On Sky Test of the Pyramid Wavefront Sensor

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ABSTRACT

The Adaptive Optics for the Telescopio Nazionale Galileo module (namely AdOpt\textsuperscript{TNG}) implements the pyramid wavefront sensor as a unique feature. This allows to get valuable information on its performance on the sky. An updated overview of the results obtained so far is shown, including a discussion on the sources of errors in the closed loop operation, distinguishing them between the ones specific of the pyramid wavefront sensor and the one more related to the system as a whole. This system allows also for a number of experiments and check of the sensitivity of such a wavefront sensor, especially in comparison with other types of sensing units. The ways to accomplish such an experiment in a convincing way are shown along with the first results obtained so far. Finally, we describe how and up to which extent a number of practical problems encountered in the near past can be solved implementing the recent new ideas on the pyramid theme, many of which popped up from our "lessons learned".

Keywords: Adaptive Optics, wavefront sensing, limiting magnitude

1. INTRODUCTION

The Telescopio Nazionale Galileo\textsuperscript{1} is the first astronomical telescope that implements the Pyramid Wavefront Sensor (PWFS in the following) in its Adaptive Optics system (AdOpt\textsuperscript{TNG}).\textsuperscript{2} We chose the innovative solution of the PWFS\textsuperscript{3} because from the theory it seemed to be a competitive wavefront sensor, easy to implement, superior in gain especially in closed loop,\textsuperscript{4} easily rebinable without extra RON or extra optics, and being a pupil plane wavefront sensor is easily scalable to multi-reference layer oriented wavefronts, being in this manner ideal for Multi Conjugate AO (or MCAO\textsuperscript{5}). Laboratory experiments also have shown some of the PWFS capabilities.\textsuperscript{6} In short words the choice of the PWFS with respect to the Shack–Hartmann is simply due because the PWFS finds its superior gain using the whole aperture of the telescope to sense the aberrations on the wavefront, instead of subapertures which produce spots that in closed loop are $D/\theta_0$ greater than the PWFS one. The advantage of using a PWFS is even more if the number of subapertures of the SH increases.

We have at the TNG the opportunity to demonstrate on sky what the PWFS can do when pointing at real stars and we have found that at least it is not inferior to what other wavefront sensor offers (see Fig.1). But we found something more.

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2. THE ADOPT@TNG SETUP

As described in many previous papers\(^7\), the main component of the PWFS is the pyramid which splits the light of the guide star in a 2-dimensional Foucault–like way. The one for AdOpt@TNG was made by the Golem group of Merate Observatory, derived from a BK7 lens, and has \( \approx 13\mu m \) turned edges.\(^8\) A system of two lenses reproduces the F/32 focus on the pin of the pyramid, then another system of lenses, after the pyramid, reimages the pupil into the WFS detector.

The pyramid can be kept fixed in its position or moved in a circular way to obtain a modulation (other solutions that we didn’t choose are to move the beam instead of the pyramid with a tip/tilt mirror\(^7\) or to introduce a static modulation with a diffusing plate in a pupil plane\(^9\)). The modulation allows the PWFS to have a variable gain that can be tuned to optimally sense the incoming wavefront perturbation. Our pyramid is mounted on a Phisike Instruments XY stage, orthogonal to the optical axis, and frequencies and amplitudes of the modulation have been checked with an oscilloscope to correspond to the desired ones. The frequency of the modulation is essentially determined by the WFS detector exposure time (an EEV 39) and must be chosen properly in order to complete an integer number of periods between two exposures.

An important feature of the PWFS is that it can also be used to simulate a SH sensor, for example with a pupil sampling of \( 4 \times 4 \), when modulating at an amplitude of \( \pm 4\lambda/D \), where \( D \) is the diameter of the pupil. When modulating the pyramid with such amplitude in fact the spot size (even if in closed loop and approaching the diffraction limit) is equivalent to the spot produced by each single lens of the SH sensor, that is equal to \( \lambda/\pi \), and in any case not smaller than \( 4\lambda/D \) for a \( 4 \times 4 \) sampling. Four pupil images are produced on the detector and a simple reordering of the pixels (by taking from each of the 4 pupils the corresponding pixels, see also\(^8\)) is enough to reconstruct and simulate the pixels organization of a SH sensor, thus providing informations on the derivatives of the incoming wavefront. This allowed us to easily do the on sky comparison of these two kind of sensors with the further advantage of keeping the other overall conditions similar for the two sensors. We simply had to switch on (SH) and off (PWFS) the modulation of the pyramid to change between the two sensors. The procedure we adopted also ensured that the seeing condition were not changing considerably between the observation with the two sensors.

