Status Progress of AdOpt@TNG and offer to the international astronomical community.

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ABSTRACT

The Adaptive Optics Module of the Telescopio Nazionale Galileo (AdOpt@TNG) has enjoyed a huge refurbishment. A new WaveFront Sensing CCD (EEV39 80x80pixels by SciMeasure) has been mounted, allowing for up to 1KHz frame rate. Thanks to the versatility of the pyramid wavefront sensor, the fast changing of the 4x4 and 8x8 pupil sampling has been easily and successfully implemented. A dual pentium processor PC with Real-Time Linux has substituted the old VME as Real Time Computer. The implementation of the new Deformable Mirror by Xinetics will be also discussed. A new Graphical User Interface has been built to allow for user-friendly utilization of the module by astronomers. On-sky observations will be presented in terms of FWHM and Strehl Ratio for different values of guiding star magnitudes and seeing conditions. The encouraging on-sky results and overall system stability pushed to offer AdOpt@TNG to the international astronomical community.

Keywords : Adaptive Optics, Pyramid Wavefront Sensor, TNG

1. INTRODUCTION

In every modern ground-based telescope, there is an Adaptive Optics System compensating the atmospheric turbulence in such a way to fully exploit the theoretical resolution power fixed by the telescope diameter and by the observing wavelength. Not only the **T**elescopio **N**azionale **G**alileo (**TNG**) has an Adaptive Optics System, but it is the first ground-based telescope that implemented a wavefront sensor of new conception : the **P**yramid **W**ave**F**ront **S**ensor (**PWFS**).

The **Ad**aptive **Opt**ics module @ **T**elescopio **N**azionale **G**alileo (**AdOpt@TNG**) allows for **T**ip-**T**ilt (**T/T**) and **H**igh **O**rders (**HO**) correction of wavefronts distorted by atmospheric turbulence.

The T/T correction can be obtained by mean of two different systems:

- 4 **A**valance **P**hoto **D**iode (**APD**) detectors to measure the tilt aberration introduced in the wavefront by the atmospheric turbulence and a fast-steering off-axis parabolic mirror to correct it in real-time;
- the innovative **P**yramid **W**ave**F**ront **S**ensor (**PWFS**) to measure the tilt aberration introduced in the wavefront by the atmospheric turbulence and a fast-steering off-axis parabolic mirror to correct it in real-time.

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The HO correction is based on the **PWFS** to measure the high order aberrations introduced in the wavefront by the atmospheric turbulence and on a **D**eformable **M**irror (**DM**) to compensate them in real-time.

Now, the PWFS+DM system is offered to the AdOpt@TNG User.

The AdOpt@TNG was implemented on 1998. Since then a lot of tests were done and encouraging results were obtained. Avalanche PhotoDiode Tip/Tilt (APD-T/T) first close-loop was successfully got on early 1999. The star selected to be first sharpened has been HD 116258 of magnitude V=7.9 and at the moment of the observation its zenithal distance was about 37 degrees. The seeing was about 1.5" (V band), then not so suitable to perform a very good T/T correction. The signal reaching the APD-T/T wavefront sensor was sampled at 2ms and filtered with a low pass filter having a single pole at 5Hz. In Figure 1 images taken in K' band (λ=2.1 μm) with the infrared camera Arnica (pixel size 0.14arcsec) and an exposure time of 60s are shown.

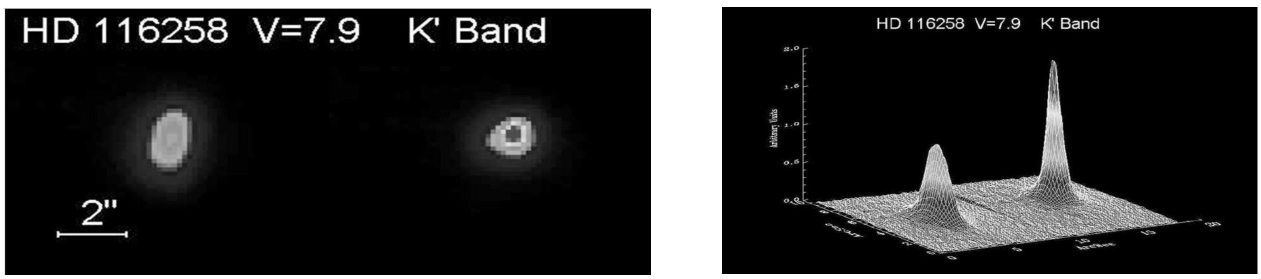

Figure 1 : In the left side of the figures there is the open loop image (no Tip-Tilt correction) showing an elliptic shape of FWHM 1.15x1.85arcsec^2 where the elongation is due to a residual tracking jitter. In the right side there is the image obtained with the Tip-Tilt correction system switched on (closed loop): the star is nearly round, the tracking jitter is completely removed and the FWHM is 0.95arcsec.

