SAOLIM, Prototype of a Low-Cost System for Adaptive Optics with Lucky Imaging. Design and Performance

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ABSTRACT. A prototype of a low-cost adaptive optics (AO) system has been developed at the Instituto de Astrofísica de Andalucía (CSIC) and tested at the 2.2 m telescope of the Calar Alto Observatory. We present here the status of the project, which includes the image stabilization system and compensation of high-order wavefront aberrations with a membrane-deformable mirror. The image stabilization system consists of a magnet-driven tip-tilt mirror. The higher-order compensation system comprises a Shack-Hartmann sensor, a membrane-deformable mirror with 39 actuators, and the control computer, which allows operations up to 420 Hz in closed-loop mode. We have successfully closed the high-order AO loop on natural guide stars. An improvement of 4 times in terms of FWHM was achieved. The description and the results obtained on the sky are presented in this article.

Online material: color figures

1. INTRODUCTION

The use of adaptive optics with reasonable spatial-order correction and temporal bandwidths in astronomy has been restricted for many years to observatories with a high instrumentation budget. In current versions, such systems use expensive deformable mirrors (DMs), and digital signal processors to apply the reconstruction algorithms. This results in complex systems (e.g., Hippler et al. 2000), taking several years to develop. Nowadays, the total cost can be reduced by several orders of magnitude (e.g., Dainty et al. 1999) thanks to the availability of relatively cheap membrane-deformable mirrors (Vdovin 1995), single-photon detectors with a reasonably high frame rate based on electron multiplying charge-coupled device (EMCCD) technology (e.g., Dussault & Hoess 2004), and low-cost tip-tilt systems.

In this article we describe a system of adaptive optics with lucky imaging (hereafter SAOLIM). We present the design, construction, and results of a low-order AO system for 1–2 m class telescopes, almost entirely developed with available commercial components, and with a total cost of ~35000 euros in hardware components.

The optical design enables a field of view (FOV) of 90 × 90 arcsec² for the scientific camera. SAOLIM is optically corrected and transparent for a wavelength range between 1.0–2.5 μm.

Our system is based on a membrane-deformable mirror (e.g., Paterson et al. 2000) and a single PC to perform all the computations and hardware control, integrating everything in a simple and compact design as we will describe. The dual wireless/ethernet communication of the device allows an easy setup, because no cabling has to be installed at the telescope, considerably reducing the potential for problems.

This instrument can be used for input correction with applications where reaching the diffraction limit of the telescope is required, such as a lucky imaging system, e.g., ASTRALUX (Hormuth et al. 2008), or as a complement for the shift-and-add approach (e.g., Bates & Cady 1980). This device can take advantage of a low-order AO system in such a way that the rate of useful images is increased, improving the performance of the system. This innovative technique has been tested recently at the Palomar Observatory, with excellent results (e.g., Law et al. 2008).

2. SYSTEM DESCRIPTION

Figure 1 shows a picture of the instrument attached to the telescope. Labels indicating the main components have been included. A detailed view of the optical components in Figure 2 and the inside of the instrument (located at the lab) identifies the main optical elements. Table 1 summarizes the mean instrument parameters.
2.1. Mechanical and Optical Design

A sketch of the optical setup is shown in Figure 3. The optical design is similar to that of ALFA, the AO system that was operated at the 3.5 m telescope of the Calar Alto Observatory between 1997–2005 (e.g., Hippler et al. 2000). A Shack-Hartmann wavefront sensor (hereafter SHS) is placed optically conjugated with the membrane-deformable mirror (MDMM) and the entrance pupil of the whole system. To align the pupil on the DM, a camera is temporarily located in different parts of the optical axis, until a sharp image of the main mirror is obtained. Two achromatic doublets (E1), separated by 5 mm with focal distances of 300 mm, conjugate the entrance pupil over a 20 mm diameter circular area on the deformable mirror. Another pair of achromatic doublet lenses (E3 and E6) is configured as a Kepler telescope and conjugates the membrane’s selected zone on the SHS. The SHS consists of a microlens array (E7, focal length 45 mm) and two achromatic doublet lenses (E8 and E9) to reimage the subaperture spots on the EMCCD with an appropriate pixel scale yielding a value of 0.48" pixel⁻¹. An aplanatic lens (E2) is placed between the MMDM and E3 to reduce coma aberration in the Kepler telescope. A dichroic beam splitter (E4) reflects the near-infrared part of the spectrum to the scientific camera with the visible part to go to the SHS. Finally, a motorized flat mirror (E5) folds the optical path to keep the design compact.

