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Commissioning Multi-Conjugate Adaptive Optics with LINC-NIRVANA on LBT

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ABSTRACT

This paper reports on early commissioning of LINC-NIRVANA (LN), an innovative Multi-Conjugate Adaptive Optics (MCAO) system for the Large Binocular Telescope (LBT). LN uses two, parallel MCAO systems, each of which corrects turbulence at two atmospheric layers, to deliver near diffraction-limited imagery over a two-arcminute field of view. We summarize LN's approach to MCAO and give an update on commissioning, including the achievement of First Light in April 2018. This is followed by a discussion of challenges that arise from our particular type of MCAO and the solutions implemented. We conclude with a brief look forward to the remainder of commissioning and future upgrades.

Keywords: MCAO, pyramid wavefront sensing, layer-oriented, LBT, Commissioning

1. INTRODUCTION

LINC-NIRVANA is a high-resolution, near-infrared imager operating in the JHK photometric bands on the Large Binocular Telescope. LN uses sophisticated, two-layer Multi-Conjugate Adaptive Optics to deliver a near diffraction-limited field two arcminutes across. Originally designed as an interferometer, the instrument images light from both 8.4-m mirrors of the LBT onto a single science detector. We currently only use single-eye mode during commissioning of MCAO, but will soon attempt incoherent binocular imaging, and (pending resource availability), full interferometric Fizeau mode.

Previous publications in this conference series (Herbst et al. 2016[1] and references therein) present the detailed design of LINC-NIRVANA and discuss laboratory assembly and testing activities prior to delivery to the telescope. At the time of the last SPIE meeting, the LN team was in the final stages of re-integration of the instrument in the LBT mountain lab. This paper reports on activities since that time, specifically our early commissioning results (including First Light), and how we address a number of challenges to performing MCAO this way.

2. LINC-NIRVANA'S APPROACH TO MCAO

LINC-NIRVANA employs Layer-Oriented, Natural Guide-Star (NGS), Multi-Conjugate Adaptive Optics using the Multiple Field of View approach. LN actually has two identical MCAO systems, one for each of the 8.4 m mirrors of the LBT, and each channel contains separate pyramid-based wavefront sensors (WFS) for the ground layer and a high layer ~7 km above the site. We use the facility, 672-actuator adaptive secondary mirrors and up to twelve NGS for ground-layer correction, and two, 349-actuator Xinetics deformable mirrors (DM) and up to eight NGS for the high layer. LN accepts light from both telescopes and is designed for incoherent overlap and eventually, interferometric beam combination with off-axis fringe tracking.

LN's Ground-layer Wavefront Sensors (GWS) were designed and constructed by the AO group in Padova. Each of the sensors weighs approximately 700kg and sits near the telescope focus on the LINC-NIRVANA optical bench. At this

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location, an annular mirror directs light from a region 2-6 arcmin in diameter into the GWS and its 12 separately controllable "Star Enlarger" (SE) star probes on X-Y stages. Each probe magnifies the focal plane locally and places the star image on the tip of a glass pyramid. To accommodate the strong curvature of the LBT focal plane, alternate SE are displaced by 2.3mm along the optical axis. In operation, odd-numbered SE explore the inner regions of the focal plane, while even-numbered ones operate further out. Behind the star enlarger mechanisms, a single pupil imager collects the starlight from all illuminated probes and, as with conventional pyramid wavefront sensing, produces four pupils on a CCD detector, which itself can move in X-Y-Z. Because LBT is an alt-azimuth telescope, the sky rotates during observation. As a result, the entire GWS assembly rotates within a large (73cm diameter) bearing and communicates with the rest of the instrument through a cable twister. The correction signals from the GWS feed the 672-actuator facility adaptive secondary mirrors of LBT.

The LN team in Bologna produced the High-layer Wavefront Sensors (HWS). Optically, the HWS have a configuration similar to that of the GWS, but there are fundamental differences. The HWS use light that passes through the hole in the annular mirror near the telescope focus, and thus sample the same portion of sky as the science channel, that is, the central 2 arcminutes. Because it patrols a smaller region, the HWS host eight, rather than 12 star enlargers. Finally, the high-layer sensors are fixed to the optical bench and use an external K-mirror for de-rotation. The HWS send their correction signals to a pair of 349-actuator Xinetics deformable mirrors placed upstream on the bench.

