

MADOCS: Integrated Adaptive Optics for Free-Space Optical Communication in LEO

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ABSTRACT

We present the development and laboratory characterization of MADOCS (MOCA Adaptive Optics Control System), a purpose-built adaptive optics (AO) control system for free-space optical communication (FSOC) ground terminals serving satellites in low Earth orbit (LEO). Such terminals must contend with high angular slew rates, rapidly evolving turbulence, and control bandwidths in the hundreds of hertz combined with sub-millisecond closed-loop latency — constraints further amplified at field-deployed sites outside traditional astronomical observatories. MADOCS is the real-time control system of the Back-end Optical Conditioner (BOC), the post-focal AO and signal-conditioning instrument of the MOCA optical telecommunication antenna, a 1.5-m class ground station developed by AMOS under ESA's ARTES 4.0 program. Evolved from the calibration and reconstruction framework of the SALTO demonstrator, where a 97-actuator AO system achieved diffraction-limited correction at 1.55 μm on a 1-m class telescope, MADOCS implements a dual-loop architecture that decouples fast tip-tilt correction (4 kHz, fast steering mirror) from high-order wavefront control (2.5 kHz, 192-actuator deformable mirror), with both loops sensed by InGaAs cameras operating near the 1550 nm FSO communication band. The real-time controller achieves sub-100 μs median computational latency and microsecond-level jitter through algorithmic optimization of a CPU-based, Python/C++ software platform built on the MILK/CACAO shared-memory framework. Laboratory tests under representative simulated turbulence conditions (Fried parameter $r_0 = 3\text{--}5$ cm, elevation $20^\circ\text{--}80^\circ$) demonstrate stable closed-loop operation with residual wavefront errors of 170–270 nm RMS, meeting the MOCA system requirements derived from single-mode fiber coupling efficiency across operational and degraded atmospheric scenarios. We discuss the design trade-offs specific to adapting astronomical AO technology to the temporal requirements of FSOC and present the commissioning plan for on-sky validation on the SALTO telescope.

Keywords: adaptive optics, free-space optical communications, real-time control, wavefront sensing, optical ground station, deformable mirror

1. INTRODUCTION

The deployment of satellite-to-ground free-space optical communication (FSOC) links is driving a growing need for adaptive optics (AO) systems capable of operating at ground terminals outside traditional observatory sites. While astronomical AO has matured over several decades, FSOC imposes a distinct set of constraints on the control system. Optical ground stations (OGS) are typically located at low-altitude, non-astronomical sites where seeing conditions are significantly worse than at dedicated observatories. The relative angular motion of satellites, particularly in low

Earth orbit, demands loop bandwidths beyond those of conventional astronomical AO. Also, the performance metric is no longer the Strehl ratio or image sharpness, but rather the efficiency with which the corrected wavefront can be coupled into a single-mode fiber (SMF) to feed a coherent communication receiver.

These considerations motivate the development of MADOCS, the MOCA ADaptive Optics Control System. MOCA (Medium-size Optical telecommunication Antennas) is a 1 m to 1.5-m class optical telecommunication antenna developed by AMOS under ESA's ARTES 4.0 program. The antenna is designed to support laser communication with satellites in LEO (and, by extension, MEO and GEO orbits), as well as quantum key distribution (QKD) experiments. MADOCS is the real-time AO control system integrated within the Back-end Optical Conditioner (BOC), the post-focal instrument that conditions the received signal and distributes it among the wavefront sensor and instruments, such as a fiber-fed receiver.

MADOCS builds on the heritage of the SALTO project, a 1-m class telescope equipped with a single-conjugate AO system developed jointly by the University of Liège, AMOS, and partners [1] [2]. SALTO demonstrated diffraction-limited correction at $1.55 \mu\text{m}$ under $2\text{--}3''$ seeing at the ESA Redu Station in Belgium, using a 97-actuator deformable mirror and a software real-time controller (RTC) achieving approximately $600 \mu\text{s}$ computational latency at 1 kHz frame rate [1]. The FSOC application required a step up from that baseline: doubling the actuator count to 192, implementing a dedicated dual-loop architecture for simultaneous tip-tilt and high-order correction, pushing both loops to multi-kHz frame rates, and reducing computational latency to well below a single frame period.

