

CIICLOPE: Towards active, controllable, ground-based calibration.

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ABSTRACT

Calibration systems play a critical role in ensuring the radiometric, spectral, and geometric performance of a satellite payload throughout a mission's operational lifetime. Traditional in-flight calibration systems provide robust performance measurement and calibration, however, introduce mass, volume, and operational penalties to the satellite. This paper presents the architecture, theoretical performance estimation, and preliminary tracking test results of CIICLOPE (Collimator for Inflight Instrument with Laser for Optical Parameters Estimation), a proposed ground-based calibration concept intended to support characterisation and calibration of Earth observation Instruments in orbit.

CIICLOPE would utilise an active, controllable optical source coupled to a telescope-based tracking and projection system to illuminate the entrance aperture of an orbiting payload. The preliminary phase of this project combines a theoretical modelling framework with an experimental tracking campaign using ESA's Portable Optical Ground Station (POGS) located at ESTEC. The theoretical modelling framework was developed to assess the feasibility of in-flight calibration of optical Earth-observation instruments using a ground-based illumination system under realistic atmospheric conditions. Atmospheric turbulence was described using a multi-layer propagation model, using measured turbulence and wind profiles, to assess the temporal and spatial evolution of phase distortion and, consequently, the flux stability at the satellite aperture.

A Radiometric model using as inputs the transmitted source power, target telescope aperture, illumination wavelength, and atmospheric transmission has been developed and used to predict the irradiance at the space instrument entrance pupil. This combined modelling framework enabled quantitative estimation of the flux stability, seeing condition sensitivity, transmitter aperture requirements and integration time providing key design requirements for CIICLOPE. Using Sentinel-3 OLCI parameters as a reference case, we concluded that the proposed system could illuminate the Sentinel-3 OLCI entrance aperture with a level irradiance compatible with the instrument's dynamic range without saturation. Suitable payload illumination is achievable with a source power of 30 nW at the wavelength 620 nm and under a seeing of 0.7".

The preliminary tracking tests were performed in the Netherlands using ESA's Portable Optical Ground Station, with an off-the-shelves telescope and under limited atmospheric stability conditions during active tracking of Sentinel-3A. Once aligned, the system consistently achieved stable closed-loop tracking, within 1-5 arc seconds, sufficient for the system's illumination projection stability requirements.

This work represents the theoretical foundation and justification for CIICLOPE, representing a first step towards ground-to-space active, controllable, calibration. Subsequent development will focus on the implementation of the custom optics chain and fibre coupling mount for payload illumination testing next experimental steps will be the active illumination of a payload aperture, under controlled conditions, to test various calibration modalities including spectral, radiometric, and straylight calibration capabilities.

Keywords: Optical payload, Calibration, Earth Observation

1. INTRODUCTION

Earth Observation (EO) missions rely on calibrated optical instruments to deliver reliable and traceable measurements of the Earth's Atmosphere, Oceans and Land surfaces. Radiometric, spectral, geometric and straylight calibration protocols are essential to ensure high-quality scientific products throughout a mission's operational lifetime. Extensive calibration campaigns are implemented before launch; however, instrument performance and response can evolve over the lifetime of a mission. As a result, ongoing in-flight calibration is required to monitor the instrument response and maintain measurement accuracy.

Traditional in-flight calibration systems generally necessitate dedicated on-board calibration hardware such as solar diffusers, shutters or equivalent equipment integrated into the payload/platform [1], [2], [3]. While these systems are well understood and reliable they introduce additional Size, Weight and Power (SWaP) demands, complexity, development costs, and operational constraints. Furthermore, these calibration methods are fixed -during the design phase and cannot be modified, upgraded, or repaired during mission operation.

To address these limitations, we are investigating the concept of active, ground-based calibration of orbiting optical payloads. The proposed concept, CIICLOPE (Collimator for Inflight Instrument with Laser for Optical Parameters Estimation), aims to illuminate the entrance aperture of an in-orbit optical using a controlled source coupled to a telescope located on-ground and pointing toward the space instrument. The objective is to propose a flexible and upgradable test facility to perform the in-flight radiometric, spatial, spectral or straylight calibrations of space instruments while reducing onboard system complexity and space segment overall SWaP.

The feasibility of such a concept relies on the ability to illuminate the instrument entrance pupil with a controlled flux in a repeatable manner. Several key factors impact this feasibility, including atmospheric turbulence, atmospheric transmission, radiometric link budget, source characteristics, and the ability to accurately track fast-moving Low Earth Orbit (LEO) satellites. The aforementioned feasibility factors are strongly coupled. Atmospheric turbulence determines the spatial and temporal distribution of the projected irradiance at the payload aperture, while transmitter aperture, wavelength, and source coherence determine the diffraction-limited beam footprint. The resulting illumination pattern of the payload aperture must be sufficiently stable over the acquisition time required to reach the required calibration efficiency.

CIICLOPE combines modelling and experimentation to evaluate whether stable, and measurable optical flux can be delivered from ground to an in-orbit payload aperture under realistic operating conditions. The feasibility question underpinned in this work is therefore not limited to whether light can be projected to the satellite. The delivered flux must also be radiometrically relevant, temporally stable, compatible with the target instrument response and maintainable under realistic atmospheric conditions.

This paper presents the theoretical and experimental foundations of the CIICLOPE concept. First the CIICLOPE concept is introduced, followed by the atmospheric turbulence modelling to the project and the performance model used to simulate the ground-to-space optical propagation and estimate the radiometric performance is described. The model is applied to Sentinel-3 Ocean, Land and Colour Instrument (OLCI) to estimate achievable flux levels and illumination stability.

Finally, preliminary tracking experiments performed with ESA's Portable Optical Ground Systems (POGS) are presented to evaluate the pointing accuracy and tracking feasibility for future ground-to-space calibration demonstrations. This work constitutes a first step towards, active, controllable, ground-based calibration of operational EO instruments and establishes the technical framework for the future end-to-end in-orbit illumination experiments.

2. CIICLOPE

CIICLOPE optical ground station is composed of a calibrated and controllable light source coupled to a transmitting telescope to generate a collimated beam to intercept the target payload aperture. Additionally, the optical ground station utilises an active tracking system to compensate for the target's apparent motion across the FOV, enabling sufficient illumination of the target aperture. The target instrument would then measure the received flux and transmit the resultant data to ground for processing and calibration. CIICLOPE separates the calibration source from the flight payload. The

source wavelength, temporal modulation, and emitted power can be selected on ground and tuned for a specific target instrument or calibration objective without spacecraft modification.

