ALFA: Three Years of Experience in Adaptive Optics with a Laser Guide Star

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ABSTRACT

The Max-Planck institutes for astronomy and for extraterrestrial physics run a high order adaptive optics system with a laser guide star facility at the Calar Alto 3.5-m telescope in southern Spain. This system, called ALFA, saw first light in September 1996. Today, ALFA can compensate for atmospheric turbulences with natural guide stars as faint as 13.5th magnitude in R-band. ALFA recently succeeded in overcoming this limiting magnitude with the deployment of its laser guide star. This paper briefly reviews the ALFA project and its progress over the last 3 years. We further discuss the impact of sodium-layer laser guide stars on wavefront sensing and present results obtained with both kinds of guide stars.

Keywords: wavefront sensing, adaptive optics, laser guide star, lagoon nebula

1. INTRODUCTION

Diffraction limited imaging with infrared adaptive optics (AO) will become the standard technique on large ground-based telescopes in the 21st century. Future space-based telescopes like NGST or DARWIN might also require AO for their optical instrumentation.[1] At present, about 10 natural guide star (NGS) and 3 laser guide star (LGS) AO systems are operational. Another 5–10 LGS guided AO systems are planned or near completion.

The achieved peak performance of NGS AO systems is quite promising[2–6] whilst that of LGS systems is still (1–2 years) behind but getting there.[7–10]

Published astronomical data taken with AO systems often exhibit image qualities that are way below what the AO system can deliver under optimum conditions. Even the diffraction limit in K-band cannot always be reached under mediocre conditions (seeing around 1.5" or guide star brightness close to the limiting magnitude of the wavefront sensor). Another important issue one should keep in mind is the imperfection of the entire AO system itself: the wavefront sensors (e.g. pupil alignment, detector noise, dynamic range), the deformable mirrors (e.g. hysteresis, actuator malfunctions), the control techniques (alignment for zonal control, set of modes for modal control,[11] choice of closed loop compensator), the optical interfaces to the telescope and the science camera, the software and the staff who supervise and operate the entire system; all these components can degrade the performance of the system.

This paper describes our experiences with the Calar Alto 3.5-m telescope *Adaptive optics with a Laser guide star For Astronomy* system ALFA. We show images of the Lagoon Nebula obtained using an NGS and the best result so far using the LGS. We discuss some LGS specific issues (e.g. focus maintenance) and outline the differences between NGS and LGS wavefront sensing from a practical point of view. An outlook on planned further improvements of the ALFA system is given at the end of this paper.

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2. OVERVIEW OF THE ALFA PROJECT

