On-sky verification of a solution to the MCAO partial illumination issue and wind-predictive wavefront control

R. Santhakumari, K., Arcidiacono, C., Bertram, T., Herbst, T., Ragazzoni, R., et al.

K. K. R. Santhakumari, C. Arcidiacono, T. Bertram, T. M. Herbst, R. Ragazzoni, J. Berwein, M. Klettke, F. Briegel, "On-sky verification of a solution to the MCAO partial illumination issue and wind-predictive wavefront control," Proc. SPIE 10703, Adaptive Optics Systems VI, 107035L (11 July 2018); doi: 10.1117/12.2313235

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

On-Sky Verification of a Solution to the MCAO Partial Illumination Issue and Wind-Predictive Wavefront Control

K. K. R. Santhakumari[a], C. Arcidiacono[b], T. Bertram[a], T. M. Herbst[a], R. Ragazzoni[c], J. Berwein[a], M. Klettke[a], and F. Briegel[a]

[a]Max-Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
[b]INAF-Osservatorio Astronomico di Bologna, Via Piero Gobetti, 93/3, 40129 Bologna, Italy
[c]INAF-Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio, 5, 35122 Padova, Italy

ABSTRACT

We have tested and confirmed the proper functioning of our solution to the MCAO partial illumination issue in the context of the LINC-NIRVANA (LN) MCAO module, both in the laboratory and on-sky. We present the results in this paper. Availability of direct AO-telemetry for individual layers from the LN MCAO system can be potentially used to improve not only the stability of the independent AO loops, but also the wavefront sensor efficiency. We introduce this idea, called "wind-predictive wavefront control".

Keywords: LINC-NIRVANA, adaptive optics, MCAO, layer-oriented, LBT, partial illumination, wind-predictive control

1. INTRODUCTION

Multi-Conjugate Adaptive Optics[1] (MCAO) systems promise to provide uniform PSF across a wide field of view (FoV), using multiple stars (laser-guide stars (LGS) or natural-guide stars (NGS)). Two (or more) prominent turbulent layers are corrected by the same number of deformable mirrors (DM), which are conjugated to the respective altitudes. "Star-oriented" and "layer-oriented" are the two possible ways of implementing MCAO.[2] Star-oriented MCAO uses the full-cylinder of atmospheric information from individual wavefront sensors (WFS) to computationally estimate (tomographic reconstruction) the wavefront corresponding to the conjugated layer. The corresponding signals are then sent to the respective DMs to correct the aberrations. In contrast to star-oriented MCAO, in which a WFS is associated with each reference star, layer-oriented MCAO uses one WFS and DM per corrected layer. In other words, light from multiple stars are used by a WFS, sensing the wavefront for a particular layer and drives the corresponding DM. One could design the optical system to optically co-add the light from multiple guide stars at the WFS. In both the star- and layer-oriented approaches, one common feature is the partial illumination at the high altitude conjugated layer. That is, full information of the aberrations in the high conjugated layer is not available from the WFS data. Only partial illumination data is available, according to the asterism of stars present. In star-oriented case, the tomographic reconstruction takes care of the partial illumination issue. For the layer-oriented case, naturally, the footprints of the stars do not completely overlap for a high-altitude conjugated layer, and the illumination pattern depends on the brightness and asterism of stars. Using only NGSs almost always results in a partial illumination scenario. Although layer-oriented MCAO has the advantage of computational simplicity compared with star-oriented MCAO, solving the partial illumination problem is a pre-requisite to taking advantage of this. In this paper, we report our on-sky results of our solution to the layer-oriented MCAO partial illumination issue with regard to the LINC-NIRVANA instrument.

LINC-NIRVANA[3] (LN) is a high-resolution near-infrared imager, installed[4] on the Large Binocular Telescope[5] (LBT). LN is equipped with an advanced and unique layer-oriented MCAO module.[6] The ground layer and a high layer are sensed using NGSs from a wider annular FoV and the inner FoV respectively. This multiple-FoV[7,8] pyramid wavefront sensing[9] approach is the first of its kind. Ultimately, LN is expected to provide a uniform 2' FoV correction for both "eyes" of the LBT, eventually allowing Fizeau interferometric beam combination.

