

Upgrading the Skinakas 1.3 m telescope to an Optical Ground Station

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ABSTRACT

Optical communications (OC) are emerging as a transformative technology for satellite and terrestrial networks, offering high-capacity data transfer, narrow-beam transmission, and enhanced resistance to interception. Beyond secure classical links, OC also enables optical quantum communications, where the physical properties of light can provide stronger protection for information exchange. Within this framework, Optical Ground Stations (OGS) are essential elements of free-space optical satellite communication systems, linking spaceborne optical terminals with terrestrial infrastructure. However, converting an existing astronomical observatory telescope into an operational OGS requires careful integration of optical, mechanical, control, and operational subsystems while maintaining the facility's original scientific capabilities.

This paper describes the main phases of upgrading the 1.3 m telescope at Skinakas Observatory into an OGS, including its current status, achieved capabilities, and remaining development steps. The upgrade follows a modular and minimally invasive strategy that preserves astronomical functionality while enabling optical communication experiments. A key component is a dedicated optical breadboard with active stabilization, mounted on a port of the telescope's Guiding and Acquisition Module (GAM). This arrangement allows compensation of pointing disturbances, and reliable coupling of incoming or outgoing beams. It also supports rapid transition between astronomical observations and optical communication operations. The proposed approach is relevant to similar observatories seeking to join emerging optical satellite communication networks without replacing existing infrastructure. By demonstrating a practical pathway for adapting a meter-class astronomical telescope into an OGS, the Skinakas upgrade contributes to flexible ground-segment architectures for future high-speed and secure space-to-ground optical links.

Keywords: Optical Communications, Satellite Optical Communication, Space Technologies, Optical Ground Station

1. INTRODUCTION

Skinakas Observatory is a joint research facility of the University of Crete and the Foundation for Research and Technology – Hellas (FORTH). The observatory is located on top of Ida Mountain in Central Crete at an altitude of 1750 m (longitude is 24° 53' 57" East, latitude 35° 12' 43" North). The line-of-sight distance of Skinakas from the city of Heraklion is 25 km and can be accessed by car via a one hour, 50 km drive. Skinakas Observatory currently houses three fully functional optical telescopes: an equatorially mount 1.3m modified Ritchey–Chrétien telescope, of 7.64 focal ratio, an equatorially mount 1.0 m robotic Ritchey–Chrétien telescope of 7 focal ratio and a recently installed Ritchey–Chrétien, altazimuth mount, 1.2 m 7.1 focal ratio robotic telescope.

In this work we present the upgrade of the 1.3 m telescope of Skinakas Observatory to dual use as an astronomical observations and optical ground station (OGS). The upgrade of a telescope in an operational Observatory to an OGS is complex and demanding procedure. One of the challenges we faced was that tracking a LEO is a demanding task for such large telescopes. Besides the need for tailoring the optical design for the specific optomechanical configuration, often the available mechanical drawings, if available, need to be updated by taking on-site measurements. Furthermore, the upgrade of both the coarse tracking and the telescope's dome control electronics was necessary to reach the tight specs. Although

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critical components were obtained using commercially available solutions, we have also designed and developed many of the components in house. This spans from the optical design to automatization tasks. This approach has allowed us to build on new technical knowledge and technology development capabilities.

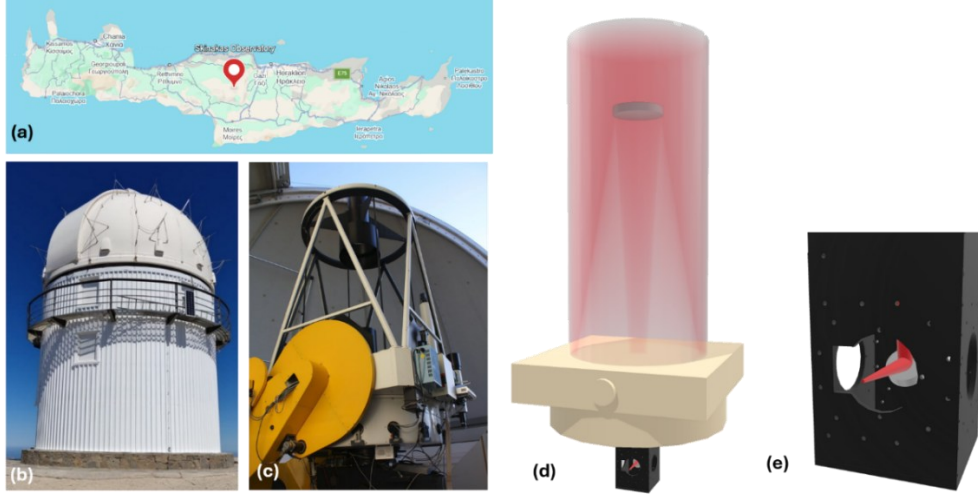


Figure. 1. a) Skinakas Observatory location on the island of Crete b) the telescope dome c) the 1.3 telescope (d) optomechanical design and (e) detail of the GAM with light exiting from the east port

Our approach involved establishing the critical operational parameters [1] and designing the OGS terminal. Furthermore, we designed and developed focal plane instrumentation (FlexBoard) as well as man-machine interfaces and software, capable of detecting and high-speed tracking of satellites visible by illumination from sunlight, or by their laser beams. FlexBoard incorporates a DL, Rx port that supports optical data reception and a provision for quantum channel port and adaptive optics port. A key feature of the board is that it is entirely re-configurable, e.g. for quantum communication or novel adaptive optics. Furthermore, a separate UL beacon module capable of data transmission was designed and developed. Both DL and UL channels support data reception/transmission according to the optical on-off keying (OOK) standard. The observatory location, dome and optical details of the telescope can be seen in Fig. 1.

We performed a preliminary study of the performance of the 1.3 m telescope by using analytical calculations and raytracing simulation to estimate critical parameters of the optical link. The characteristics of the telescope opto-mechanics and guiding system are summarized in Table 1:

Table 1. Characteristics of the 1.3 telescope of the Skinakas OGS [2]

Telescope type: Modified Ritchey–Chrétien <i>Manufactured by Carl Zeiss Oberkochen</i> Aperture of main mirror: 129 cm Aperture of secondary mirror: 45 cm Central hole of main mirror: 35 cm Distance main to secondary: 245.34 cm Focal length: 985.7 cm Focal ratio: 7.64	Telescope mount: Equatorial Computer controlled Manufactured by DFM Engineering Autoguiding System Off-axis guiding manufactured by Baader Planetarium, Digital Camera CDD, model STT-1603 by SBIG. Upgraded with the SITECH ForceOne 1500 controller
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2. LINK BUDGET AND THE EFFECT OF TURBULENCE

