ALFA–
The Laser Guide Star Adaptive Optics System for the Calar Alto 3.5-m Telescope

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Abstract

We present the concept and first results of the Calar Alto (Spain) LGS adaptive optics system. ALFA is a joint project between the Max-Planck-Institute for extraterrestrial Physics, providing the laser guide star, and the Max-Planck-Institute for Astronomy, responsible for the adaptive optics. In this contribution, we will concentrate on the requirements and the design of an LGS adaptive optics system. Matters regarding the observing procedure will be discussed as well. The laser and launching system are presented by Qirrenbach et al. in these proceedings.

1 Introduction

The performance goal for ALFA was to achieve above 50% Strehl ratio in the near infrared at 2.2 μm under average seeing conditions, and to have a good sky coverage. Thus, a laser guide star is mandatory, and, given the weather conditions at Calar Alto with a median seeing of $0.9''$ at 2.2 μm, the number of corrected modes on the 3.5 m telescope has to be larger than 50. Under these seeing conditions, the perfect correction of 50 modes gives a Strehl ratio of 78% [2]. Taking the finite bandwidth, the detector noise and other error sources into account 50 modes were considered to be sufficient to achieve 50% Strehl ratio.

Since the project was planned on a time scale of two years between starting the design in 1994 and first light in 1996 we decided to purchase the main parts of the system. The 97-actuator deformable mirror was purchased from Xinξtics, Littleton, USA[1], the high order wave-front sensor with a maximum of 100 subapertures and the soft- and hardware to do the wave-front reconstruction and to control the deformable mirror was provided by Adaptive Optics Associates (AOA), Cambridge, USA, the fast CCD camera for the Shack-Hartmann sensor is a product from Lincoln Laboratories, MIT, Lexington, USA, and the laser system with a 3-W dye laser was bought from Coherent, Santa Clara, USA. The camera and the software of the tip-tilt system are the same as in CHARM, our tip-tilt tertiary system [1]. The opto-mechanical design was done in house as well as the electronics for the optical elements that can be controlled remotely.

[1]The reason for buying a 97-actuator mirror instead of a 50-actuator mirror was simply that it was an off-the-shelf product of Xinetics. The next smallest mirror has 37 actuators which seemed too small for ALFA.

2 Optics

The diameter of the deformable mirror determines the basic parameters of the optical system displayed in Fig. 1. With the f/10 telescope focus in the front focal plane of the f/10 paraboloid its focal length has to be 662 mm to image the telescope pupil onto the (tilted) deformable mirror with an effective diameter of 66 mm. After reflection at the deformable mirror, the parallel beam is intercepted by the f/25 paraboloid with a focal length of 1594 mm to reimage the telescope focus into the infrared camera. As a result of the optical design the f-ratio of the reimaged focus was changed to f/24 instead of f/25. Out of habit, we keep calling it f/25.

Similar to CHARM, it was the design goal to have the reimaged telescope focus in the same position as the telescope focus without any optical elements from ALFA. Thus, in case of very bad seeing or mal functioning of the adaptive optics system the telescope can be used without ALFA by sliding two mirrors out of the beam. Since the image quality of a high order adaptive optics system is always close to the diffraction limit the pixel scale of the infrared camera should be chosen accordingly. Without ALFA, large pixels are more convenient. Therefore the f/10 telescope focus is converted to an f/25 focus by the relay optics.

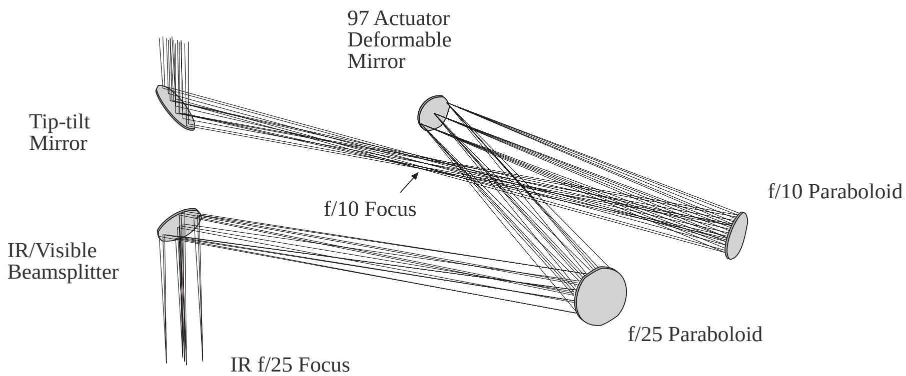

Figure 1: The main optical elements of the optical system of ALFA.

