

Channel Characterisation for Free-Space Optical Communication: On-sky Results from the ESA OGS

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ABSTRACT

Earth-satellite optical communication links are subject to wavefront path length differences due to fast-changing temperature variations throughout the atmosphere, which thereby disrupt communications from space-to-ground (downlink) and ground-to-space (uplink). An Adaptive Optics (AO) system - installed at Optical Ground Station (OGS) - can mitigate these disruptions. This study uses downlink AO telemetry with the Slope Detection and Ranging (SLODAR) technique to measure the integrated strength of atmospheric turbulence. Simulated AO telemetry showcases the accuracy and robustness of SLODAR. On-sky AO telemetry from the Alpha-Up and Down Experiment (AUDE) is used to perform site characterisation at the ESA OGS, Tenerife. The downlink received by AUDE was transmitted by Alphasat. A total of 4 on-sky campaigns were spread across a 12-month period, resulting in 25,680 measurements that span over 35 hours. Defined along the line-of-sight and at 1064nm, the median daytime Fried parameter at the ESA OGS was found to be 10.9cm.

Keywords: Channel Characterisation, Adaptive Optics, Free-Space Optical Communication

1. INTRODUCTION

Satellites conventionally communicate with the Earth using Radio Frequency (RF) transmissions. Free-space Optical Communication (FSOC) is a forefront technology which performs data transmissions using optical wavelengths; a compelling advantage being that, in comparison with RF, the data rate offered by FSOC is greater by several orders of magnitude. The narrow beam divergence of FSOC also means that it greatly reduces the likelihood of eavesdropping. A complimentary security advantage is that FSOC enables quantum encryption methods such as Quantum Key Distribution (QKD),¹ which future-proof the network from sophisticated attacks.

In a ground-space FSOC network a number of satellites will be able to establish a link with the Earth by propagating their optical signal to an Optical Ground Station (OGS). This type of data transfer is referred to as downlink. High-throughput data transfers require that - once received by an OGS - the downlink is coupled into a Single Mode Fibre (SMF).

The overwhelming advantages of FSOC make it a highly desired space sector asset. ESA leads a number of FSOC missions under Secure and Laser Communication Technology (ScyLight). EAGLE-1 is a flagship ScyLight mission and aims to deliver Europe its first sovereign, end-to-end space-based QKD system. The EAGLE-1 satellite is scheduled to launch 2027 and is planning to make links with a number of OGSs, including an upgraded DLR OGS.^{1,2} Another flagship mission under ScyLight is High Throughput Optical Network (HydRON), which aims to demonstrate the first ever multi-orbit network with terabit-per-second capacity.³ The first in-orbit HydRON demonstrations are planned for 2028-2029.

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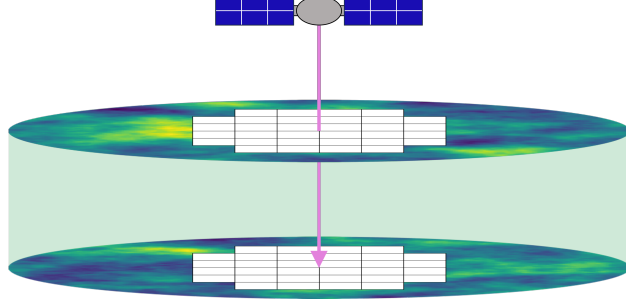


Figure 1. Sub-aperture optical paths of a single-source 6×6 SHWFS through atmospheric turbulence (green volume). The pink line represents the optical axis of the downlink.

There remain a number of challenges as FSOC infrastructure comes online. One of the most critical stems from the fact that fast-changing temperature variations throughout the atmosphere cause optical wavefronts to experience path length differences and intensity fluctuations, which ultimately result in SMF coupling losses and thereby link disruptions. Daytime atmospheric turbulence is typically stronger than at night.⁴

Adaptive Optics (AO) technology⁵ is one of the most promising solutions for mitigating the effects of atmospheric turbulence. These systems are installed at an OGS and typically use a Wavefront Sensor (WFS) and a Deformable Mirror (DM). This study will concentrate on the use of a Shack-Hartmann Wavefront Sensor (SHWFS), the measurements from which are in turn used to bring a Deformable Mirror (DM) into the required shape for reconstructing the downlink into a planar wavefront. The SHWFS measurements must update the DM many thousands of times per second to compensate for fast-changing phase distortions along the Line-of-Sight (LOS). The targeted outcome from such an AO system is stable, high-throughput SMF coupling.

