Use Cases Analysis of Free Space Optical Communication System

K. Saab, F. Bart, Y.-M. Seveque

***Abstract*—**The deployment of Free Space Optical Communications (FSOC) systems requires the development of robust and reliable Optical Ground Stations (OGS) that can be easily installed and operated. To this end, the Engineering Department of Airbus Defence and Space is actively working on the development of innovative and compact OGS solutions that can be deployed in various environments and provide high-quality connectivity under different atmospheric conditions. This article presents an overview of our recent developments in this field, including an evaluation study of different use cases of the FSOC with respect to different atmospheric conditions. The goal is to provide OGS solutions that are both simple and highly effective, allowing for the deployment of high-speed communication networks in a wide range of scenarios.

***Keywords*—**End-to-end optical communication, laser propagation, optical ground station, turbulence.

I. Introduction

FREE space optical links offer a promising alternative to RF links for high-speed communication, which are becoming increasingly saturated due to the exponential growth of data traffic. These links can provide secure and high-bandwidth connectivity for various applications, such as inter-satellite communication, earth observation, deep-space exploration, airborne and maritime surveillance, and disaster management.

However, the performance of free space optical links is limited by atmospheric turbulence, which causes fading and distortion of the optical signal. To address this challenge, the Engineering Department of Airbus Defence and Space is involved in the development of end-to-end optical communication systems and OGS that respond to different application cases.

II. Objective and Methodology

On the receiver side, to take advantage of fiber optic communication technologies such as EDFA, QAM, DWDM, etc., it is necessary to couple the received beam into a Single Mode Fiber (SMF). However, atmospheric turbulence significantly degrades the telescope's resolution and makes coupling impossible. Two phenomena are at the origin of this problem: intensity scintillation and phase disturbances. While increasing the telescope's diameter reduces the effect of scintillation, it exacerbates the phase disturbances and makes focusing the light impossible. In this case, a phase correction system such as adaptive optics or optical recombination must be implemented. Moreover, the larger the diameter, the greater the number of correction modes required to correct the phase, making the correction system heavier and more complicated to implement. Therefore, it is essential to find a compromise between the telescope's diameter and the number of modes needed to achieve the necessary resolution for a stable and sufficient injection, ensuring that the link is robust and reliable, while keeping the deployment simple.

This study aims to address the dimensioning of ground optical terminals in the context of establishing reliable optical links with space terminals. In pursuit of this objective, different use cases are evaluated for their performance in terms of static and dynamic optical losses.

The total loss budget mainly consists of free space propagation losses a_{FS}, in addition to the emitter and receiver telescope gains, which are calculated according to [1]. By considering a phase decomposition based on Zernike modes, dynamic losses are estimated as a function of $\mathrm{D/r_0}$ and the number of Zernike modes considered. This calculation is done using an analytical law developed according to [2] and [3]. Thus, the temporal phase correction error is estimated as a function of the average wind speed, telescope diameter, and sampling frequency of the correction loop, according to [4].

For a rough estimate of performance, we assume that after correction, the coupling efficiency is on average equal to 82% of the Strehl ratio, as described in [5]. Thus, the coupling efficiency is given by the following relation:

$$\mathrm{a_{smf_{CL}}} \approx 0.82exp(-\sigma^2\varphi_{res}), \qquad (1)$$

where $\sigma^2\varphi_{res}$ is the total residual phase.

To better estimate real-life turbulence conditions, we will use the Hufnagel-Valley profile [6] (Fig. 1), recommended by the International Telecommunication Union in the ITU-RP.1621-1, to evaluate the vertical turbulence profile.

III. Modulation Formats and Sensitivities

Currently, the most commonly used modulation technique in optical fiber communication systems is On-Off Key (OOK) modulation, which is based on intensity modulation. However, this method requires adaptive thresholding and high signal-to-noise ratios, which can be challenging in free-space links due to the variable atmospheric conditions and power losses. In contrast, phase modulation techniques like Differential-Phase-Shift-Keying (DPSK) and Phase-Shift-Keying (PSK) are better

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suited for free-space links, as they use inherent thresholding and offer improved sensitivity.