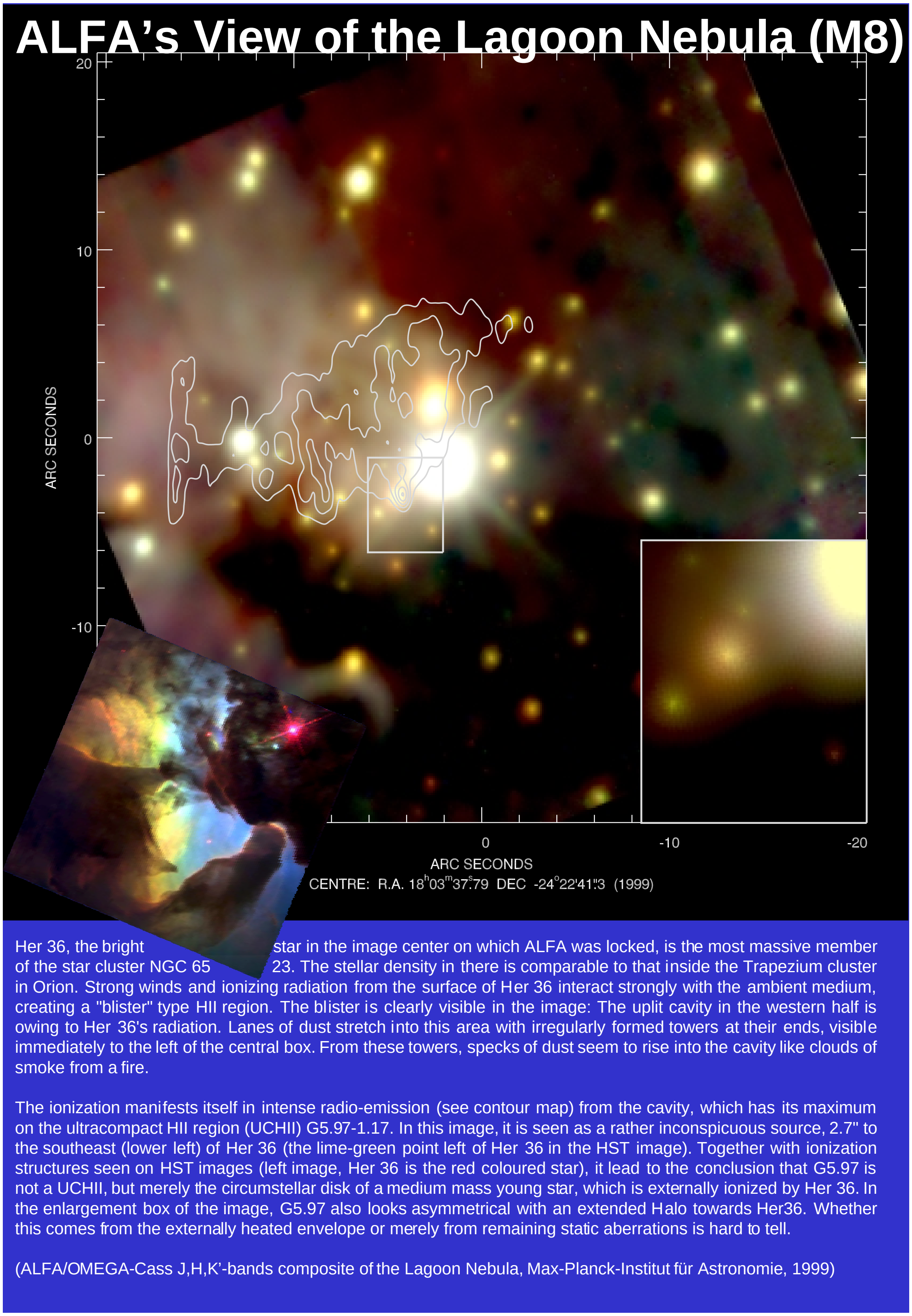
The ALFA project was started in spring 1994 on a short time scale of about 2 years with the goal to be ready before the HST/NICMOS camera became operational. The performance requirements were to achieve diffraction limited images in K-band with Strehl numbers greater than 60%. Typical uncorrected Strehl numbers in K-band are 1–2%. In September 1996, the ALFA system had first light and could improve the image quality sufficiently (near-diffraction limited core of the point-spread function (PSF) in K-band with an FWHM of 0.15” and 10% Strehl). Then it took about 15 months to successfully close the high order AO loop on the LGS (FWHM of 0.4” in K-band with an improvement in peak intensity by a factor of 2). The performance with NGSs was improved during that time by a factor of 2 (diffraction limited cores of the PSFs of 0.13” in K-band and maximum Strehl numbers of 20%). Another 9 months later, in summer 1998 we achieved our first goal: Strehl numbers $>$60% in K-band with natural guide stars of 8th magnitude in V-band (best result of ALFA so far is 72% Strehl in K-band). In J-band we obtained 12% Strehl and FWHMs below 0.1”. Finally, in June 1999 we reached our second goal: diffraction limited images with the sodium-layer LGS in K-band (23% Strehl, FWHM of 0.14”). The efforts that led to these final (June 1999) performance characteristics are described in various papers (for a continuously updated list of publications about ALFA please check our web page at: http://www.mpia-hd.mpg.de/ALFA).