Further author information: (Send correspondence to Kalyan Kumar Radhakrishnan Santhakumari)
E-mail: kalyan@mpia.de, Telephone: +49-6221-528-215

Adaptive Optics Systems VI, edited by Laird M. Close, Laura Schreiber, Dirk Schmidt, Proc. of SPIE Vol. 10703, 107035L · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2313235

Herbst et al.[6] explain in detail the LN optical path. An overview of the LN MCAO system appears in this paper[6] as well. The complex adaptive optics system and stringent requirements due to interferometry make the alignment of the components on the LN bench and each of the sub-systems a complicated task. The details of the alignment procedures, the problems we faced, and the solutions we found to overcome them can be found in references.[10–12] Currently, LN is in commissioning at LBT, and on April 3, 2018, we declared formal 'First Light'.[13]

2. THE PARTIAL ILLUMINATION ISSUE

2.1 What is it and why is it important for LN?

The reference star light focused at the pin of a four-sided pyramid is split into four beams, forming four pupil images at the WFS CCD. Each of the illuminated pixels is typically associated to a respective sub-aperture of the pupil. Comparing the local fluxes in the four pupil images corresponding to the same sub-aperture gives the local tilt. Note that for the ground layer, the star footprints overlap perfectly. Therefore, the pupil images also overlap for stars from different directions, and optical co-addition increases the signal for each sub-aperture uniformly for the ground layer (the purple shaded region in Figure 1).

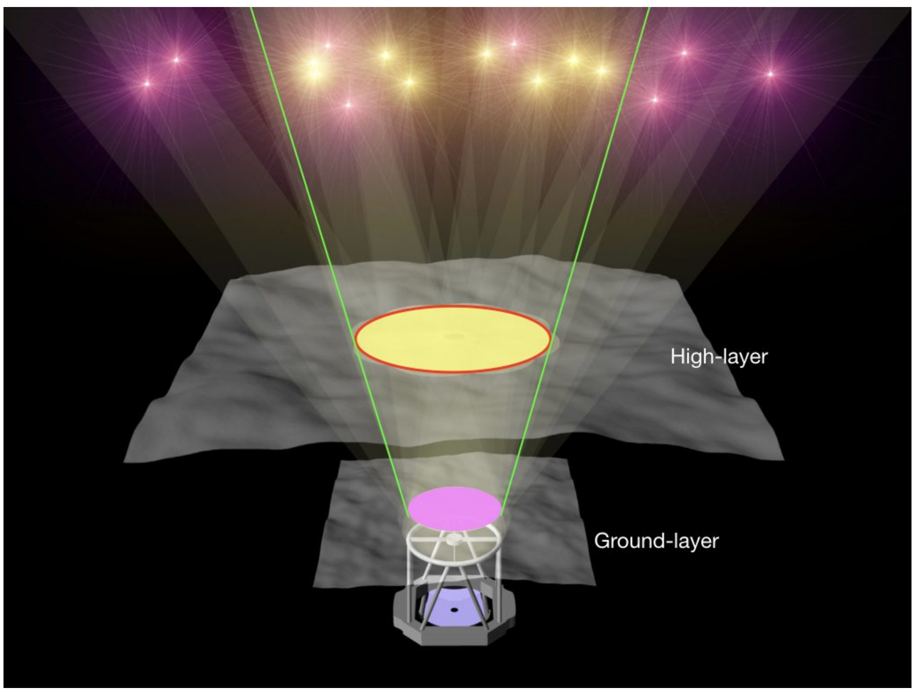

Figure 1. LN MCAO module concept: The ground layer is sensed using the purple NGSs from the 2'-6' annular FoV, and correction is done with the adaptive secondary mirror of the LBT. The high layer, conjugated to 7100m above the telescope pupil, is sensed by the yellow NGSs in the inner 2' diameter FoV. A commercial Xinetics DM on the LN bench corrects the aberrations sensed by the high layer WFS. Note that the yellow shaded region within the red circle denotes the metapupil, and the angle subtended by the green lines represent the 2' FoV.

For the high layer, the WFS and the respective DM are conjugated to 7100m above the telescope pupil (for LN). By optical design, the DM covers the footprints from any source within the 2' FoV. This area is called the metapupil (see yellow shaded region within the red circle in Figure 1). The diameter of the metapupil is about 1.5 times that of a single pupil. The modal base to reconstruct the wavefront is defined over the entire metapupil (or DM). Depending on the asterism and brightness of the guide stars, only a part of the metapupil or the aperture of the deformable mirror is illuminated (see Figure 2). The star footprints on the WFS are spatially decorrelated. The slopes in the illuminated regions can be directly measured. Reconstructing the wavefront within the entire metapupil, having information only from the partially illuminated region, and without wasting precious nighttime for calibration, is the crux of the partial illumination issue.

