Beam quality and polarization analysis of the ALFA-Laser at Calar Alto and the influence on brightness and size of the laser guide star

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Abstract

The ALFA-Laser of the MPE/MPIA adaptive optic system utilizes a 4W cw-laser for the creation of a sodium layer guide star. The artificial star serves as a reference source for the adaptive optics system installed at the Calar Alto observatory in southern Spain. Several distortion sources are affecting the laser beam and result in a laser guide star spot size too large on which to lock the adaptive optics loop properly. Therefore a number of analysis tools have been installed just before the last beam expander and measurements of the beam quality have been performed. In this contribution we present parts of the experimental setup and results of these measurements.
In addition we report on experimental studies of the guide star brightness when exciting the sodium layer with different polarization states of the laser radiation. A surprisingly large gain in response flux, when using circular polarization, has been measured. The complicated behavior of the polarization state with telescope position, due to phase changes at the beam relay mirrors, makes a control loop necessary to keep the projected beam optimal.

Keywords: Laser guide star, beam quality control, polarimeter, optical pumping

1. Introduction

Correction of the atmospheric seeing with an adaptive optic system requires a reference source on which the wavefront distortion can be measured. This source has to fulfill several demands to be suitable for a good correction: It has to be within the isoplanatic patch object one wants to observe, has to be bright enough to give a reasonable signal to noise ratio on the wavefront sensor and must not be too extended to allow a good centroid calculation in the case of a shack-hartmann based sensor. Suitable reference stars with state-of-the-art wavefront sensors have to have magnitudes of around 12-13. This is crucial limiting the sky coverage of an adaptive optics system when using natural guide stars for the correction. For that reason artificial guide stars with lasers have been proposed, either with rayleigh scattered light from air molecules in the upper atmosphere or with resonant excitation of sodium atoms at 90 km height.
The ALFA system (Adaptive optic with Laser for Astronomy) is an adaptive optics system which can utilize an artificial laser guide star to correct the distorted wavefront. As a joint project between the Max-Planck-Institut f r Extraterrestrische Physik in Garching and the Max-Planck-Institut f r Astronomie in Heidelberg, the laser facility was provided by MPE and the AO by MPIA. An overview of the adaptive optic system has been given by A.Glindemann (1997)[1] and S. Hippler (1998)[2].
For a brief overview of the laser system the reader is refereed to A. Quirrenbach et al.(1997)[3]. In this contribution only a coarse description for general understanding is given.
The laser system consists of a cw dye laser pumped by a multiline argon ion laser and is capable of emitting 4W of narrowband light tuned to the peak of the sodium D_2 transition. The 4W output are reached under normal operating conditions with 25W of pump power in an eight-shaped ring laser (modified coherent model 899). The laser facility is installed at the coud laboratory at the 3.5m telescope at Calar Alto, where a room is available which is separated from the telescope dome. The advantage of the separated place is, that the sensitive laser components are supplied with a constant temperature and can be effectively protected from dust with filtered air and in addition the waste heat produced by the laser cannot enter the telescope dome and cause additional seeing. The disadvantage is the long path from the laser laboratory to the final beam expander beside the main telescope. We are utilizing a mirror beam relay along the coud path where eight mirrors and several optical windows are installed. With so many elements as well as the air in the telescope dome and the beam pipes that can cause distortions due to turbulence, a careful control of the beam quality is required.
During the observing periods in 1998 the spot size we did produce was always much larger than what is expected from theory. There are several possible distortion sources that can affect the size of the laser beacon: Static aberrations caused by bad or misaligned optics, wavefront deformations and fast jitter in the laser beam from turbulent air inside the dome. To discriminate between the various possibilities a series of measuring instruments have been installed during 1998 at an optical bench just before the launch telescope. With these instruments we are capable of detecting the angular and parallel deviation of the laser beam in respect to the optical axis of the launch telescope, the power of the laser beam, the

collimation and the wavefront distortions at this point of the beam relay. A description of the optical layout and an overview of the used instruments and first measurements are given by Rabien et al.(1998)[4]. Here we show further results that have been obtained with new beam quality measurements and a study on the polarization dependence of the resonant backscattering from the mesospheric sodium layer.

2. Beam quality

2.1 Position detection and the influence on the spot size

While passing the air in the telescope dome the laser beam is influenced by turbulence cells with differing temperatures. In particular there are some places in the beam path that have a high temperature difference, for example when the beam passes near the main mirror, which is cooled. One effect is a tip-tilt movement of the beam. If that movement is strong and fast enough it can affect the laser beacon size as appearing on the wavefront sensor. To test this, we made measurements with a position sensitive device before the launch telescope. This device is a 4 mm^2 silicon PIN diode with four contacts that is capable of sensing the position of an incident light spot fast and accurate. The spot is created in the focal plane of a lens with a long focal length, so angular deviations can be detected with an accuracy of better then 0.2 arcseconds. Because the measurement is done before the launch telescope, the angular deviation of the spot at the sodium layer from its nominal position is 16 times less than that measured in the small laser beam (the telescope has an expanding factor of $\approx$16). A lot of data points have been taken under very different conditions in the dome. An example of such a position measurement is shown in Figure 1.