The link budget is a useful tool that can be used to predict the performance of optical communication systems since it provides a key to system design and component selection. The link budget represents the relationship between the transmitting power P_{Tx} and the optical power received at the input of the optical detector, P_{Rx} and can be estimated by using the link equation [3]:

$$P_{Rx} = P_{Tx} \cdot \tau_{Tx} \cdot AG_{Tx} \cdot \tau_{mp} \cdot \tau_{Atm} \cdot FSL \cdot AG_{Rx} \cdot \tau_{Rx},$$

where we assume circular Tx and Rx apertures. $AG_{Tx} = (\pi D_{Tx}/\lambda)^2$, is the Tx antenna gain, $FSL = (4\pi z/\lambda)^{-2}$ is the free-space loss, $AG_{Rx} = (\pi D_{Rx}/\lambda)^2$ is the Rx antenna gain, $\tau_{mp} = e^{-2(\theta_{mp}/\theta_w)^2}$ is the mispointing loss, θ_{mp} is the Tx angular

mispointing and θ_w is the Tx angular waist radius, τ_{Tx} is the Tx transmission loss with typical values between 0.7–1.0, τ_{Atm} is the atmospheric loss with typical values between 0.6 – 0.9, τ_{Rx} is the Rx transmission loss with typical values of 0.2 – 0.7. The link margin (LM), which is calculated as the ratio of the received optical power PRx to the detector sensitivity DS for a specific data rate and BER, is defined as $LM = \frac{P_{Rx}}{DS}$. Typically, for a reliable link it should be $LM > 2$.

Table 2 Simplified Link Budget

Parameter description	Parameter	Downlink (DL)				Uplink (UL)			
		Value	Unit	Value	Log Units	Value	Unit	Value	Log Units
Tx telescope diameter	DT_x	0.02	m	-	-	12	mm	-	-
Link distance	z	570	km	-	-	570	km	-	-
Wavelength	λ	1536	nm	-	-	1536	nm	-	-
Tx transmit power	P_{Tx}	0.1	W	20	dBm	20	W	43.01	dBm
Tx transmission loss	τ_{Tx}	0.9	%	-0.5	dB	0.9	%	-0.5	dB
Atmospheric loss	τ_{Atm}	80%	%	-1	dB	80%	%	-1	dB
Rx telescope diameter	DR_x	1.3	m	-	-	0.02	m	-	-
Detector diameter	dp	100	μm	-	-	50	μm	-	-
Rx focal length	f	9.857	m	-	-	0.02	m	-	-
Rx filter bandwidth	FB	10	nm	-	-	10	nm	-	-
Detector sensitivity	DS	38.02	nW	-44.2	dBm	15.85	nW	-48	dBm
Tx antenna gain	AG_{Tx}	$1.673 \cdot 10^9$		92.2	dB	$6.021 \cdot 10^8$		87.8	dB
Free-space loss	FSL	$4.60 \cdot 10^{-26}$		-253.4	dB	$4.6 \cdot 10^{-26}$		-253.4	dB
Rx antenna gain	AG_{Rx}	$7.067 \cdot 10^{12}$		128.5	dB	$1.673 \cdot 10^9$		92.2	dB
Power link budget	PR_x	11745.5	nW	-19.3	dBm	667.2	nW	-31.8	dBm
Link Margin	LM	308.94		24.9	dB	42.1		16.2	dB

On the other hand, the propagation of optical waves through the atmosphere is a complex, multi-scale, multi-parametric process which the link budget presented above does not fully consider. Propagating waves can be affected by scattering, atmospheric absorption and most importantly atmospheric turbulence. In the typical scenario the presence of moisture, pressure and temperature gradients leads to a chaotic, turbulent motion of the atmosphere. Likewise, this turbulent motion gives rise to changes in the air density which translates to perturbations in the atmospheric refractive index [4] that finally result in perturbation in the wavefront of the propagating wave. We refer to the local areas in which this phenomenon occurs as optical eddies. These perturbations, although small in amplitude, accumulate over hundreds of meters or even kilometers of propagation and finally reshape both the phase and intensity distribution of the propagating wave. To study these effects, numerical simulations have become an indispensable tool. In particular, the random phase screen method has enabled fast and computationally efficient modeling of light propagation through turbulence along [5, 6], by statistically encoding the effects of atmospheric refractive index fluctuations into two-dimensional phase screens. Moreover, such numerical simulations are often used as a reference for the development of link budget models [3].

We performed 2+1D numerical simulations to analyze the propagation of the Rx/Tx beam in a free space optical link through turbulent atmosphere between Skinakas Observatory and a LEO satellite, using a slit-step technique involving the propagation of the angular spectrum. The effect of atmospheric turbulence was approximated by a sequence equally spaced along the propagation of thin random phase screens [5, 6], using the modified von-Karman power spectral density of the refractive index fluctuations $\Phi_n(\kappa)$ described by the equation [7, 8]:

$$\Phi_n(\kappa) = 0.033 C_n^2 f_n \left(\frac{\kappa_s}{\kappa_l} \right) e^{-\left(\frac{\kappa_s}{\kappa_l} \right)^2} (\kappa + \kappa_0^2)^{-\frac{11}{6}}$$

where $\kappa_l = \frac{0.33}{l_0}$, $\kappa_0 = \frac{2\pi}{L_0}$, C_n^2 is the refractive index structure constant, indicating the strength of turbulence, and l_0 , L_0 the inner and outer scale of the turbulence respectively. Likewise, the function f_n is defined as:

$$f_n(x) = 1 + 1.802 x - 0.254 x^{7/6}$$

The two simulation schemes are graphically depicted in Figure 2. In both cases, the simulations are performed in three distinct steps. One step refers to the beam propagation for ~ 1.5 km through a turbulent atmosphere (assuming ~ 3 km of turbulent atmospheric medium and considering the altitude of Skinakas Observatory), another to the propagation through 567 km of free space, and finally the collection and focusing by the Rx optics. Although the total optical path is the same for the UL and DL, the inherent asymmetry leads to quite different behavior.

