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GUIELOA: ADAPTIVE OPTICS SYSTEM FOR THE 2.1-M SPM UNAM TELESCOPE

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RESUMEN

GUIELOA es el proyecto del sistema de Óptica Adaptativa (AO) para el telescopio de 2.1-m SPM. Este sistema es de tipo Curvatura, con 19 sub-aperturas. GUIELOA es muy similar a PUEO, el sistema de óptica adaptativa del telescopio CFHT. Puede compensar los efectos de la turbulencia atmosférica desde la banda R hasta la banda K. Se planea aplicar GUIELOA al estudio de sistemas binarios OB, a la detección de binarias muy cercanas, así como al estudio de discos, chorros y otros fenómenos asociados a las estrellas muy jóvenes.

ABSTRACT

GUIELOA is the adaptive optics system project for the 2.1-m SPM telescope. This is a 19 sub-apertures curvature-type system. It corrects 8 Zernike terms. GUIELOA is very similar to PUEO, the CFHT adaptive optics system and compensates the atmospheric turbulence from the R band to the K band. Among the planned applications of GUIELOA are the study of OB binary systems, the detection of close binary stars, and the study of disks, jets and other phenomena associated with young stars.

Key Words: **INSTRUMENTATION: ADAPTIVE OPTICS — ATMOSPHERIC EFFECTS**

1. INTRODUCTION

High spatial resolution imaging in astronomy using Adaptive Optics (AO) has been crucial for recent discoveries about binary and multiple systems. In the last few years, we have worked at the Institute of Astronomy of the National Autonomous University of Mexico (IAUNAM) on two AO systems. The first one was named LOLA and was an experimental tip-tilt correction system for training purposes (Cuevas et al. 1998). Lately, we have been working on a low order system which corrects up to the 8th Zernike term. This system is named GUIELOA. This name means "our eyes" in the Zapotec language. It resembles the CFHT PUEO AO system (Rigaut et al. 1998) with the same number of actuators (19). It will be installed at the 2.1m telescope at the San Pedro Mártir National Astronomical Observatory site (SPM).

The performance of AO systems is very sensitive to the value of the seeing and its temporal variations. In order to tune GUIELOA to the seeing conditions different campaigns have been conducted at the SPM site. The results of the campaigns showed that SPM is one of the best astronomical sites in the northern hemisphere. In the first part of this work we will show some of the results of the seeing campaigns and their impact on the GUIELOA design. We will discuss some of the GUIELOA design parameters and the instrumentation we intend to install at the GUIELOA-corrected focal plane.

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2. SAN PEDRO MÁRTIR SEEING

The SPM site, where the National Astronomical Observatory is placed, has been operated and developed by IAUNAM. The site is located in a national park at 31°02′39″ N and 115°27′49″ W and 2830 m above the sea level. This site is about 100 km from the Baja California west coast. Three Ritchey-Chrétien telescopes of 0.84 m, 1.5 m and 2.1 m diameter are in operation. The superb darkness and transparency conditions, H_2O atmospheric content and atmospheric turbulence are described in a recent RMxAA(CS) volume (Cruz-Gonzalez, Avila, & Tapia 2003).

An arsenal of atmospheric turbulence techniques has been applied for the characterization of seeing conditions in SPM. There have been long-term seeing campaigns where data have been gathered for hundreds of nights using one or two instruments (Michel et al. 2003). Also, intensive campaigns have been carried out, where several instruments and techniques were applied simultaneously during tens of nights. The conclusions for long-term campaigns are that the mean seeing is 0.55″ for 600 nights (123 nights using a Differential Image Movement Monitor: DIMM), and the best measurements are 0.37″ during 8 hours of continuous observations.

One intensive observing campaign took place from 2000 May 7th to 22nd (Avila et al. 2003).

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A number of different instruments were deployed: a generalized SCIDAR from Nice University, the DIMM, and a mast equipped with microthermal probes and instrumented balloons which measured turbulence profiles and the usual atmospheric data.

The seeing is produced by several turbulent layers above the site. The instruments of the intensive campaigns show that the turbulent layers are placed at the first 1.2 km; between 2-4 km; 9-16 km; 16-21 km and 21-25 km. The strongest contribution is generated in the first 1.2 km atmospheric layer.

Layer speed is a very important parameter for the closed-loop bandwidth of the AO systems. The generalized SCIDAR allowed the measurement of this parameter. In the first 2.2 km and above 17 km the turbulent layers move relatively slowly, with median speeds of 2.3 $\mathrm{m\,s^{-1}}$ and 9.2 $\mathrm{m\,s^{-1}}$. The fastest layers,with median speeds of 24 $\mathrm{m\,s^{-1}}$, are found between 10 and 17 km, where the tropopause and the jet stream are located. Turbulent layers above 9 km remained notably calm during 9 consecutive nights. This is very encouraging for AO.