The LINC-NIRVANA MCAO system is purely sequential, in the sense that the ground-layer sensors and their associated deformable mirrors operate on the incoming light and deliver their wavefronts to the HWS and their associated DMs. The HWS then operates independently from the GWS on the partially corrected wavefronts. This simplifies control and improves stability. The configuration of focal planes and conjugation altitudes brings advantages as well as challenges. Because all of the stars overlap in the ground layer pupil, we can optically combine the signal with the pupil imager onto a single detector, reducing the read noise penalty and improving performance. The high-layer stars overlap, but only partially. This helps performance, but forces us to deal with only partial information on the high layer turbulence (see Section 4.1 below). Note that we refer to the individual stellar footprints at the high layer as "pupils" and to the area encompassing the ensemble of all possible footprints as the "metapupil" (Figure 1).

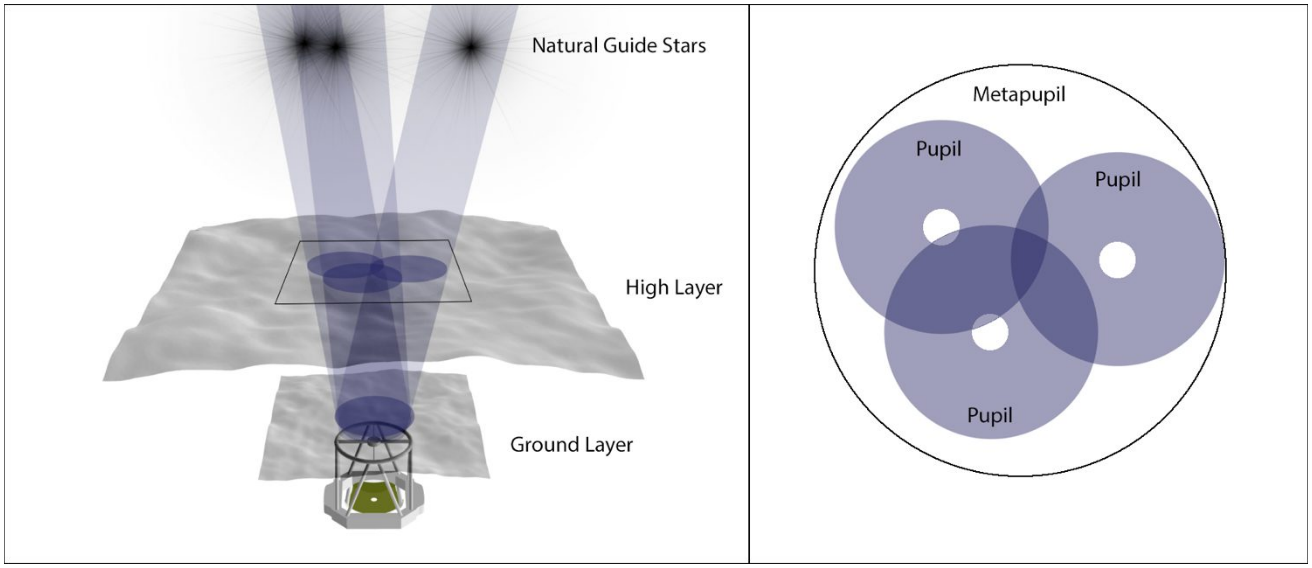

Figure 1. Pupils and metapupils. All of the look directions overlap at the ground layer, but for higher layers, the cylinders of light decorrelate (left). We refer to the individual stellar footprints as *pupils* and to the area containing all possible pupils as the *metapupil* (right).

3. COMMISSIONING PROGRESS AND FIRST LIGHT

Shortly after the last SPIE meeting in 2016, we mounted the internally-aligned instrument on the LBT for the first time. Herbst et al.[2] in this conference provide further details of this challenging operation. A month after installation, we began with a pair of "pre-commissioning" runs which focused on telescope-to-instrument alignment and the calibration of the facility adaptive secondary mirrors with our ground-layer wavefront sensors. LN achieved "first technical light" in November 2016 during the first of these runs (Figure 2).

