GEOStar: Demonstration of laser guide star adaptive optics for free space optical communications

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ABSTRACT

Free Space Optical Communications (FSOC) links with satellites are limited by atmospheric turbulence in up and downlink. Adaptive Optics (AO) systems at the Optical Ground Station (OGS) can mitigate the adverse effects on the uplink by "predistorting" the transmitted laser beam such that its wavefront is corrected by the turbulence. The Point Ahead Angle (PAA) means that the downlink light is not a perfect wavefront reference for the AO system. GEOStar is a project created to demonstrate the feasibility of using a Laser Guide Star (LGS) in the direction of the uplink path to enable better predistortion of the transmitted beam. A novel setup uses a sub-pupil of the 1m diameter ESA-OGS to transmit the communications light to the satellite and a sub-pupil on the opposite side of the telescope aperture is used to launch the LGS. An LGS WFS observes the light from the LGS whilst a similar Near Infra-Red WFS observes downlink light from the satellite such that the measurements can be directly compared. A deformable mirror is used to predistort the uplink beam. The system is currently being integrated ready for shipment to Tenerife and measurements with the optical terminal TDP-1 on AlphaSat are scheduled for Q2 2024.

Keywords: Adaptive Optics, Laser Guide Star, Free Space Optical Communications

1. INTRODUCTION

Free Space Optical Communications (FSOC) promise the possibility of transmitting a virtually unlimited amount of data from Optical Ground Stations (OGS) to future telecommunication satellites, without the need for spectrum licensing as is the case in the radio frequency (RF) domain. However, FSOC faces two main problems – cloud coverage and atmospheric turbulence. Cloud coverage is unavoidable but can be mitigated by OGS redundancy (placing multiple OGSs in meteorologically uncorrelated locations — meaning at least 500 km apart). Adaptive Optics (AO) systems can be used to mitigate the effects of atmospheric turbulence.[1,2] This is conceptually clear for the downlink light where the communications light itself can be observed by a wavefront sensor and used as a wavefront reference, however improving the uplink stability is more complicated. It is possible to "predistort" the uplink beam with the inverse of the expected phase aberrations, such that the atmosphere flattens the wave-front. However, the orbital motion of a spacecraft (S/C) requires a small angular split between the transmitted and the received communication beams, which introduces a flaw into the predistortion concept. This angular split, called the point ahead angle (PAA), is illustrated in Figure 1 and is typically small (approximately 4" for ground to GEO links), but it nevertheless introduces an error into the AO system termed "angular anisoplanatism" .

Depending on the atmospheric conditions, the anisoplanatic errors make using the downlink light from the satellite unsuitable as a reference in the uplink direction. Without effective predistortion, the feeder uplink beam will experience severe intensity fluctuations as well as outages (potentially lasting up to hundreds of milliseconds) when reaching the spacecraft. It therefore becomes impossible to base a reliable telecommunications service on

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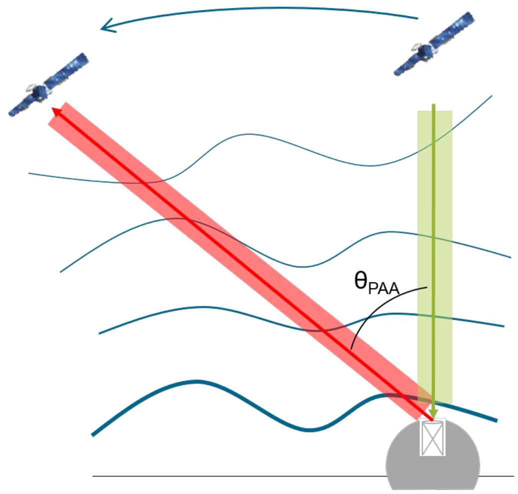

Figure 1. Illustration of the affect of the point ahead angle. The uplink (red) must be pointed ahead of the satellite to account for the satellite's orbital motion by the PAA (θ_{PAA}). It then passes through different turbulence to the downlink (green) beam, hence there is an error when using the downlink measurements for uplink predistortion.

