Active optics system for the 4m telescope of the Eastern Anatolia Observatory (DAG)

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ABSTRACT

An active optics system is being developed by AMOS for the new 4m-class telescope for the Turkish Eastern Anatolia Observatory (DAG). It consists in (a) an adjustable support for the primary mirror and (b) two hexapods supporting M2 and M3. The M1 axial support consists of 66 pneumatic actuators (for mirror shape corrections) associated with 9 hydraulic actuators that are arranged in three independent circuits so as to fix the axial position of the mirror. Both M1 support and the hexapods are actively controlled during regular telescope operations, either with look-up tables (open-loop control) or using optical feedback from a wavefront sensor (closed-loop control).

Keywords: telescope, active optics, wavefront error, hydraulic mirror support, pneumatic mirror support

1. INTRODUCTION

AMOS has recently been awarded for the design, manufacturing and installation of a new 4m-class telescope for the Turkish Eastern Anatolia Observatory (DAG). The telescope is based on a Ritchey-Chretien configuration with two folded Nasmyth focal planes, with a focal length of 56m. The optical train is composed of three mirrors: the primary mirror (M1) with an optical aperture of 4m, a convex secondary mirror (M2), and a flat folding mirror (M3). Because the telescope will be ultimately used with an adaptive optics system in order to reach diffraction-limited performances, specific design provisions need to be implemented at telescope level for enhancement of its intrinsic quality and mitigation of the requirements applied to the adaptive optics. Consequently, an active optics system is developed at telescope level so as to meet its challenging top-level requirements.

The goal of the active optics system is to provide corrections of telescope low-order aberrations at a low temporal bandwidth (typically 0.01 Hz to 1 Hz). It compensates the effects of static errors (such as mirror polishing residuals, and mirror integration errors), as well as slowly varying perturbations (such as deformations of the tube due to temperature or telescope elevation angle changes). In the specific case of this 4-m telescope, the active optics system consists in (a) an adjustable support for M1, and (b) two hexapods supporting M2 and M3. Both M1 support and the hexapods are actively controlled during regular telescope operations.

The telescope top-level requirements are expressed in terms of wavefront error (WFE) decomposition in low-order Zernike modes. The breakdown of the WFE requirement into the Zernike coefficients is shown in Table 1. The Zernike coefficients follow the Noll numbering[1]. Low-order modes are defined from Z5 (astigmatism) to Z78. These requirements are to be fulfilled with active corrections.

The paper is organized as follows. First, the general active optics strategy for the telescope is described. Then, the design of the adjustable primary mirror support is discussed. In particular, it is shown how its performances are modelled and evaluated with respect to the requirement. Finally, the M2 and M3 hexapods are discussed.

Table 1. Top-level low-order WFE requirements

Telescope WFE [nm – RMS]	Zernike coefficients < 78	Zernike 5-6	Zernike 7-10	Zernike 11-15	Zernike 16-21	Zernike 22-28	Zernike 29-78
Requirement	**49**	**25**	**19**	**23**	**19**	**13**	**18**

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2. ACTIVE OPTICS STRATEGY

The M1 axial support and the hexapods supporting M2 and M3 are used during the telescope operations for correcting the residual WFE. The degradation of the telescope WFE may arise from several contributors:

1. Mirror manufacturing (mirror prescriptions and surface shape errors),
2. Mirror position (axial and lateral),
3. Mirror support integration errors (mirror support print-through),
4. Tube deflection with the elevation angle, and
5. Tube deflection with temperature change.

In order to compensate for these errors, a specific strategy is implemented in the telescope (see Table 2.). The focus and field-astigmatism are corrected by M2 and M3 hexapods. The remaining aberrations are corrected by the M1 active support (including the portion of astigmatism that is constant in the telescope FoV, i.e. global astigmatism). The numbers of Zernike modes that can be theoretically corrected by the mirror support only depend on the number of supporting points. However, in practice, it is very difficult to accurately extract the complete set of available modes from the measurement of the telescope WFE, and hence, to be able to correct them afterwards. There are two main reasons: (a) it requires a wavefront sensing system with a very high resolution while keeping a reasonable S/N ratio, and (b) the seeing contribution on high spatial frequency modes dominates the measurement and it is not possible to rely on such noisy measurements for efficient telescope corrections. According to our experiences[2,4], we propose to consider that only the 22 first Zernike modes can be measured accurately and that the active optics control system only allows 22 modes to be corrected.

