Long Term Irradiance Statistics for Optical GEO Downlinks: Validation with ARTEMIS Experimental Measurements

Theodore T. Kapsis, Nikolaos K. Lyras, and Athanasios D. Panagopoulos[*]

Abstract—In this Letter, a methodology for the generation of received irradiance/power time series for a GEO downlink concentrated on small aperture receiver terminals is reported. The synthesizer takes into account the atmospheric phenomena that degrade the propagation of the optical signal and especially the turbulence effects. For modeling the scintillation effects, Kolmogorov spectrum is assumed, and the Rytov's approximation under weak turbulence is also used. The time series are generated using the theory of stochastic differential equations. Finally, the proposed synthesizer is compared in terms of first order statistics with experimental data from the ARTEMIS GEO optical satellite link campaign with very good agreement.

1. INTRODUCTION

During the last years, laser communication system technology has become increasingly mature making it an attractive opportunity for space communication systems. Optical communication systems demonstrate important advantages compared with the already existing Radio Frequency (RF) satellite communication systems, like [1, 2] a) reduced mass, power and volume of needed equipment, b) hundreds of times more spectral bandwidth and higher data rates can be accomplished c) there is improved security and no interception due to the highly directive antennas d) up to now there is no need of frequency regulation. Therefore, many experimental missions are being conducted for the investigation of the performance of optical satellite communication systems. Experimental missions have been demonstrated for inter-satellite links, for bi-directional ground to GEO and ground to LEO among others [1, 2]. The main purposes of these missions are firstly the feasibility analysis of optical satellite communication systems and secondly the characterization of the atmospheric phenomena that impair the optical link. When optical beam propagates through the Earth's atmosphere it is affected by the several atmospheric phenomena with clouds constituting the dominant one. The attenuation induced by clouds is so intense that the blockage of the link is caused with cloud occurrence [1–3]. For mitigation of cloud coverage site diversity technique is employed [1–4]. However, even under cloud free line of sight conditions (no clouds) the optical beam is affected by the atmospheric absorption, scattering, cirrus clouds and mainly by the atmospheric turbulence. Atmospheric turbulence comes from the variations in wind speed, pressure and temperature which result in variations in the refractive index [1, 2, 5]. Therefore, the strength of turbulence effects depends on the time of the day, the slant path, i.e., the elevation angle of the link, and the altitude of the station among others. Turbulence is more severe during the day, in lower elevation angles (longer propagation path) and for low altitude stations (denser atmosphere) [1, 2, 5].

This Letter is concentrated on downlink propagation case. In downlink, atmospheric turbulence is closer to the receiver and causes the scintillation of the signal i.e., random fluctuations of optical signal. For mitigation of scintillation effects aperture averaging technique is used [1, 2, 5]. Large apertures are employed to increase the average signal power collected and to reduce the signal fluctuations [1, 2, 5].

Aperture averaging effect is higher with the larger aperture diameters. However, for small apertures the scintillation effects are present and degrade the performance of optical signal. Since, the cost of a large receiving aperture may be forbidden for a great variety of possible optical satellite applications for the reliable design of an optical GEO downlink, the accurate prediction of scintillation for small apertures is required. In Figure 1 the downlink irradiance cumulative distribution functions (CDFs) for two different apertures Figure 1(a) 1 m diameter (ESA's Terminal), and Figure 1(b) 0.26 m diameter (LUCE Terminal), are presented [6, 7]. For the estimation of these curves experimental measurements (time series) from the ARTEMIS optical campaign are used. More information about the ARTEMIS campaign is reported in Section 2. It can be easily pinpointed that in the case of 1 m receiver the effects of turbulence are minimized. However, in the case of 0.26 m receiver for probabilities of interest losses more than 4–5 dBs may be caused.

In this contribution a synthesizer for the generation of received irradiance/power time series taking into account the turbulence effects among others for an optical GEO downlink is proposed. The synthesizer is benefited of the use of stochastic differential equations for the incorporation of scintillation effects. The synthesizer is validated in terms of first order statistics with actual experimental data from ARTEMIS campaign [6, 7].