The optical performance of the design was evaluated with the optical software ZEMAX. Figures 4 and 5 show the spot sizes at different field angles at the scientific camera of SAOLIM. The geometry and sizes of the spots are comparable to those of the Airy disk in different angles, whose amplitudes have been selected to match the isoplanatic angle in the K band. The Strehl ratio expected is about 72%, close to the theoretical value of 82% foreseen by ZEMAX. The image quality is almost constant through the different angles, with a wavefront distortion smaller than \( \frac{\lambda}{4} \) (Fig. 4). The system is equipped with an artificial point source fed by an optical fiber and has other movable motorized components such as a filter wheel, shutters, and focus of the wavefront sensor (WFS, hereafter).

Finally, the tip-tilt mirror is located just before the DM. The only drawback of not being located in the pupil plane is that it is moved around the ground-layer turbulence. According to ZEMAX, this produces a shift in the science camera’s pupil of less than 1% of its size, for a typical atmospheric tip-tilt. This would not harm even coronagraphic observations with an undersize stop. On the positive side, at least two optical elements (which would be required to reimage the pupil) are saved. Similar designs have been adopted in other working AO systems (e.g., Hippler et al. 2000; e.g., Peter et al. 2010).

2.2. Wavefront Sensor

The wavefront reflected by the deformable mirror can be sampled by two different lenslet arrays with different configurations. The first one is a keystone-shaped array with 28 microlenses (Fig. 6) which is detected by a 128 × 128 pixel EMCCD camera. The focal length of the microlenses is 45 mm. This geometry allows for an optimum filling of the annular telescope aperture unlike other designs such as hexagonal or square grids. In addition, if the subapertures in the different rings are designed in such a way that all of them have the same area, the spots are equally bright, and the noise pattern is uniform. The

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1 At http://www.zemax.com.
reconstruction benefits of this configuration with respect to other more common ones (e.g., hexagonal) are described by Kasper & Hippler (2003).

A second array comprises a $5 \times 5$ hexagonal-shaped lens configuration (Fig. 6) with a focal length of 36.1 mm and 1 mm pitch. The focal length is different than in the previous case, so a linear motorized stage can place the relay lenses in such a way that the pixel scale remains constant at the detector. This setup can be used with fainter targets due to the smaller number of microlenses than the previous one.

A variety of wavefront reconstruction algorithms using data provided by SHS are available (Li & Jiang 2002). The modal reconstruction algorithm will be better in case of low signal-to-noise ratio (S/N) conditions (Li & Jiang 2002). For that reason we used the modal one for our project. In this procedure the measured focal position of each microlens is used to determine the local wavefront gradients, in such a way that the wavefront shape can be reconstructed by means of a vector of coefficients in a polynomial basis. The Karhunen-Loeve polynomials are used here.

The modal reconstruction algorithm is described in Southwell (1980). Here we summarize the main steps of this procedure. The desired coefficient vector $a$, representing the reconstructed wavefront, can be derived from the array of measured wavefront gradients, by applying an inversion method:

$$a = (A^\top \cdot A)^{-1}A^\top \cdot S,$$

where $A$ is a rectangular matrix with $2N$ rows and $M$ columns (with $N$ being the number of microlenses and $M$ the total number of Karhunen-Loeve terms used). Its coefficients can be calculated from the partial derivatives of the polynomials (Dai 1995). The local slopes can be organized to form a slope vector $S$ of size $2N$ (Southwell 1980).