The optimization of the telescope WFE occurs in three successive steps:

1. Mirror position errors during integration into the tube are corrected by M2, M3 and focal plane alignment means during the initial integration phase (correction only based on mechanical measurements). During this initial phase, the manufacturing errors of the 3 mirrors, i.e. deviations from nominal radius of curvature, conic constant and optical axis orientation, are corrected since they are measured during the manufacturing of the mirror.

2. During the alignment and calibration step, residual mirror position and manufacturing errors are corrected by direct measurement of the telescope WFE. The support errors are also compensated during this step. The mirror position shifts due to tube deflection (with elevation and temperature) are also tracked by WFE measurements and are directly compensated by the two hexapods with an open-loop.

3. The remaining errors are corrected by a closed-loop based on WFE measurements with a wavefront sensor.

Table 2. Active optics implementation strategy

Zernike mode	Compensation strategy
Focus	M2 hexapod (focus at center FoV) M3 hexapod (correction of FP tilt)
Field-Astigmatism	M2 hexapod
Global Astigmatism	M1 active support
Coma	M2 hexapod
Trefoil	M1 active support
Spherical aberration	M1 active support
Zernike 12-22	M1 active support

3. DESIGN OF THE PRIMARY MIRROR SUPPORT

The design of the support of the primary mirror is driven by the need of (1) minimizing the support-induced mirror distortions under telescope operating conditions, (2) shaping the mirror surface to the desired profile, and (3) providing a high stiffness against the wind loads. In order to fulfill these requirements, AMOS proposes an innovative design that consists of 66 pneumatic actuators associated to 9 hydraulic actuators that are arranged in three independent circuits (see Figure 1). The pneumatic actuators actively compensate for low-order telescope pupil aberrations (mainly astigmatism, 3rd-order spherical and trefoil) that are generated by the mirror support itself or by the polishing residuals of the mirrors. Associated with an optical feedback from a wavefront sensor, the active support of the primary mirror can be adjusted on a regular basis during telescope operations so as to minimize the induced errors on the telescope pupil. Under this condition, the active support of M1 allows limiting the induced telescope wavefront aberrations to less than 20 nm RMS WFE.

The axial support contains 66 axial actuators that are controlled independently in force. They use a pneumatic chamber that is continuously controlled so as to apply the desired forces to the mirror. The total number of actuators is optimized for low support print-through, good ability to shape the mirror according to Zernike modes and fast and reliable integration in the cell.

The actuator force is optimized so as to (1) sustain the total mass of the mirror (~ 4300 kg) and (2) apply the appropriate set of deformation forces to get the minimum support print-through. In order to minimize the parasitic forces that could be applied to the mirror during integration of the support, the actuators are connected to the mirror pad by means of two rotational flexures (see Figure 2). The flexures allow rotations of the actuator so as to match the as-built mirror pad orientation, without introducing large parasitic forces and torques in the mirror. The impact of these parasitic forces is considered in the support performance analysis.

Because the actuators are only controlled in force, they exhibit no axial stiffness and cannot fix the axial position and tip/tilt orientation of the mirror. The pneumatic actuators need to be coupled to a system of fixed points. In order to increase the stiffness of the support and limit the impact of wind pressure on the telescope WFE, a distributed fixed-point system is foreseen. It consists in 9 hydraulic actuators that are assembled in 3 sectors. Each sector connects 3 hydraulic chambers together.

