

Experimental Validation and Atmospheric Turbulence Characterization of Optical Satellite-to-Ground Links

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ABSTRACT

Although Free-Space Optical (FSO) communications offer unprecedented bandwidth for space-to-ground segments, their operational viability is heavily constrained by pointing accuracies and atmospheric seeing conditions. To address these requirements, this work presents a comprehensive methodology for optimal Optical Ground Segment (OGS) site selection, supported by experimental validation of the satellite-to-ground link. Evaluated within a five-location dataset, the selected site was validated as a viable OGS location achieving over 95.3% sky visibility with stable trajectory tracking experimentally confirmed during an overpass between the 6GStar-Lab satellite and the deployed station. This analysis is further complemented by an atmospheric characterization via a co-located sky monitor. Preliminary measurements demonstrate local conditions with a Fried parameter ranging from 5.8 (12.76) to 9.41 (20.56) at 808 (1550) nm, confirming the site's feasibility for high-rate optical communication at those wavelengths and, generally, good location for FSO links testing against turbulence.

Keywords: Free-Space Optical communications, ground segment, atmospheric modeling, CubeSat

1. INTRODUCTION

The transition from Radio Frequency (RF) to optical communications is currently a key driver for modern satellite constellations, offering increased data transfer speed, and significantly higher bandwidth, among others. However, achieving full operational capability is contingent upon overcoming two fundamental challenges. Firstly, signal quality degrades during the propagation due to the atmospheric gases and aerosols present at the lower layers of the atmosphere, a limiting factor especially for optical signal propagation. Additionally, the nature of the narrow optical beamwidth requires a very precise system to point two terminals with high-precision stability, often referred to as a Pointing, Acquisition, and Tracking (PAT) system.

Consequently, the strategic selection of the Optical Ground Station (OGS) location becomes a critical design factor to mitigate these effects. This work details a comprehensive analytical procedure for optimal OGS site selection, which is subsequently validated through experimental satellite-to-ground communication links between the optical payload aboard the 6GStarLab¹ and the OGS at 41.07° N, 0.66° E (Tarragona, Spain).

First, a 2D and 3D topographical analysis was conducted to determine the optimal placement for the OGS, using a Digital Elevation Model (DEM) with 2x2 meters resolution to compute elevation masks. Additional infrastructures, such as other ground stations and buildings, were generated by the authors. Afterwards, a full 360 degrees elevation mask is presented to characterize azimuthal visibility in clear-sky and quantify how

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surrounding installations will impact total contact time. This is complemented by a spatial assessment across different locations to evaluate the influence of terrain slope and nearby elements on link availability. Finally, the analysis is complemented by the integration of an atmospheric monitoring equipment, allowing to gather real atmospheric turbulence data, critical for the optical channel. We present here the preliminary data from the start of the measuring campaign at the site. Continuous data is being acquired to form a dataset for atmospheric conditions correlation with link budgets once the satellite commissioning phase concludes and operation begins.

The remaining of this paper is structured as follows: Section 2 introduces the site selection and visibility modeling methodology; Section 3 evaluates the telemetry data and atmospheric performance results, and Section 4 highlights the main conclusions of the work.

2. METHODOLOGY

The followed methodology comprises four key steps: first, the initial selection of the regional location; second, a topographical analysis in which the digital environment is composed of natural surrounding and structural elements; third, a visibility analysis to determine the sky dome accessibility; and finally, a theoretical atmospheric turbulence modeling to characterize the optical propagation channel.

2.1 Ground Station Site Assessment

2.1.1 Selection of the regional location

The regional site selection directly addresses two core operational requirements. First, placing the facility away from urban centers mitigates both optical light pollution and RF spectrum congestion. Second, a region with a moderate height preserves a longer atmospheric path. This extended atmospheric column is essential for characterizing local turbulence and thoroughly analyzing the degrading impact on signal propagation, particularly interesting in the optical domain. Based on these criteria, a rural region in Tarragona, Spain (41.07°N , 0.66°E), Móra la Nova, was selected as the optimal location for the facility.

2.1.2 Topographical model

A comprehensive 2D and 3D topographic and spatial modeling was conducted over the selected geographical area using the spatial visualization software, QGIS. This tool enables the integration of both terrain features and custom objects to analyze the environment.

