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E. Fischer

Th. Berkefeld

Mikael Feriencik

Marco Feriencik

et al.



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USE OF ADAPTIVE OPTICS IN GROUND STATIONS FOR HIGH DATA RATE SATELLITE-TO-GROUND LINKS

E. Fischer¹, Th. Berkefeld¹, Mikael and Marco Feriencik¹, V. Kaltenbach¹, D. Soltau¹, P. Adolph¹, R. Czichy¹,
J. Kunde¹; F. Heine², K. Saucke²; R. Meyer³, I. Richter³, Z. Sodnik⁴

¹Synopta GmbH, CH-9034 Eggersriet, Switzerland

²Tesat-Spacecom GmbH&Co KG, D-71522 Backnang, Germany

³Space Administration, German Aerospace Center (DLR), Bonn, Germany

⁴European Space Agency - ESA/ESTEC, The Netherlands

Abstract— Over the past years we have successfully applied adaptive optics (AO) in some optical ground stations (OGS) to improve the signal-to-noise ratio of satellite to ground laser communications. In the paper we present the realized setups including optics and components, the reconstruction scheme especially latest performance measurements of the AO system implemented at the 26cm TAOGS optical terminal which is presently at the Observatorio del Teide, Tenerife. Furthermore, we present the concept for the upgrade of ESA's OGS (1 m telescope) with an AO system for satellite-to-ground links. The system is suited to be operated with coherent laser communication systems at 1064nm. However, the upgraded ESA OGS can also be operated with laser light in the 1550nm range. The wavefront sensor is a Shack-Hartmann-sensor (21 sub-apertures across the pupil), matched to a 22x22 actuator deformable mirror (DM). Due to a special high speed infrared camera, the control loop can run at speeds of typically 4-7 kHz, depending on the received laser power.

I. INTRODUCTION

The European Space Agency (ESA) started mid of the 1970s first development activities regarding free space optical inter-satellite communication. The activities resulted then in 2001 in the world's first optical inter-satellite communication link. Said link was demonstrated in the SILEX program between the ARTEMIS data-relay satellite in geostationary orbit (GEO) and the SPOT-4 Earth observation satellite in low earth orbit (LEO) [1].

The achievements of the SILEX program constituted an important technology milestone; it was demonstrated for the first time in orbit that the stringent pointing and tracking requirements needed for inter-satellite laser communication can be mastered. However, the optical communication technology used for SILEX was not able to compete with state-of-the-art radio communication technology, i.e. achieved data rate 50Mbps at a terminal mass of 160kg.

Consequently, a second generation of Laser Communication Terminals (LCT) with improved mass and data rate figures has been developed by Tesat Spacecom under contract of the German Space Agency (DLR). The second generation LCT technology achieved a data rate of 5.7Gbps at a mass of 35kg. Two of these terminals have been launched in 2007 as experimental payloads onboard of two LEO spacecrafts (TerraSAR-X and NFIRES). During the following experimental phase inter-satellite communication links at a data rate of 5.6Gbps over distances up to 6'000km have been demonstrated [2].

A third 2nd generation LCT has been modified for use as a mobile optical ground station (OGS) for satellite-to-ground link (SGL) activities. In order to mitigate the influence of turbulent atmosphere effects the OGS telescope's receiving aperture has been reduced to half the size of flight LCT receivers. Bidirectional coherent communication has been achieved through the atmosphere during SGLs [3]. The results achieved with the mobile OGS when performing SGLs provided a proof of the capability to operate, through a turbulent atmosphere, a coherent optical communication system which is using homodyne binary phase shift keying (BPSK) modulation [3].

II. PRECURSOR ACTIVITY

Because of its small receiving aperture, the aforementioned OGS was only capable to communicate with LCTs which were orbiting in LEO. An additional limitation was the Fried parameter, r_0 , required for proper operation had to be larger than the OGS's receiver aperture. Therefore, a development activity was started with a twofold aim:

- To increase the usable OGS receiver aperture for coherent optical SGLs beyond the size of the Fried parameter, i.e. r_0 .
- To develop a transportable OGS which is capable to establish coherent optical SGLs with LCTs in GEO.