The main assumptions of the methodology are summarized: a) Downlink Transmission, b) GEO to Ground satellite links, c) Rytov theory is assumed and the Kolmogorov spatial spectrum of refractive index is used, d) links with elevation angle greater than 20 deg are assumed e) Weak fluctuations are considered f) One Gaussian beam is transmitted.

The remainder of the paper is structured as follows. In Section 2 a recap of ARTEMIS campaign is exhibited. In Section 3 the proposed synthesizer is reported, and in Section 4 it is validated with experimental results from ARTEMIS campaign. Finally Section 5 concludes this paper.

(a)   (b)
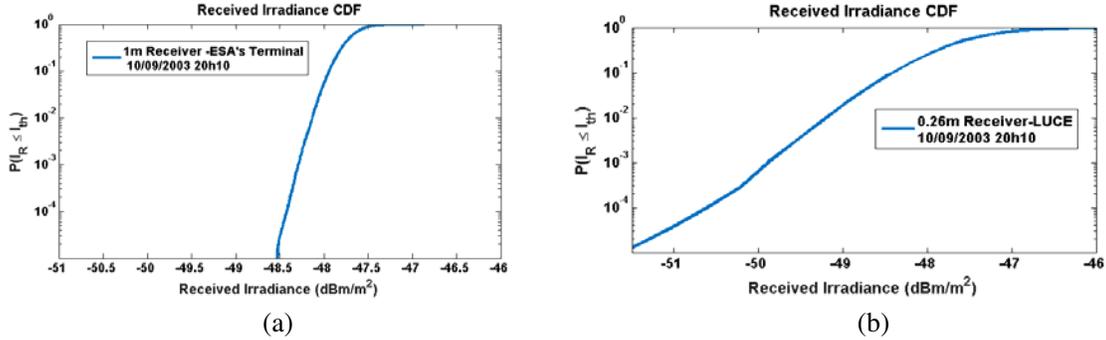
Figure 1. (a) Downlink Received Irradiance CDF, (a) 1 m aperture and (b) 0.26 m aperture.

2. RECAP OF ARTEMIS OPTICAL CAMPAIGN

During 2003 European Space Agency (ESA) established bi-directional optical links between the ESA's ground station in Tenerife Spain at an altitude of 2.4 km over the sea favorable for optical satellite communications and the ARTEMIS GEO satellite (launched in 2001) at 21.5 deg East for the study and characterization of laser beam propagation through atmospheric turbulence [6]. Additionally, the Japanese Aerospace Exploration Agency (JAXA) developed the LUCE optical terminal and set it up at ESA's OGS in Tenerife, where bi-directional sessions were established. Therefore there are measurements using as a receiver both the ESA's 1 m terminal [6] and the 0.26 m LUCE receiver [7]. The elevation angle of the link was 37 deg. For downlink transmission the wavelength used is 819 nm and the laser diameter is 125 mm [6]. In this paper we concentrate on LUCE terminal which has a shorter receiver. In Figure 2(a) the configuration of the experiment is exhibited while in Figure 2(b) a snapshot of concurrent irradiance measurements for both LUCE and ESA's terminal are reported. The aperture averaging effect is higher in ESA's terminal which is equipped with a larger receiver and as a result the measurements appear with smaller fluctuations. Additionally, in accordance with the experimental measurements, concurrent meteorological recordings were available.
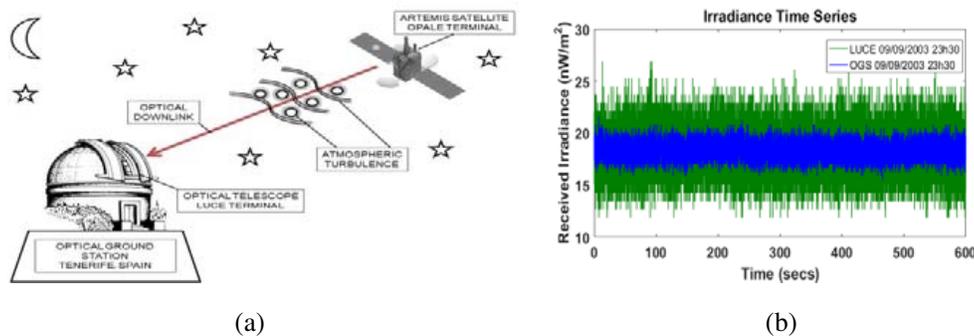
Figure 2. (a) ARTEMIS campaign configuration, (b) concurrent irradiance time series.