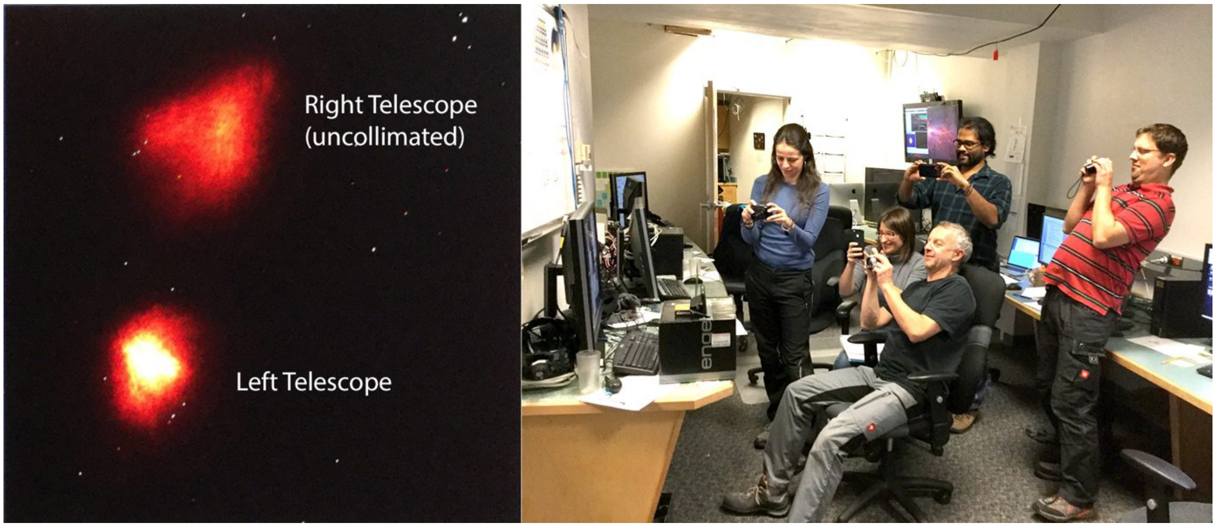

Figure 2. First photons for LINC-NIRVANA. On 22 November 2016, during the first pre-commissioning run, we were granted one hour on sky at the beginning of the night. About ten minutes after opening, LINC-NIRVANA saw starlight for the very first time. The left panel, which depicts a region approximately 5 arcseconds square on the science detector, shows that the image quality "out of the box" was better than an arcsecond, and the co-pointing of the two arms was very good as well. Note that only the left-hand telescope was adjusted for low order aberrations (focus, astigmatism, coma, etc.).

Formal commissioning began in March 2017 with a focus on the ground-layer wavefront sensors. As mentioned above, these devices drive LBT's adaptive secondary mirrors to correct turbulence ca. 100m above the telescope. Such correction is a prerequisite to full MCAO, since the high-layer, Xinetics deformable mirrors within LN do not have sufficient dynamic range to remove atmospheric tip-tilt and windshake. During this first commissioning run, we demonstrated the expected closed-loop ground-layer correction with five natural guide stars (Figure 3).

Initial commissioning of the high-layer WFS took place in June 2017. Poor weather and other factors reduced our on-sky time, but we were nevertheless able to close the ground and high-layer loops simultaneously. While this was technically two-layer, stable correction, we did not call it "First Light" or MCAO, since the improvement in image quality was modest. The high-layer WFS only saw sky for about 45 minutes and operated with a low number of correction modes (*ca.* 5-7). Later examination of the data identified flexure-induced motion of the wavefront sensor CCD's as the root cause of the reduced performance. In January 2018, we returned to the telescope with the goal of testing our preliminary flexure tracking algorithms (for X-Y motion only) and improving performance. Unfortunately, poor seeing and an overall short run limited our usable sky access to little more than a single night. Nevertheless, we did demonstrate CCD tracking and again stably closed both the ground and high-layer loops with modest performance.