In addition to the axial support, the mirror is supported laterally by two sets of 12 lateral pneumatic actuators that apply independent forces on the mirror (one set is pushing the mirror and the other one is pulling it). These forces holds back the mirror lateral weight according to an optimized Schwesinger distribution[3], they are not used to control the mirror shape deformation as the axial support does. Three lateral definers set the lateral position of the mirror and its orientation around the optical axis. When coupled to the three virtual definers that are generated by the hydraulic sectors, they establish an isostatic support for the mirror in which its 6 degrees of freedom are univocally set by the definer position.

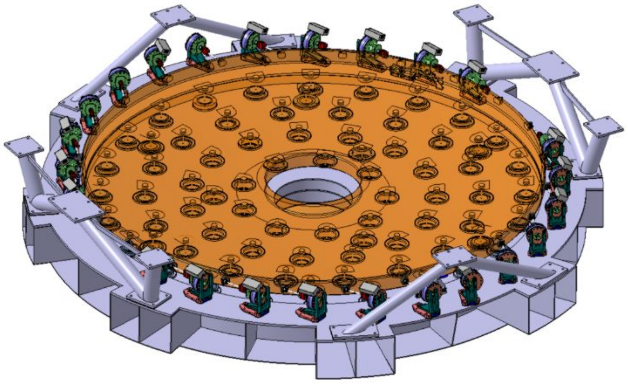


Figure 1. CAD view of the M1 support

Figure 2. Axial actuator: schematics and picture of hardware

Mirror surface figure error budget

A comprehensive analysis of the support is required to demonstrate the adequacy of the proposed support design to the top-level requirement. In particular, the M1 support performances are broken down to lower-level contributions, as developed in Figure 3. The surface errors attributed to each contributor are calculated by FEM and are coupled to the active optics loop for the shape correction, except for the active optics error contributors (e.g. accuracy of the pneumatic force) that cannot be corrected. Five main contributors groups are highlighted:

1. The nominal residues, when the mirror cell is pointing to Zenith (pure axial support) or to horizon (pure lateral support),
2. The deviations of nominal mirror dimensions,
3. The mount errors that consist in alignment errors between the actuator and the mirror pads,
4. The environment, including the temperature, gravity and wind influences, and
5. The active optics errors that contain the errors associated to the actuator forces.

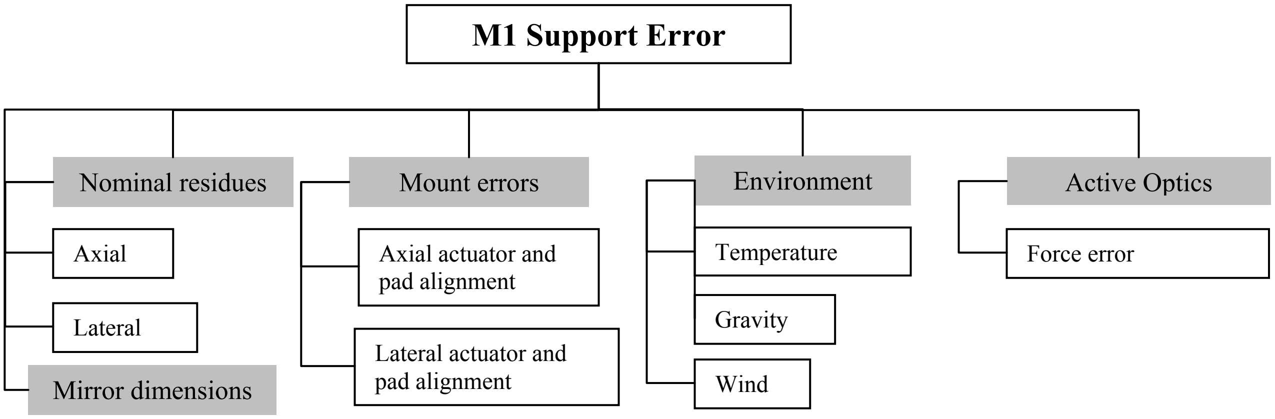


Figure 3. M1 support error budget breakdown.