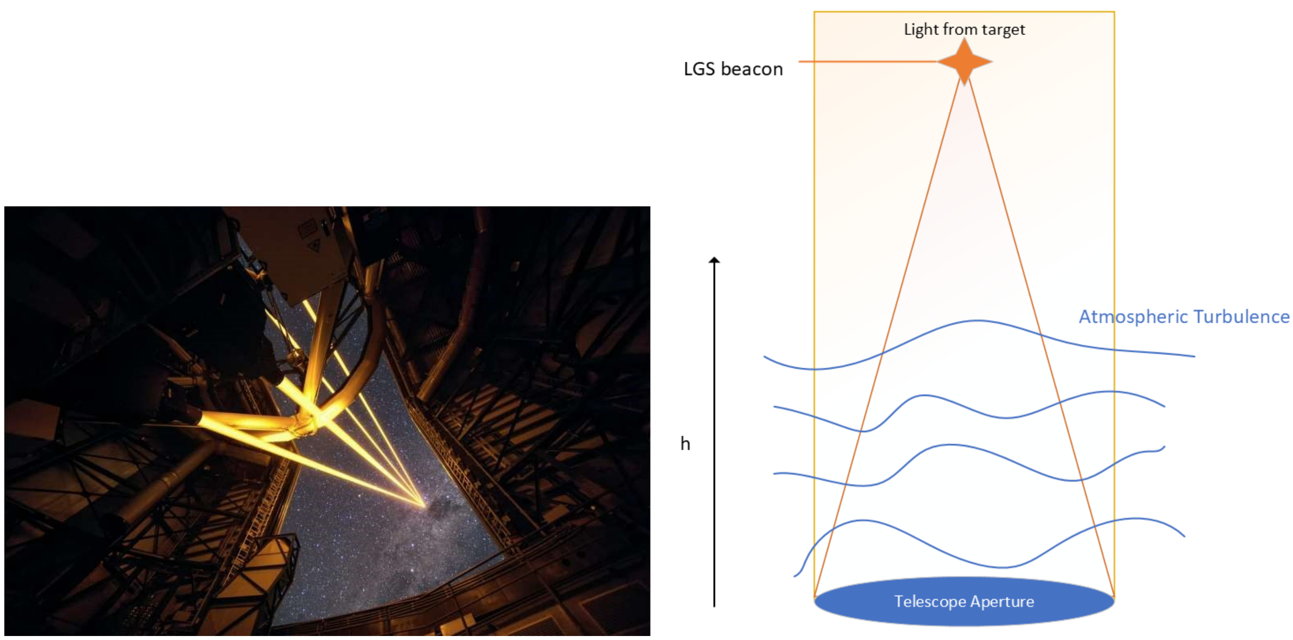

Figure 2. Sodium Laser Guide Star at the European Southern Observatory (left) and a diagram illustrating how the Sodium laser guide star beacon is high (90km) above the turbulence ($<\approx$20km) and therefore samples the majority of the turbulence seen by the target.

the unreliable channel. Laser Guide Stars are a technique with the potential to solve the PAA problem by creating a wavefront reference in the uplink direction.[3,4]

LGS are in operation in most large astronomical observatories to increase the portion of sky over which AO is available,[5,6] for example the LGS at the European Southern Observatory's "Very Large Telescope" (VLT) as shown in Figure 2.[7] This is typically a Sodium LGS, which forms a beacon by illuminating a layer of Sodium atoms at 90km above the Earth. The 589 nm LGS light drives the D_2a transmission in the sodium atoms, which then emit light back down to the telescope.[8] As the LGS also travels up through turbulence before forming a beacon, it moves slightly in the sky. This means that the LGS WFS cannot sense tip/tilt aberrations from an LGS. Similarly, the mesospheric sodium layer of atoms can change altitude, so defocus aberrations can also not be measured from the LGS WFS. To measure tip/tilt and focus, the downlink light from the satellite must be used, however such aberrations are common over a larger patch in the atmospheric turbulence, hence this is typically acceptable.

GEOStar is a project proposed as a response to the ESA ITT "Reliable GEO optical feeder-link demonstration", which has been underway since January 2022. It is a collaboration between the Institute for Communications and Navigation at the German Aerospace Centre (DLR) and Kampf Telescope Optics (KTO), based in Munich, Germany. An LGS will be demonstrated at the ESA OGS at Observatorio del Teide, Tenerife (Spain) in optical links between the OGS and the terminal TDP-1 on board the satellite AlphaSat. Here, an overview of the design of GEOStar is presented. First, the system concept and main design drivers are discussed in Section 2, next the opto-mechanical (Section 3) and software/electronics (Section 4) designs are given. Finally, the conclusions and outlook for the project are presented in Section 5.

2. KEY DESIGN DRIVERS AND SYSTEM CONCEPT

In this section, key design drivers, including the LGS return flux and WFS selection, are discussed that influenced the final design of GEOStar. The final high level system concept is then presented.