In this paper, we describe the MADOCS system architecture and its laboratory characterization on the BOC test bench under representative simulated turbulence conditions. Section 2 describes the optical and control system design, with emphasis on the dual-loop architecture and the real-time computing platform. Section 3 presents the laboratory test setup and closed-loop performance results. Section 4 discusses the implications for FSOC link performance and outlines the on-sky commissioning plan.

2. SYSTEM OVERVIEW

2.1 BOC optical context

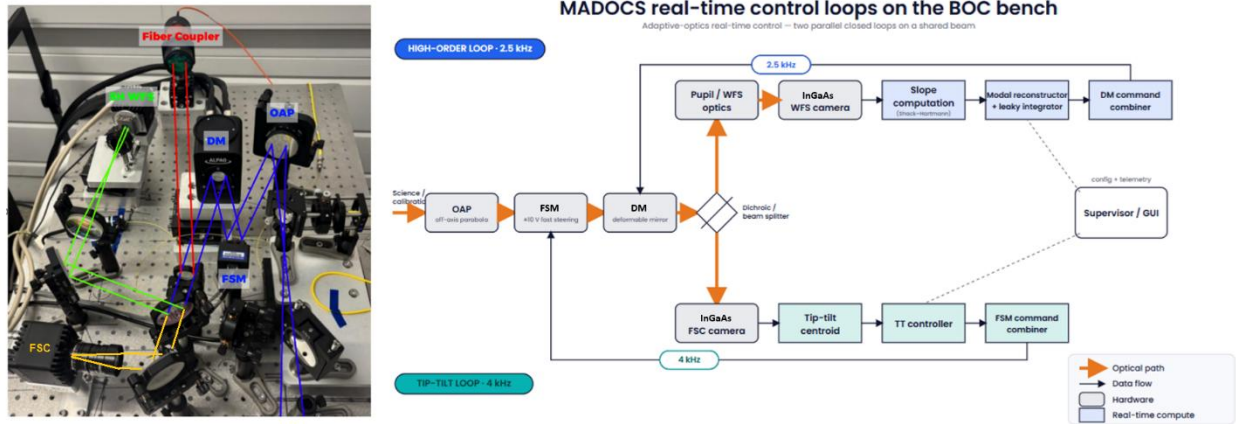


Figure 1 : Left: the assembled BOC bench at AMOS, with the main light paths overlaid on the photograph. The blue path traces the incoming beam from the telescope through the off-axis parabola (OAP), the fast steering mirror (FSM), and the deformable mirror (DM) to the dichroic; the red path traces the science beam from the dichroic to the single-mode fiber coupler; the green path traces the wavefront sensing beam from the dichroic to the Shack-Hartmann wavefront sensor; the yellow path traces the beam to the fast steering camera (FSC). Right: block diagram of the MADOCS dual-loop architecture, showing the optical path, the data flow, the hardware, and the real-time processes of the tip-tilt and high-order loops.

The BOC is designed to be installed at the Nasmyth focus of the MOCA antenna. The converging F/10 beam from the telescope is collimated to a 21-mm diameter beam matched to the DM clear aperture. The common optical path traverses the fast-steering mirror (FSM), the deformable mirror (DM), and a beam splitter that directs the bulk of the signal toward the science instruments while transmitting approximately 2% to the wavefront sensing path. The science path feeds a fiber-coupled SMF interface and a potential free-space instrument port; the wavefront sensing path is split further between a Shack-Hartmann wavefront sensor (WFS) and a fine tracking camera. An internal calibration source, a 1550 nm fibered laser injected at the telescope focal plane, enables daytime calibration independent of telescope availability. A picture of the BOC optical layout is given in the left panel of Figure 1.