Despite the apparently high deviation, in peak sometimes more then 10 , we could evaluate that the diameter of the laser guide star is not affected by the tip-tilt movements of the beam. The reason is, that the readout time of the wavefront sensor is quite small compared with the timescale of the angular deviations. The lowest rate at which the wavefront camera is running is 50 Hz and below that rate there is no reasonable correction of the atmospheric turbulence possible. In a plot of the numbers of intervals with 16ms (the maximal integration time of the WFS) versus the angular deviation that occurs within that intervals, one can see that more than 90% are below 0.4 , see Figure 2. Transferred to the size of a gaussian spot at the sodium layer, the mean additional broadening from tip-tilt with the worst conditions of dome turbulence is never more than 0.0015 . This result was obtained by summing up gaussian shaped intensity distributions for each measured position within the integration intervals.

To answer the question whether any mechanical oscillations contribute to the tip-tilt, power spectra have been calculated from the data. An example is given in Figure 3. To make sure that no instrumental instabilities and noise are included, the data was always compared with the power spectra of a reference source that is mounted at the analysis board as well. The shape of the spectrum is very similar to power spectra of atmospheric turbulence (see for example Max et al. (1994)[5]) with a slope that is near the value that is expected for a Kolmogorov[6] turbulence, $p \propto \omega^{-2/3}$.

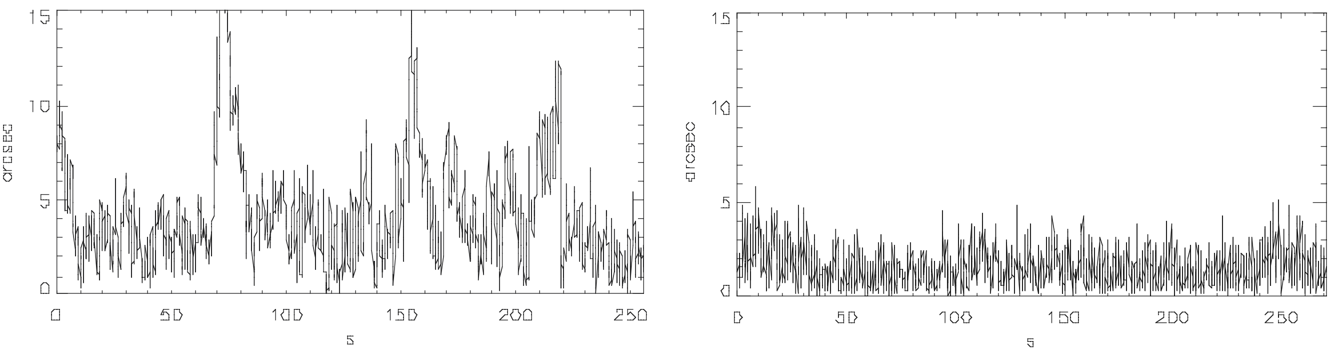


Figure 1: Radial deviation of the laser position from the optical axis of the launch telescope calculated from the measured x and y data. On the left a high wind speed and strongly varying temperature was present in the dome, the right picture shows the same but at much more quite conditions. The position was measured at a rate of 1 kHz. For these measurements the control loops that normally stabilize the beam position were switched off.

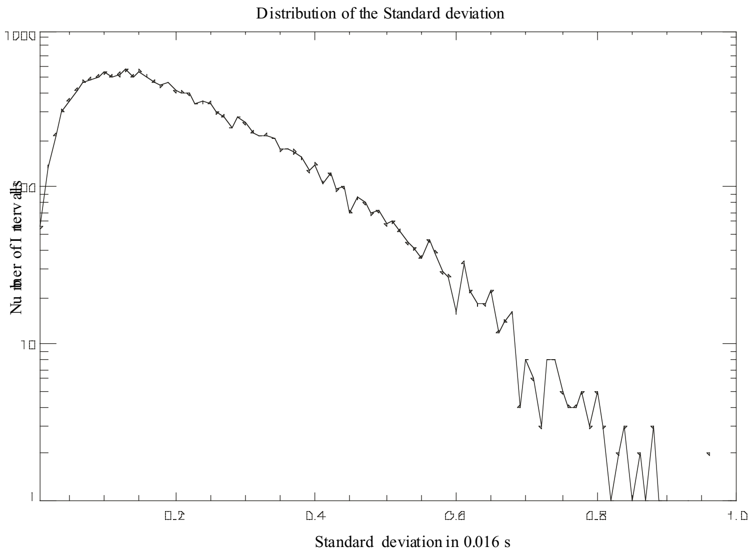


Figure 2 The standard deviation of the beam position that occurs in intervals of 16ms plotted against the number of the intervals with the specific deviation. More than 90 percent of the intervals have deviations that are below 0.4 . From that calculation it can be shown that tip-tilt of the laserbeam does not contribute to the size of the laser spot.