2.1 LGS Return Flux

The return flux from the LGS is a critical parameter, as it defines the signal to noise ratio on the LGS WFS. Several studies have been performed on the return flux using the TOPTICA LGS.[9,10] It has been shown that the return flux greatly depends on the elevation angle, which is to be expected as it alters the total path length (and hence attenuation) back and forth to the sodium layer. The azimuthal angle can also affect the return flux as it influences the apparent orientation of the sodium atoms in the sodium layer, which changes with the Earths magnetic field. To point to AlphaSat from the ESA OGS, an altitude of $\approx 35°$ and azimuth of $\approx 116°$ is required. To attempt to estimate the likely return flux, figures from Holzloener et al[10] are reproduced here. Figure 3 (left) shows the return flux from a Sodium laser when pointed at an elevation of 35°, but at a slightly different azimuth angle from AlphaSat, and in Figure 3 (right) the return flux when pointing at the correct azimuth angle, but at a higher elevation angle. The increase in flux observed with higher elevation angle is that expected when considering the difference in LGS path length, therefore it seems reasonable to assume that similar results as found in Figure 3 (left) may be observed in the direction of AlphaSat. The laser return flux is approximately linear with laser output power therefore it is expected that increasing the laser power from 20W to 30W would result in approximately $10 - 12$ $\mathrm{Mphs^{-1}m^{-2}}$ being observed on the ground. It should be noted that the sodium layer density varies with time, so this value may change on short time-scales.

2.2 Wavefront Sensor Selection

A detailed trade-off between WFS options was performed during the design stage of the project including Shack-Hartmann, Pyramid, interferometric and focal plane based methods. A Shack-Hartmann type WFS (SH-WFS) was selected based on its simplicity and proven reliability when observing an LGS.

The WFS sub-aperture diameter is a critical design parameter in the SH-WFS design. The sub-aperture size is expressed as the diameter of the sub-aperture when projected onto the main telescope aperture, rather than the physical diameter of the sub-aperture on the optical bench. The value impacts the spatial resolution with which the LGS WFS can sample the atmospheric turbulence and hence with which any aberration caused by optical turbulence can be corrected by the deformable mirror (DM). Smaller sub-aperture diameter implies a high spatial resolution.

However, the smaller WFS sub-aperture also results in a smaller light collecting area and this effect is proportional to the square of the sub-aperture diameter. In order to select a suitable WFS resolution for GEOStar, potential WFS designs with 15 (FSOC LGS 1) and 5 (FSOC LGS 2) sub-apertures across the $\approx$ 30 cm telescope sub-pupil can be compared to currently operating LGS systems, such as the ESO Adaptive Optics Facility (AOF) WFS at Paranal. This is presented in Table 1. The AOF operates successfully using

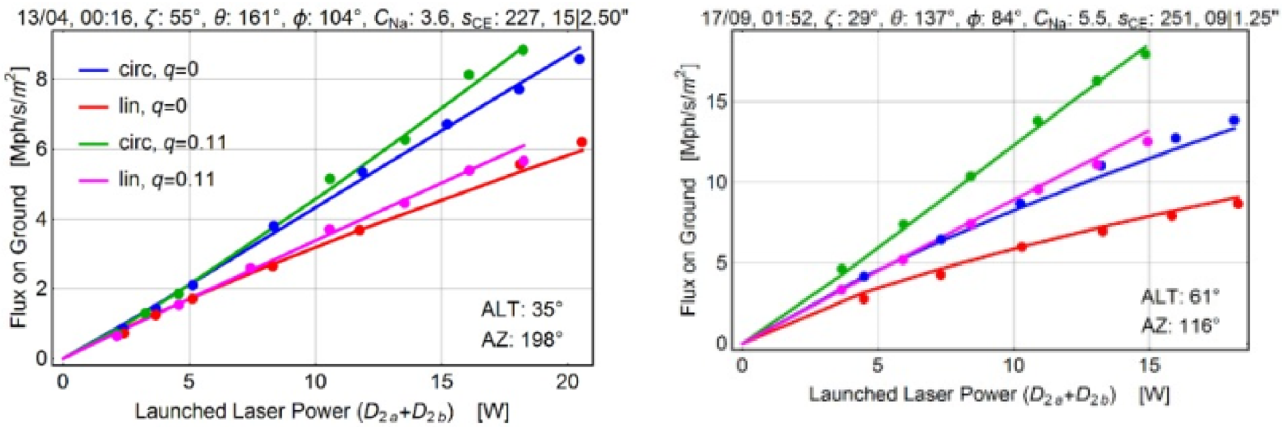

Figure 3. Measured return flux values when pointing the LGS at (left) Alt: 35°, Az: 198° and (right) Alt 61°, Az: 116°. (Reproduced from Holzloener et al.[10])

Parameter	Unit	VLT AOF WFS	FSOC LGS 1	FSOC LGS 2
Laser Guide Star power	W	20	<30	<30
Read noise of detector (OCAM 2K)	e^-	0.3	0.3	0.3
Iteration rate	Hz	≤ 1000	>1000	>1000
Primary Mirror diameter	m	8	0.3	0.3
WFS Sub-apertures across diameter		40	15	5
WFS Sub-aperture diameter	cm	20	2	6
Light collecting area	cm^2	400	4	36
Relative flux on sub-aperture (to VLT)		1	**< 0.015**	**< 0.135**
Relative flux on sub-aperture (to VLT)	dB	0	**< -18.2**	**< -8.7**