During nominal on-sky operations, the signal acquisition follows a hierarchical field-of-view cascade. A co-aligned pointing, acquisition, and tracking (PAT) telescope performs initial satellite acquisition over a ~ 20 -arcmin field. Beam control is then handed off to the fine tracking camera integrated in the BOC, which stabilizes the image within the 13-arcsec WFS field-of-view and the sub-arcsecond acceptance cone of the SMF core.

2.2 Dual-loop architecture

The central design decision in MADOCs is the separation of tip-tilt correction from high-order wavefront control into two independent loops, each with its own sensor, actuator, and control cadence (see right panel of Figure 1). This separation is driven by the FSOc use case: satellite tracking residuals and wind-driven telescope vibrations produce large-amplitude, broadband tip-tilt disturbances that demand the highest possible rejection bandwidth, while higher-order atmospheric aberrations evolve more slowly and are corrected by the deformable mirror with a larger but slower actuator set. Assigning tip-tilt to a dedicated steering mirror also prevents the large-amplitude tip-tilt excursions from consuming the limited ± 10 μm stroke of the deformable mirror, preserving its dynamic range for the correction of higher-order aberrations.

Tip-tilt loop. The fast-steering mirror is a commercial piezo-driven two-axis mirror with 25.4 mm aperture, 26 mrad peak-to-valley mechanical stroke, and a closed-loop bandwidth exceeding 850 Hz. It is located at a conjugated pupil plane, ensuring that tip-tilt commands produce pure image motion without pupil translation, a prerequisite for maintaining the registration of the Shack-Hartmann subapertures. The tip-tilt sensor is a dedicated commercial InGaAs camera (the “fast steering camera,” FSC), an uncooled detector with 15 μm pixels, operated in a 128×128 pixel region of interest at approximately 4000 Hz. The RTC computes a thresholded center-of-gravity on the FSC image, applies a leaky proportional-integral (PI) control law, and issues analog voltage commands to the FSM driver via a digital-to-analog PCIe board. The measured median computational delay, from frame release to command issuance, is 52 μs , with a 99.7th-percentile value of 86 μs .

High-order loop. The deformable mirror is a commercial unit with 192 actuators arranged on a 16×16 grid at 1.5 mm pitch, providing a 21 mm clear aperture and ± 10 μm wavefront peak-to-valley stroke. It is driven by its dedicated controller interfaced to the RTC over Gigabit Ethernet. The wavefront sensor is a second commercial InGaAs camera (the “wavefront camera,” WFC) behind a Shack-Hartmann lenslet array (214.5 μm pitch, 7 mm focal length), producing a 13×13 grid of useful subapertures in Fried geometry across a 192×192 pixel region of interest, with each subaperture spanning 12×12 pixels, at approximately 2500 Hz. A two-lens beam compressor relays the pupil from the DM to the lenslet plane.

The high-order controller operates in modal space, and several modal bases are supported: Zernike polynomials, deformable mirror eigenmodes (mirror modes), and Karhunen-Loève modes. A modal interaction matrix is acquired by sequentially exciting each mode of the selected basis on the DM and recording the corresponding WFS slope response. The resulting modal reconstructor maps the measured slope vector into modal coefficients, which are then converted to actuator commands. This approach provides efficient correction of low- and mid-order aberrations while naturally filtering noise from poorly sensed high-order modes and from edge actuators that fall partially outside the

illuminated pupil. In its initial test configuration for which the results are reported in Section 3, the loop corrected the first 50 Zernike modes (Z4 through Z50), but in the nominal use case the loop is expected to be closed over 100 KL modes. A standard integrator controller with anti-windup clipping is employed: commands exceeding the DM stroke are clipped before being sent, and the integrator state is back-corrected accordingly. We are currently investigating the use of advanced predictive controllers (EOF, LQG). The measured median computational delay for the high-order loop is 97 μ s, with a 99.7th-percentile value of 173 μ s.

2.3 Real-time computing platform

The MADOCs RTC is a CPU-based platform, deliberately avoiding FPGA or GPU, to preserve the development flexibility and rapid-prototyping capability inherited from SALTO. The hardware centers on a high-core-count, server-class CPU housed in a standard rack-mount server. Camera frames are acquired through commercial frame grabbers in a Camera Link configuration.

