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MCAO with LINC-NIRVANA at LBT: Preparing for First Light

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ABSTRACT

LINC-NIRVANA is an innovative, high-resolution, near-infrared imager for the Large Binocular Telescope. Its Mult-Conjugate Adaptive Optics system uses natural guide-stars and the layer-oriented, multiple-field of view approach for high sky coverage and eventual interferometric beam combination. We describe LINC-NIRVANA's particular flavour of MCAO and its associated challenges, and report on final lab integration and system level testing. LINC-NIRVANA is currently at the telescope undergoing final alignment and tests before First Light late this fall.

Keywords: near-infrared, imaging, multi-conjugate, adaptive optics, interferometry, Fizeau, LBT

1. INTRODUCTION

After more than a decade of design, development, and testing, the LINC-NIRVANA instrument (LN) is finally at the Large Binocular Telescope (LBT) in Arizona, where it is currently undergoing final testing and calibration prior to installation in September 2016. Since our last SPIE report (Herbst *et al.* 2014), the team has made enormous progress, completing integration and instrument-level testing in Heidelberg, disassembly and packing, shipping to Mt. Graham, and re-integration and verification in the mountain lab. In this paper, we provide a description of the particular flavour of Mult-Conjugate Adaptive Optics (MCAO) that LN exploits to provide panoramic, diffraction-limited imagery, and we report on laboratory testing activities in Heidelberg and at the LBT.

2. LINC-NIRVANA'S FLAVOUR OF MCAO

2.1 Multi Versus Single-Conjugate Adaptive Optics

Multi-Conjugate Adaptive Optics (MCAO) seeks to overcome the shortcomings of conventional adaptive optics (AO) through the use of multiple reference beacons and two or more deformable mirrors (DM) conjugated to different altitudes. Specifically, traditional, single-conjugate AO suffers from *anisoplanatism*, a loss in correction performance which increases with the angular distance to the reference beacon, due to the fact that the column of turbulence sampled by the science target diverges from that sampled by the beacon (Figure 1, left panel). With the atmosphere well approximated by a small number of distinct layers of turbulence, this effectively means that both single and multi-conjugate AO correct layers near the ground well, but only MCAO can handle the higher layers (Figure 1, right panel). The end effect of this is that MCAO can deliver a panoramic, diffraction-limited image with very uniform point spread function quality over a wide field of view. For 8-meter class telescopes and typical turbulence, this field can be 2-3 arcminutes across, compared to the 10-20 arcseconds with the single conjugate approach.

2.2 Maximizing Performance with the Optically-Combined, Layer-Oriented, Multiple Field-of-View Approach

Producing uniform, high-quality correction over such a wide field of view effectively means measuring and compensating the turbulence in the entire volume above the telescope depicted in Figure 1b. There are several ways of doing this, including the so-called *star-oriented* and *layer-oriented* approaches. Both methods employ separate deformable mirrors optically conjugated to the altitudes of strongest turbulence. In the star-oriented approach, separate wavefront sensors measure the cylindrical turbulent column to several reference "stars," (throughout this discussion, this

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can mean either natural stars or artificial stars generated by a laser). A reconstruction process known as *tomography* yields an estimate of the full turbulence volume, from which the correction signal is calculated to drive the DMs. LINC-NIRVANA uses the layer-oriented approach, in which two or more wavefront sensors focus on the turbulence within particular layers, sampling the signal from multiple stars simultaneously. While the star-oriented approach can be simpler opto-mechanically, the layer-oriented scheme offers a significant advantage: while each of the reference stars in the star-oriented approach must be bright enough to produce a useful signal, the layer-oriented approach permits *optical combination* of the individual star light. This has two benefits. First, the wavefront sensor does not pay a separate read noise penalty for each star, and second, reference stars that would not otherwise be bright enough to be useful on their own can be combined to improve the signal-to-noise ratio of the measurement. The result is the ability to use fainter natural stars and as a consequence, the correction performance and the sky coverage both increase.

