Impact of Tropospheric Scintillation in the Ku/K Bands on the Communications Between Two LEO Satellites in a Radio Occultation Geometry

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***Abstract*—A theoretical analysis of the impact of clear-air tropospheric scintillation on a radio occultation link between two low Earth orbit satellites in K- and Ku-bands is presented, with particular reference to differential approaches for the measure of the total content of water vapor. The troposphere is described as a spherically symmetric turbulent medium satisfying Kolmogorov theory. Rytov's first iteration solution for weak fluctuations is used to derive an expression for the variance of amplitude fluctuations of the wave as well as their spectrum and the correlation between fluctuations at different frequencies. The validity of the assumptions made and the influence of atmospheric parameters on the quantities of interest are also investigated and discussed. Finally, numerical results are presented to provide an estimate of the level of scintillation-induced disturbances.**

***Index Terms*—LEO–LEO link, low Earth orbit (LEO), microwave propagation, radio occultation, random media, satellite communication, scintillation.**

I. Introduction

RADIO occultation techniques, exploiting changes of phase and amplitude of the signal propagating along a satellite-to-satellite link during an occultation (rise or set) event, are promising methods to investigate climatological parameters [1]–[4]. The retrieved vertical profiles of refractivity are used to extract information on temperature, pressure, and water vapor content as a function of height. ACE+ mission studies [5], carried out within the framework of Earth Explorer Opportunity Missions supported by the European Space Agency (ESA), have investigated for the first time the possibility to exploit radio occultation at frequencies close to the water absorption peak at 22.235 GHz through radio links between two counter-rotating low Earth orbit (LEO) satellites. At such frequencies, the propagation of radio waves is subject (due to tropospheric turbulence and the rate at which the LEO–LEO radio link immerses in the atmosphere) to important scintillation effects. Experimental results relevant to occultation measurements between an orbital spacecraft and a geostationary satellite using both decimeter and centimeter waves have shown significant amplitude fluctuations of the received signal [6], [7].

Such fluctuations—though filtered—may have a nonnegligible residual impact when implementing a radio occultation with standard single-frequency measurement methods. Recently, a differential method for the retrieval of atmospheric transmissions, based on the use of a canonical transform, has been proposed to overcome this impairment [8]. Furthermore, two of the authors investigated the potential of the so-called normalized differential spectral attenuation (NDSA) approach [9], [10] for the estimate of the total content of water vapor [integrated water vapor (IWV)] along the propagation path between two LEO satellites. The method is based on the ratio of simultaneously measured total path attenuations at two relatively close frequencies in the K-band. The interest toward the NDSA approach was prompted not only by the fact that NDSA measurements are highly correlated to the IWV along the LEO–LEO link but also by the foreseen potential of limiting the aforementioned scintillation effects. Before proceeding to confirm this through *ad hoc* simulations, it was deemed important to focus on scintillation models and analysis.

The influence of atmospheric turbulence on Earth-to-satellite links and its dependence on the main link parameters have been the subject of several papers ([11], [12], and references therein). A theoretical analysis of scintillation effects on radio occultation links has been presented in [13] and [14], with reference to planetary flyby missions. The model proposed in [13] has been recently applied in [15] and [16] to study the impact of scintillation on LEO–LEO radio occultation links in the Ku- and K-bands. However, due to differences in the geometry and frequencies involved, the applicability of such a formulation to the analysis of LEO–LEO links has to be more accurately investigated.

In this framework, the first objective is to develop a theoretical model for the analysis of turbulence-induced scintillations, which is tailored on LEO–LEO radio occultation links. In particular, the applicability to this problem of some commonly assumed approximations is investigated and discussed. The proposed model is then applied to estimate the impact of scintillation effects on radio occultation measurements, with particular reference to the NDSA approach. To this end, two quantities are of great interest, namely: 1) the variance and 2) the frequency correlation of the amplitude fluctuations. Indeed, only high correlation values between the fluctuations of signals at different frequencies allow NDSA measurements to outperform standard single-frequency approaches at all altitudes in the troposphere [9], [10].

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In Section II, the weak fluctuation theory for line-of-sight propagation is briefly revised and specified to the problem under consideration. In Section III, analytical expressions are derived for the variances of the amplitude fluctuations of the wave, their temporal frequency spectrum, and the zero-lag correlation coefficients between fluctuations at different frequencies. Such expressions have been numerically evaluated to provide a quantitative estimate of the scintillation effects, and the results are shown in Section IV. The range of validity of different scintillation models presented in the literature is also discussed. Finally, Section V will draw the conclusions.

II. Turbulence Model for the LEO–LEO Link

In the lower troposphere, scintillations are mainly caused by small-scale fluctuations of the refractive index due to atmospheric turbulence [6]. The turbulent medium can be statistically characterized by defining its refractive index n as a stochastic function of position and time; here, for the sake of simplicity, only spatial dependence is considered first. The refractive index $n(\vec{r})$ is written as the sum of the ensemble average $\langle n(\vec{r})\rangle$ and the fluctuation, i.e., $n(\vec{r}) = \langle n(\vec{r})\rangle(1 + n_1(\vec{r}))$. In this section, n_1 will be assumed real; this means that only random changes in the real part of the refractive index are considered, whereas absorption and scattering due to rain or fog are not included in the analysis.

Because under clear weather conditions depolarization effects are usually negligible [17], the field propagating through the medium can be determined by solving the scalar wave equation

$$\nabla^2 E(\vec{r}) + k^2(\vec{r})\left[1 + n_1(\vec{r})\right]^2 E(\vec{r}) = 0 \tag{1}$$

where $k = k_0\langle n\rangle$ is the mean wavenumber of the medium. Equation (1) can be solved by applying Rytov approximation [17]. This consists of first expressing the unknown solution as the product of the field strength E_0, which would be measured in the absence of irregularities, and a correction term, which is represented in an exponential form (i.e., $E(\vec{r}) = E_0(\vec{r})e^{\psi(\vec{r})}$), and then developing a series solution for the complex function ψ, i.e., $\psi(\vec{r}) = \psi_1(\vec{r}) + \psi_2(\vec{r}) + \psi_3(\vec{r}) + \cdots$.

Under the hypothesis of weak scattering, whose validity is assumed in this paper and verified *a posteriori*, the first term of the series is sufficient to accurately describe the propagation. This term, which is called the first Rytov solution, can be written as [17]

$$\psi(\vec{r}) \simeq \psi_1(\vec{r}) = \iiint\limits_{V'} h(\vec{r},\vec{r}\,')n_1(\vec{r}\,')d\vec{r}\,' \tag{2}$$

where

$$h(\vec{r},\vec{r}\,') = \frac{2k^2 G\left(|\vec{r}-\vec{r}\,'|\right)E_0(\vec{r}\,')}{E_0(\vec{r})} \tag{3}$$

and $G(\vec{r}-\vec{r}\,') = (e^{-jk|\vec{r}-\vec{r}\,'|})/(4\pi|\vec{r}-\vec{r}\,'|)$ is the free space Green's function. In (2), the point $\vec{r} \equiv (x,y,z)$ represents the observer position, whereas $\vec{r}\,' \equiv (x',y',z')$ represents the scattering eddy position (Fig. 1).

