PIGS – First results on sky

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ABSTRACT

The next generation ground based telescopes deploy their full potential in terms of resolution only with Adaptive Optics (AO). A limiting factor for such systems is the sky coverage with natural guide stars. A way to overcome this problem is a artificial star, i.e. laser guide star (LGS) generated in the sodium layer of the mesosphere at an height of approximately 90km-100km. Sensing the wave front of such a LGS, whose photons are collected by a next generation ground based telescope up to 100m pupil diameter leads to new problems. They are related to the finite distance of the altitude where the artificial star forms with respect to the telescope entrance pupil. We present a new wave front sensing concept to overcome this problem and we show first results of an open loop experiment done on sky. Measurements have been carried out November 2003 with the Rayleigh laser of the University of Durham at the WHT in La Palma as a result of collaboration between MPIA and the AO group of the University of Durham. The geometry of the LGS created in 4km altitude with respect to the 4m aperture of the WHT scales by a factor 1:25 with a sodium LGS at 100km and a telescope with 100m entrance pupil diameter.

Keywords: Adaptive Optics, Laser Guide Star, wave front sensor, MCAO

1. INTRODUCTION

AO systems are now a reality at telescopes worldwide and have shown their reliability since over one decade. Several methods are used to measure the phase perturbation of an incoming wave front, which becomes distorted after traveling trough the turbulent atmosphere. These are well known systems like Shack Hartmann, Curvature and Pyramid sensors. They all have proven their feasibility up to 8m class telescopes and they are used for sensing light coming from either a Natural Guide star (NGS) or - in some cases – a Laser Guide star (LGS). LGSs provide one possibility to overcome the well known sky coverage problem in modern astronomical Adaptive Optics. In the visible band for instance the wave front sensor needs a relatively bright reference star (14^{th} magnitude and brighter) within the isoplanatic patch in order to reach Strehl Ratios up 45% in the H band[1]. This limits the sky coverage of an NGS system to a few percent.

At the moment, there are two possibilities known to create a LGS. In both cases a laser beam is projected from a launch telescope up to the atmosphere and focused to a certain height. That issue generates an artificial guide star along the line of sight close to the science target. In the first case the Rayleigh backscattered light originated at the lower parts of the atmosphere (up 10 km) is used as input for a wave front sensor. Although this idea is still attractive for ground layer AO systems[2], the information obtained by this technique is strongly limited, since perturbations induced by high altitude layers can not be measured. Hence one likely favors a second option: The sodium LGS[3]. In this case the adopted Laser is tuned to the sodium lines and excites sodium in the mesosphere of the earth atmosphere (around 90km to 100km). The resonant backscattered light samples nearly the complete atmosphere and leads furthermore to a smaller sensing error due to the reduced cone effect. This kind of LGS is already established at some telescopes like at Lick and Keck observatory. Moreover first scientific results[4,5] have been obtained.

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It becomes very ambitious and challenging when we think to use LGS at Extremely Large Telescopes[6,7] (hereafter ELT) with conventional wave front sensors (hereafter WFS). Due to the dimensions of such telescopes (apertures up to 100m), the finite distance of the guide star leads to several limitations:

1. Perspective elongation
2. Huge defocus
3. Huge focal anisoplanatism
4. Large ray skewness
5. Large field FoV
6. Absolute tilt[8,9]

All this problems are reviewed in more detail by Ragazzoni et al (Paper in preparation).
Some major difficulties mentioned above can be eliminated by a novel kind of wave font sensing technique (PIGS = Pseudo Infinite Guide Star). Its feasibility was already proved in a laboratory setup[10]. Here we present first results of accomplished measurements in open loop done on the sky.

2. CONCEPT OF PIGS

At first we want to summarize in a very comprehensive form the basic concept and functionality of the novel wave front sensor (hereafter WFS).