The first folding mirror is used as a tip-tilt mirror and the last folding mirror acts as a beam splitter reflecting the infrared downwards into the infrared camera and transmitting the visible into the wave-front sensor arm. The field of view has a diameter of 3 arcmin. The optical design was provided by E. Harvey Richardson of the University of Victoria, Canada.

The complete system mounted on a breadboard is presented in Fig. 2. One can recognise the five optical components described above (the IR/Vis beamsplitter is partially hidden). The additional components form five groups: the *FISBA interferometer* (FISBA Optik, St. Gallen, Switzerland), the *f/10 reference fiber*, to provide a perfect point source in the telescope focus, the *TV guider*, the *Shack-Hartmann sensor* and the *tip-tilt sensor* with the Na/Optical beamsplitter to separate the light of the sodium guide star from the natural tip-tilt guide star.

The FISBA interferometer, a Twyman-Green interferometer, is a commercial product, to control the surface of the deformable mirror. This interferometer does not obstruct the telescope beam as it "looks" perpendicular at the mirror. The rms aberration of the reflected wave is about 600 nm when the same voltage is applied to all actuators and about 100 nm after adjusting the voltages. In the infrared this is equivalent to a phase variance of about 0.1 rad^2.

The f/10 reference fiber is a monomode fiber with a core diameter of 3.6 μm that serves as a perfect point source for alignment and calibration. It can be moved remotely in and out of the beam.

The TV guider is used for acquisition. As the field of view of the infrared camera is only 1arcmin it is very helpful to have a sensitive camera with a 4 arcmin field of view to acquire the astronomical object.

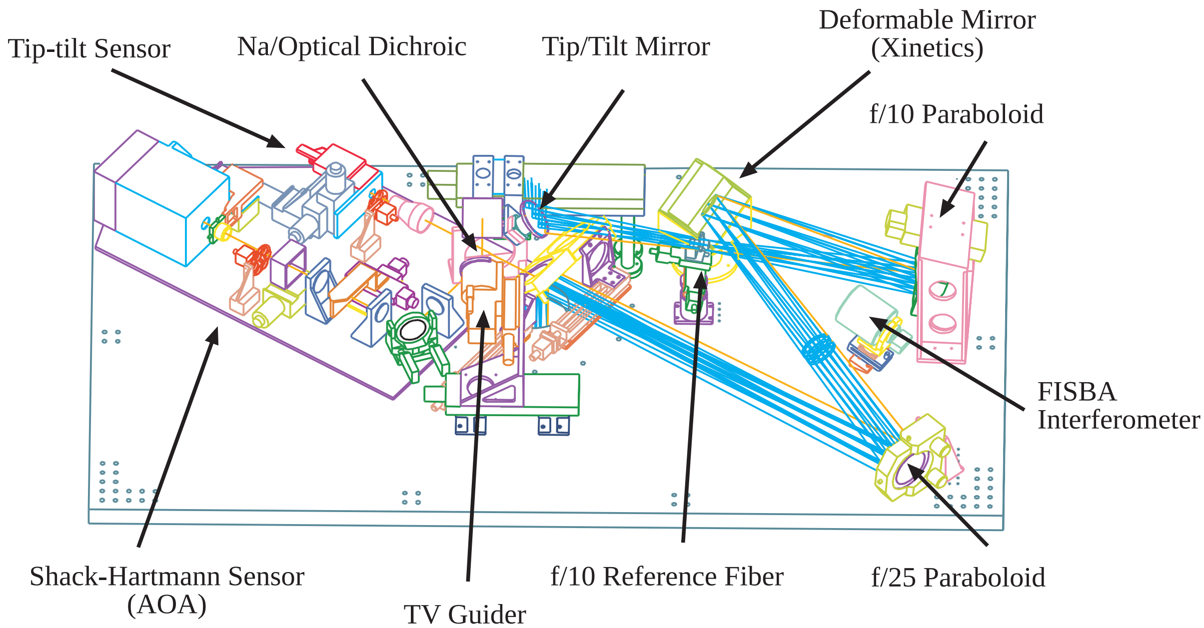

Figure 2: The ALFA breadboard with all opto-mechanical elements.