The most recent commissioning run took place in the first week of April 2018. With a total of four nights allocated, the team planned to implement both full X-Y-Z flexure tracking, as well as test more sophisticated and efficient search and acquisition algorithms for the reference stars. Immediately before starting night-time operations, we also tweaked the alignment of the high-layer star enlargers to improve the fidelity of overlap of the pupils. After a difficult start due to technical issues, the team began work in earnest just after sunset on 3 April 2018. After acquiring four ground-layer and five high-layer reference stars, the team closed the ground and high layer loops. Within 20 minutes, we were able to declare formal First Light for LINC-NIRVANA. Although all of our detectors and control loops had seen light and operated successfully beforehand, we had established a strict First Light criterion that all loops be closed simultaneously and stably, and that LN deliver image quality expected of MCAO. Figure 4 shows our First Light image, which has a measured Strehl ratio of 25%.

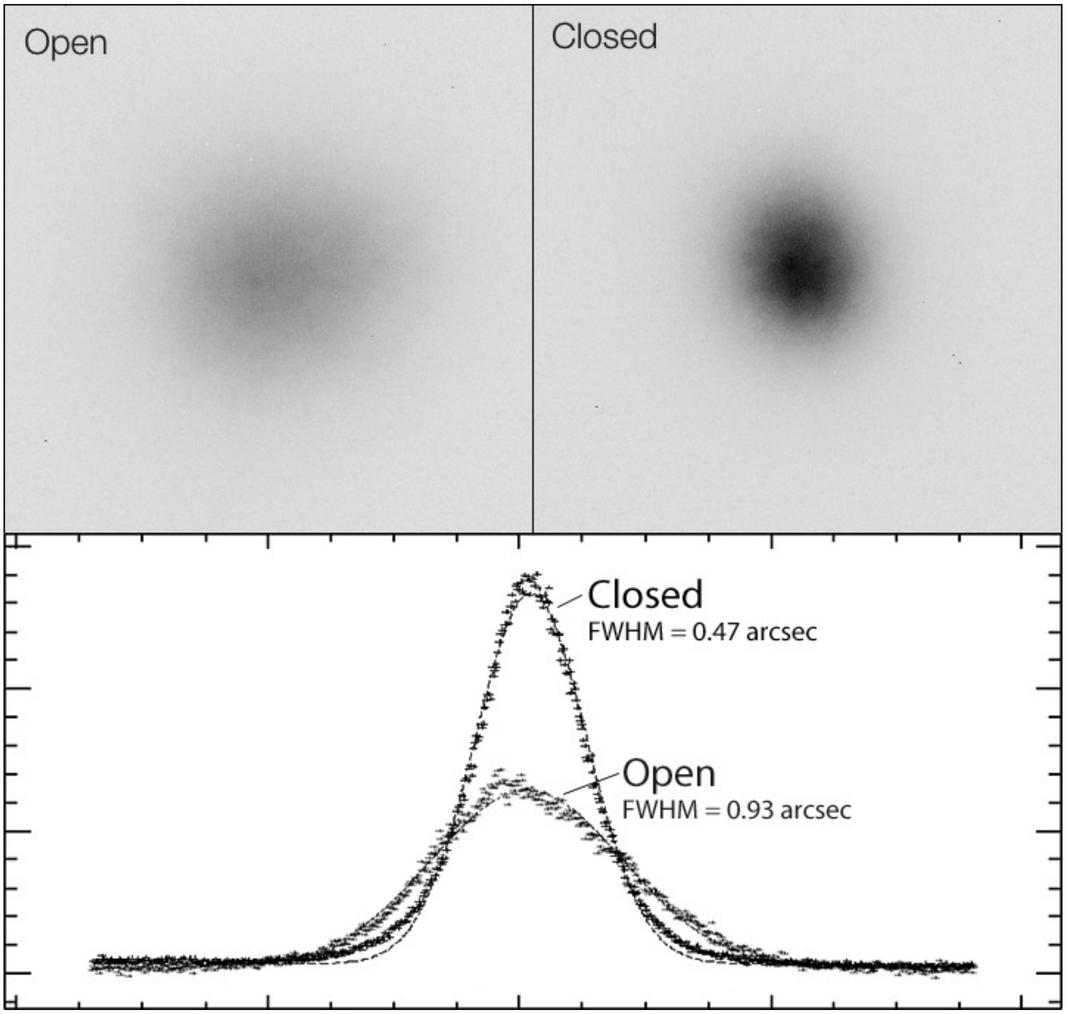

Figure 3. First ground-layer adaptive optics with LINC-NIRVANA took place on 29 March 2017. Closing the GWS loop with the facility adaptive secondary mirrors produced a factor of two reduction in the K' band seeing.

The remainder of the April commissioning run was plagued by cloud, poor seeing, and minor technical glitches. We will return to the telescope at the end of June 2018 – 3 days after this SPIE conference– to continue commissioning.

Note added on 28 June 2018: Our fifth commissioning run began three days after the end of this conference in June 2018. This run was very successful, and we performed MCAO repeatedly and stably.