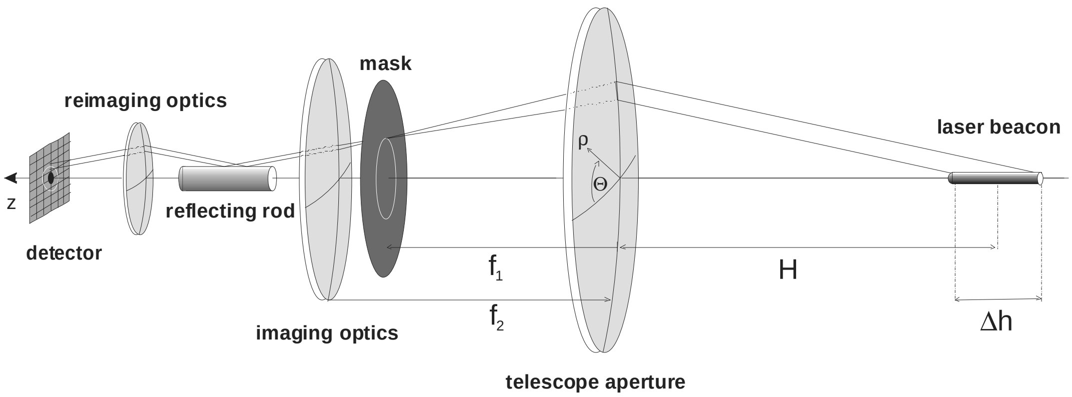

Fig 1: Conceptional drawing of the pseudo infinite guide star sensor. From right to left: LGS, telescope aperture, mask with circular slit placed at infinity focus, imaging optics in order to create telecentric exit pupil, highly reflecting rod, reimaging optics focused on pupil, CCD camera

All major problems of LGS are due to its finite distance. Therefore the problems can be overcome by treating the light as from an infinite distant source. Fig. 1 presents a drawing of a possible setup for such WFS. The sensor itself consists of two independently working sensing devices: A mask with thin circular slits and a highly reflective rod. The mask is placed in the focal plane of the telescope. Due to this position only light originated from a certain direction with respect to the optical axis will pass the mask (Fig. 2). Moreover the mask performs a sensing of the wave front in radial direction. Depending on the amount of a radial wave front distortion within a certain subaperture more or less light will be refracted into the slit (See Fig. 3) and results in a fluctuation of the intensity distribution pattern of the imaged pupil. This can be calculated by:

$$\frac{\Delta I}{I} = \frac{I - I'}{I} = \frac{4H}{D^2} \cdot \frac{\partial^2 W(r,\Theta)}{\partial r^2} \tag{1}$$

H describes the distance of the LGS from the telescope aperture and D is the pupil diameter. I and I' denote the perturbed and non perturbed intensity pattern in the pupil. According to equation (1) an increase of the signal (gain) due to the mask depends on the ratio between the distance of the LGS altitude H and the telescope diameter D squared.

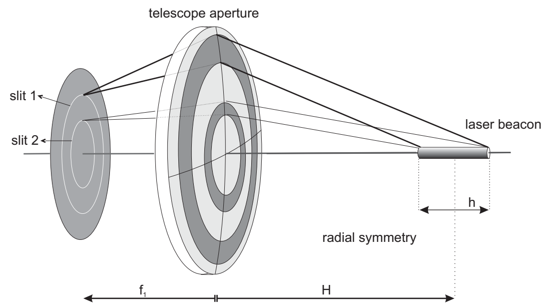

Fig 2: A mask with circular slits is able to select light from a certain direction

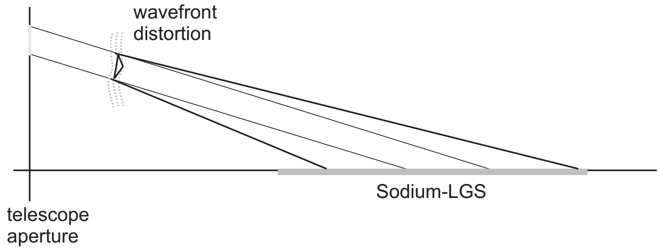

Fig 3: Depending on the wave front distortion (here approximated by a roof like form) more or less light of the LGS will be refracted into the sub-aperture. The sensitivity depends strongly on the ratio H/D^2

A sensing of the incoming wave front in azimuthal direction is accomplished by using a highly reflective rod[11]. In order to have an optimum sensing quality it is favorably but not necessary to sample an incoming wave front from a virtually infinite distant pupil. The azimuthal deflection angle depends on the impact position on the rod. A ray with aberration hits the rod at a different position as a ray without aberration. The reflection of the distorted wave front on the rod generates an intensity pattern which is proportional to $\frac{\partial^2 W(r,\Theta)}{\partial \Theta^2}$.