3. WHAT WE HAVE LEARNED: EVERY DETAIL MATTERS

Building a high order adaptive optics system together with a laser guide star facility for an existing telescope is in itself a challenge. Making the system work and deliver good scientific data with an acceptable efficiency increases this challenge even more. The average time overhead of an AO observation with ALFA is currently around 25% using very faint NGSs. Operating ALFA in combination with the LGS increases the overhead time to about 40%, i.e. almost as much time is spent for laser and AO operation as for scientific observations. These numbers can be accepted if — and only if — the results are excellent. ALFA has started producing such results as we will show in the next sections. All components in the system are now well understood and optimized for the 3.5-m telescope and the average weather conditions at Calar Alto (median seeing of 0.9” at 2.2 μm). A simple “how to prepare and run ALFA” recipe can be summarized in the following manner.

1. Align all optical components of the AO bench accurately.
2. Flatten the DM to an rms flatness of 50 nm using in-situ control with an interferometer.
3. Take out all static aberrations measured with the science camera (we reach 90% Strehl in K-band using the deformable mirror and an artificial white light source) before calibrating the Shack-Hartmann sensor.
4. Switch to a bright star and measure the remaining telescope aberrations. Let the DM correct those in its nominal “open loop” shape. This improves the measurement of the atmospheric modes.
5. Find the best LGS focus: point the 3.5-m telescope to the science object; focus the laser launch telescope on the sodium-layer; focus the Shack-Hartmann sensor on the sodium-layer. Repeat the last two “focus” steps if necessary.
6. Calibrate the AO system with the calibration source in this final LGS reference focus position.
7. Block the backscattered Rayleigh light (see section 5) on the wavefront sensor. ALFA uses a field-stop for that purpose.
8. Close the tip-tilt loop on a natural guide star.
9. Stabilize the LGS jitter on the wavefront sensor, e.g. with a fast steering optical element in front of the wavefront sensor. This option will be implemented in the ALFA system in summer 2000. As an alternative we stabilized the LGS jitter (see section 5) with the secondary mirror of the laser launch telescope.
10. Close the high order AO loop on the laser guide star.
11. Start your science program.

This list reflects in a sense the most important steps we made from first light until now. For instance item 3: during the first commissioning runs, we could calibrate the AO system only with a reference laser at 632 nm without being able to verify the beam quality on our science camera. After replacing the reference laser with a white light source, we could measure the significant remaining aberrations on the science camera.



ALFA’s View of the Lagoon Nebula (M8)

Her 36, the bright star in the image center on which ALFA was locked, is the most massive member of the star cluster NGC 6523. The stellar density in there is comparable to that inside the Trapezium cluster in Orion. Strong winds and ionizing radiation from the surface of Her 36 interact strongly with the ambient medium, creating a "blister" type HII region. The blister is clearly visible in the image: The uplit cavity in the western half is owing to Her 36's radiation. Lanes of dust stretch into this area with irregularly formed towers at their ends, visible immediately to the left of the central box. From these towers, specks of dust seem to rise into the cavity like clouds of smoke from a fire.

The ionization manifests itself in intense radio-emission (see contour map) from the cavity, which has its maximum on the ultracompact HII region (UCHII) G5.97-1.17. In this image, it is seen as a rather inconspicuous source, 2.7" to the southeast (lower left) of Her 36 (the lime-green point left of Her 36 in the HST image). Together with ionization structures seen on HST images (left image, Her 36 is the red coloured star), it lead to the conclusion that G5.97 is not a UCHII, but merely the circumstellar disk of a medium mass young star, which is externally ionized by Her 36. In the enlargement box of the image, G5.97 also looks asymmetrical with an extended Halo towards Her36. Whether this comes from the externally heated envelope or merely from remaining static aberrations is hard to tell.

(ALFA/OMEGA-Cass J,H,K’-bands composite of the Lagoon Nebula, Max-Planck-Institut für Astronomie, 1999)

Figure 1. ALFA’s view of the Lagoon Nebula.

4. ALFA'S VIEW OF THE LAGOON NEBULA

The Lagoon nebula (M8) is a site where new stars are being born from interstellar molecular clouds. The ALFA image in figure 1 shows the infrared view of the central part of M8 around its energizing star, Herschel 36. Clouds of dust can be seen in the image as well as a lot of stars invisible on (visual) HST images. For the first time in the infrared, the ultracompact HII region G5.97-1.17 about three seconds of arc southeast of Her 36 (visible also as the peak of the radio emission from the region denoted by the contour map from Wood and Churchwell[12]) could be resolved as a non-pointlike object.