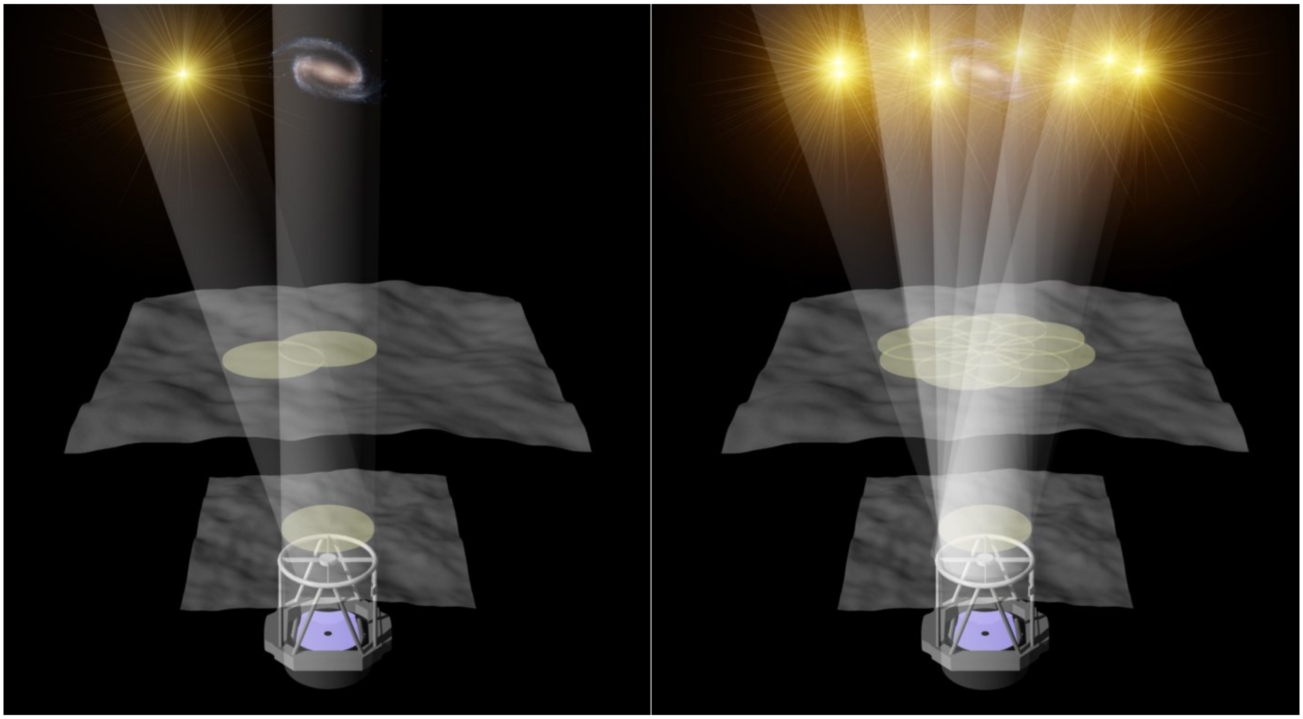

Figure 1. In conventional single-conjugate adaptive optics (left), the column of atmosphere sampled by the reference star diverges from that of the science target, an effect known as anisoplanatism. In Multi-Conjugate AO (right), multiple reference stars permit an assessment of the complete turbulence volume above the telescope.

LINC-NIRVANA exploits one further benefit of the layer-oriented approach. The right panel of Figure 1 makes clear that to sample the high layer, the reference stars must be relatively close together (in fact, within a 2’ field). For the ground layer, however, stars from the full, unvignetted field of the telescope pass through the same turbulence. This permits us to select reference stars from a considerably larger field of view (6’ at LBT) to correct the ground layer turbulence. This is the *multiple field-of-view* approach. Given the spatial and brightness distribution of natural guide stars, this means that, on average, we will have brighter references in the larger, ground-layer, field. This, too, improves both correction performance and sky coverage. Ragazzoni *et al.* (2002) provide further information on this approach.

2.3 LINC-NIRVANA Optical Path

Figure 2 illustrates the LINC-NIRVANA optical path superimposed on an image of the instrument during testing (the figure depicts one side of LN; the other side is a mirror image). Light from the LBT tertiary mirror enters the instrument close to the telescope focus. At this location, a 45° mirror directs the light from a 2 to 6 arcminute annular region into the Ground-layer Wavefront Sensor (GWS). This device contains glass pyramids on individually movable probes, allowing us to sample up to 12 reference stars. The light from these stars is optically combined on a common pupil imager, and the correction signal drives the LBT facility 672-actuator deformable secondary mirrors.

