Multiconjugated Adaptive Optics for ELT's
An enhancement of the PIGS setup

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ABSTRACT

ELTs depent on Adaptive Optics (AO) to reach the diffraction limit. To achieve sufficient sky coverage with AO, several Laser Guide Stars (LGS) will be needed, but the finite distance of the LGSs introduces optical problems which can not be solved easily, especially at telescopes with a diameter larger than 30m. PIGS (Pseudo Infinite Guide Star) is a novel sensing technique proposed to overcome some of these problems by using a slit mask and a reflective rod measuring in radial and azimuthal direction the wavefront abberations. The sensor was already demonstrated with a single LGS in laboratory and on sky. Currently we investigate the PIGS concept in a MCAO (Multi Conjugated Adaptive Optics) fashion by building a test setup in the laboratory. MCAO will solve the cone effect, one of the remaining problems with PIGS. The PIGS MCAO experiment goals on engineering problems and demonstration of the layer orientated concept with the PIGS technique. The PIGS concept and its extension to MCAO will be described and preliminary results presented.

Keywords: Adaptive Optics, ELT, Laser Guide Star, wavefront sensor, PIGS, MCAO

1. INTRODUCTION

With adaptive optics one can reach diffraction limited imaging. But the sky coverage with natural guide stars is not satisfactory. Laser guide Stars (LGS) are a good solution to solve this problem. Currently there are two possibilities used in astronomy to create a LGS. The Rayleigh LGS, where Rayleigh backscattered light from about 10 km height in the atmosphere is used (i.e. WHT, MMT) and the sodium LGS, where resonant backscattered light from a natural sodium layer in about 90-100 km height is used (i.e. ALFA at Calar Alto Observatory, Lick, Keck, PARSEC at VLT). But the finite distance of the LGSs leads to new difficulties, which are even harder to overcome in the case of an Extremely Large Telescope (ELT).

- Cone effect
- Perspective elongation
- Defocus
  - Extended focal depth
  - Dynamical focal plane
  - Telescope abberations

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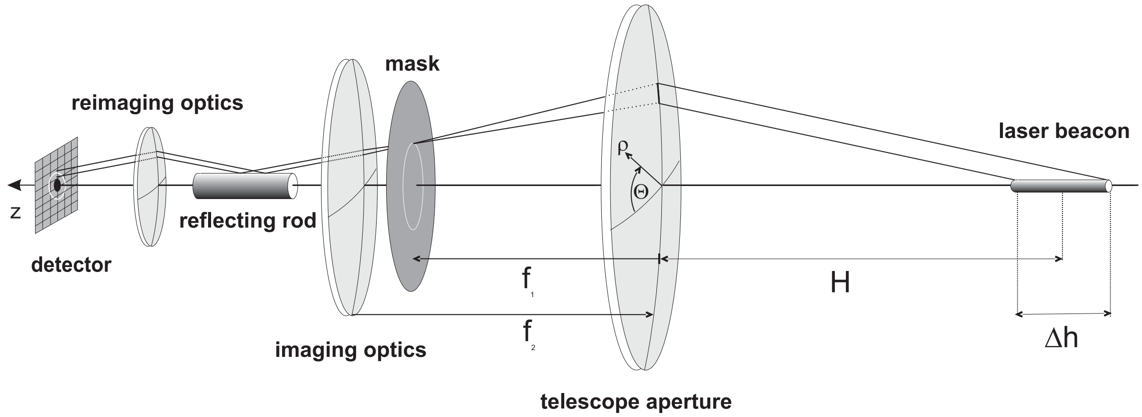

Figure 1. PIGS setup with the two sensing devices: a mask with annular slits in the infinity focus (f_1), for radial sensing and a reflective rod in the LGS focus for azimuthal sensing, where f_2 is the infinity focus of Lens 2 (imaging optics), ρ and θ are the radial and azimuthal coordinates in the entrance pupil(telescope aperture), H is the distance (height) of the laser beacon from the aperture and Δh is its vertical extension. (The figure was taken from the PhD-Thesis of S. Kellner)