On 2001 the PWFS began to work allowing for measuring all the optical perturbations caused by atmospheric turbulence and compensating them by means of the T/T and the deformable mirrors. The diffraction limit of the telescope had been regularly reached with a V<15 guiding star magnitude in <0.8arcsec V seeing conditions with the old DM. A **F**ull **W**idth **H**alf **M**aximum (**FWHM**) of ~ 0.14arcsec in K' and a **S**trehl **R**atio (**SR**) of ~ 0.4 have been measured in star field such as the one reported in Figure 2 (summer 2005). Some technical problems arose during this long way but finally they have been solved permitting to offer the module fully working to the international astronomical community.

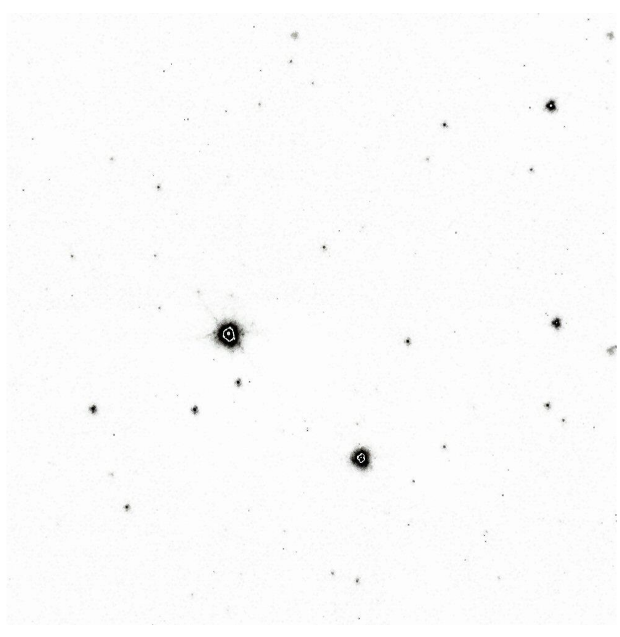

Figure 2 : K' image of star field U1200_13900162

2. AdOpt@TNG MODULE and the FIRST HUGE REFURBISHMENT

In Figure 3 the AdOpt@TNG is shown. It is attached on one of the two Rotator Adapters of the telescope, at Nasmyth A focus side. It mainly lies on an optical table attached there. This peculiar configuration introduces some problems. First of all, accessibility to some opto-mechanical components is quite uncomfortable and make it difficult on-site alignments and maintenance. Moreover, it causes flexures in some optomechanical components which introduce small changes in the optical path which obligate to reset some parameters for each Rotator Adapter observing range.

