# International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

*Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,*

# *ALASCA: the ESA Laser Guide Star Adaptive Optics Optical Feeder Link demonstrator Facility*

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 1277756 · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690989

# ALASCA: the ESA Laser Guide Star Adaptive Optics Optical Feeder Link demonstrator Facility

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## ABSTRACT

We report on the novel ALASCA (Advanced LGS AO for Satellite Communication Assessment) facility being built for ESA by a consortium of industry and national research institutes under the ScyLight program.

The aim of ALASCA is to create a facility for Optical Feeder Links (OFL) field tests, as well as to demonstrate at the ESA Optical Ground Station in Tenerife, starting in 2023, 24/7 reliable operation of optimal Optical Feeder Links based on Laser Guide Star Adaptive Optics (LGS-AO) to solve the point-ahead problem on ground-space laser communications.

Space optical communication represents a technological challenge due to its specific requirements and merit parameters; the consortium's extensive experience in LGS-AO in the astronomical field allows an expert technology transfer to earth-space communication. This will enhance the review of the ALASCA's main requirements, their implementation by a proper tailoring of the modular solutions that will be adopted by the design, facing the new challenges at system level posed by the OFL applications compared to astronomical solutions. The ALASCA project will, last but not least, provide a technology assessment and a development roadmap towards the industrial exploitation of a 24/7 operational Optical Ground Station (OGS).

We will provide an overview of the ALASCA project, its goals, phases and planned timeline up to the field experiments; the presentation will then focus on the project status, including also the simulations results of LGS-AO assisted OFL.

**Keywords:** Optical Communication, Laser Guide Star, Adaptive Optics, Optical Feeder link, Optical Ground Station

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# 1 INTRODUCTION

In nowadays data-driven society, Free Space Optical Communication, FSOC, is gaining momentum worldwide, considering the radio-technology limited bandwidth bottleneck. The market for a widespread exploitation of FSOC requires 24/7 operability of reliable optical channels. The ALASCA project (*Advanced LGS AO for Satellite Communication Assessment*) aims to prove the effectiveness of 24/7 optical feeder links with Laser Guide Star Adaptive Optics to solve the Point Ahead problem, towards ground to space optical communication.

Establishing reliable optical channels between an Optical Ground Station and a satellite offers challenges mainly due to turbulence in the Earth's atmosphere affecting the transmission through the atmosphere itself, especially during daytime conditions; and to the motion of the satellite, inducing an angular split, the Point Ahead Angle (PAA), between the beams transmitted (uplink) and received from the satellite (downlink), thus limiting the reliable compensation of the uplink signal based on the downlink signal.

The use of Laser Guide Star Adaptive Optics technologies, so far developed in the astronomical and defence communities, is potentially an optimal solution for uplink wave-front measurements and pre-compensation of the feeder-uplink beam. As the typical PAA becomes critical in harsh turbulence conditions, an LGS-AO system would represent an enabling technology for the 24/7 operation of the free-space optical communication ground station, in order to reliably cope with the variability of the seeing conditions. The existing technology, developed so far for astronomical observatories, has to be adopted and adapted to the OFL space communication application.

Figure 1. ESO CaNaPy laser Commissioning at the AVSO observatory in Germany, with frequency chirping from Toptica Projects

This paper describes the test facility infrastructure, its modular approach, its status, with a particular focus on the methods followed to solve the main issues posed by free space optical communications.

# 2 ALASCA PROJECT OVERVIEW

## 2.1 Project outlines

The ALASCA project is targeted towards the development of a reliable optical communication uplink from an optical ground station (OGS) to communication satellites. The project aims towards the creation of a full-fledged, TRL6 operational Optical Feeder Link (OFL) test facility at ESA OGS in Tenerife targeting 24/7 operability, based on the Laser Guide Star Adaptive Optics (LGS-AO), to solve the point-ahead problem on ground for space laser communications.

Figure 2. ALASCA project logo. LGS laser is depicted in yellow, IR laser in red

The system uses CaNaPy system as a backbone [1]. CaNaPy is an LGS AO facility designed for night-time operation on astronomical targets, with a 50 W 589 nm laser. CaNaPy is developed by ESO with the support of INAF, Durham University, MPBC for the Raman amplifier and TOPTICA Projects for the laser chirping.

ALASCA will upgrade the hardware and software of the CaNaPy facility to be suitable for ground-satellite optical communication development, upgrading the control electronics, control software and adding new subsystems for infrared optical feeder links, properly extending SatComm operation to harsh turbulence conditions, including daytime operation, with fast, predictive adaptive optics loop mode.

The primary objective of ALASCA is, thus, to demonstrate how to remove atmospheric effects that prevent reaching the highest communication rates. The compensation of the atmospheric disturbance is furthermore affected by the Point Ahead Angle problem caused by the satellite motion, that is field anisoplanatism, and by the needed increase in AO loop speed due to the fast tracking for e.g. LEO satellites. LGS-AO application to OFL for correcting the uplink wavefront distortion induced by the turbulence in the atmosphere may become one fundamental technology for free space optical communication, as it strengthens and stabilizes the uplink communication signals received at the satellites, allowing an effective uplink pre-compensation, mitigating the effect of the point-ahead-angle; this will represent a milestone in guaranteeing a reliable optical channel ensuring 24/7 operations.

Highlights:

- The project will create a TRL6 operational OFL test facility at OGS Dome Coudé focus in Tenerife, initially to be used with Geostationary (GEO) Alphasat; thanks to its modular approach, the ALASCA facility forms the basis for future experiments related to LGS AO 24/7 with Low Earth orbit (LEO) satellites;

- the test facility targets 24/7 operation, night- and day-time configurations; the latter is particularly challenging due to the stronger atmospheric turbulence and the background light compensation in severe turbulence conditions;

- the possibility of obtaining the tip-tilt correction via LGS-AO is proactively pursued via R&D in the project institutes and will benefit from the ALASCA facility. According to our End2End numerical simulations, see section 4.2 for details, the detection of the uplink tip-tilt from the LGS will significantly improve the fading rate; in addition, this possibility would represent a key milestone for optical communications [1]. Hence the R&D for the detection of atmospheric tip-tilt and focus from the LGS itself constitutes an important synergy between space and astrophysics developments of LGS-AO.

### 2.2 ALASCA team

The project team, see Figure 3 for details, is led by Microgate and involves the participants listed herein:

- Microgate (IT)
- A.D.S. International (IT)
- LumiSpace (UK) – Durham University (UK)
- Toptica Projects (DE)
- INAF (IT) – in collaboration with ESO for all aspects related to the CaNaPy project

The team combines some of the most experienced teams from LGS-AO in Europe, together with industrial teams specializing in adaptive optics and lasers. The group has been proficiently delivering projects together since 2000.