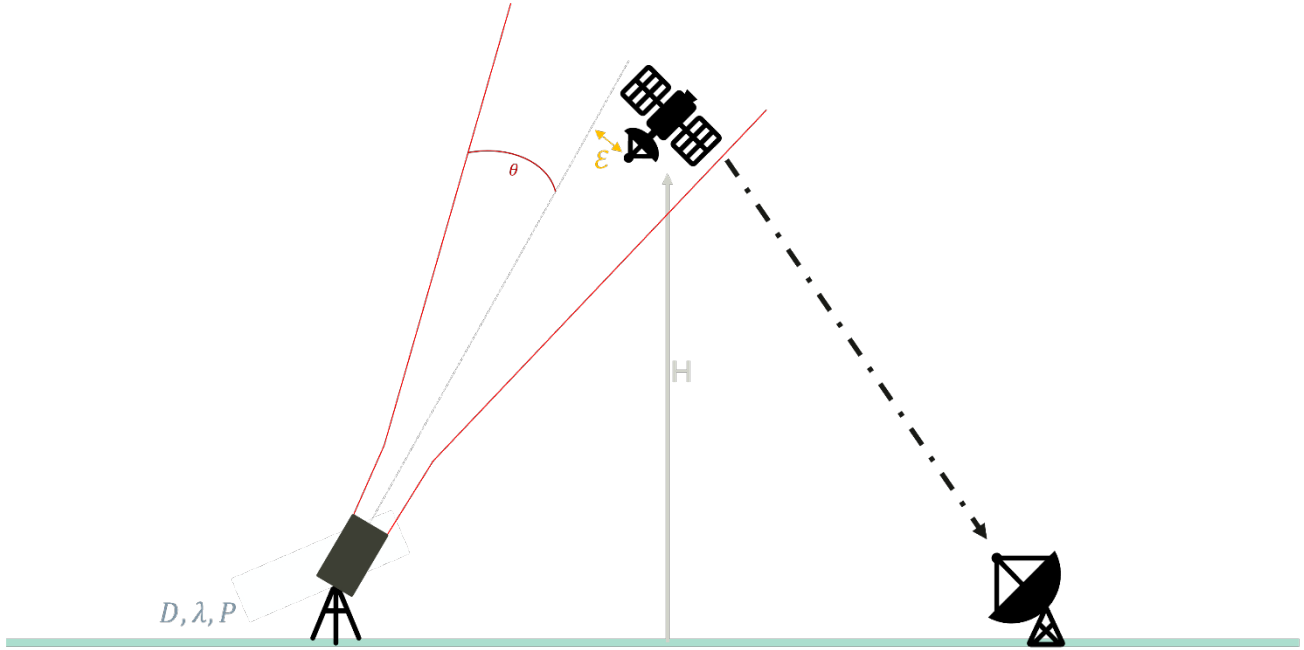


Figure 1: Diagram of the CIICLOPE Calibration Concept: A calibrated and controllable ground based optical source of power (P) and wavelength (λ) is coupled to a transmitting telescope unit of aperture D is projected towards the entrance aperture of an orbiting payload with beam spread θ , to a target satellite payload aperture with a tracking error of ϵ .

The beam emitted by the CIICLOPE telescope will be affected by diffraction and atmospheric wavefront perturbations, resulting in a time-varying irradiance distribution at the satellite. The radiometric performance of the calibration system is driven by the source power, optical transmission losses within the ground station, atmospheric transmission, and the payload entrance aperture. To ensure adequate payload illumination and enable successful calibration, the requirements of CIICLOPE performance are the following: i) the flux collected by the instrument shall remain within the instrument's dynamic range, ii) the flux collected by the instrument shall yield a signal-to-noise ratio (SNR) sufficient to achieve the targeted calibration accuracy, and iii) the flux collected by the instrument shall be sufficient to reach the targeted calibration accuracy. We have developed a dedicated model to estimate the CIICLOPE performance based on time-dependent atmospheric propagation using as an input the ground-station instrument parameters, and the in-orbit payload parameters and performance.

3. OLCI

In order to evaluate the feasibility of CIICLOPE, the Ocean, Land and Colour (OLCI) instrument onboard Sentinel-3 was chosen as a representative target payload. OLCI utilises a push-broom imaging spectrometer to monitor global marine and terrestrial environments in the visible range. The Sentinel-3 satellite orbits at approximately 814km. The onboard OLCI instrument observes channels across the visible to near infrared range (VNIR), with its 21 spectral bands collecting 300 m square acquisitions every 44ms for monitoring. The relevant OLCI parameters utilised in this work are summarised in Table 1 [1]. Each OLCI band has a designated central wavelength and bandwidth, with accompanying reference radiance values for normal operation. The Oa7 (620 nm) band was selected for this study, with the relevant band parameters and reference radiances also provided in Table 1.

OLCI acquires calibrated TOA spectral radiances across 21 spectral bands spanning the visible and near-infrared wavelength range. For the purposes of this study, the spectral band Oa7 ($\lambda=620$ nm, $\Delta\lambda = 10$ nm) was selected, and reference TOA radiance values used to derive a target for delivered flux to the payload.

Parameter	Reference Value
Target Payload	OLCI
Altitude	814km
Payload aperture geometry	33.3 mm diagonal (Square aperture)
Ground sampling area	300m x 300 m
Integration Time	44 ms
Number of Spectral Bands	21
Spectral Range	400 – 1020 nm
Oa7 central wavelength	620 nm
Oa7 band width	10 nm
Reference TOA radiance	21.14 W/(m ² srμm)
Minimum TOA radiance	8.86 W/(m ² srμm)
Maximum TOA radiance	397.9 W/(m ² srμm)

Table 1. Summary of key Sentinel-3 OLCI parameters adopted as the reference payload for the CHCLOPE feasibility assessment and radiometric budget [1].

4. ATMOSPHERIC TURBULENCE

Optical turbulence arises from random fluctuations in atmospheric refractive index. Following Kolmogorov’s description of turbulent flow, kinetic energy introduced at large scales, the outer scale, cascades through an inertial range to the inner scale, where it dissipates [4]. Within the inertial range, the refractive-index fluctuations are treated as statistically homogeneous and isotropic, with spatial statistics following a power law characterised by the refractive-index structure parameter, which governs the local turbulence strength. The turbulence of the entire atmosphere is then described by the turbulence profile, the map of the C_n^2 across increasing altitude, which is strongest near the ground and decreases with altitude. To enable evaluation at both poor- and good-seeing sites, we utilised the Hufnagel-Valley Boundary (HVB) parametric model [5] with a high-altitude wind speed of 21 m/s (denoted HV-21) for the former case, and a profile derived from SCIDAR measurements and accompanying wind-speed measurements at the high-quality astronomical site Teide Observatory for the latter case [6], [7]. The HV-21 parametric model is commonly used to represent a poor seeing site as it encodes strong active turbulent ground layer and high velocity in the upper altitude layers, resulting in high turbulence across the path and astronomical seeing $\sim 2''$. The cumulative effect of the profile along the path of interest is captured by the Fried parameter, described by Equation 1.

$$r_0 = [0.423k^2 \int C_n^2(h)dh]^{-3/5} \quad (1)$$

Where r_0 is the Fried parameter that represents the area over which the RMS wavefront aberration introduced by turbulence is equal to 1 radian, and $C_n^2(h)$ that represents the refractive-index structure constant profile.