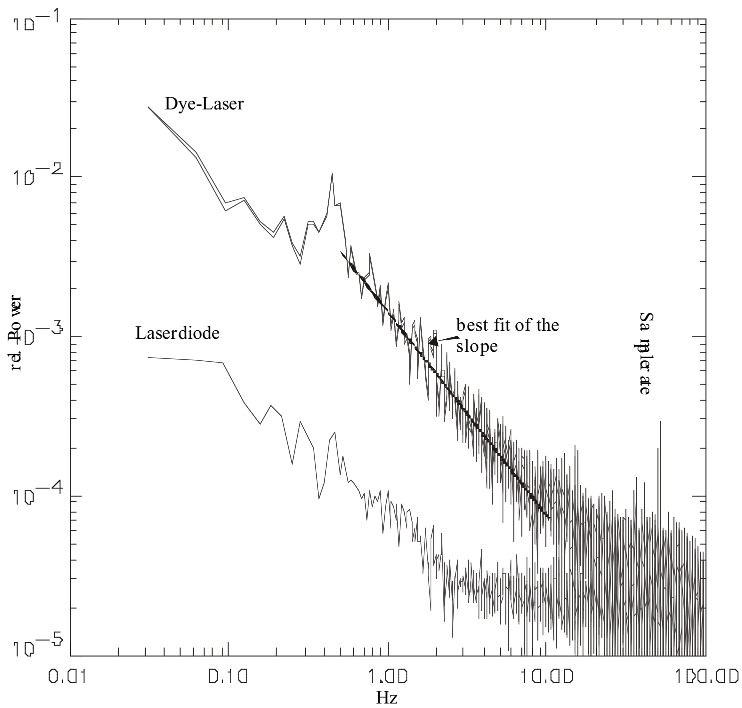


Figure 3 shows the power spectrum of the tip-tilt movement before the launch telescope. This data was obtained with a slightly lower sample rate of the detector which can be seen as peak in the fourier analysis. For comparison the spectra of a reference laserdiode is shown. The peak around 0.4 Hz results from the slow, not completely uniformly tracking mirror in the coud path. To evaluate the slope a least square fit was performed in the region from 0.5 to 10 Hz.

2.2 Wavefront deformation

Dynamic and static wavefront deformations caused by errors in the optics can be detected in our diagnostic system with two independent instruments. We have installed a shearing interferometer to control the collimation and static aberrations of the beam and additionally a shack-hartmann sensor for higher order deformations that could appear fast due to the turbulent air in the dome. The evaluation of the shearing interferograms taken during runs in 1998 showed that a small amount of spherical aberration was present in the beam. After changing optics of the beam pre-expander we could remove that aberration in March 1999, so that the beam now shows a nearly perfect interferogram. An example of a shearing interferogram is shown in Figure 4.

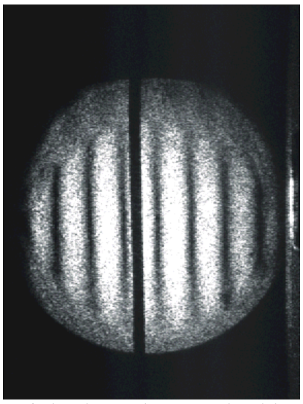


Figure 4.: Shearing interferogram of the laser beam. The black bar in the middle serves as a reference for a fringe orientation for a perfectly collimated beam. The shape of the fringes doesn t show any deformation within the sensitivity of the interferometer at ≈$\lambda/10$

Higher order distortions could be detected with a shearing interferogram as well, but the evaluation is somehow more difficult than with other methods (see for example Rimmer(1974)[7] or Shen(1994)[8]). For testing the higher order aberrations and possible fast changes in the wavefront we installed a Shack-Hartmann sensor. Measurements with a various number of subapertures and beam diameters from 8 to 15 mm have been performed. A typical picture of the hartmann spots and the calculated wavefront gradients across the laser beam are shown in Figure 5. The calculated mean wavefront error due to dynamic distortions under different conditions (wind speed and temperatures in the dome) was in all cases less then $\lambda/10$, indicating that with the small beam diameter we use, nearly all power of the turbulence is present in the tip-tilt mode.