The real part of ψ_1, denoted here by χ, represents the fluctuation of the logarithm of the amplitude ($\chi = \Re e\{\psi_1\} = \ln(|E|/|E_0|)$) and is called the log-amplitude fluctuation. The imaginary part, denoted by φ, represents the phase fluctuation ($\varphi = \Im m\{\psi_1\} = \angle E - \angle E_0$). In the following section, we will focus on the statistical characteristics of the stochastic variables χ and φ. In particular, the average values of χ and φ are zero; hence, their variances are the first measure of the variability of the signal.

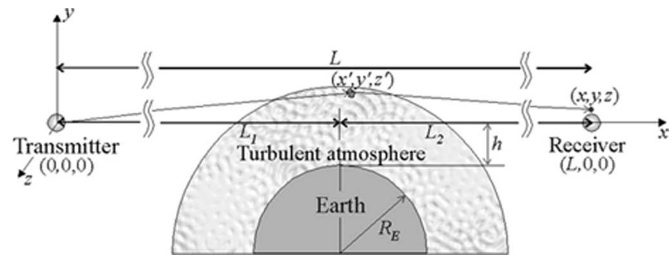


Fig. 1. Geometry for the LEO–LEO link.

In order to analyze the effect of tropospheric scintillation on LEO–LEO communication, (2) must be specialized for the link under consideration, whose geometry is shown in Fig. 1. The transmitter is located on-board the first LEO satellite and the field is observed at a point near the second satellite. A point receiver is considered; thus, the spatial filtering due to the finite size of the antenna aperture is not accounted for. Turbulence is supposed to be localized and smoothly varying, with the intensity exponentially decreasing with altitude. For the sake of simplicity, a straight ray path is assumed for the scintillation analysis. This is a justifiable assumption because the ray is practically straight within the segment of effective interaction with the atmosphere; the effects of bending due to refraction can be accounted for *a posteriori* in order to obtain the relationship between the actual satellite position and the ray tangent altitude. A Cartesian coordinate system is introduced, with the origin coincident with the transmitter and the x axis along the radio path; the distance from the x axis is indicated with ρ. Finally, h denotes the tangent altitude of the propagation path, L the distance between the two satellites, and R_{E} the Earth radius.

First, a model has to be chosen to describe the field E_0 generated in free space by the transmitting antenna on the LEO satellite. As a rule, inasmuch as all the practical sources are of limited extent, the spherical wave and beam theory are always most adequate. In particular, the beam nature of the wave needs to be taken into account only if the random medium is located in the near field of the source [18], whereas in other cases a good approximation is provided by a spherical wave source model. For the problem at hand, the far zone distance is a few hundred meters and the turbulent zone is localized around the tangent point ($x = L_1$, $\rho = 0$), about 3000 km from the transmitter; hence, the source can be well approximated by a spherical wave.

After representing the unperturbed field as $E_0(\vec{r}) = e^{-jkr}/r$, the h function takes on the form

$$h(\vec{r},\vec{r}\,') = \frac{k^2}{2\pi}\frac{e^{-jk|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|}\frac{e^{-jkr'}}{r'}\frac{r}{e^{-jkr}} \tag{4}$$

where $r = |\vec{r}|$ and $r' = |\vec{r}\,'|$. Inasmuch as the most influential turbulent blobs are large compared to the wavelengths of interest (between 1 and 2 cm), and the scattering from an inhomogeneity of size l is confined within a forward angle of the order of λ/l, scattering takes place in the neighborhood of the x axis. Furthermore, the irregularities, which can provide a significant contribution to the field received at the observation point, are those contained in the first Fresnel zone, whose radius, given by $L_S = \sqrt{(L-L_1)L_1\lambda/L}$, is about 150 m for the frequencies of interest. Hence, a paraxial approximation can be exploited; in particular, the scalar quantity r' is represented by means of a truncated Taylor expansion given as

$$r' \simeq \sqrt{x'^2+y'^2+z'^2} \cong x'\left[1+\frac{y'^2+z'^2}{2x'^2}\right]. \tag{5}$$

Although the second term is much smaller than the first one and can be neglected in the denominator of (4), it must be kept in the exponent in order to accurately describe the phase of the field illuminating the turbulent region. As a matter of fact, retaining only the first term of the expansion is equivalent to assuming a plane wavefront, and for the geometry of interest, it would introduce phase errors up to 90° within the first Fresnel region, the maximum phase error being approximately given by $k[L_s^2/(2L_1)]$. On the other hand, the phase error introduced by neglecting the third term of the expansion is negligible. Similar expansions can be introduced for $|\vec{r}-\vec{r}'|$ and r.

With these approximations, the h function in the plane $x = L$ is obtained as

$$h(\vec{r},\vec{r}') \simeq \tilde{h}(L-x',\vec{\rho}'-\gamma(x')\vec{\rho}) = \frac{k^2}{2\pi}\frac{e^{j\frac{k}{2}\frac{|\vec{\rho}'-\gamma(x')\vec{\rho}|^2}{\gamma(x')(L-x')}}}{\gamma(x')(L-x')} \tag{6}$$

with $\gamma(x') = x'/L$ and $\vec{\rho} = y\hat{y} + z\hat{z}$.

It is worth noting that the plane wave incidence model provides (6) with $\gamma = 1$ [18]. As a matter of fact, such a model constitutes an accurate approximation when the incident phase front can be the assumed plane throughout the influential portion of the turbulent region. This is the case of geostationary Earth orbit (GEO)–LEO links, for which $\gamma \simeq 1$, being $L_1 \simeq L \gg L_2$. In [16], the plane wave model has been applied also to the analysis of a LEO–LEO link. However, for a LEO–LEO link, $\gamma \simeq 1/2$, being $L_1 \simeq L_2 \simeq L/2$. A similar case has been recently considered in [19], and it has been shown that the Fraunhofer diffraction approximation cannot in general be used in the theory of scattering by distributed scatterers in the far zone of the antenna. Hence, the accuracy provided by the plane wave approximate model needs to be checked.

In this paper, both spherical and plane wave models are jointly considered by defining the variable γ in (6) as

$$\gamma(x) = \begin{cases} \frac{x}{L}, & \text{for spherical wave incidence} \\ 1, & \text{for plane wave incidence.} \end{cases} \tag{7}$$

Then, the results are compared in order to evaluate the impact of the source model on the estimate of scintillation effects.