The Shack-Hartmann sensor was provided by AOA. Two field stops and a reference fiber source can be inserted into the reimaged focus. The field stops are required if a natural guide star is in a dense star cluster leading to cross talk between subimages, or if the laser guide star is used and the Rayleigh scattering has to be blocked for the same reason. The lenslets can be changed remotely from 3×3 subapertures to 12×12 subapertures. The focal length of all lenslets is identical so that the pixel scale in the Shack-Hartmann sensor is always 0.75″. The CCD camera can be focused remotely, also allowing to adjust the difference in foci between a natural guide star at infinity and the laser guide star at 100 km. The difference in focal position is 70 mm in the f/25 beam.

The Lincoln Labs CCD camera has a thinned 64×64 pixel chip that is used in frame transfer mode. The maximum frame rate is 1206 Hz with a read noise of 6 e^-. At the slowest frame rate of 100 Hz the read noise is slightly higher at 9 e^- due to increased dark current as the chip is only cooled to -5^{o}C. An upgrade of the camera will have a two stage thermo-electric cooler (-35^{o}C) eliminating the problem with the dark current and reducing the read noise well below 5 e^-.

The tip-tilt sensor has an AstroCam (Cambridge, UK) CCD camera with a 4201 controller giving 6 e^- read noise. Except for the relay optics in front of the camera this is exactly the CHARM system. In October 1997, we will have a new CCD camera head with less than 2 e^- read noise and a quantum efficiency that is roughly doubled since the chip will be thinned.

The size of the breadboard is 2.7 m ×1.5 m and the whole assembly is mounted via aluminium struts to an aluminium flange that is bolted to the telescope mounting flange. The total weight (including infrared camera) is 1.1 tons. Fig. 3 shows a photograph of the telescope with ALFA being mounted at the mirror cell and Team ALFA in front of the instrument.

3 Calibration and wave-front reconstruction

The calibration procedure consists of the following steps: After the system is optically aligned using the f/10 reference fiber as a perfect point source, the spots in the Shack-Hartmann sensor are defined as default positions. The procedure of finding the spots and defining the subimage size as a small box around the spots is controlled by the software. These boxes are about 4″×4″ in size depending on the number of subapertures. In the following step, the positions of the subimage cen-

Figure 3: ALFA mounted at the mirror cell of the 3.5 m telescope at Calar Alto and Team ALFA in front: Ralf-Rainer Rohloff (mechanics), “Sam” Wagner (electronics), Stefan Hippler (software), Andreas Glindemann (Co-PI), Donald Hamilton (Co-PI), (from left to right).

troids are determined as a function of the Zernike modes. This process is done by applying the Zernike modes (in suitable order and slightly modified to take the actuator pattern into account) to the deformable mirror, and then measuring the spot pattern in the Shack-Hartmann sensor directly. This defines the interaction matrix Θ, with $\vec{m} = \Theta\vec{a}$. $\vec{m}$ is the vector with all centroid positions and $\vec{a}$ is the vector with the Zernike coefficients. The wave-front reconstruction, *i.e.* the determination of the Zernike coefficients is done by computing the inverse of the matrix product $\Theta^T\Theta$ numerically, and calculating $\vec{a} = (\Theta^T\Theta)^{-1}\Theta^T\vec{m}$ which is the least-squares solution of $\vec{m} = \Theta\vec{a}$ [3].