It is worth noting anyway that we experienced a discrete number of downtime for many reasons among which the WFC electronic, the DM, and the IR camera. A broken actuator on the edge of the DM forced us to put an off-axis obstruction over that zone of the mirror thus reducing of about the 5% the amount of light that goes through the AO system but also, and maybe this is the worse part, leaving behind the mask some uncontrolled actuators. Furthermore, for the same reason, we had to reduce the input for the high voltage of the actuators drivers thus loosing half of the available stroke, a constraint that turned out to be of extremely
importance at the moment of building the reconstruction matrix: we had to reduce considerably the steps of
the actuators in order to avoid system instability and divergence. We also still experience in the system several
non-common-path aberrations, which up to now we have not begun to identify and remove. The result is a net
decrease in the final Strehl of the images.

Another point worth mentioning is that to override some major arithmetic faults of the WFC we decided
to not divide the wavefront sensor slopes by the total flux on the subapertures, thus being forced to change
the value of the slopes accordingly to the magnitudes of the observed stars. There is now an automatic procedure
inside the WFC that scales the value of the slopes to the measured total flux but we had previously to be sure
of the linearity of the measured slopes with respect to the incident flux. Results are reported in Fig.2.

![Figure 2. Linearity of slopes versus flux variation](image)

The fact that the pyramid can be modulated or not, and also modulated at different amplitudes, forced a
discussion about what was to be considered as the right equivalent gain for when the modulation is off (PWFS)
and on (SH). It has been well pointed out that the sensitivity of the PWFS can be varied by changing the
modulation amplitude of the pyramid, and for the same wavefront aberration the response is higher when
the dinamic modulation is smaller. This simply means that if you find the best gain for the correction when
simulating a SH sensor and then decide to shift to no modulation, you have to scale the gain accordingly
otherwise the system becomes instable.

One solution could be to change of a factor $K$ the gain between the modulations, with $K$ roughly proportional
to the amplitude of the modulation expressed in terms of $\lambda/D$. Otherwise one could decide to start from the
highest value of gain for the no-modulation, which is the case when the PWFS experiences the highest sensitivity,
and keep that gain fixed when changing the amplitude of the modulation. One further option is to increase
the gain of the system, for each amplitude, up to the instability regime and then reducing it to the previous
stable step. This is the solution we adopted also because it is the way we would use to decide the gain during
the observations. In order to avoid the accumulation of rounding errors we had some practical constraint in the
way we could change the gain and, actually, we cannot change it continuously but at some predefined steps.
Although we observed that the finest gain changes do not play any significant role, in some cases we have been
forced to keep the gain essentially unchanged even under different conditions.

3. OBSERVATIONS

The measurements described in the following have been made shortly before re-coating of the three main
mirrors of the telescope, two of which were more than 5 years old. Moreover the AdOpt@TNG module itself
introduces 10 further reflections and 18 air-glass interfaces before the WFS detector. Although the scientific optical channel incorporates only 4 silvered reflections and of course a couple of air-glass interfaces at the dichroic level, the coating of these surfaces were not, at the moment of taking the measurement, in good shape. We are not, however, in the position to quantify how much the coating deterioration is decreasing our light collecting capabilities. In the following of this paper we discard all these considerations, simply because such hampering is common to both the SH and the PWFS approach. However one is warned that some improvement in the absolute limiting magnitude can be obtained by a refurbishment of the optical surfaces involved.