The conical anisoplanatism is bigger the larger the aperture diameter is. Hence, one prefers the sodium LGS as with the lower altitude of the Rayleigh LGS the cone effect is larger. Additionally one cannot measure perturbations induced by higher layers with the Rayleigh LGS.
Beside the cone effect the vertical extension of the LGS leads to other difficulties. The perspective elongation results from the projection of the extended LGS on the image plane and increases with the distance of the subaperture from the optical axis.
The vertical extension also makes it impossible to get one focused image of the LGS in the focal plane. Usually only a small part of the LGS is used (temporal gating). The increasing distance to the sodium layer with increasing zenith distance has to be considered, too. As well as the circumstance that the telescope is optimized for targets in infinity and not for LGSs in finite distance. This introduces internal abberations of the telescope to the AO system. Some of this problems, like perspective elongation and extended focal depth, can be solved with a new wavefront sensor concept: PIGS (Pseudo Infinite Guide Star)[2].[3] It was already demonstrated in a lab experiment and on sky with open loop measurements.[1] As PIGS is a pupil plane sensor, it can also be used in a layer orientated fashion, with which one overcomes the cone effect. Here we present a Multi Conjugated Adaptive Optics (MCAO) setup with three sensors for open loop measurements in the lab and preliminary test results with one of the three rods. This experiment goals on understanding the engineering problems of the PIGS sensor in MCAO fashion and to demonstrate the layer orientated concept with PIGS.

2. PIGS PRINCIPLE SENSING CONCEPT AND SETUP

PIGS is a sensing technique which consists of two separately and independent working sensing devices. A mask with annular slits, which is placed at the infinity focus of the telescope for measuring the radial part of the wavefront and a reflective rod placed at the focus of the LGS for azimuthal sensing (see Figure 1). It is a pupil plane wavefront sensor which measures, like the curvature sensor, the second derivative of the wavefront. Due to this, PIGS cannot measure tip/tilt, what is not so crucial, as with LGSs the absolute tip/tilt has to be measured separately anyway.[7] The signal is composed of the radial and azimuthal part and can be written as shown in Equ.(1).

$$\frac{I' - I}{I} \propto \left(\frac{4H}{D^2} \cdot \frac{\partial^2 W}{\partial \rho^2} + \frac{4F}{\varrho r} \cdot \frac{\partial^2 W}{\partial \theta^2} \right) \tag{1}$$

With D=aperture diameter, W=wavefront, ϱ= normalized radial pupil coordinate, r=radius of the rod, F=focal ratio of the telescope, I'=measured intensity with distortions and I=reference intensity without distortions.
The derivation of the formulas can be found in Ragazzoni et.al.[3] Hence the rod is a 3D- device, it can use the

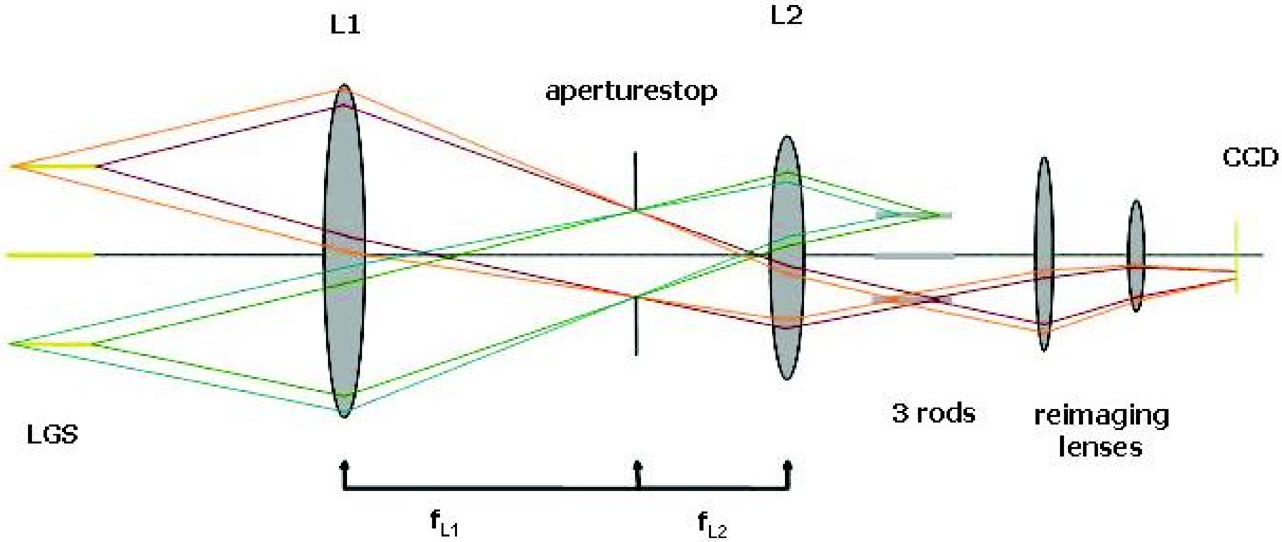

Figure 2. Schematic setup for the MCAO experiment in the lab. L1 and L2 are the telecentric lenses, with focal length f_{L1} and f_{L2}. For simplicity, only one complete light path is shown.

light from the LGS over its full vertical extended length and does not loose light like in the case of temporal gating.

