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Installation and Commissioning of the LINC-NIRVANA Near-Infrared MCAO Imager on LBT

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ABSTRACT

This paper reports on the installation and initial commissioning of LINC-NIRVANA (LN), an innovative high resolution, near-infrared imager for the Large Binocular Telescope (LBT). We present the delicate and difficult installation procedure, the culmination of a re-integration campaign that was in full swing at the last SPIE meeting. We also provide an update on the ongoing commissioning campaigns, including our recent achievement of First Light. Finally, we discuss lessons learned from the shipment and installation of a large complex instrument.

Keywords: Near-infrared imager, adaptive optics, MCAO, LBT, Commissioning

1. INTRODUCTION

LINC-NIRVANA (LN) is a high-resolution, near-infrared imager operating in the JHK photometric bands on the Large Binocular Telescope (LBT). LN uses sophisticated, two-layer Multi-Conjugate Adaptive Optics (MCAO) 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 our 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 the delicate and complex installation procedure, our early commissioning results (including First Light), and lessons learned from shipment, re-integration, and installation.

2. THE "BIG LIFT" – INSTALLATION ON LBT

LN arrived at LBT in late October of 2015 after a seven-week journey of almost 17,000 km from the MPIA in Heidelberg to the summit of Mt. Graham. The shipment required some expensive custom logistics (see Section 4.1 below) but was very successful: of the 37 tonnes of cargo distributed across ten containers, only a single part was broken due to improper fixation in the packing box.

During the period November 2015 through June 2016, the LN team made a total of eight visits to the observatory to re-integrate the instrument in the mountain lab. At the end of this period (in fact, just a few days before the previous SPIE conference), LINC-NIRVANA was re-integrated and aligned and ready to go on the telescope.

Sustained poor weather (the "monsoon") forces closure of the observatory between early July and the end of August. The LBT takes advantage of this time to perform major construction and maintenance projects, such as re-aluminization of the

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primary mirrors. These activities are incompatible with installation of an instrument such as LN, so the team had to wait until September 2016 to do the "Big Lift."

The journey from the mountain lab to the installation location on the telescope involves five distinct phases, each of which brings their own challenges (see Figure 1):

1. Lab roll-out and lifting traverse installation
2. Transit from the high bay into the rotating enclosure
3. Coordinated telescope install and traverse removal
4. Fine positioning of LN with a laser tracker
5. Dust cover installation

Roll-out from the lab is relatively straightforward, since the custom wheels on which LN rides allow easy maneuvering without mechanical assistance (see Section 4.2 below). Installing the custom lifting traverse is considerably more complicated, however. This device is large (ca. 4.8 x 3.8 x 5.0 m) and heavy (3.3 tonnes), and must be assembled beforehand. It also fits quite closely to LINC-NIRVANA, and thus requires extra care during the mating process.

The transit from the fixed environment of the high bay to the rotating enclosure is perhaps the highest risk phase of the entire operation. At its narrowest, clearance between the instrument and the walls of the enclosure is approximately 11mm on each of two sides. This means very carefully balancing of the tall load to hang exactly vertically, and ensuring that no swinging is induced by either the crane operator or wind shake of the rotating enclosure to which the crane is mounted.

Once inside the rotating enclosure, LN faces further obstacles on the road to its final destination. The instrument is too large to fly over the centerline of the telescope, and there is a very sensible ban on craning objects over the exposed primary mirrors. As a result, the LN and LBT teams developed a choreographed "dance," in which the LBT tips to horizon and LN moves slowly over the midline as the telescope returns to zenith. The instrument can then be lowered into place at the rear of the shared instrument platform. Once LINC-NIRVANA is secured in place, the lifting traverse can be (carefully) removed and set aside before returning through the hatch to the high bay.

For interferometric operation, LN depends on a threefold hierarchy of centering: 1. mechanical bolting to an accuracy of approximately 1mm; 2. motion of the bulk optics of the telescope to a centering accuracy of $<50\ \mu$m; 3. optical path difference removal with an internal delay line with a stroke of $150\ \mu$m. For step 1, the teams used fine-positioning screws to shift the optical bench to the midline of the telescope before bolting it in place. To achieve the needed accuracy, they mounted laser tracker targets on LN and dialed it into the telescope metrology network.