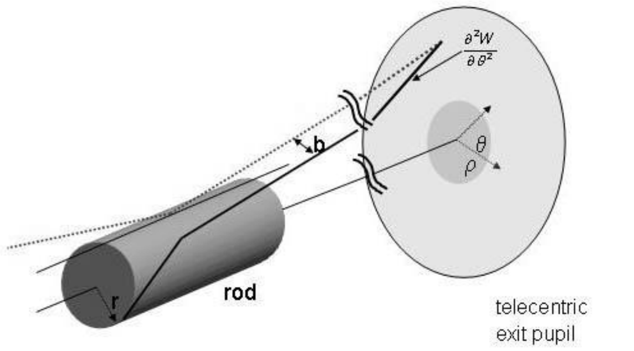

Fig 4: An non aberrated ray will be reflected by the rod in the same direction, while a aberrated ray is parallel shifted by an amount b and becomes deflected

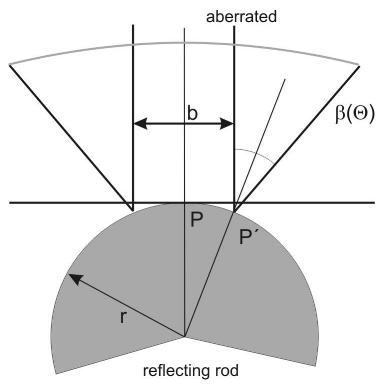

Fig 5: A spot of the size b reflected by the rod will be transformed into an arc. The angle of the arc is a function of the radius r of the rod

The signal for azimuthal sensing device can be calculated as follow:

$$\frac{\Delta I}{I} = \frac{I' - I}{I} = \frac{4F}{\rho r} \cdot \frac{\partial^2 W(r,\Theta)}{\partial \Theta^2} \qquad (2)$$

In equation (2) the F describes the focal ratio of the incoming beam, ρ is a radial weighting factor normalized to the pupil radius and r denotes the rod radius.

A possibility to increase the gain of the azimuthal sensing device is by decreasing the rod radius. However, the extended spot size of the LGS has to be taken in account. A spot will be elongated into an arc with increasing length for smaller rod radius. This introduces aliasing if the arc exceeds the dimensions of a sub-aperture.

3. PIGS EXPERIMENT ON SKY

We already proved the functionality of the rod sensing device in a laboratory experiment. Encouraged by the positive results we tested the entire PIGS sensor during a 4 day campaign in November 2003 under more realistic conditions on sky at the William Herschel Telescope (hereafter WHT). The experiment was done in collaboration with the AO group of the University of Durham, which is operating there a Rayleigh Laser Guide star demonstrator since 2001[11].
Our main goal was to realize a fully 1:25 downscaled version of the ELT- sodium LGS case (D=100m, H=100km and ΔH = 10km). Such scaling can be accomplished by a low altitude Rayleigh LGS system on a 4m class telescope focused to 4km and 400m gating range. The WHT with a 4.2m diameter of the primary mirror satisfies almost this condition. For the experiment the laser was focused to a height 3.9km and the light was taken over a range of ±250m around the focus position. The gating depth was adjusted by the length of the rod.