The aim of the test was, as we said previously, to measure the performances of the PWFS as compared to another sensor, the SH, by keeping the overall conditions of the system unchanged. Our intention was also to investigate on the sky if it is simply better to not modulate than to do it. For this we introduced a further amplitude of $\pm \lambda/D$ in the modulation to extend the test comparison to the option suggested in another work. We chose for this purpose a set of stars with scaling magnitudes and for each star we took a series of closed loop images, with the IR or visible camera, alternatively switching the modulation of the pyramid off and on, for a total of 3 modulations of the PWFS on each star, namely $0$, $\pm \lambda/D$, $\pm 4\lambda/D$. At our plate scale on the pin of the pyramid, being the effective F ratio $F/32$, and at the effective wavelength of sensing ($\lambda = 800\,\text{nm}$) the modulations of $\pm \lambda/D$ and $\pm 4\lambda/D$ correspond respectively to a circular modulation with diameter $\approx 51\,\mu\text{m}$ and $\approx 205\,\mu\text{m}$. Actually we splitted the pupil into $\approx 8 \times 8$ subapertures, although correction was performed only up to the first 14 K-L polynomials. Accordingly to the number of corrected polynomials we would need a SH sensor with something more than $4 \times 4$ subapertures. However we conservatively used a modulation of $\pm 4\lambda/D$ to mimic such WFS, in order to make even more robust our conclusions. Another point to remind is that the pyramid we used, one of the first to be made for AO purposes, is not a perfect pyramid, having some turned edges of $\approx 13\,\mu\text{m}$ in size, as we said before. The effect of these edges is to produce a light loss that depends on the amplitude of the modulation. To a small amplitude corresponds a high scattering of the flux, so much that considering as 1 the flux when the pyramid is stopped, we measured fluxes of 1.14, 1.24, 1.26 respectively for amplitudes of $\pm \lambda/D$, $\pm 4\lambda/D$, $\pm 8\lambda/D$. Again, not accounting for this light loss will result in favour of the simulated SH with respect to the PWFS. At the level of the data discussed here we did not consider this effect, pushing in the direction of more conservative measurements.

The differences in performance were obtained by direct Strehl measurements on the scientific cameras. It can be seen from Tab.1 that because of the changing conditions, between the sets of measurements (and not during the observations of the same star), we could not directly compare the data. We decided to refer all the measurements to the same observing wavelength ($2.2\,\mu\text{m}$) and removing the effect of some attenuation factors, as we explain in the following.

Occasionally one set of observations was performed with two 50-50 beam-splitters in the WFS channel in order to simultaneously recover engineering data with an ICCD camera, not described here. The flux attenuation (only 25% of the light reached the detector) introduced by these have been carefully measured with differential throughput measurement (with and without dichroics) and performed directly with the WFS detector. Moreover we have not trusted at all the specification on the optics given by the manufacturer and we are very confident on the measure we got experimentally for the decrease in flux introduced. The magnitudes have then be simply

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<td>z</td>
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Table 1. Stars observed for the test on the Pyramid Wavefront Sensor

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scaled by a factor of $\Delta mag_{BS} = 2.5 log(4)$ to the case where such dichroics were absent.

The same measurements were also affected by low atmospheric transmission (Sahara sand and dust particles in the sky, also called Calima) and we scaled them of $\Delta mag_{calima} = 0.45$ following the independent extinction measurements available on the WEB of the Carlsberg$^{12}$ and of the Mercator$^{13}$ telescopes.

Also due to the downtime of the IR camera some measurements have been obtained in the visible channel, with a $z$-Gunn filter. The Strehl Ratios we derived from these data, obtained at a different observational wavelength, had then$^{14}$ to be scaled properly in order to compare them to the IR measurements. The effect on the Strehl of observing at different wavelengths deserves a bit more of discussion. In fact computing the Strehl as

$$S = e^{-\sigma^2}$$

where $\sigma^2$ is the wavefront variance, the latter can be expressed$^{15}$ as the sum of several independent components of photon noise, sensor noise, bandwidth delay, aliasing and fitting as:

$$\sigma^2 = \sigma_{ph}^2 + \sigma_n^2 + \sigma_{bw}^2 + \sigma_{aliasing}^2 + \sigma_{fit}^2.$$  