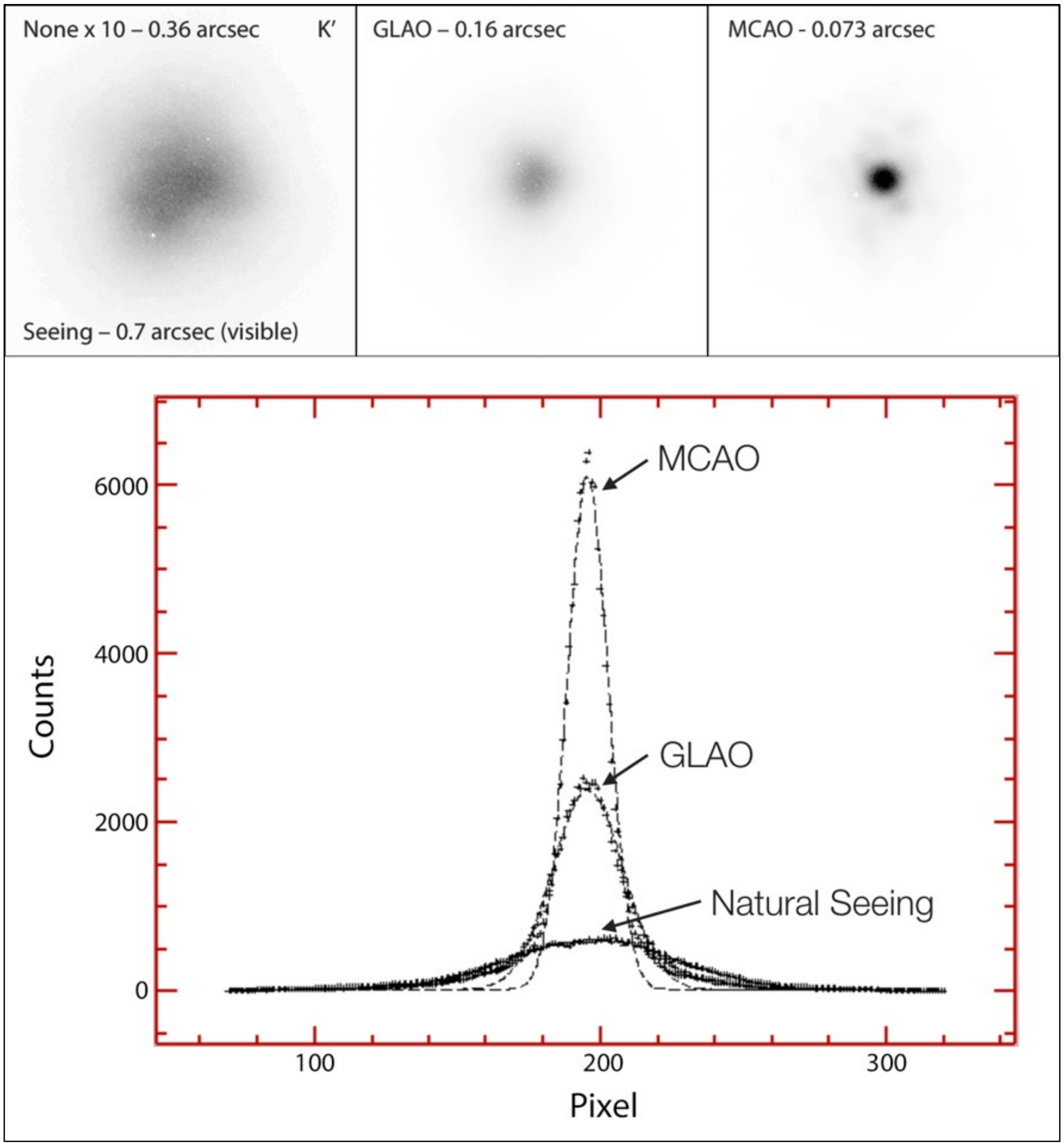

Figure 4. First Light for LINC-NIRVANA on 3 April 2018. During conditions with visible seeing of 0.7 arcsec, the uncorrected full-width at half maximum (FWHM) in the K' band was 0.36 arcsec, as expected (top left panel – note that the grayscales have been stretched by a factor of 10 for clarity). Closing the ground-layer loop on four stars reduced the FWHM by a factor 2.3 to 0.16 arcsec (top center panel). Adding high-layer correction with five stars produced a further factor of 2.2 gain and a delivered PSF with 73mas FWHM (top right panel). Note that the diffraction limit of LN at this wavelength is 57mas. The lower panel shows cuts through the three images. The gain in both FWHM and peak signal is clear.

4. UNIQUE CHALLENGES FOR LN MCAO

4.1 Partial Illumination of the Metapupil

As mentioned in Section 2, the partial overlap of the stellar pupils in the high-layer metapupil poses an interesting challenge for adaptive optics. Typically, inverting the interaction matrix (IM) of the system provides the AO reconstructor needed to convert modal coefficients (whether Zernike or in our case, Karhunen-Loève) into deformable mirror commands. The problem is that, after calibration, this reconstructor is based on full illumination of the metapupil and applying it in the normal circumstance of partial illumination (and hence partial information) leads to instability and loop breakage. Note also that both the metapupil coverage and signal to noise ratio depend on the particular stellar asterism used.

Our solution to the partial illumination problem is straightforward and effective. It depends on the fact that there is a one-to-one correspondence between WFS subapertures and deformable mirror actuators (assuming 1:1 sampling). We determine the actual, current illumination from either a threshold applied to an integrated