The inset in figure 1 clearly shows an extended halo pointing towards Her 36, a feature indicating the externally (by Her 36) heated shell of dust and ionized gas (see also Stecklum et al.[13]). Other interesting features visible in the image, like e.g. the coincidence of the second, elongated radio emission region at (+9",-2") with thin layers of dust, and several heavily reddened single and binary sources are currently under examination. The infrared camera used for this observation was OMEGA-Cass, a 1024x1024 pixel HAWAII array based instrument.[14] ALFA was locked on Herschel 36 (V=10 mag). The Shack-Hartmann sensor was set up with 18 subapertures and operating at a readout speed of 60 Hz. The achieved Strehl ratios are: 26% in K'-band, 18% in H-band, and 5% in J-band. Mind that all these values apply after the complete data reduction, which in this case involved registering and co-adding 5 frames per band.

Further results obtained with ALFA system are presented in this issue.[15–17]

5. WAVEFRONT SENSING WITH A LASER GUIDE STAR

The ALFA laser is a 4 Watts continuous wave dye laser tuned to the sodium D2 line at 589 nm. The laser projection telescope (launch telescope) is located off the side of the 3.5-m telescope. The separation between the optical axes is about 2.5 m. Detailed information of the ALFA laser subsystem is given by Rabien et al.[18] and references therein.

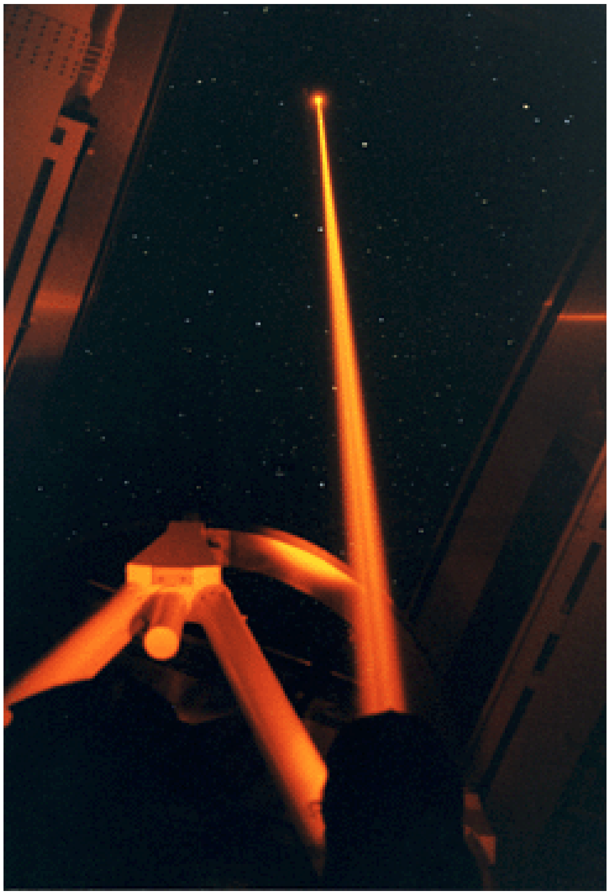


Figure 2. The ALFA laser beam projection.

Figure 2 shows the laser beam projected on the sky and blocked at a cloud. One can see that the laser beam leaves the telescope dome close to the illuminated front-ring of the 3.5-m telescope structure which holds the secondary mirror. This side projection geometry (off-axis) has some disadvantages compared with on-axis projectors. The LGS spots on the wavefront sensor are elongated due to the thickness of the sodium-layer (see right part of figure 3 for a rather extreme example) and the FWHM of the LGS image is about $\sqrt{2}$ to 3 times larger than the FWHM of a natural star. The latter effect is a result of the laser having to travel twice through the turbulent layers of the atmosphere. For an on-axis setup it has been shown [19] (for a small 75-cm telescope), that the core of the LGS can be smaller than the long exposure of a natural star because the upward and downward tip-tilt compensate each other. From a wavefront sensing point of view the effect of different apparent sizes of LGS and NGS can easily be handled e.g. by changing the pixel-scale of the wavefront sensor. [20]

