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On Aperture Averaging Effects for Central Obscured Telescopes: Experimental Validation with ARTEMIS Experimental Downlink Measurements

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ABSTRACT

In this paper, a methodology for the estimation of aperture averaging factor for a central obscured aperture is briefly presented and tested against experimental results. The modeling is based on the methodology reported in the NASA's report edited by Fried [10]. For the validation of the methodology, experimental data from the ARTEMIS bi-directional optical link is employed. Experimental data sessions from 2003 with the ARTEMIS GEO satellite as space segment and the 1.016m Cassegrain central obscured telescope of ESA in Tenerife at 2.4km altitude as ground segment are used.

Keywords: aperture averaging, obscuration, turbulence, scintillation, optical, satellite, ARTEMIS, FSO

1. INTRODUCTION

Optical Space to Ground communication links have already gathered a lot of attention as an alternative solution to the Radio Frequency satellite communication systems. The already congested frequency spectrum in accordance with the demand for high speed internet and multimedia applications has posed the necessity of using higher frequency bands. Optical satellite communication systems offer a great variety of advantages compared to RF satellite systems. More specifically, they offer higher data rates, more spectral bandwidth, with less power consumption, mass and size. In addition, no frequency regulation is needed up to know, there is limited risk of interception and thus improved security [1], [2].

Experimental missions for the investigation of the performance of optical satellite communication systems have already conducted [1]-[3]. In these missions the performance of uplink and downlink satellite communication systems with either LEO or GEO satellites is examined with the main scope the characterization of the atmospheric phenomena that impair the optical link. Among the atmospheric phenomena that affect the signal cloud coverage is the dominant one which causes the blockage of the link [1]-[7]. The most efficient technique for the mitigation of cloud coverage is site diversity [1]-[7]. Under cloud free line of site conditions optical satellite communication links are mainly affected by atmospheric turbulence among others. Atmospheric turbulence comes from the variations in wind speed, temperature and pressure and results on variations on refractive index. For downlink case where turbulence is close to the receiver mainly random fluctuations of the optical signal-scintillation effects are caused. For mitigation of downlink scintillation, aperture averaging technique is performed. Large apertures are employed to increase the average signal power collected and to reduce the signal fluctuations.

To quantify the aperture averaging effect, the aperture averaging factor is defined as the ratio of the variance of received irradiance collected by a finite aperture to the corresponding collected received irradiance of a point aperture receiver. In the literature a variety of expressions for the estimation of aperture averaging factor exist [1], [2], [8], [9]. However, these expressions assume finite receiving apertures clear of central obscuration. In the NASA report edited by Fried [10] firstly the aperture averaging factor for an obscured aperture is defined and a methodology is reported where remarkable differences between a central obscured and a clear of obscuration aperture can be pinpointed as far as the aperture averaging factor is concerned.

In this paper, a modified methodology for the estimation of aperture averaging factor for a central obscured aperture is presented and tested against experimental results. The methodology is based on [8] and [10], following the assumption that the fluctuations of the aperture averaged signal are due to redistribution of the energy from one point in the aperture to another [10]. For the validation of the proposed methodology, experimental data from the ARTEMIS bi-directional optical link will be employed [11]. The experimental data has been provided by ESA within the framework of ONSET project. Experimental data sessions from 2003 using the ARTEMIS GEO satellite as space segment and the 1.016m Cassegrain central obscured telescope of ESA in Tenerife in 2.4km altitude as ground segment are used.

The remainder of the paper is structured as follows: In Section 2, some important information about the ARTEMIS experimental campaign is recalled. In Section 3, the proposed methodology in accordance with some important metrics about the downlink scintillation effects are reported. In Section 4, the proposed methodology is validated against experimental data. Finally, Section 5 concludes the paper.