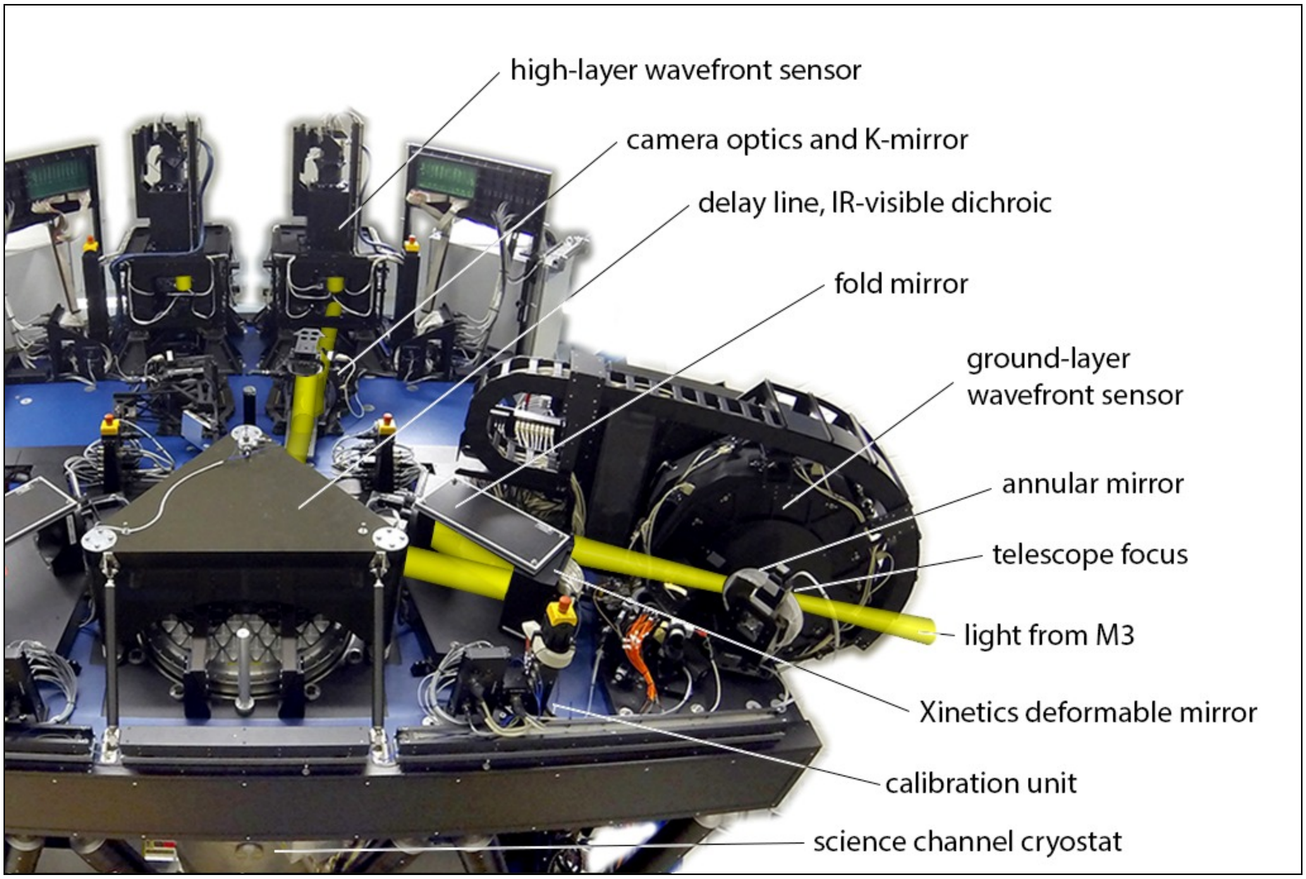

Figure 2. The LINC-NIRVANA optical path (yellow beams), showing all components between the telescope tertiary mirror M3 and the high layer wavefront sensor. Reference 2 explains the complete optical path, including the camera inside the cryostat. Note that this image portrays only one side of the instrument. The other channel is a mirror-image copy.

The central 2 arcminute field of view continues into the instrument and into the collimator optics. A pair of fold mirrors, one of which is a Xinetics 349-actuator DM, redirects the light into the central, beam combination area. At this location, a down-folding mirror, which can also act as a delay line for interferometry, feeds the light into the science channel cryostat. Just before entering the cryostat, a visible-NIR dichroic intercepts light from 600-1050 nm and directs it through camera optics and a K-mirror de-rotator and eventually into the High-layer Wavefront Sensor (HWS). This sensor operates similarly to the GWS, with 8 pyramid probes exploring the central 2 arcminute field, and delivering its correction signal to the Xinetics DM upstream. The HWS has a companion Patrol Camera to assist in guide star acquisition.