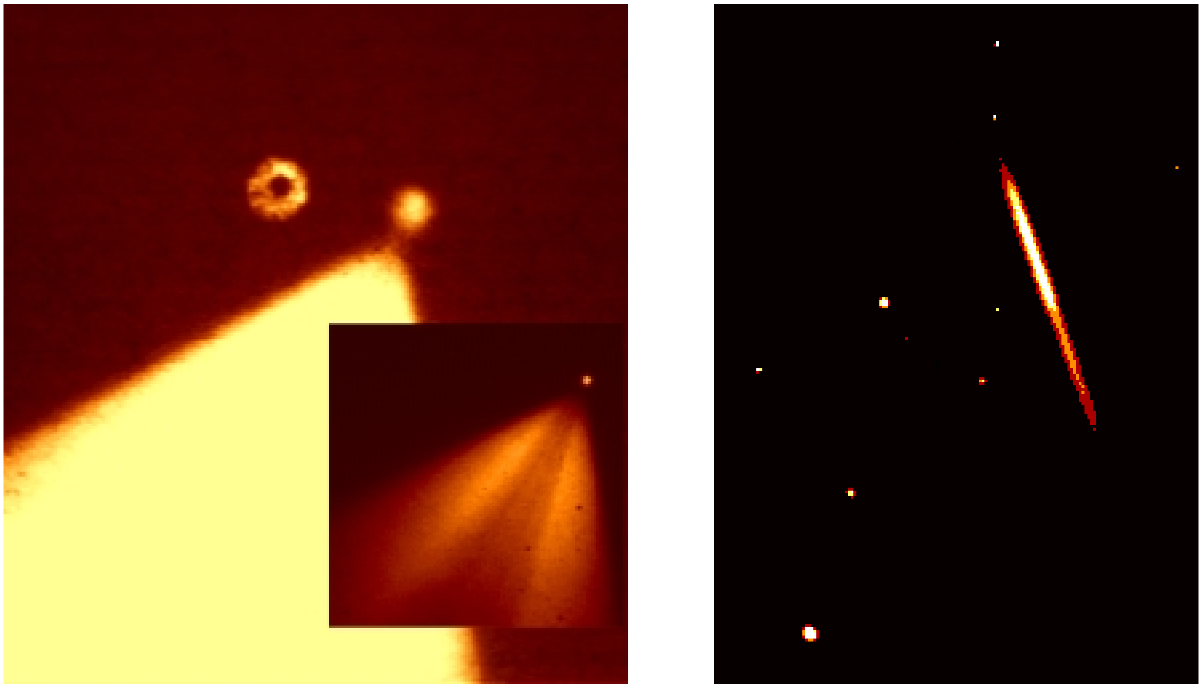


Figure 3. left) Rayleigh cone, LGS, and defocused NGS. The small image in the lower right shows a better focused LGS than the large image. The pupil-like defocused star SAO 055924 has a V-magnitude of 9.5.
right) The LGS seen from the side (laser cigar). The LGS launch telescope and the observing 1.2-m telescope (60 s exposure time) are 265 m apart. The length of the laser-cigar is about 100" on the sky which corresponds to about 12 km under the assumptions, that the laser-cigar starts at an altitude of 75 km and the launch telescope points perfectly to zenith.

The tip-tilt image motion of the LGS spots on the ALFA Shack-Hartmann wavefront sensor is often larger than one would expect if it was due to the atmosphere only. This extra jitter (see Rabien et al. [21]), which mainly originates in the laser beam relay system has to be compensated in order to provide stable closed loop operations. In ALFA we plan to compensate the overall image motion of the LGS spots with a fast steering lens in front of the Shack-Hartmann sensor. Alternatively, we already used the secondary mirror of the laser launch telescope to compensate for LGS jitter. The latter method helped stabilizing the overall LGS spots movements but cannot compensate for the higher "jitter" frequencies.