III. Log-Amplitude Variance, Frequency Correlation, and Spectrum

A. Log-Amplitude Variance

An important feature of electromagnetic scintillation is the spatial correlation function, which provides a measure of the similarity between fluctuations of signals at adjacent points. The random process n_1 is assumed to be localized, with smoothly varying mean characteristics in the yz plane. Under this hypothesis, the effect of inhomogeneity can be accurately characterized by describing the turbulence as a locally homogeneous medium, according to the model developed by Silverman [20] and applied to the study of atmospheric turbulence by Ishimaru [14], [21]. In particular, in the Appendix, it is shown that if the Fresnel zone length is small compared to both the vertical scale b of the turbulence and the quantity $\sqrt{L_0 b}$, where L_0 is the outer scale of the turbulence, the log-amplitude fluctuation variance at the observation point is given by the well-known expression for a locally homogeneous medium [22], modulated by the function C_n^2, accounting for the variation of turbulence intensity with altitude. Inasmuch as this quantity is proportional to the atmospheric pressure, in this paper, it has been modeled through an exponential, as shown in [14]. Furthermore, the Kolmogorov isotropic model has been assumed for the spectrum of refractive index fluctuations. Although large-scale irregularities are usually anisotropic, they do not contribute to the signal amplitude fluctuation of waves propagating in the troposphere inasmuch as the low-frequency part of the spectrum is filtered out by the weight function [17]. As a consequence, the Kolmogorov model can be used with confidence, as confirmed also by experimental results [6], [23]. On the other hand, in the stratosphere refractive index, inhomogeneities are strongly horizontally prolated, and these anisotropic irregularities provide a significant contribution to the amplitude fluctuations of radio waves [24], [25].

Under the aforementioned hypotheses, the following expression is finally obtained for the log-amplitude fluctuation variance, i.e.,

$$\sigma_\chi^2(L,\vec{\rho}) = 4\pi^2k^2a\sqrt{\pi}\,0.033C_n^2\left(L_1,\frac{L_1}{L}\vec{\rho}\right) \times \int_0^{+\infty}\Phi_n^0(\kappa)\sin^2\left(\frac{L_s^2\kappa^2}{4\pi}\right)\kappa d\kappa \tag{8}$$

where a represents the variation scale of turbulence in the $x-z$ plane. It is worth noting that the function C_n^2 is to be evaluated at $(L_1,(L_1/L)\vec{\rho})$, which is the location where the propagation path crosses the turbulent atmosphere.

A more general expression, which is valid for a smaller scale of variation of turbulence, is given in the Appendix. The validity of (8) is numerically investigated in Section IV for different values of the vertical scale b.

Closed-form approximations of the integral in (8) are available in the literature; their applicability depends on the relative values of the size of the Fresnel zone L_S, the outer scale L_0, and the vertical and horizontal characteristic sizes of the turbulent medium. Concerning the evaluation of these integrals, the so-called Region 2 approximation [18] has been employed in [16]. Such an approximation, which reads $\sigma_\chi^2(L,0) = 0.693 \times C_{n0}^2 e^{-h/b} L_0^{5/3} k^2 a$, can be obtained from (8) under the hypothesis $A_1 = [L_1(L-L_1)]/kL \gg L_0^2$ [14]. However, by assuming for L_s and L_0 the realistic values chosen in [16], it results in $A_1 < L_0^2$. Hence, the Region 2 approximate expression does not provide a good estimate of the integral in (8), and the numerical evaluation of the latter is required to obtain accurate results. Notice also that, whereas in the range of $L_0 \ll L_s \ll \sqrt{L_0 b}$ the variance is the same for both plane and spherical wave incidences, this is not the case for $L_0 \simeq L_s$. Numerical results, as shown in Section IV, corroborate these conclusions.

B. Two-Frequency Amplitude Correlations

To evaluate the impact of scintillation on differential methods exploiting simultaneous measurements of attenuation at two different frequencies for the analysis of water vapor content [6], [9], [26], it is extremely useful to consider the correlation coefficient between waves at two different operating frequencies f_1 and f_2. Theoretical expressions for the frequency correlation of amplitude fluctuations for both plane and spherical wave incidences have been derived by exploiting the weak-scattering propagation theory [21], [27], [28]. It has been found that the correlation remains rather high even for a relatively large frequency separation. However, in [29], by deriving the covariance of fluctuations at two frequencies as a function of the spatial wavenumber of the atmospheric inhomogeneities, it has been shown that the correlation diminishes rapidly for inhomogeneity scale sizes smaller than a certain critical value, depending on the given couple of frequencies and on the path geometry.

Under the hypotheses made in the previous paragraphs and assuming that the two frequencies are close enough to each other to propagate along coincident paths, by applying Rytov approximation, the amplitude frequency correlation at $\vec{r} = (L, 0)$ [17] is obtained as

$$\rho_\chi = 4\pi^2 k_1 k_2 a\sqrt{\pi} B_n^v(L_1, 0) \times \frac{\int_0^{+\infty} \Phi_n^0(\kappa) \sin\left[\frac{\gamma_1(L-L_1)\kappa^2}{2k_1}\right] \sin\left[\frac{\gamma_1(L-L_1)\kappa^2}{2k_2}\right] \kappa d\kappa}{\sigma_{\chi 1}\sigma_{\chi 2}} \tag{9}$$

where $k_1 = 2\pi f_1/c, k_2 = 2\pi f_2/c$, and $\sigma_{\chi 1}$ and $\sigma_{\chi 2}$ are the log-amplitude standard deviations at the two frequencies. It is worth noting that as long as the conditions $b \gg \sqrt{L_0 b}$ and $b \gg L_s$ are satisfied, the frequency correlation function does not depend on the structure constant profile.

C. Temporal Frequency Spectra

In the previous sections, the refractive index fluctuation was assumed to be a random function of position only and independent of time. This is of course not the case during a radio occultation inasmuch as the satellites are moving at a considerable speed with respect to turbulence. A statistical description of the fluctuation may be given in terms of the temporal frequency spectrum [14], [30], [31], which provides information on which frequency components contribute effectively to the variance of the random process and is, therefore, essential for studying the effects of a possible filtering on the power of the received fluctuation. Similarly, information on the frequency correlation of fluctuations of the filtered signals can be obtained by the analysis of the multifrequency coherence function [32].

The log-amplitude temporal frequency spectrum is defined as

$$W_\chi(L, \vec{\rho}, \omega) = 4\int_0^\infty R_\chi(L, \vec{\rho}, \tau)\cos(\omega\tau)d\tau \tag{10}$$

where ω is the temporal angular frequency and $R_\chi(L, \vec{\rho}, \tau) = \langle \chi(L, \vec{\rho}, t)\chi(L, \vec{\rho}, t+\tau)\rangle$ is the time-lagged autocorrelation function at $(L, \vec{\rho})$. Such a function can be related to the spatial autocorrelation function B_χ by assuming that the time variations of the refractive index fluctuations seen by the signal are dominated by the effects of the satellites movement transverse to the propagation path. Under this assumption, which is known as Taylor's frozen-in hypothesis [33], it results in

$$n_1(\vec{r}, t) = n_1(\vec{r} + \vec{v}t, 0) \tag{11}$$

where v is the satellite velocity transverse to the propagation path, which is, in general, a function of position. Under this hypothesis and assuming that the coordinate system is moving with the transmitter, the first Rytov solution can be written as

$$\begin{aligned}\psi_1(\vec{r}, t) &= \iiint_{V'} h(\vec{r}, \vec{r}' - \vec{v}t) n_1(\vec{r}', 0) d\vec{r}' \\ &\cong \iiint_{V'} \tilde{h}(x - x', \vec{\rho}' - \vec{v}t - \gamma\vec{\rho}') n_1(\vec{r}', 0) d\vec{r}' \\ &= \psi_1\left(\vec{r} + \frac{\vec{v}t}{\gamma}, 0\right).\end{aligned} \tag{12}$$

