Layer-oriented wavefront sensor for a multiconjugate adaptive optics demonstrator

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1 Introduction
Since the launch of the Hubble space telescope, particular effort has been made to develop adaptive optics (AO) systems in the main astronomical observatories. The AO goal is to reach diffraction limit images from the ground. Classical AO systems are limited by several constraints: only science objects located at less than a few arcseconds from a bright enough reference guide star can be observed at the diffraction limit, hence high angular resolution from the ground is only achieved for a small number of interesting sources.

To overcome such limitations, the multiconjugate adaptive optics (MCAO) concept was proposed at the end of the 1980s. The basic idea is to use several reference stars to sense the atmosphere in several directions and correct it in three dimensions using several correctors. By the mid-
In the 1990s, extensive theoretical studies on MCAO appeared in the literature. An MCAO system is usually composed of several wavefront sensors (WFSs). In the so-called interferometric (I) technique, each WFS is associated with a specific reference guide star. The detector registers the intensity map coming from the reference star distributed uniformly over the turbulence, and then applies the tomography method, it is possible to measure the wavefront aberration in three dimensions. Several interconnected real-time computers retrieve the correction to be applied to each deformable mirror. In 2000, a new technique of sensing called layer-oriented (LO) sensing was proposed. In the LO technique, each WFS is conjugated to a specific altitude. The detector integrates the photons coming from all the reference stars and registers the intensity map visible at this altitude. The different loops can work independently, with each deformable mirror (DM) being driven by slope measurements obtained from the WFS, conjugated to the same altitude with specific optimized spatial and temporal samplings directly defined from the statistical properties of the layer. This MCAO method is particularly suited when using pupil plane WFSs: the light coming from all the guide stars is optically combined by the instrument to reproduce an anamorphic copy of the 3-D atmosphere close to the pupil plane.

The most important astronomical observatories are now building their own MCAO systems to improve the image quality on a substantial field of view (FOV). The goal of MCAO systems is to increase the number of scientific targets to be observed with limited diffraction from the ground, allowing both high resolution imaging and spectroscopy on faint objects. MCAO is also a key point for the extremely large telescopes (ELTs), which are currently in their conceptual phase. There is a general consensus that such ELT projects will be pursued only if limited diffraction images are achievable on a reasonable sky coverage, allowed by enloring the equivalent isoplanatic patch or solving the conical laser guide star (LGS) problem. Both approaches require some sort of MCAO.

2 MAD Overview

The ESO multiconjugate adaptive optics demonstrator (MAD) has been developed to demonstrate MCAO feasibility and to determine the achievable gain using both Shack-Hartmann WFSs in the SO configuration or pyramid WFSs in the LO configuration. The system will be first tested in the laboratory for one year before being installed at Paranal for test on sky.

The scientific instrument is a 1×1 arcmin FOV near-infrared (IR) camera scanning a diameter of 2′ FOV. The entire system is placed on a bench, which will be mounted directly on the Nasmyth platform of one of the Very Large Telescope (VLT) units at Paranal in Chile.

The mechanical design of the overall system is outlined in Fig. 1(a). The 2-arcmin FOV is derotated at the entrance of the MAD. The F/15 input beam is collimated to reimagine the telescope pupil at 60 mm diam. The larger DM with a 100-mm pupil is conjugated to 8.5-km altitude, while the smaller DM with a 60-mm pupil is conjugated to the reimaged telescope pupil. The IR light is transmitted by the dichroic to the IR camera, while the visible light is reflected toward the WFS path. The WFS input beam is a flat telecentric /20 beam. The correction is optimized at 2.2 μm (K band) to give the best correction to the 2k×2k IR detector. Two calibration units with multiple reference stars are also available to emulate different positions of guide...
stars and calibrate the system both with all the optics or without passing through the dichroic and deformable mirrors. The two WFSs cannot be used simultaneously. A WFS selector folds the light either to the LO WFS located above the bench or to the SO WFS that is on the bench.

Pyramid WFSs (PWFSs) have been selected for the LO WFS for MAD among various pupil plane WFSs. The PWFS\textsuperscript{16–19} is a 2-D Foucault-like WFS. The light is split into four beams whose distributions of illumination depend on the aberrations of the wavefront. The four pupil images are reimaged on the detector. It has been demonstrated theoretically,\textsuperscript{20,21} numerically,\textsuperscript{22–24} and experimentally\textsuperscript{25} that the PWFS has a gain in sensitivity respectively to other WFSs. We describe more extensively the pyramid features for this instrument and the required quality in Sec. 3.4.