On one hand, several geographical maps from the Centro Nacional de Información Geográfica (CNIG) were evaluated to include the surrounding terrain and vegetation. Specifically, the Digital Terrain Model (DTM) 2008-2011² and the Digital Vegetation Surface Model (NDSM),³ with spatial resolutions of 2 and 2.5 meters, respectively, were initially evaluated. Nevertheless, the Digital Surface Model (DSM) 2016⁴ at a 2-meter resolution was selected for the final analysis, as it is the most updated map available and integrates both terrain and vegetation obstacles into a single layer. Once the DSM model was selected, a total of 16 datasets were used for the subsequent analysis to cover the geographical area shown in Fig. 1–left. In addition, two supplementary

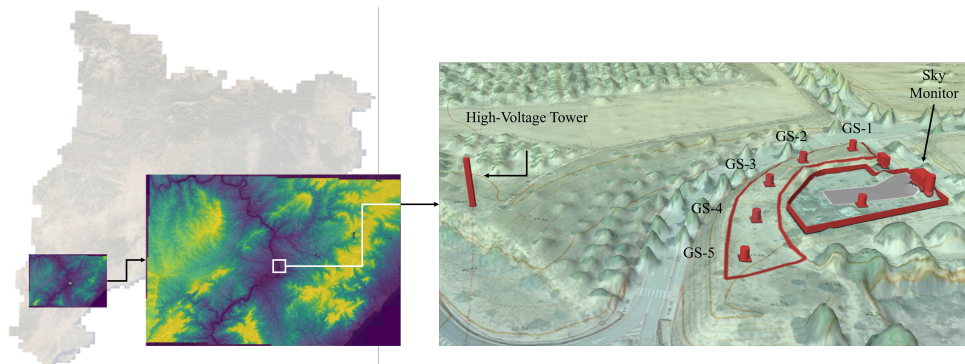


Figure 1. Geospatial datasets and physical structure.

layers from the Institut Cartogràfic i Geològic de Catalunya (ICGC) were integrated into the project (see Fig. 1–right). First, a high-resolution true-color orthophoto provided a visual baseline to identify surface features, such as vegetation, buildings, and road infrastructure, which aided the proper interpretation of the color-coded DSM maps. Second, the ICGC topographic map was utilized to delineate land parcels and site boundaries.

On the other hand, additional structures were generated to complete the digital layout (see Fig. 1–right). These include a perimeter wall (2 meters high), a high-voltage tower (15 meters high), two buildings (3 meters high) the left of which hosts a sky monitor on its roof, and five ground stations (designated GS-1 through GS-5). Each ground station was identically modeled with a 0.3 meters pillar topped by a 3.3 meters cylinder, separated 20 meters apart to ensure uniform distribution within the available space.

2.1.3 Sky visibility

A dedicated QGIS plugin called *Sky Visibility Analysis* was developed and integrated into the simulation workflow to evaluate sky visibility for the OGS five candidate locations. It computes sky visibility by analyzing both terrain topography and surrounding physical obstacles from each station location. The inputs required by this tool are the DEM, OGS location, obstacle generated layer, OGS height, maximum distance, angular resolution, and radial step size. Then, the algorithm determines the complete 360-degree elevation mask and quantifies the percentage of visible versus obstructed sky dome. The values configured for all scenarios (i.e., different OGS locations along with their corresponding obstacle layers) are detailed in Table 1. The altitude of the OGS is set to 1.5 meters corresponding to the telescope height, while the obstacles layer configures the rest of the ground stations to 3.3 meters height.

The developed tool exports the outputs as structured JSON files, with optional polar plots generated to visualize the resulting horizon mask (see Fig. 2). The sky visibility assessment reveals consistently high accessi-