The final step in the operation is installation of the dust cover and Upper Instrument Access Platform. The latter is a steel balcony, affectionately known as the "roof garden," which allows access to the interior of the instrument. The cover is also large, and hence requires its own "dance," although the reduced vertical dimension compared to the optical bench means that the telescope does not have to travel all the way to horizon to begin.

The complex installation procedure required two full days. While the telescope was in principle usable during the intervening nighttime, the observatory elected to not schedule science time. This provided contingency in the case of difficulties and avoided exposure of LN's internal optics to the open sky.

3. COMMISSIONING PROGRESS AND FIRST LIGHT

LINC-NIRVANA commissioning began in earnest in March 2017. Prior to that date, we undertook a pair of pre-commissioning runs that focused on alignment of the bulk optics of the telescope to the instrument and calibration of the ground-layer wavefront sensors with the facility adaptive secondary mirrors. We also had a couple of hours on-sky to propagate light through the instrument for the first time (see Herbst *et al.,* 2018[2]).

During the first commissioning run, which focused on the Ground-layer Wavefront Sensors (GWS), we succeeded in closing the ground-layer loop on five natural guide stars, reducing the seeing FWHM from 0.89 to 0.43 arcsec in the K' band. The second run took place in June 2017 and saw the successful and stable closing of both ground and high-layer loops, albeit with only a few (5-7) modes for the latter. Urgent LBT facility work forced the postponement of the Com-3 run from Fall 2017 to January 2018. This run was short (2.5 nights) and unfortunately plagued with poor seeing, but we did manage to improve performance in a variety of ways (see Herbst *et al.,* 2018[2] for details).