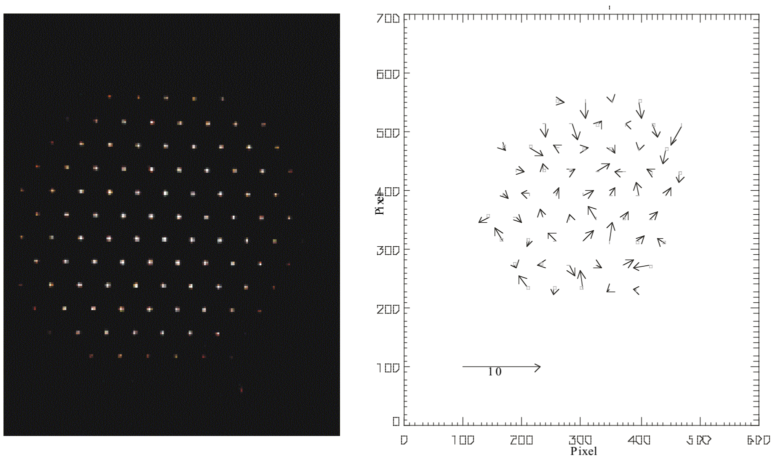


Figure 5: left: Shack-Hartmann spot pattern of the laser beam taken at the diagnostics board. Right: Local wavefront gradients that have been calculated from the deviation of the centroid of the spots from a reference position. The arrows are pointing in the direction of the local wavefront slope, while the length indicates the strength. For the evaluation of the dynamic gradients a mean position of each spot was calculated out a large number of single frames. An arrow for a deviation of 10 is plotted with the gradients as a reference for the eye.

Since we knew that there must be some distortion present and we could not find aberrations in the laser beam before the launch telescope that are strong enough to explain the spot diameter at the sodium layer we concentrated in our technical run in May 1999 on the alignment of the launch telescope and the choice of a final beam diameter that is matched properly to the seeing conditions. The alignment of the telescope was done by imaging a natural star on a CCD camera that we installed for this purpose under the launch telescope. This method proved to be sensitive enough but is very time consuming. In a successful first iteration we managed to reduce the laser spot size from former ≈3 to 1.7 with actual seeing conditions of ≈1.3 . This is still ≈1.5 times larger than expected from diffraction at the chosen beam diameter, which should have created a spot of 0.8 at the sodium layer. The remaining error still belongs to aberrations present in the launch telescope alignment, that we could see in the images of the natural star. With the next step, motorizing our secondary mirror, we will be able to reduce the amount of time that has to be spent on this topic and hopefully reach the diffraction limit for the laser spot.

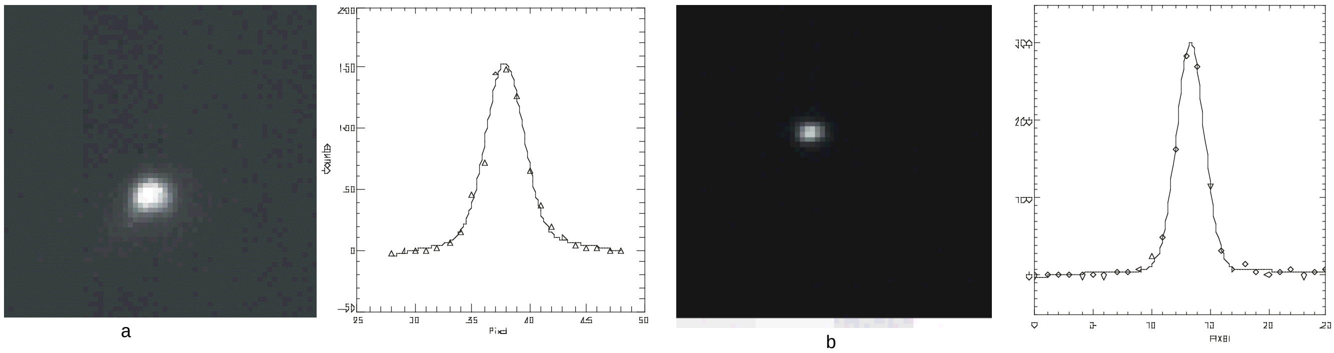


Figure 6: The laser spot sizes a) before and b) after the alignment. The laser beacon is imaged here with the wavefront CCD and a single lens instead of the lenslet array. To the right of the images is the cut through the maximum pixel shown with a gaussian fit. The FWHM of the left image is around 2.8 , with the new alignment 1.7 were reached at comparable seeing conditions.

3. Measurement of the polarization dependence of the resonant backscattering from the sodium layer

Optical pumping effects have been a known phenomena for a long time [9]. When exciting the sodium layer with a narrowband laser the backscattering efficiency is dependent on the polarization state of the incident beam. Because of the higher line strength the frequency of the laser beam is always centered on the F=2 multiplet of the sodium D_2 transition. Once excited to the 3P level the atoms can decay either to the F=1 or the F=2 groundstate. With the large separation of the two possible groundstates of 1.77 GHz, any atom that decays to the F=1 level can t be re-excited by a laser with a linewidth of several MHz. Choosing the right polarization can minimize this loss mechanism by pumping the atoms in the F=2 m_f=2 level so that a cyclic interaction between the F=2 m_f=2 level of the groundstate and the F=3 m_f=3 excited state is possible.
For an enhancement of the fluorescence signal from the sodium layer circular polarization of the laser is required. How large the effect is depends on the linewidth of the laser. Calculations of the gain that can be achieved when shooting with circular polarization in respect to linear for pulsed lasers has be performed by Bradley (1992)[10] or Morris (1994)[11]. Milonni (1997)[12] showed the results of calculations for a cw-laser including the magnetic sublevel relaxation due to the earth s magnetic field. Simultaneous measurements of the sodium abundance vs the guide star brightness with a 1W cw laser reported by Jian Ge (1997)[13] showed an increase in fluorescent return of ≈30% from linear polarization to circular. Experiments on the same topic have been perfomed during 1998 with our laser at a launched power of 2.3W. For the control of the polarization state a suitable photopolarimeter has been developed and installed at the exit of the launch telescope after all optical surfaces that could influence the polarization state.