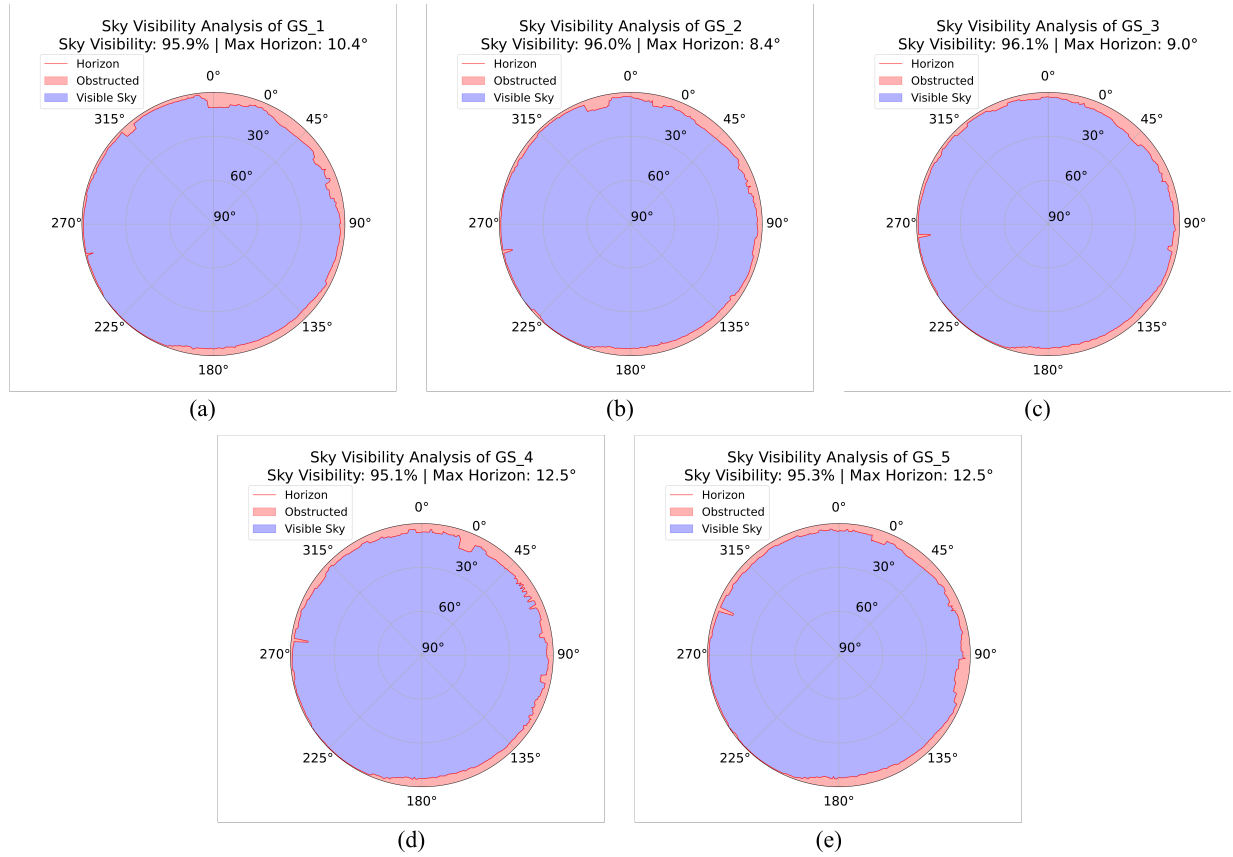


Figure 2. Visibility mask for OGS five candidate locations: (a)–(e).

Table 1. Input settings parameters for the sky visibility assessment tool.

DEM	OGS Site	Obs. Layer	OGS Alt. [m]	Max. Dist. [m]	Ang. Res. [deg]	Rad. Step [m]
DSM 2016	1/2/3/4/5	1/2/3/4/5	1.5	8000	0.5	1

bility across all five candidate sites, with total visible sky dome coverage exceeding 95% in all scenarios. While Location 3 achieved the highest overall visibility at 96.1%, closely followed by Location 2 (96.0%), Location 2 presented the most favorable horizon profile peaking at a maximum angle of 8.4°. Whereas Locations 4 and 5 experienced the highest local obstructions, both reaching a maximum horizon elevation of 12.5°.

Location 1 was ultimately selected for the deployment. It features a sky visibility of 95.9% and a maximum elevation of 10.4°. Its proximity to the sky monitor guarantees that atmospheric data collected by the monitor remains highly representative of the ground station environment.

2.2 Atmospheric Turbulence

Continuous multi-spectral atmospheric characterization is paramount for optimizing Free-Space Optical Communication (FSOC) links between OGS and satellite payloads. The methodology for the Móra la Nova OGS atmospheric characterization campaign uses Miratlas Sky Monitor equipment measuring continuous parameters including the Fried parameter r_0 , seeing, isoplanatic angle θ_0 , cloud screening, and vertical refractive index structure profiles $C_n^2(h)$. Wavelength scaling models and boundary layer thermal dynamics are analyzed to evaluate performance across operational optical links.

2.2.1 Measurement equipment

Cloud screening is characterized using wide field visible and infrared observations, complemented by calibrated measurements of zenithal sky temperature and atmospheric infrared emission. The visible all sky camera provides wide field observations over the 400–1000 nm spectral range, while long-wave infrared (LWIR) measurements provide complementary information on cloud structure, precipitable water column (PWC), and down-welling infrared radiation. These observations are used primarily for environmental characterization and cloud screening, rather than as direct measurements of optical attenuation at the communication wavelength.⁵

Daytime optical turbulence is characterized using the solar scintillation monitor (SSM) and the shadow band ranger (SHABAR), while nighttime conditions are characterized using the Compact Differential Image Motion Monitor (C-DIMM). The SSM provides integrated daytime Fried parameter r_0 and seeing at $\lambda_0 = 550$ nm, with standard products at approximately 60 s cadence. The C-DIMM provides nighttime r_0 , seeing, isoplanatic angle θ_0 , scintillation, and transparency from stellar observations, also at approximately 60 s sampling. At Móra la Nova, Polaris provides a stable stellar reference.^{6–8}

SHABAR provides complementary vertically resolved daytime estimates of $C_n^2(h)$. The data contains 24 altitude samples from 1 m to a stored maximum of approximately 3.5 km. However, according to the manufacturer, samples above approximately 1 km are calculated, rather than measured, to ensure retrieval convergence and are therefore not interpreted as independent high altitude measurements. The present analysis consequently focuses on the lower atmospheric profile. The SHABAR also measures integrated r_0 , seeing, θ_0 , coherence time τ_0 , and the boundary layer Fried parameter $r_{0,BL}$, defined over the 0–500 m layer. All SHABAR data is referenced to $\lambda_0 = 550$ nm and corrected towards zenith, while the vertical profile is stored as $\log_{10}(C_n^2)$.