Each contributor is analyzed separately, and a partial budget for the telescope wavefront error with active optics correction is established. The pneumatic correction forces used for active optics are also included in these budgets (the maximum correction force is considered, independently of the axial actuator location). The RMS WFE are built up with an RSS approach, while the maximum force budget assumes a linear summation. The resulting budget is summarized in Table 3, and the decomposition of the predicted M1 support performances into low-order Zernike modes is reproduced in Table 4.

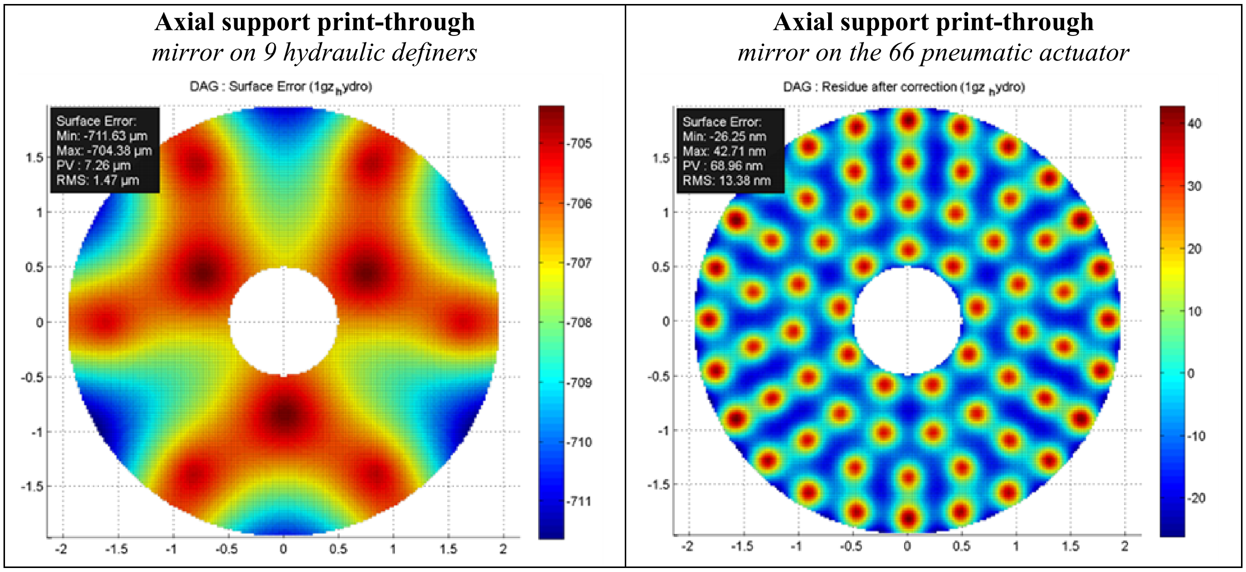
When AO correction is not taken into account, the most important contributions are the print-through of the axial support and the deviations from the nominal mirror dimensions. With active optics corrections, these contributions are significantly reduced. The AO-corrected WFE budget is rather dominated by the active optics errors. These errors mainly induce astigmatism, as shown in the decomposition of the budget into Zernike low-order modes in Table 4.

Table 3. Mirror surface figure error budget and associated correction force budget.

	Telescope WFE w/o active correction Zernike < 78 [nm RMS]	**Telescope WFE w/ active correction** Zernike < 78 [nm RMS]	**Active correction force [N]**
Axial support print-through	**2800**	**10**	**670**
Lateral support print-through	**6**	**1**	**10**
Mirror dimensions	**1000**	**2**	**10**
Axial mount errors	**20**	**1**	**9**
Lateral mount errors	**260**	**1**	**30**
Environment	**40**	**1**	**10**
Active optics errors	**14**	**14**	**-**
TOTAL	**2 985 nm RMS**	**17 nm RMS**	**739 N**

Table 4. Mirror surface figure error budget and associated correction force budget.