This implies that the temporal and spatial autocorrelation functions at a given position $(L, \vec{\rho})$ can be linked through the relationship $R_\chi(L, \vec{\rho}, \tau) = B_\chi(L, \vec{\rho}, \vec{\rho} - (\vec{v}\tau)/\gamma)$. Hence, by employing for B_χ (22) in the Appendix, it is obtained as

$$W_\chi(L, \vec{\rho}, \omega) = 16\pi^2\sqrt{\pi}k^2 a B_n^v(L_1, \gamma_1\vec{\rho}) \times \int_0^\infty \kappa\Phi_n^0(\kappa)\sin^2\!\left(\frac{\kappa^2 A_1}{2}\right)\int_0^\infty e^{-\frac{v\tau}{2b}} J_0(\kappa v\tau)\cos(\omega\tau)d\tau d\kappa. \tag{13}$$

The integral in τ has been evaluated in closed form by exploiting the result reported in [34, p. 11, eq. (46)], thus obtaining the following integral representation for the temporal frequency spectrum as

$$W\chi(L, \vec{\rho}, \omega) = \frac{16\pi^2 k^2\sqrt{\pi}a}{v} B_n^v(L_1, \gamma_1\vec{\rho}) \times \int_0^{+\infty} \kappa\Phi_n^0(\kappa)\sin^2\left(\frac{A_1\kappa^2}{2}\right)\frac{\sqrt{\sqrt{M^2 + \frac{\omega^2}{v^2 b^2}} + M}}{\sqrt{2}\sqrt{M^2 + \frac{\omega^2}{v^2 b^2}}} d\kappa \tag{14}$$

with $M = 1/(4b^2) + \kappa^2 - \omega^2/v^2$. This formula accounts for the inhomogeneity of the turbulence in the direction transverse to the propagation path; for $b \to \infty$, it reduces to the one provided in [18] for homogeneous media.

IV. Numerical Results for Scintillation Parameters

In order to evaluate the impact of scintillation on a LEO–LEO link, we ought to know the profile of the structure constant. As anticipated, the average altitude dependence of the structure constant has been described by an exponential model. In particular, the following four profiles corresponding to different regions, from high to tropical latitudes [35], have been considered:

Case 1) $C_n^2 = 1.0\,10^{-16}e^{-h/2000}$
Case 2) $C_n^2 = 1.3\,10^{-15}e^{-h/2000}$
Case 3) $C_n^2 = 1.0\,10^{-14}e^{-h/1500}$
Case 4) $C_n^2 = 2.0\,10^{-13}e^{-h/1000}$

where h is the quote expressed in m. These profiles have been derived by Sterenborg *et al.* by applying the procedure described in [36] and are in good agreement with those presented

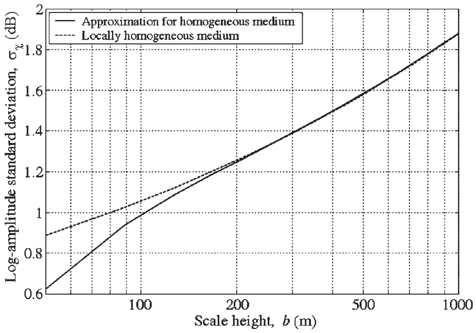


Fig. 2. Log-amplitude standard deviation versus scale height b at 20 GHz with $C_n^2 = 1 \times 10^{-14} e^{-h/b}$ and $h = b$. Comparison between homogeneous (continuous line) and locally homogeneous (dashed line) medium model.

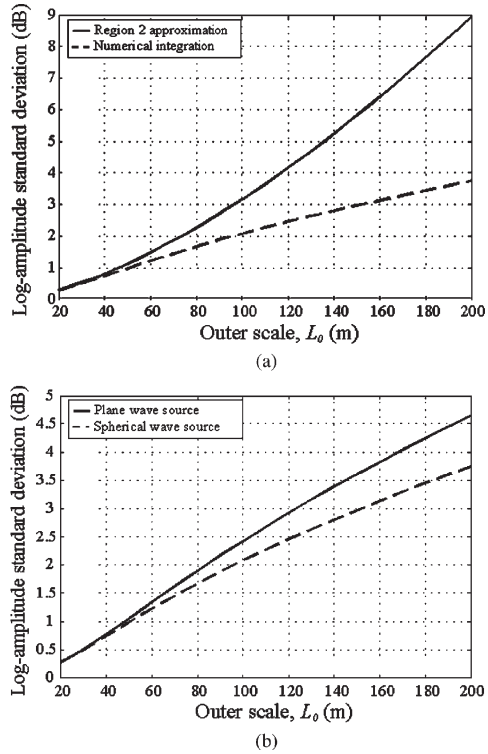


Fig. 3. Log-amplitude standard deviation versus the outer scale of turbulence L_0 at 20 GHz. The turbulence structure constant is described as $C_n^2 = 1 \times 10^{-14}(L_0/100)^{4/3} e^{-h/b}$, and the analysis is performed at $h = b$. (a) Comparison between the numerical integration and the approximated formula for Region 2. (b) Comparison between the plane and spherical wave source model.

in [37]. Although this is only a rough model of the structure constant variation, it is suitable to investigate the performance of radio occultation experiments in the presence of turbulence because it can provide a correct averaged dependence of the log-amplitude variance while maintaining the simplicity of calculations.

First, several analyses were performed, varying the inner scale l_0 between a few millimeters and a few centimeters, in accordance with the values reported in the literature [17]. Inasmuch as the precise value of this parameter has been found not to have a significant influence on the scintillation effects for the link under analysis, the value of 10 mm has been employed in the following section.

As far as the outer scale of turbulence is concerned, its value is imprecisely defined because there are very few reliable experimental results, and it depends significantly on meteorological conditions. Accordingly, the relevant estimates presented in the literature vary in a very wide range. In this paper, the value $L_0 = 100$ m, which represents a compromise between the experimental results reported in [38] and those presented in [39], has been assumed.

The geometry of the link assumed in the simulations is the one considered in the ESA ACE+ Mission [5], for which the transmitter and receiver altitudes are 850 and 650 km, respectively. The distance between the transmitter and the turbulent zone is $L_1 \simeq 3400$ km, and the turbulence-receiver distance is $L_2 \simeq 2900$ km. Finally, the transverse sweeping velocity of the satellites was estimated to be about 3 km/s.