The ratio of D/r_0 , where D is the transmitting aperture diameter, provides a useful indication of the strength of the atmospheric phase distortion across the transmitter pupil. Ratios greater than unity are less severely affected by turbulence.

Both a poor and good seeing site location were selected to evaluate geographical constraints for the CIICLOPE ground station. For the purpose of these simulations the layer altitudes, and their corresponding turbulence strengths, were derived from $C_n^2(h)$. The Hufnagel-Valley (HV-21) parametric model is described by equation (2).

$$C_n^2(h) = Ae^{-\frac{h}{100}} + 5.94 \times 10^{-53} \left(\frac{v}{27}\right)^2 h^{10} e^{\left(\frac{-h}{1000}\right)} + 2.7 \times 10^{-16} e^{\left(\frac{-h}{15000}\right)} \quad (2)$$

With h in meters, v the high altitude windspeed, and A the ground-level structure constant. In the case of HV-21, $v = 21\text{m/s}$, and $A = 1.7 \times 10^{-14}\text{m}^{-2/3}$.

The Teide Observatory in the Canary Islands site was selected to represent a ‘Good’ seeing location with optical turbulence profile from the work of B. García-Lorenzo and J. J. Fuensalida [6], and wind velocity profiles taken from the work of J. Osborn et al. for the nearby Muchachos Observatory [7]. The optical turbulence profile and wind velocity profile measurements are provided in Figure 2. The r_0 values are obtained by integrating the relevant $C_n^2(h)$ profile over each layer, referenced from the ground station altitude. The resultant seeing quality (at 500nm) for Teide observatory is 0.7”.

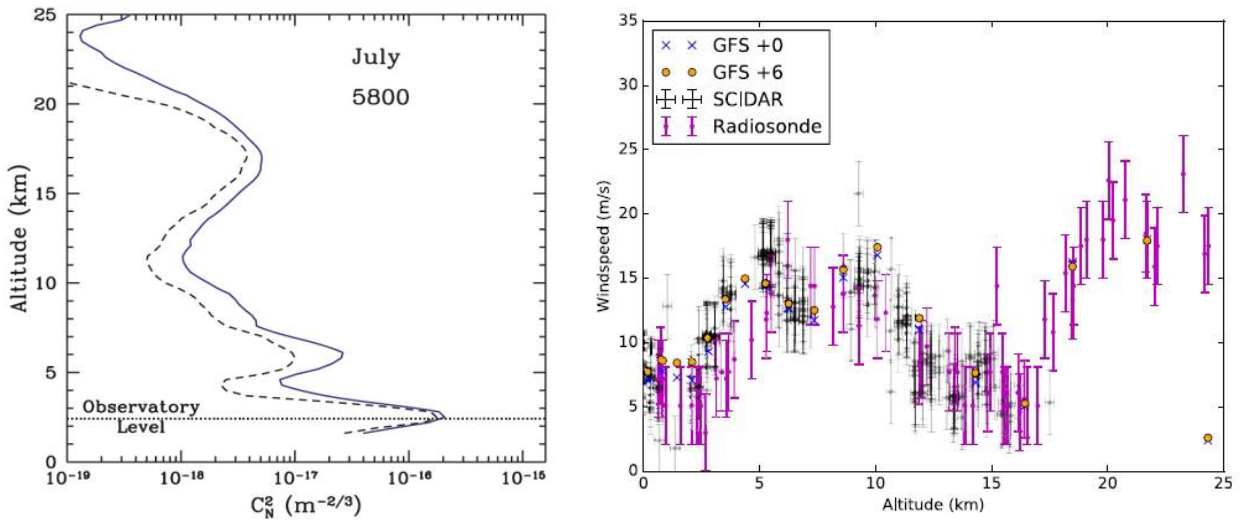


Figure 2. Optical Turbulence profile of Teide observatory (Left) [6]. Wind velocity profile measurements of Muchachos observatory using Stero-SCIDAR, the National Oceanic and Atmospheric Administration (NOAA) Global Forecast system (GFS) model and radiosonde data (Right) [7].

Figure 3 compares the local and cumulative distributions of turbulence adopted for the simulations. The C_n^2 profile describes the turbulence strength at a given altitude, while the normalised cumulative integral indicates the fractional profile turbulence accumulated below a given altitude relative to the individual site profile:

$$J(h) = \frac{\int_{h_{GS}}^h C_n^2(z) dz}{\int_{h_{GS}}^H C_n^2(z) dz} \quad (3)$$

Where h_{GS} is the corresponding ground station altitude for each profile, and h_{top} the top of atmosphere altitude.

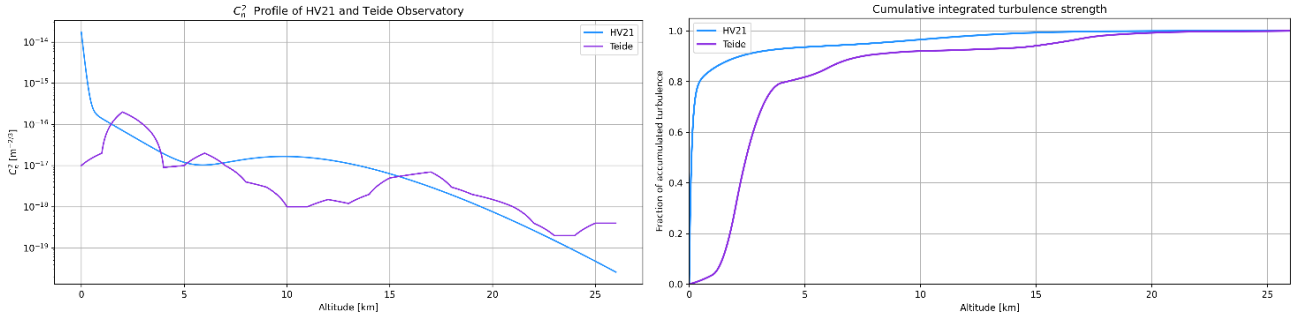


Figure 3. Left: Vertical C_n^2 profiles used in the wave-optics propagation simulations. The HV-21 atmosphere is dominated by strong near-ground turbulence, whereas the Teide profile exhibits reduced turbulence close to the observatory altitude and weaker overall. Right: Independently normalised cumulative turbulence strength for Teide and HV-21 atmospheric models. The HV-21 profile accumulates the majority of its turbulence near ground, whereas Teide exhibits a more gradual accumulation with altitude.