Table 1. A comparison of potential FSOC LGS WFS designs vs the case of the VLT AOF.

the TOPTICA 20W LGS, so it makes an interesting reference case. Following discussions with LGS supplier TOPTICA, it is expected that a higher power of ≈ 30 W will be possible for GEOStar using an upgraded laser system. We note that there is likely some flux margin on the AOF WFS design, such that the AOF will operate in poorer than expected laser or turbulence conditions. GEOStar may use faster iterations rates to cope with expected stronger turbulence conditions, however here 1kHz is assumed as a baseline for all systems.

It is apparent that an FSOC LGS WFS must cope with significantly less light than in the astronomical case. In the FSOC LGS case 1 with 2 cm diameter sub-apertures, the WFS must cope with 1.5 % of the light available to the WFS in the ESO AOF, perhaps less if a higher iteration rate is required to cope with stronger turbulence. This is unfeasible, even if the AOF system included some margin. In the second case, where 5 cm sub-apertures are envisaged, the WFS must operate with 10 % of the flux available to the AOF WFSs. Though still a significant drop in flux, this may be closer to the operating margin of the AOF WFS and given noise mitigation strategies, be adequate to perform wave-front sensing. A sub-aperture diameter of 6 cm implies 5 sub-apertures across the aperture. This is adequate to sense of the order of 15-25 Zernike modes, hence still provide significant correction vs the uncorrected case. Larger sub-apertures could increase the available flux still more, but would result in fewer modes corrected, perhaps not many more than the 3 (tip/tilt focus) that must be corrected using data from the downlink communications light in any case. For that reason, a Shack-Hartmann WFS design with 5 x 5 sub-apertures of approximate diameter 6 cm has been pursued. End-to-end simulations performed during the design phase of the project supported this decision and demonstrate the feasibility of the design. These will be presented in a later work.

2.3 System Concept

The preliminary concept of GEOStar is demonstrated in Figure 4. All light is observed and received through the main aperture of the OGS , however the LGS laser light is launched from a sub-pupil (LGS Uplink in Figure 4)