Telescope WFE [nm – RMS]	Zernike coefficients < 78	Zernike 5-6	Zernike 7-10	Zernike 11-15	Zernike 16-21	Zernike 22-28	Zernike 29-78
M1 support contribution	**17**	**13**	**1**	**6**	**1**	**5**	**8**
Requirement for global telescope WFE	49	25	19	23	19	13	18



Axial support print-through
mirror on 9 hydraulic definers

Axial support print-through
mirror on the 66 pneumatic actuator

Figure 4. Nominal axial support print-through.

Table 4 compares the predicted active support performances to the top-level requirements. While a comfortable margins is shown, it must not be omitted that other contributions needs to be included into the WFE budget such as the mirror polishing errors and the supporting errors of M2 and M3. Therefore, the contribution of the M1 active support must be kept as low as possible. In this respect, two error contributions are identified as critical:

1. **The print-through of the axial support**. It is shown in Figure 4 where it is modelled as follows. First, the surface error when the mirror lies on the hydraulic definers is calculated by FEM. At that time, there is only a force in the hydraulic actuators, the force in the pneumatic actuator is null. Since the mirror is only supported on 9 points, a large residue (1.5 µm RMS with large impact of trefoil) is observed at zenith. Then, the pneumatic forces are computed so as to optimize the axial support print-through. After the force optimization, the mirror mass is entirely supported by the pneumatic actuators. The pneumatic forces are not uniform so as to compensate for low-order deformations that would be induced if the forces were uniform. Up to 50N of force variations are needed to obtain the low axial print-through of 13 nm RMS SFE, as shown in Figure 5. It is mainly composed of high-order Zernike modes that reflect the signature of the 66 supporting points.

2. **The accuracy of the active optics system**. This contribution encompasses the *imperfect* control of the pneumatic forces. These errors mainly arise from the actuator intrinsic accuracy. The actuators are controlled in closed-loop with regular feedback from force sensors whose accuracy is varying with temperature and orientation. The resulting telescope WFE is less than 14 nm RMS.

Performances of the mirror shape adjustment

The mirror active support is designed to allow Zernike aberrations to be induced on the M1 optical surface. The performances of the support to correct Zernike aberrations are analyzed with the AO correction model. 1 µm of Zernike aberrations are generated on the mirror surface and the correction forces are computed. Residuals RMS SFE and required maximum force (absolute value) are reported in Table 5.

Table 3 reports the efficiency for the corrections for focus, astigmatism, coma, trefoil and spherical aberrations. The required maximum force is also indicated. The efficiency for focus and coma are only indicated for information, as these modes can be easily corrected by the adjustment of the M2 and M3 position.

Table 5. AO performances for Zernike mode correction

Zernike Mode	Amplitude of aberrations [RMS SFE]	Residuals after correction [RMS SFE]	Needed pneumatic force [N]
Focus	1 µm	16 nm	50
Astigmatism	**1 µm**	**4 nm**	**14**
Coma	1 µm	122 nm	230
Trefoil	**1 µm**	**44 nm**	**80**
Spherical Aberration	**1 µm**	**130 nm**	**500**

4. DESIGN OF THE M2 AND M3 HEXAPODS

In parallel, the M2 and M3 mirrors are mounted on hexapods whose position can be adjusted during telescope operations. This adjustment compensates telescope mis-alignments that regularly occur due to variations of the conditions of observations (change of temperature or tube elevation angle). The active control of the position of M2 and M3 is performed either with look-up tables (open-loop control) or using optical feedback from a wavefront sensor (closed-loop control). Hexapods with high accuracies allows positioning the M2 and M3 with a precision better than 1µm and 2 arcsec.

The M2 hexapod is used to correct for focus, field-astigmatism and coma aberration. The other aberrations are corrected by the M1 support. The M3 hexapod is used to correct the tilt of the focal plane. The CAD model of the M3 hexapod, as well as the pictures of a similar hexapod is shown in Figure 5.

The passive support for the M2 and M3 mirror is located atop the hexapod. These supports are optimized to induce very low telescope WFE (below 10 nm RMS WFE).