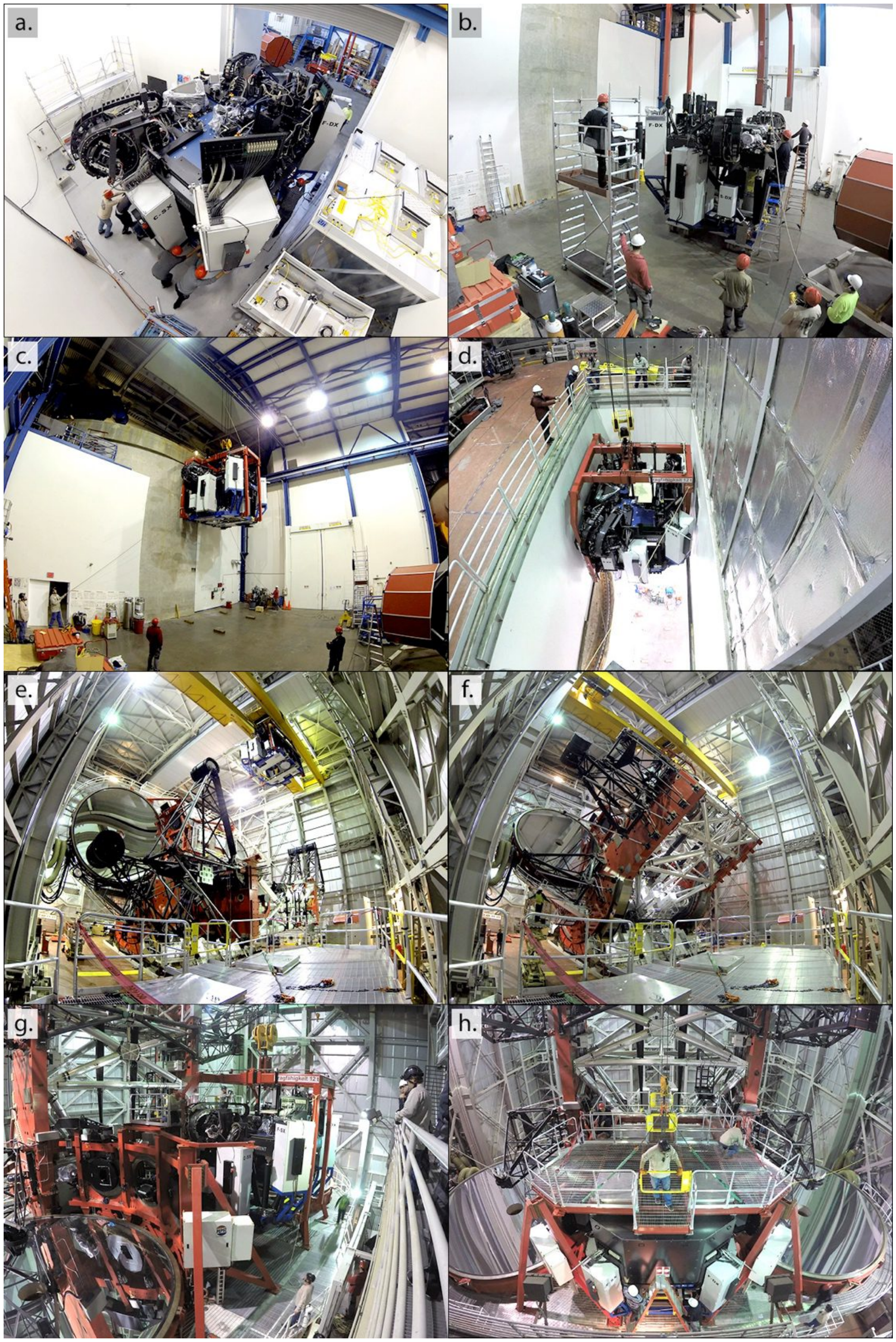

Figure 1. Final installation of LINC-NIRVANA on the LBT. The team pushes the instrument out of the mountain lab (panel a) and into the high bay, where the bridge crane assists in installing the lifting traverse (panel b). Flying the instrument from the high bay into the enclosure is an interesting challenge, since the clearance between instrument and building is only about 11mm (panels c and d). A well-choreographed "dance" with the telescope (panels e and f) allows LINC-NIRVANA to travel to the rear of the enclosure to its final mounting location (panel g). A similar dance brings the dust cover and "roof garden" into place (panel h). The entire operation took two full days.

The major breakthrough came in Com-4, which took place in March 2018. The favourable combination of good weather conditions and newly-tested algorithms for actively maintaining internal alignment meant that we could stably close the ground layer loop with 40 modes on four reference stars and the high layer loop with 30 modes on five. Figure 2 shows the result.