The Miratlas sky monitor integrates a weather station that provides temperature, atmospheric pressure, relative humidity, wind speed and direction. These measurements provide the environmental context for interpreting temporal variations in optical turbulence and, together with the cloud and atmospheric water column indicators, support the identification of periods affected by precipitation or other non comparable observing conditions.

All datasets are referenced to UTC and synchronized using their acquisition timestamps. Where required, measurements are resampled to a common temporal basis for statistical analysis while preserving the native resolution of the individual products whenever possible. SHABAR acquisitions are retained only when the retrieval algorithm provides a valid converged solution. Daytime and nighttime turbulence statistics are treated

separately, and cloud affected periods are excluded from clear sky turbulence statistics when appropriate. The resulting quality controlled dataset provides the basis for the subsequent analysis of the vertical turbulence structure, its temporal variability, and its relationship with local meteorological conditions.

2.2.2 Turbulence parameterization and inversion methodology

Atmospheric turbulence is characterized through the refractive index structure parameter $C_n^2(h)$ and the corresponding integrated optical parameters. These quantities provide a common framework for comparing the daytime SHABAR and SSM measurements with the nighttime C-DIMM observations and for assessing the atmospheric contribution to the ground to space optical propagation. Turbulence effects are described primarily through the Fried parameter r_0 , seeing, isoplanatic angle θ_0 , and coherence time τ_0 , together with the vertically resolved $C_n^2(h)$ profiles provided by SHABAR.^{9,10}

For a vertical turbulence profile, the integrated Fried parameter is obtained from the path integral of the refractive index structure parameter according to

$$r_0(\lambda, \xi) = \left[0.423 \left(\frac{2\pi}{\lambda} \right)^2 \sec \xi \int C_n^2(z) dz \right]^{-3/5}, \quad (1)$$

where λ is the optical wavelength and ξ is the zenith angle. The corresponding seeing is related to the Fried parameter through

$$\varepsilon = 0.98 \frac{\lambda}{r_0}, \quad (2)$$

for Kolmogorov turbulence under the standard long exposure approximation.

The isoplanatic angle is obtained from the altitude weighted turbulence integral

$$\theta_0(\lambda, \xi) = \lambda^{6/5} \left[\sec^{8/3} \xi \int C_n^2(z) z^{5/3} dz \right]^{-3/5}, \quad (3)$$

following the standard atmospheric turbulence formulation.^{10,11} These relations provide the basis for comparing vertically resolved SHABAR profiles with the integrated turbulence parameters reported by the SSM and C-DIMM.

The SHABAR vertical profiles are treated according to the retrieval limitations described in section 2.2. The physically meaningful profile is primarily considered over the lower atmosphere up to approximately 1 km, and the remaining span up to 3 km is not interpreted as independent observations. Consequently, integrated quantities derived from SHABAR are evaluated with explicit consideration of the altitude range used in the integration.

The coherence time is not independently reconstructed from the local surface wind measurements because τ_0 depends on the altitude dependent wind profile. Instead, the SHABAR reported τ_0 product is used where required, while local wind measurements are treated as supporting meteorological variables rather than as a substitute for an inexistent vertical wind profile.

All primary optical turbulence measurements are referenced to $\lambda_0 = 550$ nm. To assess their relevance to the operational optical channels, wavelength dependent parameters are scaled to the wavelengths of the acquisition beacon at $\lambda = 808$ nm and the telecommunication and QKD channels at $\lambda = 1550$ nm using the standard Kolmogorov wavelength dependence

$$r_0(\lambda) = r_0(\lambda_0) \left(\frac{\lambda}{\lambda_0} \right)^{6/5}, \quad (4)$$

and

$$\theta_0(\lambda) = \theta_0(\lambda_0) \left(\frac{\lambda}{\lambda_0} \right)^{6/5}. \quad (5)$$

This spectral scaling is applied to the turbulence parameters used for optical link assessment, while the original measurements at 550 nm are retained as the reference dataset. The resulting parameters provide a consistent basis for evaluating the atmospheric turbulence contribution to ground to space propagation at the operational wavelengths.

3. RESULTS

This section presents the experimental validation structured into two key parts. Section 3.1 evaluates the optical link performance recorded during a mission pass with the 6GStar-Lab satellite, validating the operational readiness of the OGS at the selected site. Section 3.2 provides an upward atmospheric analysis from the ground facility to quantify local propagation conditions across the optical channel.