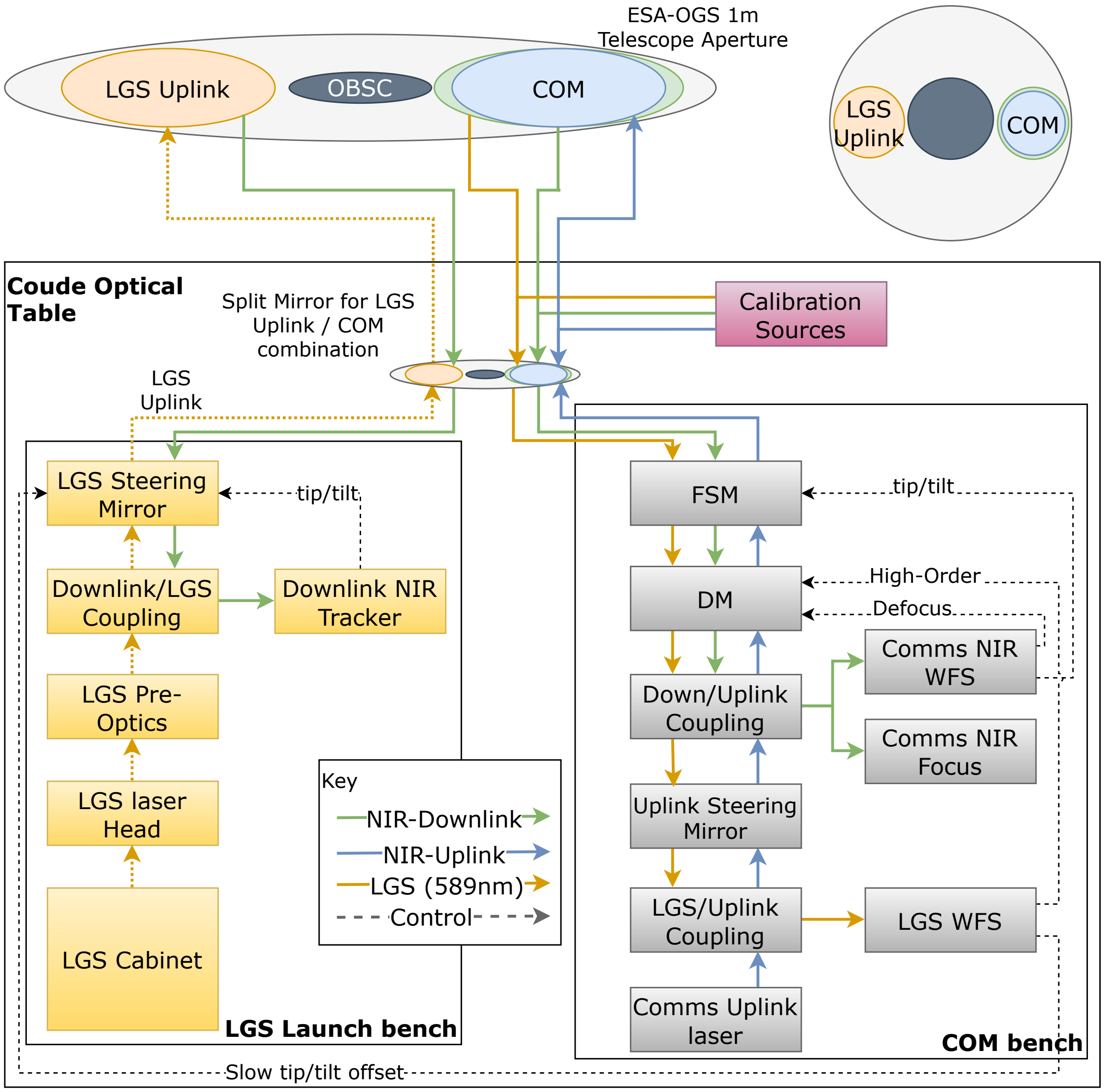

Figure 4. GEOStar system concept block diagram showing main optical and control interfaces. COM represents the "Communications Path" and OBSC is the telescope central obscuration.

on the opposite side of the aperture to that used to transmit communications light (COM in Figure 4). The NIR and LGS downlink light is also observed through this second sub-pupil. This configuration enables separation of uplink and downlink LGS light close to a re-imaged pupil plane on the Coudé bench. This avoids alternative separation strategies which would reduce the received flux or introduce increased complexity to the project. The LGS laser head is situated on the Coudé optical table and light from the LGS is routed from the laser head, passed through steering optics and launched from a sub-pupil of the main aperture. The "LGS launch" light is coupled spatially with the light in the "communications path" at a pupil plane. A tracking camera in the LGS launch path observes downlink light from the satellite through the same aperture through which the LGS is launched and controls an LGS steering mirror to stabilise the uplink path of the LGS beam, ensuring its pointing can be precisely controlled.

Light from the satellite downlink and return flux from the LGS is received from a 275 mm diameter sub-pupil on the main OGS 1 m diameter aperture. This is close to the largest clear aperture available between the edge