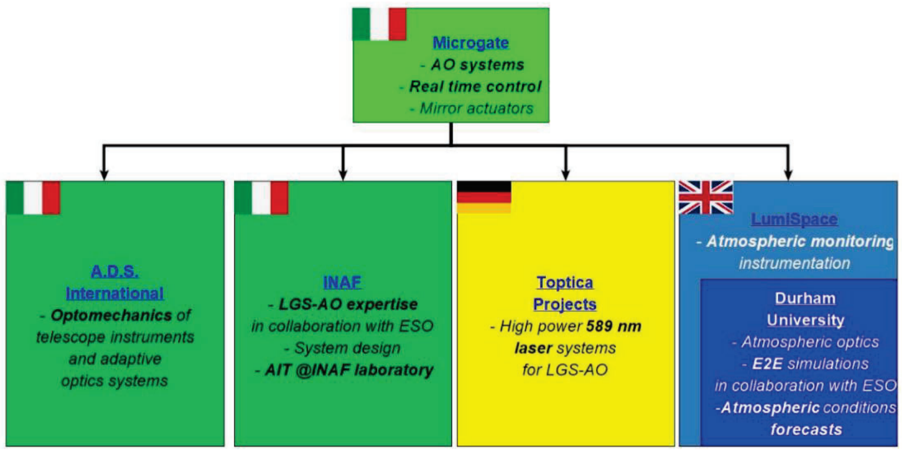


Figure 3. Industrial group structure and responsibilities

### 2.3 Project plan

The ALASCA project will deliver the first set of reliable Optical feeder Link (OFL) tests within 2 years from project kick off; in the third year it will deliver the complete 24/7 operation test.

In particular, the project activities foresee a first part mainly focused on the design activities of the system, its preliminary test and integration. Once this phase is completed, the system is shipped to Tenerife at the ESA OGS, for the integration, commissioning and test activities in situ.

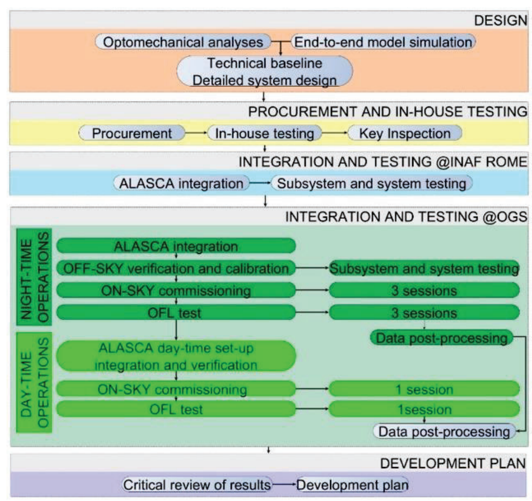


Figure 4. ALASCA project plan

## 3 ALASCA SYSTEM OVERVIEW

### 3.1 System outline

The ALASCA system is designed to allow OFL test with LGS-AO system and uplink pre-compensation, in night- and day-time configurations, by an exchange of the interfaces, one for each configuration, with the OGS.

The architectural concept block diagram is shown in Figure 5.

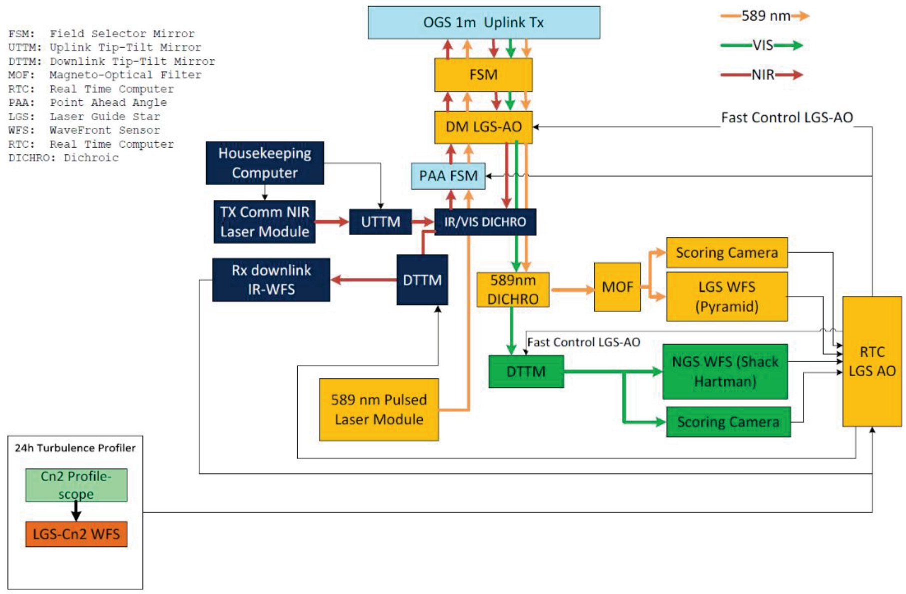


Figure 5. ALASCA system block diagram. Besides important features introduced in the control electronics, the dark blue modules are the ALASCA addition to the CaNaPy LGS-AO system built by a consortium of institutes with ESO. The modular approach grants flexibility in the type of measurements and tests, which will benefit both, SatComm and Astrophysics LGS-AO system developments towards optimized configurations. Paths towards optimization for industrial exploitation are one of the outcomes of the activities

The system's main features are listed below:

- Two lasers, a single frequency 75W CW 589nm for LGS and a 100W NIR OFL 1055nm communication fiber laser from IPG Photonics, both propagated in monostatic configuration for uplink pre-compensation; the LGS unit will be used in long-pulsed mode to avoid blinding the wavefront sensor cameras.
- Reliable 75W, 589nm laser, built at ESO in collaboration with MPBC – which has provided the unique 1178nm, 100W narrow-band RFA, based on the ESO patented Raman Fiber Amplifier technologies [6]. The ALASCA facility, thanks to Toptica Projects, will further exploit and improve the ESO CaNaPy 75W CW 589nm laser, with emission spectral and temporal formats finely tuned to maximize the LGS return flux. ALASCA introduces laser frequency chirping and fundamental improvements in the efficiency of the amplitude modulation needed for the uplink correction. The LGS return flux is enhanced by optical pumping, the emission of repumper lines and by frequency chirping based on Toptica proprietary technology, thus suppressing LGS saturation effects at high mesospheric irradiances due to spectral hole burning effects – which is a must at high laser irradiances at the mesosphere.
- LGS and IR pyramid WFS, built on INAF decadal experience. The usage of the Py-WFS is a result of a multi-parametric trade-off vs Shack-Hartmann WFS. A SH-WFS is foreseen for Natural Guide Star operation, used for the initial optimization studies of the uplink pre-compensation, for the LGS-AO loop commissioning with the Py-WFS to detect NGS tilt and focus, and as reference benchmark for the loop performance.
- Use of LGS-AO for adaptive optics correction at Point-ahead angles, with tip-tilt and defocus optical modes sensed using as reference the satellite itself – via an Infrared Pyramid WFS. R&D towards sensing the same modes via the LGS itself is part of synergic ongoing activities with ESO, to be continued with ALASCA.
- Optimal LGS-AO operation by uplink pre-compensation of the 589nm laser beam, producing small LGS spot sizes – optimally coupled with a Pyramid wavefront sensor. This requires monostatic propagation geometry for both, the LGS-AO system and the OFL system.