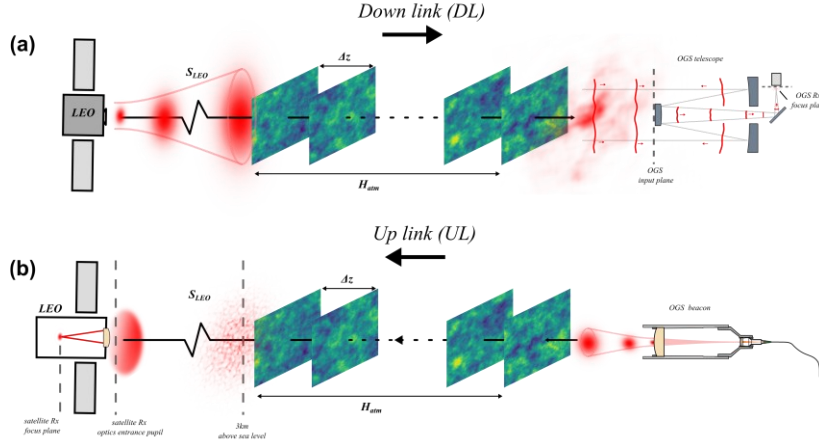


Figure 2. Graphical representation of the numerical simulation schemes. (a) Downlink, the satellite Tx beam reaches the turbulent atmospheric layer after first propagating for ~ 567 km in free space (~ 3 km above sea level). Then, after propagation of 1.5 km through a turbulent atmosphere it reaches the OGS input plane. There it is collected by the 1.3 m telescope mirror and is focused on the OGS Rx focal plane located 9.85 m away. (b) Uplink: the OGS beacon/Tx beam, first propagates for 1.5 km through a turbulent atmosphere and reaches ~ 3 km above sea level. Then it propagates for ~ 567 km in free space, reaching the satellite Rx optics entrance pupil. There it is collected by a 100 mm (in diameter) lens and is focused at the Satellite Rx focal plane located 200 mm away.

In our simulations, the values of the refractive index structure constant C_n^2 as well as the values of the inner and outer scales (l_0 , L_0) were set as a function of the altitude. Assuming that turbulence is important below an altitude of 3 km and using typical reference values for the inner and outer scales [9] we have simulated the effect of turbulence on the Rx of the OGS (DL) and the satellite (UL) for weak to moderate/strong turbulence. The values of the simulation parameters for the two cases are shown in detail in Table 3.

Table 3. Turbulence simulation parameters.

Height (km)	Inner scale l_0 (mm)	Outer scale L_0 (m)	refractive index structure constant C_n^2 ($\text{m}^{-3/2}$)		
			Very weak	Weak	Moderate
1.75	21	500	$1 \cdot 10^{-18}$	$1 \cdot 10^{-17}$	$1 \cdot 10^{-16}$
2.0	26	100	$4.4 \cdot 10^{-16}$	$4.4 \cdot 10^{-15}$	$4.4 \cdot 10^{-14}$
2.25	23	50	$3 \cdot 10^{-16}$	$3 \cdot 10^{-15}$	$3 \cdot 10^{-14}$
2.50	46	100	$2 \cdot 10^{-17}$	$2 \cdot 10^{-16}$	$2 \cdot 10^{-15}$
2.75	54	440	$6.0 \cdot 10^{-18}$	$6.0 \cdot 10^{-17}$	$6.0 \cdot 10^{-16}$
3.0	54	220	$2.0 \cdot 10^{-18}$	$2.0 \cdot 10^{-17}$	$2.0 \cdot 10^{-16}$
Fried parameter [10]			840 mm	211 mm	53 mm

Uplink (UL)/beacon

Three scenarios for the Uplink/beacon beam (UL) were considered in our numerical simulations. The beam is described by a Gaussian distribution with a FWHM of 10 mm, 100 mm, and 1000 mm respectively. In all cases, the initial beacon power is set to 1W. Due to the large propagation distance, the turbulence-induced perturbations on the phase of the uplink wave have smoothed out, especially for Rx optics diameters of 100 mm, so the uplink beam does not exhibit wobbling or a speckly distribution, but power variations. This is because now the speckle size is in the order of meters, which is much larger than the satellite Rx entrance pupil. Thus, either a bright or a dark speckle illuminates the satellite resulting in variation of the signal power.

The scintillation index (defined as $\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$), was estimated by analyzing the variation of the uplink signal on the satellite Rx receiver focal plane. As shown in Figure 3, the 10 mm beacon exhibited the lowest scintillation and the 1000 mm the highest, on the satellite Rx focus. These results confirm that the use of a small diameter beacon (~10 mm FWHM) is beneficial for the UL.

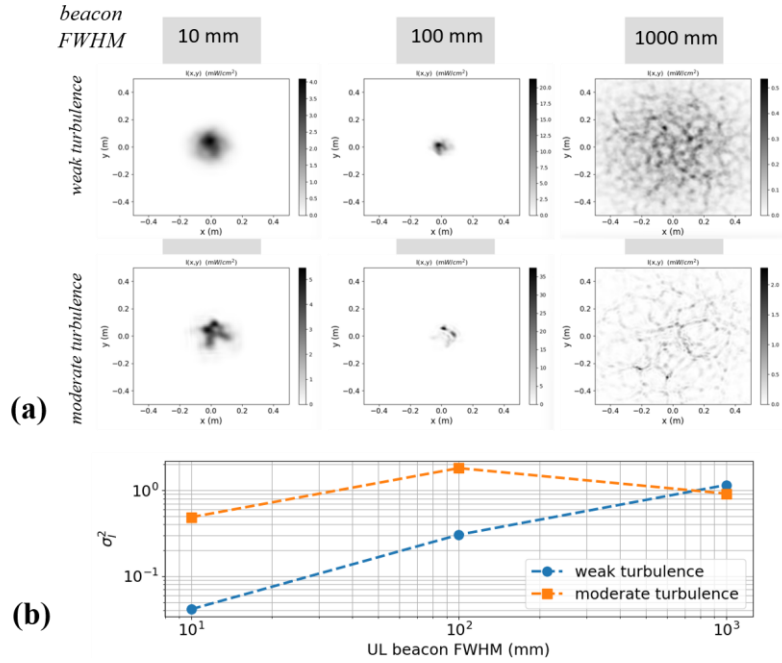


Figure 3. Numerical simulation results of the UL beam propagation as a function of the beacon beam FWHM. In all cases the initial beacon power is 1W (a) Typical intensity distribution at 3 km above sea level for weak and moderate turbulence. Note that as the beacon FWHM is increased speckles appear in the beam profile (b) Scintillation index at the satellite Rx focal plane (assuming a focusing lens of $f = 200$ mm focal length and $D = 100$ mm diameter).

Downlink (DL)

In our numerical simulations the downlink beam (DL) is described by a Gaussian distribution with a FWHM of 10 mm which is emitted by the satellite Tx optical system. Then it propagates through 567 km of free space where it reaches the turbulent layer, 3 km above sea level and 1.5 km from the Skinakas OGS, having spread to an FWHM of ~76 m. The initial beacon power is set to 1W.