As far as the frequency is concerned, two values close to the frequencies proposed for the NDSA method [9], namely, 17 and 20 GHz, have been considered. At these frequencies, the Fresnel zone length for the LEO–LEO link is

$$L_S = \sqrt{\frac{\lambda L_1 L_2}{L_1 + L_2}} \cong \begin{cases} 166 \text{ m}, & \text{at 17 GHz} \\ 153 \text{ m}, & \text{at 20 GHz.} \end{cases} \quad (15)$$

Having assumed that the turbulence transverse scale of variation ranges between 1 and 2 km, this quantity is small compared to $\sqrt{bL_0}$, thus justifying the modeling of the refractive index fluctuations as a homogeneous process with a slowly varying variance. This conclusion has been verified numerically by comparing, for different values of the scale height b, the values of the log-amplitude standard deviation obtained from (8) with those provided by the more rigorous formulation based on the concept of local homogeneity [(22) for $\rho_1 = \rho_2$]. Fig. 2 reports the results obtained at 20 GHz, which clearly show that the first approach provides a very good approximation for $b > 300$ m. Similar results have been obtained at 17 GHz and are not shown for the sake of brevity. In all the examples considered, the relationship $\sigma(\text{dB}) = 8.686\ \sigma(\text{Np})$ has been employed to convert the log-amplitude variance σ into decibel units.

The integral in (8) exhibits a rapidly oscillating integrand and cannot be easily evaluated numerically. In order to speed up its computation while maintaining a good accuracy, it has been rephrased as

$$\int_0^{+\infty} \Phi_n^0(\kappa) \sin^2\left(\frac{A_1\kappa^2}{2}\right) \kappa d\kappa = \int_0^{+\infty} \left[\Phi_n^0(\kappa) - \Phi_n^{\text{asym}}(\kappa)\right] \times \sin^2\left(\frac{A_1\kappa^2}{2}\right) \kappa d\kappa - \int_0^{+\infty} \Phi_n^{\text{asym}}(\kappa) \sin^2\left(\frac{A_1\kappa^2}{2}\right) \kappa d\kappa \quad (16)$$

where $\Phi_n^{\text{asym}}(\kappa) = \kappa^{-11/3}$. The argument of the first integral in the right-hand side (RHS) of (16) is monotonic and rapidly decaying because $\Phi_n^{\text{asym}}(\kappa)$ well represents the asymptotic behavior of $\Phi_n^0(\kappa)$ for large κ, whereas the numerical value of the second integral is known [17, Vol. 2, Appendix B].

Then, the impact of the outer scale value on the log-amplitude fluctuations has been investigated. Fig. 3 shows the value of the log-amplitude standard variation for different outer scales. The C_n^2 case 3 introduced previously, along with a proper dependence of C_{n0}^2 on L_0 (i.e., $C_{n0}^2 \propto L_0^{4/3}$, [22]), was considered. In Fig. 3(a), the results obtained by the numerical integration of (8) are compared with those provided by the

TABLE I
LOG-AMPLITUDE STANDARD DEVIATION AT 20 GHz FOR THE FOUR DIFFERENT C_n^2 CASES WITH $L_0 = 100$ m, AT A TANGENT ALTITUDE $h = b$: COMPARISON BETWEEN DIFFERENT MODELS

σ_χ (dB)	C_n^2 case 1	C_n^2 case 2	C_n^2 case 3	C_n^2 case 4
Spherical wave incidence	0.11	0.40	1.04	4.20
Plane wave incidence	0.12	0.47	1.21	4.90
Region II approximation	0.17	0.66	1.58	6.40

Region 2 approximation. Clearly, this approximation can only be applied for small L_0 values, whereas for $L_0 = 100$ m, it overestimates the log-amplitude standard deviation by more than 1 dB (3.17 dB instead of 2.08 dB). In Fig. 3(b), a comparison between the plane and spherical wave incidence models is shown. It can be observed that the plane wave model provides a higher value for σ_χ and the two curves coincide only when L_0 is less than 40 m. The numerical values of the log-amplitude standard deviation at 20 GHz for $L_0 = 100$ m and $h = b$ are compared in Table I, which clearly shows how the Region 2 approximation significantly overestimates the σ_χ value. In addition, it is shown that the plane wave incidence model provides higher scintillation variances. The same considera tions hold at 17 GHz.

It is worth noting that, for the values considered for the scale variation b, the structure constant profile only affects the variation of the log-amplitude variance with altitude above the Earth. Fig. 4 shows such a variation for the four C_n^2 cases. It can be seen that at altitudes greater than 5 km, this quantity is almost always less than 1 dB; accounting for the gradual decline of the outer scale length with altitude is expected to yield an even faster variance decay. These numerical results confirm the validity of the first Rytov solution, which, as shown in [17], [40], [41], can provide a valid description of the propagation through a turbulent medium when the logarithmic amplitude variance satisfies the condition $\langle \chi^2 \rangle < 1$, which means $\sigma_\chi < 8.686$ dB. It is very important to recall, however, that the previous results can only provide a rough estimate of the amplitude standard deviation because they depend quite strongly on a number of parameters (outer scale of the turbulence, structure constant, etc.), which are not known with sufficient accuracy. As far as the behavior of the spectrum of the refractive index fluctuation in the input range is concerned, it has been verified that its effect on the variance is very small because in the cases analyzed, only about 2% of the power comes from this range.

Fig. 5 shows the log-amplitude frequency correlation versus the frequency ratio for different outer scale values. Notice that assuming $L_0 = \infty$ (and hence, $\kappa_0 = 0$) is equivalent to extending the Kolmogorov model also to the input range region. Therefore, the relevant results provide information about the influence of the input range spectrum on the correlation values. In particular, by considering the different spectrum models proposed in the literature [42], it can be inferred that for a given value of L_0, a correlation comprised between the value provided by the Von Karman spectrum and the one relevant to the Kolmogorov model can be expected, depending on the input range spectrum behavior. The lack of knowledge about the actual value of the outer scale of the turbulence is a main source of uncertainty in the evaluation of the impact of scintillation on the LEO–LEO link performance. On the contrary, it has been found that the signal fluctuations are basically not affected by wavenumbers larger than κ_s (dissipation range of the spectrum, $\kappa > \kappa_s$).

In Fig. 5(a), the correlation values obtained by assuming a spherical wave model are reported, whereas in Fig. 5(b), the ratio between such values and the ones obtained with a plane wave model is represented. It is shown that lower correlation values are obtained for the plane wave incidence, except for $L_0 = \infty$, when the two source models provide the same correlation value (the relevant curve is not reported in the graph). These results also show that correlation rapidly decreases for decreasing blob sizes, especially for plane wave incidence. On the contrary, it has been found to depend very weakly on the specific value of the two frequencies, as far as they are contained in the K- and Ku-bands.

Table II reports the amplitude correlation values for the two couples of frequencies of main interest in the aforementioned NDSA method, namely, 17.2–17.3 GHz and 20.15–20.35 GHz [9], corresponding to the frequencies ratios 1.006 and 1.010, respectively.

Finally, an example of the power spectrum at 20 GHz (C_n^2 case 4, $h = b$, $L_0 = 100$ m and $v = 3$ km/s), is shown in Fig. 6. It can be shown that the spectrum for the spherical wave incidence exhibits a slight predominance of higher frequencies due to the lower value of the Fresnel zone size [31]. A similar behavior has been found at 17 GHz. The curves obtained by employing the classical expression for a locally homogeneous medium [18] are compared with the ones provided by (14), and it is found that the modulation introduced in the spectrum by the structure constant variation is negligible.