The expected performance of an AO system is determined by the characteristics of the atmospheric turbulence along its LOS. The integrated strength of the atmospheric turbulence is typically defined by the Fried parameter, r_0 .⁶ The structure of the turbulence profile, i.e. the distribution of layer strengths as a function of propagation distance, is often defined by the isoplanatic angle, θ_0 .⁷ The mathematical expressions for these parameters along the LOS are given below.

$$r_0 = 0.185\lambda^{6/5} \left[\int C_n^2(z) dz \right]^{-3/5} = 0.185\lambda^{6/5} K_0^{-3/5} \quad (1)$$

$$\theta_0 = 0.057\lambda^{6/5} \left[\int C_n^2(z) z^{5/3} dz \right]^{-3/5} \quad (2)$$

Two measurements are required to calculate Eq. (1) and (2): the propagation distance to each layer, z ; and the strength of each layer, known as the refractive index structure function, $C_n^2(z)$.⁸ Eq. (1) depends only on the integral of the refractive index structure function, K_0 . The wavelength of interest, λ , is defined by the user.

Astronomical applications have led many of the developments in the field of atmospheric turbulence characterisation. Slope Detection and Ranging (SLODAR)^{9,10} is one of the most notable techniques for recovering $C_n^2(z)$. It has already been shown that SLODAR is applicable to FSOC AO telemetry.¹¹

The work in this manuscript proceeds an upcoming journal publication which will introduce a novel technique for using FSOC AO telemetry to perform complete channel characterisation. This manuscript will present the r_0 results obtained using SLODAR.

The on-sky AO telemetry used in this study is from Alpha-Up and Down Experiment (AUDE),¹² an AO system developed by General Atomics Synopta and stationed at the ESA OGS, Tenerife. AUDE uses a 6×6 SHWFS and has already made a number of Geosynchronous Earth Orbit (GEO) links with Technology Demonstration Payload No.1 (TDP1) onboard Alphasat.¹³

Section 2 outlines the SLODAR technique used to measure r_0 . Section 3 uses end-to-end AUDE simulations to showcase the performance of SLODAR over the range of expected channel conditions. Section 4 presents ESA OGS site characterisation results using AO telemetry from AUDE.

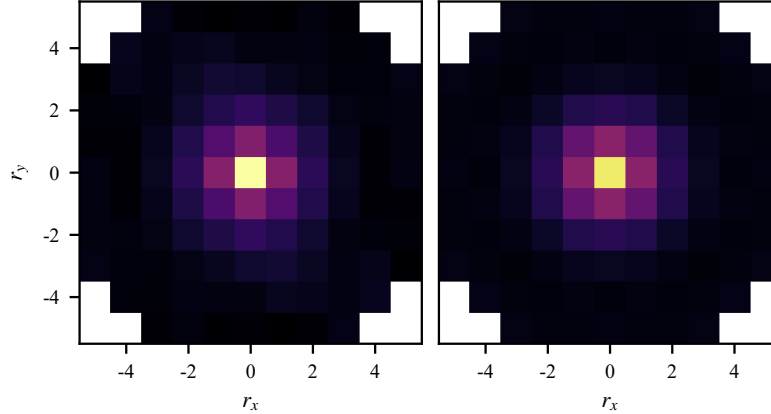


Figure 2. On-sky autocovariance map (left) and the corresponding analytical model after least-squares fitting (right).

2. MEASURING THE INTEGRATED TURBULENCE STRENGTH

In an AO system the SHWFS lenslet array is typically conjugate to the pupil plane of the telescope and the incoming light across its sub-apertures is focused onto a detector. Phase distortions along the optical channel result in the focused spots being displaced. The tip-tilt across each sub-aperture corresponds to the x - y centroid of each spot.

Closed-loop AO systems convert their centroid measurements into DM commands. This conversation is commonly performed using an interaction matrix, i.e. the matrix which relates the response of the SHWFS centroids to specific DM commands. The closed-loop system therefore works to minimise any centroid displacements. However, open-loop centroids are required for studying the atmospheric channel. Closed-loop systems achieve this by using the DM commands with the corresponding interaction matrix to calculate the pseudo open-loop centroids. To demonstrate the completeness of the technique presented here, all of the results presented in this study come from pseudo open-loop centroid data.