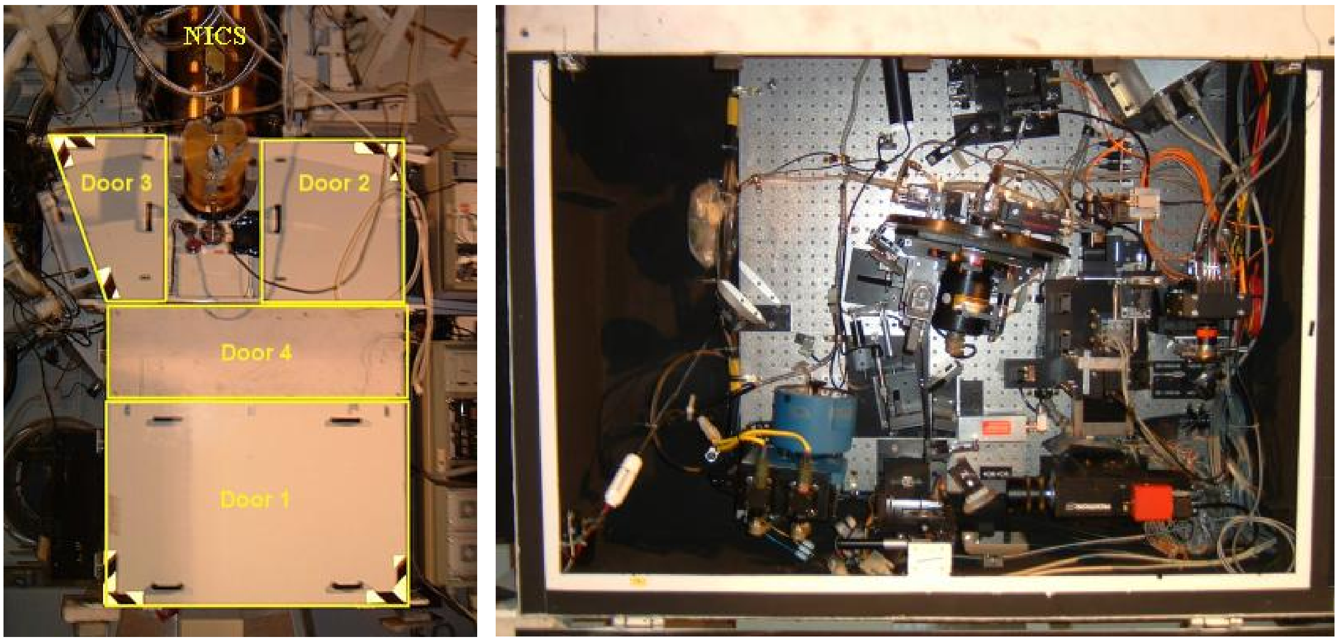

Figure 3 : A photo of AdOpt@TNG Module and its accessing doors (left). On top, the NICS infrared scientific camera is also partially visible.

To briefly describe the AdOpt@TNG Module, a layout is sketched in Figure 4. The wavefront, collected from the telescope, is driven by M3 towards the Pick-Up Mirror (AO_M1) which sets the F/11 focus in the position shown in the same figure. Here the first real image of the sky field-of-view is formed. A micron stage allows for moving the Fiber Holder (FH) in the F/11 focus position so that 1 to 4 fibers could simulate a 1 to 4 stars field-of-view of ~1 arcmin diameter for the following optical system so that to test the module in daylight time. A multi-mode fiber, emitting HeNe Laser (632.8nm) or red LED light, or a single-mode fiber, emitting visible and infrared light till $\lambda \sim 2\mu$m, can be set in FH. Then, the wavefront focused in F/11 follows its path towards the AO_M2 mirror which is the first Off-Axis Parabola (OAP1) of the overall system. It is a fast-steering mirror and corrects for the tilt component of the wavefront distorsion caused by the atmospheric turbulence according to the information coming from the APD system or from the HO **W**ave**F**ront **C**omputer (**WFC**).

The wavefront proceeds towards the AO_M3 mirror, that is the Deformable Mirror (DM), which compensates the HO optical aberrations caused by the atmospheric turbulence according to the commands coming from the Waverfront Sensor Computer.

Then, the wavefront proceeds towards the second Off-Axis Parabola (OAP2) which drives the beam towards the AO_BS1 Beam Splitter system composed by a wheel in which one open window and 3 dichroics are mounted and selectable. The open window is selected when the Speckle system (not visualized in the sketch) is used. The 3 dichroics split the wavefront into two ones with different percentage of reflected (visible) and transmitted (infrared) components. The infrared (scientific) component is used by the scientific channel (NICS) while the visible (reference) one is used by the wavefront sensing channel.

The dichroics are slightly tilted in such a way the wavefront sensing component refocuses in F/32 focus, previously passing through AO_M5 and AO_M6 mirrors. Then, AO_L1 lens images the pupil in the mechanical center of the x-y tilting mirror AO_M7 which allows to adjust alignments and to set the reference star in the right calibrated position for closing the loop. The following optomechanical component AO_BS2 allows to set a dichroic to 50/50 split the beam or to set an hole to let it totally passing. One component of the split beam is focused by the camera AO_L2 passing through AO_M8 and AO_M9 mirrors and the corresponding image is used to center the reference star in the right calibrated position by means of the x-y tilting mirror AO_M7 or the telescope itself. The other component of the split beam passes through lens AO_L3 and the optomechanical component AO_BS3 which allows : i) to set a 50/50 dichroic which splits it in a part towards the PWFS and the other one towards the APD, ii) to set an hole through which all the beam passes to the APD or iii) to set a small mirror which reflects all the beam towards the PWFS.

