (2018).

In Carrano et al. (2011), a model for ionospheric irregularities in the electron distribution within the F region was introduced in a scenario of RO propagation. A region of irregularities was integrated with the Multiple Phase Screen (MPS) method (Knepp, 1983) in order to model the wave propagation and to reproduce the scintillation observed in the amplitude of GPS signals. The implementation consists of a 2-D propagation model suitable to model isotropic irregularities along the propagation direction and neglecting existence of elongated regions of irregularities in perpendicular plane (along magnetic field lines). A measurement performed by C/NOFS satellite system, featuring weak scattering, was evaluated. The data from an incoherent scatter radar and a GPS ground station collocated to C/NOFS satellite were combined in order to estimate the parameters of the single-slope power law model. Simulated signal-to-noise ratio (SNR), scintillation index (S4), and power spectral density (PSD) of the normalized intensity around the altitude of the plasma bubble were used to validate the results obtained in the simulator. Other techniques treating ionospheric irregularities, resulting in scintillation in radio signal, with three-dimensional and arbitrary geometry have been investigated in Gherm et al. (2005), Zernov et al. (2009), and Gherm and Zernov (2017). Such models cover cases of propagation along anisotropic irregularities. A comparison between these and some other related models is found in Strangeways et al. (2014).

In this paper, the single-slope model for ionospheric scintillation described in Carrano et al. (2011) was integrated to MPS method in order to replicate the disturbances, that is, scintillations, on the neutral bending angle as observed in RO measurements. Three measurements in low latitude performed by Meteorological Operational Satellite Program (MetOp) constellation in the early hours of DOY 76, 2015 (Wang et al., 2019) have been considered in the investigation. In this simplified model, parameter such as spectral slope, outer scale, and root-mean-square (RMS) level of fluctuation have been adjusted in simulations. S4 index, standard deviation (STDV) of the retrieved neutral bending angle (BA), PSD response, and autocorrelation interval have been used to evaluate the agreement between MetOp measurements and the results achieved in simulations. Simulations included neutral atmosphere refractivity and geometric optics was applied in the derivation of bending angles (Kursinski et al., 1997). The simulation tool is valuable for verification of RO instrument tracking techniques as well as for processing and interpretation of the bending angle measurements.

This paper is structured as follows: Section 2 describes the characterization of the ionosphere required in the analysis and an overview of the scintillation model integrated with MPS. Section 3 introduces the RO measurement assumed in this study, and section 4 provides details about our implementation. Section 5 presents the results obtained with simulations, and section 6 concludes the analysis with final remarks.

### 2. Characterization and Modeling of Ionosphere

Given the geometry of an occultation and due to the accumulative characteristics of the excess phase, amplitude, and phase recorded in LEO satellites are affected by the gradient in the density of ionized particles in the ionosphere. The contributions of solar and magnetic activity, season, local time, and geographic coordinates are observed in measurements and vary between observations (Liu et al., 2013, 2015).
Electron density profiles (EDPs) and TEC provide a local characterization of the ionosphere. EDPs describe the electron density as functions of altitude and its representation in the form of refractivity are commonly applied to simulations involving transionospheric propagation. The relationship between electron density and refractivity is defined by

\[ N_{\text{iono}} = -40.3 \times 10^6 \frac{\rho}{f}, \quad (1) \]

where \( N \) is the refractivity with contribution of the neutral atmosphere (pressure, temperature, water vapor, and scattering) and ionosphere (Kursinski et al., 1997). Accordingly, the refractive index is \( n = 1 + N \times 10^{-6} \). In particular, for the ionosphere, \( \rho \) is the electron density (el/m³) and \( f \) is the carrier frequency. The ionospheric refractivity \( (N_{\text{iono}}) \) is a function of frequency as shown in Equation 1. Therefore, signals carried by different frequencies are refracted and propagated in slightly different paths. The availability of multicarrier signals in GNSS allows a linear combination between RO measurements in different carrier frequencies in order to mitigate the ionospheric contribution in excess phase. The approach, known as standard ionospheric correction, typically involves L1 and either L2 or L5 bending angles as function of the same impact heights. The ionospheric correction is a common practice at different data processing centers to remove the first-order term of the ionospheric contribution and to obtain the so called ionosphere corrected bending angle (Culverwell & Healy, 2015; Syndergaard, 2000; Vorob'ev & Krasil'nikova, 1994).