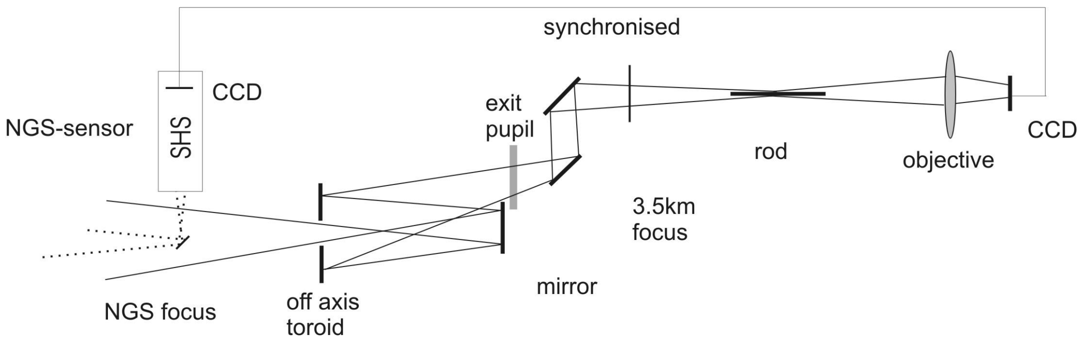

Fig. 6: Schematic overview showing the key components of the on sky experiment at the WHT. Light of a NGS was deflected by a pick up mirror close to the NGS focus to a conventional SH sensor. We used the reconstructed wave fronts of the SHS as reference. The light of the LGS was deflected and focused on the rod via a mirror system and imaged by an objective to a CCD. The CCD of the PIGS sensor was focused to the exit pupil. Both CCD cameras had external trigger capabilities and were synchronized by the means of a pulse generator.

Figure 6 depicts an overview over the experimental setup. The incoming light of the LGS was reflected by a mirror and focused via an off axis toroid onto the rod. Two additional folding mirrors (see Fig 9, 4a and b) were used to align the beam to the rod. The slit mask used had a diameter of 27 mm (outer slit), contained 9 circular slits with 0.1mm thickness and has been manufactured at the Telescopio Nazionale Galileo (TNG) at La Palma. A CCD camera (DVC 1412) with an objective (f=700mm, d=50mm) was placed behind the rod to re-image the exit pupil. Figure 8 shows all key components of the setup.
We obtained reference measurements of the distorted wave front by the means of a conventional SH system (lenslet array with 78 sub-apertures), sensing the incoming light of a Natural Guide Star. Both CCD cameras were featuring an external triggering capability, which was used to synchronize them via TTL pulses generated by a pulse generator.

4. MEASUREMENTS

We performed several series of wave front measurements using the complete PIGS sensor setup with both sensing devices. Additionally we obtained several data sets, where we used each sensing device separately. For a fixed configuration we carried out several runs. Each run included a series of 512 frames taken simultaneously with the CCD cameras of each sensor (PIGS and SH). The time difference of 2 subsequent frames was 100ms, the exposure time 30ms.