V. CONCLUSION

The Rytov method has been applied to describe the effects induced by atmospheric turbulence on signals in the K- and Ku-bands propagating along a LEO–LEO link in a radio occultation geometry. Analytical expressions have been derived for the variance, spectra, and frequency correlation of log-amplitude fluctuations of signals and then numerically evaluated to yield an estimate of the scintillation effects on the radio link, with particular reference to the quantities of interest for the NDSA approach.

On the basis of the numerical results, it can be inferred that the weak fluctuation theory can provide a valid description of the wave propagation in the problem under consideration. Nevertheless, a nonnegligible amount of uncertainty still remains due to lack of a precise estimate for the actual turbulence parameters. However, the formulas presented here provide information on the order of magnitude of the disturbances due to the scintillation effects to be expected in this kind of applications, and on the dependence of the scintillation variance and frequency correlation on the atmosphere's characteristics.

In particular, it has been found that, with the values assumed for the parameters describing the turbulence, the effects of inhomogeneity can be described by simply introducing a proper dependence of the structure constant on the tangent altitude. As far as the source model is concerned, it has been shown that a spherical wave source is more adequate than a plane wave one to model the transmitter. It also has been verified that the plane wave model leads to a slightly higher value of scintillation power and to lower frequency correlation values.

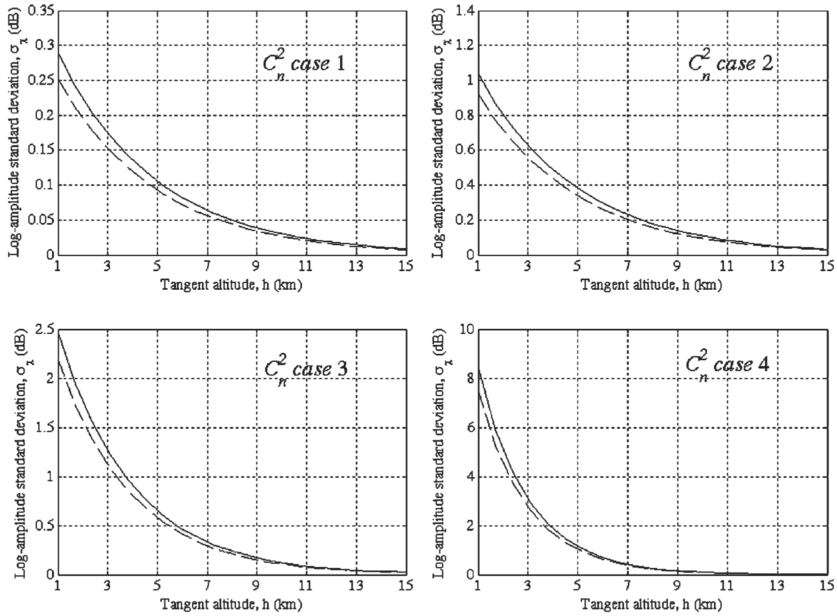
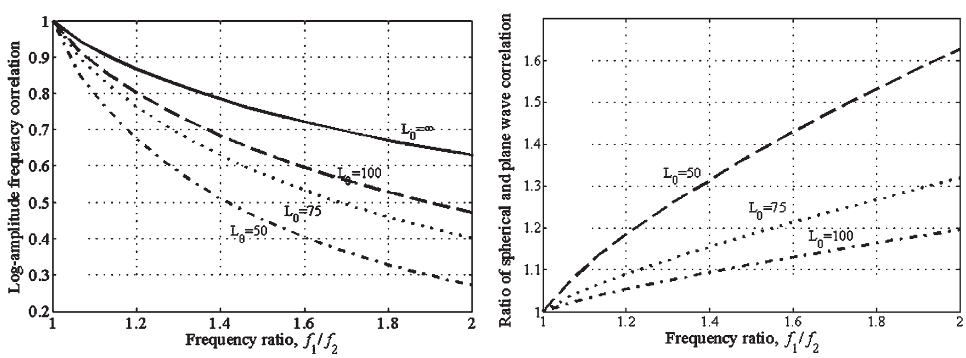


Fig. 4. Log-amplitude fluctuation standard deviation versus the tangent altitude for four different C_n^2 profiles at 17 GHz (dashed line) and 20 GHz (continuous line).



(a) (b)

Fig. 5. Log-amplitude frequency correlation as a function of the frequency ratio for different outer scale values. (a) Spherical wave case. (b) Ratio between frequency correlation for spherical and for plane wave.

TABLE II
TWO FREQUENCIES AMPLITUDE CORRELATION VALUES FOR DIFFERENT OUTER SCALE VALUES AT THE FREQUENCIES OF INTEREST FOR THE NDSA APPROACH

ρ_χ	$L_0 = \infty$	$L_0 = 100$ m	$L_0 = 75$ m
$f_1 = 17.3$ GHz and $f_2 = 17.2$ GHz	0.994	0.990	0.989
$f_1 = 20.35$ GHz and $f_2 = 20.15$ GHz	0.990	0.985	0.982

Finally, it has been found that the Region 2 approximation for the log-amplitude variance does not provide accurate results for the outer scale values of interest, and the rigorous expression must be considered.

As far as the amplitude frequency correlation is concerned, the results show that very close frequencies, as those chosen in the NDSA approach, are required to assure high correlation values regardless of the outer scale value and of the behavior of the spectrum in the input range.

All the results presented are relevant to the unfiltered signals. Further studies—possibly supported by measured data—concerning the scintillation spectrum and the two-frequency mutual coherence function would be required to evaluate the impact of a possible filtering of the scintillation signal in terms of reduction of the scintillation power and increase of the frequency correlation.

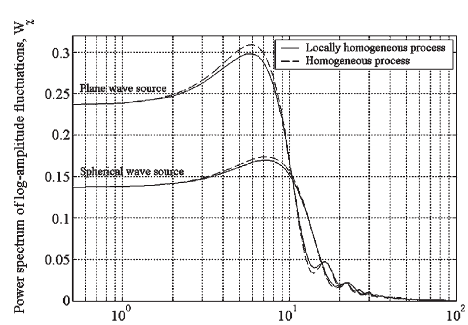


Fig. 6. Power spectrum of the log-amplitude fluctuation at 20 GHz (C_n^2 case 4).

APPENDIX

In this Appendix, the derivation of the log-amplitude correlation function and variance for the general case of locally homogeneous medium is reported. Then, the conditions under which such expressions reduce to the ones relevant to a homogeneous medium (weighted by a structure constant describing the turbulence intensity) are determined. The derivation is performed by applying the procedure outlined in [21], to which the reader is referred for more details, and is based on the description of the turbulence as a locally homogeneous medium. This consists of expressing the correlation of the refractive index fluctuation as a product between a function of the average coordinate and a function of the difference coordinate. The relevant spatial spectrum is also given by a product of a function of the difference wavenumber and a function of the average wavenumber. The first is the Fourier transform of a smoothly varying function $B_n^v(\vec{r})$ describing the spatial dependence of turbulence intensity; the latter, denoted with $\Phi_n^0(\cdot)$, is the Fourier transform of the spatial correlation function of n_1. The behavior of this function in the so-called inertial range of the turbulence (that is, for $1/L_0 = \kappa_0 < \kappa < \kappa_s = 1/l_0$, where l_0 and L_0 are the inner and outer scales of the turbulence, respectively) is predicted by the well-established Kolmogorov theory [43], which assumes isotropy. As a matter of fact, it is not possible to develop a universal theory to extend the Kolmogorov theory for values below κ_0. Fortunately, due to the effect of the weighting function, this range does not have a significant influence on the signal amplitude fluctuations. However, different empirical models can be employed for mathematical convenience [42]. One of the most commonly used is the Von Karman spectrum given by

$$\Phi_n^0(\vec{\kappa}) = \Phi_n^0(\kappa) = \left(\kappa^2 + \kappa_0^2\right)^{-\frac{11}{6}} e^{-\frac{\kappa^2}{\kappa_m^2}} \tag{17}$$

with $\kappa_m = 5.92/l_0$, which will be assumed also in this paper.