image of the metapupil or from the known locations of the reference stars. We then eliminate the rows of the fully-illuminated "mother" interaction matrix corresponding to unilluminated regions, before inverting it to produce the needed "daughter" reconstructor. This method has been verified both in the lab and on sky. See Santhakumari *et al*[3] (2018 this conference) for a complete description.

4.2 De-Rotation

Because it will eventually function as a Fizeau interferometer, many of LN's components must be fixed with respect to the entrance pupil of the binocular telescope. Using natural guide stars thus brings the imperative to track and de-rotate. LINC-NIRVANA contains a total of five separate de-rotators that must be aligned and controlled in rotation rate and optical center. As mentioned above, the GWS employ large bearings, while the HWS are fed by dual K-mirrors. The science detector mechanism hosts the final de-rotator to eliminate image blur during integration. The ground-layer de-rotators pose an alignment challenge, since the large size and weight of the GWS prevent post-installation adjustment of their location. An additional difficulty arises in setting up the various de-rotators for an observation, since some parts of the sky require clockwise motion, while others need counter-clockwise motion, and indeed other locations force motion in one direction followed by the opposite direction. Coordinating all this for an extended measurement, given the differing travel ranges and backlash issues associated with the various mechanisms is a non-trivial matter. Nevertheless, our experience in all the commissioning runs to date indicates that this situation is manageable: we have spent hours without difficulty on a single asterism configuration, and have "survived" transit near zenith (*i.e.* very high de-rotation rates) without difficulty.