### Table 1: Main Instrument Parameters

| AO System | Focal ratio | Cassegrain f/8 |
|-----------|-------------|----------------|
| Principle of operation | Adaptive optics system |
| AO closed-loop sample speed | 420 Hz |
| Modes of reconstruction | 15 |
| Wavefront Sensor | Principle of operation | Shack-Hartmann sensor |
| Detector | EMCCD Andor IXON DU860 |
| Chip size | $128 \times 128$ pixels |
| Lenslet arrays | $5 \times 5^a$ and $KS28^b$ |
| Pixel scale | 0.45 pixel$^{-1}$ |
| FOV of each spot | 10.5$^c$ |
| Wavelength range | 400–950 nm |
| Filter wheel | 6 positions. Neutral density filters |
| Deformable Mirror | Principle of operation | Membrane-deformable mirror |
| Actuators | 39 |
| Diameter | 30 mm |
| Maximum depth | 8 $\mu$m$^2$ |
| Voltage range | 0–250 V |
| Sample speed | 1 kHz |
| Reference voltage | 180 V |
| Useable diameter | 20 mm$^2$ |
| Tip-Tilt System | Principle of operation | Magnetic pivots |
| Model | AO-7 SBIG |
| Sample speed | 50 Hz |
| Scientific Camera | Principle of operation | Back-illuminated CCD $1024 \times 1024$ |
| Scientific camera FOV | $90 \times 90$ arcsec$^2$ |
| Pixel scale | 0.08 pixel$^{-1}$ |
| Pixel size | 24 $\mu$m |
| Filter wheel | 4 positions, 50 mm diameter each |
| Wavelength range | 950–2500 nm |
| Control | Principle of operation | Single PC: Intel Pentium IV 3.4 Ghz, 2 Gb RAM |

$^a$ $5 \times 5$ hexagonal microlenses.  
$^b$ Keystone-shaped microlenses.  
$^c$ According to the manufacturer.
2.3. The Deformable and Tip-Tilt Mirrors

The micromachined MDMM consists of a chip with a silicon nitride membrane coated with aluminum. It was manufactured by OKO Technologies (Vdovin 1995). The membrane shape is driven electrostatically by the voltages applied to 39 control electrodes. Since the force between the membrane and the electrodes is attractive, the membrane can be pulled only toward its base. Therefore deformations in both directions can be led by biasing the mirror to a nonzero voltage. The reference value is 180 V for this bias, with an effective mirror diameter of 20 mm according to the manufacturer.

The membrane is coated with an evaporated layer of aluminum to make it reflective and conductive. Two digital drivers provide an 8 bit voltage control for the output channels, whereas two high-voltage boards amplify the digital signals (0–250 V) that are subsequently applied to each electrode.

The MDMM control is based on the previous knowledge of the so-called influence functions. These functions are the responses of the membrane to the action of one particular isolated electrode. They were obtained by direct measurements of the wavefront, using the SHS system, when the highest voltage is applied to each actuator keeping the rest to the bias level (Claflin & Bareket 1986). The surface’s wavefronts are expressed as a Karhunen-Loève’s polynomial expansion with 14 terms (including the tip-tilt), which corresponds to the fourth order of these polynomials. The set of functions can be grouped into the so-called influence functions matrix (IFM). Assuming that the total deflection of the mirror is a linear superposition of the deflections resulting from each control channel, we can obtain the shape of the membrane as a response to a given set of voltages applied to the electrodes by a simple matrix multiplication:

![Optical design of SAOLIM](image)

Fig. 3.—Optical design of SAOLIM. See the electronic edition of the PASP for a color version of this figure.

![Ray fan diagram showing the aberrations](image)

Fig. 5.—Ray fan diagram showing the aberrations of different angles (±39.6°) at the SAOLIM scientific camera, estimated by Zemax. See the electronic edition of the PASP for a color version of this figure.

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![Optical design of SAOLIM](image)

Fig. 6.—Left panel: Keystone-shaped lenslet array in 28 microlens configuration. Right panel: 5 × 5 lenslet array configuration. See the electronic edition of the PASP for a color version of this figure.
where vector $V$ is the set of $k$ squared voltages applied to each electrode and $a$ is the shape of the membrane expressed in terms of an expansion of Karhunen-Loeve’s polynomials (Dai 1995).

The control matrix (CM) is obtained as the inverse matrix of IFM. It relates the vector of coefficients ($S$) to the required voltages by

$$CM \ast S = V.$$  \hspace{1cm} (3)

Because of the particular shape of the mirror, the CM is not a square matrix. Therefore a pseudoinversion procedure to the IFM matrix is required in order to derive the CM. The singular value decomposition method (SVD) was adopted. Some membrane modes may be removed by setting to zero a singular value in the IFM during the inversion process to avoid infinite values. This operation reduces the capability to reproduce some surfaces but it makes the control of the mirror more stable.

Finally, the procedure to create different surfaces or to compensate for the effects of the turbulence is applied iteratively. The iterative process is a negative feedback loop and is similar to the one used by other AO systems (e.g., Hippler et al. 2000). This allows us to obtain better performance than with a single iteration, due to the nonlinearity effects. Therefore the wavefront sensing errors or any overshooting in the applied voltages are minimized during this iterative operation (closed loop).