Besides the aforementioned issue, radio signals propagated through the ionosphere can be affected by amplitude and phase scintillation. One way of characterizing these disturbances is to calculate the normalized standard deviation of the signal intensity, that is,

\[ S^4 = \sqrt{\frac{\langle (I - \langle I \rangle)^2 \rangle}{\langle I \rangle}}, \quad (3) \]

where \( I \) is the normalized signal intensity. The expectation operator providing the average value is denoted by \( \langle \rangle \) and in this study represents the average taken over one second (Syndergaard, 2006). Further, \( \langle I \rangle \) denotes a filtered version of the average signal intensity used as reference in the calculation. Commonly, a sixth-order low-pass Butterworth filter is applied to create the intensity reference with cut-off frequency at 0.1 Hz (Rino, 1979a). Scintillations are commonly categorized as weak for \( (S^4 < 0.3) \) (Yue et al., 2016) and moderate to strong within \( (0.3 < S^4 < 1) \). This categorization can be defined with slightly different limits.

Correlation interval or decorrelation time is a complement parameter to the scintillation index. The decorrelation time takes into account the fluctuation rate observed in the signal scintillation rather than the amplitude of the fluctuation. It is defined by the interval of 50% decay in the autocorrelation function (ACF) of the normalized detrended signal intensity (Umeki et al., 1977).

Particularly to RO measurements, the computation of the standard deviation of the difference between the ionosphere corrected bending angle and an reference model is used operationally to account, among other sources of random error, small-scale fluctuation in the ionosphere (Schreiner et al., 2011). The parameter, hereafter referred as bending angle STDV, is computed within 60 and 80 km impact height.

### 2.1. Ionospheric Scintillation in F Region

Carrano et al. (2011) introduced an approach to model scintillation in radio occultation systems in the \( F \) region. The region of random irregularities is modulated to an EDP as

\[ \rho(y, z) = \rho_r [1 + \Delta \rho(y, z) \sigma_{\Delta \rho} B(y, z)], \quad (4) \]

where \( B(y, z) \) defines the region of irregularities, \( \rho_r \) is the reference EDP, and \( \Delta \rho \) is the 2-D random realization defined by
\[ \Delta \phi(y, z) = \mathcal{F}^{-1}\{ \sqrt{\Phi_{\Delta \rho}} \, SF \, r_m \}. \]  

in which \( SF = L/2\pi, L \) is the height of the region of fluctuations, and \( r_m \) is a matrix of Gaussian variables (Knepp, 1983). The random realization in Equation 5 is limited by the spectral density function (SDF)

\[ \Phi_{\Delta \rho}(k_y, k_z) = 4\pi k_0^{(2\nu-2)} \frac{\Gamma(\nu)}{\Gamma(\nu-1)} \frac{1}{(k_y^2 + k_z^2 + k_0^2)^\nu}. \]  

In Equation 6, \( k_y \) and \( k_z \) are the wave numbers in \( y \) and \( z \) directions, \( \nu \) is the spectral slope, \( \Gamma \) denotes the Euler's gamma function, and \( k_0 = 2\pi/L_0 \) is the wave number outer scale.

The SDF in Equation 6 corresponds to an single-slope power law determined by an outer scale \( (L_0) \) and a spectral slope \( (\nu) \). The value of the outer scale is obtained ideally by in situ measurements, but its typical range of values is within few kilometers up to 100 km (Strangeways et al., 2014), which is significantly larger than Fresnel scale defining the irregularities size. The spectral slope is given by the relation \( p = 2\nu \), where \( p \) is the phase spectral index. Under condition of weak scattering \((S4 < 1)\), normalized intensity and phase power density spectral have approximately equal spectral index (Rino, 2011; Yeh & Liu, 1982).

The small-scale irregularities defined in Equation 4 are limited by the maximum RMS fluctuation level \((\sigma_{\Delta \rho})\), which is given by the ratio of the standard deviation of electron density fluctuation \((\sigma_{\Delta \rho})\) to the electron density peak in the \( F \) region \((\rho_F)\),
The PSD analysis is applied to characterize the ionospheric scintillation in GPS signals between weak and strong scattering (Carrano & Rino, 2016; Rufenach, 1975), and it allows to estimate the spectral slope. The PSD analyses of the detrended normalized intensity affected by ionospheric scintillation presented in this study were computed with Welch’s method, assuming a Hamming window with 50% overlap (Carrano & Groves, 2010).