The azimuthal sensing part with the rod has already been verified in the lab and in open loop measurements on sky. In the lab experiment correlations between the PIGS measurements and interferometer measurements, as references have been derived up to 88%.[1] The mask has been tested shortly in the lab but could not be verified due to constraints of the laboratory setup (see section 5 for more details).

3. MCAO SETUP FOR A LAB EXPERIMENT

The original PIGS setup had to be modified for a test of MCAO in layer orientated AO fashion with the azimuthal part. A new setup with 3 rods, everyone conjugated to one LGS, arranged in a isosceles triangle with side length of 10.81mm and the optical axis in the middle point of the triangle was designed (see Figure 2). This uneven distance between the rods is due to the best solution to arrange the rods and the corresponding light sources. If we decrease the distance of the light sources to the optical axis, the incoming and reflecting angle on the rods would increase, which leads to double reflection between the rods. In the other case, if we want to match a larger field of view and increase the distance between the rods and to the optical axis, the reflecting angle would decrease which leads to longer rods and to double reflection, too. Because of this, the rods have to be very short, the minimum aluminized length is 80.72mm, while the rods we use are 100mm long to assure we map the full light coming from the simulated LGSs. The rods have to be placed accurately in the setup to ensure no double reflection.

One major difficulty was the arrangement of the light sources to simulate the LGSs. If we put them in a way as if they are launched from one point on the optical axis, eg. in the middle above the telescope, the original setup, as in Figure 1, has only to be extended with more rods. But in the lab the three light sources we want to use, are mounted on one motorized translation stage and can only be moved parallel to the optical axis, eg. LGSs launched from different points on the edge of the telescope. For such parallel arrangement of the light sources, the rods in the original PIGS setup need to be aligned inclined to the optical axis due to the fact of image-size changes for different distances of the object (here: light source) from the entrance pupil.

Therefor we had to redesign the setup in a way to be telecentric on both sides of the entrance pupil. We inserted

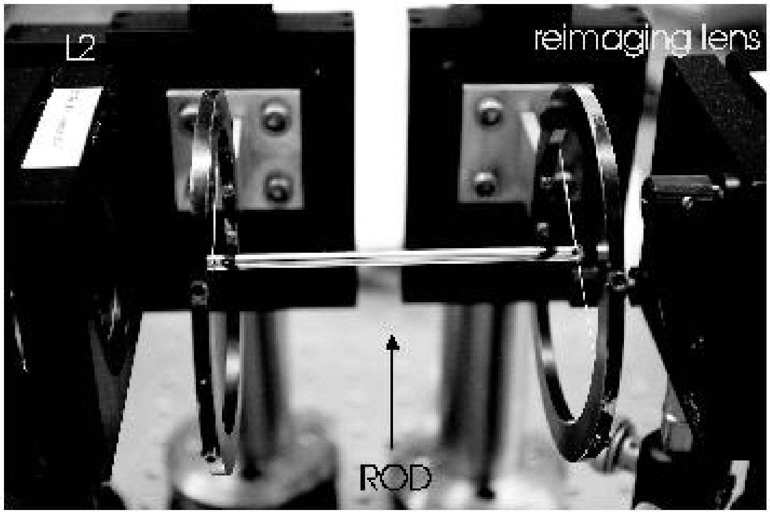

Figure 3. Close-in picture of the rod with its mounting (middle), L2 (left) and the first re-imaging lens (right).

an aperture stop which now defines our entrance pupil, and changed the position of Lens 2. To achieve the object- and image-side telecentricity the aperture stop is located at the infinity focus of the first lens (L1) and the second lens (L2) is located at the distance of its infinity focus after the aperture stop. The stop has a central obstruction, to ensure no light hits the rod on its front and passes through the sensor without internal reflection. The light from the source, which has a distance of 920-1000mm from L1, is focused on the rods after L2 and mapped onto the CCD with two re-imaging lenses (see Figure 2).

With this setup the image size stays constant at the position of the rods for different distances of the light sources. For the final lab setup three glass rods were coated with aluminium for better reflection. A motorized translation stage with the light sources mounted on it, simulates the extended LGSs.