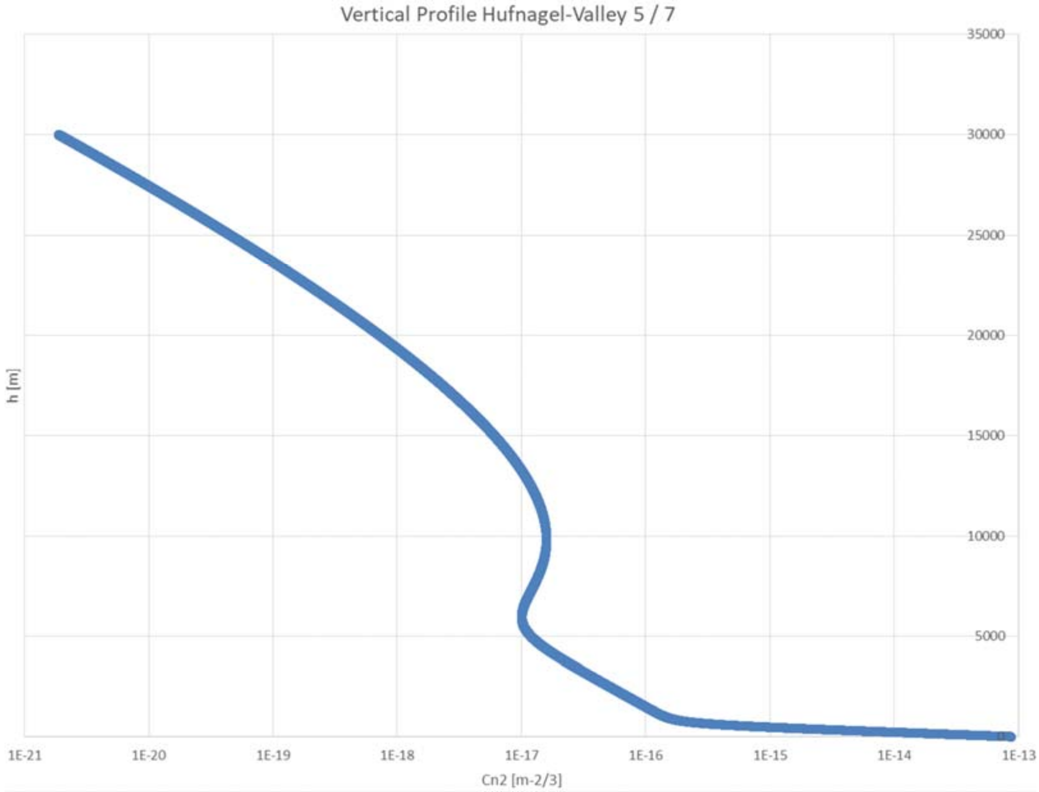


Fig. 1 Worst Vertical turbulence profile according to Hufnagel-Valley model; Averaged wind velocity: 15 m/s; Turbulence Structure function at the ground reference $C_n^2(0) = 8.7E - 14\ m^{-2/3}$

Reference [7] shows that an enhanced Reed-Solomon error correction code with a 255/239 FEC coding can convert a 10^{-3} bit error rate (BER) target to a 10^{-9} output BER with only 7% overhead. This method provides an approximate margin of 6 dB compared to the minimum sensitivity previously achieved. For the purposes of our analysis, we focused only on the DPSK modulation format and fixed the sensitivity reference for three selected data rates (1, 10, and 30 Gbps) at a BER of 10^{-3}. The receiver sensitivities we will use, corresponding to a BER of 10^{-3}, are -55 dBm for 1 Gbps, -45 dBm for 10 Gbps, and -40.5 dBm for 30 Gbps.