To measure r_0 , SLODAR requires a time series measurement of the (pseudo) open-loop centroid data. This time series array is two-dimensional. Its length spans the sub-aperture number with centroids recorded in both x and y , meaning its size is equal to twice the total number of sub-apertures. Its height spans each frame, giving a size equal to the total number of frames recorded. It has already been shown that adequate sampling is achieved with an observation time of 10 – 20s combined with a frame rate of 500Hz.¹¹

The autocovariance matrix from a SHWFS centroid time series array can be broken down into three regions: $\text{cov}(x, x)$, $\text{cov}(y, y)$ and $\text{cov}(x, y)$. The $\text{cov}(x, y)$ region is typically discarded because of its relatively low Signal-to Noise Ratio (SNR).¹⁴ The corresponding autocovariance map can be found by calculating the mean value of $\text{cov}(x, x)$ and $\text{cov}(y, y)$ as a function of sub-aperture separation. The sub-aperture separation in x and y is given by r_x and r_y , respectively.

The autocovariance map has been presented in previous publications.^{4,11} There already exists a model for analytically generating autocovariance maps.^{9,10} The analytical generation of an autocovariance map requires knowledge of the SHWFS physical parameters, e.g. its the sub-aperture diameter. The required atmospheric parameters are $C_n^2(z)$ and the outer scale profile, $L_0(z)$.⁸

Projected onto the autocovariance map are integrated measurements of both $L_0(z)$ and $C_n^2(z)$. These can be measured by using a single-layer analytical model to perform an iterative least-squares fit. Both the measured autocovariance map and its corresponding model must be tip-tilt subtracted to ensure the mitigation of systematic vibrations.¹⁴ The resulting measurement gives K_0 , which is used to calculate r_0 (see Eq. (1)). Fig. 2 shows an example on-sky autocovariance map from a 6×6 SHWFS (left) alongside the resulting analytical model after least-squares fitting (right).

Table 1. AUDE key system parameters.

Aperture diameter	0.216m
Wavelength	1064nm
SHWFS dimensions	6×6
Sub-aperture pixels	9×9
Pixel scale	$13\mu\text{rad}$
DM dimensions	9×9
Frame rate	500Hz
Observation time	10s
Elevation angle	35°

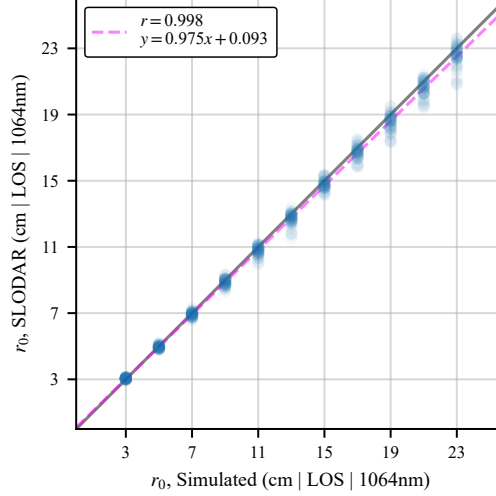


Figure 3. Scatter plot of the simulated r_0 values against the output measurements from SLODAR. The pink dashed line shows the linear regression. The Pearson correlation coefficient is denoted r .

3. SIMULATION RESULTS

The DLR end-to-end simulation tool for FSO AO systems is referred to as Extended Light Simulation Engine (ELSiE).^{15,16} Electric field fluctuations are achieved via the angular spectrum propagation between consecutive layers. AUDE is the AO system presented in this study and its key system parameters are listed in Table 1.

The standard Hufnagel-Valley (HV) model was used to calculate the simulated $C_n^2(z)$ values.¹⁷ A routine was developed for generating the LOS $C_n^2(z)$ values:

1. The user inputs the elevation angle along with the LOS r_0 and θ_0 values
2. The LOS r_0 and θ_0 values are scaled to be at zenith
3. The HV profile is generated using these values at a resolution of 1m and up to 30km
4. The HV profile is binned to 7 layers, i.e. at zenith, a layer at 0km and at every 5km
5. The HV profile is scaled to the elevation angle, i.e. z and $C_n^2(z)$ are multiplied by the air mass
6. A constant is used to scale $C_n^2(z > 0)$ to ensure it matches the LOS θ_0 input
7. A constant is used to scale $C_n^2(0)$ to ensure the profile matches the LOS r_0 input