3. Evaluation Cases

Figure 1 shows the measured SNR in low-latitude on DOY 76, 2015 (Wang et al., 2019). The labels in the figure indicate the calculated S4 index, decorrelation time ($\tau_I$) and standard deviation of neutral bending angle (STDV). The measurements in Figures 1d, 1f, 1g, and 1h are categorized as strong scintillations ($S4 > 0.6$), whereas the other cases are medium scintillations ($0.3 < S4 < 0.6$). Figure 1d shows an unreasonably high bending angle STDV level, which may not be related to the random noise added by the ionosphere and accounted by this parameter. In Schreiner et al. (2011), the measurements with STDV $> 10\mu$rad have been classified as outliers and are more likely to be consequence of tracking errors.

The decorrelation time based on the ACF of the detrended normalized intensity is short in the measurements with high fluctuation rate in the SNR, such as in Figures 1c and 1h, whereas it is long in measurements given in Figures 1e, 1f, and 1j. The PSD analysis of the gray regions is presented in Figure 2 with the estimated spectral index ($p$).

The PSD in Figures 2c–2f and 2j are characteristic for single-slope power law spectra, the same type defined by Equation 6 and related to weak scattering (Rufenach, 1975). Figure 2d also presents a single-slope PSD even though the scintillation observed in the measurement is categorized as strong scintillation by the S4 index. Generally, strong scintillation leads to a two-component inverse power law spectrum as observed in Figures 2g and 2h (Carrano & Rino, 2016; Rino, 1979b). Power spectral densities without an evident roll-off, such as in Figures 2a and 2l, are not suitable for the modeling discussed in this work. These
spectral densities have similar characteristics to a stationary random process, even though irregularities are observed in the gray region of Figures 1a and 1i and S4 values are intermediate. Therefore, the following three measurements have been considered in the investigation:

1. Occultation #1: Measurement (c), MTPB.2015.076.02.51.G11;
2. Occultation #2: Measurement (f), MTPB.2015.076.04.51.G09;
3. Occultation #3: Measurement (b), MTPB.2015.076.01.17.G28;

4. Implementation

The capability of the single-slope power law to replicate ionospheric scintillation observed in RO measurements was evaluated by simulation using the MPS method to model the wave propagation by Carrano et al. (2011). The approach was introduced to equatorial orbits where the irregularities are assumed to be isotropic and occur exclusively in the plane perpendicular to the magnetic field lines. In addition to calculated S4 index and normalized intensity PSD, this study extends the model to neutral atmosphere and also present comparisons between the simulated neutral bending angle STDV and MetOp measurements.

4.1. Defining the Ionospheric Irregularity

The ionospheric scintillation created by the power law described in Equation 6 is dependent on three parameters regarding the ionospheric inhomogeneity spectrum, namely, the spectral index, outer scale, and RMS level of fluctuation; and two spatial parameters, that is, the dimension of the fluctuation region and its distance to the observational plan.

From the measured SNR, the spectral index ($p$) is inferred by the linear regression in log-log domain between the break frequency (roll-off point) and noise floor of the PSD curve. Given a weak scattering process ($S4 < 1$), the spectral slope is estimated by $\nu = p/2$ (Rino, 2011; Yeh & Liu, 1982).

Since no complementary data collocated to the RO measurement was considered in this work, the approach to define the region of irregularities was simplified. The fluctuation region, $B(y, z)$, in Equation 4 was

Figure 3. IRI-2016 electron density profiles. Labels indicate height ($h_p$) and respective value of the electron density peak in F region ($\rho_p$).
delimited to a layer within the $F$ region, specifically between 220 and 600 km. A tapered cosine window was applied in order to create a smooth transition in the lower and upper edges (5 km long).

The resultant 2-D random realization was modulated to the International Reference Ionosphere model, Version 2016 (IRI-2016) (Bilitza et al., 2017), used to define the EDPs in simulations. Occultation attributes such as latitude, longitude, year, month, date, and time were used as inputs to extract the EDPs depicted in Figure 3. Further, the resultant EDPs were converted to refractivity and combined to neutral refractivity profiles available in RO measurement files by applying Equations 1 and 2.