The HV-21 profile exhibits strong turbulence concentrated near the ground, with the Teide profile characterised by a substantially weaker boundary layer, and a larger fraction of the turbulence distributed at higher altitudes. The resulting atmospheric descriptions were utilised to derive the corresponding layer parameters for wave-optics simulations.

At the wavelength $\lambda = 620$ nm, the integrated fried parameters used in simulation were approximately $r_0 = 6$ cm for HV-21 and $r_0 = 18$ cm for Teide observatory. In this case, for an uplink, scintillation, beam wander, and beam spreading contribute most to the degradation of the uplink beam, and the modulation of the flux at the payload aperture. The selected 5 cm aperture diameter remains below r_0 for both sites. A 10 cm diameter transmitter exceeds r_0 in the poor seeing case, and a transmitter aperture of 20cm exceeds r_0 even in the good seeing case.

A summary of the resultant parameters derived from the atmospheric structure profiles for each observation site is provided in Table 2, in the case of HV21, and Table 3 for Teide Observatory. The HV21 instance results in lower coherence lengths at all equivalent layers, as expected.

Parameter	Symbol	Station altitude	Equivalent Layers		
Altitude	H	0 km	5 km	12.5 km	25 km
Fried Parameter	r_0	-	7 cm	40 cm	73 cm
Wind Speed	v	-	8 m/s	10 m/s	15 m/s

Table 2. Phase screen parameters for the HV-21 three-layer simulation, derived from the parametric model profile.

Parameter	Symbol	Station altitude	Equivalent Layers		
Altitude	H	2.39 km	5 km	12.5 km	25 km
Fried Parameter	r_0	-	24 cm	158 cm	115 cm
Wind Speed	v	-	8 m/s	10 m/s	15 m/s

Table 3. Phase screen parameters for the Teide Observatory three-layer simulation, derived from the SCIDAR measurements profile.

5. MODEL DESCRIPTION

In order to estimate the beam degradation from the ground-based calibration source, the turbulence along the ground system LOS was discretised into three layers, at altitude h_1 , h_2 , and h_3 to sufficiently capture turbulent behaviour while maintaining manageable computational cost [8]. Each atmospheric turbulence layer was represented by a Kolmogorov phase screen to encode the atmospheric dynamics utilising the AOTools Library [9], defined by the relevant seeing site atmospheric profile coherence length (r_0), outer scale (L_0) and windspeed (v) provided by the parametric model presented in section 4, and the SCIDAR measurements respectively. The CIICLOPE telescope, called the transmitter in this paper, was modelled as a circular aperture (D) with a source of wavelength (λ). A demonstrative schematic of the modelling architecture is provided in Figure 4.

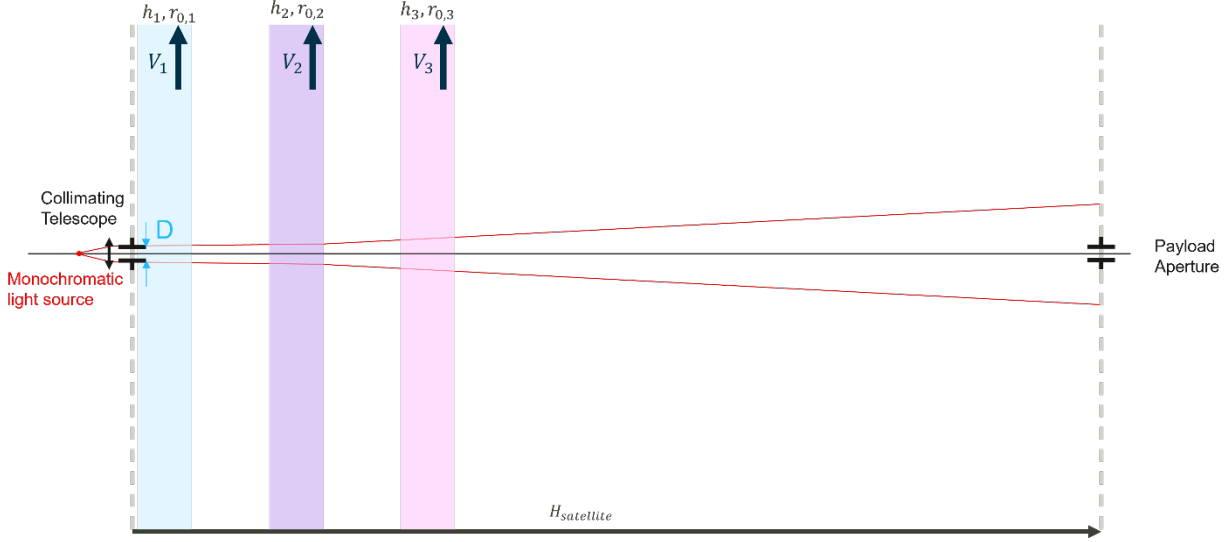


Figure 4. Diagram of the three-layer atmospheric turbulence modelling framework, indicating the successive phase screens with discrete coherence lengths, wind speeds, and phase variations. Note not to scale.

Temporal evolution of the turbulence model was introduced following the Taylor frozen flow hypothesis: the assumption that atmospheric turbulence does not internally evolve over short timescales but is rather advected by wind in the atmospheric layer [10]. For modelling purposes each phase screen was translated independently at its own wind speed, adding subsequent rows to the screen using cumulative pixel shift method.

At each layer, the field is multiplied by the time-dependent phase screen to determine the new complex field:

$$E(x, y) = P(x, y)e^{i\phi(x, y, t)} \quad (4)$$

The field is then propagated to the next phase screen, or in the case of the final phase screen, the satellite altitude ($H=814$ km) via the Fresnel (two-step) transform within the AOTools optical propagation functionality [9], to allow tailored grid spacing between planes to ensure all planes were adequately sampled and large enough to contain the expected beam:

$$E_H(x, y) = \mathcal{F}_{fresnel} \{P(x, y)e^{i\phi(x, y, t)}\} \quad (5)$$

The final complex field is evaluated at the satellite altitude to obtain the instantaneous irradiance distribution, I :

$$I = |E_H(x, y)|^2 \quad (6)$$

Figure 5 provides a visual representation of this process for a single-phase screen modelling architecture, with the multiplication and propagation step repeated for each subsequent atmospheric layer.