The Gaussian wind model was used to generate the wind speed profile.¹⁸ The wind direction profile was taken from an example at the ESA OGS published by the European Centre for Medium-Range Weather Forecasts (ECMWF).¹⁹

This study defines the atmospheric parameters to be along the LOS and at $\lambda = 1064\text{nm}$. The range for r_0 was selected to be $3 \rightarrow 23\text{cm}$ with steps of 2cm . The range for θ_0 was $4 \rightarrow 34\mu\text{rad}$ with steps of $3\mu\text{rad}$. Each simulation was repeated 5 times, giving a total of 605 simulations. Fig. 3 shows the linear regression results.

4. ON-SKY RESULTS

AUDE performed 4 on-sky campaigns between September 2024 and July 2025. Each campaign was conducted over several days and on each day several 30-minute links were planned with TDP1. The breakdown of the planned links is given in Table 2. A campaign log was kept which detailed whether the link was nominal. Anomalies are categorised as cancellation events as well as links which noted the presence of anything undesired, e.g. clouds. Only nominal links are considered because this study concentrates on atmospheric turbulence characterisation.

Table 2. Breakdown of the AUDE on-sky campaigns with TDP1.

	1	2	3	4	Total
Start date	22.09.2024	11.01.2025	01.05.2025	30.07.2025	-
Duration (days)	8	12	9	10	39
Planned links	49	75	65	66	255
Nominal links	28	40	15	29	112
r_0 measurements	5864	9083	3865	6868	25680

The AUDE AO telemetry was recorded in closed-loop and had 5 modes of operation. This study considers all modes of operation and works with the pseudo open-loop data.

The telemetry from AUDE was recorded in continuous streams throughout each link. The data was reduced from approximately 4 to 0.5kHz as well as broken down into 20s datasets. A time step of 5s was given between datasets, i.e. for a start time of 0, the first measurement would be made over 0-20s, the consecutive measurement 5-25s, and so on.

A large number of datasets were studied before determining the photon flux threshold per sub-aperture, i.e. the number of photons each sub-aperture required to achieve accurate centroiding. Any frame which detected a sub-aperture below this threshold was discarded. It was a requirement that each dataset had a minimum of 10s of data after photon flux thresholding.

Only $3 \leq r_0 \leq 32.7\text{cm}$ were considered as successful measurements, i.e. those listed in the bottom row of Table 2 are all within this range. The SHWFS sub-aperture diameter was equivalent to 3.6cm across the aperture of the telescope and Section 3 showed that $r_0 = 3\text{cm}$ can still be accurately measured. However, below this scale the SHWFS focussed spots will no longer be diffraction limited. It was therefore decided to set 3cm as the lower limit. The chosen upper limit is equal to 4λ divided by the pixel scale, i.e. measuring r_0 values above this limit would require unrealistic sub-pixel centroiding.

Fig. 4 plots all of the r_0 measurements as a probability density function time series. The r_0 measurements have been binned down to 6-minute windows. The green line tracks the median. There is clearly a large spread in the probability density functions. It can also be observed that, as expected, r_0 tends toward higher values as the days progress into evening.

Fig. 5 shows the probability and cumulative density functions across all 25680 r_0 measurements. The green dashed line indicates that the median value is 10.9cm . The range of measurements corresponds well to those which were simulated (see Fig. 3).

Fig. 6 plots the cumulative density function of the r_0 measurements from each campaign, giving a seasonal analysis insight to how r_0 evolves throughout the year. In spring and summer the r_0 is comparable, and marginally lower compared with autumn. There is a significant difference when these seasons are compared with winter - the median r_0 value in winter is approximately 7cm larger. Without considering cloud coverage statistics this suggests that the optimal time for seeing at the ESA OGS is during the winter months.