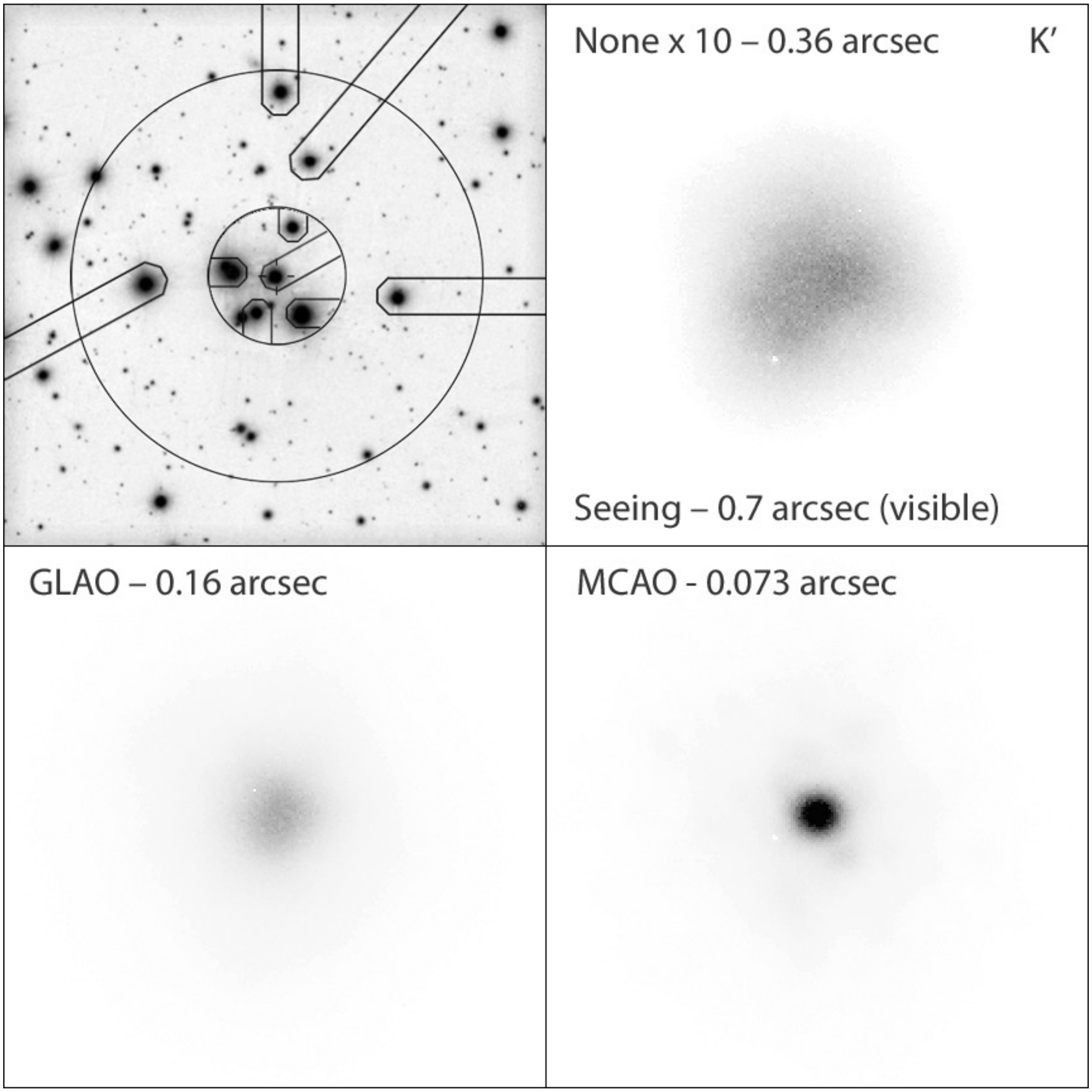

Figure 2. First Light for LINC-NIRVANA. The upper left panel shows schematically the four ground-layer (outer annulus) and five high-layer (inner circle) star probes in place. Without any correction, the K' PSF's display a full-width at half maximum (FWHM) of 0.36 arcsec in 0.7 arcsec visible seeing (upper right – note that the grayscales of this panel have been stretched by a factor of 10 for clarity). Ground layer correction reduces the PSF to 0.16 arcsec (lower left), while full MCAO produces an image with FWHM of 73mas (lower right), close to the diffraction-limited value of 57mas. The measured Strehl ratio of this image is 25%.

Well in advance of this milestone, we had set a strict criterion for First Light (the various sub-systems had all seen light and been used individually beforehand): LINC-NIRVANA must operate with both ground and high-layer loops closed and stable, and it must deliver corrected imagery of a quality expected from a well-functioning MCAO system. The frames taken on 3 April fulfilled these requirements and, on that date, we declared formal First Light.

4. LESSONS LEARNED FROM SHIPMENT, RE-INTEGRATION, AND INSTALLATION

The Assembly, Integration, and Verification (AIV) phase of LINC-NIRVANA represented the culmination of more than a decade of work designing, building and testing the individual sub-systems. With LN, AIV had to be conducted twice: once in the cleanroom assembly hall at MPIA in Heidelberg, and then again after shipment in the mountain lab. This section reports on lessons learned from the shipment and re-integration of LN, with the goal of highlighting issues that will face future large instruments, such as those for the ELT's. Note that each of the lessons below are inter-related.

4.1 Shipping Challenges

We reported briefly on the instrument shipment at the last SPIE conference (Herbst et al. 2016[1]). Here, we reflect on various difficult choices that will confront instrument teams attempting to transport their hardware across the globe.