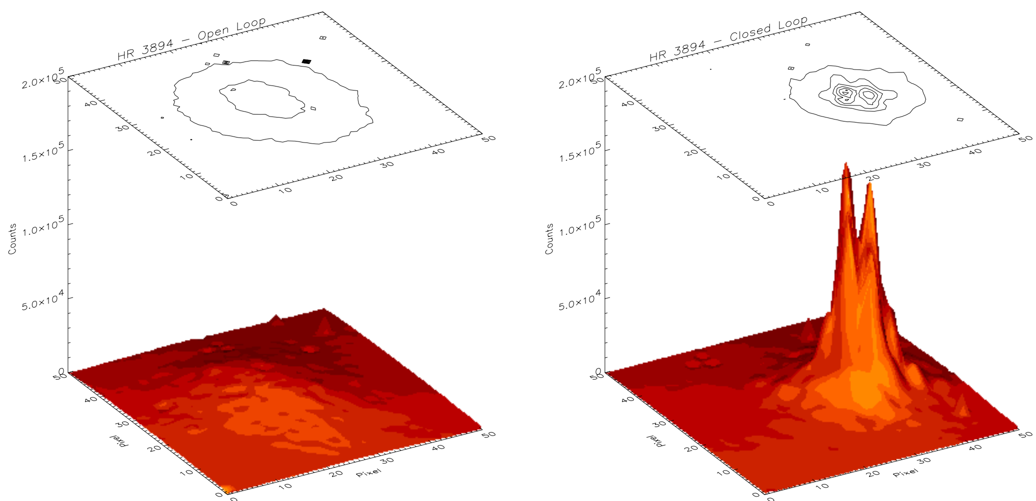

Figure 4: A near infrared image of the 0.24$''$ binary ϕ Ursa Majoris (HR 3894, $m_V = 4.6$) observed through clouds in 1.7$''$ seeing on March 1, 1997. The observing wavelength was 2.2 µm. 20 Zernike modes were corrected with a frame rate of 900 Hz. This is a raw image without any image processing adding up single images to a total exposure time of 50 sec. The two components are clearly resolved.

Since the reconstruction of the wave-front and the subsequent computation of the mirror drive signals has to be done in less than 1 msec there are twenty digital signal processors (DSP) performing this task partially in parallel. The DSPs are mounted in groups of four on Ariel Hydra-II boards and are manufactured by Texas Instruments (TMS320 C40). Four DSPs process the subimages, subtracting the bias and correcting the gain, eight DSPs determine the image centroids and wave-front gradients, four DSPs then perform the wave-front reconstruction by multiplying the gradients with the reconstructor matrix, two DSPs apply the parameters of the control algorithm to the reconstructed modes, and two DSPs handle the input of the data from the Lincoln Labs CCD camera and the output to the deformable mirror. The total computing time is *e.g.* 0.7 msec if 15 modes are reconstructed from 20 subapertures.

4 Results

ALFA was taken to the telescope in September 1996, and as soon as the weather allowed we could close the loop on bright natural guide stars. During the following observing runs with a total of approximately 40 nights the progress was slower than anticipated partially due to very bad weather conditions; more than half the nights were lost, during the other half the seeing was worse than $1.5''$ with very few exceptions.

After the FISBA interferometer was installed and the mirror flattened, the image quality in the corrected image improved considerably. In Fig. 4, the $0.24''$ binary ϕ Ursa Majoris is clearly resolved although the star was observed through a thin layer of clouds. The star itself was used as a guide star for the adaptive optics system in the Shack-Hartmann sensor. 20 Zernike modes were corrected, and the system was running at 900 Hz. The improved image quality compared to the very first result shows particularly in the lower halo and in the reduced number of subsidiary peaks.

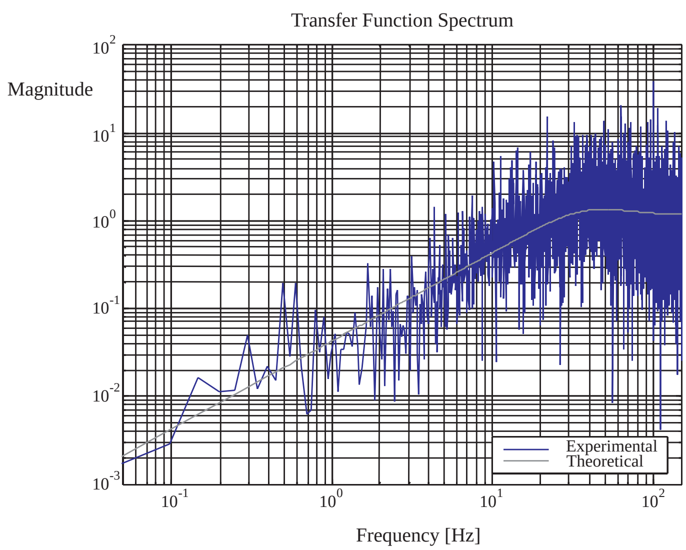

Figure 5: The measured and the theoretical transfer function of the closed loop system for the Zernike mode $J = 4$ (focus). The measured transfer function is the quotient of the uncorrected and the corrected spectrum. The theoretical function is calculated using the parameters of the control loop.