The set of $39$ voltages $V_n$ at instant $n$ is given by

$$V_n = V_{n-1} + \alpha \cdot \omega(CM \cdot \phi),$$  \hspace{1cm} (4)

where $\phi$ contains the SHS measurements of the wavefront shape expressed in terms of an expansion of the Karhunen-Loeve’s polynomials ($F_i(x, y)$), $w$ is a vector of weights for each mode, and $\alpha$ is a damped parameter with values between 0 and 1. The value finally adopted for $\alpha$ was 0.75, derived empirically to grant the convergence of the iterative process. The surface generated with this set of voltages is the closest solution, in the least-squares sense, to the surface $S$. The rms of the residual can be expressed by

$$rms = \left| \sum_i \phi_i F_i(x, y) - \sum_i \phi_i' F_i(x, y) \right|.$$  \hspace{1cm} (5)

Therefore,

$$rms = \left| \sum_i (\phi_i - \phi_i') F_i(x, y) \right| = \sqrt{(\phi_i - \phi_i')^2}.$$  \hspace{1cm} (6)

The tip-tilt mirror can be compensated with the deformable mirror, at the expense of consuming a substantial fraction of the dynamic range of the actuators. As an alternative solution, a steering mirror is used for that purpose.

The tip-tilt mirror was manufactured by SBIG.\(^2\) It consists of a steering mirror capable of achieving motion rates up to 50 Hz. This tip-tilt mirror has magnets on the back size. That interact with the current flowing through a set of voice coils on the housing module to rapidly move the mirror. The technique is very similar to that employed in loudspeakers, except that there the magnet is fixed and the wires are on the speaker cone. The mirror and magnets are suspended using a flexible beryllium copper membrane. A needle pushes up against a jewel bearing mounted at the center of the mirror to hold the focus constant. SBIG has developed a proprietary technique to rapidly damp the motion of the mirror, so small movements are precise, with very little overshoot or fluctuations. The tilt of the mirror during operation is very small, and it does not lead to any measurable defocus at the edges of the frame. The correction range of the tip-tilt mirror is about $\pm 250 \mu m$, representing approximately $10''$ on the sky, which is sufficient for the application. A specific 50 Hz algorithm is used for the tip-tilt mirror. The telescope is tracking at sidereal rate, but we do not autoguide on off-axis guide stars.

### 3. INSTRUMENT CONTROL

#### 3.1. Instrument Control Electronics

SAOLIM is operated by a remote control without direct human interaction with the instrument. This control electronics was designed to contain all subsystems and is packed into a single electronic rack located just below the optical bench. Everything is mounted in a rigid custom-designed aluminum frame. It contains the following major components: a Pentium IV 3.4 Ghz PC as master hardware controller, a MDMM electronics with DC and high-voltage amplifiers, a tip-tilt mirror controller, some stepper motor controllers, shutter controllers, alternative power supplies, and a variety of support and auxiliary electronic units. The amount of dissipated heat is negligible with no effect at the optical bench. However, two fans remove the air inside the electronic rack. They do not cause detectable vibrations. A liquid-cooled heat exchanger is installed in this level to remove the heat produced by the EMCCD inside the optical bench. This allows us to turn off its fan during the observations at the telescope, avoiding potential turbulence in the optical path.

The following motorized functions are served by different electronics subsystems: a control unit of the SHS shutter, a linear stage to focus the relay lens onto the SHS, a filter exchange stage for SHS, a tip and tilt stage of the folding mirror (E8 in Fig. 1), and finally a linear stage to place the white reference fiber in the optical path.

The PC control is connected via ethernet through a router providing direct access from any terminal. Also available is a

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\(^2\)At http://www.sbig.com.
wireless connection, which is very convenient when the instrument is controlled next to the telescope for diagnostic purposes.

### 3.2. Instrument Control Software

The system is operated under a Windows XP operating system. Thanks to the very fast processors of modern PCs, all procedures can be run under such an operating system without detectable speed losses. Its use is an innovation that reduces hardware costs considerably. The control software is written in Microsoft Visual C++ and provides enough computation power for the reconstruction algorithms without requiring detailed knowledge of the device parameters by the user.