4. THE LAB EXPERIMENT

4.1. Alignment procedure

First the last two lenses are inserted and mounted on the x/y/z stages on the optical bench. To align the first two lenses and the aperture stop properly, one needs to find the the focal points of the infinity focus of the two lenses exactly. This was done with an alignment laser, equipped with a beam expander. To proof, if the light coming from the laser is parallel, a shear-plate was used. After this, Lens 1 (L1) was inserted and the infinite focus point was derived by holding a mask with two very small holes close to each other in the optical path at the lens's position. Only at the infinity focus these two holes are imaged as one, at other positions one can still see a small black line between them. This point was marked exactly on the bench and will be the position of the aperture stop. If the second lens (L2) is exactly positioned at the distance of its infinity focus after the aperture stop, the light rays should be parallel again after the lens. To proof this, the shear-plate is used once again.

After marking all positions exactly on the bench, the lenses and the aperture stop were inserted and aligned successively, beginning with the last lens of the pupil re-imaging lenses. At the end the CCD was put in and focused on the cross of the aperture stop, which is the entrance pupil. Now the rod can be mounted in the setup between L2 and the re-imaging lenses.

To align the rod the central obstruction of the entrance pupil is used. Only if the cross is imaged perpendicular, the rod is aligned properly, otherwise the spiders are curved. The alignment of the rod is the most crucial part of the whole alignment process.

4.2. Measurements

To simulate the extended LGS the motorized translation stage is driven over a certain distance in small steps. At each step an image is taken and at the end of the measurement these images are added. In the measurements

