Testing Active Optics For the National Telescope GALILEO
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Abstract
During february 93 we have made an extensive run of tests at Zeiss (Oberkochen) with the primary mirror commissioned for the Telescopio Nazionale Galileo (TNG) and its active support cell. This test run, succesfully concluded, has been an important step in the process of construction and testing of the optics of TNG.

A review of the results obtained and a brief overview of the TNG cell system is here given.

1. Introduction
The TNG primary mirror support cell allows, like on the ESO's NTT telescope, a high degree of intervent on the optical shape of the reflecting surface acting on the elastic mirror structure. This correction is called modal because subdivided in nearly independent terms (four in the TNG case) matematically represented by Zernike polynomials (ESO's nearly orthogonal polynomials in our case).

The modal action is obtained via astatic levers allowing a computer adjustable contact force with the mirror; moreover, this exchange of force must be monitored through load-cells in order to correctly set the required force on each support and to detect changes of force (for instance during elevation motion).

So particular care is required in understanding the problem of load cells calibration and the hysteresis behaviour of actuators and the way they reflect on the overall optical quality attainable by the Active Optics correction. It is also to point out the crucial importance of a correct calibration of the three fixed support points, taking into account that they are directly concerned with the calibration of the 5th order triangular coma.

The primary mirror of TNG has been manufactured by Zeiss using a passive support cell. The contract specification put the maximum attention to the optical quality for the higher distortion terms, being not affected by active correction. While during manufacturing tests the lower order distortion terms have been analytically removed, during our test phase this operation has been made in active mode in order to verify the overall concept.

The same Zeiss interferometric equipment used during mirror polishing phase has been used during tests in order to assure the best uniformity between results obtained with the passive manufacturing cell and the TNG active cell.

Hereinafter all distortion intensities (with the only exection of 5th order triangular coma) are given in the ESO's nearly orthogonal Zernicke polynomials obtained fitting terms up to the 4th order.

2. The TNG active cell
The TNG active optics cell system is mainly subdivided in:
• the mechanical astatic lever system;
• the computer based control system for actuators.

Both systems are described in detail in Bortoletto et al., 1992, ESO proc. 42, 323; here it is worth only to mention the main properties of the system.

Taking into account only the axial support of the mirror we have:

• 75 astatic actuators placed in four rings;
• 3 rigid actuators, at 120 deg. angle of symmetry.

Each astatic actuator can be computer driven in order to react to the mirror contact with a force between 50 and 100 Kg (force range can be extended making use of springs); this force can be monitored with a precision of about 100 gr through a load-cell. The force delivered by the astatic actuator must take care of the distributed weight of the mirror (passive force), the delivery of the force required for mirror elastic deformation (active force with nearly zero mean on the overall mirror) and the compensation of force changes when the elevation angle changes.

The three fixed supports (only equipped with load-cells) are present in order to define the mirror position on the cell (to avoid spurious tilt and piston terms) and to absorb force residuals after active correction.

The control of the overall system is via a mesh of 80 transputers driven by a host computer. This system must assure:

• computation of correction force patterns based on modal tables;
• fast, parallel intervent and monitoring of actuators when required.

3. Purpose of tests

The foreseen goal of tests to accomplish was:

• to recognize whether it was possible to obtain similar optical quality as the one obtained by Zeiss (nearly perfect) using our cell and active correction of low frequency modes;
• to calibrate each active correction mode using the interferometric results and to compare them with modal tables as given by Schwesinger (J. of Mod. Opt. 1988, 35, 1117);
• to understand the effect of support errors (load-cell readout-noise, support hysteresis, calibration errors) on the obtained result;
• to verify the effect introduced by the presence of the three fixed points;
• to have a global verification of the informatics control system (speed and reliability) when loaded with the complete system.
Preliminary tests on the assembled cell were made, during a previous run, in Ansaldo (Genova) in order to check both the mechanical parts and the control equipment. At that time we made a calibration of load-cells in grams using two calibrated sample weights and a simple linear transformation of units.

In fact it was not expected to have, in this way, a good absolute calibration; it was more important to have a good estimate of increments or decrements of force because they are directly concerned with the modal correction on the mirror shape. This calibration has been adopted throughout all the performed tests.