Based on these definitions, the outer scale and the RMS level of fluctuation remained as free variables in the model.

### 4.2. Simulating the Propagation

The MPS method was used to simulate the propagation through the region of irregularities. The distance between points in the screens ($\Delta y$) depends on the gradient of the phase, related to the refractivity of the medium and the irregularities defined by Equation 5. Therefore, the minimum estimated value should follow $\Delta y < \lambda/2\theta$ in order to avoid aliasing, where $\theta$ is the angle between the wave front and the screen (Gorbunov & Gurvich, 1998). In our simulations, the phase screens had $2^{20}$ sampling points and were placed along $z$ axis with interdistance of 3 km. Larger steps between phase screens, which would reduce the computational requirements, could be achieved by creating random realizations of the phase path between screens rather than the irregularities in the refractivity (Gorbunov et al., 2015).

Part of the Earth was considered inside of the simulation box in our implementation. Figure 4 shows the dimension of the simulation box and the placement of the Earth, with its center aligned to $z = 0$.

Figure 5 shows the PSD of the averaged random variables among screens for different spectral slopes and outer scales.

The envelope of the power spectrum is analogous to a low-pass filter. Different spectral slopes modify mainly the frequency components. Consequently, filtered random variables assuming $p = 3$ allows higher frequencies components than the same random variables filtered with a SDF, $p = 5$. The outer scale shifts the break frequency point without significant change in the spectral slope, that is, larger outer scales shifts the envelope toward lower frequencies. The influence of these two parameters in the PSD response served as guideline to achieve similar features between measurements and simulations.

### 4.3. Evaluating the Scintillation

Different values for spectral slope and outer scale were evaluated in order to reach comparable PSD response, $S_4$ index, decorrelation time, and bending angle STDV. At the last phase screen, the complex signal was propagated to LEO orbit by the computation of a diffraction integral (Ludwig-Barbosa et al., 2019). Instrument noise was added to sampled signal accordingly to the signal-to-noise power density budget.
\( (C/N_0) \) for GRAS instrument, 47.5 dB Hz (Bonnedal et al., 2010). Assuming unitary signal power and sampling bandwidth \( B = 25 \text{ Hz} \) in simulations,

\[
P_n[W] = 10^{\frac{C}{10(N_0)}} \times B.
\]

In accordance with the unit assumed in simulations (V/V), the amplitude of the noise scaling the complex Gaussian vector is

\[
A_n = \sqrt{\frac{P_n}{2}} = 0.0149.
\]

Finally, the resultant signal amplitude was used in the calculation of the S4 index and PSD analysis within the same range of straight line tangent altitude (SLTA) adopted for measurements in Figure 1. The resultant

\[\text{Figure 5.} \] Power spectral density of filtered random variables among screens for (left) different spectral slopes and (right) different outer scales. Curves with different outer scales assume \( p = 3 \).

\[\text{Figure 6.} \] SNR and normalized intensity PSD for Occultation #1. Panel (a) shows the measured C/A L1 SNR and its PSD. Panel (b) shows the simulation result achieved with \( L_0 = 10 \text{ km} \) and \( \sigma_{\Delta \rho} = 8\% \).
excess phase was considered in the derivation of the bending angles and computation of STDV. Since the bending angle in low atmospheric layers (troposphere) is not required in procedure, the inversion of bending angles involved exclusively the excess phase and the geometry of the occultation (Kursinski et al., 1997). The same filtering approach was used to solve the excess phase derivative in measurement and simulated BA inversion. The inversion based on the measured excess phase was needed since the bending angles processed by COSMIC Data Analysis and Archive Center (CDAAC) are only available up to 60 km impact height.

The ionosphere corrected bending angle was obtained after the standard ionospheric correction (Vorob'ev & Krasil'nikova, 1994). The difference between the corrected bending angle with 100 m resolution and Committee on Space Research International Reference Atmosphere (CIRA-86) climatology model (Chandra et al., 1990; Kirchengast et al., 1999) was used in the calculation of the bending angle STDV.

5. Results

Figure 6 shows the measured SNR, its respective PSD response for Occultation #1 and MPS results. Simulations assumed a spectral slope \( \nu = 1.565 (p = 3.13) \). The dotted curve in PSD figures represents the measurement and it is used as reference to the simulation PSD (red curve).