3. PROPOSED SYNTHESIZER

In this section, the proposed synthesizer is reported. To begin with, for a downlink optical GEO satellite communication system the received irradiance time series can be given according to the next formula:

$$I_R(r, L, t) = L_T \cdot L_R \cdot L_{atm} \cdot I(r, L, t) \tag{1}$$

where $L(m)$ is the link distance (slant path), t the time(s), and r the radial distance from the beam center. L_T, L_R are efficiencies of the transmitter and receiver respectively. In L_{atm} the atmospheric transmittance and cirrus clouds transmittance are incorporated. In $I(W/m^2)$ the transmitter gain, free space losses, and turbulence effects are incorporated. From Equation (1) received power in Watts can be given as $P_R = I_R * \pi D_R^2/4$, where D_R is the receiver's aperture diameter.

Firstly I will be expressed in the case of no turbulence without the time dependence [2, 5]:

$$I(r, L) = \frac{2}{\pi} \cdot \frac{P_T}{W^2(L)} \cdot e^{-\frac{2r^2}{W^2(L)}} \tag{2}$$

where $P_T(W)$ is the transmitted power, and $W(L)$ is the beam waist in meters after propagation of distance L given according to the next formula [2, 5]:

$$W^2(L) = W_0^2 \left[1 + \left(\frac{\lambda L}{\pi W_0^2} \right)^2 \right] \tag{3}$$

where $W_0(m)$ is the beam radius of the source at which the irradiance falls to $1/e^2$ (spot size).

In order to incorporate in I the turbulence effects, the structure constant of refractive index $C_n^2(h)$ for the whole slant path is required. Therefore, a modified version of Hufnagel-Valley Model (H-V) where the altitude above the sea level (h) and the ground station's altitude $H_{GS}(m)$ are incorporated is employed [1, 2].

$$C_n^2(h) = A_0 \exp\left(-\frac{H_{GS}}{700}\right) \exp\left((H_{GS} - h)/100\right) + 5.94 \times 10^{-53}$$

$$\times \left(\frac{u_{rms}}{27}\right)^2 h^{10} \exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16} \exp\left(-\frac{h}{1500}\right) \tag{4}$$

where $A_0(m^{-2/3})$ is the refractive index structure parameter at ground level, and $u_{rms}(m/s)$ is the rms wind speed on slant path:

$$u_{rms} = \sqrt{\frac{1}{15 \times 10^3} \int\limits_{5\times10^3}^{20\times10^3} V^2(h)dh} \tag{5}$$

where $V(h)$ can be estimated using the Bufton wind model [5].

Now for downlink propagation where turbulence causes only scintillation effects (no beam wandering) and assuming that there is perfect tracking of beam center then assuming that the Rytov theory and Kolmogorov spectrum expression (2) is modified in order the turbulence effects are incorporated as follows [2, 5]:

$$I\left(L, t\right) = \frac{2}{\pi} \cdot \frac{P_T}{W_{LT}^2\left(L\right)} \cdot e^{2X\nu} \tag{6}$$

$W_{LT}(L)$ is the effective beam spot size after propagation distance L considering the scintillation effects. However since in the downlink the beam spreading due to scintillation is negligible it is assumed that $W_{LT}(L) = W(L)$.