After inserting the two-dimensional spectral representation of the refractive index fluctuations in the log-amplitude fluctuation correlation function and performing some algebraic manipulations, it is finally obtained [21] as

$$B_\chi(L, \vec{\rho}_1, \vec{\rho}_2) = 2\pi \int_{-\infty}^{\infty} \iint B_n^v\left(x, \gamma(x)\vec{\rho} - \vec{\rho}\,'\right) \times G_\chi(x, \vec{\rho}\,', \vec{\rho}_d) d\vec{\rho}\,' dx \tag{18}$$

where $\vec{\rho}_d = \vec{\rho}_1 - \vec{\rho}_2$, $\vec{\rho}_c = (\vec{\rho}_1 + \vec{\rho}_2)/2$, and

$$G_\chi(x, \vec{\rho}_c, \vec{\rho}_d) = \frac{k^2}{2A^2}\Phi_n^0\left(\frac{\rho_c}{A}\right)\cos\left[\frac{\gamma(x)\vec{\rho}_c \cdot \vec{\rho}_d}{A}\right] - \frac{k^2}{2\pi A} \times \iint e^{j\gamma(x)\vec{\kappa}\cdot\vec{\rho}_d}\Phi_n^0(\kappa)\sin\left(A\kappa^2 - \frac{\rho_c^2}{A}\right) d\vec{\kappa} \tag{19}$$

with $A = A(x) = [\gamma(x)(L - x)]/k$.

It is then assumed, in accordance with Woo and Ishimaru [14], that the turbulence intensity function, which is related to the structure constant function C_n^2 through the relationship $B_n^v(\vec{r}) = 0.033\ C_n^2(\vec{r})$, varies exponentially with altitude and can be described by the following model:

$$B_n^v(\vec{r}) = 0.033\ C_n^2(x, \vec{\rho}) = 0.033\ C_{n0}^2 e^{-\frac{h+y}{b}} e^{-\frac{\left[(x-L_1)^2 + z^2\right]}{a^2}} \tag{20}$$

where b and $a = (2(R_{\mathrm{E}} + h)b)^{1/2} \cong (2R_{\mathrm{E}}b)^{1/2}$ represent the variation scale along y and in the xz plane, respectively. For $a \ll L$, A and γ are very smooth functions of x in the turbulent region; hence, the following approximation can be used to evaluate the integral along the propagation path in (18):

$$\int_{-\infty}^{\infty} f(x) e^{-\frac{(x-L_1)^2}{a^2}} dx \simeq f(L_1) \int_{-\infty}^{\infty} e^{-\frac{(x-L_1)^2}{a^2}} dx = f(L_1)\sqrt{\pi}a. \tag{21}$$

After straightforward but tedious calculations, it can be demonstrated that (18) reduces to the classical expression for locally homogeneous turbulence with slowly varying structure constant function [22], i.e.,

$$B_\chi(L, \vec{\rho}_1, \vec{\rho}_2) = 4\pi^2\sqrt{\pi}k^2 a B_n^v(L_1, \gamma_1\vec{\rho}_c) \times \int_0^{\infty} \kappa J_0(\kappa\gamma_1\rho_d)\Phi_n^0(\kappa)\sin^2\left(\frac{\kappa^2 A_1}{2}\right) d\kappa \tag{22}$$

where $\gamma_1 = \gamma(L_1)$ and $A_1 = A(L_1) = L_s^2/(2\pi)$ only under the conditions $L_s \ll b$ and $L_s \ll \sqrt{L_0 b}$.

References

[1] E. Kursinski, G. Hajj, J. Schofield, R. Linfield, and K. Hardy, "Observing Earth's atmosphere with radio occultation measurements using the Global Position System," *J. Geophys. Res.*, vol. 102, no. D19, pp. 1897–1914, 2002.

[2] M. Gorbunov and S. Sokolovskiy, "Remote sensing of refractivity from space for global observation of atmospheric parameters," Max-Planck-Inst. Meteorologie, Hamburg, Germany, Tech. Rep. 119, 1993.

[3] S. Sokolovskiy, "Inversion of radio occultation amplitude data," *Radio Sci.*, vol. 35, no. 1, pp. 97–105, 2000.

[4] ——, "Modeling and inverting radio occultation signals in the moist troposphere," *Radio Sci.*, vol. 36, no. 3, pp. 441–458, 2001.

[5] ACEPASS Study Consortium, "The ACE+ phase a scientific support study ACEPASS: Summary report ESA/ESTEC No. 2/2005, 2005.

[6] O. I. Yakovlev, S. S. Matyugov, and I. A. Vilkov, "Attenuation and scintillation of radio waves in the Earth's atmosphere from radio occultation experiments on satellite-to-satellite links," *Radio Sci.*, vol. 30, no. 3, pp. 591–602, 1995.

[7] O. I. Yakovlev, S. S. Matyugov, and V. A. Anufriev, "Scintillations of centimeter waves and the atmospheric irregularities from radio occultation data," *Radio Sci.*, vol. 38, no. 2, pp. 2-1–2-11, 2003.

[8] M. E. Gorbunov and G. Kirchengast, "Processing X/K band radio occultation data in presence of turbulence," *Radio Sci.*, vol. 40, no. 6, pp. 1–11, 2005.

[9] L. Facheris, F. Cuccoli, and F. Argenti, "End-to-end simulation of a K-band LEO–LEO satellite link for estimating water vapor in the low troposphere," in *Proc. SPIE Conf. Sensors, Systems, and Next-Generation Satellites VIII*, R. Meynart, S. P. Neeck, and H. Shimoda, Eds, Nov. 2004, vol. 5571, pp. 226–237.

[10] F. Cuccoli and L. Facheris, "Normalized differential spectral attenuation (NDSA): A novel approach to estimate atmospheric water vapor along a LEO–LEO satellite link in the Ku/K bands," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 6, pp. 1493–1503, Jun. 2006.

[11] Y. Karasawa, M. Yamada, and J. Allnutt, "A new prediction method for tropospheric scintillation on Earth–space paths," *IEEE Trans. Antennas Propag.*, vol. 36, no. 11, pp. 1608–1614, Nov. 1988.

[12] F. S. Marzano and C. Riva, "Cloud-induced effects on monthly averaged scintillation amplitude along millimeter-wave slant paths," *IEEE Trans. Antennas Propag.*, vol. 51, no. 4, pp. 880–887, Apr. 2003.