3.1 Description of the polarimeter

Several methods are known to measure the polarization of light. We have developed a polarimeter that is similar to the division of amplitude polarimeter of Azzam (1982)[14], but with only three detectors to evaluate a set of parameters that describe the state of polarization completely without using the full set of Stokes parameters.
In general the electric field vector describes an ellipse in a plane perpendicular to the direction of light beam as indicated in Figure 7.

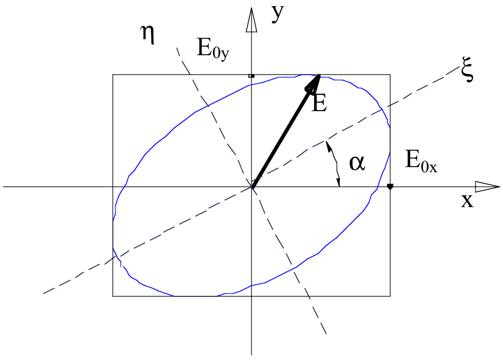


Figure 7 In general the electric field vector $\vec{E}$, of light propagating in the z-direction, describes an ellipse in a coordinate system (x,y) that is fixed in space and tilted with an angle α in respect to the main axis (η,ξ) of the ellipse.

The mathematical description as a vector has the following x- and y-components:

$$\vec{E} = \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} E_{0x}\cos(kz-\omega t) \\ E_{0y}\cos(kz-\omega t+\varepsilon) \end{pmatrix} \tag{1}$$

where ε is the phaseshift between the E_x and E_y components. The angle α can be expressed as follows:

$$\tan 2\alpha = \frac{2E_{0x}E_{0y}\cos\varepsilon}{E_{0x}^{2} - E_{0y}^{2}} \tag{2}$$

As can be seen from (1) three parameters are necessary to describe the complete ellipse. We chose a vector of the parameters $J = (E_{0x}^{2}, E_{0y}^{2}, E_{0x}E_{0y}\cos\varepsilon)^{T}$ that can be calculated out of the signals from three linear photodetectors, described by a vector $U = (\zeta_1, \zeta_2, \zeta_3)^T$, and a specific set of polarizing filters and a measured instrument matrix *M*. The following matrix equation is then valid:

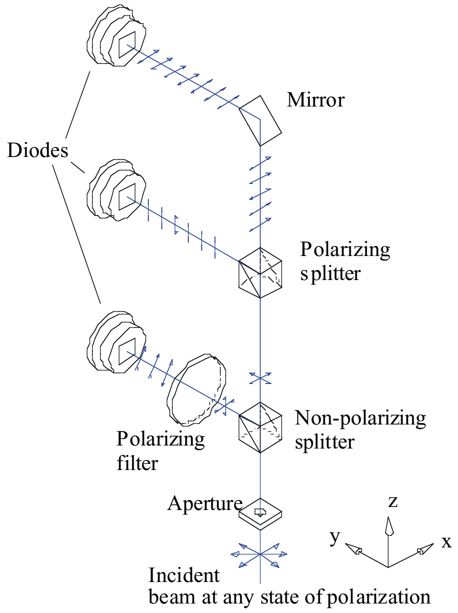
$$U = MJ \tag{3}$$

which can be solved by inverting *M*:

$$J = M^{-1}U \tag{4}$$

as long det $M \neq 0$.M is a 3 by 3 matrix which contains the angular settings of the polarizing filters and transmission properties of the optical elements and can be measured in the laboratory.

The construction we are using consists of two beamsplitters and one polarizing filter and is fed with one small beam of light, so the measurement at the three diodes can be done simultaneously. This makes the instrument independent of any fluctuations in the light amplitude that can occur at the place of the polarimeter due to turbulent air in the beam. The principal layout and a photograph of the instrument are shown in Figure 8.