Fig. 5 shows the measured closed loop transfer function, *i.e.* the quotient of the corrected and the uncorrected spectrum, that is compared to the theoretical transfer function which follows from the control loop parameters. The latter has been calculated by Douglas Looze of the University of Massachussetts, USA, who designed the control loop algorithm for AOA. The theoretical and the measured transfer functions agree very well indicating that the control loop is working properly.

The limiting magnitude of the current tip-tilt system is $m_V = 13.5$. With the new CCD we expect it to be around $m_V = 16$. In the Shack-Hartmann sensor we could close the loop on a $m_V = 11$ magnitude star in $1.5''$ seeing. The upgrade of the CCD camera should improve this value by about two magnitudes.

The best result todate is shown in Fig. 6. The image of the star 14 Peg is improved from 2.4% to 20% Strehl ratio in 0.85 ″ seeing. The star itself was used for wave-front sensing. Each of the displayed images is the sum of 100 exposures of 0.2 sec. The Shack-Hartmann sensor was running at 100 Hz correcting 15 modes, and the tip-tilt sensor was running at 80 Hz. Thus, the system was running under the same conditions as with a laser guide star without any obvious problems.

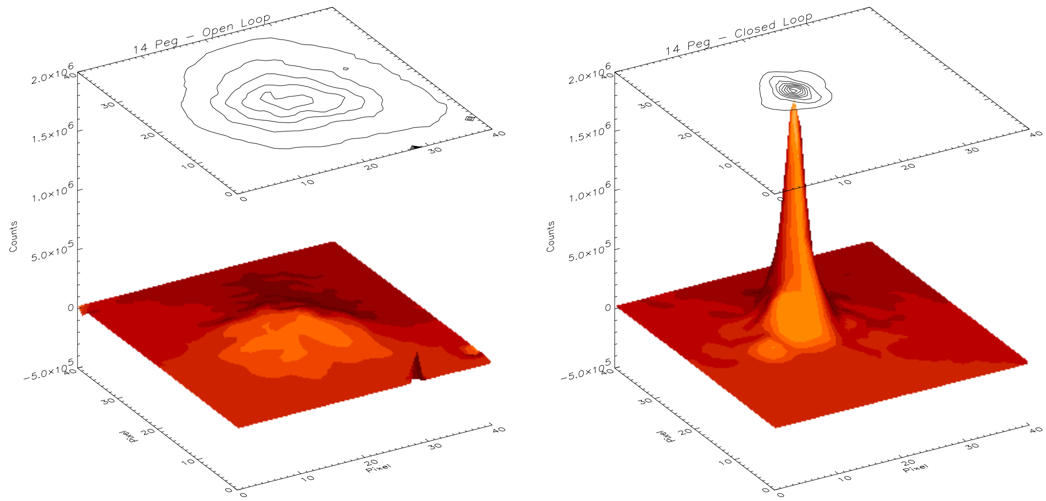

Figure 6: Uncorrected and corrected images of 14 Peg ($m_V = 5.04$) at 2.2 μm taken on July 21, 1997. Correcting 17 Zernike modes with a loop frequency of 100 Hz the Strehl ratio is improved from 2.4% to 20% in 0.85″ seeing. No image processing was applied.

A Strehl ratio of 20% corresponds to a phase variance of 1.6 rad^2. Perfectly correcting 17 modes reduces the wave-front phase variance to 0.6 rad^2 [2], with $r_0 = 0.53$ m, corresponding to 0.85″ seeing. The rms flatness of the deformable mirror of 100 nm is equivalent to a phase variance of 0.1 rad^2 at 2.2 μm. The finite servo bandwidth adds approximately 0.5 rad^2. The remaining variance of 0.4 rad^2 is due to all remaining errors in the optical alignment etc.. Estimating the variances due to finite bandwidth and imperfect alignment cannot replace the measurement of these quantities but it can give an idea of the source of the residual phase variance.

5 Conclusions

After two years of designing and building the instrument, and after about 20 usable nights on the telescope, ALFA is starting to work reasonably well on natural guide stars. So far, we have always used the system in “laser guide star mode”, *i.e.* running the tip-tilt loop and the high order loop in parallel without encountering significant problems. However, we have yet to close the loop on the laser guide star. With the laser guide star and the expected limiting magnitude of the tip-tilt guide star ($m_V = 16$) we should be able to observe almost anywhere in the sky.

References

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