In the LO WFS for MAD, up to eight pyramids can be positioned over the 2-arcmin FOV to catch the light from eight reference guide stars [for simplicity, only three are represented in Fig. 1(b)]. The maximum number of guide stars is a tradeoff between the the system complexity and the achievable sky coverage.\textsuperscript{26} Marchetti et al. have shown that more than 400 asterisms are accessible from Paranal with eight guide stars.

The various errors of misalignment are listed in the following sections, and the induced specifications are discussed. We have studied numerically the translation of subaperture blurring in terms of wavefront errors (WFEs).\textsuperscript{27,28} We have selected a reasonable blur of 1/10 subaperture as the tolerance requirement for most of the subsystems, which corresponds, for instance, under normal seeing conditions, to a WFE of 24 nm.

3 Optical Design

The optical design has been optimized to reproduce an anamorphic copy of the atmosphere inside the instrument without reducing the sharpness of the pupil images. In its original approach, the layer-oriented concept imposes a practical limit on the minimum size of the reimaged pupils.\textsuperscript{29} We propose several techniques to overcome it. The star enlarger technique has been implemented in this instrument. Two lenses are introduced on the path of each reference guide star to enlarge their focal ratio individually rather than collectively. As a result, the pupil size, which is inversely proportional to the focal ratio, can be arbitrarily shrunk, while the distances between the various stars across the covered FOV remain unchanged.

The layout is shown in Fig. 2. The focal plane before the LO WFS is indicated by the vertical gray line. Rays are arriving from a certain FOV in telecentric mode at a focal ratio $F$. The beam of each reference star is collimated by a lens of focal length $f_1$, producing a small pupil image for each star. A second lens of focal length $f_2$, placed at a distance $f_2$ after the intermediate pupil (the exit pupil remains at infinity), forms an enlarged image of the reference star with an equivalent focal ratio $F' = kF$, where the enlarging factor is given by $k = f_2/f_1$. In this position, a pyramid can be placed to split the light in four beams, which are focused by an objective of focal length $f_1$ onto the detector. The reimaged pupils corresponding to different reference stars are collected by the objective, which optically co-adds the light of all the stars. It is easy to show that using small angles approximation, the size of each reimaged pupil can be equal to $s = E_i\theta D/k$, with $\theta$ being the FOV and $D$ the telescope diameter.

3.1 Size of the Detector: a Limitation

The size of the detector is one crucial parameter to determine the optics characteristics. The detector chosen for the MAD instrument is a EEV39 with $80 \times 80$ pixels. Because of practical reasons and limited capabilities of the controllers, only $64 \times 64$ pixels of the central zone are used to reimage the four metapupils. To avoid light contamination among the four different metapupils in the high-altitude channel, only a $28 \times 28$ pixel array near each corner has been considered to map one pupil image (Fig. 3), allowing a band of eight pixels between two different metapupils. The central part of the DM (including the inner 40 actuators) has to be mapped onto this $28 \times 28$ region. The meta-
The focal lengths chosen for Optics of Star Enlargers for MAD are given in Sec. 3.3, while the details of the characteristics of the objective are adopted focal lengths equal to those indicated in Sec. 3.2, with the details of the characteristics of the objective for MAD are given in Sec. 3.3.

3.2 Optics of Star Enlargers

We have adopted focal lengths equal to \( f_1 = 10 \) mm and \( f_2 = 150 \) mm for the two achromat lenses to obtain a new focal plane equal to \( F/300 \). The diameter of the second lens fixes the minimum separation between two reference guide stars. The two lenses used for each star enlarger are custom ones, optimized to reduce chromatic effects. The quality of the pyramid pin is actually essential for the output pupil image. Specifications are indicated in Sec. 3.4.