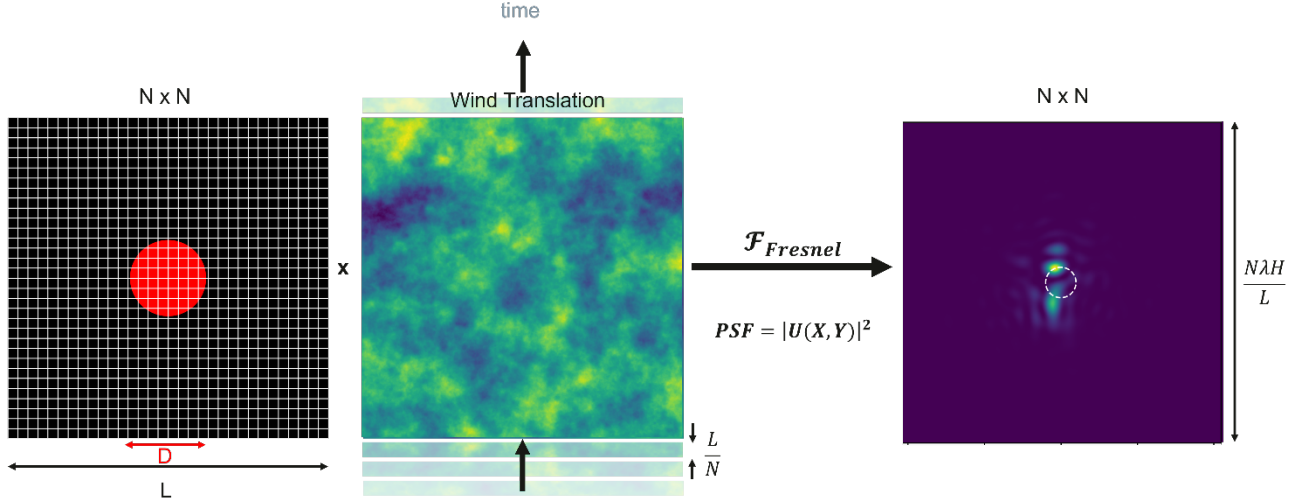


Figure 5. Schematic representation of numerical propagation model, for a single layer architecture. Circular aperture is multiplied by Kolmogorov phase screen representing atmospheric turbulence of a given layer. Phase screen evolves according to frozen flow hypothesis, with wind speed driving evolution. Fresnel propagation yields far-field PSF of the source. The included model parameters are representative for this demonstration and not included in the simulation for this work.

At each time step the on-axis intensity, Strehl ratio, and Integrated energy within the first airy disk was recorded. The normalised Intensity, I_{norm} , is calculated as the turbulent intensity normalised to the diffraction limited peak intensity:

$$I_{norm}(x, y, t) = \frac{I_{turb}(x, y, t)}{\max(I_{DL})} \quad (7)$$

Where $I_{turb}(x, y, t)$ is the turbulent irradiance distribution at the payload plane, at a given time t .

6. MODELLING RESULTS

To determine the most suitable parameters for the system the Teide Observatory profile, and illumination wavelength of 620 nm, was used to simulate the beam degradation due to turbulence at a variety of apertures: $D = 5$ cm, 10 cm, and 20 cm and compared, the Strehl ratio of the central pixel for each aperture is provided in Table 4. The satellite-plane irradiance depended strongly on the ratio of the transmitting aperture to r_0 . Where the ground-based telescope aperture exceeds the coherence length, the irradiance at the payload entrance pupil level exhibits significant disruption of the uplink beam. In the good-seeing case, with low turbulence and an aperture of the ground-based telescope smaller than the coherence length, the irradiance at the space payload entrance pupil level is distributed similarly to the diffraction-limited case. A transmitting aperture of 5 cm was selected for further simulation and as a preliminary sizing constraint for the future CIICLOPE prototype.

Diameter	Strehl Ratio
5 cm	0.9
10 cm	0.85
20 cm	0.37

Table 4. Summary of the on axis Strehl ratio for $D=5$ cm, $D=10$ cm, $D=20$ cm for Teide Observatory.

A source wavelength of 620 nm was selected as to correspond with the Oa7 OLCI channel for this work. However, the CIICLOPE concept could be modified to target multiple payload configurations and band centres.

The temporal stability of the uplink is critical for the calibration strategy proposed as the payload records measurements over the finite integration period required to reach the targeted calibration accuracy. To evaluate the impact of turbulence on the delivered flux, the propagated irradiance was normalised to the diffraction limited case and integrates over successive 44 ms intervals to correspond to the OLCI acquisition period.

Representative examples of the normalised propagated irradiance distributions are provided in Figure 6 for HV-21 and Teide Observatory, respectively. The beam degradation and subsequent on-axis irradiance reduction at the HV-21 site indicate insufficient robustness of the beam for imaging under such conditions.