3. GUIELOA THEORETICAL PERFORMANCE

3.1. *Image Quality*

Numerical simulations (Iriarte, Cuevas, & Martinez 2003) show that a 19-actuator curvature AO system corrects the first 8 Zernike terms of a turbulence aberrated wave-front, confirming the performance reported for the PUEO Adaptive Optics CFHT telescope. An AO system's performance is given in terms of the Strehl ratio of the obtained point spread function, including the telescope's corrected aberrations. A telescope without an AO system has a Strehl ratio given by (Roddier 1999):

$$S_{s.corr} \approx \left(\frac{r_0}{D}\right)^2 . \qquad (1)$$

For a telescope equipped with an AO system the Strehl ratio is given by:

$$S = \exp\left[-0.3(\frac{D}{r_0})^{5/3} N_{eff}{}^{-5/6}\right], \qquad (2)$$

where D is the telescope diameter, r_0 is the Fried parameter and N_{eff} is the effective number of Zernike terms that the AO system corrects.

The seeing FWHM is given by $\epsilon = \lambda/r_0$. $r_0 = 10$ cm when $\epsilon = 1''$ and its wavelength-dependence is given by:

$$r_0(\lambda') = \left(\frac{\lambda'}{\lambda}\right)^{6/5} r_0(\lambda). \qquad (3)$$

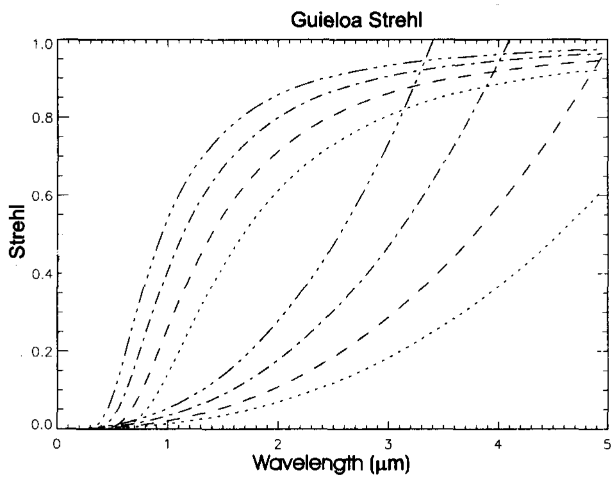

Fig. 1. Strehl ratios for an AO system correcting 8 effective Zernike terms on the 2.1m telescope (top plots). Bottom plots correspond to Strehl ratios without AO correction. Dotted line: bad seeing ($\epsilon_1 = 1''$, $r_0 = 10$ cm); dashed line: sub-arcsec seeing ($\epsilon_2 = 0.8''$, $r_0 = 12.5$ cm); dot-dashed line: good seeing ($\epsilon_3 = 0.6''$, $r_0 = 16$ cm); dashed-dot-dotted line: excellent seeing ($\epsilon_4 = 0.5''$, $r_0 = 20$ cm).

The theoretical Strehl ratio calculated for GUIELOA from these equations is shown in Figure 1.

The efficiency of AO systems is given by the ratio of the corrected image Strehl ratio to the non-corrected one, $G = S/S_{s.corr}$. This efficiency was calculated for GUIELOA for different wavelengths and is shown in Figure 2. From that figure it can be concluded that GUIELOA efficiently corrects even at the R band for the mean seeing conditions. It will also correct for the J band for not-so-good seeing. In order to take advantage of the performance of GUIELOA from the R to the K band it is wise to use simultaneously both a CCD and a NIR detector, such as a Hawaii NICMOS. A NICMOS-Hawaii detector camera named TEQUILA is being developed at IAUNAM.

3.2. *Isoplanatic Angle*

The isoplanatic angle is roughly the angle measured from the guide star at which the optimal Strehl ratio falls to 1/2 (Roddier 1999). This angle depends on the AO effective number of actuators. It also depends on wavelength as $\lambda^{1.2}$ and on airmass as $X^{-1.6}$. From the measured turbulent profiles (Avila, Vernin & Cuevas 1998; Cuevas et al. 1998) can be calculated the isoplanatic angle for a partial-compensation system such as GUIELOA. The calculated isoplanatic square fields are $14''\times 14''$ to $22''\times 22''$ for the R and I bands and $33''\times 33''$ to $67''\times 67''$

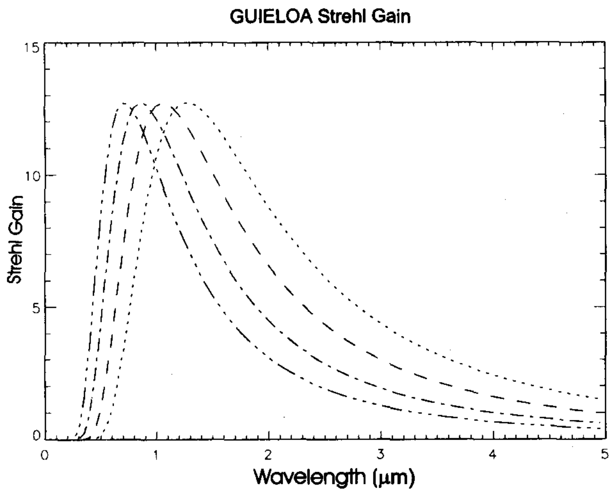

Fig. 2. Strehl ratio gain for an AO system correcting 8 effective Zernike terms on the 2.1m telescope. Dotted line: bad seeing ($\epsilon_1 = 1''$, $r_0 = 10$ cm); dashed line: subarcsec seeing ($\epsilon_2 = 0.8''$, $r_0 = 12.5$ cm); dot-dashed line: good seeing ($\epsilon_3 = 0.6''$, $r_0 = 16$ cm); dashed-dot-dotted line: excellent seeing ($\epsilon_4 = 0.5''$, $r_0 = 20$ cm).

for the H, J and K bands. These figures correspond to the mean seeing at the SPM site.