The software architecture builds on the SALTO implementation [1] and uses the MILK/CACAO shared-memory data stream paradigm [3] [4]: each process in the real-time chain writes to a shared memory buffer and increments associated semaphores, triggering downstream processes that are waiting on those semaphores. This design encapsulates all inter-process communication within the data stream itself, delivering microsecond-level inter-process communication (IPC) latency with low jitter. The real-time processes (slope computation, control law, command combination) are implemented in Python 3, accelerated through Numba just-in-time compilation and Cython type-annotated compilation of numerically critical sections. Hardware interface drivers (camera acquisition, DM and FSM communication) are implemented in C or C++.

A key contribution relative to the SALTO baseline was algorithmic optimization of the wavefront slope computation, the most time-critical step, responsible for roughly half of the total computation time. Refactoring the subaperture chopping and centroid calculation using Numba and Cython yielded a 10-fold reduction in median slope computation time for MOCA-sized WFS frames relative to the original SALTO algorithm, with a corresponding reduction in timing jitter. This speedup was essential for reaching multi-kHz operation on the larger 13×13 and up to 15×15 subaperture grid, preserving the flexibility of Python.

3. LABORATORY CHARACTERIZATION

3.1 Test setup and turbulence emulation

The AO performance of MADOCs was evaluated on the BOC bench at AMOS under controlled, representative atmospheric conditions. The internal calibration source, a 1550 nm single-mode fiber laser injected at the BOC entrance focal plane, provides a diffraction-limited point source filling the 21 mm DM pupil. To emulate atmospheric turbulence, phase screens were generated offline using the AOtools simulation framework [5], configured for a range of Fried parameters and satellite elevation angles. Temporal evolution was modeled by shifting the screens according to both wind velocity vectors and satellite tracking trajectories, producing time-varying phase disturbance sequences representative of line-of-sight propagation during a satellite pass.

These phase sequences were then decomposed and injected in real time onto the MADOCs actuators: the high-order component was projected onto the DM actuator space by inverting the measured influence matrix, while the tip-tilt component was extracted and converted into FSM commands using the FSC calibration data. This hardware-in-the-loop approach exercises the full correction chain (sensors, reconstruction, control law, and actuator response) under physically representative disturbances, while maintaining the repeatability of a laboratory environment.

Six atmospheric scenarios were defined, spanning two coherence lengths ($r_0 = 5$ cm and 3 cm at 500 nm, zenith) and three elevation angles (20° , 50° , 80°). These cover both the operational performance envelope ($r_0 = 5$ cm, elevation $> 50^\circ$) and the functional survival envelope ($r_0 = 3$ cm, elevation $> 20^\circ$).

3.2 Closed-loop performance

For each scenario, both AO loops were closed with user-tuned gain parameters optimized for stability and performance. System telemetry (WFS slopes for the DM loop and FSC centroid measurements for the FSM loop) was recorded throughout closed-loop operation.

Residual wavefront error. The residual WFE was reconstructed from the WFS slope measurements at each loop iteration by mapping the measured slope vector, formed by the local x- and y-gradients of the wavefront sampled at each illuminated subaperture, back into a wavefront estimate over the pupil. The slope vector is first converted into a set of zonal coefficients through the zonal reconstructor, the slope-to-coefficient matrix obtained from the inverse of the measured slope-response (interaction) matrix; these coefficients are then expanded into a continuous wavefront map through the DM influence matrix, which relates actuator displacements to the resulting wavefront. After removal of the global tip and tilt modes, which are corrected by the separate FSM loop, the spatial RMS of the residual wavefront over the illuminated pupil yields the per-frame residual WFE. The resulting RMS values are summarized in Table 1.

Table 1. Residual WFE achieved by the MADOCs AO system under simulated atmospheric conditions.

r_0 (cm)	Elevation ($^\circ$)	Residual WFE (nm RMS)
5	80	170
5	50	180
5	20	200
3	80	214
3	50	228
3	20	272

Under the nominal operational conditions ($r_0 = 5$ cm, elevation $\geq 50^\circ$), the worst-case residual is 180 nm RMS, below the 187 nm RMS system specification. Even at the most degraded functional scenario ($r_0 = 3$ cm, 20° elevation), the system remains stable and delivers 272 nm RMS, which corresponds to an estimated SMF coupling efficiency of 30%, well above the 10% minimum required at low elevation.