In order to achieve the first objective one has to introduce adaptive optics in the OGS receive path to cope with the increased coherent receiver aperture, at the given wavelength, at any low quality OGS site.

The second objective can only be achieved by a consequent miniaturization and by ruggedizing the opto-mechanical system. In a first development step an adaptive optics prototype was implemented in the Coudé path of ESA's OGS on Tenerife (see Fig. 1).

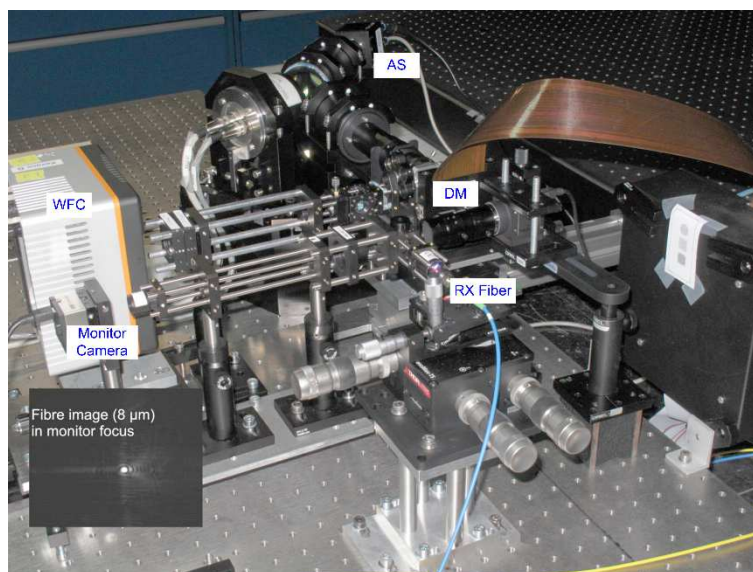


Fig. 1. Photograph of prototype adaptive optics, inset depicts image of monitor camera

For correction of the incoming wavefront two actuators were applied:

- Fast steering mirror for correction of tip-tilt errors, i.e. Zernike modes 1 and 2.
- Microelectromechanical system (MEMS) deformable mirror (DM) for correction of remaining higher order aberrations.

Within this first development activity it could be demonstrated that

- Adaptive optics can successfully be used for wavefront correction even when tracking objects with high angular velocity (which is necessary to track LCTs residing on a LEO satellite) and in fully developed speckle fields; see Fig. 2.
- The usable aperture of a coherent receiver can be increased by means of adaptive optics beyond the Fried parameter size. The received wavefront from the counter station can be made (nearly) diffraction limited by means of wavefront correction in the pupil (or image thereof) of the receiver optics. Thus, light in receive direction (Rx) can be coupled efficiently into a single mode fiber, i.e. Rx-fiber, as interface to the coherent receiver.

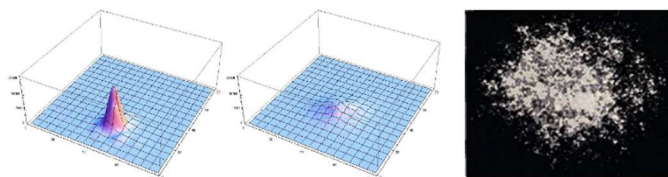


Fig. 2. Intensity distribution of received laser light from a LCT residing on a LEO satellite: adaptive optics operational (left), with adaptive optics not operational (middle), monitor camera image for case adaptive optics not operational (right)

III. TRANSPORTABLE ADAPTIVE OPTICS GROUND STATION

A. Ground Station Design and Realization

Based on the lessons learnt with the aforementioned precursor activity the transportable adaptive optics ground station (TAOGS) was then designed and built (see Fig. 3 and Fig. 4). The TAOGS comprises two containers:

- Optics container (OCO), comprising all optics, opto-mechanics and associated electronics.
- Operations container, a 20 feet long high bay container, serving also as transport compartment for the OCO during transports.

Both containers are inter-connected with an electrical harness and cooling liquid tubes of the air conditioning system in the optics container.

