The pyramid wavefront sensor aboard AdOpt@TNG and beyond: a status report

Roberto Ragazzoni\textsuperscript{a}, Simone Esposito\textsuperscript{b}, Adriano Ghedina\textsuperscript{c}, Andrea Baruffolo\textsuperscript{a}, Massimo Cecconi\textsuperscript{c}, Emiliano Diolaiti\textsuperscript{d}, Jacopo Farinato\textsuperscript{e}, Luca Fini\textsuperscript{b}, Enrico Marchetti\textsuperscript{c}, Alfio Puglisi\textsuperscript{b}, Massimiliano Tordi\textsuperscript{a} and Elise Viard\textsuperscript{a}

\textsuperscript{a}Astronomical Observatory of Padova, Padova (Italy)
\textsuperscript{b}Astrophysical Observatory of Arcetri, Firenze (Italy)
\textsuperscript{c}Centro Galileo Galilei, Santa Cruz de la Palma (Spain)
\textsuperscript{d}Department of Astronomy, University of Padova, Padova (Italy)
\textsuperscript{e}European Southern Observatory, Garching (Germany)

ABSTRACT

The concept of Pyramid Wavefront sensor has been introduced as a more compact and flexible alternative to Shack–Hartmann wavefront sensing. In the past five years, however, such a novel concept promised a much larger sensitivity and an inherent easiness to be implemented in a multiple reference wavefront sensor: AdOpt@TNG, a natural guide star based adaptive optics module implemented at the 3.5m TNG telescope is equipped with such a sensor. We report here on the updated status, including on-sky experimental verification of various of the several features of such a sensor. We discuss the results obtained, their scalability and the lessons learned in building, aligning and operating it. Some comparison with theoretical and laboratory-based result, is also tentatively reported.

Keywords: Wavefront sensors, pyramid, multi-conjugate adaptive optics, layer-oriented

1. INTRODUCTION

The pyramid wavefront sensor\textsuperscript{1} (PS) has been conceived in 1995. It uses the same principle as the Foucault\textsuperscript{2} knife-edge optical test but in two directions: a pyramid pin placed at the vertex of the telescope focus divides the incoming light in four beams and a lens forms four images of the telescope pupil. The modulation of the pyramid, realized for instance by vibrating the pyramid itself or by an oscillating tip-tilt mirror conjugated to the exit pupil, allows to collect quantitative information on the wavefront derivatives along orthogonal directions. The PS gain can be adjusted changing the modulation amplitude, while sampling can be tuned by either changing the focal length of the aforementioned lens or by rebinning in various formats the detector.

Extensive tests have been performed in the laboratory\textsuperscript{3,4} in order to investigate the capability of the sensor to correct a static wavefront aberration. In closed loop, a RMS wavefront error of about 30nm has been achieved with a starting RMS error ranging from 170nm to 300nm.

In parallel Ragazzoni and Farinato\textsuperscript{5} have pointed out the higher sensitivity of the PS with respect to a SHS in closed loop operation. In such a condition, in fact, the pyramid modulation tends to zero and the spot size on the pyramid is very small, essentially determined by the diffraction on the telescope aperture $D$. A low-order wavefront aberration, for instance a tilt of magnitude $\lambda/D$, produces a spot shift comparable to the spot size itself and therefore a large signal. In the case of a SHS, instead, the spot size is determined by the diffraction on the lenslet aperture, so that the spot shift due the same wavefront tilt is only a small fraction of the spot size and the resulting signal is much lower. The same reasoning applies also to higher orders, even though the largest gain occurs on the low orders. The main consequence of this higher sensitivity is a gain on the limiting

\footnotesize{Further author information: (Send correspondence to R.R., Email: ragazzoni@pd.astro.it)}
magnitude of the reference source. This result has been extended by Esposito and Riccardi\textsuperscript{6} also to the partial correction regime.

The PS noise propagation coefficients have been obtained for three different tip-tilt modulation amplitudes; a comparison to the theoretical Shack-Hartmann wavefront Sensor (SHS) noise propagation coefficients\textsuperscript{7,8} has shown a good match and the above mentioned expected performances have been experimentally verified.

The PS has been implemented on AdOpt@TNG\textsuperscript{9,10} the adaptive optics module of the Telescopio Nazionale Galileo\textsuperscript{11,12} (TNG). In this paper we report on the current status of the sensor aboard the adaptive optics module and we discuss the possible future developments related to layer-oriented Multi-Conjugate Adaptive Optics (MCAO) systems.