- Possibility to run the ALASCA system without LGS-AO, i.e. in 'classical mode' with Adaptive Optics based solely on the Satellite IR reference source, to be used also as bench-mark comparison.
- 24/7 operation. Two operation modes for nighttime and daytime: monostatic propagation with telescope aperture diameters of 100 cm with central obstruction (ESA OGS telescope in Tenerife) and 30cm without central obstruction, respectively. LGS-AO closed loop in daytime using ultra-narrow band magneto-optical filters to suppress the sky background [8]
- Flexibility of using double Axicons module to create annular Bessel laser beams and avoid vignetting the Gaussian laser beams from the telescope central obstruction
- Automatic, Laser pointing smart cameras from Astrel Instruments, to control uplink laser beams pointing, monitor LGS brightness, presence of cirrus clouds, sodium abundance in real time.
- Fast and highly efficient AO loops with minimum latency, to cope with hard seeing conditions. Adaptive modal control with provision for predictive control algorithms, including machine learning. The AO loop rate at any time will depend on the atmospheric conditions and the LGS return flux. In order for the system to be operated at frame rates of up to 3 kHz, especially for the day-time operation of the system, a highly deterministic and extremely low latency image processing, as well as the minimization of the pixel processing latency incurred by the RTC and the very low jitter of the control loop, are fundamental. It is also mandatory to guarantee a very accurate synchronization of the different components (cameras, mirrors, including also the Py WFS beam steering ones, laser and optical beam shutters), in the order of µs, to avoid detrimental effects on the loop performance. In the ALASCA design, this will be assured by the Microgate interface module that centralizes all sensors acquisition, actuators command and synching on a FPGA-based platform.
- Instrument Control Software (ICS) regulates and commands at high level with graphical user interfaces the facility, with the AO systems, the lasers, the OGS telescope, the laser pointing camera and the external turbulence monitoring unit. ICS monitors also environmental parameters in the ALASCA instrument, and stores non-real-time observing data.
- Soft and hard Real Time Computer software optimizes performance via refined methods of adaptive calibrations and control, coming from two decades of LGS-AO experience in astronomical applications. It displays and stores user-selected data during operation.
- True modular design by subsystems: ALASCA is a TRL6 class facility allowing multiple operation modes, multiple configurations and changes in experimental setups.
- Gravity invariant, stable optomechanical system optimized for maximum throughput at the ESA OGS Dome Coudé focus.
- Dust-free, overpressured when not in operation, thermally controlled environment regulated at 13 °C ± 3°C on the ALASCA optical table, with provisions for clean-room maintenance (see Figure 6).
- Atmospheric monitoring module (24h turbulence profiler) produced by Lumi Space, to continuously evaluate the atmospheric turbulence, giving feedback to the LGS-AO control. In-depth knowledge of the vertical structure of the atmospheric turbulence during operation is of critical importance in FSOC system. As pointed out by J. Osborn in [2], if the turbulence level can not only be measured, but also forecasted in advance, this will enhance the throughput of the FSOC service allowing a better planning and schedule of the communication scheme, especially for 24/7 operation.

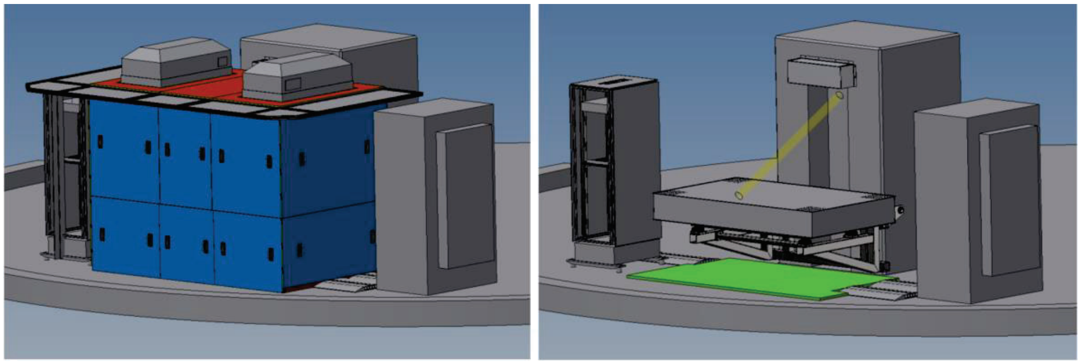

Figure 6. ALASCA optical facility mounted at the South Pier Dome Coudé port of the ESA Optical Ground Station. The system optomechanics is temperature stabilized, in a dust-free environment. The optical table supports are attached directly to the telescope Pier, avoiding differential vibrations. The cover structure, laminar flow modules, and optimal maintenance clean-room curtains are supported from the telescope floor and not in contact with the optical table. A laser cabinet and a control cabinet are mounted on the left and right sides of the optical table, respectively

### 3.2 The 589 nm laser

The 589 nm laser utilizes the same narrow band, high power Raman Fiber Amplifier (RFA) technology as developed and patented by ESO in 2009 [6], engineered and optimized by MPBC to produce, in consortium with Toptica as main ESO contractor, the 22 W CW "Guide Star Laser", installed since 2015 at the VLT Paranal Observatory and nowadays deployed at a good number of large observatories worldwide.

Thanks to the MPBC novel development of a 100W CW RFA, the ESO CaNaPy laser could demonstrate 75 W CW of laser output power at 589nm, exceeding the original specification of 50W CW while keeping the same optical beam and functional properties as the commercial 22 W CW 589nm Toptica-MPBC lasers [5]. We must stress that to reach daytime operation (i.e. with harsh seeing conditions) in ALASCA the 75W power level is mandatory.