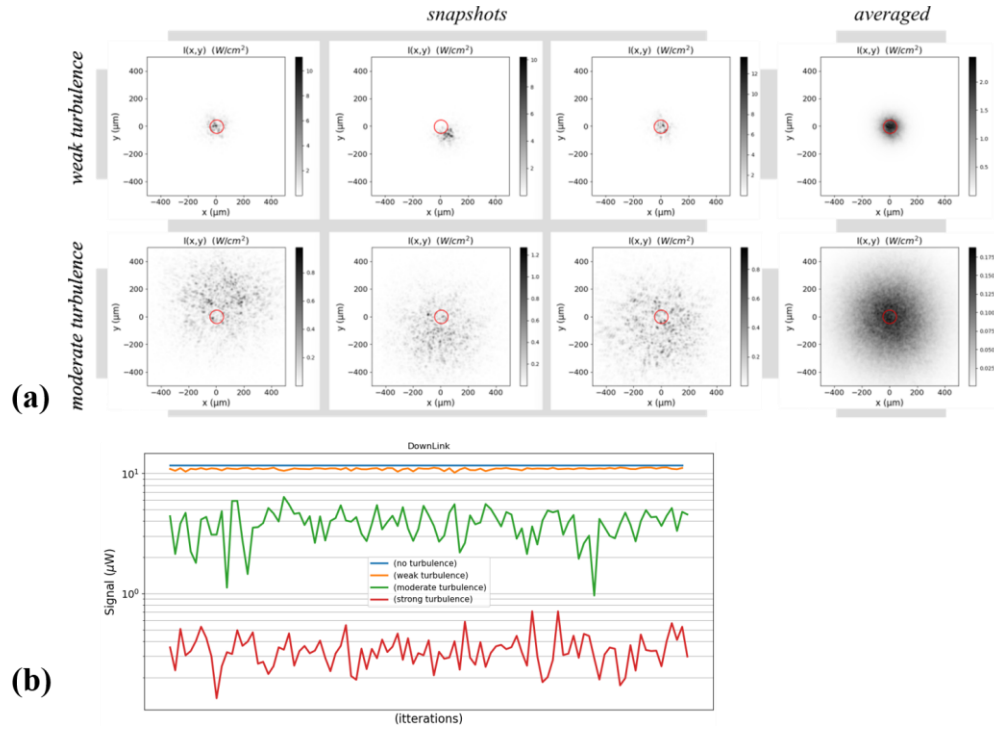


Figure 4. Numerical simulation results of the DL beam at the OGS telescope focal plane for weak turbulence assuming a 100 μm diameter detector. (a) typical snapshots of the intensity distribution. The average images (1000 iterations) simulate the effect of a long exposure. The red dashed circle denotes the detector diameter. (b) Signal scintillation at the focal plane of the OGS Rx focal plane.

The DL beam is finally collected by the OGS telescope and focused by the OGS Rx optics. In Fig. 4 we show typical snapshots of the beam spot and the average images over 1000 iterations, as well as the variation of the DL of the telescope Rx receiver and focal plane. Clearly, turbulence not only leads to signal scintillation but also a considerable drop in the average signal level as summarized in Table 4.

As we can see, without the action of adaptive optics to correct the beam deformation caused by turbulence the signal drop can easily exceed 4 dB, a factor that needs to be considered in the link budget. These results are very useful to fine-tune the re-estimate the Link Margin (LM) since critical parameters, such as a realistic estimation of the effect of turbulence, the telescope obstruction at the receiver chain, and the intensity distribution at the detector were not considered in Table **Error! Reference source not found.** In this way, the numerical simulation enhanced link budget model (NSELB) can be used as a reliable reference during the design phase of an optical or a QKD link.

Table 4. Average DL Signal for a 100 μm diameter detector. (left) results as obtained from numerical simulations (right) Link Margin, re-estimated using numerical simulation results.

Turbulence strength		Average Signal		Estimated Signal loss due to turbulence	Numerical simulation enhanced link budget model (NSELB)
	Fried parameter	(μW)	(dBm)	(dB)	
<i>no turbulence</i>	-	11.74	-19.3	0.0	Power Link Margin
<i>very weak</i>	840 mm	10.90	-19.6	-0.32	309
<i>weak</i>	211 mm	3.87	-24.13	-4.8	287
<i>moderate</i>	53 mm	0.342	-34.66	-15.4	102
					8.9

3. SYSTEM ARCHITECTURE

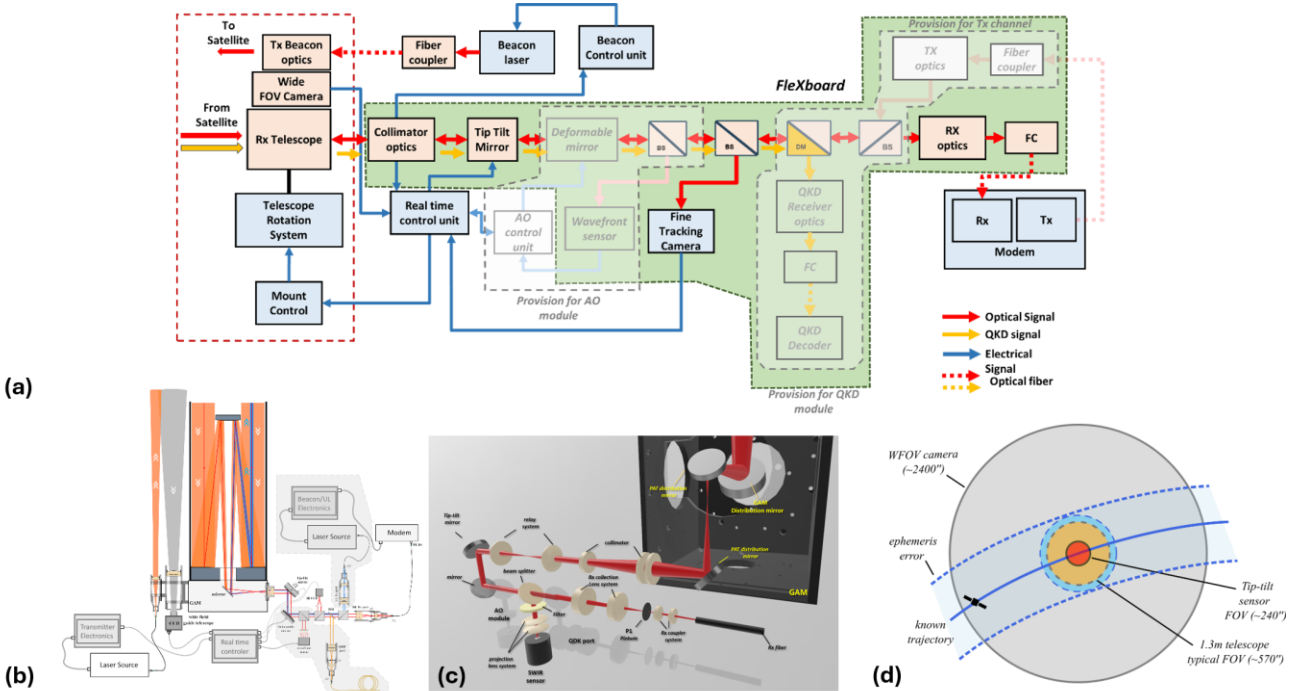


Fig. 5. FlexBoard system architecture. Provisional ports and capabilities are greyed out (a) block diagram of the system operation (b) schematic of the key building blocks of the OGS, (c) Preliminary optomechanical design of the OptCom, with provisions for QCD and adaptive optics ports included (d) Schematic of the field of view of the various subsystems of the optical system and ephemeris error of the LEO satellite