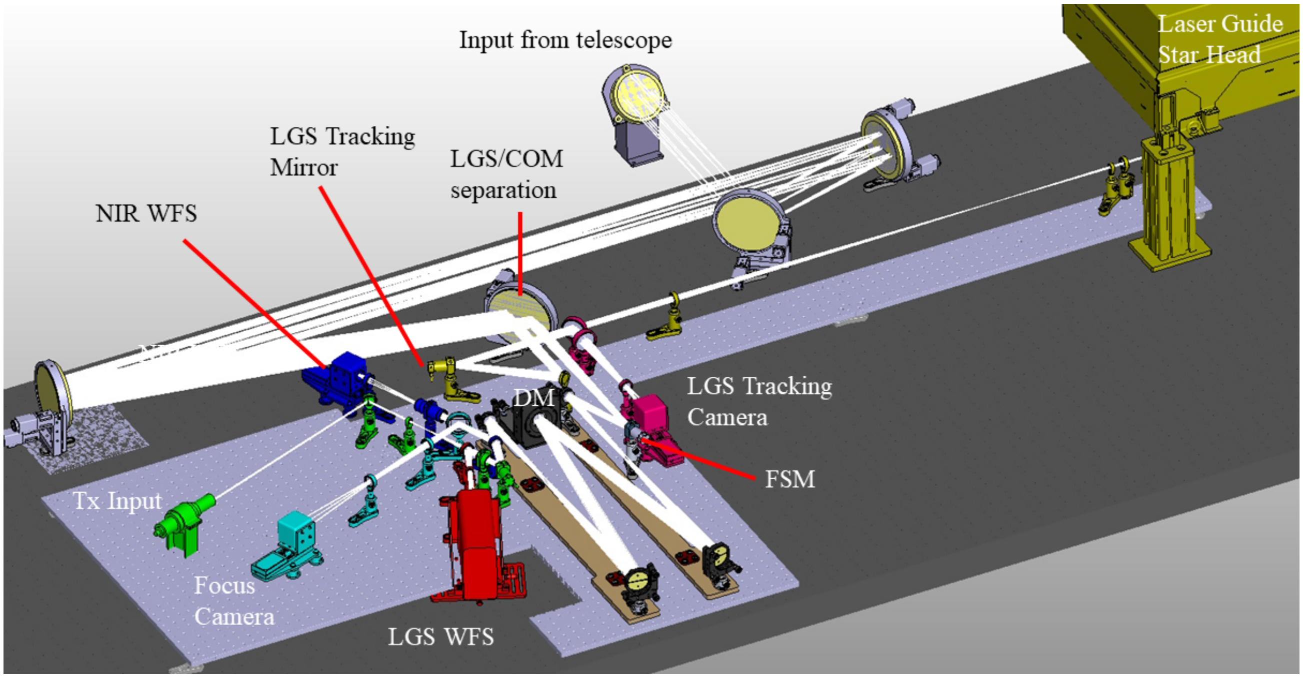

Figure 5. A CAD diagram of the opto-mechanical design showing the positions of major components.

of the pupil and central obscuration (OBSC in Figure 4). The light is directed down to the Coudé laboratory of the OGS, and projected onto a Fast Steering Mirror (FSM), used to correct tip/tilt aberrations and other fine pointing errors. Next in the optical train comes the DM, which is used to correct higher order aberrations.

The NIR light received from the satellite is picked off using a wavelength splitting dichroic beamsplitter and again separated into two paths. In one, the light is brought to a focus and the focal plane observed on an imaging camera to assess the quality of correction (from the downlink point of view). A SH-WFS observes the light in the other path. In normal operation, this WFS measures tip/tilt and focus aberrations, to be corrected by the FSM and DM respectively. The WFS will be of a similar specification to the LGS WFS, allowing the measurement of the difference in high order aberrations in uplink and downlink directions. Finally, it will be possible to use this WFS to provide measurements to the controller for high order correction, allowing comparisons between using an LGS or the downlink signal for predistortion.

In the main optical train, an uplink steering mirror is used to select the offset of the uplink path from the downlink path, i.e. the PAA. Both the LGS and uplink light are projected from this mirror, ensuring that the LGS field of view tracks the direction of the transmitted beam. The light from the uplink optical fibre is collimated and projected onto this steering mirror. Light from the LGS is separated from the communication light path using a dichroic beam splitter and is observed by a visible light SH WFS, used to measure the wavefront in the direction of the transmitted communications light and providing high-order aberration measurements to be corrected by the DM. The LGS WFS field of view is centred upon the uplink launch direction and so any long term offset of the LGS from the central position represents an offset of the LGS launch pointing. A slow control loop will act to keep the LGS centred in the LGS WFS field by supplying an offset to the LGS Launch tracking loop.

Calibration sources for the NIR and LGS wavelengths will be present in a separate calibration path. It will be possible to enable these sources via a flip mirror located between the FSM and Coudé entrance.

3. OPTO-MECHANICAL DESIGN

GEOStar makes use of a novel opto-mechanical design (shown in Figure. 5) to fit the many components required, and separate the light from the LGS launch and communications sub-systems. The system is present in the Coudé