2. RECAP OF ARTEMIS EXPERIMENTAL CAMPAIGN

During 2003 bi-directional optical links between the ESA's optical ground station (OGS) at the Observatorio del Teide at Izaña, Tenerife, Spain, at an altitude of 2400m and the geosynchronous satellite ARTEMIS were performed. ESA's OGS is equipped with 1.016 m receiving aperture and it can transmit up to 4 incoherent optical beams while ARTEMIS is equipped with 0.25 m receiving aperture and transmits one optical beam. Detailed information about the campaign can be found in [11]. In Table 1 the OGS and ARTEMIS satellite technical characteristics are summarized [11].

Table 1 ESA's OGS and ARTEMIS satellite technical details

	OGS	**ARTEMIS**
Longitude:	16.5101° West	21.5° East
Latitude	28.2995° North	21.5
Altitude	2.393 km	35787 km
Link distance to ARTEMIS satellite in GEO	38008 ±176 km (June 2004)	
Telescope		
Entrance Pupil	1016mm	250mm
Central Obscuration/ Central Bore	330mm/215mm	
Transmitters LCT		
Laser power out of aperture	300mW (maximum)	10mW (average)
Laser beam diameter ($1/e^2$)	40 mm – 300 mm, four incoherent beams	125mm one beam
Communication wavelength	847 nm	819nm

3. THE PROPOSED METHODOLOGY

In this Section the methodology for the estimation of aperture averaging for central obscured telescopes is presented. Firstly, some important metrics regarding the turbulence effects on downlink are summarized.

3.1 Theoretical Background

To begin with, for the incorporation of turbulence effects, the structure constant of refractive index $C_n^2(h)$ along the slant path is needed. Several expressions for $C_n^2(h)$ have been proposed [1], [2], [9].$C_n^2(h)$ varies with time of day (different atmospheric conditions during day, pressure, temperature, etc.) , the height and the wind speed among others [12]. In this analysis, a modified expression of Hufnagel-Valley (H-V) model which takes into account the altitude of the ground station and the elevation angle among others is used:

$$C_n^2(h) = A_0 \exp(-H_{GS}/700)\exp(-(h-H_{GS})/100) + 5.94\times10^{-53}\times\left(\frac{u}{27}\right)^2 h^{10}\exp(-h/1000) + 2.7\times10^{-16}\exp(-h/1500) \tag{1}$$

A_0 ($m^{-2/3}$) is the refractive index structure parameter at ground level where different values regarding the location the time during day etc. can be used, u (m/s) is the RMS wind speed on slant path estimated according to Bufton wind model and H_{GS} (m) is the altitude of ground station.

Scintillation index is defined as the normalized variance of received irradiance fluctuations given from experimental data according to the next expression:

$$\sigma_I^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} = e^{4\sigma_\chi^2} - 1 \tag{2}$$

I is the downlink received irradiance. σ_χ^2 is the log amplitude variance. For a downlink path, plane wave transmission is assumed. For weak turbulence conditions $\sigma_I^2<1$ using Rytov method, the downlink lognormal variance for a plane wave can be given according to the next formula assuming no aperture averaging:

$$\sigma_\chi^2 = 0.56k^{7/6}\sec(\theta)^{11/6}\int_{H_{GS}}^{H} C_n^2(h)(h-H_{GS})^{5/6}\,dh \tag{3}$$

k is the optical wave number, θ is the zenith angle and $H=H_{GS}+L*\cos(\theta)$ where L is the link slant path. For spatial spectrum of refractive index Kolmogorov spectrum is usually assumed.

For downlink propagation, aperture averaging technique is used. Aperture averaging factor is defined as follows:

$$A(D) = \frac{\sigma_I^2(D)}{\sigma_{I,point}^2} \tag{4}$$

where $\sigma_{I,point}^2$ is the SI of a point receiver computed using expressions (2) and (3), D (m) is the diameter of the receiver and $\sigma_I^2(D)$ is the SI for an aperture of diameter D. There are several expressions for the estimation of aperture averaging factor [1], [2], [8], [9]. For weak turbulence, for downlink plane wave propagation according to [8], the aperture averaging factor for finite size collecting aperture with no central obscuration is evaluated analytically using the following expressions:

$$A(D) = \left[1 + 1.1\left(\frac{D^2}{\lambda h_s \sec(\theta)}\right)^{7/6}\right]^{-1} \tag{5}$$

$$h_s = \left[\frac{\int C_n^2(h)(h-H_{GS})^2\,dh}{\int C_n^2(h)(h-H_{GS})^{5/6}\,dh}\right]^{6/7} \tag{6}$$

where λ (m) is the wavelength used.