### 3.3. Scientific Camera

All of the tests presented in this article were done using a nonoptimal 1k × 1k back-illuminated CCD camera. At the time of development of the instrument, we did not have access to a more adequate detector such as a NIR camera, which is the usual scientific camera in AO systems. This camera was used only for testing purposes to check the goodness of the operation of the reconstruction algorithms. Therefore, no scientifically useful data were obtained at this stage. All of the observations were performed in the very near-infrared regime, using a narrowband filter with a central wavelength of 1033 nm and a bandwidth of 10 nm. The transmission was measured and revealed no blue leaks. At this wavelength range, the camera has ~5% quantum efficiency (QE). For that reason, only bright stars could be observed. This will not hamper the results presented here, since our main goal was to test the design and construction, not to produce scientifically useful data at this point.

In a second future stage, a fast frame rate EMCCD camera is intended to replace the current scientific camera.

### 4. PERFORMANCE OF THE INSTRUMENT

#### 4.1. Mechanical Stability of the Prototype

The mechanical design of the instrument is provided by a solid aluminum cast housing, which keeps all the optical elements in place. During some bad weather nights, flexure tests at the telescope were performed. The telescope was pointed to

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**TABLE 2**

| Star Name | $m_v$ | Total Flux | S/N$^*$ | EMCCD Setup |
|-----------|-------|------------|--------|-------------|
| HR 7315   | 5.3   | 136785     | 187.7  | EMGain = 100, Freq = 135 Hz |
| HD 171827 | 7.7   | 61428      | 128.7  | EMGain = 210, Freq = 103 Hz |
| SAO 67491 | 8.6   | 10944      | 52.9   | EMGain = 210, Freq = 103 Hz |
| SAO 68044 | 9.7   | 4213       | 38.5   | EMGain = 210, Freq = 103 Hz |
| PPM 82785 | 10.7  | 956        | 19.1   | EMGain = 255, Freq = 103 Hz |
| GSC 2662  | 11.8  | 192        | 7.5    | EMGain = 255, Freq = 103 Hz |

*Note.*—Average seeing, FWHM 1.3"–1.6"; 2008 Mar 7.

$^*$ Robbins & Hadwen 2003

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Fig. 7.—Left panel: RMS of the wavefront reconstruction measured with SHS versus standard deviation for different seeing conditions. Units of RMS are in radians. Right panel: S/N per lenslet channel measured with SHS vs. standard deviation for different seeing conditions. In this case, all plots are very similar because the photometric aperture was constant and larger than the simulated seeing value.

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different positions in hour angle and declination. At each position, the reference fiber pattern was recorded at the Shack-Hartmann sensor which computes the resulting tip and tilt values of the image. Flexures of the instrument were determined to be negligible at any location. Their maximum value was $\sim 0.5''$ at 30° of telescope elevation pointing to the south. In addition, the motorized stages were tested at very low telescope elevations and showed an acceptable performance, reproducing the same available positions.

4.2. Sensitivity of the WFS

One innovative aspect of the SHS design was the use of an EMCCD as a detector. This pioneering camera has had a profound influence on photon-starved imaging applications, such as photon counting in astronomy (e.g., Dussault & Hoess 2004). The back-illuminated device combines photon collection efficiencies of up to 95% QE with single photon sensitivity through the virtual elimination of the readout noise. It is likely that some false detections may arise. Their effect will be to increase the net rms of the reconstructed wavefront. For that reason, the final performance of the instrument has to be measured on real stars.

During the commissioning of the instrument, in the observing period of 2008, a set of stars with different brightnesses were observed to estimate the overall sensitivity of the instrument. The results are summarized in Table 2. The photometry was performed by using a circular aperture of 6 pixels and the DAOPHOT package of IRAF. The table shows the star name, $V$-band magnitude measured by SHS for different seeing conditions. See the electronic edition of the PASP for a color version of this figure.

| Date       | Goals                                                                 |
|------------|------------------------------------------------------------------------|
| 2007 Jul 2–5 | Determination of the pixel scale, flexures, wavefront sensitivity.     |
| 2007 Sep 28–30 | First image obtained on the scientific camera of a real star with tip-tilt compensation. |
| 2008 May 11–14 | First images obtained on the scientific camera of a real star with high-order compensation (under very poor seeing conditions, performance from 2.5° to 1.2°). |
| 2008 Aug 16 | Evaluation of performance of the high-order loop on the scientific camera under average seeing conditions. |

![Fig. 8.](image.png) Simulated relation between the Strehl ratio and $V$ magnitude measured by SHS for different seeing conditions. See the electronic edition of the PASP for a color version of this figure.