IV. Use Cases Performances Analysis

The use cases studied in this article have been selected based on the current market needs for space or ground communication systems. We have considered three types of links: horizontal links, air to ground links, and satellite to ground links. For each case, we have compiled a list of parameters, which are summarized in Table I. These parameters impact the link design and expected performance, and include factors such as propagation distance, angle of elevation, Fried parameter, scintillation factor, isoplanatic angle, average wind velocity, beam divergence, and static channel losses for irradiance conversion without turbulence. It should be noted that the average velocity given for reference is for the GEO to ground link, and a conversion is applied for each case to account for the velocity of the remote moving terminals (such as LEO, MEO, and aircraft). The received optical power is calculated using (2):

$$ROP\ (dBm) = P_{Tx} + G_{Tx} + G_{Rx} - \left(a_{FS} + a_{atmo} + a_{Tx} + a_{Rx} + a_p + a_t + a_{smf_{CL}}\right) \quad (2)$$

The suggested transmitted power, P_{Tx}, can be customized based on the specific needs of the user's application. The power level also depends on the optical amplifier used. The transmitter antenna gain, G_{Tx}, is estimated using a 5 cm diameter for all of the cases. The receiver gain, G_{Rx}, varies with respect to the diameter of the receiver used.

The static losses include the free space losses a_{FS}, and an additional factor related to the defocusing of the beam to simplify the pointing. The added defocus is considered only for the horizontal link, i.e., Aircraft and HAPS to ground link.

A constant atmospheric absorption loss a_{atmo} of 4.5 dB is considered only for the satellite to ground link.

To be able to simplify the study and concentrate the analysis on the telescope gain and the number of correction modes, the pointing and tracking losses (a_p *and* a_t) are not considered. Also, for the same reason, the losses related to the transmitter and receiver calibration (a_{Tx} *and* a_{Rx}) are not included.

Finally, the losses of single mode fiber, $a_{smf_{CL}}$, are estimated using (1) after simplifying the estimation of turbulence perturbation correction by n Zernike mode. Three correction formats are considered: 3, 6 and 10 modes correction. The piston mode is included, so the effective number of spatial mode correction should be n-1. The temporal error is included for all cases and estimated for a sampling frequency of 5 KHz, taking into account the wind velocity of each case.

Three sensitivity levels are considered: -40.5 dBm, -45 dBm, and -55 dBm. These levels consider a DPSK modulation format and respective data rates of 1 Gbps, 10 Gbps and 30 Gbps at a BER of 10-3 [7].

TABLE I
SUMMARY OF PARAMETERS OF THE DIFFERENT CASES ANALYSED IN THIS STUDY

Use Cases	L (m)	α (Deg)	r_0 (cm)	σ2I/I	Θ0 (µrad)	<L> (m)	<v> (m/s)	Def L (dB)	Θ (Deg)	IL (dB/m^2)
HL (Altitude 150 m)	1000	90	5.2	0.4	30	555	15	-44.44	0.377	-15.31
HL (Altitude 500 m)	5000	90	13.8	0.3	15	2773	15	-38.42	0.188	-23.27
AIRCRAFT (DL)	9000	20	8	0.10	25	991	43	-21.94	0.028	-16.40
HAPS (DL)	20000	30	7.6	0.12	22	1075	15	-18.42	0.019	-19.81
LEO (DL)	500000	45	6.7	0.18	16	1317	35	0.00	0.002	-29.36
MEO(DL)	2000000	45	6.7	0.18	16	1317	20	0.00	0.002	-41.40
GEO (DL)	38609000	60	5.5	0.33	9.15	1863	15	0.00	0.002	-67.11

TABLE II
ABBREVIATIONS USED IN TABLE I

L	Propagation Distance
α	Elevation to the Zenith
r_0	Global Fried Parameter
σ2I/I	Scintillation Index
Θ0	Isoplanatic Angle
<L>	Averaged Turbulence Position
<v>	Averaged Wind Velocity
IL	Total Static Loss for Irradiance conversion (dB/m2)
Def L	Defocus Loss (dB)
Θ	Angular Beam size (Deg)
HL	Horizontal Link
DL	Downlink