Two specific features are being further developed by Toptica Projects and added to the CaNaPy 75W laser, to suit the needs of ALASCA:

- Chirping: to avoid saturation effects due to the high irradiance at the mesospheric sodium layer, Toptica Projects has developed and integrated remarkable frequency chirping capabilities, on a laser architecture that remains similar to the commercial 22 W version. The goal of the chirping system is to apply an optimized sawtooth modulation with fundamental frequencies in the 1 – 10 kHz range and shift amplitudes up to a few hundred MHz to the guide star laser frequency, to overcome the spectral hole burning effect and increase the number of atoms the laser is interacting with – hence the LGS brightness. This is done by performing repeated excitation/emission cycles with slower atoms while changing (chirping) the laser frequency synchronously to their recoil Doppler effect. This leads to a pile-up of atoms in a single velocity class during the chirp, analogous to the effect of a snow plough. Experiments to anchor the numerical models with reality are being done jointly by ESO and Toptica at the Wendelstein Laser Guide Star facility in La Palma.
- Amplitude modulation: ALASCA system uses a monostatic configuration for the lasers. The usage of the same telescope to propagate the guide star laser and collect the return signals allows for Adaptive Optics pre-compensation of the guide star laser beam itself. This is a pre-requisite for the stronger turbulence conditions expected during the daytime. The drawback of this setup is the scattering of laser light within the telescope, and as this straylight has the same frequency as the fluorescence light, it cannot be filtered using any spectral filtering technique. The facility implements a pulsing unit into the laser system based on electro-optical modulators and detects the return flux only when the laser is not emitting, alternating between LGS laser launch and detection with a laser pulsing frequency and a specific duty cycle tailored according to the projects' needs. Due to the extremely high sensitivity of the LGS wavefront sensor, laser photons entering the optics mainstream Tx-Rx common path need to be completely blocked during WFS detection periods. A combination of three methodologies for attenuating the laser amplitude is developed and implemented by Toptica Projects: a free-space electro-optic amplitude modulator, a rotating-disk optical chopper,

and a technique based on fast frequency tuning of the laser resulting in the laser frequency being out of resonance with the frequency-doubling resonator (a.k.a. second-harmonic generation cavity).

### 3.3 Atmospheric Monitoring Unit

The ALASCA facility aims at demonstrating a reliable 24/7 Free-Space Optical communication link between satellite and OGS; to that aim, atmospheric turbulence monitoring and forecasting plays a key role in optimizing the LGS-AO control and tests.

Lumi Space and Durham University are developing an atmospheric monitoring system to characterize the Earth's atmospheric turbulence during day and night. The instrument is called a Shack-Hartmann Image Motion Monitor (SHIMM). Figure 7 and Figure 8 show a photograph of the set-up and instrument, respectively. The instrument contains a Shack-Hartmann wavefront sensor to measure local wavefront tilt gradients in a grid of sub-apertures over a small (approximately 30 cm) telescope. The intensity variance (scintillation) in each sub-aperture is also measured. These two sources of data allow concurrent measurement of the turbulence parameters $r_0$ (Fried parameter, describing overall turbulence strength) and $\theta_0$ (isoplanatic angle, describing turbulence angular correlation). The instrument will observe a single bright star close to zenith to minimise the potential effects of strong turbulence, a regime in which the instrument can no longer measure turbulence parameters. For more details, refer to [3].

Figure 7. Image of prototype SHIMM being installed at the Isaac Newton Telescope, La Palma

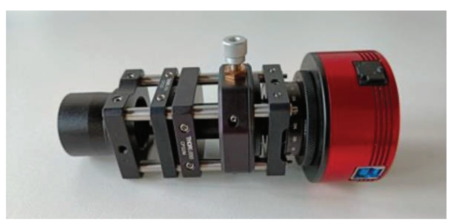

Figure 8. Photo of prototype SHIMM instrument after assembly in the laboratory

### 3.4 OFL IR Module

Two optomechanical modules, one for the Tx of the OFL uplink laser and one for the Rx downlink GEO satellite signal are being developed by the consortium. A downlink fast tip-tilt mirror and an uplink fast beam steering mirror to compensate atmospheric induced jitter is included as part of the modules. The receiver section has an IR Pyramid WFS to be used either standalone, for AO without LGS, or as tip-tilt sensor for LGS-AO, using in both cases the satellite downlink laser signal as reference.

The baseline operation wavelength is 1064nm, with provisions for 1550 nm.

### 3.5 ALASCA Control System Overview

The Instrument Control Software (ICS), the Real Time Control (RTC) and Microgate Control Electronics are the three main components of the ALASCA control system, as per Figure 9 . The control software is split in two sections, the fast control (Real Time Control Software) and the slower instrumentation control (Instrument Control Software).

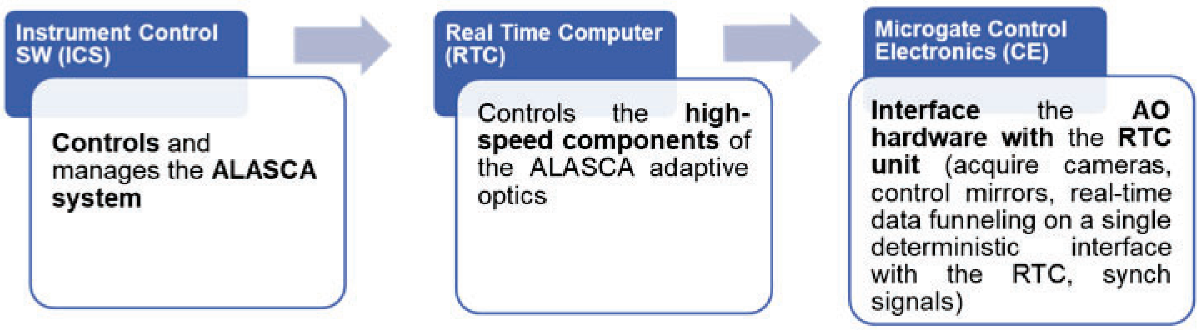


Figure 9. ALASCA control system overview. The ICS will allow the use of Observing blocks with automated or pseudo automated observations and data collection at OGS.

- The ICS controls and manages the system, interacting with the subsystems, the safety and cooling systems and the external workstations for the control. See Figure 10 for details. The ICS GUI will allow the control and monitoring of all subsystems, and will coordinate the acquisition and observation sequences. It is foreseen to implement the Observing Block mode, which allow to user to specify automated acquisition and observing sequences, with data collection and pre-analysis display.

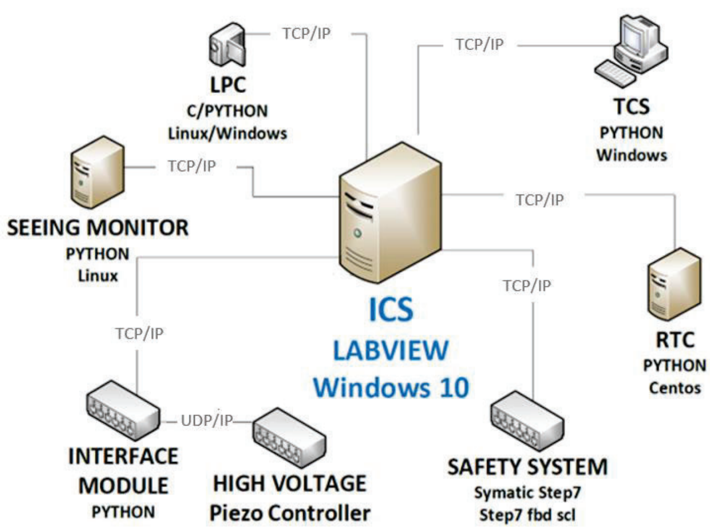


Figure 10. A schematic of the ICS with server software communication among different units.

