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# Preliminary optical design of an Active Optics test bench for space applications.

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## Abstract

This communication presents a preliminary optical design for a test bench conceived within the European Space Agency's TRP project (Active Optics Correction Chain (AOCC) for large monolithic mirrors) with the goal of designing and developing an Active Optics system able to correct in space on telescopes apertures larger than 3 meters. The test bench design uses two deformable mirrors of 37.5 mm and 116 mm, the smallest mirror to generate aberrations and the largest one to correct them. The system is configured as a multi-functional test bench capable of verifying the performance of a Shack-Hartmann wavefront sensor as well as of a Phase Diversity based wavefront sensor. A third optical path leads to a high-order Shack-Hartmann wavefront sensor to monitor the entire system performance.

## 1 Introduction to Active Optics in Space

In the last few decades, Active Optics has been applied to ground-based telescopes [1, 5] to correct deformations due to: the effect of gravity, thermal expansion, wind or mechanical stress. Because of the way these effects scale with aperture size, this technique has become significantly more important in the era of the extremely large telescopes [3]. Use of these techniques is essential to guarantee the optimal shape of the large primary mirror and, consequently, to fully exploit the capabilities of these powerful instruments. In the new generation of space telescopes, large and lightweighted primary mirrors are required to observe faint sources with higher image resolution and better optical quality. The application of Active Optics to space telescopes corrects for: in-flight effects, thermo-elastic deformations, radiation effects on optical materials and gravity release. It could also reduce the requirements on the manufacturing quality. All these important advantages of Active Optics motivate the development of the AOCC project, an initiative from the European Space Agency to design, develop and test an Active Optics Correction Chain for large monolithic mirrors. The development of Active Optics for space [6, 4] is a challenge, however, the advantages that this application offers make a strong case for a study that will provide remarkable results for the new era of space missions.

The space telescope missions can be divided in two categories with very different requirements: Earth observation missions and missions for scientific astronomical observations. Our project focuses on the Earth observation case and this communication describes the preliminary optical design of the system to test the proposed approach in the laboratory. In parallel, the astronomical observation case is studied by another consortium [2].

## 2 Specifications and components

The presented design corresponds to a breadboard to test the AOCC capabilities in laboratory, able to: (1) emulate typical reference objects (extended sources); (2) generate wavefront aberrations; (3) emulate the real AOCC instrument (perform wavefront sensing and correct aberrations) and (4) verify that the out-coming wavefront satisfies the requirements.

Conceptually, the breadboard is composed of three sub-systems: the object and telescope emulation, the emulated AOCC instrument and the performance monitor. The object and telescope emulation models the telescope and generates the aberrations. The object is an extended source, associated to the observation of the Earth surface. The aberrations are introduced by a deformable mirror, denoted as DM1, whose diameter is 37.5 mm. An interferometer monitors the DM1 to verify the generated aberrations. The system has to generate and correct for the first 28 Zernike with amplitudes between 25 nm RMS and 300 nm RMS, and a Tip-Tilt of 0.5 mrad.

The emulated AOCC instrument measures these aberrations and corrects them, using a second deformable mirror, DM2, whose diameter is 116 mm.

The Performance Monitor will measure the out-coming wavefront at three points in time for each of the aberrations that are required to be corrected: (1) before the DM1 introduced the aberration; (2) after the DM1 has introduced the aberration, but the AOCC has not yet corrected for it and (3) after the DM1 has introduced the aberration and the AOCC has corrected for it. The difference between the first and the last out-coming wavefront should be as small as possible; the size of this difference is the measure of the performance of the AOCC. The residual wavefront is required to be 70 nm RMS, but the goal is 50 nm RMS.

The specifications for the design of the optical test bench evolved during the design phase. Initially, a field of view of $0.08^{o}$ for the telescope was considered, which is equivalent to a field of view of $7.47^{o}$ on the test bench. This field of view was decreased to $5.60^{o}$, which was the value considered for the preliminary design. Finally, the field of view was reduced to the area that will be used for wavefront sensing, $0.39^{o}$, improving the final performance, especially the optical quality. Both designs, the initial and the improved ones, are shown, explaining the changes considered and the achieved improvements leading to a diffraction limited optical quality.

