First laboratory results with the LINC-NIRVANA high layer wavefront sensor

Xianyu Zhang,1,2,3,4∗ Wolfgang Gaessler,1 Albert R. Conrad,1 Thomas Bertram,1 Carmelo Arcidiacono,5 Thomas M. Herbst,1 Martin Kuerster,1 Peter Bizenberger,1 Daniel Meschke,1 Hans-Walter Rix,1 Changhui Rao,2,3 Lars Mohr,1 Florian Briegel,1 Frank Kittmann,1 Juergen Berwein,1 Jan Trowitzsch,1 Laura Schreiber,6 Roberto Ragazzoni,7 Emiliano Diolaiti8

1Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
2The Laboratory on Adaptive Optics, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China
3The Key Laboratory on Adaptive Optics, Chinese Academy of Sciences, Chengdu 610209, China
4Graduate School of Chinese Academy of Sciences, Beijing 100039, China
5INAF - Arcetri Astrophysical Observatory, Largo Enrico Fermi 5, I-50125 Firenze, Italy
6Universit di Bologna, Astronomy Department, Via Zamboni 33, I-40126 Bologna, Italy
7INAF - Astronomical Observatory of Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy
8INAF - Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy

∗zhang@mpia.de

Abstract: In the field of adaptive optics, multi-conjugate adaptive optics (MCAO) can greatly increase the size of the corrected field of view (FoV) and also extend sky coverage. By applying layer oriented MCAO (LO-MCAO) [4], together with multiple guide stars (up to 20) and pyramid wavefront sensors [7], LINC-NIRVANA (L-N for short) [1] will provide two AO-corrected beams to a Fizeau interferometer to achieve 10 milliarcsecond angular resolution on the Large Binocular Telescope. This paper presents first laboratory results of the AO performance achieved with the high layer wavefront sensor (HWS). This sensor, together with its associated deformable mirror (a Xinetics-349), is being operated in one of the L-N laboratories. AO reference stars, spread across a 2 arc-minute FoV and with aberrations resulting from turbulence introduced at specific layers in the atmosphere, are simulated in this lab environment. From the wavefront data, the approximate residual wavefront error after correction has been calculated for different turbulent layer altitudes and wind speeds. Using a somewhat undersampled CCD, the FWHM of stars in the nearly 2 arc-minute FoV has also been measured. These test results demonstrate that the high layer wavefront sensor of LINC-NIRVANA will be able to achieve uniform AO correction across a large FoV.

© 2011 Optical Society of America

OCIS codes: (010.1080) Active or adaptive optics; (010.7350) Wave-front sensing; (010.1285) Atmospheric correction; (050.1960) Diffraction theory; (120.4640) Optical instruments; (350.1260) Astronomical optics; Multi-conjugate adaptive optics
References and links


1. Introduction

Atmospheric turbulence distorts images to the extent that, at most commonly observed wavelengths, large telescopes perform well below their diffraction limit. Without the benefit of adaptive optics, they acquire images with an angular resolution that is no better than that which might be achieved with telescopes whose apertures span only a few tens of centimeters. But thanks to adaptive optics (AO) systems, which compensate for the blurring effects of the atmosphere, the huge aperture available with today’s ground based telescopes can now be utilized for high angular resolution [3]. Unfortunately, traditional AO systems provide correction over only a small FoV, typically only a few arc seconds and the quality of correction degrades rapidly with distance from the reference star. In order to increase the FoV, a LO-MCAO system employs more than one deformable mirror (DM), each conjugate to, and therefore compensating for, a different turbulent layer in the atmosphere. By employing pyramid (as opposed to Shack-Hartman) wavefront sensors, the aims of a LO-MCAO system are more easily achieved [4].

To realize the concepts outlined above, we use two DMs in each arm of the LBT to compensate for turbulence in two layers of the atmosphere (one is the ground layer and the other is at 7.1 km). In a 6 arcminute diameter FoV, up to 12 guide stars can be used to correct the ground, while in the high layer up to 8 guide stars can be used. Following correction by these AO systems, the piston error between the two arms is removed by a delay line. Then, finally, the Fizeau interference pattern is imaged by the science detector.