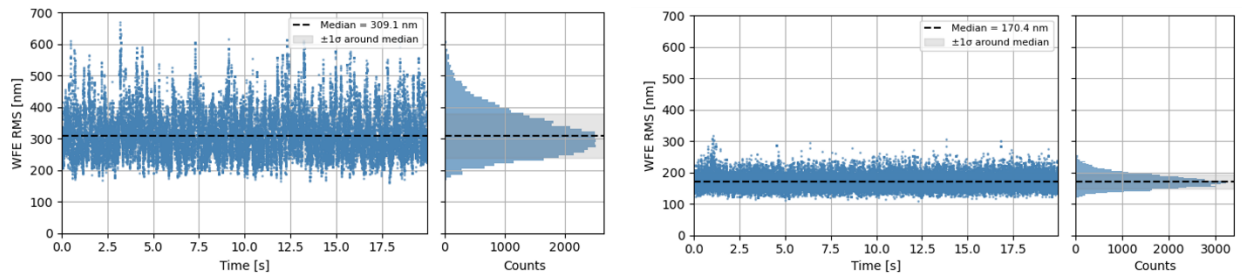


Figure 2 : Residual wavefront error under the nominal scenario ($r_0 = 5$ cm, 80° elevation), measured at the wavefront sensor. Left: open-loop WFE, averaging 310 nm RMS. Right: closed-loop WFE for the same turbulence sequence; the residual drops to 170 nm RMS on average, and the WFE standard deviation is reduced by a factor of two.

Modal correction efficiency. The modal content of the wavefront was analyzed by comparing the median amplitude of each corrected mode (Z4 through Z50) in open-loop and closed-loop telemetry. Under the nominal scenario ($r_0 = 5$ cm, 80°), the correction is dominated by low-order modes, with power spectral density (PSD) suppression of -12 to -15 dB; the residual energy in higher-order modes is modest, consistent with the turbulence power spectrum dropping rapidly with spatial frequency under these conditions. Under the harshest scenario ($r_0 = 3$ cm, 20°), a larger fraction of the turbulent power falls in mid- and high-order modes beyond the 50 corrected modes. This uncorrected content cannot be rejected by the loop and increasingly dominates the residual error budget, leaving the system fitting-error limited. On the corrected low-order modes, the deeper PSD suppression of -20 dB reflects the larger open-loop power the integrator must reject as turbulence strengthens.

Temporal performance. The rejection transfer functions derived from the PSD ratio of open-loop to closed-loop telemetry confirm that the FSM tip-tilt loop achieves a 0 dB rejection bandwidth of approximately 200 Hz. The DM modal loop reaches approximately 140 Hz, slightly below the 166 Hz specification but consistent with the MOCA WFE requirement being met. Analysis of the closed-loop to open-loop PSD ratio reveals an additional ~ 0.7 ms pure delay not captured in the per-frame computational timing, attributable at least in part to DM SDK communication overhead. This latency contribution is accounted for in performance analysis and is a primary target for future optimization, potentially through a lower-latency DM interface.