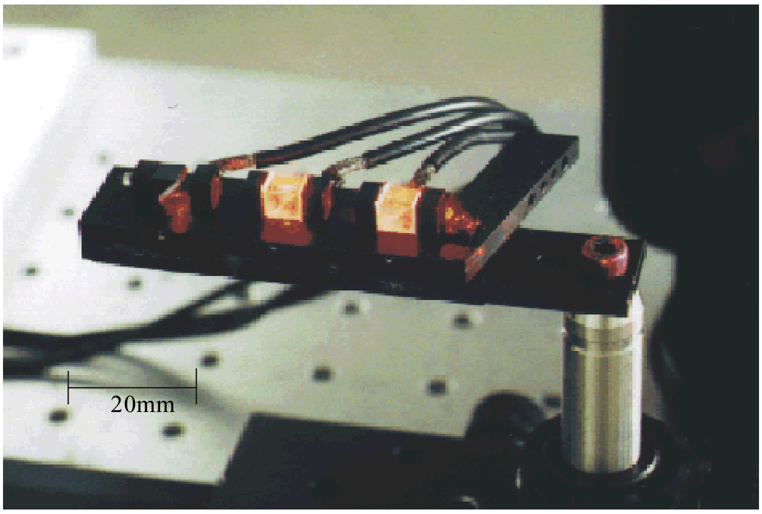


Figure 8: The Principle of the three-detector polarimeter is shown on the left. A small fraction of the incident light beam can enter the first non-polarizing beam splitter by passing an aperture. The reflected beam is directed to the first detector and polarized with a filter at a specific angle. The transmitted light enters the polarizing splitter, and the s-and p-part of the light is directed to different detectors. The advantage of this construction is a fast, simultaneous measurement and an extremely small cross-section in the main beam of only 5 mm^2.

We defined a degree of circular polarization P as the difference of photons with spin in opposite direction normalized by the total number:

$$P := \frac{N_R - N_L}{N_L + N_R} = \sin\varepsilon \tag{5}$$

Where N_R is the number of right circular photons, or intensity and N_L is the left fraction. One can show easily that tis expression is equivalent to the sine of ε, which can be derived from the measurements with the photopolarimeter. Experiments on the polarization dependence of the sodium excitation have been performed in two observing runs during 1998. The proceeding was the same in both cases: We imaged the laserspot with the wavefront CCD camera and a single lens mounted instead of the lens array to achieve the best signal to noise ratio. Simultaneously we measured the polarization state of the launched laserbeam. For several positions of the quarterwave plate the return flux and polarimeter data have been taken. The main problem was the varying atmospheric transmission that could not be calibrated properly in every case. For that reason relatively large errorbars in the photometric data are present, belonging to the flux changes we have measured on a comparable natural star. Unfortunately we could not image the reference star simultaneously, but had to switch from the laser beacon to the natural star from time to time. For the next measurements we will be able to overcome this problem and get more accurate data.

Despite this problem one can see gain when shooting with circular polarization that ranges from 20% to more than 50%. The measurements have always been performed relatively fast, i.e. within half an hour, so it is relatively unlikely that the sodium abundance has changed significantly.