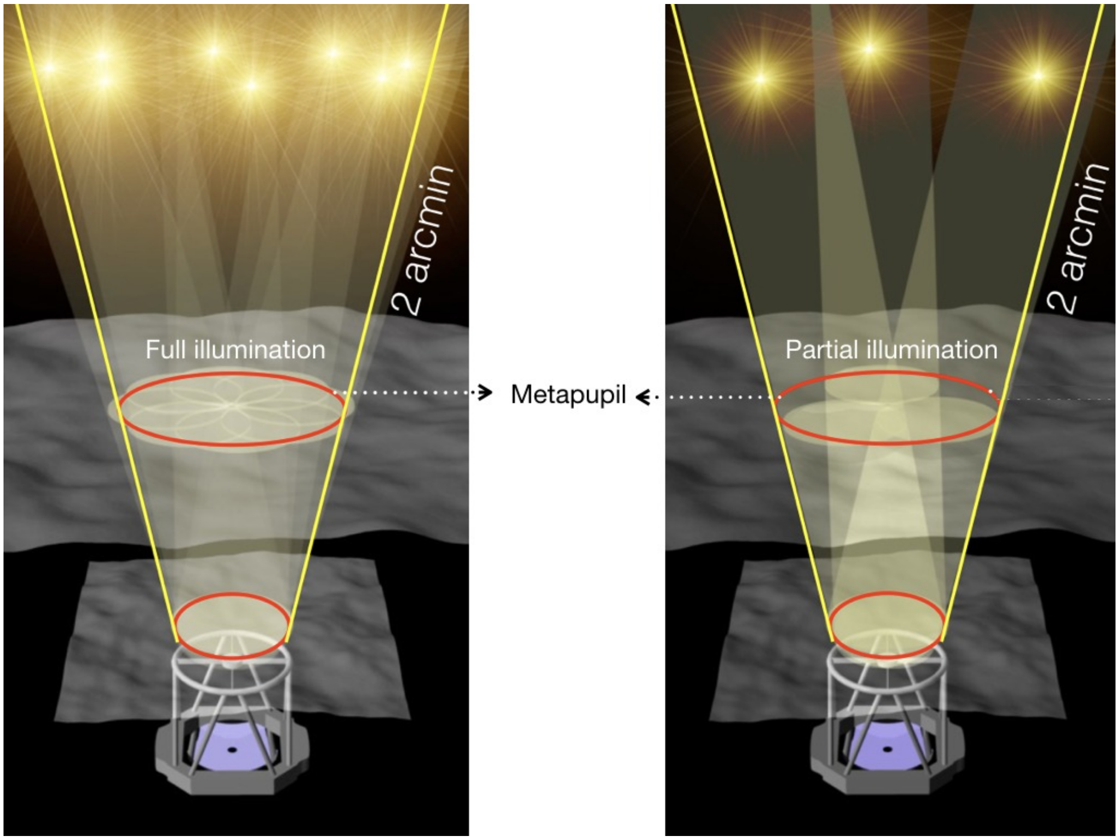

Figure 2. Left: Full illumination of the metapupil using 8 stars. Right: Partial illumination scenario, when only three stars are available. Note that, depending on the asterism of stars, their footprints illuminate different parts of the metapupil.

As the shape of the DM affects the science image, care has to be taken to not break the loop during an observation. Also, the PSF should be constant and uniform across the FoV. In the case of the LN MCAO system, the inner 2' FoV should be corrected. That is the metapupil region. Recall that the scaled version of the metapupil is imaged (i.e. conjugated) onto the DM. In order to fill the entire metapupil, in our case, eight well-distributed stars are required. Unfortunately, it is very rare to find 8 bright stars (brighter than ∼15 mag in R-band) within the 2' diameter FoV centered on the science target. Statistically speaking, the probability of finding stars with brightness greater than or equal to 12 mag and 15 mag within the 2' FoV in the galactic plane is 0.25 and 1.25, respectively.[14] This means that the chances of finding 4, 3, 2, and 1-star combinations within the 2' FoV brighter than 15 mag are 4%, 13%, 36%, and 71%, respectively. The corresponding chances of finding 3 and 2 star combinations brighter than 12 mag are 0.2%, and 3% respectively. Clearly, LN needs to address the partial illumination issue.

2.2 How do we do it? - The solution.

Previous publications[15–17] describe the strategy, including the details of the experimental setup. Therefore, only the main points are summarised. As mentioned earlier, WFS CCD pixels represent the sub-apertures in the conjugated layer. A signal-to-noise ratio (SNR) threshold is used to decide if the pixel is illuminated or not, producing an illumination mask. The threshold value can be obtained from a look-up table, depending on the brightness of the acquired stars. Note that any illumination mask will be a subset of the full illumination mask (see Figure 3).