A. Horizontal Link

Horizontal optical links provide a secure, high-speed connectivity solution in cases where the installation of fiber optic cables is not feasible. This technology eliminates the need for extensive infrastructure preparation and the associated delays. In this type of link, the structure function that characterizes the turbulence level is constant throughout propagation. Depending on the altitude at which the link is established and the distance of propagation, different levels of phase and amplitude disturbance can be obtained. In order to represent both nominal and severe conditions, we calculated the overall r_0 for two propagation distances: 1 km and 5 km. Let us assume that the 5 km link is at an altitude of 500 m and the 1 km link is at an altitude of 150 m. The value of the structure constant provided by the Hufnagel Valet profile for each altitude allows us to calculate the overall r_0 for each case. We find an r_0 of 5.2 cm for the 1 km link at 150 m altitude and an r_0 of 13.8 cm for the 5 km link at 500 m altitude. These two examples are only studied knowing that for an altitude of 500 m and a minimum r_0 of 5 cm, the maximum possible distance is 10 km.

For this analysis, to ensure safe ocular conditions, we set the emitted power to 0 dBm. To ensure sufficient received power, we applied additional beam divergence to facilitate easy pointing of the links.

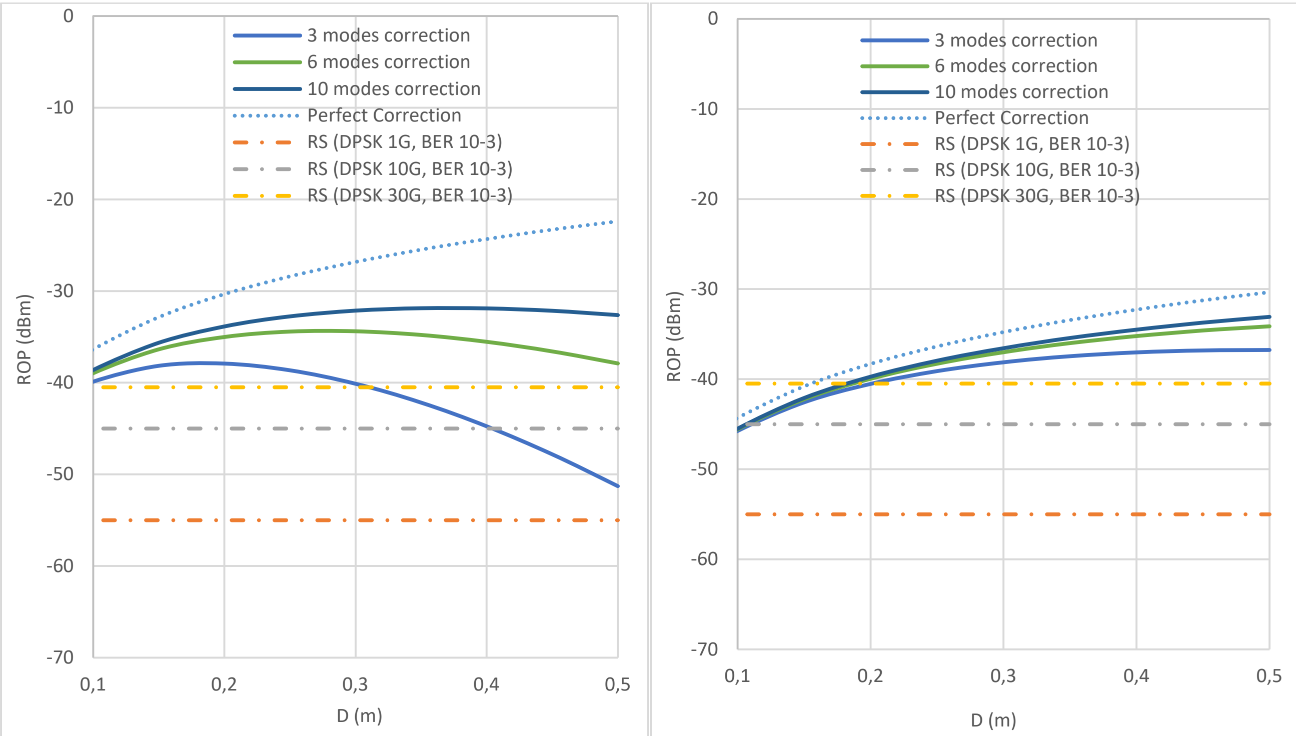
In Fig. 2, we present the results of the received powers as a function of the receiving telescope diameter for different correction cases. We observe that for n correction modes, the saturation of the telescope gain occurs at D = n.r_0. Specifically, for r_0 = 5.2 and 3 correction modes, the gain saturation occurs at around D = 15 cm. For 6 correction modes, the saturation occurs at D = 30 cm, and for 10 modes, it occurs around D = 50 cm. For the case of r_0 = 13.8, the saturation for 3 modes begins at D = 45 cm, and for 6 and 10 modes, saturation is not yet reached, but it is expected to begin at D = 55 cm.

