Testing the pyramid wavefront sensor on the sky.

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ABSTRACT

The pyramid wavefront sensor is a novel concept device whose features are attractive for adaptive optics for several reasons. We show here the first loop closure of an AO system using this kind of sensor at the focal plane of a 4m-class telescope. One of the critical optical elements of our wavefront sensor is the pyramid that splits the light from the star used for the wavefront correction. This component is essentially a four faces prism having actually a full vertex angle of 7 degrees with specifications on its edges and roof of 4-5 microns or better. The best turned edges obtained on the prototypes already built have shown values of the order of 6 microns, with roofs of the same order, not far from the required tolerances. In this article we describe the techniques and the system used for the construction of this optical component and the improvements to the polishing procedure that we plan to adopt in order to increase the quality of its edges and optical surfaces. Pixel processing is suitable to fit with existing Shack-Hartmann systems, making this device an attractive add-on option for existing SH-based AO systems. The plans for future developments in order to firmly establish the performances of the pyramid wavefront sensor are briefed out.

Keywords: Wavefront sensor; Limiting magnitude; Foucault-like WFS

1. INTRODUCTION

The pyramid sensor is a wavefront sensor recently proposed for adaptive optics compensation systems. It is a novel concept device that is actually in a development phase and that, at this stage, has been tested both in laboratory and on the sky. This sensor consists of a four faces pyramid made of optical glass which acts like an image splitter. If the pyramid is placed in the focal plane of the telescope, with its tip on a focused reference star, the beam of light is splitted in four parts. Using a relay lens located behind the pyramid, these four beams are then re-imaged onto a CCD camera obtaining four images of the pupil of the telescope. Since the four edges of the pyramid act like a knife-edge test (or Foucault test), these images contain essentially informations about the optical aberrations introduced in the beam from the atmosphere. If the pyramid is also vibrated with a frequency much higher than the integration cycle of the detector, the first derivative of the wavefront along the main axes can be retrieved at each vibration cycle. A complete description of the working principle is available elsewhere. An interesting feature of this wavefront sensor is that it permits a variable gain (against the wavefront deformation) obtained changing the vibration amplitude, a feature similar to the one of the curvature wavefront sensor. The sampling of the telescope pupil can be also be easily changed in a continuous way using a zoom as lens relay. In Fig.1 it is sketched the typical behaviour of the Pyramid sensor compared to the Shack-Hartman one from the detector plane point of view.

Recently it has been pointed out that a substantial gain (typically larger than two magnitudes) can be obtained by using such a wavefront sensor in closed loop when approaching small or zero pyramid vibration. Finally, pupil plane wavefront sensors are easily scalable to multi-references, layer-oriented wavefront sensors useful for multi-conjugated tomographic systems. It is our opinion that all these considerations have made very interesting the progress in the development of such a component. Successful open-loop laboratory experiments have been already reported. Here we report on the first, to the best of our knowledge, loop closure of an high-order system whose sensing device is a pyramid one, both on the bench and on the sky.

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2. THE WAVEFRONT SENSOR

The AdOpt@TNG module is an optical facility permanently mounted at the Nasmyth focus of the TNG 3.58m optical telescope\textsuperscript{17,18} located on Roque de los Muchachos in Canary Island. It feeds the starlight into two cameras (visible and near-IR) normally used for direct F/11 imaging. Currently the module is used with ARNICA, an infrared facility\textsuperscript{19,20} with a 256x256 detector chip. The adaptive optics module provides an optical magnification factor of nearly 3. Detailed description of the overall module and of the optical design can be found elsewhere\textsuperscript{21,22,23}.

Tip-tilt correction is performed through a tiltable off-axis parabola, forming the magnifying relay, whose actuation is given by a commercial magnetic-driven system\textsuperscript{24} provided by ThermoTreX. The telescope pupil is reimaged onto a Deformable Mirror (DM) with 97 magnetostrictive actuators (provided by Xintics) where some margin on the pupil size is retained in order to have roughly one rim of actuators outside of the pupil image. In this way the actuation of the tip-tilt and of the high-order modes are inherently free of any cross-talk component.

The wavefront sensing area deserves a few more details. The reference star, picked-up by a selectable dichroic and chosen in the covered Field of View by means of a remote-controlled steering mirror, is focused (F/32) at the entrance of the WFS optics, where three options are selectable by means of a motorised linear stage: namely two Shack-Hartmann with different pupil sampling capabilities (4 x 4 and 8 x 8) and the pyramid one.

To accomplish the three options, taking also advantage of the possibility to change the wavefront sensor gain, we preferred to vibrate directly the pyramid. The possibility to introduce a tilt in the beam refocusing the pupil onto a steering mirror (8) would have been too difficult to implement: in fact, it would have required some more undesirable foldings of the beam because of the lack of space and the need for a further reimaging system to match the path length of the two Shack-Hartmann channels.

We are aware that this option leads to a smaller bandwidth of the sensor (at least in the vibrating mode).