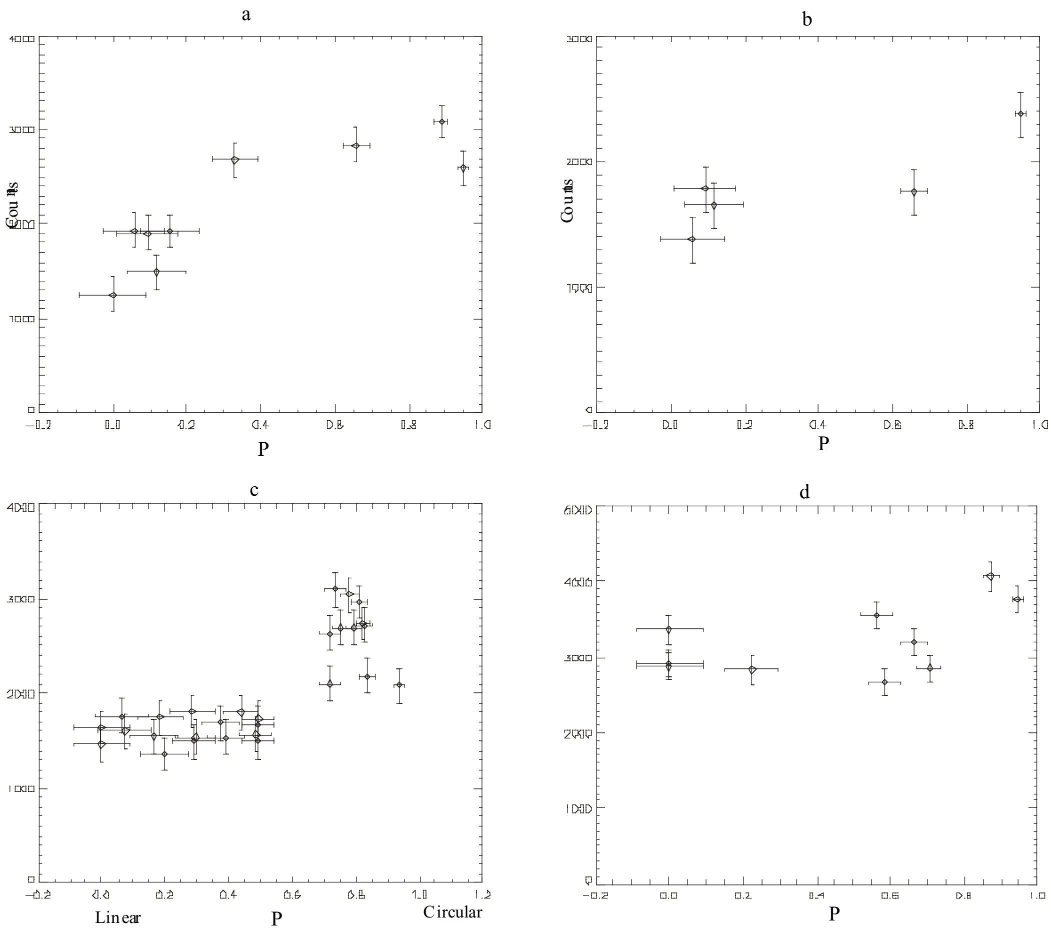


Figure 9 The measured counts on the laser spot vs. the degree of polarization of the launched laser radiation. The four measurements have been recorded under different atmospheric conditions at different nights. The plots in a) and b) are from September 1998 with a atmospheric transparency that was relatively constant. From linear polarization at the left to circular the returnflux in a) rose more than 50%, in b) ,which was measured several hours later, the enhancement is more around 30%. The measurement shown in d) was from August 1998 with a poor atmospheric transmission (the absolute counts are dependent on the amplifier settings) and the measurement in c) from October 1998 shows strange variations caused by fast moving high cirrus clouds, and therefore is not really useful, but there are always more counts with circular polarization.

An additional proof that optical alignment causes the rise in return flux we scaned the frequency of our laser across the doppler broadened profile of the sodium D_2 line. Our laser is stabilized to 10 MHz linewidth and the frequency is controlled with a stable reference cavity and compared to the doppler free lamb-dip signal of a sodium cell. The result is shown in Figure 10. The line shows a non-thermal spectral profile with a peak height ratio of the two components of 3.8:1, which was derived with the fit of gaussian profiles to the data. The FWHM of the fitted gaussian is 1.05 Ghz. The comparable measurements performed at the Steward observatory of Jacobson et al. (1994)[15] show a similar profile with a peak ratio of 3.5:1.

The gain in flux when launching circular polarized light makes it desirable to have a automatic control of that parameter. Because we are using a multiple mirror system to transport the beam from the laser laboratory to the launch telescope, the polarization is affected by the dielectric coated mirrors. The change on each mirror might be very small, but in the sum the effect cannot be ignored. Figure 11 shows the dependence of the degree of polarization while turning the quarter wave plate for different telescope positions. Two effects are present: the full circular polarization is not reached in every position of the telescope, and the angle at which the highest degree is reached varies as well. This is caused by a changing angle of incidence of the light beam onto the mirrors when moving the telescope to a new position. The correction of the quarter wave position by hand is a little time consuming and might be forgotten during normal operation. Therefore we are implementing a control-loop to track the maximum of the shown curves.

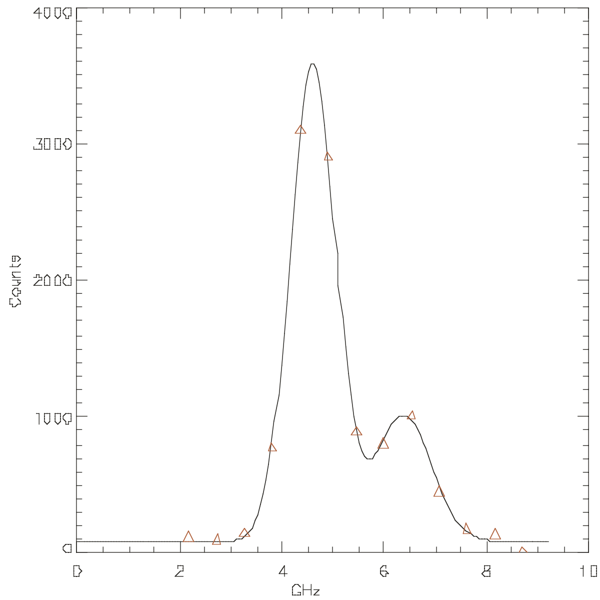


Figure 10 Frequency scan of the doppler broadened profile of the sodium D_2 line. The fitted gaussian consists of the sum of two gaussian profiles. The ratio of the peak heights is 3.8:1 which is significantly different to the ratio of 5:3 that is expected for thermal equilibrium.