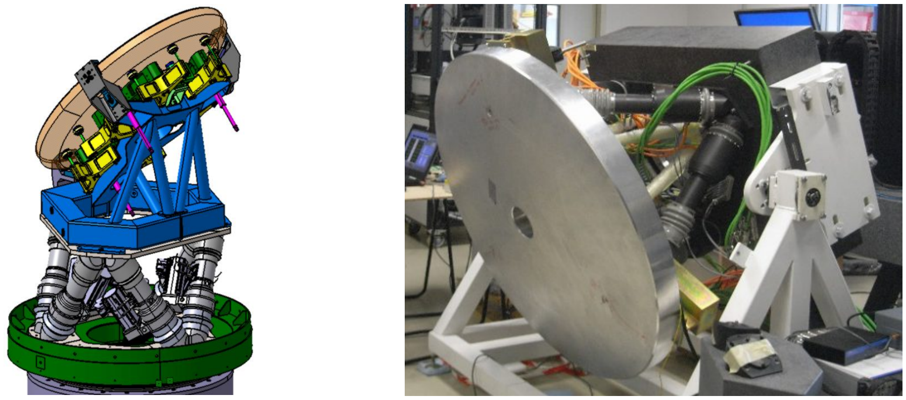


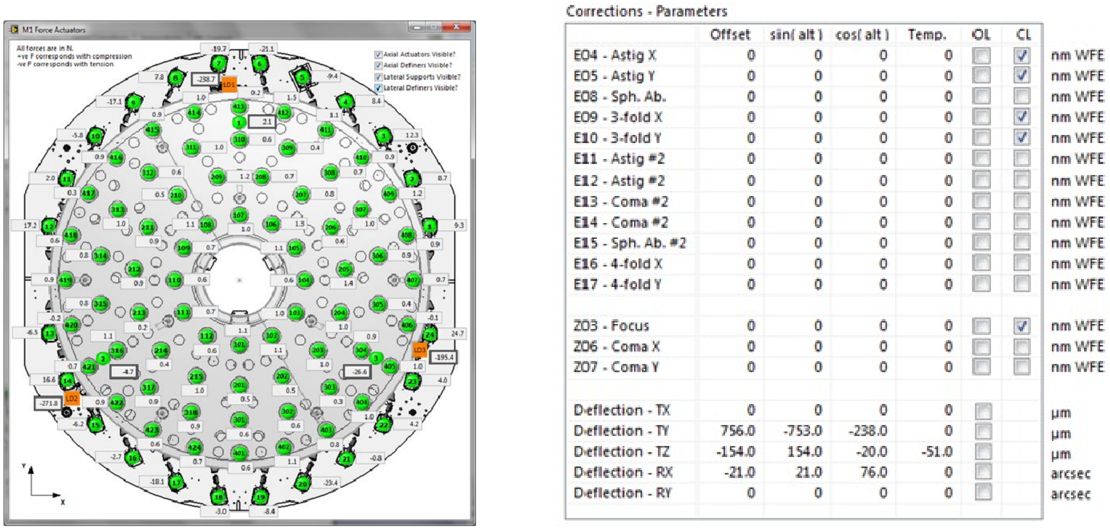
Figure 5. CAD model and pictures of a hexapod

5. ON-SKY DEMONSTRATION OF THE ACTIVE OPTICS CORRECTION

A similar strategy for the control of the active optics system of the 4m DAG telescope has already been successfully implemented on another AMOS telescope, the 3.6 m Indo-Belgian Devasthal Optical Telescope (IDOT)[2]. The active optics system for the 3.6m IDOT telescope has already been demonstrated by on-sky observations.

Figure 6 shows two particular screenshots of the software that is used to control the active optics system (support of the primary mirror and hexapod for the secondary mirror). The force for each actuator of the active support is represented on the left panel of Figure 6. These forces correspond to the corrections modes that are needed to be implemented in the telescope, as shown on the right panel of Figure 6.