The system architecture, depicted in Fig. 5, features distinct optical paths for the transmitter and receiver chains. The optical communication module (OptCom) captures the downlink beam (DL) through the main telescope, reducing crosstalk, while the beacon/UL signal is modulated up to 200 kHz according to the CCSD standard and transmitted through a dedicated auxiliary beacon telescope. The 1.3 m equatorial fork-mounted Cassegrain main telescope facilitates pointing, acquisition, and tracking, utilizing coarse tracking via a Wide Field of View telescope and fine tracking through a tip/tilt mirror and feedback loop. Additional features include a SWIR camera and feedback loop, optical fiber coupling for the Rx telecom channel, and provisions for a QCD port and adaptive optics module. The system aims for efficient optical isolation and minimal crosstalk, offering a comprehensive solution for satellite communication with advanced tracking and security features. Furthermore, a critical parameter for the design of WFOV optics is the ephemeris error of the tracked satellite and how this is compared to the FOV of the optical system. Fig. 5(d), a schematic puts this into context. The FOV of the 1.3 m telescope is ~ 570 arcsec. The blue circle represents the ephemeris error of 2 km of the satellite position (typical LEO satellite altitude). Since the ephemeris error exceeds the FOV of the Rx telescope, a WFOV sensor is necessary. The use of such a sensor offers additional advantages, like for example to the Tx beacon and receiver alignment. As shown in the figure, the field of view of WFOV sensor (designed to >2400 arcsec) allows the tracking of the LEO satellite even in the worst ephemeris error scenario.

Control logic

The telescope's pointing and coarse tracking is based on available TLE information of the target LEO satellite. Various factors, like for example the ephemeris error, can lead to a pointing error in the order of arcmins. Considering that the FOV of the SWIR camera is small (<6 arcmin) it is necessary to foresee a connection between the telescope's coarse tracking and the fine tracking loop (FSM mirror) so that the telescope can bring the LEO satellite within the FOV of the SWIR sensor. This is achieved by incorporating a slower feedback loop with the use of the WFOV camera. The control logic of the OGS operation in a Pointing - acquisition and tracking sequence is depicted in Fig. 6 below.

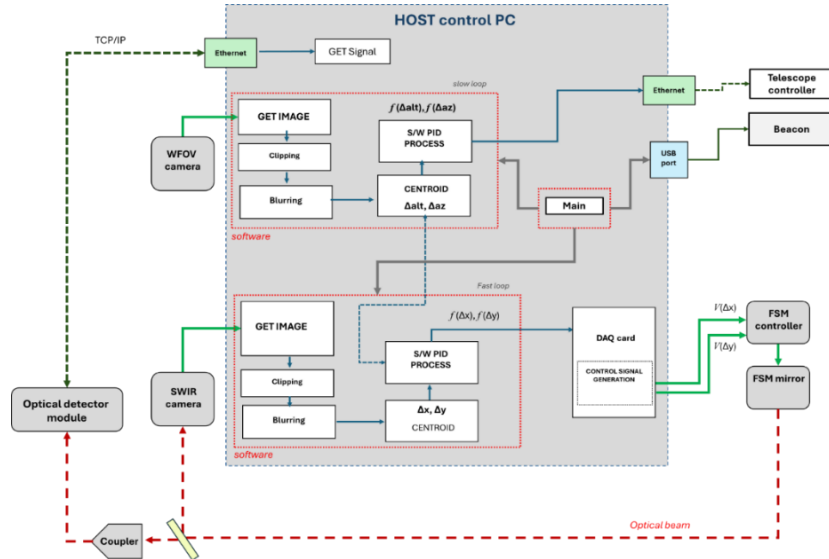


Figure 6. Control logic for the OGS operation.

4. IMPLEMENTATION

The FlexBoard-OptCom module was designed to be mounted to the east port of the 1.3 m telescope GAM, enabling fast switching from astronomical observations to optical communications. Fig. 7 shows the basic steps: from optical design to lab prototype and then on-site installation.

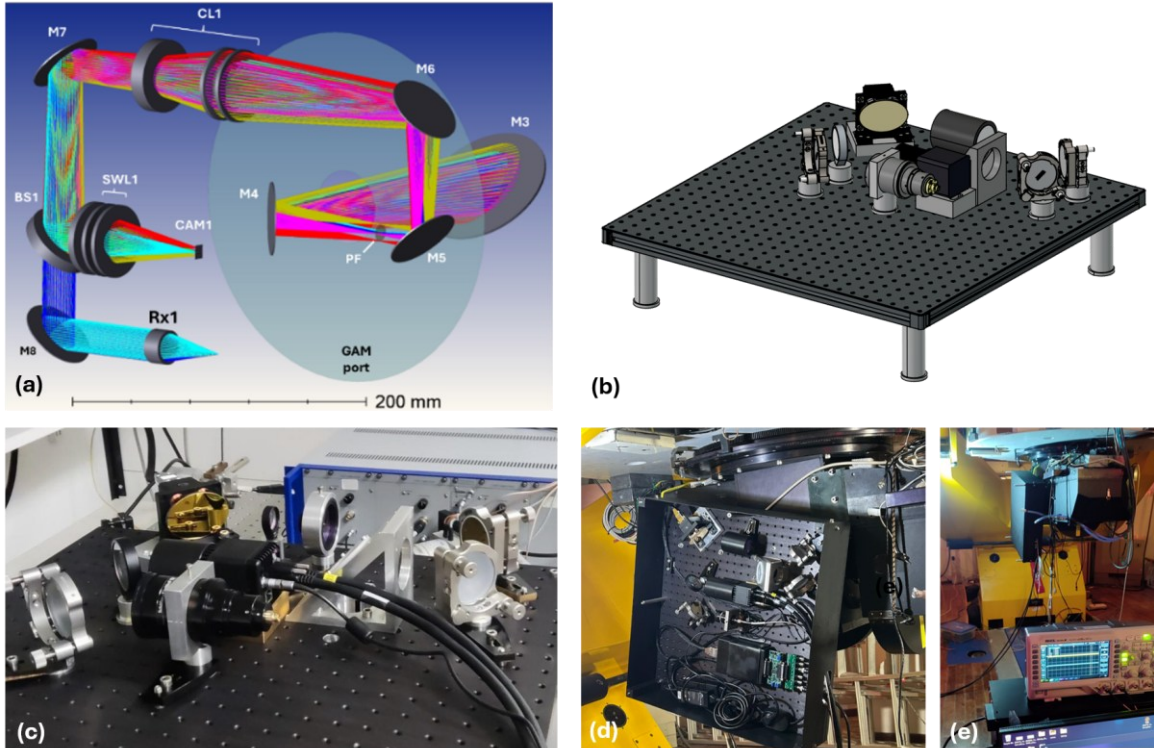


Fig. 7. FlexBoard from optical design to implementation. (a) 3D representation of the PAT optical design. M3-M8 mirrors, M7 is the FSM mirror (b) Optomechanical design (c) laboratory prototype (d) FlexBoard is installed on the east port of the 1.3 m telescope GAM. (note that the cap is left inventively open) (e) FlexBoard in operation during campaign in Skinakas Observatory.