What is of greater interest in this analysis is that a diameter between 15 cm and 25 cm with 3 to 6 correction modes can be a good starting point for a simple and lightweight system. This is evidenced by the sufficient power levels for a link up to 25 Gbps to 30 Gbps with a BER of 10^{-3}. As long as the injection into the fiber is stable and well-controlled, the use of an EDFA in reception allows for even higher data rates.

B. HAPS and Aircraft to Ground Link

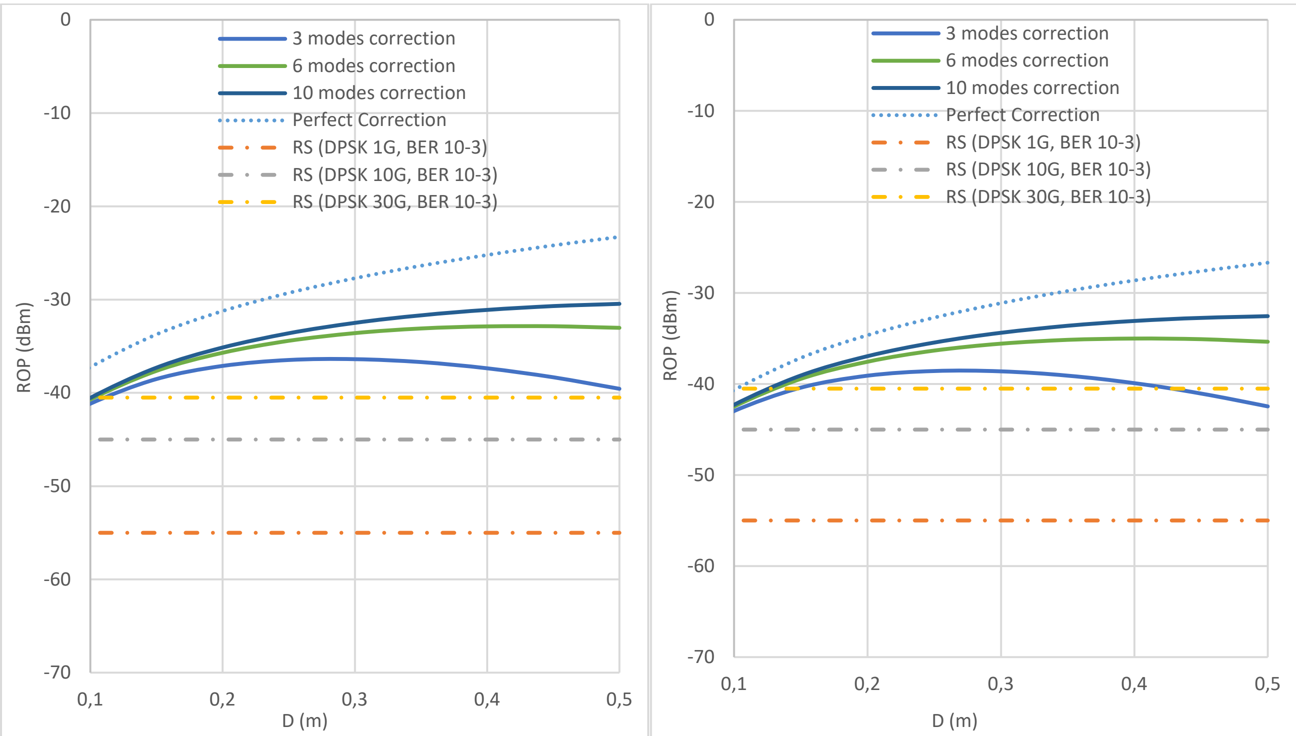
Optical links between High-Altitude Platform Stations (HAPS) or airplanes and the ground are of interest for providing high-speed connectivity as an intermediate relay point between satellite orbits and the ground. However, these links are subject to limitations due to atmospheric turbulence, which can cause errors in the signal transmission. Factors such as altitude, elevation angle, and aircraft velocity can amplify these errors, which must be addressed in order to ensure reliable communication.