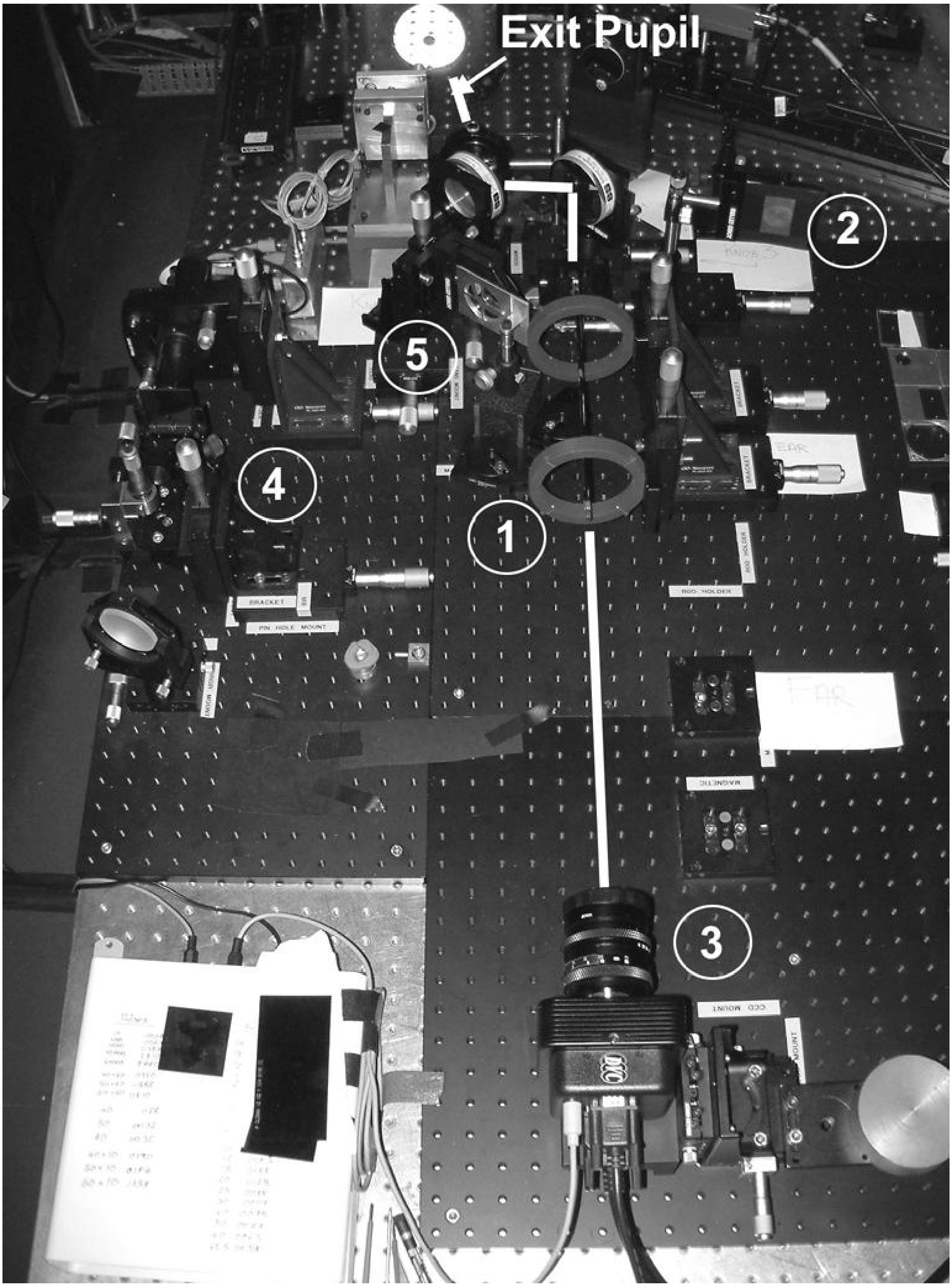

Fig. 7: Bird eye view of entire PIGS setup: 1. Rod, 2. mask (not in he beam path), 3.CCD, 4+5.optical setup to align rod, mask and CCD in respect to optical axis

5. DATA EVALUATION I: FIRST RESULTS (TEMPORAL CORRELATION)

Due to our experience with the laboratory setup we were first focusing on the data with only the rod as sensing device. Mask data will not be discussed within this paper.
In a first approach we tried to verify that both wave front sensors measure the same temporal evolution of the ground layer turbulence. Due to the gating heights of the LGS (3.7 km - 4.2 km) PIGS does only sample the ground layer of the atmosphere. Assuming in first order only frozen flow of the turbulence it is possible to extract the wind speed out of the data.
We obtained the wind speed from the PIGS and the SHS data sets by calculating the correlation of two successive frames (n and n+1). The correlation was calculated shifting frame n+1 in respect to n displacing the pupil between each frame. The parameter space of the displacement d was from 0 to a maximum of half a pupil size. Only the overlapping part of both pupils was taking into account when computing the correlation. This yields to a 2-dimensional pattern where the relative position from the center indicates the shift and the intensity the strength of the correlation. For one run 511 correlation frames are assessed. To enhance the signal from the ground layer we average over these 511 frames. Each correlation frame is contaminated by an intrinsic correlation from the superimposition of the pupil shape. This effect is removed by subtracting the time averaged auto correlation (correlating frame n with n). The reduction procedure is visualized in Fig. 8 and 9.