We consider here only two of these components, in particular photon noise $\sigma_{ph}^2$ and sensor noise $\sigma_n^2$, which depend explicitly on the ratio between the wavefront sensor and science camera wavelengths

$$\sigma_{ph}^2, \sigma_n^2 \propto \left( \frac{\lambda_{ws}}{\lambda_{sc}} \right)^2.$$  

They are also the ones which depend on the number of photons per subaperture per integration time, $N_{ph}$. We can then rewrite Eq.1 in the following manner

$$S = S_0 e^{-\sigma^2(\lambda_{ws}/\lambda_{vis})}$$

including into $S_0$ all the wavelength-independent terms. The expected result can be seen in Fig.3 and is that the performances of the system decrease together with the lack of photons, and when the signal photon noise begin to dominate we have that

$$\sigma_{ph}^2 \propto \left( \frac{\lambda_{vis}}{\lambda_{vis}} \right)^2 \frac{1}{N_{ph}}.$$  

Changing the science camera wavelength (from $\lambda_{vis}$ to $\lambda_{vis}$) produces a change in the number of photons proportional to the square of the wavelengths ratio,

$$\left( \frac{\lambda_{vis}}{\lambda_{vis}} \right)^2 = \frac{N_{ph}(\lambda_{vis})}{N_{ph}(\lambda_{vis})}$$

and thus defining in this manner the difference in magnitudes between the two sets of data of Tab.1. It turns out that we have to shift the magnitudes of a value equal to

$$\Delta mag_{d} = 2.5 log \left[ \left( \frac{\lambda_{vis}}{\lambda_{vis} - Gunn} \right)^2 \right].$$

Finally, we want to recall again that for every measurement we took several Strehl data with the three different amplitudes in the modulation of the pyramid, but within a negligible amount of time between one measurement and the following.

### 4. RESULTS

To override in the analysis of the results the above mentioned problems of the change of the atmospheric and instrumental observing conditions we also decided to explore only the ratio between the Strehls and not the absolute values, referring the data of the 51$\mu$m and 205$\mu$m amplitudes to the no-modulation data as it can
The expected Strehl decreases with magnitude and is here plotted for a 3.6m telescope \((r_0 = 20\text{cm},\ \text{8} \times \text{8 sampling},\ \text{integration time is 0.05s, total transmission efficiency of 0.02 at the WFS})\) and supposing two different values of flux reaching the WFS. The solid line corresponds to the SH case, while the dashed one is the same curve shifted of +1mag. Bottom: The ratio between the two Strehl. The height of the curve increases with the difference in magnitudes between the two upper curves; the width of the bell varies with their slopes.

Figure 3. Top: The expected Strehl decreases with magnitude and is here plotted for a 3.6m telescope \((r_0 = 20\text{cm},\ \text{8} \times \text{8 sampling},\ \text{integration time is 0.05s, total transmission efficiency of 0.02 at the WFS})\) and supposing two different values of flux reaching the WFS. The solid line corresponds to the SH case, while the dashed one is the same curve shifted of +1mag. Bottom: The ratio between the two Strehl. The height of the curve increases with the difference in magnitudes between the two upper curves; the width of the bell varies with their slopes.

A fit of the experimental data of Fig.4 shows that the PWFS performs marginally better, being the mean value of the ratio \(1.12 \pm 0.04\), when there is no dynamic modulation of the pyramid. Anyway we have to point out that the residual of the correction on the pin of the pyramid can be considered as a modulation itself, from which it seems straightforward that it is better to not modulate. However we have always been during the observations in the condition that the correction was not full but limited, that is far from the diffraction limit on the pin of the pyramid, a regime where maybe other diffraction effects could play an important role.

The plot of Fig.5 is the result of the ratio between the Strehl obtained with the PWFS and the SH, or the \(\pm 4\lambda/D\) amplitude. We suspect we had additional problems in the system during the equivalent \(V = 11\) star measurements, because the Strehl is unexpectedly low in such a case and the point simply shows that a common trouble dominates the SH and PWFS measurement. This also would explain the small experimental error bar where, in fact, because one of the Strehl would be very low, the ratio variance should be significantly larger than the data collected at lower equivalent magnitudes. For this reason we preferred to exclude this point from the data fit.