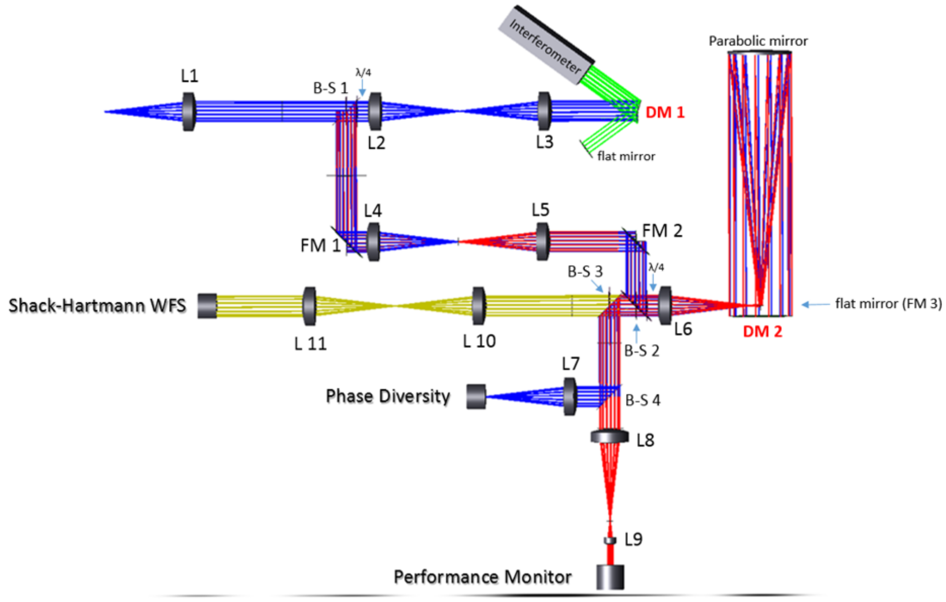


Figure 1: Preliminary layout of the AOCC test bench.

## 3 Preliminary design of the test breadboard

The preliminary design of the AOCC test bench is shown in Fig. 1, it corresponds to a field of view of 5.60°. Commercial achromatic doublets were considered for the layout. Only one commercial option was compatible with the field of view. This lens has an aperture of 80 mm and a focal length of 160 mm defining a focal ratio of F/2, which is the major factor limiting the final performance of the design. The AOCC breadboard was designed as a multi-configuration file using the sequential mode of Zemax where each configuration is represented in a different colour.

In Fig. 1 the light passes through three lenses, L1, L2 and L3 and it is reflected at the first deformable mirror (DM1) which returns the beam including aberrations. DM1 is placed at a pupil position. After the second pass through L2 the beam is split using a polarising beam-splitter (B-S 1) preceded by a quarter wave plate. A flat mirror, FM1, generates tip-tilt aberrations. The beam continues through L4, L5 and a second flat mirror, FM2, corrects the tip-tilt introduced by FM1. A second beam-splitter (B-S 2) drives the beam to L6 and a third flat mirror (FM 3), in Newtonian configuration, reflects the light to a parabolic mirror generating an obscuration comparable to that introduced by the secondary mirror at the telescope. The parabolic mirror generates a pupil image where the second deformable mirror (DM 2) is placed. This corrects the aberrations and sends the beam back to be reinjected in the system, following the optical path of the parabolic mirror, the flat mirror, L6, and a third beam-splitter, B-S 3. Until this point the optical path is common for

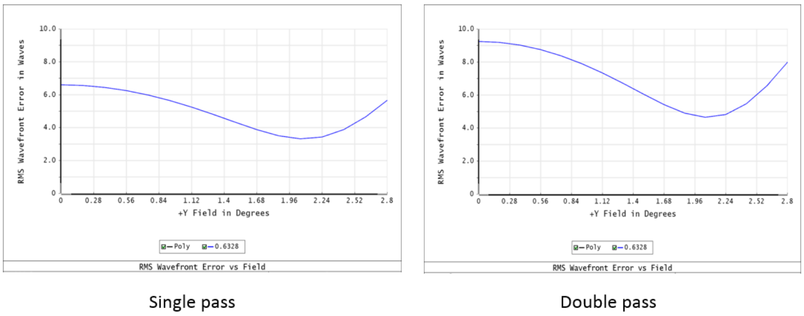


Figure 2: Comparison of the results of the wavefront error versus field obtained for single and double pass. The wavefront error increases in double-pass.

all the configurations. The third beam-splitter divides the beam into two arms, one continues in transmission through L10 and L11 which produces a pupil image for the Shack-Hartmann wavefront sensor. The rest of the light is reflected and split by a fourth beam-splitter (B-S 4) into two optical paths, one for the Phase Diversity wavefront sensor and another for the Performance Monitor, which is a high-order Shack-Hartmann sensor. The wavefront sensors are currently under design.

## 4 Constraints and improved design

Lenses L2 and L3 were included in the layout to proportionate the space needed for the interferometer, however, each optical surface contributes to the final wavefront error. To evaluate their effect a system in single and double pass was analysed and the graphics associated to the wavefront error versus field were compared (Fig. 2). In order to improve the final performance of the AOCC test bench these two lenses were eliminated.