There is an additional challenge for LN that is associated with rotation, however. Section 4.1 above mentions how the one-to-one correspondence between WFS subapertures and DM actuators assists us in solving the partial illumination issue. This is all well and good at a particular moment, but the fact that we use natural guide stars on an alt-azimuth telescope means that we have to track the sky with the WFS. This introduces a continuously evolving rotation between subapertures and actuators, which means a continuously evolving reconstructor (in fact, it would have been possible to not track the sky with the WFS CCD, but this would have required mechanisms within each star probe to de-rotate the pyramids, a solution deemed too risky to pursue).

Our solution to this challenge is to produce a sequence of mother interaction matrices for each degree of sky rotation by numerically rotating the calibrated IM. The latter represents the average of calibrations over a scatter of angles to reduce sampling effects. During observation, we decimate the appropriate rotated mother IM based on the current asterism (see section 4,1) and invert it to produce the reconstructor to upload. This method, too, was verified in the laboratory before on-sky demonstration. Arcidiacono et al.[4] and Santhakumari *et al.*[3] and references therein provide a complete description of the technique.

4.3 Flexure Tracking

As previous paragraphs have made clear, the spatial mapping between incoming light, wavefront sensor subapertures, and deformable mirror actuators is critical to proper adaptive optics function. This is particularly true when trying to achieve maximum performance, since the use of both higher loop gains or a larger number of (high spatial frequency) modes becomes more and more sensitive to alignment.

LINC-NIRVANA is a large (*ca.* 6 x 4 x 4.5 m) and heavy (9.8 tonnes) instrument mounted on the instrument platform of the LBT, which in turn tilts over with zenith pointing angle. Even with the best materials choices, such an instrument will flex due to a varying gravity vector. The wavefront sensors face a further challenge, since their (cooled) CCD assemblies must fit in a confined space and yet be adjustable in X-Y-Z. The CCD's of both the ground and high-layer sensors experience flexure induced motion with elevation angle.

Starting with our third commissioning run, we have been actively tracking the pupil / metapupil imagery to maintain consistent subaperture-actuator mapping. Our approach to this is twofold. After NGS acquisition, loop closure, and fine tuning, we save a WFS pupil image integrated over several seconds as the reference. For X-Y flexure, a cross correlation of the current, integrated pupil image with the reference gives the needed shift to be counteracted by the CCD stages. Motion along the Z or optical axis (*i.e.* WFS defocus) is substantially more difficult to assess. For the HWS sensor, we fit a circumscribed circle to the pupils within the reference metapupil and monitor the diameter of this circle with time. Focus shifts in one direction reduce the radius, while in the other direction, the circle grows. At the ground layer, where all pupils overlap, focal shifts in both directions will increase the diameter of the circumscribed circle, forcing a more complicated control strategy. Nevertheless, our measurements starting in the third commissioning run indicate that we can successfully track WFS CCD motion for several hours with good performance, and we continue to refine this aspect of instrument control.

5. THE FUTURE

With four runs complete, we are approximately halfway through commissioning, in terms of both allocated nights and tasks accomplished. Many tests have taken less time than expected, but we have also "discovered" some new aspects that require attention. The remaining commissioning runs in 2018 will focus on improving observing efficiency and working with fainter reference stars. So far, our MCAO work has been exclusively on the left "eye" of LBT, due to a planned replacement of the adaptive secondary mirror on the right side (such replacement forces an extensive recalibration of the GWS interaction matrices). The exchange should be complete in September 2018, allowing us to finish commissioning of both sides, with the goal of using the two primary mirrors simultaneously for incoherent imaging.

If all proceeds as planned, we will also begin our Early Science program in the first half of 2019. This program consists of six individual observing projects which demonstrate the capabilities of LN and can produce an impactful science result in one or two nights on sky. These observations will be interleaved with the remainder of commissioning, which should be complete by the end of 2019.

In the longer term, we have submitted proposals to build a wider-field science camera with sampling appropriate to MCAO rather than interferometry. Ideally, this would involve exchanging the cryostat and thus preserve our option to develop Fizeau mode interferometric imaging.

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