Using multiple pyramids on separately deployable arms (the pyramid wavefront sensor in L-N does not need modulation [7]), L-N adds all the photons from the guide stars in one wavefront sensor, so the magnitude requirement of the guide stars decreases and the sky coverage increases. This “optical co-addition” reduces the impact of read out noise. The co-added meta pupil of 4 guide stars in the WFS at 4km is shown in Fig. 3.
In order to understand and test the portion of L-N consisting of the high layer wavefront sensor (HWS) and its DM, this portion of the optical path has been set up in a laboratory environment. In this experiment, four guide stars are used. The wavefront sensor, together with its 349-actuator Xinetics DM, is conjugate to the 4 km atmospheric layer (this is for historical reasons, later tests will place the DM at 7.1 km). In order to assess the performance of the HWS, the phase screen in MAPS is moved to positions corresponding to 0, 4, 10 and 21 km atmospheric layers with different wind speeds.

The structure of this paper is as follows: In section 2, we describe the laboratory setup. In section 3, we report first AO performance results for the system. Finally, in section 4, we provide conclusions.

2. The laboratory setup of the high layer wavefront sensor

The high layer wavefront sensor and associated subcomponents have been integrated to form a single, closed loop system in a laboratory environment, as shown in Fig. 1. The corresponding optical path is shown in Fig. 2. We detail here the configuration settings used for each of the components shown in these figures.

![Fig. 1. The laboratory setup of the LINC-NIRVANA HWS. The corresponding optical path is shown in Fig. 2.](image)

- **MAPS** In order to test and evaluate L-N optical performance, the MAPS [2] calibration unit was used to simulate the multiple turbulent layers of the atmosphere, as seen by LBT. For the experiment described here, we used a phase screen [2], which simulates a
Fried cell size ($r_0$) of 20 cm for images observed at a wavelength of 500 nm. The motor controller driving the phase screen was set to mimic wind speeds of 2.0, 0.51, and 0.15 m/sec, respectively. For each of these turbulence settings, we operated the AO system with the phase screen at each of 4 atmospheric layers: 0, 4, 10, and 21 km, but the DM and WFS were fixed to a position conjugate to 4 km in each case. We used the IDL-based CARMA [9] software system for this experiment. Due to limitations of this system, the loop frequency is roughly 8 Hz, so turbulence resulting from 0.15 m/sec wind speed can be well corrected, as shown in Fig. 4. We would expect similar performance for a 7.5 m/sec wind velocity if we had operated at the ultimate planned rate of 400Hz.

• Asterism The fiber plate shown in Fig. 6 was used to simulate a 9-star asterism: a 5-star science field surrounded by the 4 guide stars used for wavefront sensing. To better approximate the asterism being simulated, the fibers used for the guide stars differed from those used for the science targets. For science targets, we used narrow (9 μm), single-mode fibers, while for the guide stars we used wider (200 μm) multi-mode fibers. This combination provided the best light level and image size for the respective sensors, given the restrictions of the laboratory environment. The HWS required relatively bright targets and larger size, while, for the longer integrations required for the patrol camera, the fainter and smaller spots provided by the single-mode fibers were more ideal. The multiple science targets were realized by means of a fiber splitter (Schäfeter + Kirchhoff 1-to-12, 632 nm, fiber-optic beam splitter) connected to the fiber plate in MAPS; while the guide star light sources were directly connected to the fiber plate via the 200 μm fibers.

• collimator optics The collimator optics produce a footprint on the DM matched to its active area.
• **Deformable mirror** The deformable mirror is from Xinetics Inc. with 349 PZT actuators positioned over a 150mm diameter disk; each actuator has a maximum stroke of 5.9 μm.

• **FP20 optics** The FP20 optics provide a flat focal plane to the star enlargers within the HWS.

• **Star-enlarger and stages** Each of 8 star enlargers locally increase the f/ratio of the FP20 optics to F/225, thereby reducing the angular size of the exit pupil. Thus we have a pupil image size that is compatible with available detectors. Each star enlarger can be moved, via an x-y stage, to acquire stars within a one arc-minute square. The pyramid for each guide star is located at the top of its respective star enlarger, i.e. closest to the pupil re-imaging optics.