3.2 Aperture Averaging Factor-Central Obscuration

In this subsection the methodology for the estimation of aperture averaging factor taking into account a circular central obscuration is presented. The proposed methodology is based on the analysis reported in NASA's report. In the proposed analysis it is assumed that the fluctuations of the averaged signal are not due to variation in the total optical signal power reaching the aperture, but rather are due to redistribution of the energy from one point in the aperture to another. That means that for an un-obscured circular aperture with diameter D, the variations of the averaged received signal are associated with the random relocation of energy between inside and outside of the circle. The variance of the received signal ${\sigma^2}_s(D)$ for an un-obscured aperture with diameter D can be written as:

$$ {\sigma^2}_s(D) = \sigma_I^2(D) \cdot \langle S \rangle^2 \tag{7} $$

Where $\sigma_I^2(D)$ is the scintillation index of an aperture with diameter D, $\langle S \rangle$ is the average received signal given as $\langle S \rangle = \frac{\pi}{4} D^2 I_0$, where I_0 is the mean intensity. Now using the expression (5) the variance of received signal is given as follows:

$$ {\sigma^2}_s(D) = {\sigma^2}_{I,point} \cdot A(D) \cdot \left(\frac{1}{4} \pi D^2 \right)^2 {I^2}_0 \tag{8} $$

Now assuming a circular obscured aperture with diameter D and with central circular obscuration d, it can be assumed that the aperture is randomly exchanging optical power with its external surroundings with an exchange variance, equals to ${\sigma^2}_s(D)$, as given by the clear aperture formula for diameter D, and is randomly exchanging optical power with the internal "surroundings" (i.e. , the obstruction region), with an exchange variance ${\sigma^2}_s(d)$ as given by the clear aperture formula for diameter d.

Thus the variance of the total received signal taking into account the obscuration is formulated as:

$$ {\sigma^2}_{s,obscured} = {\sigma^2}_s(D) + {\sigma^2}_s(d) \tag{9} $$

Using expressions (8) and (9), we have :

$$ \begin{aligned} {\sigma^2}_{s,obscured} &= {\sigma^2}_{I,point} \cdot A(D) \cdot \left(\frac{1}{4} \pi D^2 \right)^2 {I^2}_0 + {\sigma^2}_{I,point} \cdot A(d) \cdot \left(\frac{1}{4} \pi d^2 \right)^2 {I^2}_0 \\ {\sigma^2}_{s,obscured} &= {\sigma^2}_{I,point} {I^2}_0 \left(A(D) \cdot \left(\frac{1}{4} \pi D^2 \right)^2 + A(d) \cdot \left(\frac{1}{4} \pi d^2 \right)^2 \right) \end{aligned} \tag{10} $$

Now according to (7) $\sigma^2_{I,obscured}$ assuming that average value of the received signal for an obscured aperture is $\langle S_{obscured} \rangle = \frac{\pi}{4} I_0 (D^2 - d^2)$ the SI for obscured telescope using expression (11) is written as

$$ {\sigma^2}_{I,obscured} = {\sigma^2}_{I,point} \cdot \left(\frac{D^4 \cdot A(D) + d^4 \cdot A(d)}{\left(D^2 - d^2 \right)^2} \right) \tag{11} $$

Thus aperture averaging factor for the obscured aperture is:

$$A_{obscured} = \left(\frac{D^4 \cdot A(D) + d^4 \cdot A(d)}{\left(D^2 - d^2\right)^2} \right) \tag{12}$$

In the proposed method aperture averaging factors for *D* and *d* respectively are computed using expression (5) and (6).