- The Real Time control (RTC) software and hardware controls the high-speed components of the adaptive optics, being responsible for calculating an estimate of the incident wavefront, and computing corrections for DM and TTMs. It also encompasses the routines responsible for keeping the system stable and optimised for the atmospheric conditions. The overall RTC system will provide functionality to retrieve real-time telemetry from the HRTC and displays for control and diagnostics of the system. This is highly enhanced by the presence of the proprietary Microgate control Electronics that will be responsible for the WFS data acquisition, transfer and pre-processing, as detailed in the following section. See Figure 11 for details.

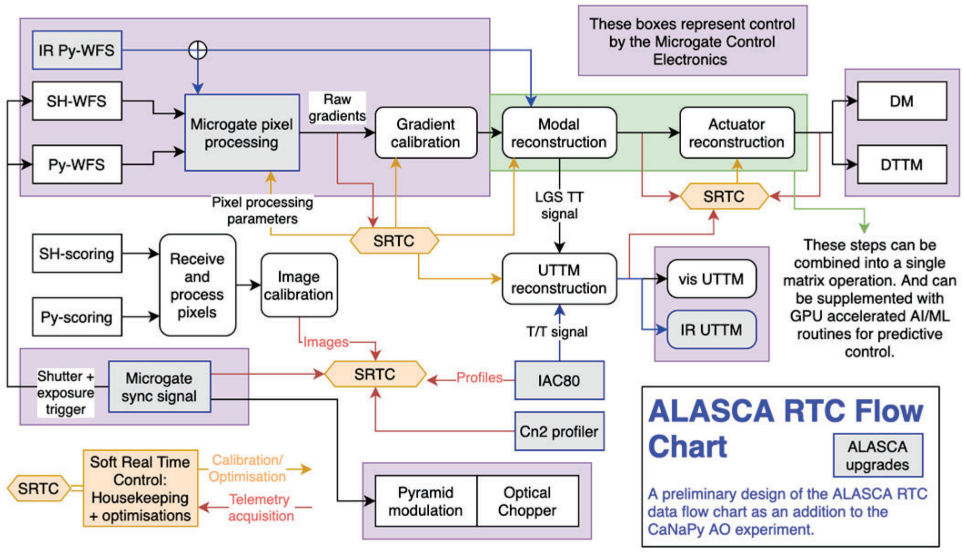


Figure 11. The main high-level view of the data flow in the system RTC. The core loop software is derived from the Durham Adaptive-optics Real-time Controller (DARC), modified and adapted.

- Microgate control electronics will interface the AO hardware (such as the mirrors and the cameras) to the RTC unit through a single deterministic link based on a standard UDP network interface and direct memory transfer to the processing core memory; this will relieve the RTC from the real/time interfaces implementation complexity, thus enabling high/speed operation, up to 3 kHz or more control loop frequency with very low jitter of the execution time of the whole real/time pipeline. Besides that, the Microgate electronics will also provide very flexible and accurate synchronization to fast beam modulation mirrors in the Pyramid WFS. See Figure 12 for details.

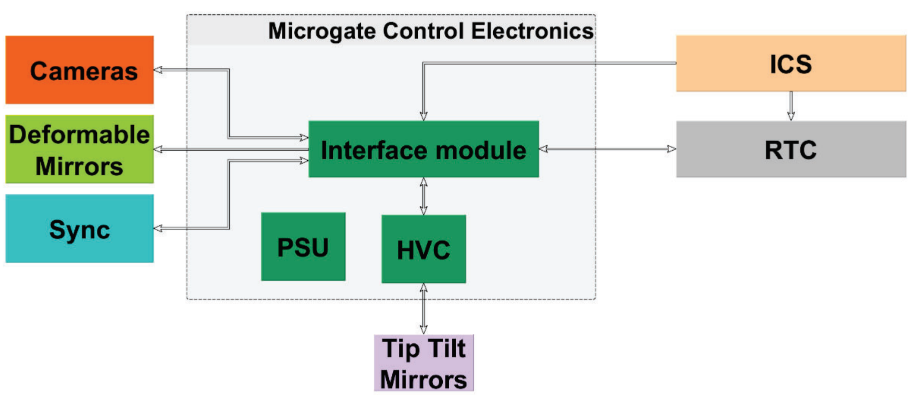


Figure 12. ALASCA control system layout. HVC, High Voltage Control, is a dedicated digital fast piezo mirror control already produced by Microgate, controlling the tip-tilt mirrors. The Interface module (IM) interconnect the hardware on the bench with the RTC, merging sensor data, synchronizing of the sensors' frames, distributing the mirror commands and configuring sensors and mirrors parameters

# 4 PROJECT STATUS AND NEXT STEPS

## 4.1 Projects tradeoffs and specific technical solutions

### 4.1.1 Wavefront Sensor Choice

We have evaluated in simulation the LGS-AO closed loop performance considering a monostatic configuration. As shown in Figure 13 below, the monostatic design (same pupil for Tx-Rx) has several advantages w.r.t. the bistatic one (offset launch and receiver pupils), because it eliminates the cone effect and the uplink propagates along the same path of the downlink; conversely, the monostatic scheme poses some challenges due to the synchronization and scattering problems.