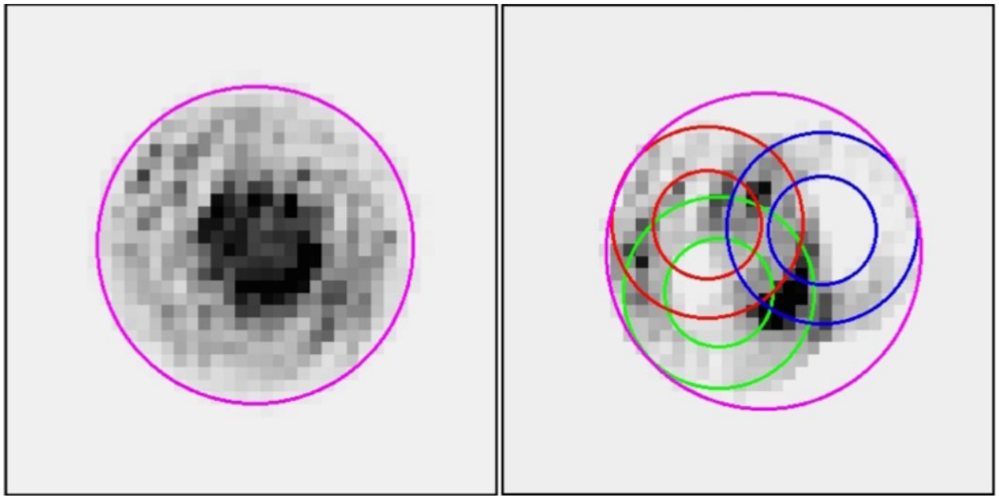

Figure 3. Images from the high layer WFS CCD. Left: Full illumination of the metapupil (magenta circle) using 8 stars. Right: An example of the partially illuminated metapupil, using three stars. Clearly, the partially illuminated sub-apertures are a subset of the fully illuminated ones. Note that a star footprint is an annulus rather than a disk. This is because there is a physical mask in the optical path to reduce background light noise coming from other sources in the FoV that are not acquired for wavefront sensing. This mask blocks less than 25% of the pupil.

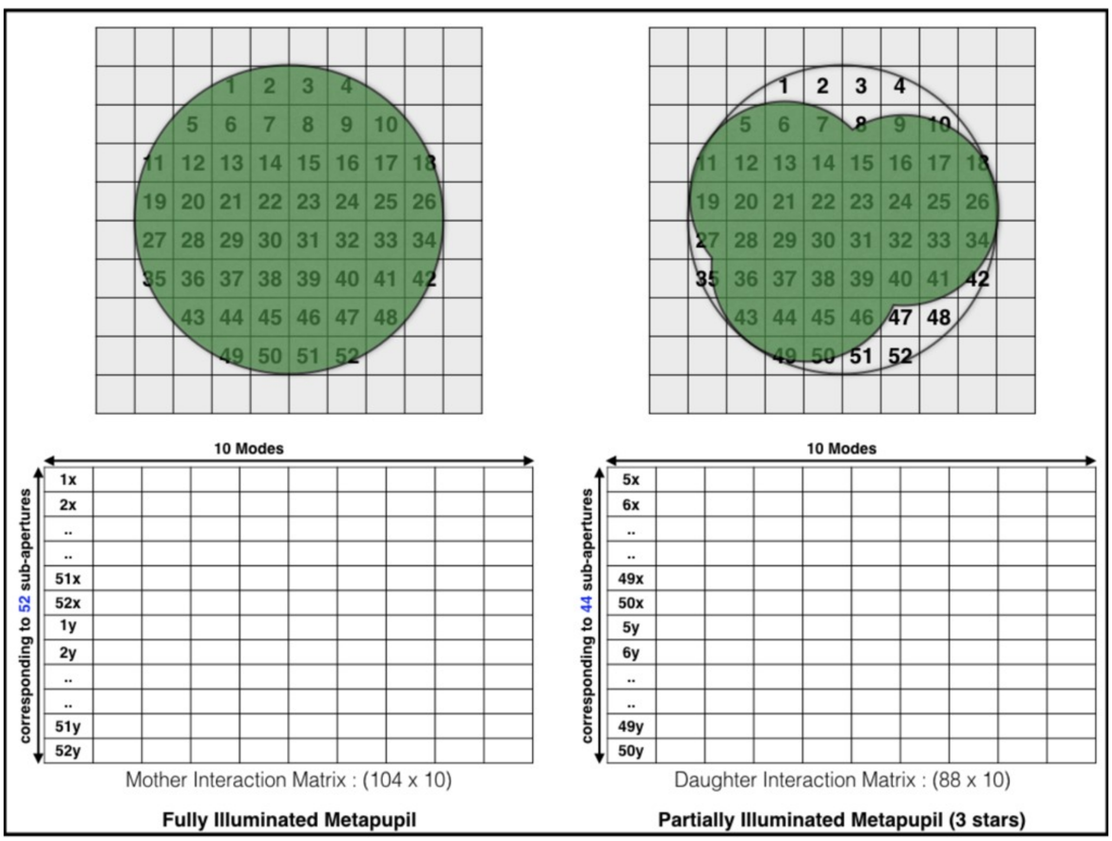

Figure 4. A schematic example explaining the extraction of the daughter interaction matrix from the mother interaction matrix for 10 modes. On the left, the fully illuminated metapupil (52 sub-apertures) and the corresponding interaction matrix can be seen. On the right, the partially illuminated metapupil appears, along with the daughter interaction matrix extracted out of the mother and corresponding to only those rows that are illuminated (44 sub-apertures in this case).