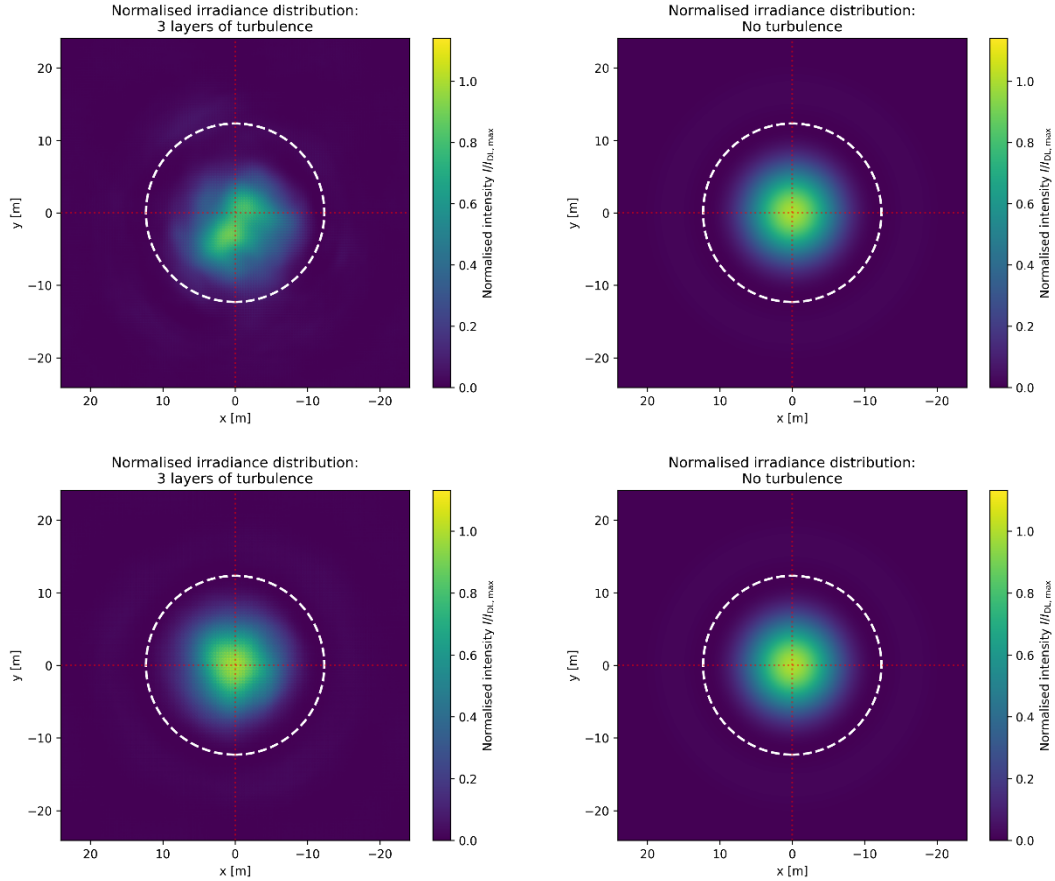


Figure 6. Top: Example of Single frame irradiance distribution in satellite plane for HV-21 parametric model for turbulent atmosphere (left) and without turbulence (right). Bottom: Single frame irradiance distribution in satellite plane for Teide Observatory site for turbulent atmosphere (left) and without turbulence (right) First Airy null corresponding to the ground-based telescope of 5cm diameter and a wavelength of $\lambda = 620 \text{ nm}$ indicated in white, centre pixel indicated in red. The atmospheric model consists of three equivalent turbulence layers. For HV-21, the layers are located at 5, 12.5 and 25 km with $r_0 = 7, 40$ and 73 cm and wind speeds of 8, 10 and 15 m s^{-1} , respectively. For Teide Observatory, the layers are located at 5, 12.5 and 25 km with $r_0 = 24, 158$ and 115 cm and wind speeds of 8, 10 and 15 m s^{-1} , respectively (see Tables 2 and 3).

Figure 7 provides a direct comparison of the optical power transmitted by the payload aperture in the diffraction-limited regime and in the case of a beam propagation through the Teide and HV-21 atmosphere profiles respectively. We notice that the Teide profile consistently provides a flux transmitted by the to the payload aperture higher than the HV-21 profile. Indeed, over the 440 ms (10-integration-step) simulation, the mean received signal corresponds to 84% of the diffraction-limited case, compared with 61% for HV-21, as detailed in Table 5. Additionally, the Teide Observatory site exhibits significantly improved stability compared with HV-21. The radiometric variability at Teide Observatory remains well within the payload dynamic range. Under good seeing conditions the mean normalised flux remained relatively stable over the payload integration window, with signal standard deviation of 14%. HV-21 exhibited significantly higher magnitude

fluctuations, with a signal standard deviation of 39%, and an overall reduced delivered irradiance due to increased beam wander, scintillation, and wavefront distortion. The stability of the received flux was evaluated by computing the 1 stability of the mean OLCI payload aperture flux over the full 440 ms simulated acquisition, yielding 0.5% and 1.38% for Teide and HV-21 respectively. The flux variation for both sites remains within 2%, with Teide observatory exhibiting lower variation as expected. In combination these results indicate for high, and stable flux at the payload aperture the transmitting aperture must remain small and operation must be in favourable seeing conditions. These requirements allowed for the calculation of radiometric budget for the system and drive future hardware choices.

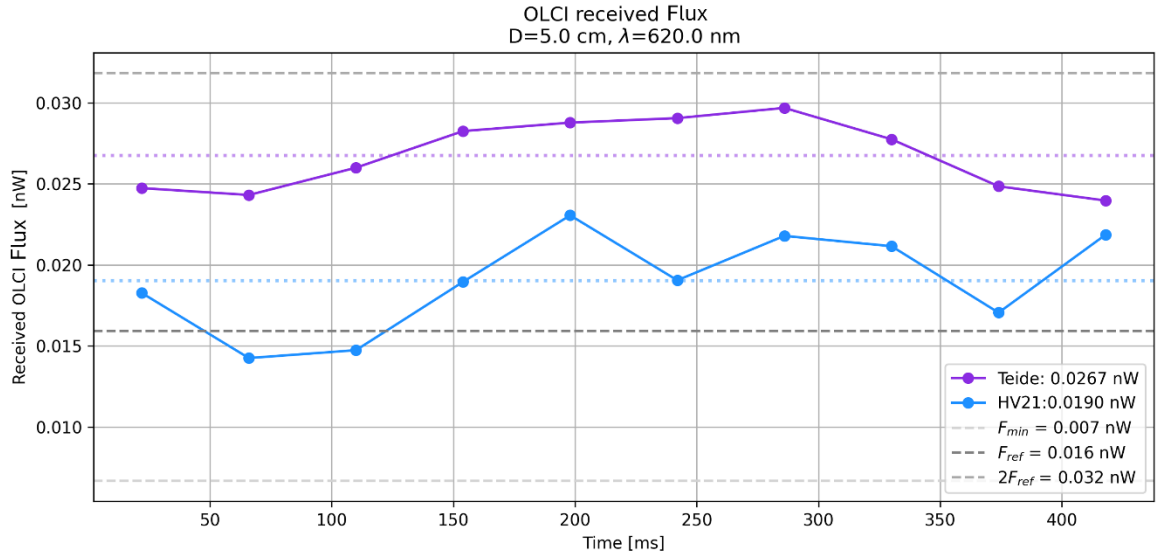


Figure 7: Flux Received by OLCI normalised such that a diffraction-limited beam produces a received signal of $2F_{ref}$, double the OLCI reference flux for channel Oa7. Mean received OLCI flux from a $2F_{ref}$ tuned source in satellite plane: 0.0267 nW (Teide) and 0.0190 nW (HV-21), corresponding to 84% and 61% of the diffraction-limited ($2f_{ref}$) reference level.

Metric	Teide	HV-21
Integrated r_0 at 620 nm	18.05 cm	6.4 cm
Flux (% of DL case)	84%	61%
Flux standard deviation	14%	39%
Mean received signal	0.0267 nW	0.0190 nW
1σ over 440 ms	1.349×10^{-4} nW (0.5%)	2.630×10^{-4} nW (1.38%)

Table 5. Summary of the principal atmospheric propagation and resultant uplink results metrics obtained for the Teide and HV-21 atmospheric models.

7. RADIOMETRIC BUDGET

With the atmospheric degradation of the CIICLOPE uplink established, the corresponding radiometric requirements of the ground-based source can be estimated. For the purpose of this analysis, the operation of CIICLOPE is limited to favourable atmospheric sites. Using the OLCI reference payload parameters introduced previously for channel Oa7 (620 nm), the target payload flux was established from the OLCI radiometric operating conditions. The calculated mean normalised signal was incorporated into the radiometric budget to calculate the source power required to deliver the desired signal under realistic atmospheric conditions.

For a reference band, we relate the spectral radiance, L , at the entrance pupil to the Flux, F , through the instrument étendue, G , and spectral bandwidth, $\Delta\lambda$:

$$F = LG\Delta\lambda \quad (8)$$

The étendue is approximated by.

$$G = \frac{A_{inst}A_{GS}}{H^2} \quad (9)$$

where A_{inst} is the instrument entrance aperture area, A_{GS} the ground projected pixel area, and H the orbital altitude. The reference spectral radiances, and instrument parameters are detailed in Table 1. The resulting reference flux values were adopted as the target signal level for illumination source sizing. Reference flux values calculated for Oa7 are detailed in Table 6.