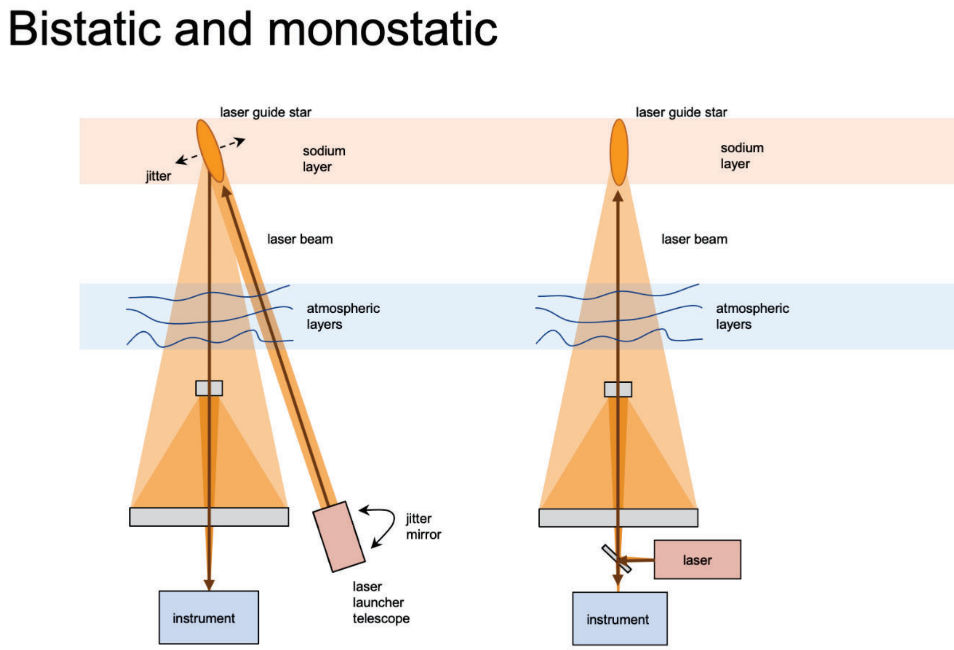


Figure 13. Bistatic (left) and Monostatic (right) propagation schemes. The uplink laser beam can be corrected (pre-compensated) in monostatic mode, since the downlink and uplink atmospheric volumes are the same, for the wavefront sampled by the Py-WFS. Note that the WFS and the uplink corrections do not suffer from cone effects (focal anisoplanatism)

The Pyramid WFS, like the curvature and shearing WFS, benefits from the full aperture advantage, i.e. it increases its sensitivity and performance when the reference source becomes smaller. In comparison with an equivalent Shack-Hartmann WFS (SH-WFS) system, the Py-WFS performance is superior whenever the reference source size is smaller than the diffraction limit of the Shack-Hartmann subapertures. Hence, considering a 1 m telescope diameter like the ESA OGS, a 10x10 subapertures Shack-Hartmann, operating at 589 nm, the Py-WFS starts showing better performances than the SH-WFS for LGS FWHM < 1.2 arcsec. In monostatic propagation with uplink correction, the simulations predict LGS FWHM of the order of 0.13 arcsec, hence there is considerable optical gain when using a Py-WFS with respect to the classical SH-WFS. The small LGS FWHM has implication in the Py-WFS modulation scheme during operation.

Non linearities in the Py-WFS may be taken care by the Soft-RTC software, adjusting the system modal gains based on the actual averaged LGS FWHM when necessary. Also, automatic modal control contributes to the optimization of loop performances.

#### 4.1.2 Double Axicon

For the use of the 1.016 m full OGS telescope aperture, to avoid the uplink laser gaussian beams losses due to the vignetting of the secondary mirror (0.35 obstruction ratio), a double Axicon is introduced in the optical beam. It transforms the laser Gaussian beam intensity distribution into a Laguerre-Gauss annular distribution on the primary mirror (see Figure 14), without changing the beam collimation. A comparison between the LGS PSF seen at 90 km, for the cases of centrally obscured Gaussian Beam, top-hat ring intensity distribution at the OGS primary mirror, and Axicon Laguerre-Gauss ring intensity distribution is shown in Figure 14 on the right. The curves are normalized to the same total intensity.

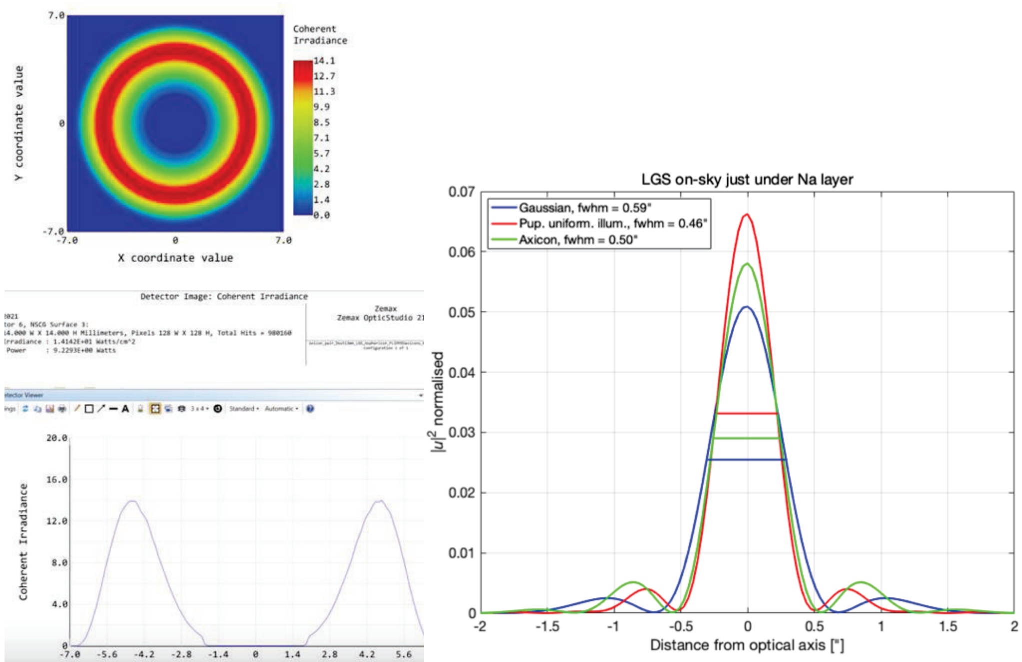


Figure 14. Left: laser beam intensity distribution at the OGS 1.016 m diameter primary mirror after conversion of the Gaussian beam into a Laguerre-Gauss annular beam, using double-axicon optics. Right: PSF of the LGS at 90 km, without turbulence, for the three cases described in the text

### 4.2 Simulations

Numerical simulations developed in the frame of the project aim at the quantification of the effect of the LGS-AO on the OFL performance. In particular, they are based on PASSATA, a proven end-to-end IDL-based code to simulate the monostatic, uplink pre-compensated LGS-AO loop with Pyramid WFS, as used in ALASCA, including physical Optics angular spectrum propagators for the OFL, developed by INAF [7]. PASSATA copes with the vertical distribution of the mesospheric sodium atoms emission, with the uplink pre-compensation and the time delays of the laser up-down links.

Durham University has developed a E2E Monte-Carlo modelling tool coded in Python, with angular spectrum physical optics propagation functionality, simulating the AO-loop with a SH-WFS. As the physical Optics propagation has been developed in PASSATA in a second time, at the beginning of the project it was decided to carry out also a hybrid simulation: SOAPY physical propagation module will utilize, as inputs at each step, the atmospheric phase screens and the actuate DM at the telescope pupil conjugate, as obtained by PASSATA. This model is now used as a cross-check of the results obtained implementing the physical propagation in PASSATA, showing a good match.