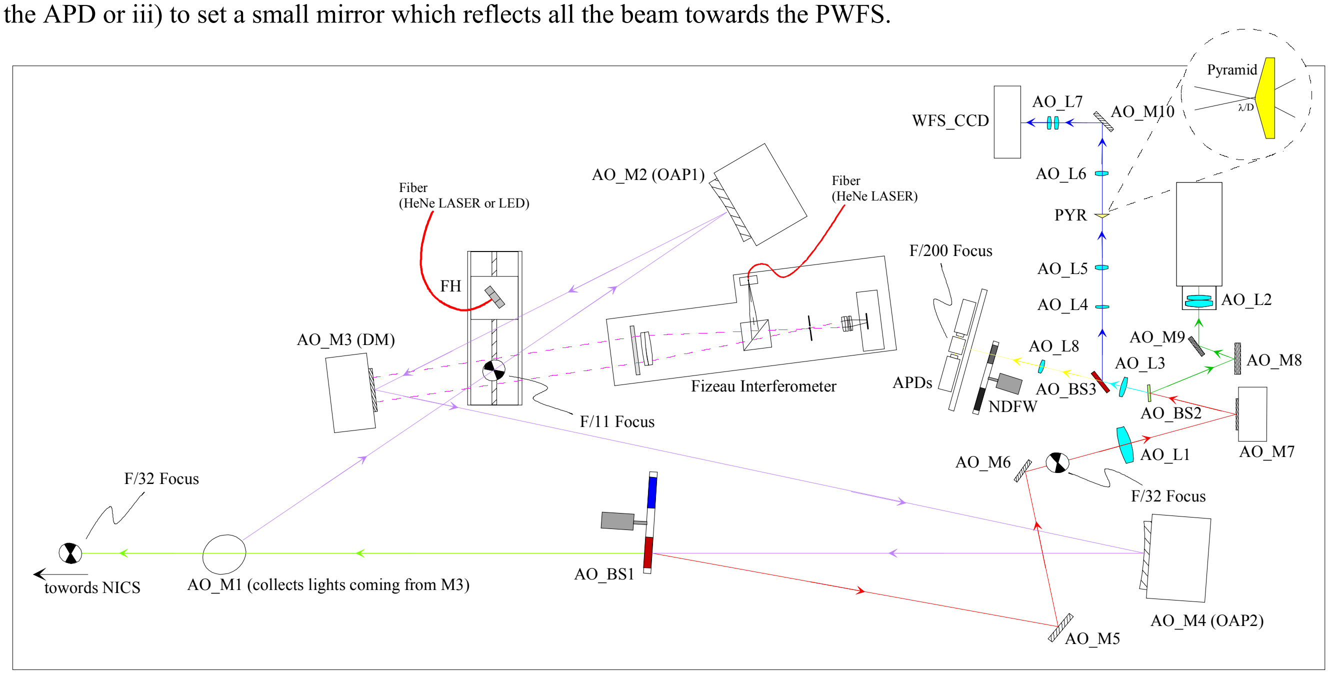

Figure 4 : Sketch of the AdOpt@TNG Module. See text for a brief explanation.

The beam driven to the APD is focused, by means of AO_L3+AO_L8 lens system, in the center of an image dissector which splits it into four beams whose 2mm pupil is imaged onto the APD detector by F/200 lenses (not sketched in the figure). By measuring the flux of each of these four beams, in normal direction each to the other, it is possible to compute the tilt component of the aberration introduced by the atmosphere and send the corresponding compensation to the AO_M2 T/T mirror to freeze image motion caused by that. A NDFW neutral density filter wheel allows to attenuate too bright reference stars.