Before we continue with the other terms firstly the scintillation index (SI) is exhibited. Scintillation index is the normalized variance of the received irradiance $\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$ where I is the irradiance. In this analysis only the weak turbulence (i.e., SI < 1) is investigated. In expression (8) the theoretical expression for the estimation of scintillation index for a point receiver [5] based on plane wave approximation is exhibited while for the incorporation of aperture averaging effect, aperture averaging factor $(A(D_R) = \sigma_I^2 / \sigma_{I,point}^2)$ is used, and SI is estimated as $\sigma_I^2 = A(D_R)\sigma_{I,point}^2$. Aperture averaging factor $A(D_R)$ can be theoretically estimated depending on the diameter of the aperture of the receiver using expression (9) as derived from [8]. In the case that experimental data are available aperture averaging factor can be estimated directly from the data as $A(D) = \frac{\langle \sigma_{I,data}^2 \rangle}{\langle \sigma_{I,point}^2 \rangle}$ where $\sigma_{I,data}^2$ is the scintillation computed from the data.

$$\sigma_{point}^2 = 2.25 k^{\frac{7}{6}} sec^{\frac{11}{6}}\left(\zeta\right) \int\limits_{H_{GS}}^{H_{GS}+H_{Turb}} C_n^2\left(h\right)\left(h - h_0\right)^{\frac{5}{6}} dh \tag{7}$$

where $k = 2\pi/\lambda\,(\text{rad/m})$ is the wavenumber, $\lambda\,(\text{m})$ the wavelength, and ζ the zenith angle.

$$A\left(D\right) = \left[1 + 1.1\left(\frac{D_R^2}{\lambda h_s \sec\left(\zeta\right)}\right)^{\frac{7}{6}}\right]^{-1}, \quad where\ h_s = \left[\frac{\int\limits_{H_{GS}}^{H_{GS}+H_{Turb}} C_n^2\left(h\right)\left(h - H_{GS}\right)^2 dh}{\int\limits_{H_{GS}}^{H_{GS}+H_{Turb}} C_n^2\left(h\right)\left(h - H_{GS}\right)^{5/6} dh}\right]^{6/7} \tag{8}$$

Additionally for weak turbulence the log amplitude variance is defined as $\sigma_\chi^2 = \ln(\sigma_I^2 + 1)/4$.

Finally in $\exp(2X_v)$ the scintillation effects are incorporated. X_ν is the normalized log-amplitude. For weak turbulence the normalized log amplitude can be considered as a zero mean-unity variance low pass Gaussian process with $-80/3\,\text{dB/decade}$ slope. Such processes can be modeled using Stochastic Differential Equations (SDEs) driven by fractional Brownian motion as described in [9].

4. VALIDATION

In this section, the proposed synthesizer is validated in terms of first order statistics of received irradiance from the ARTEMIS experimental campaign. The methodology is tested in terms of first order irradiance statistics with all the available experimental sessions with very good agreement. The results from two sessions are reported here. More specifically for each session the CDF computed directly from the ARTEMIS data will be compared with the CDF derived from the proposed synthesizer (Synthesized Data). Additionally the normalized Probability Density Functions (PDFs) derived from the experimental data are compared with the ones derived from the synthesized data, and the scintillation index resulting in each case is exhibited. Regarding the necessary inputs of the synthesizer, as receiver the LUCE terminal with 0.26 m diameter is assumed. The elevation angle is 37 deg; the altitude of the station is 2.4 km, the wavelength 819 nm; and the laser diameter $(2 * W_0)$ is 125 mm. More information can be found in [8]. Analyzing the experimental data aperture averaging factor is

estimated close to 0.1. Additionally, A_0 a value close to 10^{-15} $(\text{m}^{-2/3})$ has been chosen since the sessions took place after 20:00 pm. The wind speed on ground needed is derived from concurrent meteorological data. The proposed synthesizer has been validated using all the available downlink sessions. The first session that is reported here is on 13/09/2003 23:30. The wind speed on ground taken from the meteorological data was 0.29 m/s. The SI computed from the methodology is 0.0142 which is very close to the one computed from the experimental data which is 0.0140. In Figure 3, the synthesizer is tested in terms of first order statistics (a): CDF and (b) normalized PDF for this session.