The PSD obtained for a specific realization of random variables achieved in general a power spectrum fairly close to the one observed in the measurement. Different realizations create slight different PSD responses regarding the peak positions. However, the slope and the overall shape is maintained.

Figure 7. SNR and normalized intensity PSD for Occultation #2. Panel (a) shows the measured C/A L1 SNR and its PSD. Panel (b) shows the simulation result achieved with \( L_0 = 80 \text{ km} \) and \( \sigma_{\Delta \rho / \rho} = 60\% \) for Occultation #3.

Figure 8. SNR and normalized intensity PSD for Occultation #3. Panel (a) shows the measured C/A L1 SNR and its PSD. Panel (b) shows the simulation result achieved with \( L_0 = 13 \text{ km} \) and \( \sigma_{\Delta \rho / \rho} = 8\% \).
Figure 9. S4 index comparison. Panel (a) shows the calculated S4 index for Occultation #1 measurement (dashed black) and values obtained for the simulated intensity (red). Panels (b) and (c) show the comparisons for Occultations #2 and #3, respectively.

Figure 10. Bending angle STDV for (a) Occultation #1, (b) Occultation #2, and (c) Occultation #3. The plots show measured (black) and simulated (red) bending angle difference relative to the climatology model.
Figure 7 shows the measured SNR, its respective PSD response for Occultation #2 and MPS results. Simulations assumed a spectral slope $\nu = 1.79(\sigma = 3.58)$. Figure 8 shows the results obtained in simulations with spectral slope $\nu = 1.52(\sigma = 3.04)$ for Occultation #3.

Particularly, in Occultation #2, a larger outer scale was assumed in order to improve the agreement between measurement PSD response and the simulations. Larger outer scales create a slight shift toward low frequencies in the PSD response as depicted in Figure 5. For the model of irregularities assumed in the simulations, larger outer scales decrease the magnitude of the fluctuation. Therefore, the RMS fluctuation level was increased accordingly. The peaks located above 70 km SLTA in Figure 7a present larger amplitudes and apparent lower frequency than in the overall pattern in the signal SNR. Such feature was not properly achieved in simulations and may be related to the difference observed in panel (b) around 1 Hz.

Figure 9 presents the comparison between scintillation index obtained in simulations and the ones observed in measurements after a fair agreement is reached in the PSD analysis. The peak S4 values achieved in simulation are around the same range of values observed in measurements. The location of the peaks varies with the random irregularities, from realization to realization.

Figure 10 presents the difference between the corrected bending angle and the climatology model. The gray region shows the segment assumed in the calculation of the bending angle STDV.

In general, the STDV values observed in simulations (red) are around the same range of values when compared to the ones given in measurements. As in PSD analysis and S4 index, Occultation #2 presented a worse agreement between measurement and simulation compared to Occultations #1 and #3. The STDV value in the measurement is likely given by the increasing difference between corrected bending angle and climatology model above 60 km SLTA, see Figure 10b. This effect may not be related to ionospheric irregularities.

### 6. Conclusions

In this study, a model of ionospheric irregularities in the $F$ region was integrated with the MPS method. The simulator was used to evaluate three radio occultation measurements recorded by MetOp constellation with signatures of ionospheric scintillation in the signal amplitude. The model described in Carrano et al. (2011) was implemented, the investigation was extended to lower altitudes by including neutral atmosphere, and L1/L2 bending angles were derived to obtain the ionosphere corrected bending angle.

The RO measurements were selected based on scintillation index, bending angle STDV, and the single-slope power law observed in the PSD analyses. The single-slope pattern suits the SDF considered in our investigation. The modeling procedure was based on the estimation of the spectral slope, obtained by linear regression of the roll-off observed in the measurement PSD analysis, followed by simulations considering different values of outer scale and RMS level of fluctuation. In this context, the outer scale shows an inverse relation with the frequency break point observed in the PSD curve, also with the decorrelation time (fluctuation rate). The RMS level of fluctuation was adjusted accordingly to the EDP considered in the simulations in order to achieve an equivalent PSD response. A reasonable agreement in term of PSD between measurements and simulations generally led to comparable levels of S4 index, decorrelation time and bending angle STDV for the selected occultation cases.