On the other side, the beam driven to the PWFS is focused, by mean of AO_L4+AO_L5 lens system, onto the top of a 4-edge pyramid glass, hearth of this kind of wavefront sensor . Four beams exit from the pyramid and the corresponding four pupils are imaged onto the wavefront sensor CCD (WFS_CCD) with a given magnification by means of the AO_L6+AO_L7 lens system (being also 45° reflected by the AO_M10 mirror). The intensities of corresponding pixels of the four pupils are processed to compute the wavefront distorsion and consequently send compensating commands to the actuators of the DM. On September 2001, the Adaptive Optics Team of the Telescopio Nazionale Galileo, led by R. Ragazzoni, has successfully closed the higher orders loop using the PWFS mounted on the AdOpt@TNG module. It was the first time ever that this kind of sensor was used in an AO system to close the loop on real stars: it can be considered a milestone for the AO technology! The result is clearly seen in the K' band, 50sec images of a mv=7.7 star in the direction of Cygnus in Figure 5. The open loop image (on the left) shows a single diffuse object while the closed loop one (on the right) puts in evidence the two components of a double star with ~0.2arcsec separation. The brightest component has a FWHM~0.16arcsec, next to the diffraction limit of the TNG at that wavelength. SR, as evaluated from these first result, turns out to be ~ 0.16. Images were taken through an Optical Density=2 Neutral Filter to avoid saturation on the Near Infrared Camera Spectrometer (NICS). The loop was closed at a CCD frame rate of 25Hz. This important result has become a reality thanks to the direct effort of a lot of people and the support of many others who we would like to thank once more from here.

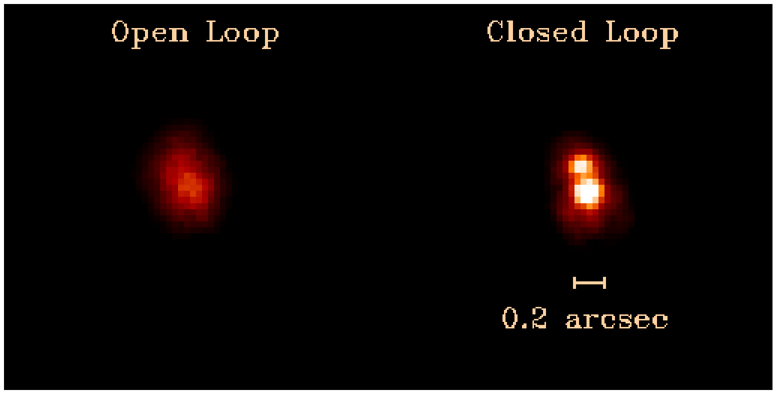

Figure 5 : mv=7.7 star in the direction of Cygnus. Open Loop (on the left) and Close Loop (on the right). This has been the first on-sky Close Loop test with the PWFS.

An on-sky test campaign was also done in a 2003 observing run (*Ghedina et al., 2003, SPIE Proc.*) followed by a huge refurbishment of the module, exploiting the stop of observations due to major works at the telescope. Such refurbishment included : i) recoating and cleaning of the optics; ii) new polishing, recoating and repairing of the DM (Xinetics); iii) setting-up of a Twymann-Green interferometer to test the DM surface; iv) substituting the old wavefront sensor CCD with a new commercial one (SciMeasure, EEV39 80x80pixels); v) substituting the VME-based Real Time Computer with a dual Pentium PC processor based on Real-Time Linux; vi) substituting the HP and SUN Spark work station with another PC Linux as User Work Station.

The new wavefront sensing control system allows for several different read-out modes (programs) listed in the Table 1. The frame rate of the old wavefront sensing control system was less than 100Hz so an improvement in speed of a factor of ~ 20 is possible taking into account the best frame rate of the new one. Moreover, a selectable pupil sampling (allowing for different limiting magnitudes of the operating reference star for given seeing conditions) is possible without any variation of the optical system, thanks to the possibility of simply changing in real-time the binning mode of the wavefront sensor CCD. This possibility underlines another advantage of the new PWFS concept in front of the traditional Shack-Hartmann one which needs a physical substitution of the lenslet arrays for a different pupil sampling. Besides that, an higher sensitivity is obtainable, increasing the limiting magnitude of the reference star.

Program	Actual Pixel Rate (kHz/port)	Image Size after binning	Binning	Filter	Filter TC (ns)	Nominal Max Frame Rate (Hz)	Actual Max Frame Rate (Hz)	Actual Min Frame Time(ms)	Actual Readnoise (e-)
0	203	40	2	4	1100	366	366,394	2,7293	3,7
1	382	40	2	3	690	672	672,359	1,4873	4,4
2	193	20	4	4	1100	1120	1110,445	0,8933	4,2
3	350	20	4	3	690	1826	1903,674	0,5253	4,6
4	204	80	1	4	1100	103	103,241	9,6861	3,6
5	455	80	1	3	690	227	227,578	4,3941	4,6
6	1136	80	1	2	48	564	553,434	1,8069	4,8
7	2038	80	1	1	30	996	977,613	1,0229	7,3

Table 1 : Read-out modes (programs) available in the new SciMeasure wavefront sensor CCD mounted on AdOpt@TNG.