Figure 7 highlights some performances of the active optics system that were measured on the 3.6m IDOT telescope. The first panel of Figure 8 shows the evolution of the telescope WFE when the active optics loop is switched on. The telescope WFE is measured by a wavefront sensor whose output is coupled to the active optics control software. The correction modes are calculated and implemented in the telescope. Thanks to this process, the telescope WFE is reduced from 500 nm RMS to about 100 nm RMS. The two remaining panels of Figure 7 illustrates the measured telescope wavefront error when 1 μm of astigmatism or trefoil are set to the primary mirror support. It is shown that the desired shapes are well generated by the active optics system.



M1 Force Actuators

All forces are in N.
+ve F corresponds with compression
-ve F corresponds with tension

☑ Axial Actuators Visible?
☑ Axial Definers Visible?
☑ Lateral Supports Visible?
☑ Lateral Definers Visible?

Corrections - Parameters

	Offset	sin(alt)	cos(alt)	Temp.	OL	CL	
E04 - Astig X	0	0	0	0	☐	☑	nm WFE
E05 - Astig Y	0	0	0	0	☐	☑	nm WFE
E08 - Sph. Ab.	0	0	0	0	☐	☐	nm WFE
E09 - 3-fold X	0	0	0	0	☐	☑	nm WFE
E10 - 3-fold Y	0	0	0	0	☐	☑	nm WFE
E11 - Astig #2	0	0	0	0	☐	☐	nm WFE
E12 - Astig #2	0	0	0	0	☐	☐	nm WFE
E13 - Coma #2	0	0	0	0	☐	☐	nm WFE
E14 - Coma #2	0	0	0	0	☐	☐	nm WFE
E15 - Sph. Ab. #2	0	0	0	0	☐	☐	nm WFE
E16 - 4-fold X	0	0	0	0	☐	☐	nm WFE
E17 - 4-fold Y	0	0	0	0	☐	☐	nm WFE
Z03 - Focus	0	0	0	0	☐	☑	nm WFE
Z06 - Coma X	0	0	0	0	☐	☐	nm WFE
Z07 - Coma Y	0	0	0	0	☐	☐	nm WFE
Deflection - TX	0	0	0	0	☐		μm
Deflection - TY	756.0	-753.0	-238.0	0	☐		μm
Deflection - TZ	-154.0	154.0	-20.0	-51.0	☐		μm
Deflection - RX	-21.0	21.0	76.0	0	☐		arcsec
Deflection - RY	0	0	0	0	☐		arcsec

Figure 6. Screenshots of the software used to control the active optics of the 3.6 m Indo-Belgian Devasthal Optical Telescope (IDOT)