FlexBoard optical design guidelines

The optical design is guided by the following principles; collimating the input beam and then distributing it to the various sub-modules and imaging the telescope's input pupil on the plane of the FSM mirror (OIM202). This approach allows the system to be modular and easily expandable. Furthermore, the system is designed to operate at dual wavelengths (1553 nm, 1536 nm) targeting communication with Eagle1 and TESAT LEO satellites. In more detail, the collimator is designed to provide $M'_a \cong -53$, angular magnification. This results in a collimated beam tilt of $\sim \pm 106$ arcmin (for a FOV of ± 2 arcmin), on the FSM mirror. The feedback for the closed loop control of the FSM mirror is provided by a SWIR sensor (C-RED 3). As shown in Fig. 7(a) a beam splitter BS1 picks up a portion of the input beam and redirects it towards the SWIR sensor optics that focus the beam. The FOV of the SWIR sensor is 369 arcsec and the angular resolution is ~ 3.5 μ rad/pixel (0.72 arcsec/pixel), well within the resolution capabilities of the FSM mirror controller. Likewise, mirror M8 directs light to the Rx1 optics coupler (Schäfter + Kirchhoff 60FC-L-4-M50L-37 coupler). In our design mirror M8 represents the provisional port for the addition of an adaptive optics system. Light is then collected into the Rx fiber (50 μ m, 0.20 NA) with a measured FOV of 3 arcsec.

The footprint of the FlexBoard optics (including optomechanical mounts) is 47 cm x 32 cm. Considering the expandability of the system (provisional ports for QKD and adaptive optics) we have used a 60 cm x 60 cm breadboard. The breadboard is drilled making a 50 mm opening for the beam to enter the breadboard and an adapter flange was used to mount the PAT breadboard on the east port of the telescope GAM.

Beacon

The beacon module optical design is shown in Fig. 8(a). Light emitted from the 10W average power beacon laser (Woodrow Scientific Limited) is transmitted through a 10 m, 0.1 NA optical fiber to a custom design collimator. The collimator design is quite straightforward, using a lens pair to control both the beam diameter and divergence. By displacing one of the lenses along the optical axis, we achieve a large beam diameter combined with a desired beam divergence that would be otherwise achieved by a smaller collimated beam. The far field PSF shown in Fig. 8(b), (c) allows us to estimate the beam divergence and thus footprint size at the LEO trajectory. Furthermore, mirror adjustments in BL1, BL2 distance (3 mm + Δz) seed the beam's wavefront with extra curvature (defocusing) and thus allows us to tune the beacon divergence.

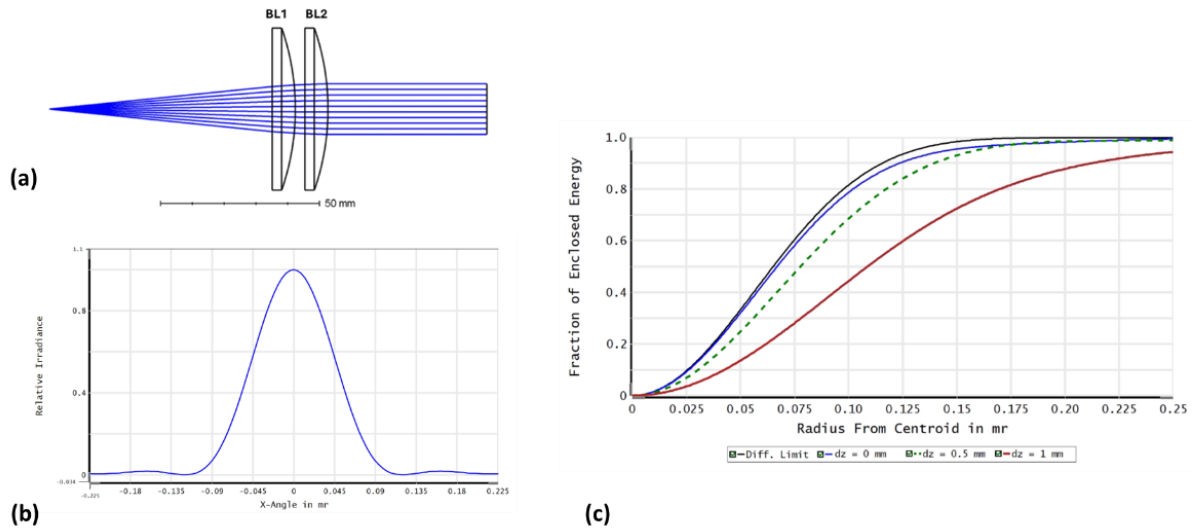


Fig. 8. Beacon module (a) optical design. (b) Beacon angular PSF (c) Enclosed energy as a function of the angular deviation from the centroid. Note that by displacing BL2 by 0.0 mm, 0.5 mm, 1 mm the beam divergence (measured at 50% of enclosed energy) ranges from 14, 16 and 22 arcsec

The optomechanical design and the laboratory prototype of the beacon and WFOV camera module are shown in Fig. 9. We characterized the beacon beam by measuring its profile using imaging and a variation of the knife edge method [11]. The image of the beacon beam profile after a propagation distance of 110 cm, along with the corresponding intensity profile are shown in Fig. 9(c), (d). From our measurements we estimate that the beacon beam FWHM is 11.3 ± 1 (mm)

and the waist $\sim 6.8 \pm 0.6$ (mm). Likewise, by measuring the beam profile as a function of the propagation distance we have also estimated the beam divergence to be: $\Delta\theta = 0.16 \pm 0.02$ mrad (33 ± 4 arcsec), a value which is within the designed divergence in our beacon optics design.