For parametric, quick analysis the ALASCA consortium uses the Durham University FAST code, which is using analytical expressions for evaluating the error terms of the AO loop, rather than numerical End2End simulations.

See Figure 15 for details.

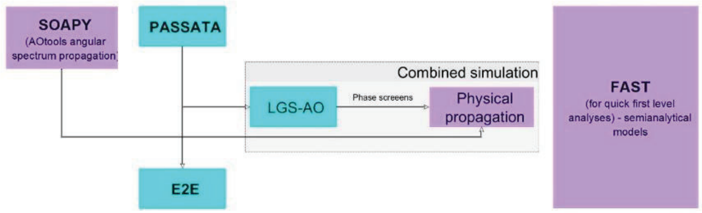


Figure 15. ALASCA project simulation concept

### 4.2.1 Adopted Turbulent Atmosphere Model

For the numerical simulations on the LGS-AO loop, we have used the mean night atmosphere from measurement campaigns done at Observatorio del Teide (OT) in Tenerife, the location of the ESA OGS telescope.

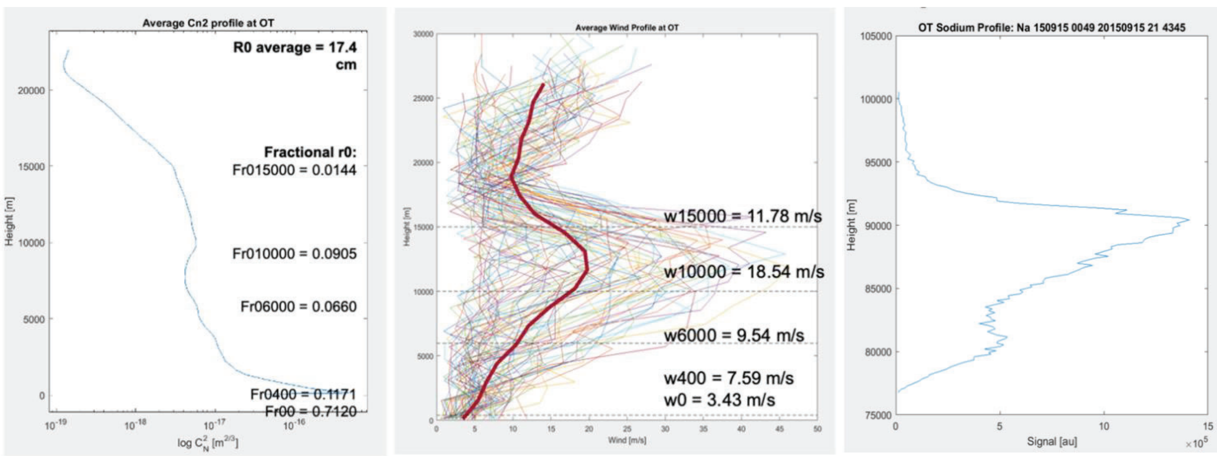


Figure 16. Mean values at OT for the vertical distributions of: Cn2 profile (left), wind speed (center) and sodium profile (right)

### 4.2.2 Simulation of LGS-AO loop Control

We have used the measured influence functions of the ALPAO 97-15 Deformable Mirror (DM) to establish the modal command matrix based on Karhunen-Loève modes. Modal gain optimization control and a simple integrator term have been used in the LGS-AO simulations. Noise terms such as photon noise, dark background, readout noise of the sensors and aliasing, as well as two-steps latency, have been taken into account. The Py-WFS has been considered adopting the following parameters; notice that no beam modulation is needed, at least for the seeing conditions used in the simulation.

Table 1. Main Py-WFS parameters

| Parameter | Value |
|---|---|
| Pupil size | 40 pixels |
| Distance between pupil centers | 72 pixels |
| Field Of View | 5 arcsec |
| Modulation radius | $\lambda/D$ |
| Detector | OCAM2S |

#### 4.2.3 Simulation preliminary results: satellite uplink signal fluctuations

The OFL 1075 nm laser is propagated concurrently with the LGS 589 nm laser, and pre-compensated in the uplink propagation by the DM of the LGS-AO loop. The LGS has a point ahead angle of 4.0 arcsec. The tip-tilt signal is derived from the downlink Alphasat signal, with the OGS telescope pointing at ALT 36 deg. The numerical simulations include the effects of air mass and anisoplanatism.

The comparative simulations have been done using the hybrid model with Passata and Durham University SOAPY (indicated as *Passata(phys)* in the legend), and the Durham FAST semi-analytical code. In addition, the geometrical propagation obtained with Passata without physical propagation has been reported for reference. The end-to-end simulation with Passata embedding the physical propagation is ongoing, showing good agreement.

The merit parameter is the distribution of received instantaneous power at the GEO satellite Alphasat, with its 15 cm diameter receiver: the signal fluctuation shall be kept within 10 dB while maximizing the power received.

We can notice the importance of considering the physical optics propagation in particular with the 0.30 m pupil, since the scintillation log-amplitude variations in the final signal are more apparent due to the smaller launch aperture.

We present Probability density results for the ALASCA nighttime (1.016 m OGS pupil) and daytime (30 cm pupil as subaperture of OGS). More results and cases obtained with three different simulation end-to-end models will be published

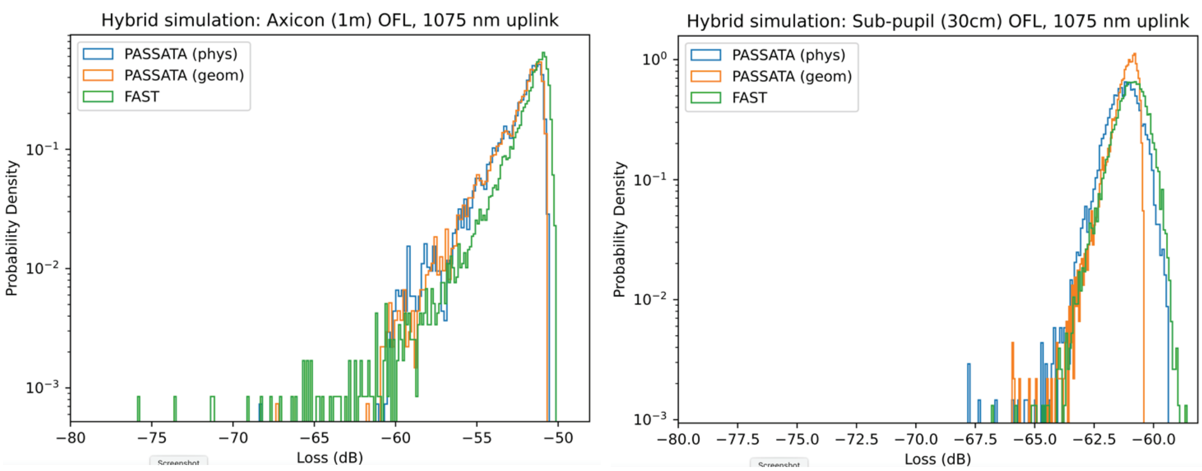


Figure 17. Histogram plots showing the distribution of power received by the ALPHASAT GEO satellite (as a fraction of transmitted power in dB) at 38000 km from Earth, when closed loop LGS-AO is used for the OFL uplink pre-compensation. The two plots correspond to nightime configuration (left, 1.016m diameter pupil) and daytime (right, 0.30m pupil) launch geometries, monostatic propagation

in a coming paper.