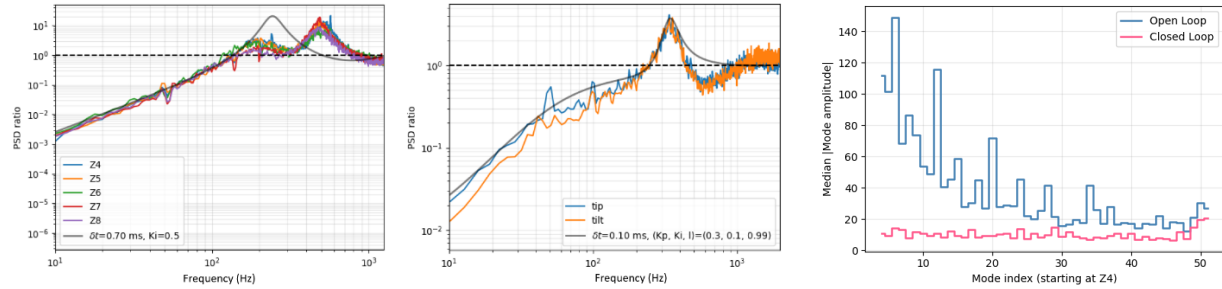


Figure 3 : Left and center: rejection transfer functions, computed as the closed-loop to open-loop PSD ratio, for the DM high-order loop (left) and the FSM tip-tilt loop (center). The 0 dB crossover gives a rejection bandwidth of approximately 140 Hz for the DM loop and above 200 Hz for the FSM loop. Right: per-mode rejection under the degraded scenario ($r_0 = 3$ cm, 20° elevation), reaching -20 dB on the lowest-order modes.

Tip-tilt residuals. Under the worst-case scenario, the FSM loop delivers residual tip-tilt of approximately 42 mas RMS per axis. This exceeds the error budget allocation of 23 mas, but the figure is limited by the coarse FSC pixel scale ($0.5''/\text{pix}$), which is insufficient to resolve residuals at this level. The true performance is likely better and will be more precisely characterized on-sky using WFS-derived tip-tilt estimates.

4. DISCUSSION AND OUTLOOK

4.1 Design trade-offs and optimization paths

The dual-loop separation proves effective: each correction stage operates at its natural bandwidth with no mutual interference evident in the laboratory data, and the MILK/CACAO shared-memory architecture delivers the determinism needed for multi-kHz operation while retaining the flexibility of a high-level language for the control algorithms.

Several performance margins remain to be exploited. The DM192 can in principle support approximately 100 controlled modes, nearly double the 50-mode baseline used during laboratory testing. The limitation to 50 modes arose from control loop stability issues traced to a combination of poorly sensed modes and noise amplification at high modal orders. The WFS currently samples the pupil on a 13×13 subaperture grid in a Fried geometry, which does not

fully cover the 16×16 actuator grid of the DM: the peripheral actuators fall outside the illuminated pupil and are therefore weakly sensed, or effectively blind, so the modes that couple to them are poorly observable. A 15×15 subaperture grid would match the actuator geometry in Fried configuration and improve the observability of these edge actuators. Following the laboratory campaign reported here, the modal basis is now constructed from the measured interaction matrix with explicit regularization of the blind actuators rather than from theoretical Zernike modes.

The 10-fold speedup on the slope computation was the single most impactful change enabling multi-kHz operation on the larger 13×13 subaperture grid. This confirms that a Python-based RTC architecture remains practical for AO systems of this scale (~ 200 actuators, ~ 170 subapertures), provided that the critical numerical kernels are properly compiled. For systems with significantly larger actuator counts, GPU offloading remains an option within the existing software framework.

The turbulence emulation approach used here, projecting offline phase screens onto the DM and FSM actuators, provides a controlled and repeatable environment for validating the correction chain but does not capture all effects encountered on sky. Amplitude scintillation, real telescope optical aberrations, tracking dynamics from the telescope control system, and wind-induced structural vibrations are absent from the lab data. These effects are being addressed during on-sky commissioning.

4.2 On-sky commissioning

The MOCA BOC is currently being integrated on the 1-m class SALTO telescope at the Redu site in Belgium (operated by Redu Space Services/SES). On-sky commissioning will evaluate MADOCs performance under real atmospheric and operational conditions. Target metrics include closed-loop residual WFE measured from WFS telemetry, SMF coupling efficiency, tip-tilt and high-order rejection bandwidth, and end-to-end communication link performance using the fiber-coupled modem interface. The SALTO telescope, which previously demonstrated diffraction-limited natural guide star AO (NGS-AO) correction at $1.55 \mu\text{m}$ with a 97-actuator DM and a 1 kHz loop rate [1], provides a well-characterized platform for validating the upgraded system.