The new SW to control the wavefront sensor CCD was completed with the implementation of the 2x2 binning in the wavefront sensor CCD (Image Size=40pixels, Pupil size = 8 binned pixels). The high-orders loop was closed, the test star (point-like fiber) was frozen even if disturbed by an artificial turbulence generated inside the module. Unfortunately, in the testing run, 4 to 5 actuators of the DM were broken and the DM was powered with a reduce voltage equal to 30% of the nominal one, limiting in such a way the stroke of each actuator and consequently the amount of turbulence compensation. A provisional mask was set to stop the beam in the pupil region with the broken actuators. A new DM was ordered. On 13 August 2004, the high-order loop was successfully closed again also on-sky, freezing the atmospheric turbulence and obtaining very promising images. The huge refurbishment on the AdOpt@TNG module was successful but other upgrades were waiting for improving more its performances.

3. The SECOND REFURBISHMENT

Before and after the poor observational summer 2005 because of few good-seeing available nights, a second (mainly electronic) refurbishment of AdOpt@TNG started.
The new (Xinetics 97-actuators) DM arrived and it has been mounted. Anyway, some electronic failure were discovered in the electronic driver which power the actuators. The power output corresponding to each of the 89 actuators was measured and the working actuator map shown in Figure 6 has been built to understand which driver channels to check.

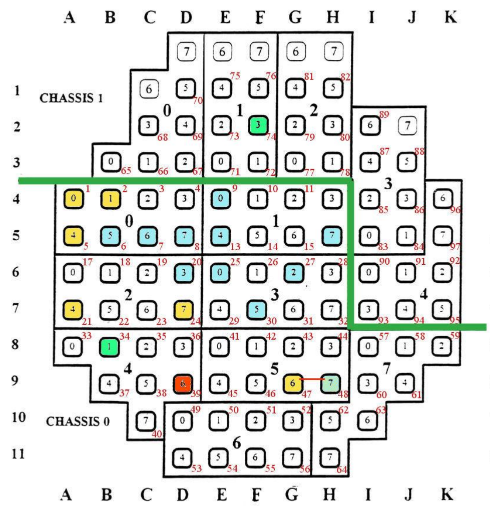

Figure 6: Map of the Channels which do not work in the Driver Boards of the WaveFront Computer.

By accurately testing of the suspected channels, the electronic experts of the team discovered some broken resistors and fuses in the electronic circuit schematically shown on the left side of Figure 7. The cause of electric overcharge that has damaged them is yet unknown. During the operation of replacement, it was noted that some of these resistors had a power dissipation ability of 1/8 to 1/2 Watts, probably too much low in respect of the flowing electric current and resistance. So, the substituted resistors saved the same resistance of 22ohm but were selected with 1Watt power dissipation ability. Some R219-type positive resistors broke while the corresponding R220-type negative one saved. Anyway, all these resistors were substituted on all channels in all the boards. Moreover, some fuses broke. All of them were of 250mA and were substituted with 315mA ones.