The dimensions and manufacturing tolerances of this pyramid component are dictated mainly from the scale of the focal plane re-imaged on its pin and hence from the size of the seeing disk of the reference star. The bench test of this sensor is the AO system of the Galileo, as already mentioned. This adaptive optics module provide a magnification factor of nearly 3 at the entrance of the Wavefront Sensor (WFS) optics table. The reference star is hence focused in this point at F/32 and this bring a plate scale of about 550 microns/arcsec. The diffraction limit PSF of the telescope (at this scale and at 550nm) is of the order of 39 microns; if we accept to lose 10% of the stars light for the scattering due to manufacturing errors (like turned edges between the faces), then these errors need to
be maintained in the range of 4-5 microns. Turned edges of this small size are very difficult to obtain. After having evaluated the performances of the turned edges on a pyramid commissioned to a commercial optical shop, obtaining values of the order of 30 microns, we decided to start a number of tests in the Astronomical Observatory of Brera to evaluate the limits of the manufacturing process and to produce "in house" a suitable pyramid for testing the wavefront sensor concept.

We decided to start from a BK7 piano convex lens having a diameter of 12.5 mm, a focal length of 25 mm and a central thickness of 3.1 mm (Ealing 43-0025) and to reshape its curved surface removing the material in four steps, creating the four faces of the pyramid. This procedure is faster than to start from a plane surface because it minimizes the quantity of material to be removed. To this purpose a Lap Master polishing machine (Fig.2) has been used, with a pitch dish having a diameter of about 38 cm. The surface of the pitch has been engraved with radial cuts having a very small section, in particular much smaller than the size of the pyramid faces required. The rotating speed of this pitch dish has been set to 20 rpm.

To hold the lens in position for the grinding it has been used a PP6 Jig by Logitech. This jig allows a very precise angular tilt and alignment of the face to be produced and allows also the control of the pressure that the piece under work exerts on the pitch plate. Another useful feature is the possibility to control with a micrometer the thickness of the removed material. The small piano convex lens can be mounted on the provided support with the convex surface facing the pitch plate. Using the tilt control of the jig, the angle to the vertex of the pyramid is presetted to the required value. For this pyramid the angle is of 3 degrees respect to the axis of the jig, producing therefore a 174 degrees, very "flat", pyramid. This angle is necessary to permit to the four pupil images to fall on a single CCD detector. The polishing agent is Cerium Oxide in water solution (10 percent). The material of the lens is removed till to a pre-computed quantity, creating in this way a surface of the pyramid. Then a new surface is made rotating the lens holder of 90 degrees and restarting the procedure. Another possible manufacturing error is the presence of a roof on the tip of the pyramid, due to the fact that the lapping procedure is not interrupted at the correct moment on the last face and the removal of the material exceeds the necessary quantity to produce a point like tip. In this case it is necessary to align again the wrong face and polishing it. Since the perfect tip of the pyramid should be a
Figure 3. Picture of a finished pyramid. The substrate is originally a plano convex lens and the pyramid is formed on the curved surface. The curvature radii is chosen in order to minimize the amount of glass to be removed.

Table 1. Irregularities, expressed in μm for the three pyramids described in the text. nX refers to the turned edge sizes for the two sides (X stands for A or B) of the n–th face. The average is computed on the turned edges only. Pyramid no.3 is the one used for the on–sky experiment.

<table>
<thead>
<tr>
<th>Pyramid no.</th>
<th>Roof</th>
<th>1A</th>
<th>1B</th>
<th>2A</th>
<th>2B</th>
<th>3A</th>
<th>3B</th>
<th>4A</th>
<th>4B</th>
<th>Average</th>
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<tr>
<td>1</td>
<td>15</td>
<td>18</td>
<td>13</td>
<td>17</td>
<td>10</td>
<td>18</td>
<td>18</td>
<td>16</td>
<td>25</td>
<td>16.8</td>
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<td>13</td>
<td>7</td>
<td>11</td>
<td>8</td>
<td>9.2</td>
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An attempt to use a protective coating like a lacquer applied on each face just produced has not given good results because it is removed quickly from the hard cerium oxide. A solution to this problem (that could also bring an improvement to the overall performances of future pyramids) is the use of alumina instead of cerium oxide. The alumina (Al2O3) is available with grain size of 0.05 microns, a size about 40 times smaller that those of the cerium. The smaller size of the grains should bring a strong reduction of the erosion effect and in the meantime also gives a further improvement of the turned edges obtainable.

The measurements of the turned edges and of the roofs of the 3 pyramids that has been till now produced has been done using an interferometric profilometer (a WYKO Topo 2D) and a phase contrast Nomarsky microscope. In Tab.1 are shown the values for the turned edges and the roofs obtained so far.

The best pyramid obtained so far is the number 3 that has a roof of 9 microns and a mean turned edge of 9.2 microns. In Fig.3 is reported a picture of the finished pyramid, while in Fig.4 is shown the appearance of the tip of this pyramid.