The large aperture propagation gives a higher signal concentration, with diffraction limited performance. The tip-tilt anisokinetism due to the angular distance between the satellite and the point-ahead LGS causes a residual uncorrected tilt which creates higher variability on the smaller OFL spot at the satellite, hence higher spread in the photometric probability density. The results for the 1.016 m pupil case could be dramatically improved if tip-tilt could be inferred from the LGS itself (not shown here). Other methods to slightly blur the OFL spot at the satellite would work as well, and are under investigation. The simulations will be extended to more atmospheric condition cases and anchored to real data once the ALASCA facility is in operation.

#### 4.2.4 LGS-AO loop Results: Monostatic vs Bistatic

The following table summarizes the long exposure performances of the LGS-AO loop, for the cases of 1 kHz and 2 kHz operation, with seeing of 0.7 and 1.0 arcsec, respectively. The Strehl values of the LGS at the mesosphere are indicated in column 3. The Py-WFS (extended) image of the LGS Strehl and FWHM values are indicated in columns 4 and 5. Compared to the bistatic case, the ALASCA monostatic architecture gives an intensity increase of the LGS image at the Py-WFS for the 1 kHz case which is 6-fold, while the shrinking of the LGS FWHM at the Py-WFS is a factor 4.4.

Table 2. Performances of the LGS-AO loop, for the cases of 1 kHz and 2 kHz operation, with seeing of 0.7 and 1.0 arcsec

| Configuration | Loop Rate and Seeing | LGS at Mesosphere Mean LE Strehl [%] | Py-WFS LGS Mean LE Strehl [%] | Py-WFS LGS LE FWHM [mas] |
|---|---|---|---|---|
| Mon | 1 kHz 0.7” | 67.23 | **20.35** | **156** |
| | 2 kHz 1.0” | 63.51 | **15.89** | **175** |
| Bist | 1 kHz 0.7” | 5.77 | **3.03** | **686** |
| | 2 kHz 1.0” | 4.7 | **2.42** | **710** |

### 4.3 Optical bench status

Procurement for the components is in progress; few items are experimenting some delays in the delivery, especially considering the well-known current problems with procurement of electronics components. In any case, no show-stopper so far have been identified.

The optical bench is currently being integrated and tested at INAF laboratory in Rome. Figure 18 shows the current status of the optical bench. The mainstream optical path modules from DM to WFS are assembled, aligned and tested interferometrically. The LGS Pyramid WFS module is assembled and aligned, together with its WFS OCAM2S and Emergent Technologies scoring cameras. The SH-WFS module is being assembled. LGS double Axicon unit is under thermal performance tests.

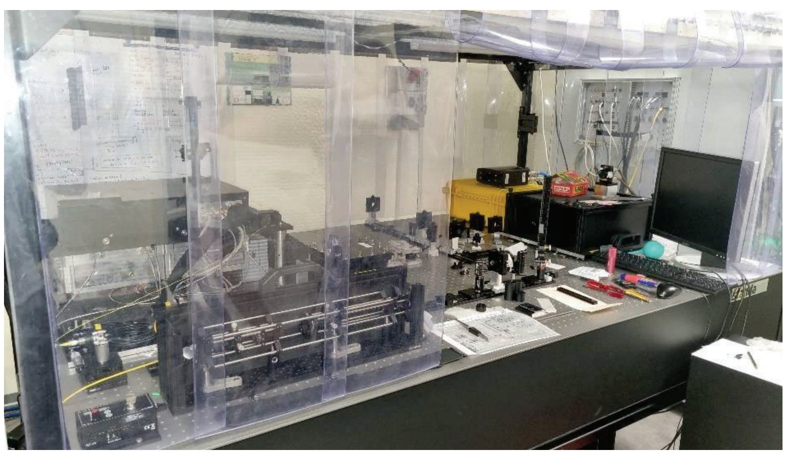

Figure 18. ALASCA optical bench under integration and testing

### 4.4 Next Steps

One important aspect that the project will address is the atmospheric scattering. The analysis of the effect of such event from free space laser propagation, considering both Rayleigh and Mie effects, has been outsourced to a specialized company with which the ALASCA team has a long heritage of collaboration. The activity is currently ongoing.

In addition to that, the procurement of the components not yet ordered will be finalized shorty, especially considering the long lead time electronics components are experiencing due to the geopolitical situations.

Subsystem testing of all the different modules not currently integrated on the optical bench will, then, be finalised before being integrated in the overall system at the INAF laboratory in Rome.

The plan is to complete the system testing in Rome by the first quarter of 2023.

## 5 OUTLOOK

- The ALASCA project produces a TRL6 test facility, at first demonstrating the reliability of an optical channel active 24/7 with a GEO satellite. This activity significantly enhances the knowledge on the compensation of the uplink beam based on the Laser Guide Star concept (LGS), especially in the optical communications fields, as until now the technique has been widely applied mainly to the Adaptive Optics methodology in astronomical telescopes. This offers the possibility to study, analyse and compare the Infrared Wavefront Sensor Adaptive Optics (IR-WFS AO) method based on the IR satellite signal as reference and the Laser Guide Star Adaptive Optics (LGS AO). Several years of operation will allow sky experiments towards the related SatComm technologies improvements.
- The open modular architecture of the test facilities and, thus, its flexibility and adaptability pave the way to further developments and field testing in the same areas, also with LEO satellites, demonstrating full Satellite Communication throughputs, with Laser Guide Star Adaptive Optics (LGS-AO) supported Optical Feeder Link (OFL).
- The project lays the foundation for a widespread exploitation of the OGS facilities with AO-LGS technology; it forms the basis for the identification of activities to bring the experiment to market with useful and useable outputs establishing a development plan and an exploitation strategy, aiming at the development of future turn-key systems.
- As vision for further outlook, the industrial consortium experience and know-how will enable the competitive production of complete OGS systems for satellite communication and space awareness applications, built also on previous hands-on experience in astronomy.

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