Note that the ground-layer and high-layer correction are purely sequential. In other words, we apply the ground-layer correction to the wavefront before attempting to measure the high layer. This simplifies the loop control enormously and is another advantage of the layer-oriented approach.

The science channel cryostat contains a cryogenic reflective camera, which images the corrected focal plane onto a near-infrared Hawaii-2 detector. A motorized wheel provides up to 22 separate filter slots for broad and narrow-band science, as well as a pupil imager for diagnostic purposes. The cryostat also hosts a Fringe and Flexure Tracker System, which uses a reference star to null the optical path difference in interferometry. It also allows continuous monitoring of system flexure.

3. MCAO CHALLENGES

Operating an MCAO system in this way brings with it numerous challenges. Among these is the fact that both the brightness and configuration of the guide stars are not fixed. This has implications on how to set up the wavefront reconstruction software, and it unquestionably influences the quality of the image correction.

3.1 Partial Illumination

A brief examination of Figure 1 should make it clear why this is so. For the ground-layer, the situation is relatively simple, since the footprints of all the reference stars overlap perfectly. Under these conditions, we can simply optically combine the light, derive the wavefront, and apply the correction to the adaptive secondary mirror. On the high layer, however, the footprints decorrelate, and there may be regions of turbulence for which we have only a faint reference star or perhaps no star at all. We have developed and are refining procedures to deal with such "partial illumination" situations and ensure stable operation.

In standard adaptive optics, the slope measurements across the pupil are translated into modes by the reconstructor, which produces modal coefficients to be passed on to the injection matrix for conversion into actuator commands. Depending on the particular asterism, however, some or perhaps many of the slope measurements will be noisy or absent. Our standard procedure for dealing with this is to add together several hundred individual frames from the HWS, and, using a threshold criterion, create a mask to remove the relevant columns in the interaction matrix. Inverting this matrix yields a new, asterism-appropriate reconstructor. This basic approach works, but there are several subtleties and refinements.

Figure 3 shows the Karhunen-Loève basis set derived from the DM actuator geometry and an assumed Kolmogorov power spectrum of atmospheric turbulence. With careful alignment of the CCD and partial illumination masks, we can correct in excess of 200 modes with only four reference stars covering only 2/3 of the high layer (the Xinetics DM has 349 actuators). Complete details appear in Santhakumari *et al.* in this conference.

3.2 Automatic Gain Control

Based on our recent experiments, it is clear that correction stability in the instance of partial illumination is sensitive to loop gain (as indeed it is in all types of adaptive optics). In order to speed the optimization process, we have developed an automatic gain optimization utility, based on standard fitting procedures. The software divides the modal gains into three categories with three separate gain values. Typically, we assign one gain to tip and tilt, a second gain to modes 3-50, and a third gain value for higher order modes. The optimizer begins with reasonable guesses for the three gains and then steps through them one-by-one, applying a classic grid search fitter to derive the optimal value and step size at each iteration. The merit function is simply the RMS value of the residual wavefront slopes. Using synthetic turbulence in the laboratory, this routine can determine optimized gains in a few minutes. We are also looking at ways to monitor and adjust the gains during observations.

3.3 Synthetic Injection Matrix

The normal procedure for generating the injection matrix is to "poke" individual actuators on the deformable mirror, measure the influence function, and then use its inverse in concert with wavefront input to apply modes to the DM, measuring the wavefront with an imaging interferometer. The geometry of the LN light path makes this difficult after optical component integration. We therefore generate a synthetic injection matrix, based purely on manufacturer's specifications. We then excise the "blind" subapertures and slave the corresponding actuators to their nearest illuminated neighbours.

4. LABORATORY TESTING

LINC-NIRVANA is a consortium instrument, with four major partners supplying sub-systems and systems. Assembly and integration took place in a hierarchical manner – sub-system to system to instrument – in the laboratories of the MPIA in Heidelberg. Testing of the MCAO system could only begin once all the components were in place and aligned in our large integration hall. Having a binocular/interferometric instrument proved advantageous, as we were able to begin "dark work" on one half of the instrument while the other half was being aligned and tested (Figure 4).