2. PYRAMID WFS ABOARD ADOPT@TNG

The AdOpt@TNG module is permanently installed at the Nasmyth A interface of the TNG telescope. Wavefront sensing and correction is splitted into tip-tilt and high orders. While tip-tilt sensing is possible using an APD-based sensor, the PS allows to measure both tip-tilt and higher orders. The pyramid component can be vibrated up to a frequency of 100Hz with 250\(\mu\)m peak-to-valley amplitude. It produces four pupil images onto a four quadrants 80 x 80 pixels EEV39 CCD. A fast CCD controller allows for up to 400Hz frame rate with \(\approx 7e^{-}\) RMS read-out-noise. The wavefront computer (WFC) is a real-time matrix multiplier able to evaluate slopes from pixel intensities and perform the matrix multiplication to transform the measured slopes into commands for the deformable mirror (DM), according to a user-specified reconstruction matrix.

![Figure 1](image)

Figure 1. The loop has been closed on a V \(\approx 6\) star, observed in K' band. The seeing FWHM was \(\approx 1.40'\). The tip-tilt correction (open circles) shrinks the image width down to FWHM \(\approx 1.10'\) and a further reduction to FWHM \(\approx 0.84'\) is achieved with high orders correction (filled circles).

The first on-sky test was done during an engineering run in 1999\textsuperscript{10}. The loop was successfully closed both on tip-tilt and higher orders, despite the very bad seeing conditions (Fig. 1). A second engineering run was done in 2000, but it was not successful due to the repeated failures of the WFC. Then the WFC, CCD and its controller have been brought back to Italy for an overall revision. A third engineering run has been recently done, mainly aimed at system characterization. Even in this case, however, the seeing conditions were not optimal (FWHM \(\approx 1.2'\)).

A major on-going effort is to implement a high-quality experimentally determined reconstruction matrix, in order to improve the high orders correction and the achievable Strehl ratio. A set of data has been obtained during the last engineering run for such a purpose. In practice the DM has been configured to reproduce a set of Zernike polynomials, which represent a basis for a modal decomposition of the aberrated wavefront. For each generated Zernike, ranging from \(Z_4\) to \(Z_{38}\), a set of 100 slope vectors has been obtained, corresponding to 100 measurements (Fig. 2). Each vector represents the PS output and is composed of 128 values (64 slopes for each orthogonal direction). The average of the 100 vectors corresponding to a given Zernike is an estimate of
Figure 2. Top: slope measurements for the first 25 Zernike polynomials (piston, tip and tilt excluded) generated on the deformable mirror. Each slope arrow is averaged over 100 measurements. Bottom: Zernike coefficients derived from the measured slopes using the reconstructor obtained by numerical inversion of the experimental interaction matrix. Each Zernike coefficient is the average of 100 values.
the expected output to the examined polynomial. All the average vectors have been collected in an interaction matrix, which has been numerically inverted to yield the reconstruction matrix. The latter, matrix-multiplied by a measured slope vector, may be used to compute the Zernike coefficients for the modal expansion of the aberrated wavefront. In order to check the accuracy of the result, the reconstructor has been applied to the measured slope vectors, thus obtaining 100 realizations of each Zernike coefficient of interest. The average value of each coefficient is in good agreement with the expected value (Fig. 2).

3. PYRAMID WFS AND LAYER–ORIENTED MCAO

A very interesting field of application of the PS is layer-oriented Multi-Conjugate Adaptive Optics (MCAO). The basic approach is to place several pyramids in the telescope focal plane, one for each reference star, and then combine the beams by means of a single relay, optically adding the light of the stars. The result is a 3-dimensional anamorphic copy of the sensed atmospheric volume, where two or more detectors can be placed, conjugated to different atmospheric layers. In the simplest version of layer-oriented, each detector drives an associated deformable mirror (DM), conjugated to the same layer.

![Figure 3](image-url) In a multi-reference, layer-oriented MCAO system, the reference beams are focused onto the telescope focal plane of focal ratio $F$. The pyramids split the light in four beams each (only one is shown here for simplicity) and an objective of focal length $f_L$ forms four pupil images of size $s$.