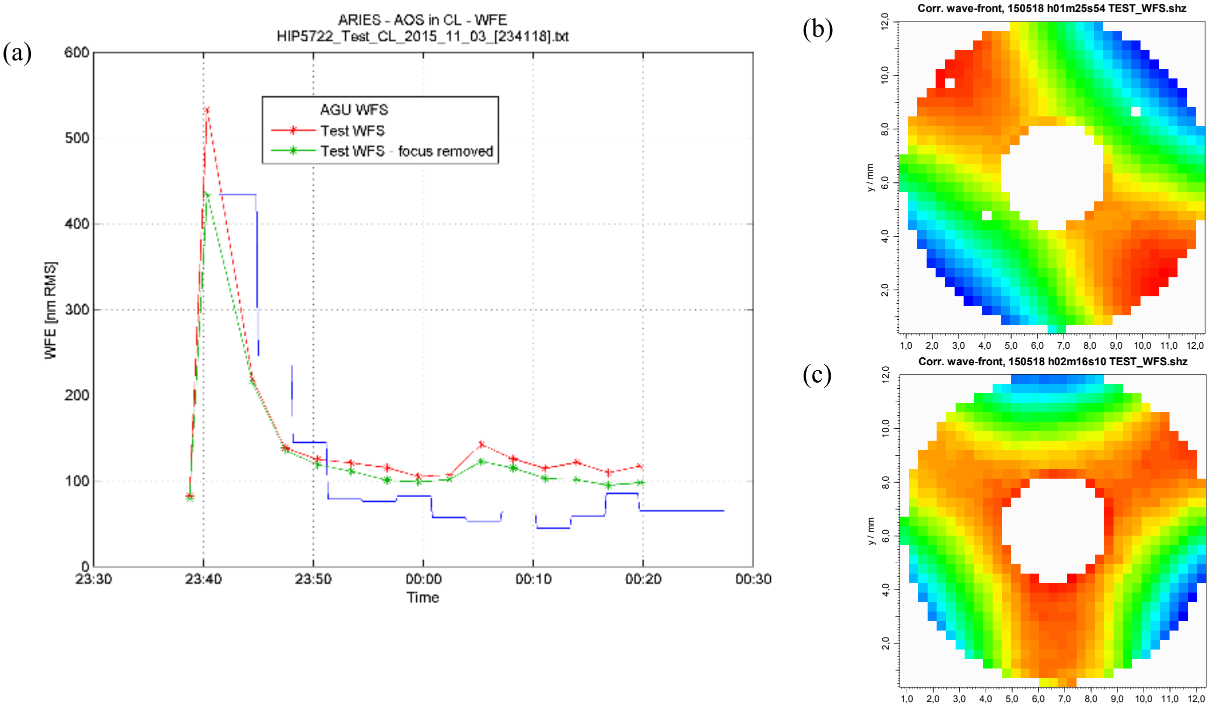


Figure 7. Demonstration of the active optics system on the 3.6 m IDOT telescope. (a) Evolution of the telescope WFE after the active optics loop is closed by feedback from wavefront sensors, (b) measured telescope wavefront error after generation of 1μm of astigmatism and (c) measured telescope wavefront error after generation of 1μm of trefoil.

6. CONCLUSIONS

The active optics system for the Turkish Eastern Anatolia Observatory (DAG) 4-m telescope is described in this paper. It is used to optimize the low-order telescope wavefront aberrations. The wavefront correction is performed by shaping the primary mirror surface thanks to a dedicated support, and modifying the position of the secondary and tertiary mirror that are mounted on accurate hexapods. The mirror position are adjusted so as to correct for focus, field-astigmatism and coma, while the M1 active support is used to compensate for remaining low order Zernike aberrations (up to Zernike mode 22).

The performances of the active support for the primary mirror are detailed and demonstrated to be compatible with the telescope top-level requirements. The impact of the primary mirror (all effects included) is limited to 17 nm RMS of telescope WFE degradation, assuming that the active optics system is used to adjust the mirror shape.

The implementation of a similar active optics system on the 3.6 m Indo-Belgian Devasthal Optical Telescope (IDOT) is finally discussed and on-sky performances of the system are reported. An improvement of a factor of 5 of the telescope WFE has been observed when the active optics system is activated.

The telescope has passed the final acceptance review in the beginning of 2016. The project is now in the procurement phase and all the hardware for the active optics system are being manufactured. AMOS is also currently developing the software for the control of the active optics of the DAG 4-m telescope. The functionalities of the active optics system will be first tested in factory before the transfer of the telescope to the observatory site. The performances of the system will be validated afterwards during on-sky observations.

REFERENCES

[1] Noll, R. J., "Zernike polynomials and atmospheric turbulence," J. Opt. Soc. Am. 66(3), 207 (1976).

[2] Ninane, N., Bastin, C., Flebus, C., and Kumar, B., "The 3.6 m Indo-Belgian Devasthal Optical Telescope: performance results on site," Paper 9906-165, to be published in SPIE Proc. (2016)

[3] Wilson, R.N. , [Reflecting Telescope Optics I], ISBN 3-540-58964-3 Springer Berlin Heidelberg New York pp 405-407 (2000)

[4] Lousberg, G. et al, " OAJ 2.6m survey telescope: optical alignment and on-sky evaluation of IQ performances," Paper 9911-8, to be published in SPIE Proc. (2016)