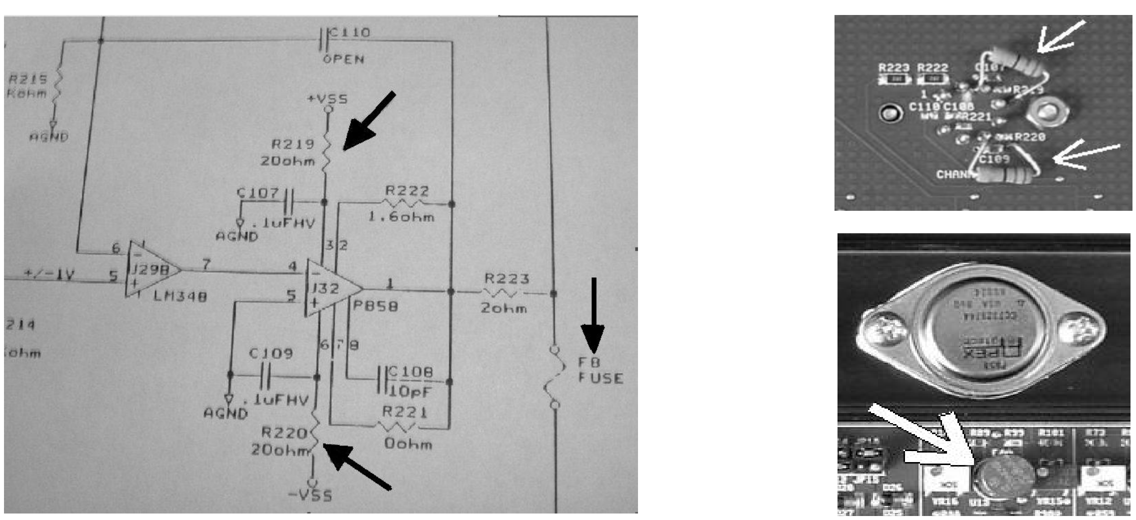

Figure 7 : The part of the electronic scheme of the damaged circuit (on the left). Some R219-like positive resistors (top on the right) and fuses (bottom on the right) broke. The R220-like negative resistors (top on the right) save but were changed anyway.

Then, the power output corresponding to each of the 89 actuators was measured again with success. Now, the digital command correctly translate in the right voltage to the piezoelectric actuator of the mirror. The cables were attached to the DM connector and an interferometer was used to test the optical response of each actuator of the DM. The result was successful. Each actuator moves according to the actual voltage digitally applied. Then, some successful on-bench test were done to close the HO loop with different control matrices, frame rates and gain of the T/T and HO mirror.
After the mounting of the new DM, the optical path was realigned with the single-mode fiber by getting a SR ~ 0.80 and a FWHM ~ 0.14arcsec in K`-band on the scientific camera NICS with the DM switched off. The same measurements will be done with the DM switched on and the surface will me examined by using the Fizeau Interferometer still in construction and shown in Figure 8.

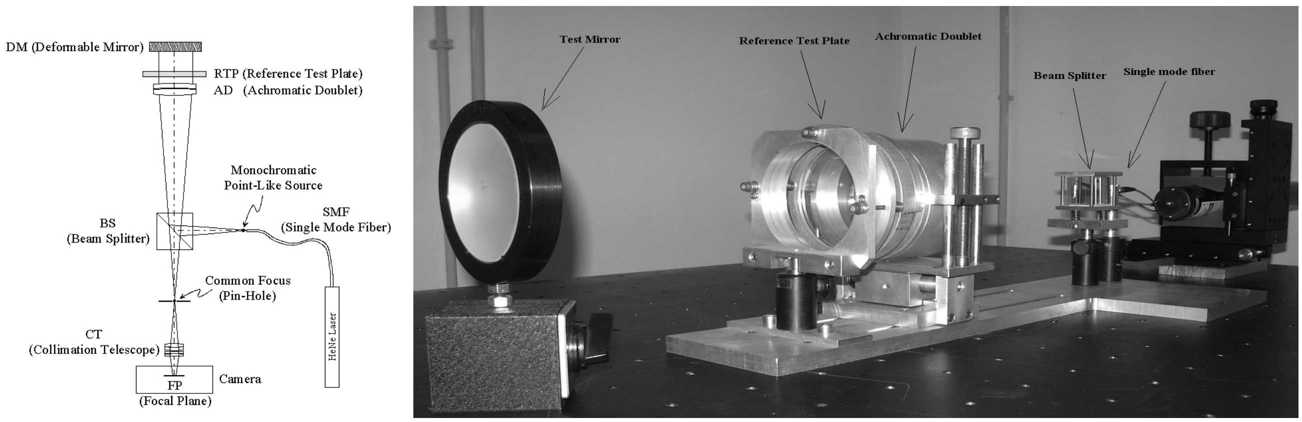

Figure 8 : The Fizeau Interferometer. Sketch (on the left) and under construction one (on the right).

The other important upgrade of AdOpt@TNG was a new User InterFace (see Figure 9) to control the loop parameters and an Engineering Interface (Figure 10) to control the parameters of other optomechanical components of the module.