3.3. *Guide Star Limiting Magnitude*

The GUIELOA wave-front sensor is similar to the PUEO system in which 19 very low noise avalanche photodiodes (APD's) are coupled to a lens array by means of optical fibers. The APD's have very high quantum efficiency (70 % at 0.63μm). The lens array and the APD's coupling were manufactured in our optical shop.

The performance of GUIELOA depends also on the magnitude of the guide star. Iriarte et al. (2003) made numerical simulations of the corrected image Strehl ratio as a function of the photon flux incident on the wave-front sensor. The results are shown in Figure 3. In the figure, the guide star magnitude for which the Strehl ratio attenuation is 50% can be read off for different bands. This can be taken as the limiting magnitude. The limiting magnitudes are found to be 8.0, 9.0, 10.5, 11.5 and 12.5 for the R, I, H, J and K bands respectively.

4. DESIGN PARAMETERS

Nearly diffraction-limited images are obtained by GUIELOA for both the R and I bands and the H, J and K bands. It is crucial to correctly sample the diffraction-limited images. Planned detectors for GUIELOA are a 2048×2048 EEV CCD (13 μm pixels) and a 1024×1024 NICMOS Hawaii detector (18.5 μm pixels). Diffraction-limited images have a central disk given by λ/D where D is the telescope diameter. Sampling the central disk by roughly 3 × 3 detector pixels determines the f-ratio of the camera. For both the CCD and NICMOS detectors this value is $f/54$. Table 1 shows the GUIELOA design parameters.

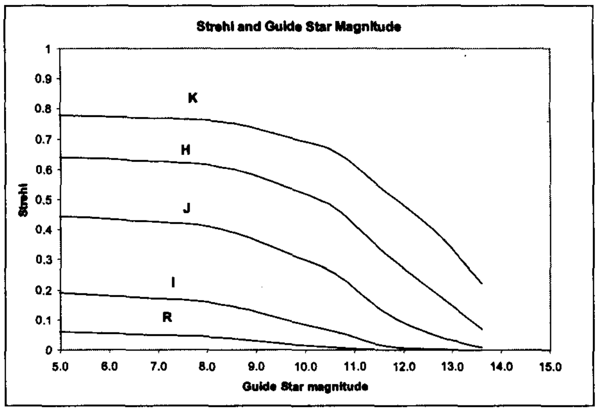

Fig. 3. Simulations of image Strehl ratio as a function of the guide star magnitude for the R to K bands. Seeing $0.6''$ ($r_0 = 15$ cm); wind speed 10 m s^{-1}

TABLE 1

GUIELOA DESIGN PARAMETERS

	HAWAII	VIS CCD
pixel (μm)	18.5	13
$f/$	54	54
sampling (mas/pix)	33.3	23.4
resolution (mas)	99	70
detector field	$34'' \times 34''$	$47'' \times 47''$
Isoplanatic Angle[a]		
R		$14'' \times 14''$
I		$21'' \times 21''$
J	$33'' \times 33''$	
H	$47'' \times 47''$	
K	$67'' \times 67''$	

[a]8 Zernikes AO system partial correction

Preliminary conceptual studies show the GUIELOA optical system can be realized with 3 off-axis parabolic mirrors (Lopez 2002). The optical system intrinsic Strehl ratio is higher than 0.8 on both the Hawaii field and the CCD field.

5. INSTRUMENTATION

The first obvious instrumentation to be coupled to GUIELOA is a direct-image system equipped with narrow and wide-band filters. We are also exploring the possibility of installing a spectrograph.

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We intend to install a coronagraph at the GUIELOA corrected beam. This device will have a black disk for classical Lyot coronagraphy and a phase mask for phase coronography (Guyon et al. 1999; Rouan et al. 2000). We are developing the phase masks in our laboratories.

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DISCUSSION

Horch – You showed very nice pictures of the bimorph mirror and the lenslet array. Have you made any tests of their performance in the laboratory?

Cuevas – The bimorph mirror was tested on an optical bench with control electronics at the University of Hawaii. Performance was analysed and satisfied the specifications.

Koenigsberger – What will you use for a guide star? What are the limiting magnitudes expected for the guide stars, if natural?

Cuevas – Guide stars will be natural stars. Guieloa is a relatively low cost system and a laser guide star was not considered. The wavefront sensor limiting magnitude is roughly $m_v = 12$, for natural guide stars.

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