The second session is on 16/09/2003 21:10. The wind speed on ground taken from the meteorological data was 2.8 m/s. The SI computed from the methodology is 0.0170 which is very close to the one computed from the experimental data which is 0.0164. In Figure 4, the synthesizer is tested in terms of first order statistics.

From both Figures 3 and 4 it can be observed that the proposed synthesizer can reproduce the first order statistics of received irradiance for a GEO optical downlink with very good accuracy.
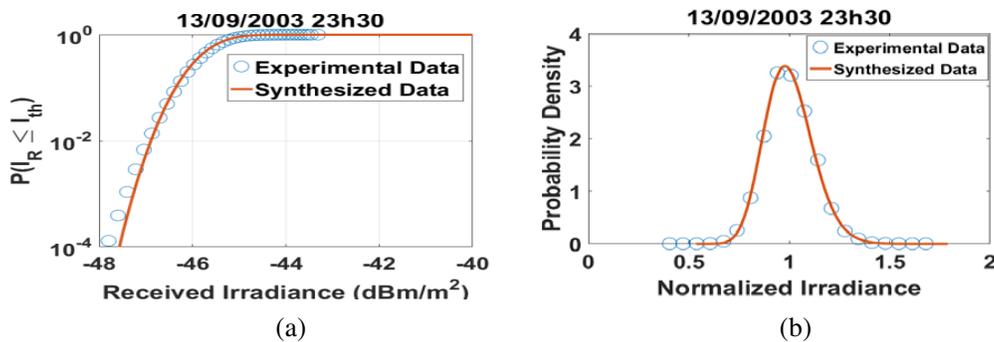
Figure 3. First order statistics validation for session on 13/09/2003 23:30, (a) experimental CDF vs synthesized CDF, (b) experimental normalized PDF vs synthesized normalized PDF.
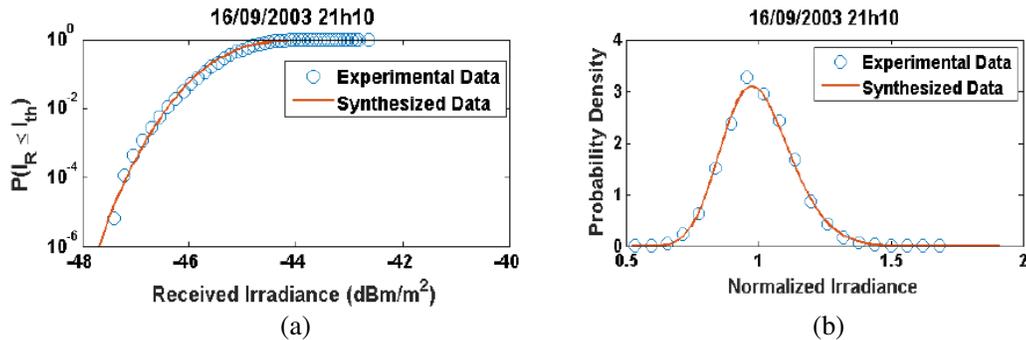
Figure 4. First order statistics validation for session on 16/09/2003 21:10, (a) experimental CDF vs synthesized CDF, (b) experimental normalized PDF vs synthesized normalized PDF.

5. CONCLUSION

In this contribution, a synthesizer for the generation of received irradiance/power time series for an optical GEO downlink is proposed. The methodology takes into account the weak turbulence effects on downlink and takes advantage of the use of SDEs for the time series synthesis. Finally, the proposed methodology is compared, with very good agreement, with experimental data from the optical GEO satellite campaign ARTEMIS .

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