The main basis of our solution comes from the fact that there is a one-to-one relation between the rows of the interaction matrix, representing the response of the sub-apertures to the defined modes of the modal basis, to the sub-apertures. Depending on the illuminated region, a new interaction matrix is extracted from the fully illuminated interaction matrix for the current derotation angle (see Figure 4 for a schematic example). We name the fully illuminated interaction matrix the "mother" interaction matrix and the reduced, partially illuminated one, the "daughter" interaction matrix. Calibrating the mother interaction matrices is a very important step, which has been explained in previous publications.[17,18]

Since LBT is an alt-azimuth telescope, LN has to deal with changing parallactic angles while the science target is tracked on sky. Therefore, each wavefront sensor is equipped with derotation mechanisms between the DM and the WFS. The derotation changes the mapping between the actuator pattern on the DM and the sub-apertures on the WFS. This necessitates uploading of the appropriate reconstruction matrix on-the-fly, depending on the derotator angle. We upload a reconstruction for every 1° sky rotation. However, due to the derotator, the position of the stars do not change at the pin of the pyramids. Therefore, the illumination mask does not change as the derotator rotates.

This solution was rigorously tested in the laboratory under multiple partial illumination scenarios involving a varying number of reference stars. The results confirmed the validity of the solution and was ready to be tested on-sky.[15,17]

2.3 On-sky results

LN was installed on LBT in September 2016. Following a few technical runs and pre-commissioning runs, we had our first commissioning run in March 2017, during which we commissioned one of the two ground layer WFSs. With the second (June 2017) and third (January 2018) runs, we tried commissioning the high layer WFS. The high layer loop could not be closed for more than 7 modes. We determined that the problem was the moving WFS CCD as the telescope tracks the science target. Note that LN moves with the telescope, and the WFS CCDs are not in a gravity-invariant configuration. The movement of the WFS CCD causes mis-registration between the sub-apertures and actuator positions. In other words, the optical conjugation varies slightly. The solution is a CCD tracking algorithm that tracks the optical conjugation and registration in real-time. This was successfully tested during the fourth commissioning run (April 2018). For the first time, both ground and high layer loops could be stably closed with a reasonable number of modes. This also provided considerable improvement of the science image, and we declared LN MCAO First Light!

Figure 5 shows the first on-sky verification (and LN MCAO First Light) of our solution to the partial illumination issue. In this case, there are 5 high layer stars illuminating the metapupil. We were able to close the high layer loop stably with 40 modes, starting from a stable ground layer corrected wavefront. The real-time extraction of the daughter interaction matrix from the respective mother interaction matrix corresponding to the derotation angle and uploading of the estimated reconstructor for every 1° sky rotation was successfully tested. We were also able to perform MCAO for another target, which had 2 ground- and 2 high layer stars with similar magnitudes. However, the performance was not as good. Previous laboratory tests showed better correction at the high layer with increasing number of illuminated sub-apertures. In upcoming commissioning runs, including one in June 2018, we will acquire more data for various other asterisms.

3. WIND-PREDICTIVE WAVEFRONT CONTROL

Taylor's frozen flow hypothesis (TFFH) states two important points about the temporal evolution of the atmosphere. First, the refractive index variations are concentrated in distinct layers and stay spatially stable through time. Second, these layers are blown by the wind, leading to a translation of the phase aberration across the pupil. In other words, the atmosphere structure at a definite layer can be considered frozen in time as far as the radiation is concerned and is just laterally translated by the wind (at least for the relevant timescale, which is $\sim$ 1 second for an 8-m telescope). TFFH has been experimentally confirmed[19,20] and the strength of the frozen-flow[19,20] measured for various sites. If there is frozen-flow, the information about the wind derived from the AO telemetry may be used to improve the efficiency, and compensate the time delays within the system.