The LGS created in the sodium-layer of the mesosphere looks quite different depending on perspective: a TV camera which looks along the optical axis of the 3.5-m telescope shows a star-like image (left part of figure 3) while a similar camera (at the Calar Alto 1.2-m telescope) located 265 m apart shows the laser-cigar (right part of figure 3). Figure 3 shows two important effects: the backscattered light from the laser beam (Rayleigh cone) can disturb the centroid measurements on the wavefront sensor and a star at infinity (pupil-like image in the upper left) is pretty defocused when the telescope is focused at an altitude of about 90 km. [22] Depending on atmospheric conditions, the LGS-to-Rayleigh brightness ratio can vary strongly (see inset of left part in figure 3).

Another well known property of a sodium-layer LGS is the cone effect or focal anisoplanatism: the science object (at infinity) wave-front differs from the measured LGS (at an altitude of about 90 km) wavefront. This leads to a less perfect wavefront reconstruction compared to NGSs. Multi-conjugate adaptive optics with multiple LGSs can reduce this image degradation [23] at the expense of a dramatic increase in complexity of the AO system. Figure 3 demonstrates another difficulty while using a LGS for wavefront sensing: the fluorescence light that contributes to the measured wave-front signal is created in a column of about 12 km length (for a detailed analysis of the mesospheric sodium layer at Calar Alto see O'Sullivan et al. [24] and Butler et al.[22]). The measured vertical LGS intensity profile is a direct measure of the sodium density or (integrated over the length) the average sodium column density. Variations in the average altitude of the sodium-layer above the telescope as well as variations in the vertical sodium distribution in the mesosphere make focus measurements on the LGS incorrect.

Figure 4 shows the effect of variations of the altitude of the sodium-layer for different telescope sizes. Changes of a few hundred meters have almost no effect on the focus error of a 3.5-m telescope. However, fast sodium-layer altitude variations of this order are a severe problem for 8m-class telescopes. Slow sodium-layer altitude drifts can be compensated in closed-loop operation via adaption of the wavefront sensor reference focus (e.g. by moving the wavefront sensor focus stage). Altitude changes which are due to zenith distance changes can be compensated in open-loop.

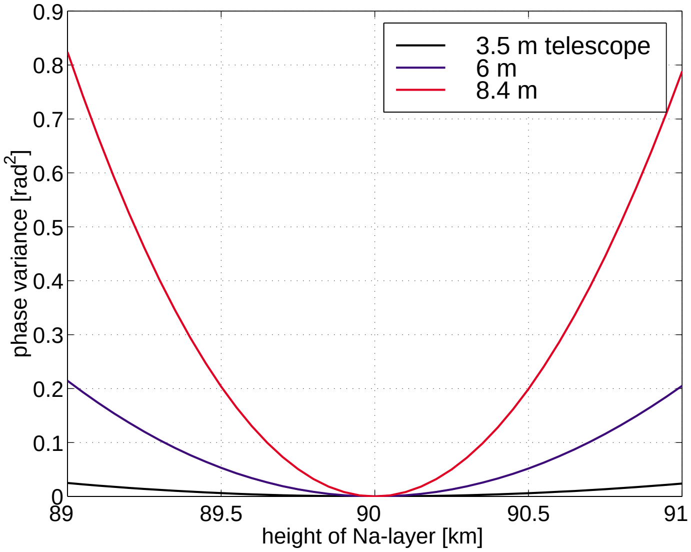


Figure 4. Focus error with laser guide stars for different telescope sizes.

To overcome these LGS focus problems a separate NGS focus sensor is the ideal solution. A 2x2 or 3x3 lenslet Shack-Hartmann sensor for tip-tilt and focus measurements on a NGS can be used for this task. Other techniques like LIDAR measurements are currently implemented[22] in the ALFA system.

6. BEST CORRECTION WITH THE LASER GUIDE STAR

A series of excellent nights in June 1999 allowed ALFA to make huge progress in correcting the wavefront using the sodium-layer LGS in order to reach high Strehl ratios. The superb performance achieved shows the exciting future potential of LGS AO. For the results shown in figure 5, the laser was pointed on-axis and imaged on the ALFA wavefront sensor through a 5x5 lenslet array at a frame rate of 75 Hz. This allowed 18 high order Kahunen-Loève modes to be corrected.