3.1 Satellite to Ground Contact

To evaluate the pass performance, satellite telemetry data was successfully obtained during a contact on August 3rd 2026, over the OGS-1 ground station (see Fig.3). The optical transmitter operated at 808 nm with a transmit power of 40 dBm and a 0.2° beam divergence, yielding a received satellite power of -66 dBm.

Fig. 4 shows the visibility mask of the OGS-1 and the trajectory of the satellite. The green triangle marks the starting point of the acquisition process at an azimuth of 159.53°, an elevation of 0.23°, and a range distance of 2594.7 km under eclipsed conditions. The satellite reached its maximum elevation of 63.73° at a 81.5° azimuth and a range of 573.2 km, which is marked with a yellow star, while still in eclipse. The pass concluded outside eclipse region at an azimuth of 351.89°, an elevation of 0.83°, and a distance of 2533 km, which is denoted with an inverted red triangle.

As shown in Fig. 4, data collection remained fully viable through the pass, as the recorded trajectory stayed within the visible region of the OGS-1. The plot also differentiates the active tracking modes throughout the pass. Open-loop tracking (orange) dominates at lower elevation angles near the start and end of the pass, where the OGS-1 follows the pre-calculated TLE ephemerids without direct signal feedback. Closed-loop tracking (lime green) is activated along the higher-elevation central segment, where the receiver detects a sufficiently strong beacon signal to enable real-time autotracking. Overlaying the orbital coordinates calculated from TLE data (blue dotted line) demonstrates excellent agreement with the recorded track, confirming stable trajectory tracking throughout the entire pass.

3.2 Empirical Turbulence Results and Wavelength Scaling

3.2.1 Atmospheric optical turbulence and vertical profile

We analyse the beginning of the measuring campaign dataset from June 2026. It provides simultaneous measurements of local meteorological conditions and atmospheric optical turbulence under daytime and nighttime conditions. The campaign includes 32,761 weather samples, 6,719 C-DIMM samples and 6,689 valid SHABAR vertical profiles. Unless otherwise stated, all turbulence parameters refer to the reference wavelength $\lambda_0 = 550$ nm.



Figure 3. Optical ground segment deployed to conduct optical communications experiments with the 6GStar-Lab satellite.

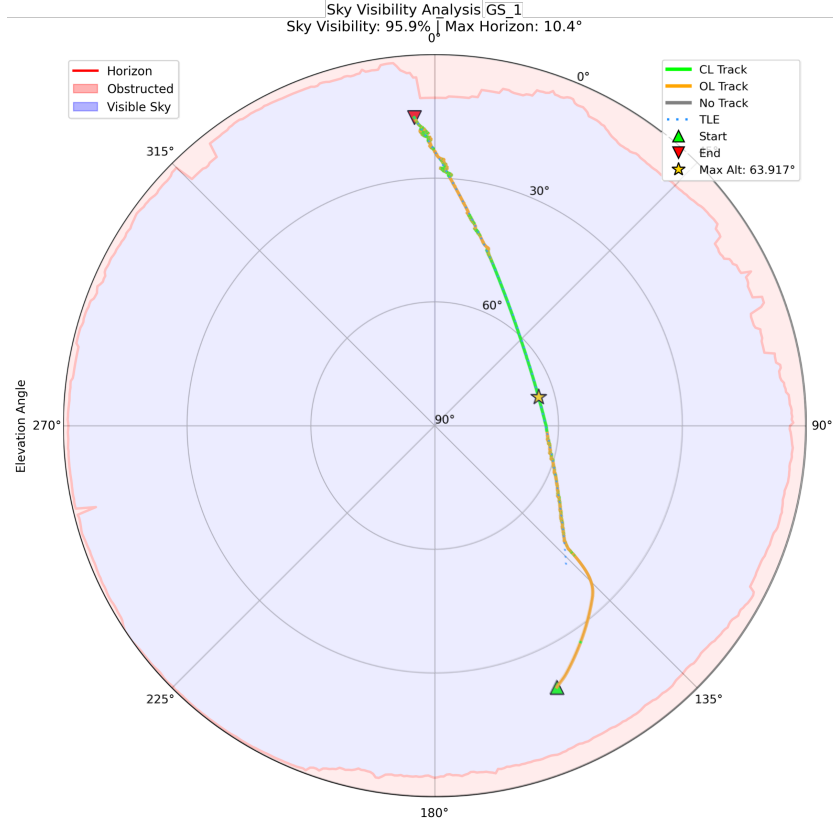


Figure 4. OGS-1 visibility mask and tracking for the 6GStar-Lab pass.