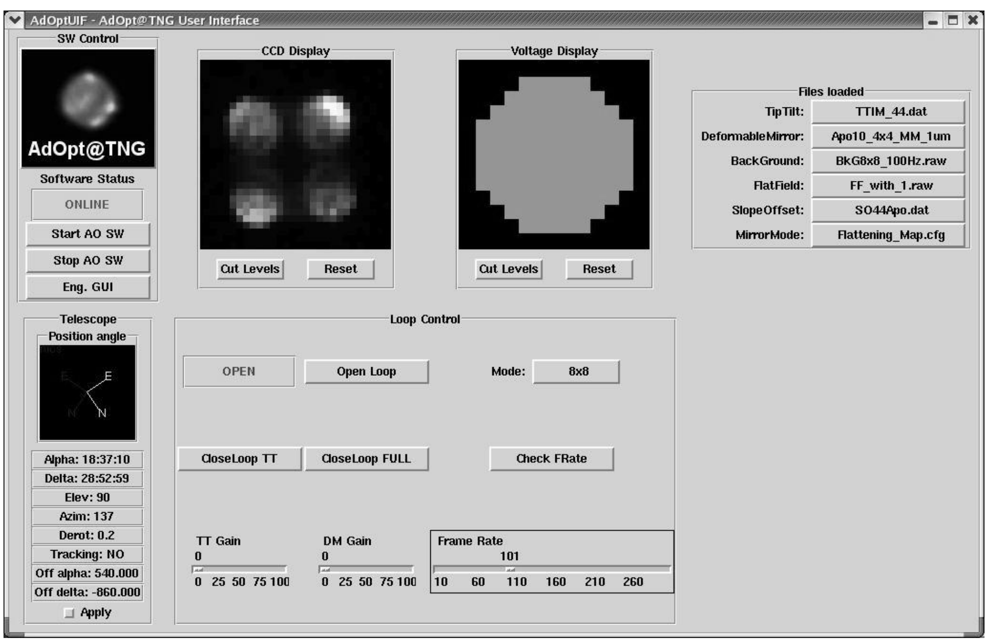

Figure 9 : The new User InterFace of AdOpt@TNG. All the loop parameters can be controlled.

Now it is also possible to offset the telescope and to move the Nutating Mirror (AO_M7 in Figure 4) in such a way to maintain the Guiding Star in the center of the Pyramid during the object observation.

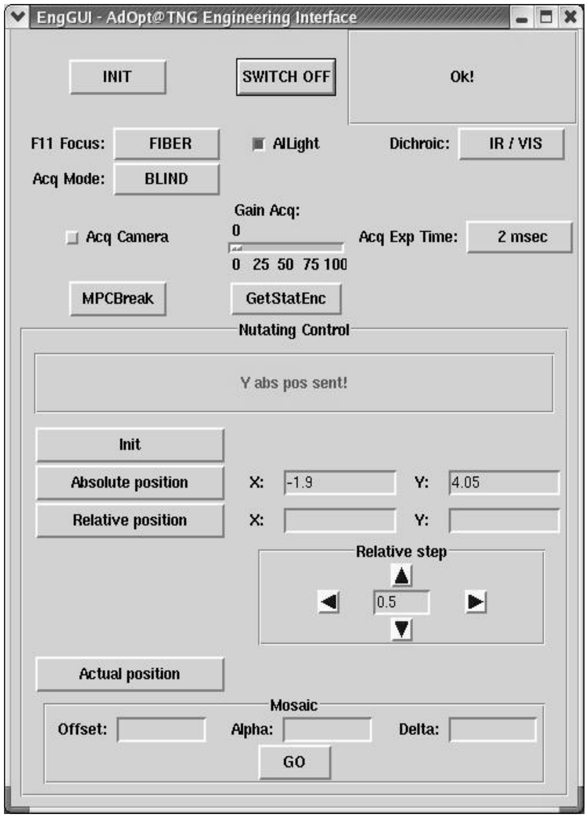

Figure 10 : The new Engineering User Interface of AdOpt@TNG. All the engineering parameters can be controlled.

CONCLUSIONS

After some years of successes, problems, refurbishments and upgrade, now the AdOpt@TNG can be offered to the international astronomical community with good working capabilities. In the running AOT13 observational program, 7 proposal were submitted and 3 of them were accepted. We are encouraging all possible candidates to apply for using this instrument. Targets inside a circle with 30arcsec radius and a V<15-16magnitude guiding star in its center will be acceptable for observation in good seeing conditions (~0.6-0.7arcsec in V in the summer, probably even worst with the new fully operative DM). For any further information, please, do not hesitate to contact cecconi@tng.iac.es or Skype account "maxcek".

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