To further investigate the feasibility of optical links between HAPS or airplanes and the ground, we considered two scenarios of downward optical links. The first scenario involves a link between a HAPS and the ground at an altitude of 20 km and an elevation angle of 30 degrees. Based on the Hufnagel-Valley atmospheric turbulence profile, the resulting r_0 is calculated to be 7.6 cm. The second scenario involves a link between an airplane flying at an altitude of 9 km and a speed of 250 m/s, with the link established at an elevation angle of 20 degrees. In this case, the r_0 is calculated to be 8 cm. In both scenarios, we assumed an emission power of 0 dBm and applied a beam divergence of 0.2 degrees to improve pointing accuracy.



(a) (b)

Fig. 2 Received Optical Power ROP (dBm) as function of the receiver telescope diameter D (m): (a) Horizontal link at 500 m, (b) Horizontal link at 150 m



(a) (b)

Fig. 3 Received Optical Power ROP (dBm) as function of the receiver telescope diameter D (m): (a) Aircraft to ground link case; (b) HAPS to ground link case

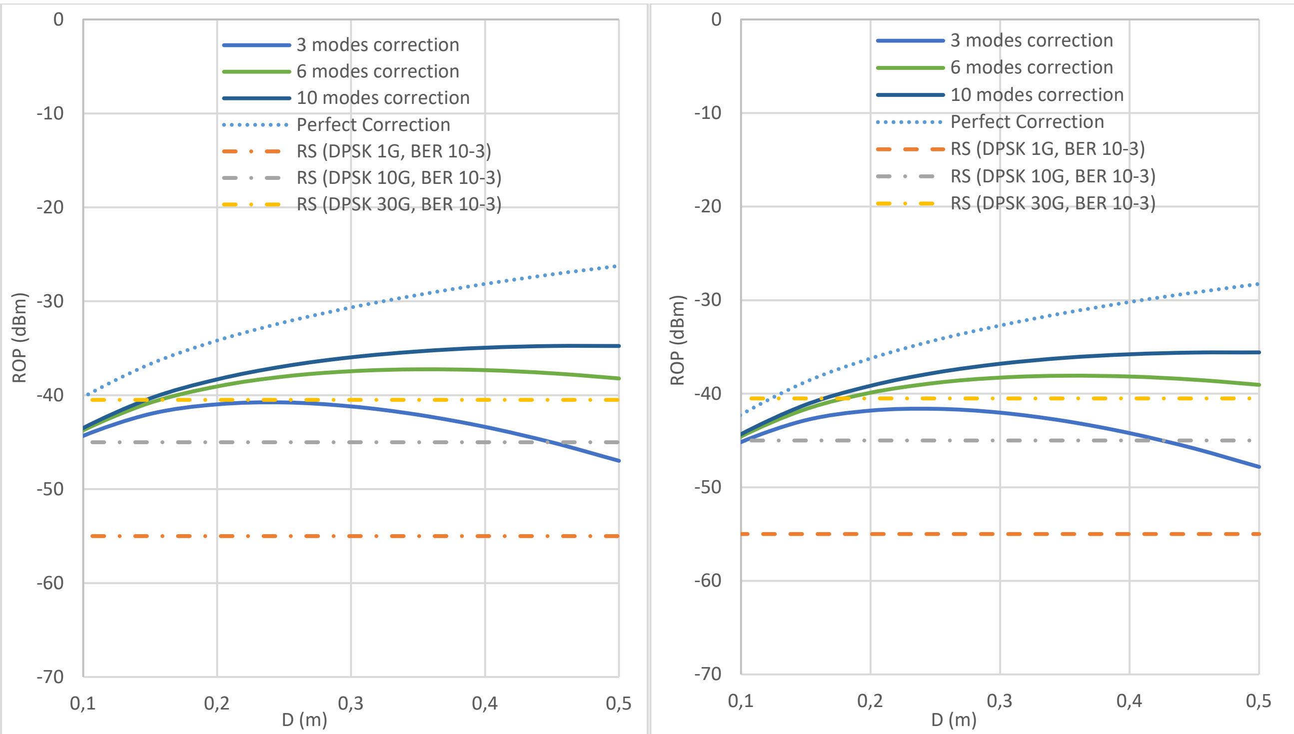
We also reproduced the same sizing parameters as for horizontal links, with diameters ranging from 10 cm to 50 cm for 3, 6, and 10 modes of turbulence correction. The received optical power results are shown in Fig. 3. For a correction of 3 modes in both scenarios, we observed a saturation of the telescope gain at D = 25 cm. For 6 modes, the saturation is reached at D = 50 cm. For 10 modes, the saturation exceeds D = 50 cm, and it is expected to be at D = 80 cm. Finally, we confirm that for a diameter of 25 cm and a correction of 3 modes, the received power ensures a link with a data rate of 30 Gbps, with a margin of 5 dB for the airplane and 3 dB for the HAPS.