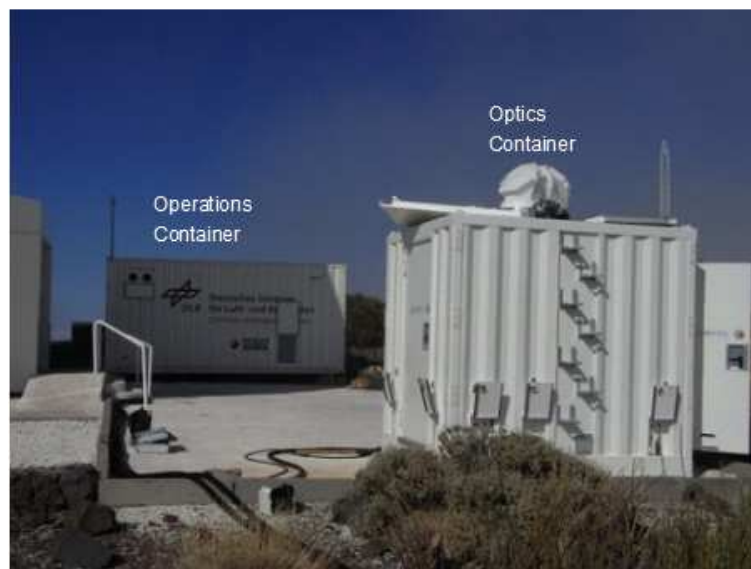


Fig. 3. Photograph of transportable adaptive optics ground station

The TAOGS operator works inside the Operations Container. A variety of environmental sensors (site cameras, meteo station, virtual RADAR, etc.) is available to ensure a safe operation of the station. One person is dedicated as laser safety supervisor during laser links, if required. In Fig. 4 a view inside the Operations Container is presented.



Fig. 4. Inside view of TAOGS Operations Container

The TAOGS optical block diagram is shown in Fig 5. The block diagram comprises several sensors and actuators:

Sensors

- AS, a CMOS camera used as acquisition and tracking sensor, the camera receives 5% of Rx light.
- WFC, an InGaAs camera used in Shack-Hartmann sensor, the camera receives 20% of incoming light, the area-of-interest read out frequency can be varied from 500Hz to 10kHz.
- CPACam, a CCD camera used as star calibration sensor in the visible and near infrared range.
- TXCam, CMOS camera used for CPA100 co-alignment check-out

Actuators

- CPA270, a hemispherical pointing mechanism used a) in receive direction, and b) in transmit direction if the transmit beam diameters is configured for ≤ 35 mm.
- CPA100, a hemispherical pointing mechanism, used normally in transmit direction if the transmit beam diameter is configured for 95mm.
- FPM, the adaptive optics tip-tilt mirror
- PAM, the tip-tilt mirror is for realization of transmit beam small scale angular movements, e.g. spiral scan, and point ahead angle implementation.
- Sensors for deriving position (GPS), inclinometer (roll and yaw), meteo data, Sun detection.