The first step would be to estimate the wind vector for the layer of interest. Each of the layers may have a different wind speed and direction, which in turn may also evolve during the night. For a layer-oriented MCAO

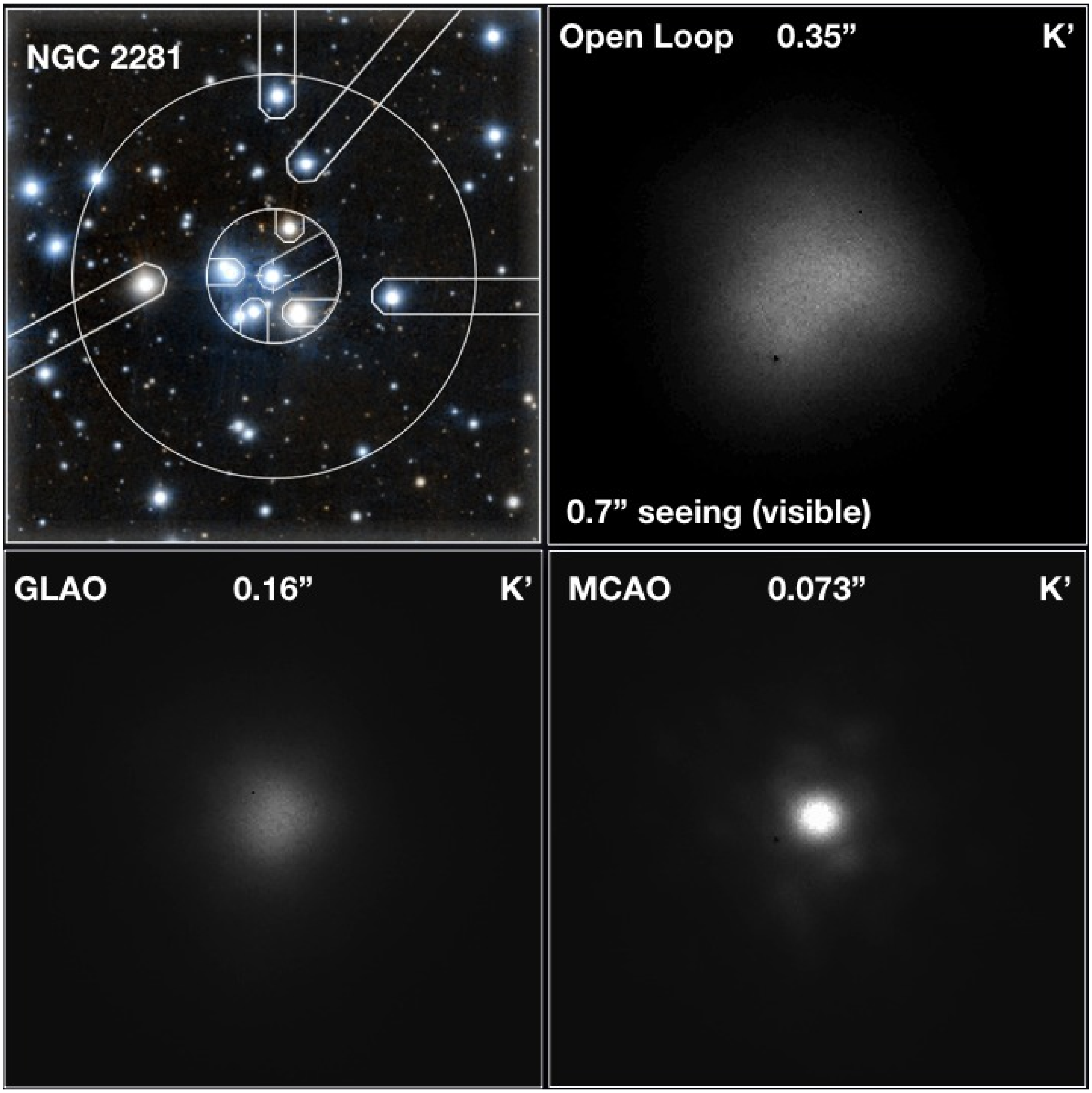

Figure 5. LN MCAO First Light! On 3 April 2018, LN successfully achieved MCAO with expected performance for the first time ever. Four ground layer stars and five high layer stars were acquired using the respective WFSs. While 50 Karhunen-Loéve (KL) modes were closed by the ground layer WFS, 40 KL modes were closed at the high layer WFS. Open loop seeing of 0.35" in the K' band (visible seeing of 0.7") was reduced to 0.16" once the ground layer was closed. high layer correction reduced this to 0.073". Note that the theoretical diffraction limit for K-band is 0.057". The brightness of the stars varied between 8.4 mag to 11.0 mag in R-band. The Strehl ratio improved from 2.5% to 24%. The best performance we anticipate in K-band is 40%. The open loop image is stretched by a factor of 10 for visibility. Clearly, the high layer metapupil was only partially illuminated, demonstrating an on-sky verification of our solution to the partial illumination issue.