C. Satellite to Ground link

Satellite-to-ground links are crucial for providing global connectivity for a range of applications, including remote sensing, navigation, mobile communications, and broadband internet access. Satellites orbit the Earth at different altitudes and speeds, each with unique advantages and limitations. Low Earth Orbit (LEO) satellites provide low-latency communication, while Medium Earth Orbit (MEO) satellites offer accurate positioning information, and Geostationary Earth Orbit (GEO) satellites provide wide coverage but suffer from high latency. Optical communication in space has gained attention due to its ability to offer high data rates, lower power consumption, and enhanced security. In this article, we will examine the specificities of optical communication in free space for each of these three satellite orbits. The ongoing development of optical links in space is expected to revolutionize global connectivity, providing high-speed internet access to even the most remote areas of the world.

For the LEO-to-ground link, we assume an emission power of 10 dBm, a 45° elevation angle, and an altitude of 500 km, resulting in a r_0 value of 6.7 cm. The average wind speed, taking into account the satellite's scrolling velocity, is 35 m/s. For the MEO-to-ground link, we assume an emission power of 20 dBm, with the same 45° elevation angle and an altitude of 2000 km, resulting in the same r_0 value of 6.7 cm. The beam divergence in both cases is assumed to be 0.002°, representing the diffraction limit for a 5 cm emission diameter telescope at a wavelength of 1550 nm.

Fig. 4 presents the received power results, with the saturation of the telescope gain found for 3 correction modes between a diameters of 20 cm to 25 cm. For 6 correction modes, saturation is found between 35 cm and 40 cm, and for 10 correction modes, saturation begins to appear for a diameter of 50 cm. With a diameter of 20 cm to 30 cm and 3 correction modes, a throughput of 25 Gbps is achievable without amplification. Wavelength-division multiplexing is also possible through fiber injection, which can increase the throughput by a factor of 10.



(a) (b)

Fig. 4 Received Optical Power ROP (dBm) as function of the receiver telescope diameter D (m): (a) LEO to ground link case; (b) MEO to ground link case

For the GEO-to-ground link (GEO-sol), we consider an emission power of 40 dBm and a fixed elevation angle of 60°, resulting in a global r_0 of 5.5 cm considering the propagation distance. Fig. 5 shows that, under these conditions, the maximum received power for 3 correction modes is found at a diameter between 15 cm and 20 cm, allowing for a data rate of up to 5 Gbps without additional optical amplification in reception. For 6 correction modes, the maximum gain is found at a diameter between 25 cm and 30 cm, allowing for a data rate of 8 Gbps to 9 Gbps, and for 10 correction modes, the maximum gain is at a diameter between 35 cm and 50 cm, allowing for a data rate of 10 Gbps.