The nighttime C-DIMM measurements yield a median Fried parameter of $r_{0,\text{night}} = 3.68$ cm, with a mean value of 3.89 ± 1.10 cm and a median seeing of approximately $3.02''$. Daytime measurements provide larger Fried parameters, with median values of 9.39 cm for the SSM and 5.93 cm for the integrated SHABAR product, corresponding to approximately $1.18''$ and $1.87''$ seeing, respectively. These differences demonstrate pronounced diurnal variability at the site. The difference between SSM and SHABAR is caused by their different observing geometries, where the SSM is limited to the boundary layer (tens of meters above the instrument) and the SHABAR measures a column up to 1500m directly and until 3500 indirectly.^{6,12,13} Boundary layer dynamics, local thermal effects, wind conditions, and spatial filtering may all contribute to the observed differences.

The SHABAR measurements provide complementary information on the vertical optical turbulence structure of the lower atmosphere. As illustrated in Fig. 5, the retrieved refractive index structure parameter decreases monotonically with altitude, from approximately $C_n^2(1 \text{ m}) = 2.80 \times 10^{-13} \text{ m}^{-2/3}$ near ground level to $1.15 \times 10^{-15} \text{ m}^{-2/3}$ at 100.8 m and $1.38 \times 10^{-16} \text{ m}^{-2/3}$ at an altitude of 1209 m. Within the physically informative altitude range, the mean vertical turbulence profile is represented by

$$C_n^2(h) = C_{n,0}^2 \left(\frac{h}{h_0} \right)^{-\alpha}, \quad (6)$$

where h_0 is a reference altitude and α is the empirical decay exponent. For the June dataset, the fitted exponent is approximately $\alpha = 1.13\text{--}1.15$, with $R^2 > 0.99$ for the selected fitting range. Bootstrap analysis gives $\alpha = 1.133 \pm 0.008$, with a 95% confidence interval of $[1.125, 1.141]$. This value is lower than the classical $4/3$ convective boundary-layer exponent, indicating a flatter vertical decay of the retrieved turbulence profile at the measurement site. We assume this as an empirical site characteristic rather than assign it to a single

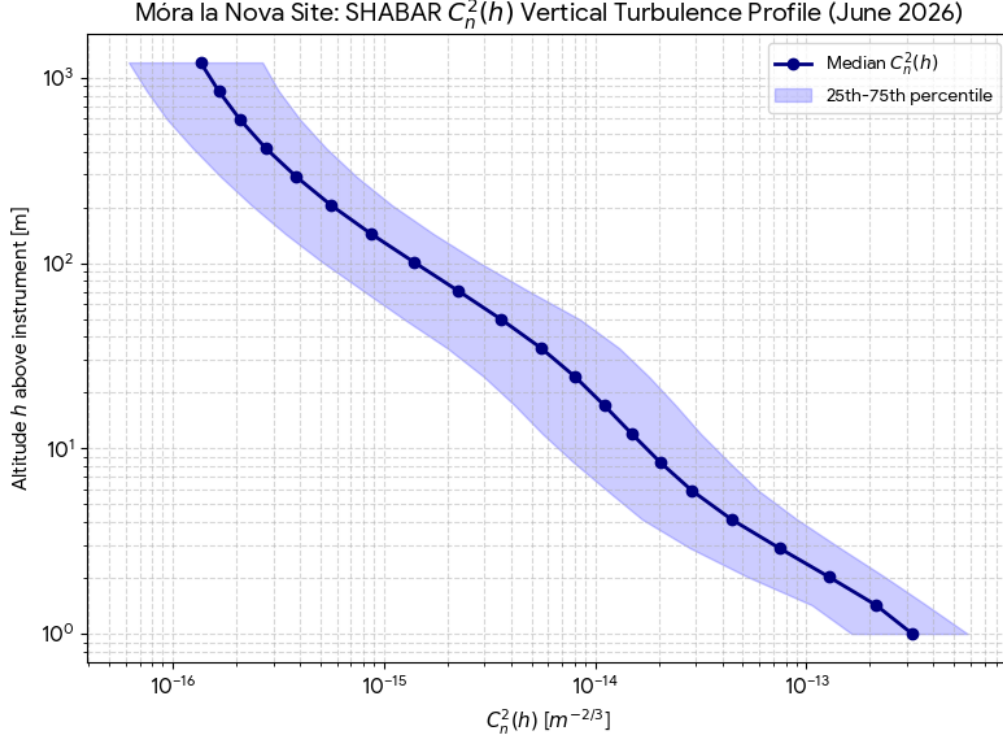


Figure 5. Vertical refractive index structure parameter profile $C_n^2(h)$ measured by SHABAR at the M'ora la Nova OGS site during June 2026. The solid curve denotes the median profile, while the shaded band represents the 25th–75th percentile interquartile range across 6,689 valid vertical profiles.

physical mechanism, with local thermal conditions, mechanical mixing, wind regime, and measurement geometry considered as possible contributing factors.