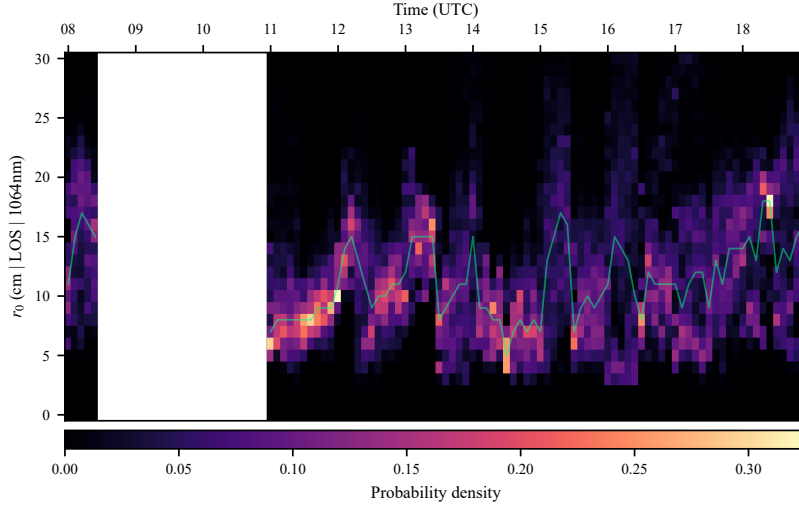


Figure 4. Probability density function time series of the 25680 r_0 measurements. The green line tracks the median values.

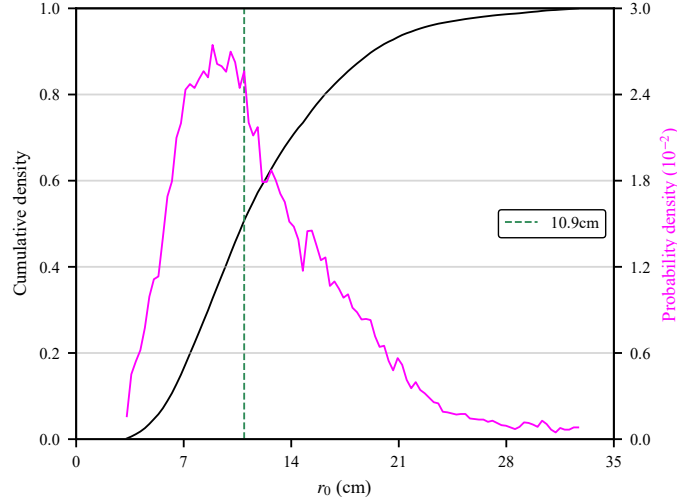


Figure 5. The probability and cumulative density functions of the 25680 r_0 measurements at the ESA OGS, Tenerife. The green dashed line indicates the median value.

5. CONCLUSION

This study further presents the applicability of SLODAR for measuring r_0 during FSO ground-space links. Its robustness was demonstrated using the DLR end-to-end AO simulation tool ELSiE. The AUDE AO system was the subject of the study. A total of 4 AUDE-TDP1 on-sky campaigns resulted in 25680 r_0 measurements at the ESA OGS.

The r_0 results demonstrated its variability at the ESA OGS and highlighted the need for real-time channel characterisation. The median (daytime) r_0 value was found to be 10.9cm. It was also shown that at the ESA OGS r_0 has a strong seasonal dependence and that the optimal seeing conditions occur during the winter months.

ACKNOWLEDGMENTS

The plots shown were rendered in Matplotlib.²⁰ All of the software was written in Python using the NumPy and SciPy libraries.^{21,22} AOtools²³ was used throughout the software development of both SLODAR and ELSiE.

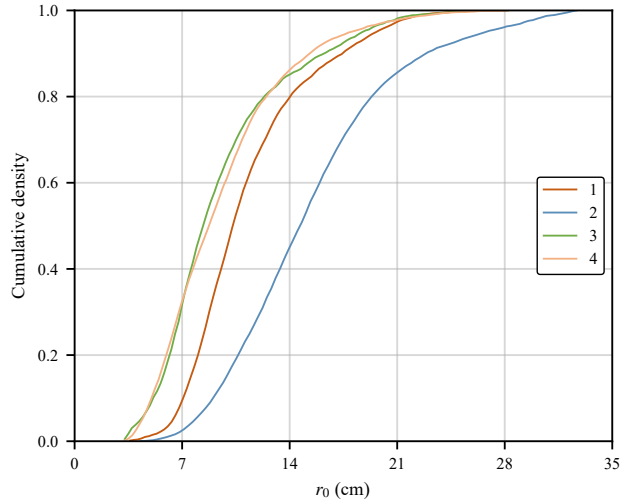


Figure 6. The r_0 cumulative density functions corresponding to each campaign number (see Table 2).

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