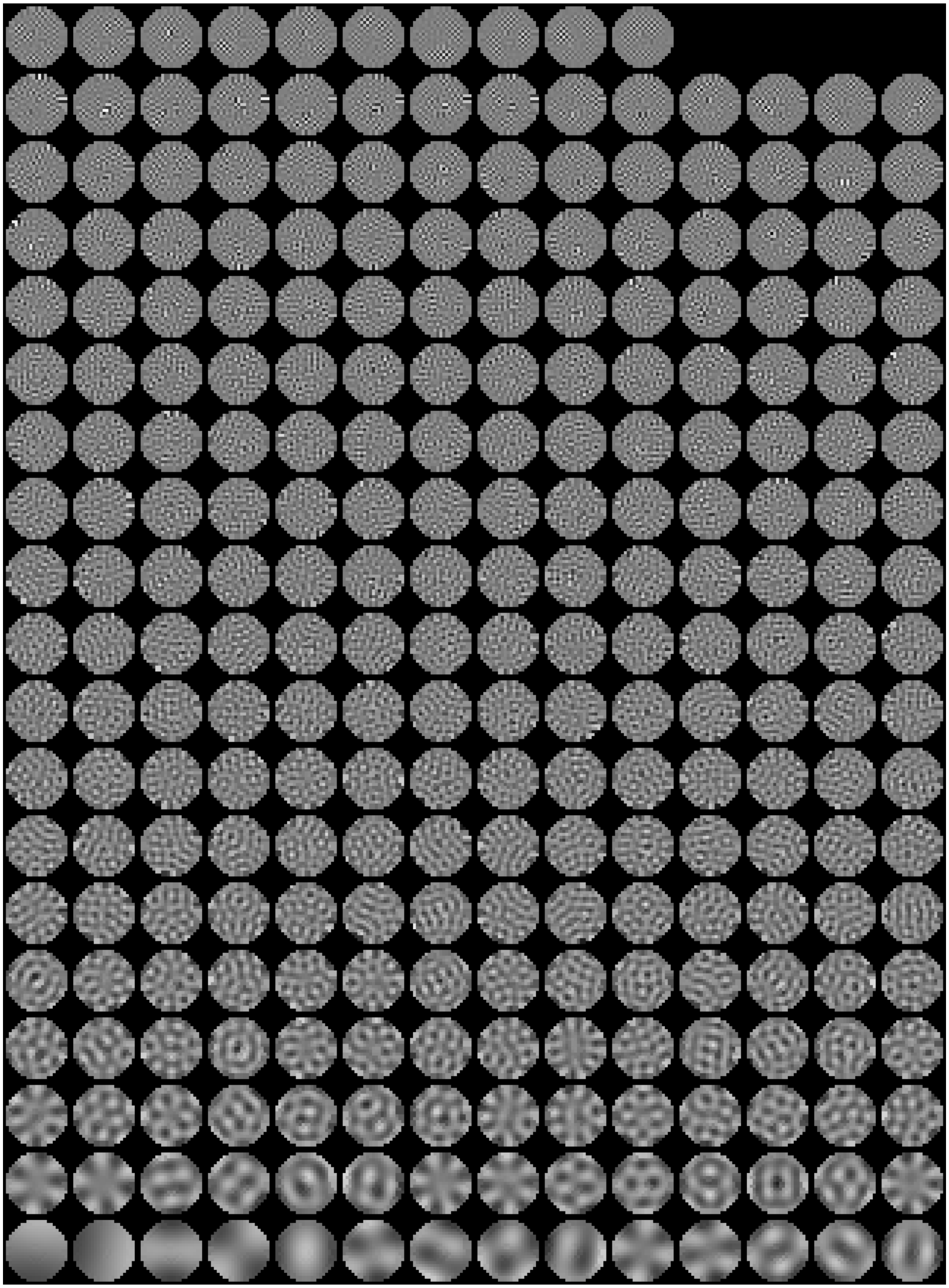

Figure 3. The 262-mode Karhunen-Loève basis set calculated from the actuator geometry of the Xinetics 349-actuator deformable mirror operating under the assumption of Kolmogorov atmospheric statistics. With this basis, we can correct more than 200 modes. The metapupil underfills the DM somewhat, and we slave actuators at the periphery. These data were generated in June 2016 in the mountain lab at LBT.