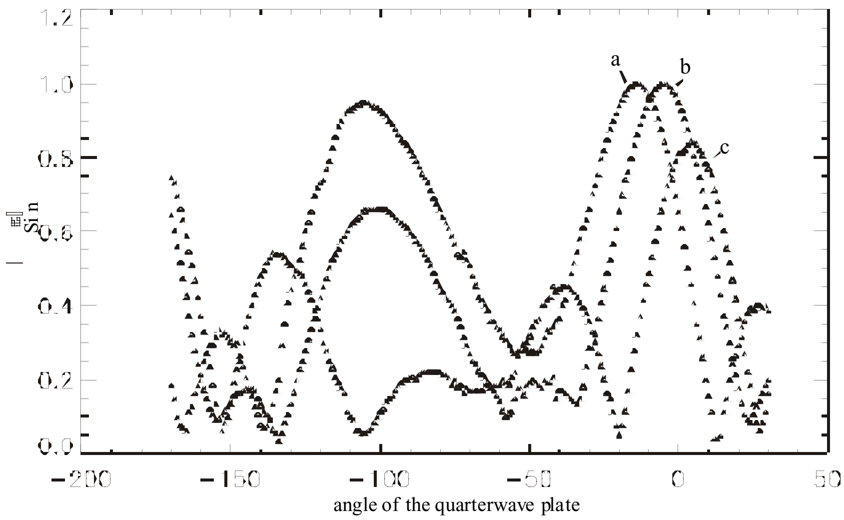


Figure 11: The degree of polarization that has been measured at the exit of the launch telescope versus the angular setting of the quarter wave plate which is located at the laser laboratory. Three different telescope positions are indicated: a) 5 hours west of zenith b) zenith and c) 5 hours to the east. The characteristic of the curves change significantly, so an automatic control is necessary to keep the light circularly polarized.

4. Conclusion

The beam quality measurements on the ALFA laser have shown that a good control of the aberrations in the beam is mandatory to achieve a diffraction limited spot size of the laser beacon. It was shown that mainly static aberrations are limiting the performance of the system while dynamic distortions due to turbulent air inside the dome are not contributing significantly. The experiments on the polarization dependence of the resonance fluorescence showed that a large gain can be achieved with the use of circular polarization even with 2 watts of launched power. The control of the polarization state in a multiple mirror beam transportation system is relatively complicated but possible with the use of a polarimeter that is capable of measuring the complete state of elliptically polarized light.

5. References

[1] A. Glindemann, D. Hamilton, S.Hippler, R.-R. Rohloff, K. Wagner, ALFA - The laser guide star adaptive optics system for the Calar Alto 3.5m telescope, in Laser Technology for Laser Guide Star Adaptive optics Astronomy, N. Hubin and H. Friedmann, eds., pp. 120-125, ESO, (1997)

[2] S. Hippler, A. Glindemann, M. Kasper, P. Kalas, R. R. Rohloff, K. Wagner, D. Looze, ALFA : The MPIA/MPE adaptive optics with laser for astronomy project, in Adaptive Optical System Technologies, Proc. SPIE 3353, Paper 05 (1998)

[3] A. Quirrenbach, W. Hackenberg, H-C Holstenberg, N. Wilnhammer, The ALFA dye laser system in Laser Technology for Laser Guide Star Adaptive optics Astronomy, N. Hubin and H. Friedmann, eds., pp. 126-131, ESO, (1997)

[4] S. Rabien, R. Davies, W. Hackenberg, A. Eckart, T. Ott, Analysis tools and beam relay system for the ALFA Laser , Proceedings of the ESO/OSA Topical Meeting on Astronomy with adaptive Optics- Present Results and future Programs, 7-11 September 1998, in Sonthofen, Germany, (1998)

[5] C.E.Max et al., Design Layout, and early results of a feasibility experiment for sodium-layer laser-guide-star adaptive optics , J.Opt.Soc.Am.A Vol11, No2, S813-824, (1994)

[6] A. Kolmogorov, in turbulence, Classic Papers on Statistical Theory , S.K.Friedlander and L.Trooper, eds. (Interscience Publishers, New York (1961)

[7] M.P.Rimmer, Method for evaluating lateral shearing interferograms, Appl.Opt. 13, 632-629 (1974)

[8] Wei Shen, Ming-wen Chang and Der-Shen Wan, Zernike polynomial fitting of lateral shearing interferometry, Opt. Eng. 36 905-913 (1997)

[9] William Happer, Optical Pumping , Reviews of Modern Physics 44 vol. 2, S. 169-249, (1972)

[10] Lee.C.Bradley, Pulse-train excitation of sodium for use as a synthetic Beacon , J.Opt.Soc.Am.B 9, S.1931-1944, (1992)

[11] J.R.Morris, Efficient Excitation of a mesospheric Sodium Laser Guide Star by Intermediate-Duration Pulses , J.Opt.Soc.Am. A 11, S.832-845, (1994)

[12] Peter W. Milonni, R. Q. Fugate, J. M. Telle, Analysis of Measured Photon Returns from Sodium Guidestars , ESO Proceedings Nr. 55, (1997)

[13] Jian Ge et al., Mesosphere Sodium Column Density and Laser Guide Star Brightness , Workshop on Laser Technology for Laser Guide Star Adaptive Optics Astronomy, ESO proceedings Nr. 55, S. 10-15, (1997)

[14] R.M.A. Azzam, Division -of-amplitude photopolarimeter for the simultanous measurement of all four stokes parameters of light , Optic Acta,Vol 29, No5, s 685-689 (1982)

[15] B. Jacobson, T. Martinez, R. Angel, M. Loyd-Hart, S. Benda, D. Middleton, H. Friedmann and G. Erbert, Field evaluation of two new contineous-wave dye laser systems optimized for sodium beacon excitation, SPIE Vol. 2201, 342-351 (1994)