We searched the best fit to our experimental data with a set of curves generated with the analytical model described before, using the overall efficiency and the equivalent gain as a free parameters. We also introduced as a free parameter the maximum slope of the curve \(S(\text{mag})\), of Fig.3top. This translates into a different aspect ratio for the Gaussian shape of the Strehl ratio in Fig.3bottom. In fact we found that the numerical simulation we performed, taking into account a number of degradation effects rising at the faint end, show that the Strehl can drop in a range much smaller than the \(\approx 7\) magnitudes seen in the theoretical plot.
Figure 4. Ratio of S for no modulation (PWFS) versus $\lambda/D$ modulation. Mean value is $1.12 \pm 0.04$. The difference in magnitudes between this plot and the observed star is explained in the text.

Figure 5. Ratio of S for the no-modulation (PWFS) versus $\pm 4\lambda/D$ (SH) modulation. See the text for an explanation of the fit.

In particular we found a well consistent fit with an overall efficiency of 2\% (considering the number of surface reflections-transmissions and the QE of the CCD), a gain of in between $\approx 0.9 - 1.0$ magnitudes and a Strehl degradation that is much faster, $\approx 50\%$, than the analytical one.

The magnitude gain is in agreement with the figures reported in Esposito & Riccardi\textsuperscript{11} for a residual correction of $1\text{rad}^2$ (looking at their Fig.5) while the Strehl slope requires an independent numerical estimation and/or an experimental verification that is under progress at the moment of writing this paper. Anyway the obtained behavior is not so different from the figures obtained in independent simulations for other wavefront sensors.\textsuperscript{17}

A short discussion deserves the absolute value of the magnitude in Figs.4 and 5. As we pointed out in advance there is still some room for improvement, especially as far as the optical surfaces coatings and the...
accuracy of edge of the pyramid are concerned, however it is worth noting that the limiting magnitudes that pop up from these measurements are similar to the ones of much other 4m class AO system\(^{18}\) at least looking carefully to measured performances rather than to predicted ones.

5. CONCLUSIONS

Even if we experienced a discrete number of problems and downtime we have been able to show some of the capabilities of our adaptive optics system. Some important results turned out from our on sky tests and we think that we are on the right way. We think that the main drawback of the pyramid sensor is that it is still in development and AdOpt@TNG is up to now the only adaptive optics system that implements this solution for the wavefront sensing. However other institutes are now following our same choice for their AO systems, in particular MPIA (with PYRAMIR\(^{19}\)) and the LBT,\(^{20}\) or have a look to the other papers in this conference\(^{21}\) which talk about the MCAO projects of LBT (NIRVANA\(^{22}\)) and ESO (MAD\(^{23}\)). Hopefully then the situation will change in the near future.

One of the important results we found here is that, at least in the conditions we experienced, it seems not necessary to modulate the pyramid of the PWFS, or the spot relative to it, or to introduce a static modulator: the residual of the correction itself acts on the pin of the pyramid as a modulation.

From the analysis of the data we reasonably think that there is a consistent gain in the use of a PWFS with respect to the SH. It is clear that when the sensitivity of the SH begins to drop the PWFS still keeps its power, for at least \(\approx 0.9 \sim 1.0\) magnitudes, even if the decrease of Strehl with magnitudes seems somehow excessive when compared to what is the expected behavior found in the literature. Our aim is now to perform further tests, with better observing conditions, to confirm and hopefully to increase the positive values obtained with these data, and maybe to find a stronger agreement with the theory.

The other important result is that from the data we have we can say that the limiting magnitude of AdOpt@TNG is well within the range of other 4-m class telescopes. It is to be noticed, at the end, that we did not experience any particular trouble in the bootstrapping phase and we have secured all the data described here without any of the bootstrap procedures suggested,\(^{4,24}\) vanishing the fear that the bootstrap capability could prevent the effective achievement of the pyramid gain.

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