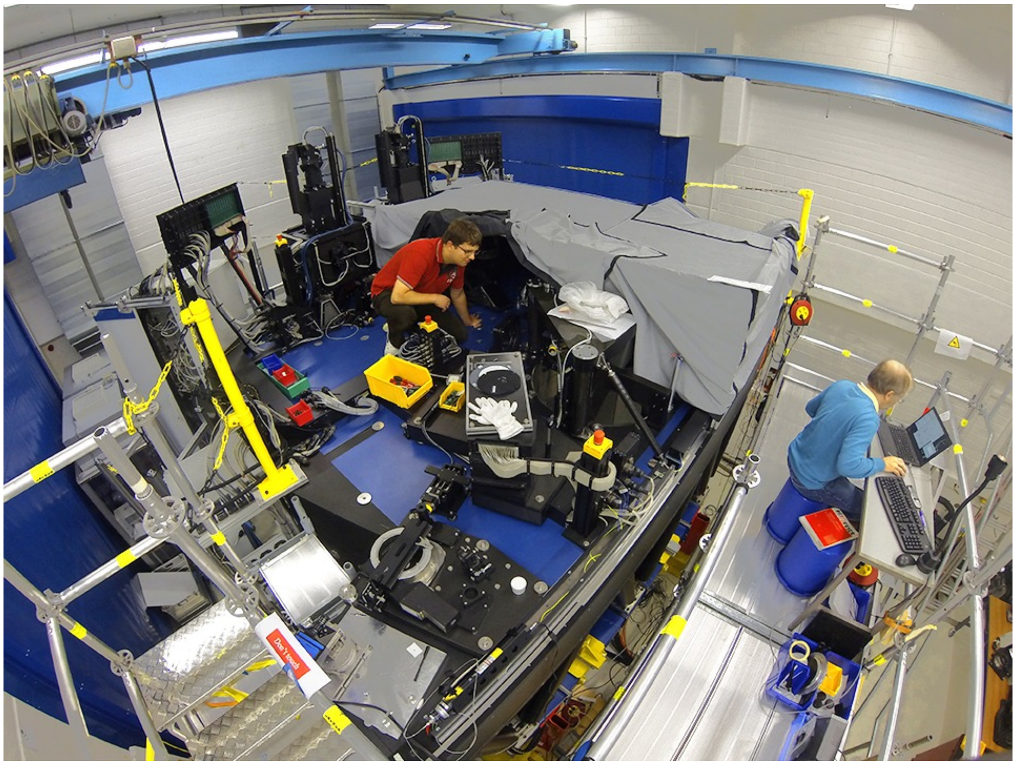

Figure 4. Final laboratory testing in Heidelberg. Note how one arm of the instrument can be tested under dark conditions while the other arm undergoes integration and alignment. All of this activity takes place on the optical bench and scaffolding approximately 2.5 meters above the laboratory floor.

Actually, Figure 4 shows work on the high-layer loop only: the adaptive secondary mirrors of LBT provide the ground-layer correction, and these were obviously not available in the Heidelberg lab. To address this situation, we initiated the Pathfinder project several years ago, with the goal of bringing one of the ground-layer sensors, as well as our electronics and software infrastructure, to the LBT for testing. We achieved First Light with Pathfinder in November 2013, and despite horrible luck with the weather, we managed to complete all of our baseline verification goals over the subsequent 15 months. We removed Pathfinder from the telescope in summer 2015 to make way for the full instrument and to perform some retrofitting of GWS hardware, based on our on-sky experience (the other GWS was similarly upgraded in in Padova and Heidelberg).

With the Pathfinder experiment concluded, we were able to concentrate on the high-layer loop in the integration hall at MPIA during winter 2014-2015. Unfortunately, the complex logistics of disassembly, packing, and shipping curtailed our European lab testing somewhat, and we were forced to head to the observatory with a couple of remaining issues. The LBT has a large, clean-room laboratory, however, and we have been able to make up for lost lab time with both remote and on-site testing. For example, Figure 3 comes from a mountain campaign approximately two weeks before this conference.

5. CONCLUSION

The long and complex development of LINC-NIRVANA has drawn to a close, and we are about to embark on the next step: getting the instrument to work on the telescope. As mentioned above, final installation will take place in September 2016, with an alignment "pre-commissioning" run scheduled two months later. Commissioning begins in the first two months of 2017, and our goal is to begin the Early Science program before the summer shutdown next year. Reference 5 contains a complete description of our upcoming activities.

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