Some interesting results have been recently obtained concerning practical issues arising in the implementation of a layer oriented system. Most of these achievements are based on the properties of the PS. The first problem is related to the size of the pupil images, given by $s = f_L/F$, where $f_L$ is the focal length of the relay lens and $F$ the telescope focal ratio (Fig. 3). Considering the minimum clear diameter of the re-imaging lens $d_L \geq \theta f$, where $\theta$ is the Field of View (FoV) and $f$ the telescope focal length, the minimum pupil size is $s \geq F_L \theta D$, where $D$ is the telescope diameter. The relay focal number $F_L$ can be reduced using a fiber taper to $F_L = 0.5$. For a 8m-class telescope with $F/20$ focal ratio and $\theta = 2''$, the resulting pupil size amounts to a few millimeters, requiring large CCD format. Furthermore, in order to match the pupil sampling to the equivalent $r_0$ size, big pixels and large binning may turn out to be required. These requirements, along with the constraint of a fast read-out, translate into some practical difficulty, that however might be solved with a suitable choice of the detector. A second issue is related to the presence of moving parts to accomplish the pyramid modulation. The solution adopted on AdOpt@TNG is to vibrate the pyramid, while in laboratory experiments the same result is accomplished by oscillating a tip-tilt mirror in a plane conjugated to the exit pupil. These implementations indicate that the dynamic modulation of the PS is feasible, even though it might be desirable to achieve the same effect without any moving part. The last issue derives from the optical co-adding of the light from the
reference sources, occurring in the layer-oriented approach. While this effect translates into the possibility to exploit the light of even very faint references sources, otherwise useless from the wavefront sensing point of view, the co-added signals are weighted by the relative intensity of the stars.\textsuperscript{13} When the references have not the same brightness, some of them are more weighted than others and this might translate into a non-uniform correction across the FoV. Furthermore, when a reference star is exceedingly bright with respect to the others, the layer-oriented loop might be unstable.\textsuperscript{14}

All these practical issues can be solved in an elegant and compact manner. The pupil size can be kept to reasonable levels enlarging the stellar images\textsuperscript{15} by increasing the focal ratio $F$ of the beams approaching the pyramids (Fig. 4, 5, 6). This can be accomplished with a star enlarger associated to each reference star. The same optical setup yields the solution to the second problem. A light diffusing plate\textsuperscript{16} is placed in the intermediate pupil image formed within the star enlarger; this device scatters the incident rays over an angle $\alpha$ and therefore the final spot on the pyramid pin is blurred. The net effect is equivalent to that obtained by a dynamic modulation, with no moving part. It should be stressed that the diffusing plate, placed in a pupil plane, does not affect the sharpness of the pupil images formed by the PS. Concerning the different intensity of the reference stars, a possible solution\textsuperscript{13} is to dim optically the exceedingly bright ones. This however translates in a loss of photons. A more effective approach is again based on the properties of the PS, namely on its adjustable gain. It can be shown\textsuperscript{16} that for small aberrations the PS signal is proportional to the wavefront derivative and inversely proportional to the scattering of the diffusing plate (or the modulation amplitude, depending on the adopted solution). In the framework of the solution proposed in Fig. 4, it is straightforward to adjust the scattering angle of each diffusing plate depending on the intensity of the corresponding reference star, in order to balance the weighting performed by layer-oriented. Once this is accomplished, the uniformity of correction across the FoV depends only on the angular distribution of the reference sources.

4. CONCLUSIONS

The PS, in the five years after its conception, has been extensively studied, both from the theoretical point of view and with laboratory tests. A number of interesting properties have been found and experimentally verified. The

Figure 4. For each reference star, a star enlarger (made of two lenses of focal length $f_1$ and $f_2$) increases the focal ratio of the beam incident on the pyramid from $F$ to $F'$, leading to a pupil size smaller by a factor $F'/F$ (compare with Fig. 3). This is a non-homothetic transformation of the focal plane, since the relative distances among the stars are left unchanged. A light diffusing plate in the intermediate pupil image allows to blur the spot on the pyramid pin with no moving component. The scattering angle of each plate can be adjusted in order to give the same weight to the signal coming from unequally bright stars.
**Figure 5.** A more detailed optical layout of the concept shown in Fig. 4. A single reference star is shown here. The beam splitter required to obtain an image of the high altitude layer is placed between the first group of two lenses and the last of three, which is therefore replicated.

**Figure 6.** Opto-mechanical layout of the concept shown in Figs. 4 and 5. The positioning of the optical cylinders, including star enlarger, diffusing plate and pyramid, is accomplished by means of XY stages.

...on-sky implementation has proceeded more slowly, due to many troubles during the engineering runs, ranging from the unfavourable seeing conditions to the WFC failures. However we are implementing the lessons learned and the WFC is being provided with an experimentally determined reconstructor to improve the high orders correction.

In the field of layer-oriented MCAO, the PS appears as a very promising solution, open to interesting developments. Some intriguing practical difficulties of the layer-oriented approach can be solved in a simple and straightforward way, mostly exploiting the properties of the PS. A study is in progress to propose the implementation aboard VLT and LBT of a layer-oriented WFS adopting the solutions discussed here.
ACKNOWLEDGMENTS

Elise Viard has benefited from the support of the European Commission RTN program 'Adaptive Optics for Extremely Large Telescopes', contract number HPRN-CT-2000-00147.

REFERENCES