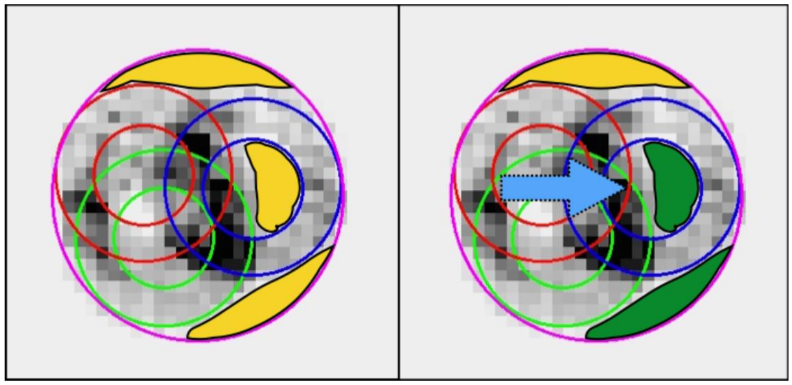

Figure 6. Virtually filling sub-apertures using wind-predictive wavefront control on the high layer loop. Left: The partially illuminated metapupil can be seen. The yellow shaded regions represent the non-illuminated sub-apertures. Right: A favourable wind direction (blue arrow) allows us to virtually fill in some of the non-illuminated sub-apertures, represented by the green shaded regions.

system, like LN, direct AO telemetry is available for the conjugated layers. Therefore, the wind vector can be directly retrieved from the WFS data. This saves significant computational time, which would be necessary for tomographic reconstruction.

We also expect performance gains in closed-loop operation of LN by implementing the wind-predictive wavefront control. For the high layer loops, wind-predictive control can improve the partial illumination situation. If the wind is in a favourable direction, some or many of the non-illuminated sub-apertures may be virtually illuminated (see Figure 6). Another advantage will be an increase in the effective exposure time at the WFS CCDs, thereby providing larger SNR.

Currently, we are studying wind-predictive wavefront control for the LN AO system, and hope to implement and test it in the coming months.

4. CONCLUSION

We have verified on-sky our solution to the MCAO partial illumination issue, in the context of the LN MCAO system. In upcoming runs, we will be testing it further and will collect more data. We propose wind-predictive wavefront control for the LN MCAO system, which will make use of the direct availability of AO telemetry. We also anticipate that wind-predictive wavefront control will mitigate the effect of partial illumination, given a favourable wind direction.

ACKNOWLEDGMENTS

The authors express their sincere gratitude to the LBT mountain crew for their continuing support and dedication, which made our remote and on-site activities very smooth and effective.

REFERENCES

[1] Beckers, J. M., "Detailed compensation of atmospheric seeing using multiconjugate adaptive optics.," in [*Active telescope systems*], Roddier, F. J., ed., *Proc. SPIE* **1114**, 215–217 (Sept. 1989).

[2] Nicolle, M., Fusco, T., Michau, V., Rousset, G., and Beuzit, J.-L., "Optimization of star-oriented and layer-oriented wavefront sensing concepts for ground layer adaptive optics," *J. Opt. Soc. Am. A* **23**, 2233–2245 (Sep 2006).

[3] Herbst, T. M., Ragazzoni, R., Bertram, T., Bizenberger, P., Briegel, F., Hofferbert, R., and Kürster, M., "LINC-NIRVANA at LBT: final preparations for first light," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], *Proc. SPIE* **9908**, 99080N (Aug. 2016).

[4] Herbst, T. M., Ragazzoni, R., Bertram, T., Bizenberger, P., Arcidiacono, C., Briegel, F., Klettke, M., Santhakumari, K. K. R., Viotto, V., Bergomi, M., and Marafatto, L., "Installation and commsissioning of the LINC-NIRVANA near-infrared MCAO imager on LBT," **This conference** (2018).

[5] Hill, J. M., Ashby, D. S., Brynnel, J. G., Christou, J. C., Little, J. K., Summers, D. M., Veillet, C., and Wagner, R. M., "The Large Binocular Telescope: binocular all the time," in [*Ground-based and Airborne Telescopes V*], **9145**, 914502 (July 2014).

[6] Herbst, T. M., Arcidiacono, C., Bertram, T., Bizenberger, P., Briegel, F., Hofferbert, R., Kürster, M., and Ragazzoni, R., "MCAO with LINC-NIRVANA at LBT: preparing for first light," in [*Adaptive Optics Systems V*], *Proc. SPIE* **9909**, 99092U (July 2016).