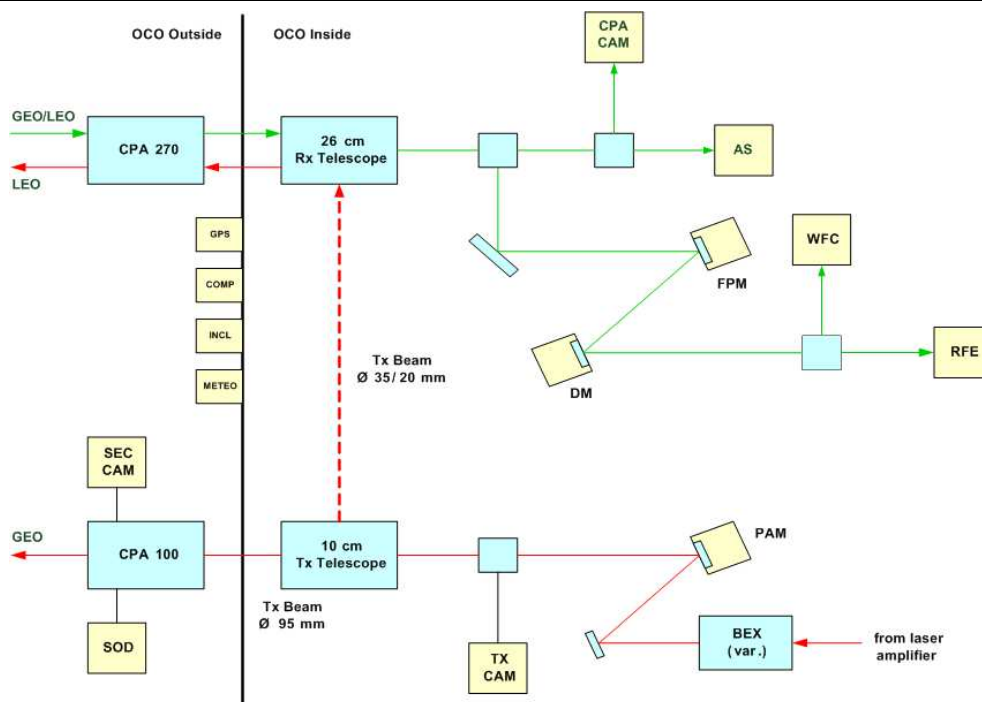


Fig. 5. TAOGS optical block diagram

A MEMS membrane mirror with 12x12 actuators is used as deformable mirror. A relative high count of 100 optical sub-apertures is implemented in the TAOGS receive path to allow for operation also at low Fried parameter values, e.g. <math><10\text{ cm}</math>.

The TAOGS optical bench has been miniaturized and is realized as a stiff and highly ruggedized structure. The adaptive optics sub-bench is forming part of it. Thus, the TAOGS can be transported on land, water or air without specific external precautions. In Fig. 6 a close-up view of the key elements is shown forming the adaptive optics.

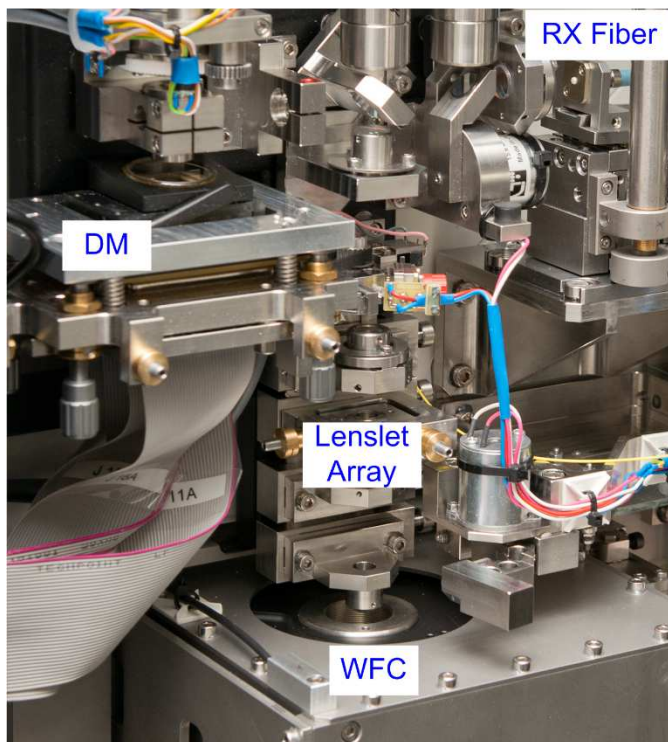


Fig. 6. Close-up photograph of adaptive optics integrated into TAOGS optical bench

It is possible to operate the TAOGS in a mode with the two pointing mechanisms used in parallel (see Fig. 7). In this case the transmit beam is routed through CPA100 and the receive beam through CPA270. During this

operational mode CPA100 is set into slave mode and follows, therefore, the movements of CPA270. This configuration is primarily implemented to enable also the use of transmit beam diameters larger than 35mm.



Fig. 7. Both TAOGS pointing mechanisms are co-aligned when operated in parallel

The TAOGS can be commanded w.r.t. to mechanical, topocentric or sky coordinates. Normally, the TAOGS is commanded w.r.t. a topocentric coordinate system. When arriving at a new site the TAOGS pointing model is determined by means of an automated star calibration process. On the basis of the pointing model the TAOGS one sigma absolute pointing error is reduced to values below 40arcsec.

B. Operational Results

After final commissioning the spatial acquisition between a spacecraft LCT and TAOGS was routinely performed, followed by frequency acquisition and transition to homodyne communication phase. In communication mode a LCT internal generated test pattern has been used for link quality evaluation.