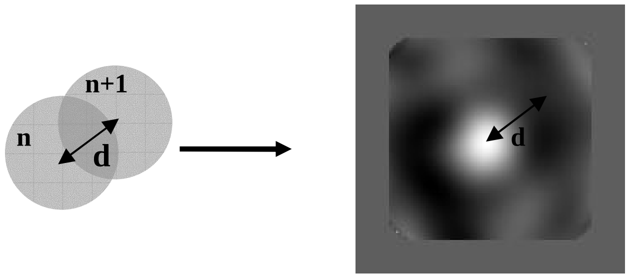

Fig. 8: For each relative shift of frame n+1 to n the correlation of the overlapping part has be calculated. To enhance the signal for one run we averaged over all correlation patterns for one run

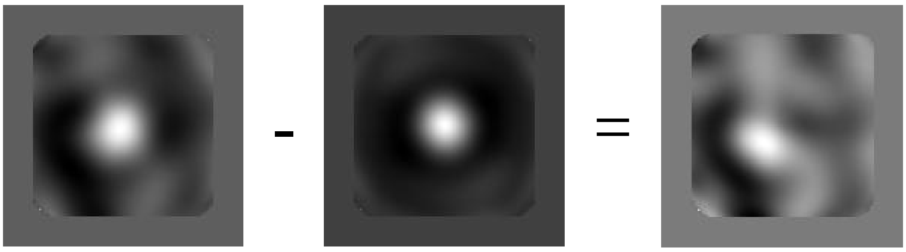

Fig 9: The averaged cross correlation peak (left) is strongly dominated by a correlation pattern induced to the shape of the pupil. Therefore the averaged correlation of frame n with itself (center) has been subtracted and makes the peak (right) induced by the ground layer turbulence visible

The results for three runs are shown in Fig. 10 for the SH data and Fig. 11 for PIGS data, respectively. Note, the SH and PIGS data have different scaling. In each frame of Fig. 10 and Fig. 11 a strong correlation peak is visible. The distance of the peak to the center is a measure for the movement of a wave front between two subsequent frames.
We find an average movement of the wave front in the SH case of **0,94±0.06 m** with a direction of **131±6 deg** (clockwise with a zero direction in the positive x-axis). In the PIGS case we receive **1,1±0.14 m** for the movement and **124±5 deg** degree for the direction. The values for the movement of the wave front are quite close. The small difference could be real, since the SH sensor sees also high layer contribution.
We further compared the result of wave front sensor data with wind speed measured by the wind gauge on the top of the WHT dome. These measurements updated every 10 minutes covering roughly the time for all three runs. The wind speed was 10.3±1 m/s. This translates into a wave front movement between two successive frames (100ms time difference) leads to 1.03m, which is consistent with the PIGS and SH data.

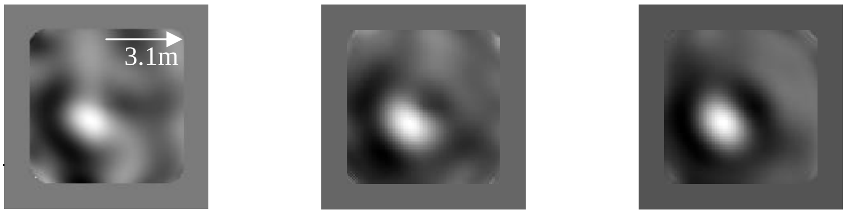

Fig. 10: Results of correlation calculations of the SH reference data obtained for 3 runs

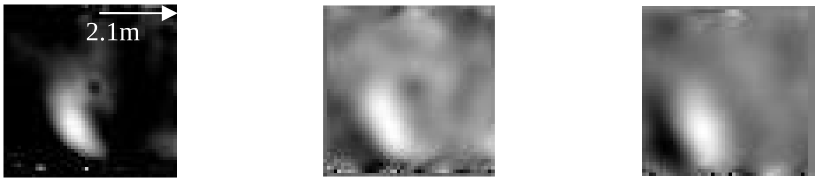

Fig. 11: Results of correlation calculations of PIGS reference data obtained for 3 runs

Run	SH	PIGS
1	1.03 m	1.1 m
2	0.87 m	1.0 m
3	1.03 m	1.2 m
mean	**0,94±0.06 m**	**1,1±0.14 m**

Run	SH	PIGS
2	126 deg	119 deg
3	130 deg	126 deg
4	138 deg	128 deg
mean	**131±6 deg**	**124±5 deg**