3.3 Reimaging Objective

With \( k = 15 \), the reimager must have a focal length equal to \( f_1 = 115.7 \) mm to fit the charge-coupled device (CCD). The equivalent FOV has been adjusted to match the CCD diagonal. The reimaging objective composed of eight lenses is shown in Fig. 4. It has a clear aperture of \( d = 110 \) mm. The design has been optimized in the full wavelength range 0.45 to 0.95 \( \mu \)m with uniform weighting. The back-focal distance has been kept to the comfortable value of 20 mm. Furthermore, the last lens is made of Silica glass and the last surface is flat. This allows us to account for the CCD window by a simple modification of the thickness of this lens. Only standard Schott glasses (except Silica) with high transmission in the wavelength range of interest have been selected. All the surfaces are spherical or plane; no cemented doublet or multiplet is present to ensure high precision in the alignment. The objective is composed of two groups of lenses. The first group is a beam compressor common to the two altitudes of conjugation, which reduces the beam cross section while collimating it. The second group focuses the beam at \( F/1.05 \) ratio. A convenient space of 125 mm is left between the two groups of lenses, allowing the insertion of the beamsplitter for the ground and high altitude channels. The beamsplitter is in a substantially collimated beam, hence it does not introduce any significant aberration.

The optical quality of the pupil reimager objective is practically diffraction limit. A detailed analysis of the optical tolerances has been carried out to provide the necessary specifications for manufacturing and alignment. Mechanical systems for adjustment have been included in the design. A detailed description is given in Sec. 4.

3.4 Key Point: Specifications and Procurement of the Pyramids

Quality of pyramids is essential for the measurement of the wavefront. Hence, the manufacturing has been done with particular specifications on the edge sharpness, the wedge of the back surface, the repeatability of the vertex angle, and the orthogonality of the faces.

The pyramid can be made of any optical material, provided that the internal transmission is acceptable. In Table 1, we report the optical specifications of the pyramids. The main parameter from the optical point of view is the divergence angle \( \beta \) between the output beams [Fig. 5(b)], which is related to the vertex angle \( \alpha \) of the pyramid and to the material refractive index \( n \), according to the relation

\[
\alpha = \frac{\beta}{n - 1}.
\]  

Using the small angles approximation, it is easy to show that the beam divergence \( \beta \) is equal to:
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\[ \beta = \frac{d_i}{f_i}, \]

when using an interpupil distance \( d_i = 1.222 \) mm to avoid light contamination between the different metapupils and \( f_i = 115.7 \) mm. The beam divergence is therefore \( \beta = 0.605 \) deg as reported in Table 1. Assuming BK7 glass and the refractive index at the reference wavelength, the vertex angle is \( \alpha = 1.176 \) deg. With a such small vertex angle, the sag is approximately 55 \( \mu \)m, as defined in Fig. 6(a).

Due to the tight specification on the transmission, an antireflection coating optimized for the full wavelength range has been applied to each pyramid. The pin of the pyramid had to be centered with respect to the outer diameter with a precision of \( \pm 0.1 \) mm. Flatness and roughness of the surface refer to the five faces of the pyramid. Since several samples are required, and due to the particular application for which these pyramids are used, the most important aspect is their similarity. A key point is the repeatability of both the vertex angle \( \alpha \) or the refractive index \( n \). For instance, with BK7 glass, the two values become \( \Delta \alpha = \pm 0.004 \) deg and \( \Delta n = \pm 0.001 \).

The edge sharpness \( \eta \) [Fig. 6(b)] affects the efficiency of light transmission in the pyramid prism. It can be shown that the fraction of lost light due to the rounded edges is given by:

\[ \varepsilon = \frac{2}{\Lambda F^2} \left[ \frac{r_0}{D (1-s)} + S \right], \]

where \( \eta \) is the edge width, \( S \) is the Strehl ratio (SR) at the wavelength \( \lambda \) of wavefront sensing, and \( F' \) is the enlarged focal ratio of the incident beam. Under normal seeing conditions, assuming \( S = 0.05 \), the loss of light varies from 1 to approximately 5% for rounded edges in the interval of \( \eta = 16 \) to 80 \( \mu \)m. This translates into a rigid shift of the SR versus magnitude curve, by an amount ranging from 0.01 to 0.06 mag, toward brighter magnitudes.