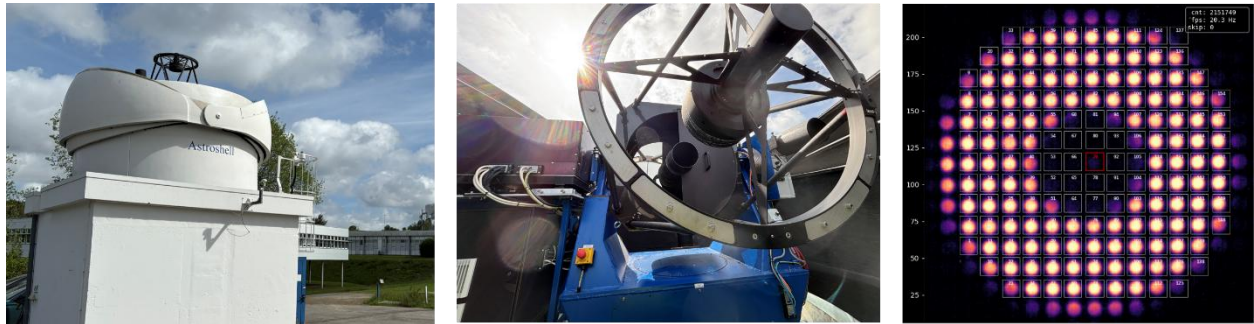


Figure 4 : Integration of MADOCs on the SALTO telescope at the ESA Redu Station. Left: the open telescope dome at the ESA Redu Station. Center: the SALTO telescope inside the dome, with the BOC optical bench mounted at the left Nasmyth port of the mount. Right: the Shack-Hartmann WFS subapertures, each spanning 12×12 pixels, illuminated by a flat sky background during pupil alignment.

5. CONCLUSION

Adapting an astronomical AO control system to the temporal requirements of free-space optical communication required more than incremental tuning: the actuator count was doubled, both loops were pushed to multi-kHz rates, and the computational architecture was redesigned to sustain sub-100 μs median computational latency on a CPU-only platform. The dual-loop architecture, separating a 4 kHz tip-tilt correction stage from a 2.5 kHz high-order

wavefront control loop, achieves this without recourse to FPGA or GPU hardware. Laboratory characterization under six representative atmospheric scenarios confirms that the system meets the MOCA performance requirements: residual WFE of 170 nm RMS under nominal conditions and below 200 nm across the full operational envelope, with estimated SMF coupling efficiencies exceeding the specified thresholds even under degraded conditions.

The modular software architecture, built on the MILK/CACAO shared-memory framework with Python real-time processes accelerated by Numba and Cython, retains the rapid-prototyping flexibility of the SALTO platform while delivering the multi-kHz throughput demanded by FSOC. On-sky commissioning on the SALTO telescope is underway and will provide the definitive validation of system performance under real atmospheric and tracking conditions.

ACKNOWLEDGMENTS

This work is supported by the European Space Agency under the ARTES 4.0 Technologies and Products program (MOCA project). The authors acknowledge the heritage contributions of the SALTO project, supported by the Walloon Region of Belgium through the Skywin program.

REFERENCES

- [1] G. Orban de Xivry, J. Paul, O. Absil, et al., “Status of the SALTO demonstrator: project overview and first on-sky operations,” Proc. SPIE 12185, 1218534 (2022).
- [2] J. Paul, G. Orban de Xivry, O. Absil et al., “Enhancing the capability of future medium-size telescopes: first light of the SALTO demonstrator,” Proc. of the 3rd BINA Workshop, pp 44-55 (2024).
- [3] O. Guyon, A. Sevin, D. Gratadour, et al., “The compute and control for adaptive optics (CACAO) real-time control software package,” Proc. SPIE 10703, 107031E (2018).
- [4] MILK (Modular Image processing Library Kit), <https://github.com/milk-org/ImageStreamIO>.
- [5] M. J. Townson, O. J. D. Farley, G. Orban de Xivry, et al. “AOtools: a Python package for adaptive optics modelling and analysis,” Opt. Express 27(22), 31316 (2019).