With the reduction of the field of view more alternatives of commercial lenses were available. For an improved design, an achromatic doublet with a focal length of 500 mm and an aperture of 50.8 mm was considered. The optical design is presented in Fig. 3. The first lens, L1, collimates the beam and the first deformable mirror is placed at a pupil position. The light is reflected in DM1 and returns passing through a quarter wave plate, a polarising beam-splitter (B-S 1), L2 and L3, which generates a pupil image where a flat mirror, FM1, corrects the tip-tilt introduced by the deformable mirror. The combination of L4 and the parabolic mirror produces a magnification of the beam of 3.0933, the ratio between the apertures of the deformable mirrors, and the pupil diameters placed at these locations. A flat mirror, FM2, is used in Newtonian configuration producing an obscuration equivalent to that produced by the secondary mirror in the real telescope. The beam is reflected at DM2 and reinjected in the system corrected of aberrations. After the second pass through L4 the beam is reflected by the second beam-splitter (B-S 2) and split by the third beam-splitter (B-S 3) in two arms, where a fraction of the beam is reflected and sent to the Shack-Hartmann wavefront sensor and the rest of the light is transmitted and divided by a fourth beam-splitter (B-S 4) feeding the Phase Diversity wavefront sensor and a high order

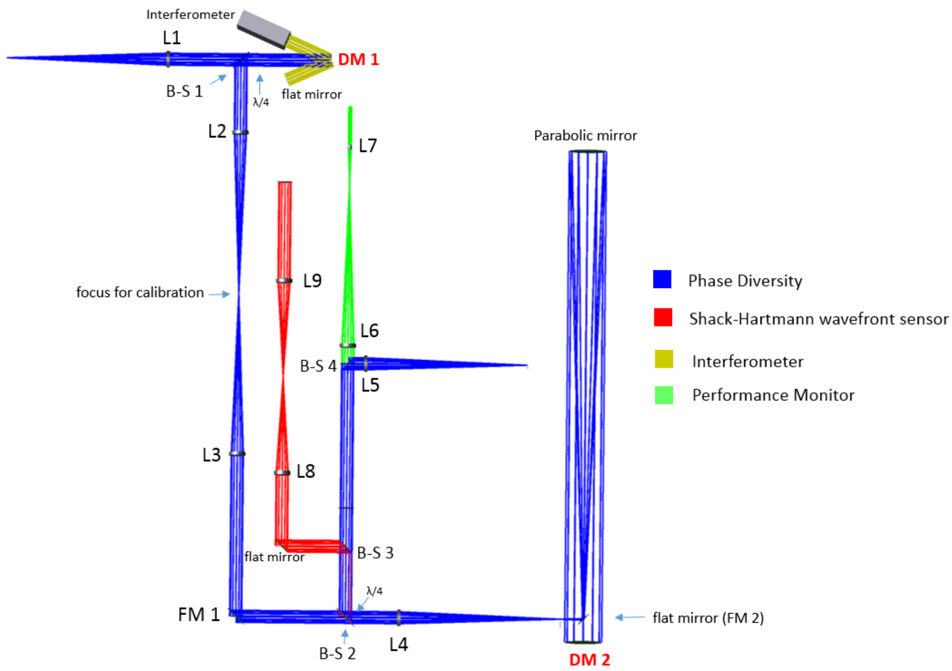


Figure 3: Current design of the AOCC test bench.

Shack-Hartmann (Performance Monitor).

The combination of the two wavefront sensors in this hybrid solution increases the accuracy of the system offering the ability to sense all aberrations. The Shack-Hartmann is used for fast correction while the observation is on-going, which is especially important for Earth observation, where correction might need to be updated frequently. The Phase Diversity system corrects the non-common path aberrations but would require the observation to be stopped. The high order Shack-Hartmann acts as a performance monitor verifying the final performance of the system. This sensor will only be present to verify the output wavefront from the test bench and not in the real AOCC system launched into space.

The combination of a smaller field of view and a slower beam leads to a better optical performance, as shown in the diffraction limited spot diagram of the improved design (Fig. 4).

## 5 Conclusions

The application of Active Optics for space presents several advantages particularly important for the new generation of space telescopes. It corrects for: in-flight effects, thermo-elastic deformations, radiation effects on optical materials and gravity release. This reduces the strict requirements on the manufacturing quality, the alignment tolerances and the complexity of structural and thermal designs. The AOCC project (Active Optics Correction Chain for large monolithic mirrors) is an initiative from the European Space Agency to design, develop and test Active Optics systems for large aperture space telescopes. This communication presents

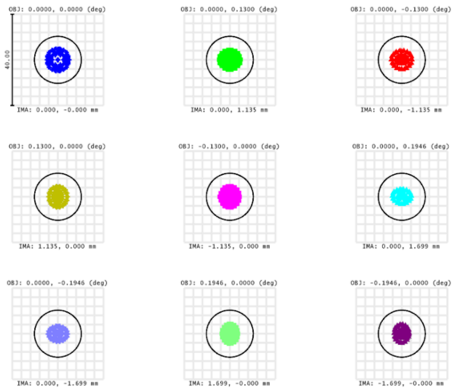


Figure 4: Diffraction limited optical quality of the current layout of the AOCC test bench.

the preliminary design of the AOCC test bench with an optical quality at diffraction limit. The AOCC test bench is a representation of the real instrument used to prove the concept. The main differences between the test bench and the instrument are: throughput is not a main driver on the test bench, space qualified optics is not required in the laboratory, the Performance Monitor is only used on the breadboard and the field of view is limited to what will be used for wavefront sensing, rather than the whole field of view used for observations with the telescope.

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