The requirements on the size of the pyramid are not critical. The diameter affects only the equivalent FOV covered by the star enlarger. The thickness tolerance is very loose. It has been verified by ray tracing that even an error of \( \pm 0.5 \) mm has no relevant effect on the pupil quality. The wedge of the back surface might introduce additional chromatism in the pupil images. The effect may be analyzed by modeling the wedged pyramid as the association of a perfect pyramid prism followed by a wedged plate of angle \( \delta \). Using the thin prism approximation, the angular blurring due to chromatism is given by:

\[ \sigma_\delta = \delta N V, \]

where \( V \) is the Abbe number of the material. Imposing a reasonable blurring of 1/10 subaperture (see Sec. 4), a maximum wedge angle \( \delta = 10^\circ \) follows. The angular separation of the four beams generated by each pyramid depends on the combined effect of the refractive index, the vertex angle \( \alpha \), and the orthogonality of the faces \( \Delta \phi \). Unless a single pyramid is considered, the scatter in the angular separation among the beams generated by different pyramids translates into a blurring of the pupil. Concerning the repeatability of the refractive index and vertex angle, a blurring of the pupil equivalent to 1/10 subaperture can be achieved with a refractive index error \( \Delta n = \pm 0.001 \) and a vertex angle error \( \Delta \alpha = \pm 0.005 \) deg. Concerning the orthogonality specification, according to Fig. 6(c), it can be shown that a nonorthogonality angle \( \Delta \phi \) translates into a shortening of the pyramid side (from \( L \) to \( L' \)) and then into a steepening of the corresponding face of the pyramid. The nonorthogonality angle is related to the error on the vertex angle \( \Delta \alpha \) by the relation:

Fig. 5 Relevant angles in the pyramid prism: (a) \( \alpha \) is the vertex angle defined as the angle between two opposite slopes, (b) \( \beta \) is the beam divergence related to \( \alpha \) by Eq. (1) in small angle approximation.

Fig. 6 Definition of the pyramid characteristics. (a) Definition of wedge \( (\delta) \) and sag. (b) Pyramid turned edges \( (\eta) \) superimposed onto a seeing-limited spot and a diffraction-limited one. (c) Tolerances on the nonorthogonality of the faces \( (\Delta \phi) \).
Imposing a pupil blur of 1/20 subaperture related to the orthogonality specification, a requirement of $\Delta \phi \pm 7'$ follows. This requirement has to be applied to each face of each pyramid separately, since each face corresponds to a separate pupil image. The last specification considered here is the flatness of the surface. Ray-tracing simulations have shown that it is not critical. An accuracy for the surface of $2\lambda$ peak to valley, for instance, translates into a negligible pupil blurring of $1-\mu\text{m rms}$.

4 Mechanical Design

The LO WFS being a subpart of MAD, the optomechanical design has been conceived to place it on the MAD bench. The LO WFS is a $0.55 \times 0.55 \times 1.2 \text{ m}^3$ box containing all the optical elements for the proper reimaging of the telescope F/20 focal plane onto the two detectors (each of them accommodating four images of the pupil), one conjugated to the ground layer DM and another one conjugated to the high altitude one. The overall weight is about 165 kg (see Fig. 7).

The mechanical structure holds the following components.

- Eight reference selection units that displace the eight star enlargers in the field to select the reference stars. The linear stages are positioned horizontally on the structure to minimize deformations due to gravity effects.
- A common path pupil reimager composed of the four first lenses of the reimaging objective.
- A beamsplitter to split the light between the two detectors.
- A ground CCD pupil reimager composed of four lenses.
- A high altitude CCD pupil reimager.
- A high altitude CCD adjusting unit.
- A ground layer CCD adjusting unit.

Adjusting tools have been implemented on the mechanical structure to align the different optical elements. To obtain good images of the pupils, we have also defined stringent specifications on particular subsystems.

4.1 Star Enlargers

The pupil superimposition on the ground layer detector is strongly related to both the global tilt of the star enlargers and the alignment of the three optical elements mounted on the star enlarger: the two achromatic lenses and the pyramid. A global tilt of the star enlarger is translated almost linearly into an angular shift of the exit pupil. When different star enlargers are randomly tilted, the net effect is a blur of the pupil images. To verify a maximum tilt of 1/10 of the wavefront sensing subaperture, the star enlargers should be coaligned with an accuracy $\Delta \theta \approx \pm 10'$. This specification is fulfilled by adjusting mechanically the tilt of each star enlarger during the alignment phase.
4.1.1 Alignment of the lenses