[13] R. Woo and A. Ishimaru, "Effects of turbulence in a planetary atmosphere on radio occultation," *IEEE Trans. Antennas Propag.*, vol. AP-22, no. 4, pp. 566–573, Jul. 1974.

[14] ——, "Remote sensing of the turbulence characteristics of a planetary atmosphere by radio occultation of a space probe," *Radio Sci.*, vol. 8, no. 2, pp. 103–108, Feb. 1973.

[15] M. G. Sterenborg, J. P. V. P. Baptista, and P. Silvestrin, "Non-ionized medium scintillation at 10, 17 and 22 GHz for LEO-LEO and at 1.5 Ghz for GNSS-LEO radio occultation," ESA, Noordwijk, The Netherlands, Tech. Rep. EWP-2259, Sep. 2004.

[16] M. G. Sterenborg and J. P. V. P. Baptista, "Scintillation effect on LEO radio-occulation," *Electron. Lett.*, vol. 41, no. 1, pp. 26–27, Jan. 2005.

[17] A. D. Wheelon, *Electromagnetic Scintillation. Part I and II*. Cambridge, U.K.: Cambridge Univ. Press, 2003.

[18] A. Ishimaru, *Wave Propagation and Scattering in Random Media*, vol. 2. San Diego, CA: Academic, 1978.

[19] V. I. Tatarski, "Theory of single scattering by random distributed scatterers," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2806–2813, Oct. 2003.

[20] R. A. Silverman, "Locally stationary random processes," *IRE Trans. Inf. Theory*, vol. IT-3, no. 3, pp. 182–187, Sep. 1957.

[21] A. Ishimaru, "A new approach to the problem of wave fluctuations in localized smoothly varying turbulence," *IEEE Trans. Antennas Propag.*, vol. AP-21, no. 1, pp. 47–53, Jan. 1973.

[22] V. I. Tatarski, *Wave Propagation in a Turbulent Medium*. New York: McGraw-Hill, 1961.

[23] A. Ludi and A. Magun, "Near-horizontal line-of-sight millimeter-wave propagation measurements for the determination of outer length scales and anisotropy of turbulent refractive index fluctuations in the lower troposphere," *Radio Sci.*, vol. 37, no. 2, pp. 12-1–12-19, 2002.

[24] V. Kan, S. S. Matyugov, and O. I. Yakovlev, "The structure of the stratospheric irregularities according to radio-occultation data obtained using satellite-to-satellite paths," *Radiophys. Quantum Electron.*, vol. 45, no. 8, pp. 595–605, Aug. 2002.

[25] A. Gurvich and I. Chunchuzov, "Parameters of the fine density structure in the stratosphere obtained from spacecraft observations of stellar scintillations," *J. Geophys. Res.*, vol. 108, no. D5, pp. 6-1–6-4, Mar. 2003.

[26] E. Kursinski, S. Syndergaard, D. Flittner, D. Feng, G. Hajj, B. Herman, D. Ward, and T. Yunk, "A microwave occultation observing system optimized to characterize atmospheric water, temperature, and geopotential via absorption," *J. Atmos. Ocean. Technol.*, vol. 19, no. 5, pp. 23439–23465, Dec. 1997.

[27] R. B. Muchmore and A. D. Wheelon, "Frequency correlation of line-of site signal scintillations," *IEEE Trans. Antennas Propag.*, vol. AP-11, no. 1, pp. 46–51, Jan. 1963.

[28] R. W. Lee and J. C. Harp, "Weak scattering in random media, with applications to remote probing," *Proc. IEEE*, vol. 57, no. 4, pp. 375–406, Apr. 1969.

[29] P. A. Mandics and R. W. Lee, "On a limitation of multifrequency atmospheric probing," *Proc. IEEE*, vol. 57, no. 4, pp. 685–686, Apr. 1969.

[30] P. A. Mandics, R. W. Lee, and A. T. Waterman, Jr., "Spectra of short-term fluctuations of line-of-sight signals: Electromagnetic and acoustic," *Radio Sci.*, vol. 8, no. 3, pp. 183–201, Mar. 1973.

[31] S. F. Clifford, "Temporal frequency spectra for spherical wave propagating through atmospheric turbulence," *J. Opt. Soc. Amer.*, vol. 61, no. 10, pp. 1285–1292, Oct. 1971.

[32] P. A. Mandics, J. C. Harp, R. W. Lee, and A. T. Waterman, Jr., "Multifrequency coherences of short-term fluctuations of line-of-sight signals—Electromagnetic and acoustic," *Radio Sci.*, vol. 9, no. 8/9, pp. 723–731, Aug./Sep. 1974.

[33] G. Taylor, "The spectrum of turbulence," *Proc. R. Soc.*, vol. A 164, no. 919, pp. 476–490, Feb. 1938.

[34] A. Erdélyi, *Tables of Integral Transforms*, vol. II. New York: McGraw-Hill, 1954.

[35] *Draft Minutes of the 6th Meeting of the Atmosphere and Climate Explorer Mission Advisory Group*, 2004. ESA internal document.

[36] M. G. Sterenborg, J. P. V. P. Baptista, and S. A. Buehler, "Determining the refractive index structure constant using high-resolution radiosonde data," *J. Atmos. Sci.*, 2004. submitted for publication.

[37] H. Vasseur, "Prediction of tropospheric scintillation on satellite links from radiosonde data," *IEEE Trans. Antennas Propag.*, vol. 47, no. 2, pp. 293-301, Feb. 1999.

[38] F. D. Eaton and G. D. Nastrom, "Preliminary estimates of the vertical profiles of inner and outer scales from White Sands Missile Range, New Mexico, VHF radar observations," *Radio Sci.*, vol. 33, no. 4, pp. 895–903, Jul./Aug. 1998.

[39] A. K. Ghosh, A. R. Jain, and V. Sivakumar, "Simultaneous MST radar and radiosonde measurement at Gadanki (13:5 °N; 79:2 °E). Determination of various atmospheric turbulence parameters," *Radio Sci.*, vol. 38, no. 1, pp. 14/1–14/11, 2003.

[40] M. E. Gracheva, A. S. Gurvich, and M. A. Kallistratova, "Dispersion of strong atmospheric fluctuations in the intensity of laser radiation," *Radiophys. Quantum Electron.*, vol. 13, no. 1, pp. 40–42, Jan. 1970.

[41] V. I. Tatarskii, *The Effects of the Turbulent Atmosphere on Wave Propagation*. Springfield, VA: Jerusalem, 1971. Israel Program for Scientific Translations. Reproduced by National Technical Information Service, U.S. Dept. of Commerce.

[42] V. V. Voitsekovich, "Outer scale of turbulence: Comparison of different models," *J. Opt. Soc. Amer.*, vol. 12, no. 6, pp. 1346–1353, Jun. 1995.

[43] A. N. Kolmogorov, "The local structure of turbulence in incompressible viscous fluid for very large Reynolds' numbers," *Comptes Rendus (Doklady) de l'Academie des Sciences de l'URSS*, vol. 30, pp. 301–305, 1941.

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