It is worth mentioning that the results are limited to a 2-D propagation using 1-D screens used to replicate equatorial RO measurements with isotropic irregularities. The fact ionospheric irregularities are a three-dimensional process, that is, anisotropic rather than isotropic irregularities, means that the model assumed in simulations can eventually underestimate the fluctuations in amplitude (Galiègue et al., 2017). A thorough comparison including 3-D simulations of the evaluation cases would be required to address this matter. However, the error given by the reduction in one dimensional should be small and still serve as a relevant representation of the scattering in GNSS signal propagation along the longitudinal cut and perpendicular to the Earth’s geomagnetic field.

Since no complementary data from other remote sensing systems rather than MetOp satellites was used in this implementation, the region of irregularities was defined as a layer within $F$ region. This assumption simplified the implementation. This assumption may also have limited the results, since the shape and the distance of the region of irregularities to the observation plane affect the scintillation observed in the GNSS...
signal (Carrano et al., 2011). Nevertheless, the results obtained with this implementation are likely to emulate a similar total integrated phase variance, such as the one experienced by the radio signals during occultation events. This simulation tool can have a relevant application in the scope of statistical analysis of bending angle measurements and tracking techniques for MetOp mission, as well as for other RO systems.

Data Availability Statement

Pyglow package is open sourced and available online (https://github.com/timduly4/pyglow/). RO measurements are processed by CDAAC and made available online (https://cdaac-www.cosmic.ucar.edu, registration required). RO measurements assumed in the publication are available at https://zenodo.org/record/3938965#.XyBcTy17HQ).