The alignment of the two achromats is also essential. A relative decentering between them can affect the telecentricity of the system. The correct spacing between the two lenses is required, otherwise the exit pupils corresponding to different star enlargers are placed at different locations along the optical axis and the corresponding pupil images do not superimpose properly. A suitable specification on the relative positioning accuracy is of the order \( \Delta z = \pm 0.1 \text{ mm} \). A similar reasoning can be applied to the relative decentering between the two lenses, which translates into an angular deflection of the corresponding exit pupil. To keep this effect to an acceptable level (a blur of 1/10 subaperture), the relative decenter should be smaller than \( \Delta \theta = \pm 0.09 \text{ mm} \). The systems for mechanical adjustment allow us to achieve less than 0.01-mm decentering between the two achromats.

The same reasoning is applied to the positioning accuracy of the star enlargers on the focal plane. The folding mirror that bends the optical beam onto the LO WFS can be moved along the optical axis to shift the position of the F/20 focal plane and match it to the entrance focal plane of the star enlargers. The accuracy required on this adjustment is of the order of \( \Delta z = \pm 0.2 \text{ mm} \), corresponding to the depth of focus at F/20 at the wavelength of wavefront sensing. Of course all the star enlargers will be prealigned in a way that their respective entrance focal planes are coincident to minimize the differential defocus among them.

4.1.2 Alignment of the pyramid

The centering of the pyramid instead is a real issue only as long as the astrometric accuracy is of concern, since a decentering of the pyramid translates into a tip-tilt signal that might introduce a local warping of the corrected image astrometry. Since MAD astrometry is not foreseen, the decentering just needs to be within the FOV of each single star enlarger, a condition easily fulfilled in our case. The axial positioning is not critical, as pyramids work in a F/300 beam with a very large depth of focus.

The differential rotation among different pyramids might introduce misalignments among the different pupils. The mounts of the pyramids allow us to adjust the orientation of each pyramid so that the beams from different pyramids are parallel, a necessary condition to ensure proper pupil reimaging. The rotation of a pyramid around its optical axis translates into a rotation of the four reimaged pupils onto the detector plane. Imposing that the corresponding pupil displacement is negligible, a tolerance of 1/10 of the subaperture size implies a tolerance on the rotation angle of the pyramid of \( \Delta \theta_p = \pm 0.25 \text{ deg} \). A mispositioning of the pyramid along the optical axis of the star enlarger translates into a defocus term. However, given the very large depth of focus of the F/300 focal plane, it is easy to achieve the required positioning accuracy.

4.1.3 Movement precision

The accuracy of the alignment of the star enlarger translates into a requirement of the stability of the motorized linear stages as they move across the focal plane to position the star enlargers. In particular, the so-called pitch and roll of the stages translates into a wobbling of the star enlargers, therefore these random angular deflections should be smaller than \( \Delta \theta_p = \pm 10^\circ \).

Another issue is related to the so-called yaw angular deflection of the stages. This kind of wobbling, orthogonal to pitch and roll, translates into a lateral displacement of the star enlarger on the focal plane. The net effect is that the reference stars to be picked up might fall outside the field of view of the corresponding star enlarger. Imposing that the lateral displacement is always smaller than the typical stellar image size—the diffraction limit at the wavelength of wavefront sensing—it is possible to derive a requirement on the maximum acceptable yaw. This figure turns out to be, in our case, of the order of 1', a specification quite easy to fulfill, being much looser than the pitch and roll.

To avoid errors of misalignment among the pupils corresponding to different stars, we require repeatability of 50-\( \mu \text{rad} \) peak to valley for each star enlarger when the various star enlargers are moved in the input focal plane to pick the reference stars. The global tilt of every star enlarger is a useful degree of freedom to compensate errors of misalignment of the optical components inside each mount. When this tilt has been adjusted, the star enlarger should translate with no significant additional tilt. A mispositioning of the star enlarger along the LO WFS optical axis might introduce differential defocus errors among the various star enlargers. In this respect, the positioning accuracy should be much better than the depth of focus of the first achromat working at F/20, i.e., \( \Delta z = \pm 0.2 \text{ mm} \) at the shortest wavelength (\( \lambda = 0.45 \mu \text{m} \)).