[7] Farinato, J., Ragazzoni, R., Arcidiacono, C., Brunelli, A., Dima, M., Gentile, G., Viotto, V., Diolaiti, E., Foppiani, I., Lombini, M., Schreiber, L., Bizenberger, P., De Bonis, F., Egner, S., Gässler, W., Herbst, T., Kürster, M., Mohr, L., and Rohloff, R. R., "The Multiple Field of View Layer Oriented wavefront sensing system of LINC-NIRVANA: two arcminutes of corrected field using solely Natural Guide Stars," in [*Adaptive Optics Systems*], **7015**, 70155J (July 2008).

[8] Ragazzoni, R., Diolaiti, E., Farinato, J., Fedrigo, E., Marchetti, E., Tordi, M., and Kirkman, D., "Multiple field of view layer-oriented adaptive optics. Nearly whole sky coverage on 8 m class telescopes and beyond," *Astronomy and Astrophysics* **396**, 731–744 (Dec. 2002).

[9] Ragazzoni, R., "Pupil plane wavefront sensing with an oscillating prism," *Journal of Modern Optics* **43**, 289–293 (Feb. 1996).

[10] Marafatto, L., Bergomi, M., Brunelli, A., Dima, M., Farinato, J., Farisato, G., Lessio, L., Magrin, D., Ragazzoni, R., Viotto, V., Bertram, T., Bizenberger, P., Brangier, M., Briegel, F., Conrad, A., De Bonis, F., Herbst, T., Hofferbert, R., Kittmann, F., Kürster, M., Meschke, D., Mohr, L., and Rohloff, R.-R., "Aligning a more than 100 degrees of freedom wavefront sensor," in [*Adaptive Optics Systems III*], **8447**, 84476F (July 2012).

[11] Radhakrishnan Santhakumari, K. K., Marafatto, L., Bergomi, M., Viotto, V., Farinato, J., Ragazzoni, R., Herbst, T., Bertram, T., Dima, M., Bizenberger, P., Briegel, F., Kittmann, F., Mohr, L., and Magrin, D., "Ground layer correction: the heart of LINC-NIRVANA," in [*Adaptive Optics Systems IV*], **9148**, 91482R (July 2014).

[12] Moreno-Ventas, J., Bizenberger, P., Bertram, T., Radhakrishnan, K. K., Kittmann, F., Baumeister, H., Marafatto, L., Mohr, L., and Herbst, T., "Final integration and alignment of LINC-NIRVANA," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], **9908**, 99082Y (Aug. 2016).

[13] Herbst, T. M., Ragazzoni, R., Bertram, T., Bizenberger, P., Arcidiacono, C., Briegel, F., Klettke, M., Santhakumari, K. K. R., Viotto, V., Bergomi, M., and Marafatto, L., "Commissioning multi-conjugate adaptive optics with LINC-NIRVANA on LBT," **This conference** (2018).

[14] Arcidiacono, C., Diolaiti, E., Ragazzoni, R., Farinato, J., and Vernet-Viard, E., "Sky coverage for layer-oriented MCAO: a detailed analytical and numerical study," in [*Advancements in Adaptive Optics*], **5490**, 563–573 (Oct. 2004).

[15] Santhakumari, K. K. R., Arcidiacono, C., Bertram, T., Berwein, J., Herbst, T. M., and Ragazzoni, R., "Solving the MCAO partial illumination issue and laboratory results," in [*Adaptive Optics Systems V*], **9909**, 99096M (July 2016).

[16] Bertram, T., Kumar Radhakrishnan Santhakumari, K., Marafatto, L., Arcidiacono, C., Berwein, J., Ragazzoni, R., and Herbst, T. M., "Wavefront sensing in a partially illuminated, rotating pupil," in [*Adaptive Optics Systems IV*], **9148**, 91485M (Aug. 2014).

[17] Santhakumari, K. K. R., [*Maximizing the Science Returns of the LINC-NIRVANA Multi-conjugated Adaptive Optics System*], Ruperto-Carola-University of Heidelberg (2017).

[18] Arcidiacono, C., Santhakumari, K. K. R., Herbst, T. M., Ragazzoni, R., Bertram, T., Briegel, F., Klettke, M., Viotto, V., Bergomi, M., and Marafatto, L., "The calibration procedure of the LINC-NIRVANA ground and high layer wavefront sensors," **This conference** (2018).

[19] Guesalaga, A., Neichel, B., Cortés, A., Béchet, C., and Guzmán, D., "Using the Cn2 and wind profiler method with wide- field laser-guide-stars adaptive optics to quantify the frozen- flow decay," *Monthly Notices of the RAS* **440**, 1925–1933 (May 2014).

[20] Poyneer, L., van Dam, M., and Véran, J.-P., "Experimental verification of the frozen flow atmospheric turbulence assumption with use of astronomical adaptive optics telemetry," *Journal of the Optical Society of America A* **26**, 833 (Mar. 2009).