A natural star (SAO 68075), 10" off-axis to avoid any of its light reaching the wavefront sensor, was used to correct tip-tilt motion at 65 Hz. A series of 40 consecutive images was taken of the star in the K-band on the OMEGA-Cass camera. Each integration was 5 sec, and the only processing performed was sky subtraction and bad pixel removal. In particular, no shift-and-add or deconvolution techniques were applied. Frames were simply co-added to produce long exposure images.

7. CONCLUSIONS AND OUTLOOK

Wavefront sensing and compensation of atmospheric turbulence with sodium-layer LGSs will certainly enhance ground-based astronomy. The presented ALFA results clearly show that our continuous efforts were worthwhile doing. ALFA will be further developed. First tests with an avalanche photo diode based quad-cell as a replacement for the existing CCD based tip-tilt tracker have been conducted in September 1999 (see figure 6 for a first result). We continue our efforts to install a fiber supported laser

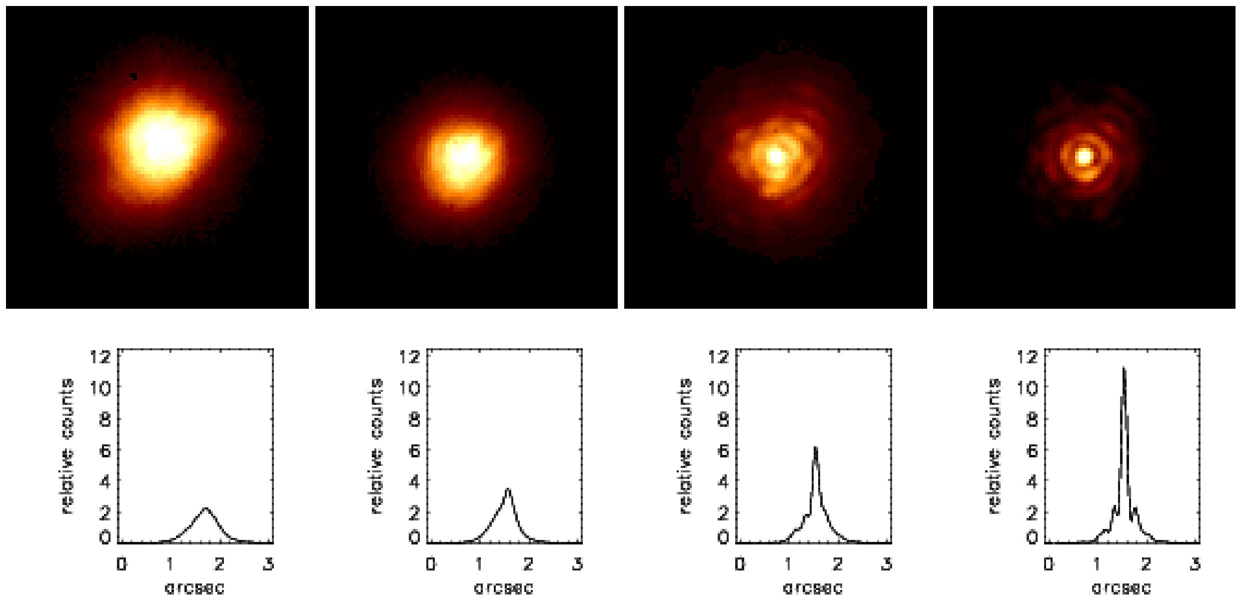


Figure 5. From left to right: a) Open loop 50 sec K-band image of SAO 68075. FWHM: 0.65”. b) 50 sec image with tip-tilt corrected on the star. FWHM: 0.49”. c) 200 sec (40 co-added images) exposure, with tip-tilt corrected on the star and high order correction on the laser guide star. FWHM: 0.19” and 12.8% Strehl. d) During the very best 10 sec, a Strehl number of 23% and a full diffraction limited PSF was obtained (FWHM: 0.14”). The first diffraction ring is clearly visible.

projection system and to increase the laser output power on a timescale of 2 years.[25] We also put efforts into better AO (science) data calibration and PSF retrieval techniques over the entire corrected field of view. This will help to achieve better deconvolution and photometric results.