Spatial Acquisition

The CPA270 on top of the TAOGS optics container is following a pre-calculated trajectory in acquisition and tracking mode. The acquisition and tracking sensor, i.e. AS, is sending correction offsets if the center of gravity of the received light spot deviates from an intended center position. The TAOGS acquisition and tracking system is designed for a two blip acquisition capability. As soon as the AS of the ground station detects a light blip centering commands are send to CPA270. Usually, with two received light blips the TAOGS is sufficiently well centered and starts tracking.

During fine acquisition phase the LCT in orbit is waiting for light sent upwards from the TAOGS. If the co-alignment error between the TAOGS transmit and receive beam has been well adjusted prior to link initiation about 130ms after switching on the TAOGS transmit laser the terminal in orbit will receive light from the ground station. If the LCT in orbit does not answer within a second by centering its transmit beam then the TAOGS will start a scan pattern with the transmit beam.

As long as the received optical power in orbit is not sufficiently high, i.e. TAOGS transmit beam well centered onto the LCT in orbit and/or scintillation low enough, the terminal in orbit will not enter into constant tracking mode. Instead, the LCT in orbit will then perform permanently small transmit beam scans. This scanning will cause an intensity modulation in the received signal of the TAOGS. As soon as the terminal in space has entered into constant tracking mode (see Fig. 8) the adaptive optics corrects the incident light wave to be coupled into the single mode receiver fiber with high coupling efficiency.

As soon as the LCT in orbit has entered into constant tracking mode the aforementioned intensity modulation is gone and the TAOGS adaptive optics control loop operates stable. In SGLs with GEO LCTs the wavefront sensor readout frequency is set typically to 6.7 kHz, in case of LEO LCT SGLs even 10 kHz are feasible. Fig. 9 shows a screen shot from an internal monitor camera. In said figure one can easily identify a diffraction limited spot. This spot is generated by the 4% of back reflected light from the tip of the RX fiber. With this monitor camera the operator has a powerful tool to get a quick impression concerning the actual quality of the adaptive optics correction. Fig. 9 was taken during a SGL with a GEO LCT.

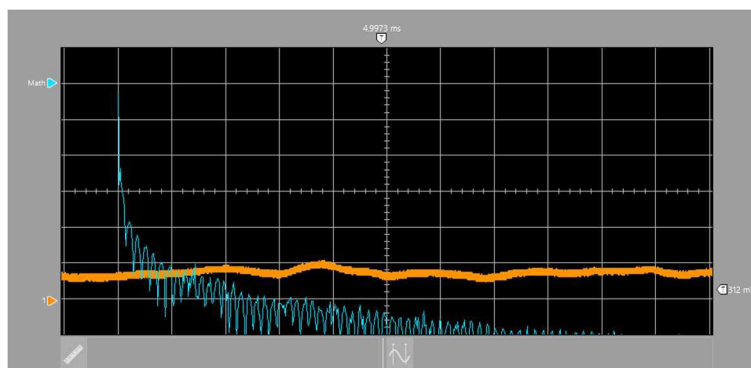


Fig. 8. TAOGS received optical power signal when counter terminal has reached constant tracking mode; Sensor signal amplitude over time (orange, 1 V/div) and Fourier transformed sensor signal (blue, vertical: 10dBV/div, horizontal 200Hz/div)

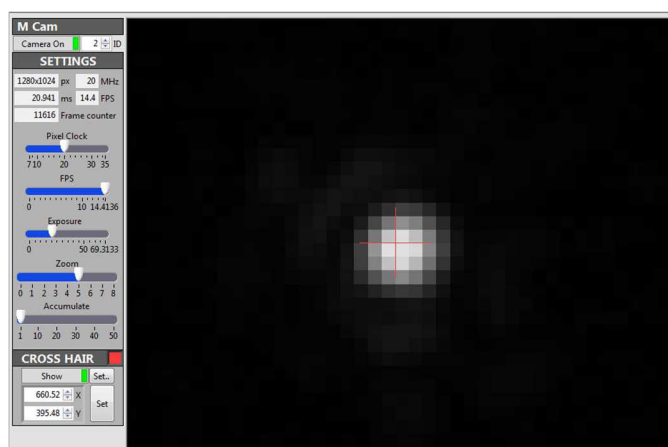


Fig. 9. Diffraction limited RX spot achieved with adaptive optics during SGL between LCT in GEO and TAOGS

Frequency Acquisition

As soon as spatial acquisition is accomplished frequency acquisition is initiated. In the moment of locking, i.e. transition from heterodyne to homodyne detection, the signal of the coherent power detector in the TAOGS receiver jumps up by 3dB.