During alignment of the system we used the sensor under very large aberrations. We observed that the dinamic range of the pyramid wavefront sensor is far larger than the Shack–Hartmann’s one. In fact in the Shack–Hartmann sensor a box of pixels around each spot must be chosen using the reference wavefront, so that there is a well defined range where the spot can be found during the wavefront analysis.
Figure 4. Microscope picture of the top of the used pyramid. At the scale of the focal plane reimaged onto the tip, a diffraction limit PSF, at a $\lambda = 500\text{nm}$, is roughly $39\mu\text{m}$ wide.

In the pyramid wavefront sensor, instead, the limit of the dynamic range is given by the ratio between the physical size of the refractive pyramid and the dimension of spot on its vertex regardless of the sampling of the pupil. Thanks to this feature, even under very poor alignment conditions leading to very large aberrations, some useful signal can be still obtained.

Of course such a signal will be saturated and, in practice, only the sign of the wavefront derivative is known. This is equivalent to the Shack–Hartmann case when the spot displacement is larger than its size, but it still requires that the spot lies within the considered box for each spot.

For the pyramid wavefront sensor the size of the equivalent box where the spot is still tracked does not depend upon the pupil sampling and, at least in our case, is nearly two orders of magnitude larger. In this way a very rough alignment can still be optimized using the wavefront signal itself.

The wavefront computer is a real-time matrix multiplier provided by ThermoTreX and it is able to evaluate slopes from pixel intensities and to multiply current and past measured slopes with a user–provided matrix. In such a matrix the tip–tilt term is subject to a completely separated calculation flow. Modal filtering is hence possible. In our case, in fact, we implemented different filtering for the tip–tilt and the high order modes. Latency time of the wavefront computer, in all of the cases considered in this letter, is completely negligible being of $258.7\mu\text{s}$, roughly 30 times shorter than the main source of time delay in the loop control system, that is the CCD read–out time chosen to be $8.2\text{ms}$.

3. FIRST ON–SKY TEST

In late November 1999 we performed the final wavefront sensor integration, alignment and calibration. A set of fiber–fed artificial point sources are remotely insertable in the optical path, a group of these is placed at the entrance of the AdOpt@TNG (F/11 focus) module and the other group just after the dichroic splitting the beam (F/32 focus) between the scientific camera and the wavefront sensor. Even though by comparison between the two point sources one can derive any non–common optical path difference between the wavefront sensor and the scientific camera, we preliminarily calibrated the system with only the F/11 artificial source. The sampling of the pupil has been set, during this run, to $8 \times 8$ pixels. We introduced onto the DM the first 15 Zernike polynomials with an estimated peak to valley aberration of $\approx 2\mu\text{m}$ and, after closing the tip–tilt loop only, we recorded 10 different slopes realizations for each mode. Averaging these and combining the results with the commands sent to the DM for each of the realizations, we obtained, by Singular Value Decomposition matrix inversion, the basic reconstruction matrix. We used this matrix as a single component to which we applied both an integral and a Finite Impulse Response (FIR) filters with a MatLab/SimuLink code, using in the loop the data available for the whole bandwidth of the elements.
Introducing as a starting point a given aberration on the DM and closing the loop we obtained successful corrections. The final aberrations are not exactly zero, but correcting from completely different starting point the final situations are, within the measurement errors, essentially identical.

The matrix used for the very first high-order compensation is shown in Fig.5, where one can note the decoupling between tip-tilt and high-order terms.

We finally performed a moderate correction on a real star observed with the telescope. We compare in Fig.6 the high-order correction vs. the tip-tilt correction (the latter obtained a substantial gain with respect to the open-loop situation, an effect that we interpreted as partially due to a wind-buffetting problem of the telescope structure). In a single observing shift of a few minutes we repeatedly integrated exposures with open-loop, tip-tilt only and then high-orders, several times in sequence. In this way we have been able to rule out the possibility that some trend in the behaviour of the natural seeing could hide the effects of the introduced correction or at least produce some false positive results. Because of the very bad weather conditions occurred during the scheduled engineering run we were able to point on the sky only the night of November, the 29th 1999. In this night we recorded a seeing of roughly 2 arcsec in the visible, but we were able to close the high orders correction loop anyway. Observing in K' band we closed first the tip-tilt correction on a star of magnitude V ≈ 6, decreasing its FWHM from 1.40" to 1.10" and then we applied the high orders correction shrinking the FWHM to 0.84" (see Fig.4). We would like to point out that this performance has been obtained in a relatively short amount of time and under unusual bad seeing conditions.
Figure 6. The comparison between the tip-tilt only component removal (open circles) and the further correction of the first 15 Zernike polynomials (filled circles). FWHM drops from 1.10 to 0.84 arcsec.

4. CONCLUSIONS

Next steps in the development of the pyramid wavefront sensor comprises an experimental verification, both in the laboratory and on the sky, of the limiting magnitude gain expected from such a device. Multi-references, layer-oriented versions of this wavefront sensor are the more interesting application one can see in the near future. Open-loop experiments can be of same value, however only a closed-loop system can use this device in its more efficient (and ambitious) way, leading to significant sky coverages with solely NGSs for 8m class telescopes. That would be also a very interesting test-bench for AO on giant telescopes where multi-conjugation can be even more efficient than in the actual class of large telescopes.

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