References

Aaron, J. (1982). Global morphology of ionospheric scintillations. Proceedings of the IEEE, 70(4), 360–378. https://doi.org/10.1109/PROC.1982.12314
Blitz, D., Altdall, D., Truhlik, V., Shubin, V., Galkin, I., Reinisch, B., & Huang, X. (2017). International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions. Space Weather, 15, 418–429. https://doi.org/10.1002/2016SW001593
Bonnedal, M., Christensen, J., Carlström, A., & Berg, A. (2010). Metop-GRAS in-orbit instrument performance. GPS Solutions, 14(1), 109–120. https://doi.org/10.1007/s10291-009-0142-3
Carrano, C. S., & Groves, K. M. (2010). Temporal decorrelation of GPS satellite signals due to multiple scattering from ionospheric irregularities. In 23rd International Technical Meeting of The Satellite Division of the Institute of Navigation (IONGNSS’10) (pp. 361–374). Portland, OR, USA.
Carrano, C. S., Groves, K. M., Caton, R. G., Rino, C. L., & Strauss, P. R. (2011). Multiple phase screen modeling of ionospheric scintillation along radio occultation raypaths. Radio Science, 46, RS0D07. https://doi.org/10.1029/2010RS004591
Carrano, C. S., & Rino, C. L. (2016). A theory of scintillation for two-component power law irregularity spectra: Overview and numerical results. Radio Science, 51, 789–813. https://doi.org/10.1002/2015RS005903
Chandra, S., Fleming, L., Shoebber, R., & Barnett, J. (1990). Monthly climatology mean of global temperature, wind, geopotential height, and pressure for 0–120 km. Advances in Space Research, 10, 3–12.
Culverwell, I. D., & Healy, S. B. (2015). Simulation of L1 and L2 bending angles with a model ionosphere (Tech. Rep. 17). Copenhagen, Denmark: ROM SAF. https://www.romsaf.org/general-documents/rsr/rsr_17.pdf
Danzer, J., Healy, S. B., & Culverwell, I. D. (2015). A simulation study with a new residual ionospheric error model for GPS radio occultation climatologies. Atmospheric Measurement Techniques, 8(8), 3395–3404. https://doi.org/10.5194/amt-8-3395-2015
Galiègue, H., Féral, L., & Fabbro, V. (2017). Validity of 2d electromagnetic approaches to estimate log-amplitude and phase variances due to 3-D ionospheric irregularities. Journal of Geophysical Research: Space Physics, 122, 1410–1427. https://doi.org/10.1002/2016JA023233
Gherr, V. E., & Zernov, N. N. (2017). Extension of hybrid scintillation propagation model to the case of field propagation in the ionosphere with highly anisotropic irregularities. Radio Science, 52, 874–883. https://doi.org/10.1002/2017RS006264
Gherr, V. E., Zernov, N. N., & Strangeways, H. J. (2005). Propagation model for transionospheric fluctuating paths of propagation: Simulator of the transionospheric channel. Radio Science, 40, RS1003. https://doi.org/10.1029/2004RS003097
Gorbunov, M. E., & Gurvich, A. S. (1998). Microlab-1 experiment: Multipath effects in the lower troposphere. Journal of Geophysical Research, 103(D12), 13,819–13,826. https://doi.org/10.1029/98JD0806
Gorbunov, M. E., Gurvich, A. S., & Shmakov, A. V. (2002). Back-propagation and radio-holographic methods for investigation of sporadic e-layers from microlab-1 data. International Journal of Remote Sensing, 23(4), 675–685. https://doi.org/10.1080/0143116010030991
Gorbunov, M. E., & Shmakov, A. V. (2014). Variations of ionospheric fluctuations of phase delay depending on solar activity. Data of the COSMIC experiment. Cosmic Research, 52(4), 251–259. https://doi.org/10.1134/S0010952514040042
Gorbunov, M. E., Vorob’Ev, V. V., & Lauritsen, K. B. (2015). Fluctuations of refractivity as a systematic error source in radio occultations. Radio Science, 50, 656–669. https://doi.org/10.1002/2014RS005639
Gubenko, V. N., Pavelyev, A. G., Kirillovich, I. A., & Lisov, Y. A. (2018). Case study of inclined sporadic e layers in the Earth’s ionosphere observed by CHAMP/GPS radio occultations: Coupling between the tilted plasma layers and internal waves. Advances in Space Research, 61(7), 1702–1716. https://doi.org/10.1016/j.asr.2017.10.001
Hernandez-Pajares, M., Miguel Juan, J., Sanz, J., Aragon-Angel, A., Garcia-Rigo, A., Salazar, D., & Escudero, M. (2011). The ionosphere: Effects, GPS modeling and the benefit for space geodetic techniques. Journal of Geodesy, 85(12), 887–907. https://doi.org/10.1007/s00190-011-0508-5
Hocke, K., Liu, H., Pedatella, N., & Ma, G. (2019). Global sounding of f region irregularities by COSMIC during a geomagnetic storm. Annales Geophysicae, 37(2), 235–242. https://doi.org/10.5194/angeo-37-235-2019
Kintner, P. M., & Ledvina, B. M. (2005). The ionosphere, radio navigation, and global navigation satellite systems. Advances in Space Research, 35(5), 788–811. https://doi.org/10.1016/j.asr.2004.12.076
Kirchengast, G., Hafner, J., & Poetzl, W. (1999). CIRA86aq_1U6G model: An extension of the CIRA-86 monthly tables including humidity tables and a Fortran95 global moist air climatology model (Tech. Rep. for ESA/ESTEC No. 8/1999). Austria: Institute for Meteorology and Geophysics, University of Graz. http://wegcwwww.uni-graz.at/publ/users/gki/web/1999/gk-imtgechrepeisa-18p-nughty1999.pdf
Knap, D. (1983). Multiple phase-screen calculation of the temporal behavior of stochastic waves. Proceedings of the IEEE, 71(6), 722–737.
Kurtsinski, E. R., Hajj, G. A., Schofield, J. T., Linfield, R. P., & Hardy, K. R. (1997). Observing Earth’s atmosphere with radio occultation measurements using the global positioning system. Journal of Geophysical Research, 102(D19), 23,429–23,465. https://doi.org/10.1029/97JD01569
Liu, C., Kirchengast, G., Zhang, K., Norman, R., Li, Y., Zhang, S., et al. (2013). Characterisation of residual ionospheric errors in bending angles using GNSS RO end-to-end simulations. Advances in Space Research, 52(5), 821–836. https://doi.org/10.1016/j.asr.2013.05.021
Liu, C., Kirchengast, G., Zhang, K., Norman, R., Li, Y., Zhang, S., et al. (2015). Quantifying residual ionospheric errors in GNSS radio occultation bending angles based on ensembles of profiles from end-to-end simulations. Atmospheric Measurement Techniques, 8(7), 2999–3019. https://doi.org/10.5194/amt-8-2999-2015