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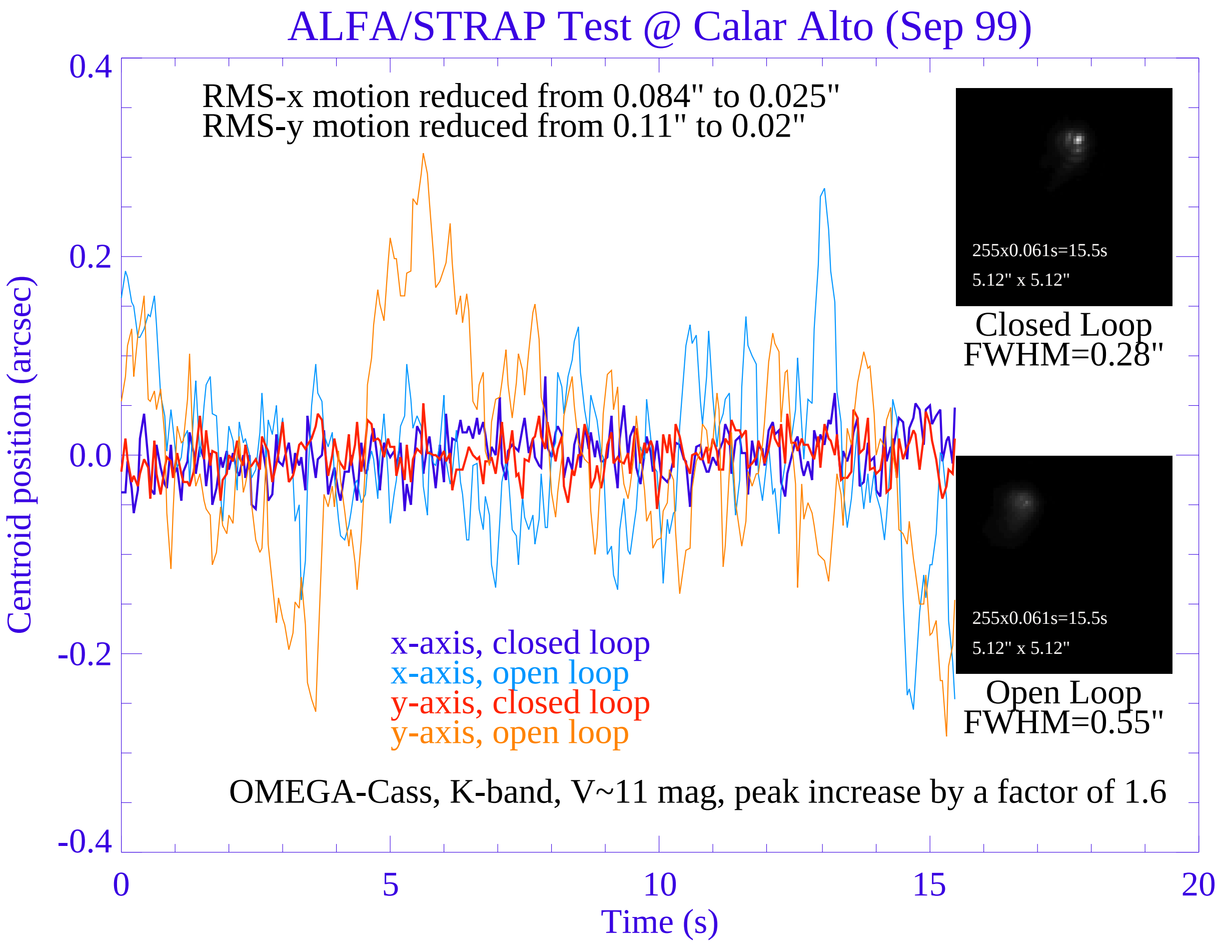

Figure 6. First results with a prototype of the new ALFA tip-tilt tracker system STRAP.[26] The centroid motion (in seconds of arc) of a star measured in K-band is plotted vs. time. Open loop motion (0.084–0.11”) is reduced by a factor of 4.2 in closed loop (0.02–0.025”). The FWHM of the point-spread function changes from 0.55” to 0.28”, only a factor of 2 larger than the diffraction limit of the 3.5-m telescope at 2.2μm (see insets on the right side).

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