4. VALIDATION AGAINST EXPERIMENTAL DATA

In this section the proposed methodology for the estimation of obscured aperture averaging factor is tested with experimental results from the ARTEMIS optical satellite link. The main steps of the validation procedure for each session used are summarized below:

- The SI from the experimental data $\sigma^2_{I,DATA}$ is computed using the expression (2).
- The SI for a point receiver $\sigma^2_{I,point}$ is estimated using the expression (3) and expression (1) for the $C_n^2(h)$.
- For $C_n^2(h)$ inputs:
    - The RMS wind speed is estimated applying the Bufton methodology using as input the wind speed on ground derived from concurrent meteorological data which are available.
    - For A_0 a value close to 10^{-15} ($m^{-2/3}$) has be chosen for sessions took place after 20:00 pm.
- Aperture Averaging factor is estimated form the experimental data $A_{DATA} = \frac{\sigma^2_{I,DATA}}{\sigma^2_{I,point}}$.
- Aperture Averaging factor is computed assuming no obscuration using expression (5) and with the proposed methodology reported in previous section taking into account the central obscuration.

In Table 2 below, in the sixth column the aperture averaging factor from the experimental data (A_{DATA}) is estimated, while in the seventh column the aperture averaging factor is estimated assuming no obscuration ($A_{no-obsc}$) using expression (5) and assuming obscuration (A_{obsc}) using expression (12).

Table 2 Experimental Validation

Date	Minutes	SI (DATA)	RMS Wind speed (m/s)	SI (Point)	A_{DATA}	$A_{no-obsc} \mid A_{obsc}$
21/7/2003	21:20-21:25	0.00165	24	0.214	0.0078	0.0051/0.0073
22/7/2003	21:20-21:25	0.0013	19.8	0.152	0.0085	0.005/0.0072
22/7/2003	21:25-21:30	0.00133	20.2	0.158	0.0084	0.005/0.0072
24/7/2003	00:35-00:40	0.00151	21.9	0.182	0.0082	0.005/0.0072
24/7/2003	00:40-00:45	0.00154	22.4	0.189	0.0081	0.005/0.0072
24/7/2003	21:21-21:26	0.00125	21.8	0.18	0.007	0.005/0.0072
24/7/2003	21:26-21:31	0.0013	22	0.183	0.0071	0.005/0.0072
9/9/2003	21:17-21:22	0.002	22.2	0.186	0.01	0.005/0.0072

Date	Minutes	SI (DATA)	RMS Wind speed (m/s)	SI (Point)	A_{DATA}	$A_{no-obsc} \mid A_{obsc}$
9/9/2003	21:22-21:27	0.00165	22	0.183	0.009	0.005/0.0072
9/9/2003	23:42-23:47	0.00155	21.7	0.179	0.0087	0.005/0.0072
10/9/2003	20:23-20:28	0.00216	26.8	0.262	0.0082	0.0051/0.0074

The average aperture averaging factor computed from the experimental data is close to 0.0083 while the average aperture averaging factor estimated using the un obscured expression is close to 0.005 while the average aperture averaging factor estimated using the proposed methodology taking into account the central obscuration is close to 0.0072. It can be easily observed that the experimental results seem to fit better with the proposed methodology.

Here, it must be noted that for the derivation of point scintillation index, the ground measurement of wind speed was used as input in Bufton model in order to obtain the RMS wind speed and use it as input to the calculation of structure constant of refractive index. Therefore, the accuracy of the validation method can be further improved employing concurrent measurements of vertical atmospheric profiles of humidity, pressure, temperature and wind speed and direction, in order to have a better estimation of C_n^2 on slant path. In addition, concurrent measurements of Fried parameters measured by the respective instrumentation can benefit such a validation process.

5. CONCLUSION

In this paper the aperture averaging technique for downlink optical satellite communication systems is examined. A methodology for the prediction of aperture averaging factor taking into account the central obscuration of the receiver telescope (if exists) is reported. The proposed methodology is validated with real measurements from the experimental campaign between the ARTEMIS GEO satellite and the ESA's OGS in Tenerife equipped with 1.016m Cassegrain central obscured telescope. Through the validation process it seems that the proposed "central obscured" methodology fits well with the experimental results.

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