Communication

In SGLs with a LCT hosted on a GEO spacecraft repeated space to Earth and even bidirectional communication was achieved. The results are currently under evaluation and will be presented elsewhere [4].

IV. ESA OGS UPGRADE

A. Background

The ESA Optical Ground Station (OGS) has been initially designed for in-orbit check-out and testing of the laser communication payload embarked on the ARTEMIS spacecraft in geostationary orbit. It is located at the Observatorio del Teide, Izaña, Tenerife (Spain), at an altitude of 2391m above sea level.

The OGS consist of a cylindrical building with a diameter of 12.5 meters, covered by a dome. The building provides all infrastructure required for execution of the check-out and test operations of laser communication terminals on board satellites in orbit.

The OGS telescope is a 1m Ritchey-Chrétien/Coudé reflective telescope with an English mount, controlled by the Telescope Control Computer (TCC). The OGS is used for astronomy, for space debris observations, and for laser communication with GEO/LEO satellites, deep space terminals, or inter-island links from La Palma.

B. Adaptive receiver optics in the OGS Telescope Cassegrain focus preliminary design

The laser communication instrumentation used so far in the OGS was designed to be mounted on an optical bench at the Coudé focus of the telescope. The OGS shall now be upgraded by Synopta with a laser communication Rx system which includes adaptive optics and can be mounted at the Cassegrain focus of the OGS telescope. The so-called Cassegrain Adaptive Receiver System (CARO) system will be designed to support the new laser communication wavelength schemes (1064nm, 1550nm). The OGS Telescope will be used with its existing Ritchey-Chretien optics.

The CARO system will be embedded into the overall OGS system during satellite-to-ground links. The CARO system is designed as a distributed system which is remotely controlled via a control panel. The interface with the Rx communication system is the output of a polarization maintaining single mode fiber. Therefore, the CARO system is designed that it picks up at its entrance port the blurred primary Cassegrain focus spot of the OGS telescope. And at the CARO exit port the received light will be delivered by means of a polarization maintaining single mode fiber.

A switching between the operational wavelength bands centered around 1064nm and 1550nm, respectively, can be initiated by the user per software command without the need of any further manipulations at the CARO system.

The core of the CARO adaptive optics system is a deformable mirror (DM). The DM from ALPAO, Grenoble, is located in the telescope pupil and equipped with 468 actuators. Further on a matched imaging transfers the DM surface into the entrance aperture of a lenslet array. This lenslet array is forming part of a Shack-Hartmann wavefront sensor (WFS).

The arrangement of actuators and wave-front sensor sub-apertures affects the control algorithm and the stability of the control system. The so-called Fried geometry is best suited for orthogonal arranged actuator patterns. Thus, the actuator count of the 468-DM allows to place 21 square sub-apertures in Fried geometry across the OGS telescope's aperture stop diameter. An outer ring of DM actuators is not used for wave-front correction. These actuators serve for a good definition of the pupil rim.

Optical Design

A collimator picks-up the telescope's primary Cassegrain focus and collimates the divergent optical beam. After the collimator a beam splitter is placed. This beam splitter passes about 5% of the incident light from the Rx wavelength bands towards an InGaAs based acquisition and tracking sensor (AS). The AS will be used during operation to keep, via OGS telescope off-set commanding, the remote communication partner inside the field of view of the wavefront sensor.

The portion of Rx light reflected at the aforementioned beam splitter enters into the wavefront sensor optics path. The Rx light is reflected first towards the fine pointing assembly (FPA) which is used for the correction of tip-tilt errors. The FPA is located such that the collimator, together with the telescope's secondary mirror, images the telescope's aperture onto the FPA mirror. As FPA mechanism a piezo-actuated tip-tilt mechanism will be used with an open loop bandwidth well in excess of 1kHz.