Ludwig-Barbosa, V., Rasch, J., Carlstrom, A., Pettersson, M. I., & Vu, V. T. (2019). GNSS Radio Occultation simulation using multiple phase screen orbit sampling. IEEE Geoscience and Remote Sensing Letters, 17, 1323–1327. https://doi.org/10.1109/LGRS.2019.2944537

Rino, C. L. (1979a). A power law phase screen model for ionospheric scintillation: 1. Weak scatter. Radio Science, 14(6), 1135–1145. https://doi.org/10.1029/RS014i006p01135

Rino, C. L. (1979b). A power law phase screen model for ionospheric scintillation: 2. Strong scatter. Radio Science, 14(6), 1147–1155. https://doi.org/10.1029/RS014i006p01147

Rino, C. (2011). The theory of scintillation with applications in remote sensing. John Willey and Sons, Inc. https://doi.org/10.1002/9781118010211

Rufenach, C. L. (1975). Power spectra of large scintillation signals. Journal of Atmospheric and Terrestrial Physics, 37(3), 569–572. https://doi.org/10.1016/0021-9169(75)90184-1

Schreiner, W., Sokolovskiy, S., Hunt, D., & Rocken, C. (2011). Analysis of GPS radio occultation data from the FORMOSAT-3/COSMIC and metop/GRAS missions at CDAAC. Atmospheric Measurement Techniques, 4(10), 2255–2272. https://doi.org/10.5194/amt-4-2255-2011

Sokolovskiy, S., Schreiner, W., Rocken, C., & Hunt, D. (2002). Detection of high-altitude ionospheric irregularities with GPS/MET. Geophysical Research Letters, 29(3), 1033. https://doi.org/10.1029/2001GL013398

Strangeways, H. J., Zernov, N. N., & Gherm, V. E. (2014). Comparison of four methods for transionospheric scintillation evaluation. Radio Science, 49, 899–909. https://doi.org/10.1002/2014RS005408

Syndergaard, S. (2000). On the ionosphere calibration in GPS radio occultation measurements. Radio Science, 35(3), 865–883. https://doi.org/10.1029/1999RS002399

Syndergaard, S. (2006). COSMIC S4 data. Boulder, CO: UCAR/CDAAC.

Umeki, R., Liu, C. H., & Yeh, K. C. (1977). Multifrequency spectra of ionospheric amplitude scintillations. Journal of Geophysical Research, 82(19), 2752–2760. https://doi.org/10.1029/JA082i019p02752

Vorob’ev, V. V., Gurvich, A. S., Kan, V., Sokolovskii, S. V., Fedorova, O. V., & Shmakov, A. V. (1999). Structure of the ionosphere based on radio occultation data from GPS microlab-1 satellites: Preliminary results. Earth Observation and Remote Sensing, 15(4), 609–622.

Vorob’ev, V. V., & Kan, V. (1994). Estimation of the accuracy of the atmospheric refractive index recovery from doppler shift measurements at frequencies used in the NAVSTAR system. Atmospheric and Oceanic Physics, 29(5), 602–609.

Wang, G., Shi, J., Bai, W., Galkin, I., Wang, Z., & Sun, Y. (2019). Global ionospheric scintillations revealed by GPS radio occultation data with FY3C satellite before midnight during the March 2015 storm. Advances in Space Research, 63, 3077–3428. https://doi.org/10.1016/j.asr.2019.01.028

Yeh, K. C., & Liu, C. H. (1982). Radio wave scintillations in the ionosphere. In Proceedings of the IEEE (Vol. 70, 4th ed., pp. 324–360). https://doi.org/10.1109/PROC.1982.12313

Yue, X., Schreiner, W. S., Pedatella, N. M., & Kuo, Y. H. (2016). Characterizing GPS radio occultation loss of lock due to ionospheric weather. Space Weather, 14, 285–299. https://doi.org/10.1002/2015SW001340

Zeng, Z., & Sokolovskiy, S. (2010). Effect of sporadic E clouds on GPS radio occultation signals. Geophysical Research Letters, 37, L18817. https://doi.org/10.1029/2010GL044561

Zernov, N. N., Gherm, V. E., & Strangeways, H. J. (2009). On the effects of scintillation of low-latitude bubbles on transionospheric paths of propagation. Radio Science, 44, RS0A14. https://doi.org/10.1029/2008RS004074