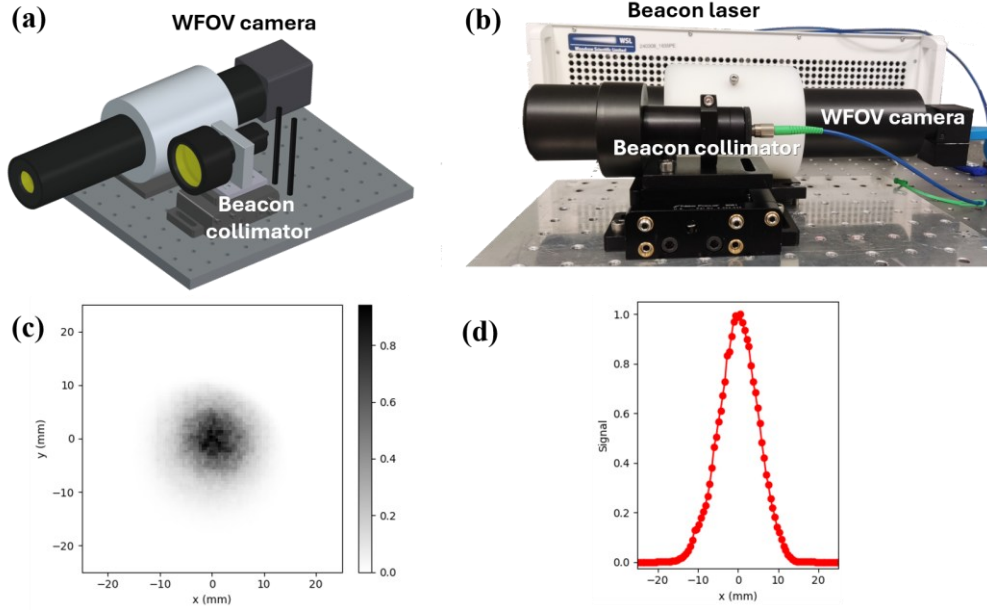


Fig. 9. Beacon and WFOV modules (a) CAD design (b) laboratory prototype with beacon laser (c) normalized 2D intensity profile. (d) normalized intensity profile across the peak

FlexBoard Capabilities

The FlexBoard was tested both on site, and in the laboratory. We have been successful in demonstrating tracking of low intensity celestial objects and in demonstrating fiber coupling in a laboratory setting using the telescope-mountable optical breadboard with emulated turbulence and pointing drift conditions. Due to a lack of suitable available satellites, however, we have not yet tested FlexBoard in communicating with LEO satellites.

Campaigns in Skinakas

We performed a series of tests including FlexBoard integrity and calibration as well using the closed loop control to compensate for turbulence induced wobbling and drifts of low intensity celestial objects on Skinakas Observatory. Typical snapshots of the live preview process are shown in Fig. 10. There the SWIR camera image is shown with overlaid cross hairs to indicate setpoint and estimated spot position.

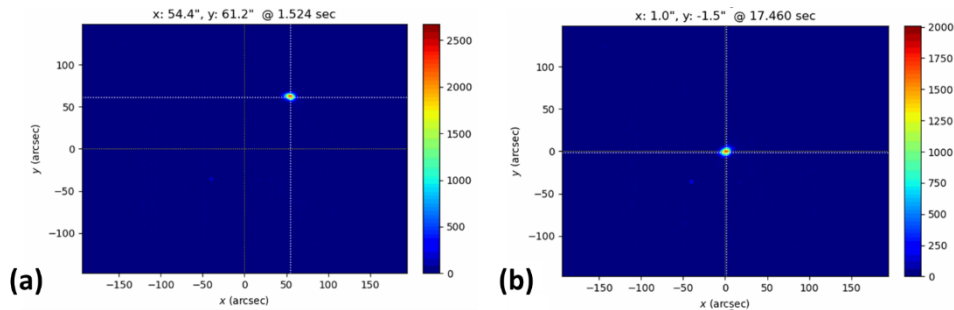


Fig. 10. Typical screen shots of the live preview feedback in false color. Note that for better visualization, processed (intensity clipped & gaussian blurred) instead raw images are shown. Yellow crosshairs indicated the setpoint while white crosshairs indicated the estimated spot position. (a) closed loop is off (b), closed loop is on.

The action of the FSM closed loop in suppressing the low frequency turbulence induced wobbling of a focal spot is shown in Fig. 11. As we can see, the low frequency wobbling clearly suppressed when the closed loop control is on.

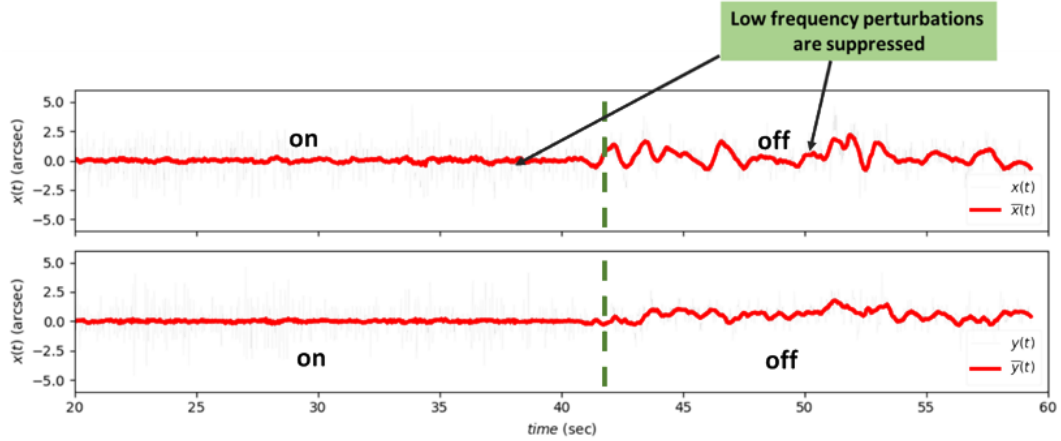


Fig. 11. Suppression of the low frequency focal spot position perturbations when the closed loop is on (tracked celestial object: Deneb). Note that when the closed loop is off the FSM mirror remains at the previous set position.

Another test we performed was to use the telescope's tracking controller to manually introduce angular offsets of $|\delta| \leq 50''$, at rates $4''/\text{sec} \leq \left| \frac{d\delta}{dt} \right| \leq 22''/\text{sec}$. Typical results are shown in Fig. 12. The lower signal curve emulates the power that would be coupled in a multimode fiber and is estimated by integrating the SWIR image counts within an area corresponding to the Rx fiber FOV. The green shaded areas (from ~ 120 sec to 250 sec) mark the time range where the FSM closed loop is on. Before and after this section, the introduced manual offsets are clearly visible as shifts in the spot position. Note that in this case the estimated signal drops to zero when the spot moves beyond the Rx fiber FOV. On the other hand, the spot position is stable when the closed loop is on and the estimated signal does not drop to zero. The action of the closed loop control is clearly visible from the control voltage $V_x(t), V_y(t)$ values which now show large variations as the closed loop control compensates for the induced offsets.