Some relay optics is involved in transferring the telescope pupil from the FPA mirror location to the DM's active mirror surface and then further to the lenslet array of the Shack-Hartmann wavefront sensor (see Fig. 10). The light required by the WFS is picked-off from the RX light which is traveling towards the Rx-fiber.

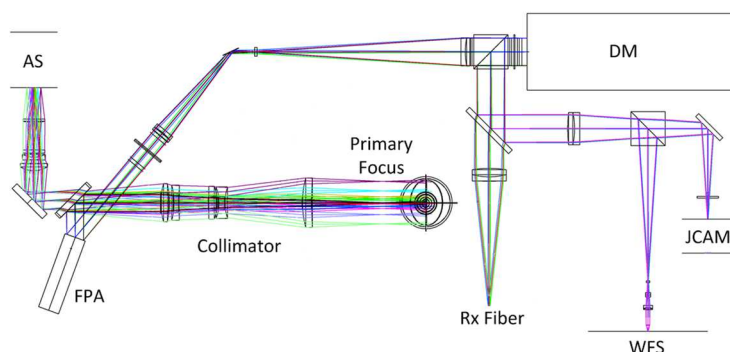


Fig. 10. CARO system preliminary optical layout

Measures are implemented in the CARO system which allow to determine the differential wavefront error between the WFS path and the Rx fiber path prior to establishing a SGL. During the SGL one can then apply this differential wavefront error as static bias to the DM to improve the fiber coupling.

In Fig. 10 a further camera, namely JCAM, is depicted. This camera is intended for diagnostic purposes during a SGL.

Opto-Mechanical Design

The opto-mechanical design of the CARO optical bench requires some care. Because the optical bench will be moved during operation together with the telescope. Therefore, the orientation of the optical bench w.r.t. the gravity-vector is undefined. As a consequence, one must carefully design and analyse the CARO bench structure as well as the optics mounts to avoid a telescope mispointing during SGLs which is caused by gravity induced component tilts in the CARO optical bench.

Performance Prediction

For the preliminary CARO system design an analysis concerning the achievable AO performance under typical environmental conditions at the OGS site has been performed. For the analysis the following parameters have been assumed:

- Telescope diameter 1m
- $r_0 = 5\text{cm}$
- $\lambda = 1064\text{nm}$
- Zenith angle 60 degrees

The predicted Strehl ratio is shown in Fig. 11 versus the actuator count or system degree of freedom of the deformable mirror. As one can read from Fig. 11 there is a fair chance that the required Strehl ratio of 0.6 can be achieved with the CARO system at $r_0 = 5\text{cm}$ @1064 nm.

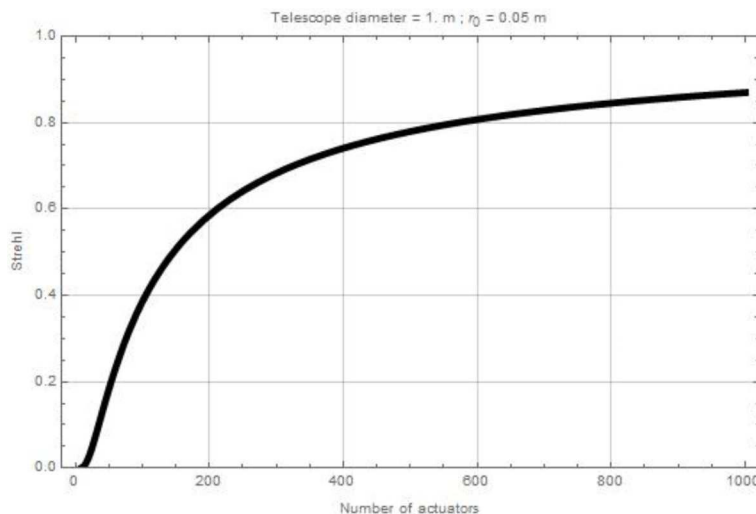


Fig. 11. Predicted Strehl ratio over deformable mirror actuator count

V. ACKNOWLEDGEMENT

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