4.2 Pupil Reimager

The groups of lenses forming the pupil reimager have to be aligned to avoid a blur of the reimaged pupil. The tolerances of alignment have been computed for a maximum acceptable degradation of the rms spot size of the order of 10%. The relative decenter between the common path pupil reimager and the ground or high altitude layer pupil reimager should be adjusted with an accuracy better than \( \pm 0.05 \text{ mm} \), while the tilt of the groups of lenses with respect to the common optical axis should be smaller than \( \pm 0.01 \text{ deg} \) for the common path reimager and \( \pm 0.15 \text{ deg} \) for the ground and the high altitude layer pupil reimagers. To perform these adjustments, the mounts of the groups of lenses have been provided with adjusting mechanisms. The tilt of each group of lenses is tuned by using three screws with two different fine tunings. Three screws fixed at 120 deg translate each group by pushing it.

4.3 BeamSplitter

While a tilt of the beamsplitter has no effect on the transmitted beam, except for a lateral displacement that can be recovered by adjusting the centering of the following group of lenses, the impact on the reflected beam is different. Indeed, a tilt of the beamsplitter introduces both a tilt and a decenter on the reflected beam going to the high altitude layer pupil reimager. By comparison of tolerances of alignment reported before, we obtain a tilt tolerance on the beamsplitter of the order of \( \pm 0.05 \text{ deg} \).
4.4 CCD

Precision on the centering of the CCD, in principle, would be of no importance. In practice, since the four reimaged pupils just fit the detector, a centering mechanism has been foreseen.

Given the very high speed of the pupil reimager, the CCD has to be aligned very precisely with respect to tilt and tilt. Imposing a maximum blur of 1/10 subaperture for the pupil as usual, different portions of the chip should be out of focus by no more than approximately $\Delta z \approx 5 \mu m$. This high accuracy is achieved by adjusting the CCD box, whose fixing points are sufficiently far apart from each other that this very tight tolerance actually translates into a much looser one.

Each CCD box is mounted onto a linear stage for proper focusing and for conjugating the detector to a specific atmospheric layer, namely at 0 and 8.5 km. Given the very high speed of the pupil reimager, the range for the full conjugation is mapped in the image space into a travel range of $\Delta z = 0.3 \text{ mm}$. To achieve an accuracy of $\Delta H = 100 \text{ m}$ on the definition of the altitude of conjugation, a resolution of $\Delta z = 3 \mu m$ is required on the linear stage. The actual resolution is better than this on average.

5 Conclusions

To estimate the final performance of the LO WFS, we computed the WFE for each source of error in all the sub-systems. Each source of error associated to a blur expressed in terms of subaperture units has been converted into WFE using a modal approach. We evaluated the WFE as the residual between the “perfect” correction expressed by the Noll coefficients and the computed correction affected by the blur of the pupil. Assuming normal conditions for the seeing, we show that the WFE is almost linearly related to the pupil blur by the equation $y = 372x - 13.6$, where $y$ is the rms of the WFE in nanometers and $x$ is the blur of the pupil in percentage of subaperture. Summing quadratically all the possible contributions to the blur of a subaperture, we obtain a global WFE budget of 85 nm of the LO WFS for MAD, which is equivalent to 94% Strehl. All the mechanical adjustments for the alignment of the system have been tested, and possible ameliorations have been considered for the construction of the LO multiple field of view WFS for NIRVANA aboard the Large Binocular Telescope.

The LO WFS for MAD is currently scheduled to have its first light in the laboratory in 2005 and on the sky in 2006. Performance of the system are promising: diffraction limited images on more than 1-arcmin FOV should be reached using six to eight reference stars with a $R = 14$ integrated magnitude. The scientific camera has a 57" diffraction limited FOV, three broad band filters ($J$, $H$, and $K$), and two narrowband filters at 2166 and 2144 nm. But before then, the system still has to be tested completely. The whole alignment of the LO WFS is now almost complete and the first laboratory tests are beginning. The testing phase is foreseen to be split into several phases, including static open loop and close loop tests after the integration onto MAD.

Acknowledgments

This work has been partially funded by the European Research and Training Network Adaptive Optics for Extremely Large Telescopes under contract number HPRN-CT-2000-00147. We would like to thank Enrico Marchetti for his useful comments.

References


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Paolo Bagnara: Biography and photograph not available.

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