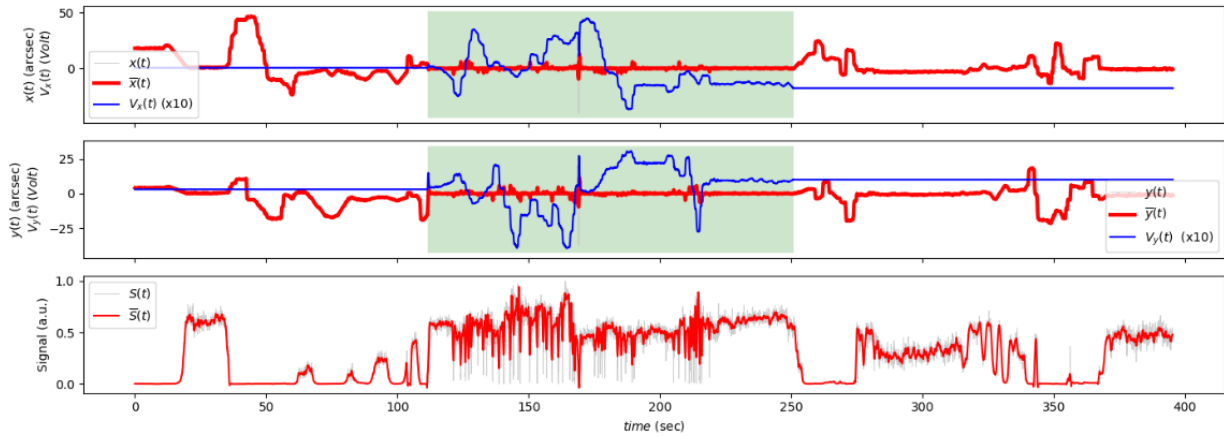


Fig. 12. Suppression of manually introduced angular offsets in the focal spot position when the closed loop is on (shaded area). The lower signal curve is a normalized estimate of the integrated signal power within the Rx input fiber FOV. (tracked star: Algol, 2 ms exposure, 100 fps) red trace indicates the $x(t)$, $y(t)$ position of the star and the blue traces indicate the respective control voltage of the FSM mirror.

Turbulence emulation experiments in the laboratory

The focal position dynamics from data retrieved during campaigns in Skinakas observatory was used to also perform lab experiments in realistic conditions. Using these measurements, we were able to simulate the turbulence effect by wobbling the input beam in a similar way. Likewise, by adding a linear drift to this erratic motion we successfully emulated a

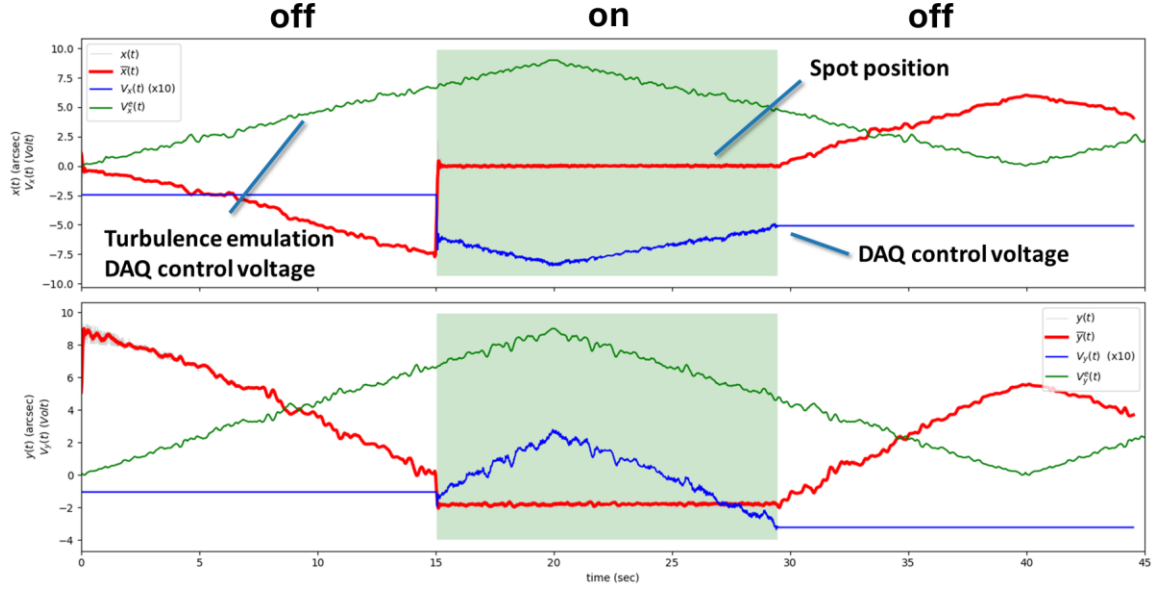


Fig. 14. Turbulence emulation lab experiments x , y (center of mass) spot position in arcsec and respective DAQ voltage (the green shaded area indicates the time interval where the closed loop is on)

5. SUMMARY AND OUTLOOK

This work has presented the main stages involved in upgrading the Skinakas Observatory 1.3 m telescope into an Optical Ground Station (OGS), together with its current operational status, demonstrated capabilities, and future development path. The upgrade was based on the design, construction, and validation of a modular optical breadboard with active stabilization, referred to as FlexBoard. This approach provides a practical and expandable route for converting existing astronomical facilities into dual-use observatories capable of supporting both conventional astronomical observations and free-space optical communication experiments. By mounting FlexBoard on a port of the telescope's Guiding and Acquisition Module (GAM), the system can be integrated without disrupting the primary astronomical function of the telescope, while still allowing rapid reconfiguration between observing campaigns and optical communication activities.

The architecture of FlexBoard is deliberately modular, enabling the receiver chain, fine-tracking optics, beacon alignment functions, and future quantum-communication and adaptive-optics channels to be developed and tested independently. The experimental results obtained both at Skinakas Observatory and in laboratory turbulence-emulation experiments confirm that the system can stabilize low-intensity optical signals, compensate for pointing drifts, and maintain coupling into the receiver fiber under representative disturbance conditions. These capabilities are essential for reliable optical links with fast-moving low-Earth-orbit satellites and provide a foundation for more demanding future scenarios. In particular, the large collecting aperture of the Skinakas telescope, combined with the favorable seeing conditions of the site, makes the upgraded facility a promising candidate for deep-space optical communication demonstrations, lunar satellite links, and future ground-segment networks supporting lunar exploration. Further development will focus on completing and validating the quantum channel, integrating adaptive-optics-based turbulence mitigation, and performing end-to-end communication tests with suitable satellite targets. Overall, the Skinakas OGS upgrade demonstrates that existing astronomical infrastructure can be transformed into a flexible, research-grade platform for next-generation optical and quantum communication technologies.

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