The measured turbulence parameters are scaled from $\lambda_0 = 550$ nm to the operational acquisition beacon at $\lambda = 808$ nm and to the telecommunication and QKD wavelength at $\lambda = 1550$ nm using the standard Kolmogorov dependence

$$r_0(\lambda) = r_0(\lambda_0) \left(\frac{\lambda}{\lambda_0} \right)^{6/5}, \quad (7)$$

with the same spectral dependence applied to θ_0 where required. Since the seeing is given by

$$\epsilon(\lambda) = 0.98 \frac{\lambda}{r_0(\lambda)}, \quad (8)$$

the corresponding seeing values are obtained directly from the scaled Fried parameter. The resulting median Fried parameters are summarized in Table 2. Relative to the 550 nm reference, the median r_0 increases by factors of approximately 1.59 at 808 nm and 3.47 at 1550 nm.

3.2.2 Link-level beam spot and divergence analysis

The measuring campaign and modeling of the site atmospheric conditions is a critical asset for the correct design, test and deployment of optical links to and from the location. We present here a first evaluation of the link-level implications of the measured atmospheric parameters on a link to a LEO satellite at an altitude of 500 km. Namely, effective beam spot diameter at the target $D_{B,\text{eff}}$ (or footprint), and effective divergence Θ_{eff} , are evaluated following the formulation in:¹⁴

Table 2. Median Fried parameter measured at 550 nm and scaled to operational optical wavelengths for the June 2026 campaign.

Dataset	r_0 @ 550 nm	r_0 @ 808 nm	r_0 @ 1550 nm
C-DIMM, night	3.68 cm	5.84 cm	12.76 cm
SHABAR, day	5.93 cm	9.41 cm	20.56 cm
SSM, day	9.39 cm	14.90 cm	32.56 cm

Table 3. Modeled effective receiver beam spot diameter and divergence for representative 500-km LEO link configurations. June 2026 C-DIMM turbulence measurements are used for the UL cases, while the DL values represent diffraction-limited geometric reference cases.

Link Channel	Configuration	λ (nm)	Metric	Elevation Angle (β)			
				20°	45°	70°	90°
Data UL	Ref.	1550	$D_{B,\text{eff}}$	13.04 m	7.62 m	5.99 m	5.67 m
	($r_0 = 10^5$ cm)		Θ_{eff}	10.64 μrad	10.64 μrad	10.64 μrad	10.64 μrad
	C-DIMM Night		$D_{B,\text{eff}}$	59.65 m	23.00 m	15.47 m	14.17 m
	($r_0 = 12.76$ cm)		Θ_{eff}	49.71 μrad	33.16 μrad	28.54 μrad	27.64 μrad
Beacon UL	Ref.	808	$D_{B,\text{eff}}$	3.96 km	2.27 km	1.76 km	1.66 km
	($r_0 = 10^5$ cm)		Θ_{eff}	3.32 mrad	3.32 mrad	3.32 mrad	3.32 mrad
	C-DIMM Night		$D_{B,\text{eff}}$	3.96 km	2.27 km	1.76 km	1.66 km
	($r_0 = 5.84$ cm)		Θ_{eff}	3.32 mrad	3.32 mrad	3.32 mrad	3.32 mrad
Data DL	Ref.	1550	$D_{B,\text{eff}}$	83.33 m	47.74 m	37.02 m	34.96 m
	($r_0 = 10^5$ cm)		Θ_{eff}	69.81 μrad	69.81 μrad	69.81 μrad	69.81 μrad
Beacon DL	Ref.	808	$D_{B,\text{eff}}$	16.65 km	9.54 km	7.39 km	6.98 km
	($r_0 = 10^5$ cm)		Θ_{eff}	13.96 mrad	13.96 mrad	13.96 mrad	13.96 mrad

$$D_{B,\text{eff}} = \left(D_T + d \sqrt{\theta_{\text{diff}}^2 + \theta_{\text{atm}}^2} \right) 10^{-F_{\text{AO}}/20}, \quad (9)$$

$$\Theta_{\text{eff}} = 2 \arctan \left(\frac{D_{B,\text{eff}} - D_T}{2d} \right) \approx \frac{D_{B,\text{eff}} - D_T}{d}, \quad (10)$$

where D_T is the transmitter aperture diameter, d is the slant range distance $L(\beta)$ between the OGS and the satellite, and F_{AO} represents the adaptive optics improvement factor. The present analysis considers the fully uncompensated case, with $F_{\text{AO}} = 0$ dB, in order to provide a conservative reference for the effect of atmospheric turbulence.