To achieve a data rate of 30 Gbps, a diameter between 20 cm and 30 cm with 3 to 6 correction modes and an optical amplification of 10 dB to 20 dB is possible with a fibered Low Noise Optical Amplifier (LNOA). Otherwise, a diameter of 50 cm to 80 cm with at least 15 to 20 correction modes would be necessary, which would make the ground station heavier and complicate the autonomous and robust implementation of the link.

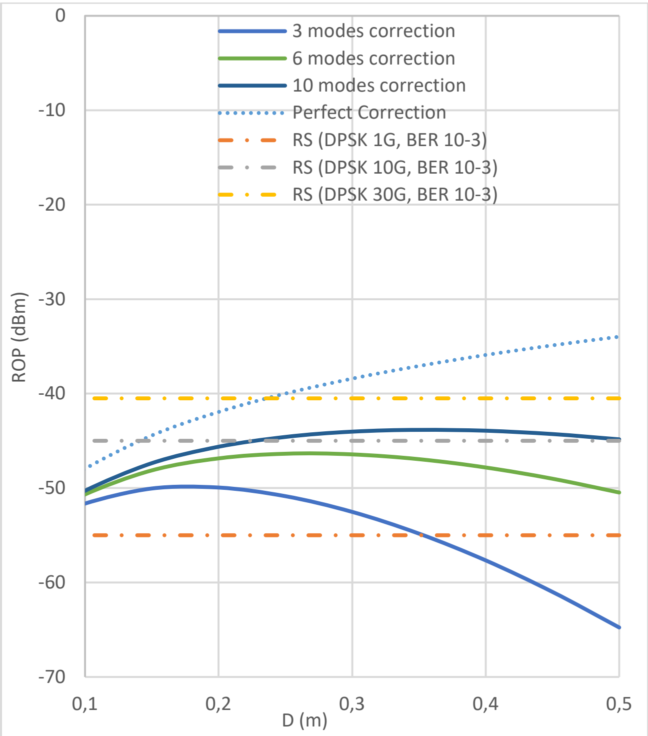


Fig. 5 GEO to ground link case: Received Optical Power ROP (dBm) as function of the receiver telescope diameter D (m).

V. Conclusion and Perspective

In this article, we have investigated the feasibility of optical links in various scenarios, including links between HAPS or airplanes and the ground, satellite-to-ground links, and horizontal links. We have also discussed the issue of atmospheric turbulence and the use of correction modes to improve link reliability. Our findings suggest that a simple and lightweight system with a telescope diameter of 15 cm to 25 cm and 3 to 6 correction modes can provide sufficient power levels for a link of up to 25 Gbps to 30 Gbps with a BER of 10^{-3}.

Moreover, we have demonstrated that for HAPS/aircraft to ground links, a telescope diameter between 20 cm and 25 cm with 3 correction modes can achieve a throughput of up to 30 Gbps. For LEO/MEO to ground links, a diameter of 20 cm to 30 cm with 3 correction modes can provide a throughput of 25 Gbps without requiring additional amplification in reception. In the GEO scenario, a diameter of 25 cm with 3 correction modes resulted in a throughput of 5 Gbps without using an amplifier or up to 25 Gbps with a 15 dB amplifier. However, increasing the diameter beyond 50 cm or even 80 cm is not beneficial unless the number of correction modes exceeds 20. This complexity results in increased weight and calibration procedures, requiring the intervention of an expert in adaptive optics or coherent beam combining.

As part of the development of operational ground stations dedicated to FSOC, based on this analysis and these results, a further study on sizing through numerical simulation and practical experimentation will be carried out within the Engineering Department of Airbus Defence and Space.

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