![Fig. 9.](image.png) Centroid distances of the SHS star pattern with respect to the SHS reference fiber when a tip-tilt compensation is applied. See the electronic edition of the PASP for a color version of this figure.

| Table 4 |
|---------|
| **Comparison between Static Coefficients of the 2.2 m Telescope at Calar Alto Obtained with Intra-Extra Focal Images vs. Those of the SAOLIM Wavefront Sensor** |
| Aberration | CAHA rms (nm) | SAOLIM rms (nm) |
|------------|---------------|-----------------|
| Astigmatism (sin) | $-7.54$ | $-6.5 \pm 1.0$ |
| Astigmatism (cos) | $21.2$ | $22.2 \pm 1.0$ |
| Coma (sin) | $5.36$ | $4.3 \pm 0.6$ |
| Coma (cos) | $8.42$ | $10.1 \pm 0.5$ |
| Trifoil (sin) | $4.81$ | $3.7 \pm 0.6$ |
| Trifoil (cos) | $5.21$ | $5.8 \pm 0.5$ |
| Spherical | $13.1$ | $12.9 \pm 0.3$ |
| Quad astig (sin) | $-0.50$ | $-0.6 \pm 0.3$ |
| Quad astig (cos) | $-2.02$ | $-2.5 \pm 0.3$ |

Found influence on photon-starved imaging applications, such as photon counting in astronomy (e.g., Dussault & Hoess 2004). The back-illuminated device combines photon collection efficiencies of up to 95% QE with single photon sensitivity through the virtual elimination of the readout noise. It is likely that some false detections may arise. Their effect will be to increase the net rms of the reconstructed wavefront. For that reason, the final performance of the instrument has to be measured on real stars.
magnitude, total flux in counts, and S/N. Each measured parameter in the table represents the average value over all subapertures. All the images were corrected for dark current and pixel-to-pixel variation. The table shows the detection limit of the instrument, which is defined as the maximum magnitude at which the control software is able to compute a centroid for every subaperture of the lenslet array and keep closed-loop operation. The limit is 11.8 mag for SAOLIM. This detection limit is similar to those of more complex and expensive AO systems such as ALFA, mounted at the 3.5 m telescope of the Calar Alto Observatory, which was able to use stars as faint as $V \sim 12$ to close the loop (Hippler et al. 2000).

An empirical relationship between the S/N per subaperture measured by the SHS and the star brightness can be established by an exponential fitting to both parameters, yielding

$$ S/N = 9538.6 \pm 1.6 e^{-0.4657 \times 0.015 m_v}. \quad (7) $$

In this way, the S/N can be estimated for any magnitude. The accuracy of the centroid algorithm during the wavefront reconstruction is determined by the S/N per subaperture. Therefore, some experiments were performed with the aim of predicting the capability of the system to compensate for turbulence under different seeing conditions and different star magnitudes.

To do so, a reference fiber is fed with a white source and placed exactly at the focal plane of the telescope, simulating a perfect reference star. By adding white noise to the whole image in steps of 0.5 counts, the rms (eq (6)) and S/N can be measured as a function of the noise on the different images recorded by the SHS. Finally, a relation between them can be established. This procedure was repeated until the S/N dropped to a low value (~10), when the uncertainty of the centroid coordinates was high. In addition, different seeing conditions were simulated by convolving the reference fiber pattern image with a Gaussian function with different widths. In total, 4000 realizations of the rms and the S/N versus the standard deviation of the input noise were performed for this simulation. An empirical relation between the input standard deviation of the

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**Table 5**

| Mode  | Open-loop | HO + TT |
|-------|-----------|---------|
| 2     | 2.59      | 0.015   |
| 3     | 0.96      | 0.002   |
| 4     | -0.45     | -0.011  |
| 5     | -0.41     | -0.002  |
| 6     | 0.13      | -0.006  |
| 7     | -1.33     | -0.14   |
| 8     | -0.05     | 0.11    |
| 9     | -0.17     | -0.08   |
| 10    | 0.22      | 0.21    |
| Average| 1.04      | 0.09    |

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**Fig. 10.**—Horizontal intensity cut of HR7331 image on the scientific camera. An improvement of 25% in FWHM and 40% in peak intensity is observed when the tip-tilt compensation is applied. The natural seeing FWHM was about 1.3″. Corrected seeing FWHM was 1.02″.

**Fig. 11.**—Wavefront rms during open-loop, tip-tilt, and closed-loop for a real star. Units are given in radians for $D/r_0 = 22$.