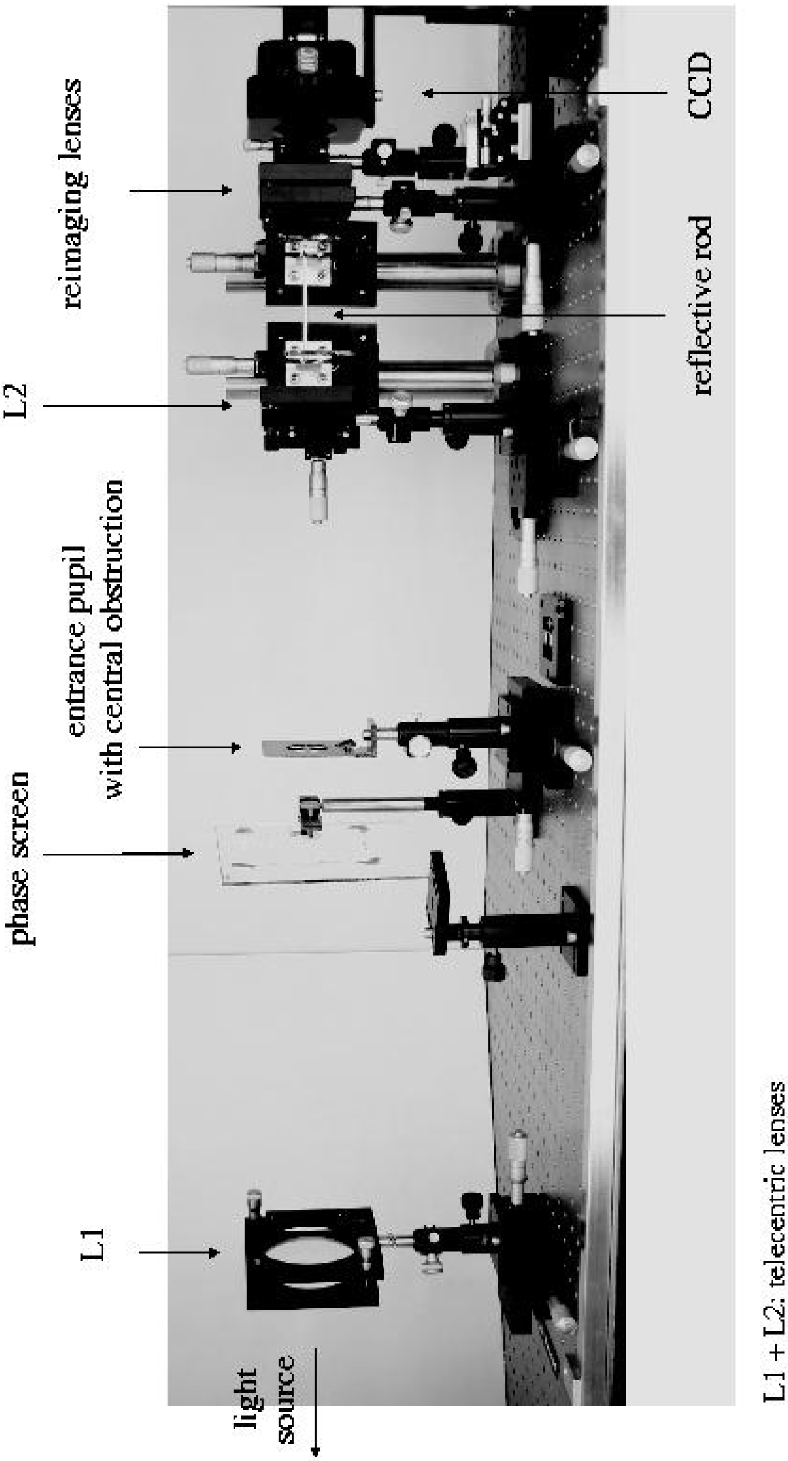

Figure 4. MCAO setup for PIGS in the lab. The light source is located on the left side and not visible in the image.

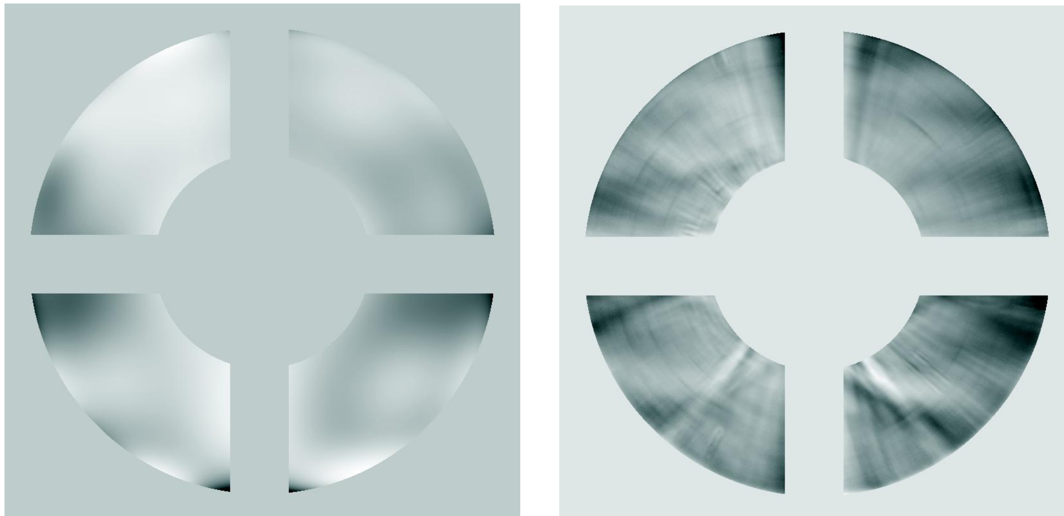

Figure 5. First results: The reference measurements with the interferometer(left sight) and the rod measurements(right side). The stripes in the lower quadrants are artifacts of the rod holders.

described here, 60 images with a step size of 1mm were taken over a distance of 60mm and added up for each measurement run.
To insert wavefront distortions a glass-plate is placed in front of the entrance pupil to simulate ground layer distortions. So far, measurements with two different glass-plates, giving us I', and one without any glass-plate, giving us I, were made with one rod on-axis to verify the new setup in the lab (see Figure 4).

4.3. Data reduction and preliminary results

To evaluate the data and to see how sensitive the sensor is, reference images of the glass-plates were taken with an interferometer which gives us the wavefront patterns without tip/tilt. These images and the PIGS images were brought into same size and orientation. As one can only measure the second derivative of the wavefront with the PIGS sensor, it was calculated for the interferometer images, giving us ($\frac{\partial^2 W}{\partial \theta^2}$). To reduce the noise, Zernike polynomials were fitted into both images, the interferometer image and the signal $\frac{I'-I}{I}$, which was calculated from the PIGS images. After this the images were cross-correlated. The whole data reduction pipeline was taken from the PhD work of Stephan Kellner and his experiments with the PIGS sensor.[1] One problem, we currently do not understand, occurs in the last step of the data reduction. The Zernike fit in the PIGS image seems to work not properly, as the correlation between the fitted interferometer image and the not fitted PIGS image results in a better correlation (see Figure 5, 6 and Table 1).

glass-plate	correlation between interferometer and PIGS image (both fitted with Zernike polynomials)	correlation between interferometer image with Zernike fit and unfitted PIGS image
1	38.7%	51.7%
1	27.9%	43.9%
3	not yet evaluated	not yet evaluated

Table 1. Correlations between the reference images and the PIGS measurements. For glass-plate No.1 a second measurement after readjustment of the rod were made. Glass-plate No. 3 inserts stronger distortions, to see if we get a better or worse correlation, but is not yet evaluated.