• **Pupil re-imaging optics** These optics re-image the meta-pupil onto the wavefront sensor. Because the photons of all the guide stars are added by the WFS as shown in Fig. 3, the magnitude of the individual guide stars can be reduced, thereby increasing the sky coverage of the system.

• **Wavefront sensor** A commercial CCD-39 with 80x80 pixels. For the experiment described here, the wavefront sensor was read out at a frequency of 100 Hz.

• **Patrol Camera** A commercial CCD-47 with 1024x1024 pixels. In LINC-NIRVANA, the patrol camera will be used to acquire seeing limited images for the HWS, so the plate scale is roughly 0.1 pixel/arcsecond. For the experiment described here the patrol camera was read out at a frequency of 0.4 Hz.

3. **The AO loop performance**

• **Wavefront sensor**

Figure 3 shows the meta-pupil from one quarter of the pyramid wavefront sensor (without modulation) with the deformable mirror and the pyramid wavefront sensor conjugated to 4km atmosphere altitude. The corresponding FoV of the guide stars is shown in Fig. 6.

![Fig. 3. The meta-pupil images for a conjugation altitude of 4km with 1, 2, 3 and 4 guide stars. Note the larger circle is the meta-pupil](image)

In order to evaluate the AO performance of the wavefront sensor, the aberrations in the first 10 Zernike modes[6] are measured and corrected, and the root mean square (RMS) wavefront error (WFE) is calculated. The RMS WFE with wind speeds of 2.0, 0.51, and 0.15 m/sec, with the phase screen positioned to simulate turbulence in atmospheric layers...
at 0, 4, 10, and 21 km, in open and closed loop are shown in Fig. 4. Figure 4 compares the RMS WFE in open loop and closed loop for all altitudes and wind speeds. RMS WFE drops very quickly in the first few loop iterations and then becomes stable.

The Greenwood frequency $f_G$ is well known [8]. Here, $v_{\text{wind}}$ refers to the wind speed and $r_o$ refers to Fried’s coherence length:

$$f_G = 0.43 \frac{v_{\text{wind}}}{r_o}$$ (1)

The Greenwood frequency is then 4.3, 1.1, and 0.3 Hz for wind speeds of 2.0, 0.51, and 0.15 m/sec, respectively.

Fig. 4. The RMS WFE versus time at different atmosphere altitudes and different wind speeds in open and closed loop. The atmosphere altitudes and wind speeds are labeled in each plot. In closed loop, a gain of 0.5 is used. The DM and WFS were fixed conjugate to 4 km for all cases. The wind speed for the open loop curves was 2 m/sec for all altitudes, although the curves are very similar for the other speeds.

- **Science Camera (patrol camera)**

In order to evaluate the AO performance for a simulated science target, the patrol camera was used. Because the patrol camera is intended for guide star acquisition in the LINC-NIRVANA system, the plate scale is too large for use as a science camera. In other words, for this experiment the science target is under-sampled. For clarity, in Fig. 5, only data for a wind speed of 0.15m/sec is shown. Figure 6 shows the asterism used for the experiment, together with representative open and closed loop images for each of the science
targets. In order to evaluate the statistical performance, sequential images are used to calculate the mean of the FWHM and the standard deviation in open and closed loop. As an example, the results for 10km at a wind speed of 0.15 m/sec are shown in Fig. 5. Then, the non-homogeneity in percent is calculated as RMS divided by mean FWHM of all stars in closed loop. For all the atmosphere layers, the mean FWHM, deviation range, and homogeneity are shown in Table 1.