**Fig. 12.**—Left panel: Image of the star SAO 88071 taken with the SAOLIM scientific camera during open-loop procedure. Both images are a subwindow of $4 \times 4$ arcsec$^2$. Natural seeing FWHM was 2.5″. Right panel: The same star and seeing conditions during the closed-loop procedure. Corrected seeing FWHM was 1.2″. The images were taken with a narrowband filter with a central wavelength of 1033/10 nm of bandwidth from the Calar Alto 2.2 m telescope. The reference star has a 4.66 $V$-band magnitude. See the electronic edition of the PASP for a color version of this figure.
simulated noise, the output rms of the reconstructed image, and the final S/N of the detected subimages was derived for each input seeing by fitting the simulated data sets with a fifth-order polynomial function, for each pair of parameters. The simulations are shown in Figure 7.

As a result of these simulations, the Strehl ratio (at $\lambda = 550$ nm) can be derived and related to the $V$ magnitude as shown in Figure 8. Therefore, reference stars used by SAOLIM should have a brightness of at least $V \sim 11.5$ with the 28 microlens array, to compensate for the turbulence. This value was obtained for a natural seeing FWHM of 1" ($r_0 = 10$ cm).

The final accuracy of the correction will depend strongly on the input natural seeing conditions.

5. RESULTS ON THE SKY

Four technical campaigns were carried out to test the performance of the instrument on real stars at the 2.2 m telescope of the Calar Alto Observatory. The goals for these observing runs are summarized in the Table 3.

5.1. Static Aberrations of the Telescope

The static aberrations of the 2.2 m telescope are well known (Thiele, U., 2002, private communication). They were analyzed previously by using the intra-extra focal images technique (van Dam & Lane 2002). This method provides a set of Zernike coefficients that characterizes those aberrations. To check the reliability of the reconstruction algorithm adopted in SAOLIM, a routine was implemented in the control software to determine them. For doing so, the routine computes the wavefront coefficients of 10,000 images. Under good seeing conditions, the mean values of the coefficients represent the static aberrations of the telescope. Table 4 lists the coefficients of the static aberration of the telescope measured by the method described. There is a very good agreement between the estimations, showing the capability of the instrument to analyze the turbulence aberrations correctly.

5.2. The Tip-Tilt Algorithm on a Real Star

In order to test the tip-tilt compensation algorithm, a real star (HR 7331) was observed under average seeing FWHM of 1.3". The star was intentionally not centered on the detector. The drift of the centroids imaged by the lenslet array, with respect to a reference image produced by a fiber placed at the focal plane of the telescope, are computed by the WFS. With a proper calibration, the tip-tilt mirror is commanded in such a way that the drift is minimized in both axes.

Figure 9 shows the variations of the centroid of the star. They are minimized when the compensation is imposed in such a way that the standard deviation of the measurements decreases from 0.27 to 0.16 pixels. Besides this, the star is brought to the center of the SHS by the system. An improvement of 25% in terms of the FHWM and of 40% in terms of peak intensity is measured on the scientific camera as shown in Figure 10.
5.3. High-Order Closed-Loop Results

The high-order algorithm (HO) was also tested with real observations on the sky. The test comprises the measurements of the r.m.s. of the wavefront (equation [6]) during the open-loop and the closed-loop procedures. In the ideal case, this magnitude should be zero when the wavefront compensation is active, which will mean that the wavefront is flat. In the closed-loop operation where the SHS only measures the residual image motion after each correction, the measured values are smaller than in open-loop operation.

Figure 11 shows the r.m.s measured by the WFS during the open-loop, tip-tilt, and high-order compensation procedures as a test of the smooth performance of the reconstruction algorithms. Again, the units are radians. Clear differences between the three processes are appreciated. A natural guide star of $V \sim 5.2$ mag was used for this experiment with an SHS frame rate of 420 Hz and a total of 21,000 counts were collected for each process. The average seeing FWHM conditions were around 1.4″. An improvement of a factor $\sim 2$–3 is observed in terms of r.m.s measured by the Shack-Hartman sensor when only the tip-tilt compensation is applied. When the HO is added, a decrease of the r.m.s by a factor of 15 is seen. On the other hand, a decrease in the median values of every mode’s coefficient is observed. The decrease for modes 2–10 is listed in Table 5.