Reference Flux Oa7	$1.56 \times 10^{-2} nW$
Minimum Flux Oa7	$0.66 \times 10^{-2} nW$
Maximum Flux Oa7	$36.8 \times 10^{-2} nW$

Table 6. Summary of the target payload reference flux values, derived from Neike et al. [1].

The actual flux delivered to the satellite payload is estimated from a closed-form link budget. The calibration source, of power P , is coupled to a multimode fibre (of core diameter D_{fibre} , numerical aperture NA) and projected toward the satellite by a collimating telescope of equivalent focal length. The collimating telescope maps the fibre core to an angular size, so at orbital height H the illuminated spot has diameter:

$$D_{beam} = \frac{D_{fibre}}{f_{eq}} H \quad (10)$$

The transmitted power is spread over the beam area:

$$A_{beam} = \pi \left(\frac{D_{beam}}{2} \right)^2 \quad (11)$$

As the payload aperture is sufficiently small compared to the beam area at the satellite altitude, the irradiance field is assumed to be sampled uniformly. The on-axis irradiance at the satellite, and collected flux F would therefore be:

$$E = \frac{PT}{A_{beam}}, \quad (12)$$

$$F_0 = EA_{EP} \quad (13)$$

where T is a transmission coefficient combining the atmospheric transmittance, and ground station optical throughput. The atmospheric transmittance was approximated using the v-band extinction coefficient, $k_v = 0.13 \text{ mag. airmass}^{-1}$, determined by Garcia-Gil et al. for the nearby Observatorio del Roque de los Muchachos (ORM) [11], yielding $T_{atm} = 0.89$. The diffraction-limited radiometric estimate was subsequently corrected using the normalised turbulence irradiance obtained from atmospheric propagation simulations. The delivered payload flux is therefore expressed as:

$$F_{payload} = F_0 I_{norm} \quad (14)$$

The relevant OLCI target flux parameters for this estimation are detailed in Table 6, normalised signal values from Table 5, with remaining optical system parameters detailed in Table 7. In order to deliver, reliably, $2F_{ref}$ in the satellite plane the source of wavelength $\lambda=620 \text{ nm}$, would need a source of power $\sim 30 \text{ mW}$, with preliminary optical design, in the case of the favourable seeing site. These values fit well within the capabilities of commercially available optical sources.

Parameter	Value	Note
D_{fibre}	$200\ \mu m$	From preliminary sizing
NA_{fibre}	0.22	From preliminary sizing
f_{eq}	812.8 mm	From preliminary optical design
T_{inst}	0.51	Estimated from preliminary optical design
T_{atm}	0.89	Estimated from atmospheric properties [11]

Table 7. Summary of the preliminary design parameters for the ground based optical system.

The radiometric assessment indicates that the required payload signal can be achieved using modest optical source powers under favourable atmospheric conditions. Combined with the atmospheric propagation results presented previously, these findings support the feasibility of active ground-to-space illumination for future calibration demonstrations. The results therefore indicate that source power is unlikely to constitute a primary design driver for CIICLOPE. Instead, atmospheric conditions, optical design, source type, and operational constraints are expected to dominate overall system performance.

8. PRELIMINARY TRACKING VALIDATION

The ESA portable ground station was utilized to carry out preliminary testing of satellite tracking operations, to inform the validation study of CIICLOPE. The Schmidt-Cassegrain telescope system includes both coarse (wide FOV) camera and fine (narrow FOV) cameras for object tracking and telescope alignment [12], detailed in Figure 8. The telescope focal length is equal to 2m, and the entrance pupil diameter is equal to 20 cm. The coarse camera utilises a Fujinon HF35XA-5M lens, with a 35mm focal lens, and aperture range of 1.9 – F16. The fine tracking camera is connected to the focal plane array, shown in Figure 8, with a beam splitter to allow for fibre coupling, and power measurement or illumination injection. The object plane of the focal plane array is placed in the image plane of the telescope: an initial lens ($f = 25mm$) collimates the focused light from the telescope directing it to the beam splitter (90:10 R:T). The transmitted light is focussed onto the fine tracking camera with a final ($f = 30\ mm$) lens. Both the tracking cameras utilise a FLIR Blackfly S monochrome camera, the details of which are provided in Table 8. The POGS system is mounted on a motorized Alt-Az mount to enable object tracking.

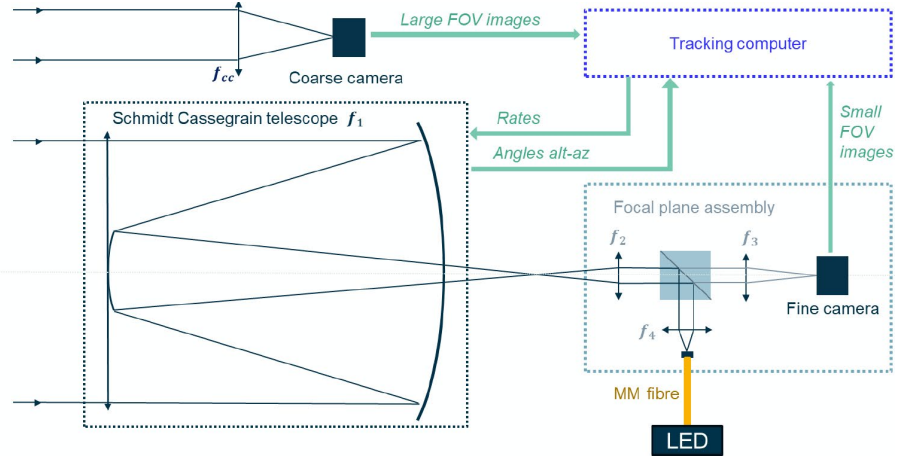


Figure 8. Left: the Portable Optical Ground Station (POGS) at ESTEC. Right: Active illumination preliminary optical design schematic of CIICLOPE system.

Sensor	<i>Progressive Scan CMOS</i>
Array	2048 × 1536
Pixel size (μm)	3.45
Frame rate (fps)	55
Exposure time	11 μs – 30 s

Table 8. Summary of the POGS tracking camera specifications.

The ESTEC POGS system utilised the PyPOGS software developed by Pettersson et al. to enable satellite tracking with the ground station and control the Alt-Az mount, enabling successively more precise tracking across the telescope camera suite [10]. The tracking system utilised frame rate 5-10 fps, and exposure times of 50-100 ms. The PyPOGS system was directed to track the Sentinel-3 satellite, with fine closed-loop tracking implemented by the system within 4 minutes [11]. The approximate footprint of the projected beam in the satellite plane is 50". Tracking accuracy below 5" RMSE was achieved with the POGS system during preliminary testing in the Netherlands, as shown in Figure 9. We thus deduce that the tracking errors should not significantly degrade the conditions of illumination of the instrument and we conclude that the tracking accuracy is sufficient for targeted application.