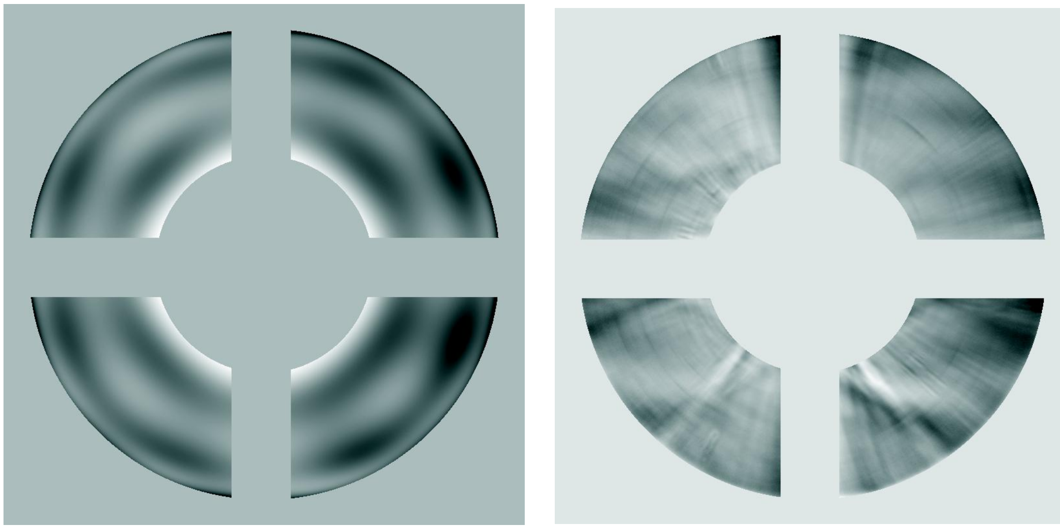

Figure 6. PIGS image after fitting with Zernike polynomials up to the 11^{th} order (left). It can clearly be seen that the fitted image does not match well to the unfitted one (right). We do not understand the gradients close to the central obstruction and the strong radial structure. The gain of the MCAO setup is different to the one of the original experiment of S. Kellner,[1] this could be a cause of such effects.

5. PIGS MASK PROBLEMS IN THE LAB

A test of the mask has only be tried with the initial PIGS setup, since in the MCAO setup exists yet no point where to place the mask. It should be placed in the infinity focus of the entrance pupil, eg. the telescope. But due to the changes in the MCAO design to achieve telecentricity on image- and object-side, there is no such point in this design.

The gain on the mask depends on the ratio of the LGS distance H over the aperture diameter squared (D^2) (see Equ. 1). With the original setup of S. Kellner,[1] this would lead to a gain of 0.1, actually a damping. Nevertheless, abberations with a large amplitude (several microns) should be seen. Therefore we did a test with a mask with 14 annular slits to derive the radial part of the wavefront, using the original setup of S. Kellner. 50 images were taken over a distance of 100mm. The preliminary results were not satisfactory, since one could get no agreement between the PIGS mask measurements and the reference measurements with an interferometer.

One assumption why the measurement does not work, is the step size we used during the movement of the light source. The light passing through one sub-aperture in the entrance pupil corresponds only to a certain part of the full length of the LGS. It seems, this part is a lot smaller than the step size of 2mm we used. In this case the distortions are smeared out in our images and we cannot resolve them. Additional measurements with smaller steps might lead to better results.

6. CONCLUSIONS AND OUTLOOK

We introduced a new setup for MCAO with the PIGS sensor for three rods, which is image sided and object sided telecentric. The first measurement results and the simulations with ZEMAX, which are made so far, indicate that the setup works in principle. We could achieve up to 51.7% correlation with reference measurements of the phase-screens done with a Twyman-Green interferometer. We still suffer from not understanding the decreased correlation after fitting the PIGS data with Zernike polynomials. One major challenge we experienced with the setup, is the proper alignment of the rod. We plan on additional tests to understand if the correlation can be increased, as with a previous lab experiment up to 88% correlation could be achieved.[1] After this, we want to study the experiment with one rod off-axis and finally measure a full three off-axis rods setup with optical co-adding.

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