Any AO system may have internal inconsistencies: i.e., the system finds that the correction is adequate, minimizing the r.m.s, but the wavefront is not correctly compensated. For instance, this may happen if the WFS has a systematic error. Then the influence functions for the membrane would be obtained with that bias, and the global failure of the system would not be noticeable only from the analysis of the r.m.s.

To be completely sure of the performance of our AO system, simultaneous images were taken with the scientific camera. Figures 12–14 show some examples of real-time closed-loop aberration compensation using a natural guide star. These preliminary results were obtained during the commissioning of the instrument at the 2.2 m Cular Alto telescope. An observing log can be found in Table 6.

The images are clearly improved when applying the closed-loop wavefront compensation, even under quite poor seeing conditions. Figure 12 shows a 4.6 mag star (SAO 88071) observed under very bad turbulence conditions, with a natural seeing FWHM of about 2.5″. The data were obtained during the observing period of 2008 May. Under such bad seeing, 30% of the actuators reached their maximum values and therefore only an improvement of a factor of 2 in terms of FWHM could be achieved. The central wavelength of the observations was the same as before. The frame rate of the reconstruction was 420 Hz and 14 modes were taken into account with the KS28 lenslet array. Under these poor observational conditions, observing techniques like lucky imaging are useless. However, SAOLIM was able to reduce the FWHM of the output image to half of its input value and to increase the peak intensity by a factor $\sim 6$. Figure 13 illustrates that correction. Since the lucky imaging technique is feasible with an input seeing FWHM of $\sim 1$″ (Hormuth et al. 2008), this experiment demonstrates how our instrument can improve the performance of a lucky imaging device.

During the 2008 September observing period, the system was tested under better seeing conditions. The left panel of Figure 14 shows an image of the double star WDS01095+4795 (with visual magnitudes of 4.59 and 5.61), taken with SAOLIM without applying any corrections. The natural seeing FWHM was 1.1″ during the observations. The separation of the star is 0.4″, hence it was unresolved and appeared as a single spot in the image. The right panel shows the same object observed with the real-time closed-loop active. The corrected FWHM was 0.32″ and as a result of this, the double star is clearly resolved. The frame rate of the loop was 300 Hz.

This result is quite promising if the prototype is attached to a lucky imaging camera. When combined with an AO system, lucky imaging selects the periods when the turbulence that the adaptive optics system must correct is reduced. In these periods, lasting a small fraction of a second, the correction given by the AO system is sufficient to give excellent resolution with visible light. The lucky imaging system sums the images taken during the excellent periods to produce a final image with much higher resolution than is possible with a conventional long-exposure AO camera (Law et al. 2006).

6. CONCLUSIONS

A low-cost adaptive optic system was developed for astronomy and tested. It uses a 39-actuator membrane-deformable mirror of 20 mm diameter, a fast frame rate EMCCD as detector of the WFS and a low-cost tip-tilt mirror. The whole prototype is running in a single PC, resulting in a compact module that is
easy to install and transport, with a total weight of only 70 kg. Experimental simulations were carried out to determine the sensitivity of the WFS and to predict the limit magnitude of the star to be used. This limit was found to be 11.5 mag. The system was made up of entirely commercial hardware components with a total cost of about 35,000 euros. We did not count here the manpower costs.

A powerful method was adopted to evaluate the capabilities of a membrane-deformable mirror to produce and correct different aberrations within the range of interest in astronomy. This is a general approach, suitable for use in every system whose control was based on a previous knowledge of its influence functions. Under the assumption of linearity, the proposed iterative algorithm works with the required precision, making it appropriate to use in real-time applications. Karhunen-Loeve’s polynomial or any arbitrary surface could be reproduced when this procedure is systematically applied, taking into account the available range of voltages of the mirror. A real-time (up to 420 Hz) closed-loop algorithm has been incorporated into the device for the compensation of atmospheric turbulence.

The system has been tested on real stars. The best images obtained had a FWHM of 0.32″ from an input natural seeing FWHM of 1.1″. Although the system does not achieve diffraction-limited images, the FWHM is improved by a factor of 4. Under very poor seeing conditions (FWHM = 2.5″), 30% of the DM actuators were saturated, but an improvement of a factor of 2 was measured in the FWHM of the images. The tip-tilt mirror showed a good behavior too reducing the FWHM from 1.3″ to 1.02″.

The use of this AO system attached to a lucky imaging system could enhance the spatial resolution of the input images and the fraction of useful images, thereby improving system performance. Both techniques will be tested in the future.

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