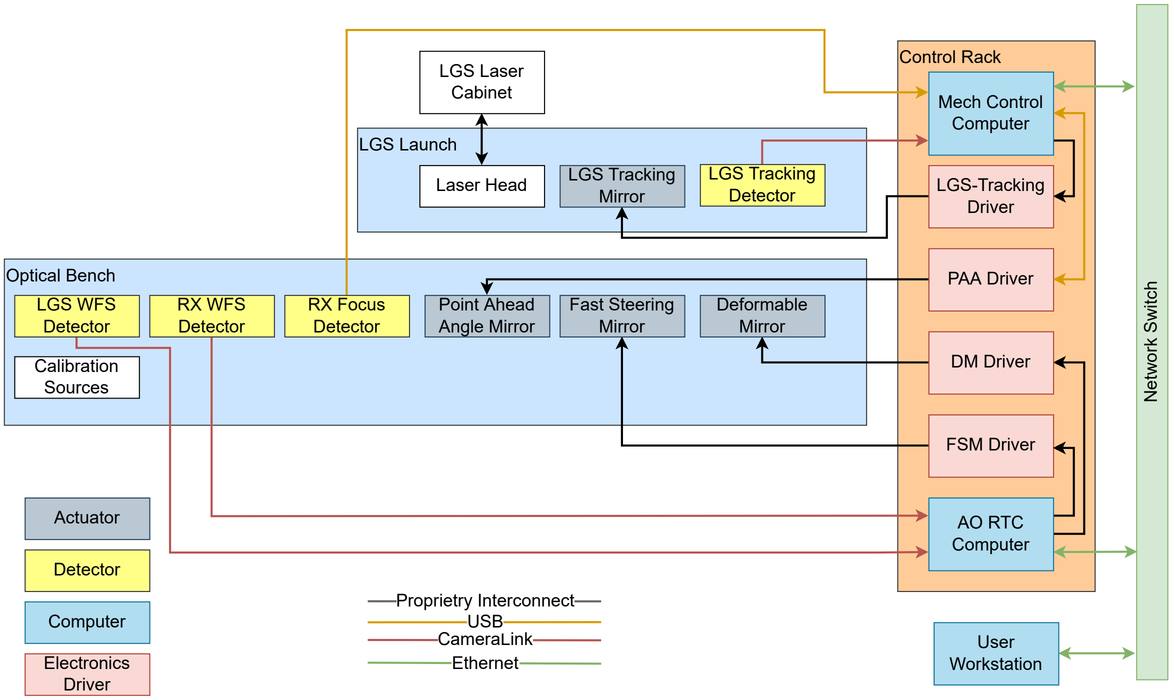

Figure 6. Electrical interfaces in the GEOStar system.

laboratory of the ESA OGS on Tenerife. The system must deal with light at three distinct wavelengths - 589 nm (LGS), 1064 nm (downlink NIR from Alphasat) and 1075 nm (uplink NIR). The system was also designed to handle downlink NIR at 1550 nm as a goal to use Arabsat which, at this moment, does not seem to be available on time for GEOStar.

A pair of Off-Axis Parabolic (OAP) mirrors are used as an achromatic relay following the interface with the telescope Coudé path. The beams from the two sub-pupils are separated into independent optical paths by a split mirror. The light to/from the LGS launch path is projected from an LGS steering mirror. A dichroic beam-splitter couples the launched 589 nm light from the LGS head and the downlink NIR-IR light, which is sent to an LGS tracking camera.

The other path is the "Communications" path, which receives LGS and downlink NIR light, and is used to launch uplink NIR light to the satellite. In this path, a FSM optically conjugated to the telescope pupil corrections for small pointing errors and tip/tilt aberrations. A second OAP relay follows, with the DM placed at another optical pupil plane. Downlink NIR light is picked off by a dichroic beamsplitter and sent to the NIR WFS and focus camera with a fine pixel scale allowing detailed analysis of the system PSF. The remaining light is projected from an uplink steering mirror, which controls the pointing of the uplink beam and the LGS WFS field of view. The 589 nm LGS return light is picked off from a final dichroic beamsplitter, with the uplink light coupled into the system via a fibre collimator from the other port.

4. SOFTWARE AND ELECTRONIC DESIGN

The GEOStar system will use a modified version of the DLR Real-Time Control (RTC) AO control system as used at the DLR Next Generation OGS. This software features a high-performance compiled core written in C++, wrapped in Python interfaces to enable complex configurations. The "real-time core" typically runs on a dedicated "headless" server computer which processes camera data and output actuator commands. Human interaction, calibration and monitoring occurs on a separate workstation computer dedicated for the tasks. This configuration avoids interrupting the RTC process with non time-critical tasks. Control commands and telemetry are shared over a dedicated high speed 10Gb Ethernet network.

In GEOStar, another "mechanics control" computer is also used for control of various mechanical components on the optical table. This includes adjustment of the uplink steering mirror, any stages required for alignment and control of the focus camera. A further AO RTC control process also runs on the mechanics control computer that computes the actuator commands required for LGS uplink beam stabilisation.

The various electrical components in GEOStar are shown in Figure 6, demonstrating which components reside on which optical bench and the nature of connections between computers, electronics drivers and components. An ALPAO DM69 is used for high-order wavefront correction and three Physik Instrument (PI) S-330 tip/tilt stages used for fast tip/tilt correction, point ahead adjustment and LGS uplink beam stabilisation. From these, the tip/tilt and LGS uplink beam stabilisation mirrors are controlled via low latency Digital/Analog Converter PCI-E boards which send analog signals to PI supplied drivers for amplification. An USB interface is used for the PAA adjustment mirror, which allows absolute positioning with an appropriate PI controller, enabling repeatable positioning of the transmitted beam.

As discussed in Section 2, sensitive detectors are required in GEOStar. A First Light OCAM2K detector that can reach sub-electron read noise is used as an LGS WFS. This is required to achieve an acceptable signal to noise ratio, despite the various issues outlined earlier. The detector is connected via CameraLink FrameGrabber cards to the AO RTC computer. First Light CRED3 detectors are used as the NIR WFS, LGS tracking camera (also observing NIR light) and the downlink focus camera. These InGaAs detectors feature $< 30\,e^{-}$ read noise, class leading in the field of high-speed Short-Wave Infra Red detectors and can operate a high frame rates - 600Hz using the 600 x 512 pixel full frame or faster when windowed. The NIR WFS and LGS tracking cameras are time critical and are therefore connected to their respective computers via CameraLink. The focus camera is not time-critical and a more flexible USB3 connection is used. The WFS detectors will be synchronised to ensure synchronisation of the WFS measurements and smooth running of the RTC.