![Fig. 5. The FWHM measured for each of the five science targets in open and closed loop for turbulence altitude 10 km and wind speed of 0.15 m/sec. The mean of these five measured values is given ("all"). To give an indication of the non-common path aberrations in the system, an open loop measurement taken with no phase screen (mean of all five stars) is given as well, indicated by the triangle symbol.](image)

<table>
<thead>
<tr>
<th>altitude</th>
<th>mean FWHM(pixels)</th>
<th>RMS (pixels)</th>
<th>non-homogeneity(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0km</td>
<td>3.147</td>
<td>0.175</td>
<td>5.565</td>
</tr>
<tr>
<td>4km</td>
<td>3.085</td>
<td>0.161</td>
<td>5.214</td>
</tr>
<tr>
<td>10km</td>
<td>3.063</td>
<td>0.206</td>
<td>6.739</td>
</tr>
<tr>
<td>21km</td>
<td>3.291</td>
<td>0.256</td>
<td>7.780</td>
</tr>
</tbody>
</table>

There are three main reasons for the apparent modest gain in FWHM performance seen in Fig. 5 compared to the reduction in RMS WFE shown in Fig. 4. First, LINC-NIRVANA was not designed for diffraction limited imaging at visible wavelengths. We can do a simple calculation: at a wavelength of 0.5μm, the $r_o$ is 20cm in the phase screen. For an 8.4m telescope, a $42 \times 42$ actuator deformable mirror is needed for high performance. Also, for a 349 actuator DM, the smallest $r_o$ for which a diffraction limited correction might be achieved on a 8.4m telescope is 42cm at 0.5μm, which corresponds to 52cm at 0.6μm. Second, uncorrected non-common path (NCP) aberrations degrade the image. For comparison see the insets which show the SS-1 fiber imaged with no phase screen in Fig. 6 and the FWHM in Fig. 5. The demonstration of uniform
Fig. 6. The AO correction for the science targets in the large FoV from the patrol camera at 10km turbulent height layer and wind speed of 0.15 m/sec. The corresponding FoV of the 5 science targets (blue circles) and surrounding 4 guide stars (green squares) are the same as shown in the fiber plate in the lower right of the figure. The blue star shows the PSF of SS-1 measured without a phase screen. Note that for each science target, the same plot scale is used.

correction across the field is unaffected by this limitation. Finally, in this experiment, only the lowest 10 Zernike modes are corrected. Higher mode aberrations are still in the system. Despite these limitations, AO correction was clearly achieved over a wide field as shown in Fig. 5 and Fig. 6.

4. Conclusions

• Wind speed

Closed loop RMS WFE increases with wind speed independent of atmospheric layer height (see Fig. 4). This means that in a LO-MCAO system, the relationship between the wind speed and the loop frequency needs to be considered.
• **AO performance with conjugated altitude**

As seen in Fig. 4, in open loop, when the simulated turbulent layer is at 21 km, the RMS WFE in open loop appears to be smaller than in the other layers; and in closed loop, good AO correction is also indicated in the figure. But Table 1 shows a much larger closed loop FWHM at 21 km. The reason for this apparent inconsistency is as follows. Mis-conjugation smears aberrations. In our experiment the DM conjugates to 4km. The mis-conjugation is largest (i.e., 17 km) when the phase screen is positioned to simulate 21 km. On the other hand, the results for 0 and 10 km are similar to what we see at the correct conjugation (i.e., 4 km). This result suggests that for a multiple guide star LO-MCAO system, good AO correction can be achieved when conjugation is correct to within approximately 5 km. This is broadly consistent with numerical simulations [10].

• **Homogeneity with conjugated altitude**

The statistical performance of the science targets in closed loop, as seen in Table 1, shows that non-homogeneity increases with mis-conjugation between the DM-WFS pair and the atmospheric layers. The best homogeneity is achieved when the DM-WFS pair conjugates to 4 km. Even when the mis-conjugation between the DM-WFS pair and atmospheric layers becomes 17 km, the homogeneity is still adequate. This indicates that MCAO systems can achieve uniform homogeneity, even when conjugation is far away from ideal.

**Acknowledgments**

The first author wishes to thank all the members of the LINC-NIRVANA team and Dr. D. Peter for helpful discussions on pyramid wavefront sensors. The first author has been supported by a PhD scholarship provided by Max-Planck Institute for Astronomy and Chinese Academic of Science.