4. Results

The first step on the test activity has been the understanding of the correct matching between our conventions on the description of the cell geometry and those used by Zeiss in their interferometric equipment. This has been obtained checking the resulting position of two confidence marks created on the mirror (see the wedge and rectangle at the border of each interferogram) and crosschecking some created artificial distortions (mainly astigmatism) on the resulting interferogram.

Fig. 1.a and 1.b show the phase map of the mirror at the beginning of operations and at the end of the correction procedure. In particular, at the start (Fig. 1.a) the mirror distortion has been dominated, as expected, by astigmatism and spherical aberration (about 1600 nanometers of spheric and 500 of astigmatism). After several trials it has been possible to reach a global RMS error on the wavefront of about 39 nanometers. The DEE (Diffraction Encircled Energy) computed for the two situations and for the pure diffraction case is reported on Fig. 2.

A calibration of the distortion tables has been independently made for the four active distortion terms applying, one at a time, a cycle of plus and minus 500 nanometers of distortion (400 in the quadratic astigmatism case due to system allowed dynamic); in all cases we used a phase angle equal to zero.

Table 1 shows the results obtained at the end of each cycle; one can show here the resulting errors in terms of:

- required force on actuators against measured force (mean error and RMS). This is in fact a check on the quality of the support system;
- required distortion against measured distortion (term by term). This is the true calibration of active modes;
- resulting cycle hysteresis (term by term).

It is to be noticed the interpretation of the error for the first two terms (SPHERIC and ASTIG) is somewhat difficult. In fact spherical aberration is extremely sensitive to the distance between mirror and the null-lens system (this distance can change during measurements) and the astigmatism is stimulated by small amount of differential force beeing it close to the first natural flexure mode of the mirror. As an example 500 nanometers of quadratic astigmatism are introduced with 15 peak kg while the same amount of astigmatism is introduced with only 2.5 peak kg.
The hysteresis is computed as the error in magnitude and phase per each term after a complete calibration cycle. They appear to be very small with a tendency to introduce a uniform rotation on the pupil plane and some undercorrection.

During the correction trials it has been verified the practical possibility to reach an RMS wavefront residual error of about 10 nanometers for each distortion term. In practice the final accuracy is dominated by astigmatism and 5th order coma residuals. For instance, when applying large corrections, like in Tab. 1, the maximum experienced spurious astigmatism was of about 100 nanometers. So a second iteration is necessary in order to clean the wavefront.

The 5th order coma residual is concerned with the presence of the three fixed points; we made a simple correction producing a uniform offset force in all astatic actuators. We found, in our case, a rough calibration of 80 nanometers of 5th order coma per Kg.

Fig. 3.a and 3.b show the 500 nanometers astigmatism calibration. In Fig. 3.b we have the simulated wavefront obtained adding the required astigmatism to the distortion terms already present on the mirror before the force application; this can be compared with the result on the mirror shown in Fig. 3.a.

The same comparison can be made from the point of view of the force map on the mirror; Fig. 4.a shows the force distribution (from inner to outer supports, ring by ring) as obtained from the cell after application of astigmatism and Fig. 4.b shows the residual errors after comparison with computed forces.

5. Conclusions

The primary mirror for the TNG telescope has been tested on the active cell. It has been practically verified the possibility to act in all low order distortion terms and to reach the required optical quality.

The active optics control system has also been extensively checked; both software and hardware demonstrated a good reliability and speed of execution. The time needed to read and display all 78 forces or to make an active correction was of few seconds.

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Fig. 1.a M1 interferogram at the beginning of operations. Predominant distortion is due to astigmatism and spherical aberration. The computed wavefront RMS error is 207 nanometers.

Fig. 1.b M1 interferogram after iterative subtraction of spheric, astigmatism, triangular coma, quadratic astigmatism and residual 5th order coma. The computed wavefront error is 39.7 nanometers.

Fig. 2 Encircled energy for the two cases reported in Fig. 1.a and Fig. 1.b compared against the diffraction limited case.
Fig. 3.a Calibration of the astigmatism mode. Interferogram obtained with +500 nanometers of distortion.

Fig. 3.b Synthetic wavefront for the calibration of the astigmatism mode.

Fig. 4.a Map of measured forces on the 78 actuators (from internal to outer ring) after application of +500 nanometers of astigmatism.

Fig. 4.b Residual force errors obtained after comparison of measured forces against computed forces.