An ALPAO DM69 was chosen due to its large stroke and pitch. This allows strong aberrations to be corrected as well as lessening the laser power density on the mirror surface compared to a more compact solution. The mirror features a 9 x 9 actuator grid across the clear aperture, however only a 6 x 6 will be illuminated, to match the 5 x 5 sub-aperture SH WFSs discussed in Section 2 in a Fried geometry. Various tip/tilt platforms based on the PI S-330 actuator are also used, controlled via PI drivers and PCIe DAC cards.

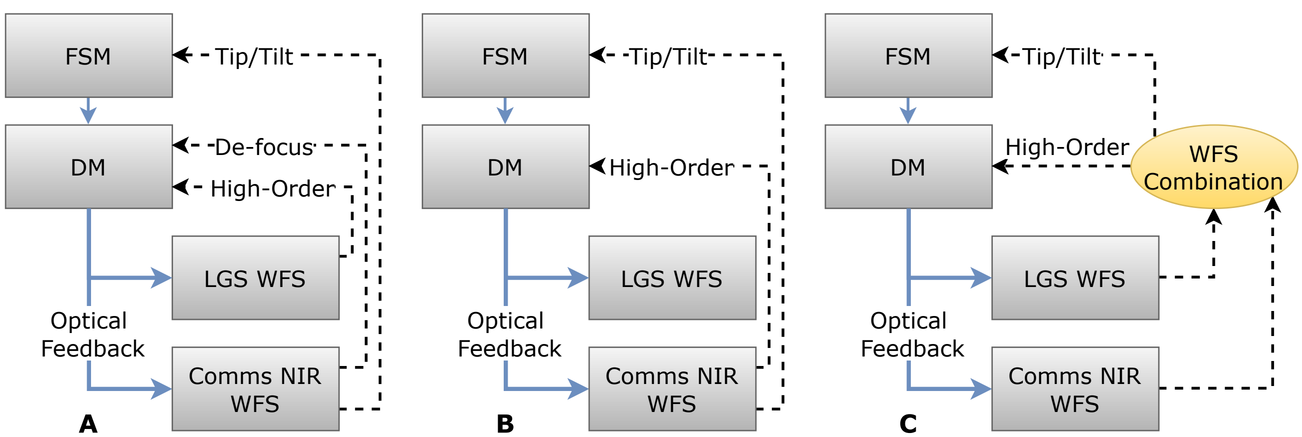

Figure 7. Different control loop strategies envisaged in GEOStar. (a): The Rx-NIR WFS measures tip/tilt/focus aberrations, all high order information comes from the LGS WFS. This is the baseline configuration. (b): All spatial orders are measured from the Rx-NIR WFS. This allows a quantitative analysis of the benefits provided by using an LGS. (c): An optimal control scheme which uses information from both WFSs. This is a goal of the project that is under development.

Three different control strategies are envisaged in GEOStar, as illustrated in Figure 7.

- (a): The first is the baseline of the project – tip/tilt/focus aberrations are sensed by the NIR WFS which observes the downlink light from the satellite and cannot be sensed from an LGS. Higher order aberrations are sensed from the LGS WFS. The measurements are combined in the controller and correction signals sent to the DM and FSM.

- (b): In the second strategy, only the signals from the NIR WFS are used to sense all spatial modes. This represents the possible predistortion available to a system without an LGS and is hence a valuable reference point to understand the impact of the LGS.
- (c): In the third case, the measurements from both sensors are combined in an algorithm which attempts to retrieve the best data from both WFS sources - LGS WFS data with no isoplanatism but likely higher detector noise and NIR WFS data with low noise but isoplanatism. This control scheme is currently under development and will be published in a later work.

5. CONCLUSIONS AND OUTLOOK

GEOStar is a system created to demonstrate the feasibility of LGS AO in the field of FSOC. The LGS is launched from inside the Coudé laboratory via a sub-pupil of the OGS 1m main aperture. LGS return light and NIR light from a GEOStationary satellite is received from a sub-pupil on the other side of the aperture. The transmitted light to the telescope is also launched from this sub-pupil. A dedicated adaptive optics system uses the LGS return light and downlink from the satellite to “pre-distort” the uplink beam to the satellite, in order to account for atmospheric turbulence and stabilise the communications link in that direction. Various control configurations are available in order that the impact of the LGS is well understood. The system is currently being integrated in the laboratory in readiness to be shipped to Tenerife for commissioning in March 2024 and multiple measurement campaigns from April 2024 through June 2024 with the *TDP-1* optical terminal on board the satellite *AlphaSat*.

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