For the OGS Data up-link (UL) transmitter, $D_T = 356$ mm (14"), the diffraction-limited angular scale is $\theta_{\text{diff}} = 2.44\lambda/D_T = 10.64 \mu\text{rad}$ at $\lambda = 1550$ nm. The Beacon UL is considered at $\lambda = 808$ nm with a configured divergence of 0.19° (3.32 mrad). For the corresponding down-link (DL) configuration, the data DL is assigned a divergence of 0.004° ($\approx 69.81 \mu\text{rad}$), while the beacon DL uses 0.8° (13.96 mrad). Calculations are performed for elevation angles $\beta \in 20^\circ, 45^\circ, 70^\circ, 90^\circ$.

For the UL cases, the nighttime C-DIMM median value, scaled to the corresponding wavelength, is used as the representative atmospheric condition. Thus, $r_0 = 12.76$ cm is used for the 1550 nm data UL and $r_0 = 5.84$ cm for the 808 nm beacon UL. An idealized reference case with $r_0 = 10^5$ cm is included to represent the diffraction-limited geometric baseline.

As shown in Table 3, atmospheric turbulence produces a substantial increase in the modeled data UL footprint for the uncompensated $D_T = 0.356$ m transmitter. At zenith, the effective footprint increases from 5.67 m in the diffraction-limited reference case to 14.17 m for the C-DIMM turbulence condition. At $\beta = 20^\circ$, the corresponding footprint reaches 59.65 m, reflecting the increased turbulence contribution associated with the longer slant path.

In contrast, the wide-angle Beacon UL is geometrically dominated by its configured transmitter divergence. The resulting footprint remains approximately 3.96 km at 20° elevation and is essentially unchanged between the diffraction-limited reference and the C-DIMM turbulence case at the precision shown in Table 3. Thus, for this wide-angle acquisition channel, the modeled turbulence contribution is negligible relative to the imposed geometric divergence.

In the DL case, turbulence close to the receiving OGS has a reduced effect on the geometric beam footprint compared with an equivalent near-transmitter perturbation. However, atmospheric turbulence remains relevant to other receiver-side effects, including wavefront distortion, angle-of-arrival fluctuations, scintillation, and coupling performance. The DL values in Table 3 should therefore be interpreted as diffraction-limited geometric reference cases rather than turbulence-free link predictions. Under this reference assumption, the data DL footprint reaches 34.96 m at zenith, while the wide-angle beacon DL reaches 6.98 km.

From a system engineering perspective, the receiver footprint diameter $D_{B,\text{eff}}$ has different operational implications depending on the link function. For Beacon channels, a broad footprint can be beneficial during the initial spatial acquisition phase because it relaxes the initial pointing requirement and facilitates spatial discovery between the OGS and the satellite. For Data channels, the beam footprint is directly related to optical power density and to the sensitivity of the received signal to pointing errors. A narrower beam therefore increases power concentration but requires tighter angular control to limit pointing losses. This trade-off motivates the use of precision tracking and fine-pointing mechanisms, such as fast steering mirrors and high-bandwidth tracking actuators, at both the OGS and satellite terminals.¹⁴

4. CONCLUSIONS

This study presents the comprehensive site assessment and experimental validation for an OGS. The evaluation combined regional geographical selection, high-resolution topographical modeling, and sky visibility analysis across five candidate locations to ensure optimal line-of-sight tracking above operational elevation limits. Regional selection prioritized mitigating optical and RF interference while preserving an extended atmospheric path at moderate altitude for optical turbulence characterization. Based on these criteria, the rural location of Mora la Nova (41.07° N, 0.66° E) was selected as the optimal site for the facility. Since all five evaluated locations demonstrated a maximum horizon elevation below 12.5° and a sky visibility exceeding 95.1%, Location 1 was selected as the optimal site for station deployment featuring a maximum horizon elevation of 10.4° and a 95.9° of sky visibility.

To evaluate pass performance, an optical link was successfully established between the OGS and the 6GStar-Lab on August 3, 2026, with telemetry recorded during the overpass. The recorded trajectory—spanning from acquisition of signal at 159.53° azimuth (2594 km slant range) to a maximum elevation of 63.73° (570 km range) and loss of signal at 351.89° azimuth—remained entirely within OGS-1’s modeled visible sky region. Furthermore, the telemetry confirms stable operation across active control modes, transitioning from open-loop tracking at lower elevations to closed-loop autotracking near peak elevation, while demonstrating excellent agreement with TLE-derived orbital predictions and validating both the station’s location and link stability.

The OGS site is completed with atmospheric monitoring equipment performing a continuous measurement campaign to fully characterise the location. The campaign will span at least a complete year, and potentially longer, to provide meaningful turbulence and weather data. We present the atmospheric monitoring equipment in detail and the first results of the starting measurement campaign. This preliminary data allows us to start modeling the actual site turbulence and weather conditions which will support future optical link deployments and OGS and satellite payload designs. As a first effective result, we calculated the effect of the measured turbulence at night on receiver footprint and divergence angle, in both UL and DL configurations.

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