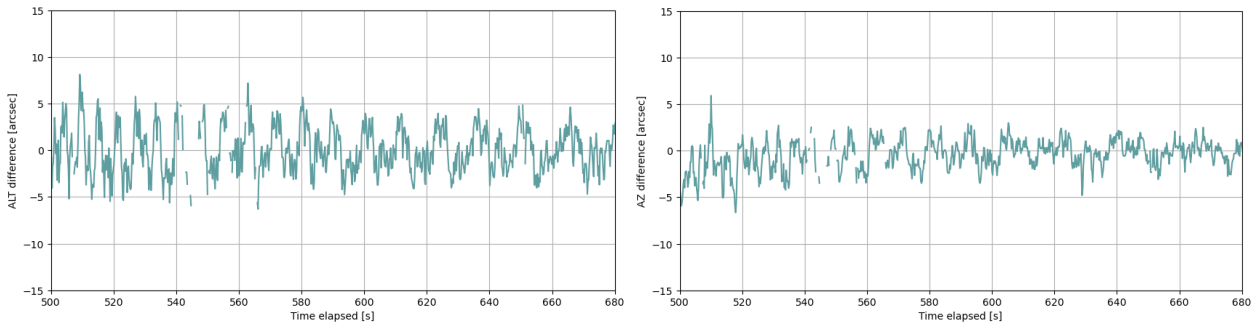


Figure 9. Elevation (left) and azimuth (right) tracking frame difference during fin control loop tracking in the Netherlands.

9. FUTURE WORK

The next stages of the CIICLOPE project will entail the inclusion of the active ground source to the preliminary CIICLOPE set up to validate satellite payload illumination with the system, resulting in returned instrument data. Several hardware requirements have already been identified for the injection unit build, as well as several performance improving measures relating to the ground system. The selection of the optical source remains a key parameter for selection and must be chosen in concert with the transmitting optics to optimise the delivered signal. Additionally, the power budget estimation utilised a preliminary set up design, and accompanying system parameters. There remains scope to optimise the source coupling system, fibre properties, and overall optical design to a specific orbiting payload target.

10. CONCLUSIONS

We have assessed the feasibility of calibrating EO instrumentation from the ground with a controlled optical source and we conclude that an active, controlled illumination of an in-orbit satellite payload for calibration purposes using a ground-based telescope should be possible. A three-layer atmospheric model was developed to assess the impact on a ground-to-space optical calibration uplink. For the selected reference configuration, $D=5\text{ cm}$, $\lambda=620\text{ nm}$, indicates optical beam quality can be sufficiently maintained for a small aperture ground system in favourable seeing conditions represented by the Teide Observatory, maintaining an 84% link efficiency. The corresponding delivered signal to the OLCI reference payload, can be provided by commercially available optical sources, maintained well within the OLCI operational flux requirements. The CIICLOPE system remains flexible for implementation for a host of other EO payloads, with key parameters tuneable to the given target. In principle the CIICLOPE architecture can be modified to support calibration across a suite of EO instruments in orbit

A proof-of-concept tracking demonstration with ESA's POGS system tracked the desired LEO target (Sentinel-3) to 5" RMSE, confirming the tracked satellite can be reliably illuminated to facilitate payload aperture illumination. In combination, these results represent a first step to active, controllable, ground-based calibration and define preliminary system requirements for CIICLOPE: small transmitting aperture, good seeing site location, and robust tracking performance. Future work will focus on end-to-end payload illumination validation of calibration measurements using an active optical source and injection unit.

REFERENCES

- [1] J. Nieke, C. Mavrocordatos, C. Donlon, B. Berruti, T. Garnier, J.-B. Riti and Y. Delclaud, "Ocean and Land Color Imager," in *Optical Payloads for Space Missions*, 2016, pp. 223-246.
- [2] E. Mazy, M. J. Hastanin, L. Clermont, L. Rossi, C. Dandumon, M. Georges, S. Marcotte and C. Thizy, "Improved BRDF metrology platform for Copernicus CO2I FCU," in *Optical Measurement Systems for Industrial Inspection XIV*, 2025.
- [3] S. G. Ungar, J. A. Mendehall and D. Reuter, "Overview of the Earth Observing One (EO-1) mission," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, no. 6, pp. 1149-1159, 2003.
- [4] A. N. Kolmogorov, "The Local Structure of Turbulence in Incompressible Viscous Fluid for Very Large Reynolds Numbers," *Mathematical and Physical Sciences*, vol. 434, no. 1890, pp. 9-13, July 1991.
- [5] A. Mohamed, "Anisoplanatic Electromagnetic Image Propagation through Narrow or Extended Phase Turbulence using Altitude-Dependent Structure Parameter," *Frontiers in Optics*, 2016.
- [6] J. J. F. B. García-Lorenzo, "Statistical structure of the atmospheric optical turbulence at Teide Observatory from recalibrated generalized SCIDAR data," *Monthly Notices of the Royal Astronomical Society*, vol. 410, no. 2, pp. 934-945, January 2011.
- [7] J. Osborn, T. Butterley, M. J. Townson, A. P. Reeves, T. J. Morris and R. W. Wilson, "Turbulence velocity profiling for high sensitivity and vertical-resolution atmospheric characterization with Stereo-SCIDAR," *Monthly Notices of the Royal Astronomical Society*, vol. 464, no. 4, pp. 3993-4007, February 2017.
- [8] T. Fusco, J.-M. Conan, V. Michau, L. M. Mugnier and G. Rousset, "Efficient phase estimation for large-field-of-view adaptive optics," *Optics Letters*, pp. 1472-1474, 1999.
- [9] M. J. Townson, O. J. D. Farley, G. O. d. Xivry, J. Osborn and A. P. Reeves, "AOtools: a Python package for adaptive optics modelling and analysis," *Optics Express*, vol. 27, pp. 31316-31329, 2019.
- [10] J. Vernin and F. Roddier, "Experimental determination of two-dimensional spatiotemporal power spectra of stellar light scintillation Evidence for a multilayer structure of the air turbulence in the upper troposphere," *Journal of the Optical Society of America*, vol. 63, no. 3, pp. 270-273, 1973.
- [11] A. Garcia-Gil, C. Munoz-Tunon and A. M. Varela, "Atmosphere Extinction at the ORM on La Palma: A 20 yr Statistical Database," *PASP*, vol. 122, p. 1109, 2010.
- [12] G. M. Pettersson, J. Perdigues and Z. Sodnik, "Unmodified Portable Telescope for Space-to-Ground Optical Links," in *2019 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, 2019.
- [13] M. Pilloix, "Calibration Of In-Flight Instruments From Ground," ESA Internal Report, Noordwijk, 2023.