Table 12: Obtained values for the distance (left) and angle (right) of the correlation peaks PIGS and SH data shown in Fig. 10 and 12

6. DATA EVALUATION II: SPATIAL CORRELATION

A more qualitative result would be to compare the wave front measured with the PIGS WFS to the one obtained with the SH WFS. But this is not a trivial task, because of the non linear distortion of the PIGS pupil image induced by the rod due to its limited positioning accuracy.
In order to compare the PIGS intensity distribution pattern with the SH wavefront several reduction steps have to be accomplished. The SH wavefront has to be scaled to the right dimensions and rotated into the proper orientation (180°). Than the 2. azimuthal derivative has to be calculated and finaly the image has to be warped with the proper distortion parameters to the PIGS pupil. Fig. 13 shows a schematic of the procedure.

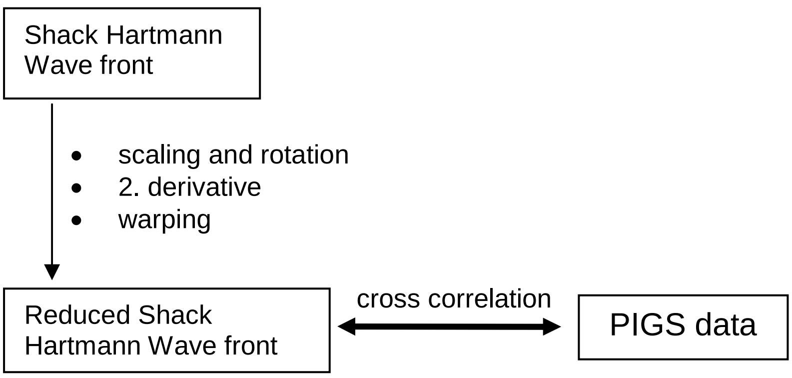

Fig. 13: Principle overview over the most important data reduction steps

A test of each reduction step is done by calculating the time averaged correlation as described in chapter 5. Fig. 14 shows the test of each step for one run as example. Examination of the correlation images could verify that the transformation applied in each reduction step behaves properly, except for the warping. The warping strongly depends on a calibration image which was used to extract the warping parameters by modeling the distorion. We could already improve the the model by increasing the parameter space but the results are still not satisfying. The prameter space is quite huge and we did not explore it fully up to now.

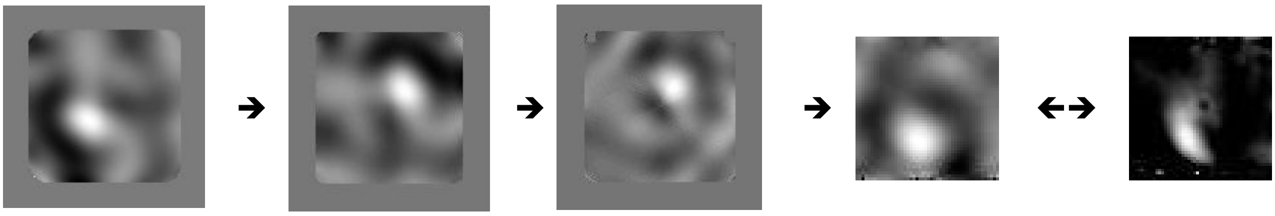

Fig. 14: Calculated cross correlation pattern after each data reduction step. The results are in good accordance with the expected position of the peak. From left to right. Initial data set. After applying right scaling and orientation. After applying the second derivative. After applying the warping. Right: PIGS data set

7. CONCLUSION

PIGS is a novel wave front sensor concept which can overcome several major problems of sodium LGS based AO systems for ELT. Since it is a pupil plane wave front sensor it can also be used for the layer oriented MCAO with light of the guide stars is optically co-added.

We presented first results of the new PIGS sensor obtained on sky. The feasibility of the rod sensing device under real conditions is demonstrated, comparing temporal evolution of PIGS wave front data and SH wave front data. We already developed a reduction pipeline to verify the spatial correlation of PIGS and SH reference data. Further adjustment in the warping modeling has to be done.

8. ACKNOWLEDGEMENTS

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