LINC-NIRVANA's shipment consisted of a single custom crate housing the assembled optical bench and nine standard 20-foot shipping containers, one of which was the "tall-cube" version. The table below provides further details. The custom crate left MPIA in mid-September 2015, traveling by truck to a local sand and rock company that had a large dock on the Neckar river. After being loaded onto a barge with a mobile crane, the LN optical bench traveled to Bremerhaven, where it was trans-shipped onto an automobile transporter for its journey through the Panama Canal to Port Hueneme in California. From there, trucks transported the crate to the Mt. Graham base camp and then on to the summit. The whole journey took approximately five weeks. The nine shipping containers left Heidelberg a couple of days later and took an entirely conventional route to the telescope, arriving at approximately the same time.

	Custom Shipping Box for Optical Bench	Shipping containers for remainder
Container Type	Custom Crate 5.5 x 4.5 x 4.1 m ; 99 m^3	9 Standard 20' shipping containers,* 8 regular + 1 "high-cube"
Road Vehicle	Adjustable-height "low-boy" trucks	Standard trucks
Ship	Automobile transporter	Standard container ship
Weight	11 tonnes	26 tonnes
Fraction of total Shipping cost	50%	50%

*We could not use 40-foot containers, due to the narrow switchbacks on the summit road

The choice of a custom crate was not straightforward. On the one hand, it allowed us to ship the instrument almost fully cabled, and thus spared considerable reintegration time on the mountain. On the other hand, the custom crate required special transport, since it did not fit on standard trucks and indeed required careful route planning for the land portions of its journey, in order to avoid bridges, narrow streets, and so on. It was also somewhat distressing that the cost of this custom part of the shipment amounted to roughly 50% of the total, despite the fact that it corresponded to only one of our ten containers and less than 1/3 of the total weight. Nevertheless, in retrospect, we would do it the same way again. Large, complex instruments face considerable challenges once they arrive at the telescope. Avoiding the nightmare of re-assembling the optical bench, and more critically, re-cabling the instrument (see "Complexity" below), is worth a great deal of additional logistics and expense.

4.2 Instrument Size, Weight, and Volume

Large instruments require a great deal of space for layout and re-assembly, and this space is inevitably at a premium at the observatory. It is not enough to merely set aside the footprint of the instrument and a little extra for contingency. For example, cryostats typically consist of two or more sections of vacuum vessel, radiation shields, and internal opto-mechanics. Re-integration of such a cryostat can easily require triple the notional space and volume.

In the case of LINC-NIRVANA, we also had to carefully plan the route from shipping crate to mountain lab to telescope. This meant maneuvering LN around corners, but there was simply not enough space to steer. Also, the weight of the instrument required spreading of the moving load to prevent damage to the resin flooring in the lab. As a result, we designed large, custom, wheels that allowed us to jack up one corner of LINC-NIRVANA at a time, rotate the wheels 90°, and then gently lower the instrument onto the floor again. This provided us with essentially zero turning radius and a smooth enough ride that LN could be maneuvered by hand (Figure 3).

Figure 3. Dealing with instrument size and weight. At almost 10 metric tonnes, LN is no light-weight, but a set of custom wheels permits handling with no motorized aid (left panel). Jacking up the corners of the instrument one at a time and rotating the assemblies 90° lets LN go around corners with zero turning radius (right panels).

4.3 Handling Equipment

Large instruments will fill even the largest labs, and they also tend to have large subsystems. Transporting and lifting these subsystems into place thus involves manipulating large, delicate loads in very restricted spaces. We designed and built literally dozens of custom handling fixtures during the LINC-NIRVANA project.

The handling rigs for our Ground-layer Wavefront Sensors provide an instructive example. Each of the two GWS weighs approximately 700 kg and contains about forty sensitive, aligned optical elements, in addition to motors and linear stages (roughly two dozen of each). The sensors had to be raised from a narrow workspace on the floor adjacent to the bench before being rotated and lowered into position. The final bolt location was outside of the footprint of the overhead crane, however. As a result, we designed and built custom handling equipment with counterweights that allowed us to execute this maneuver (Figure 4).

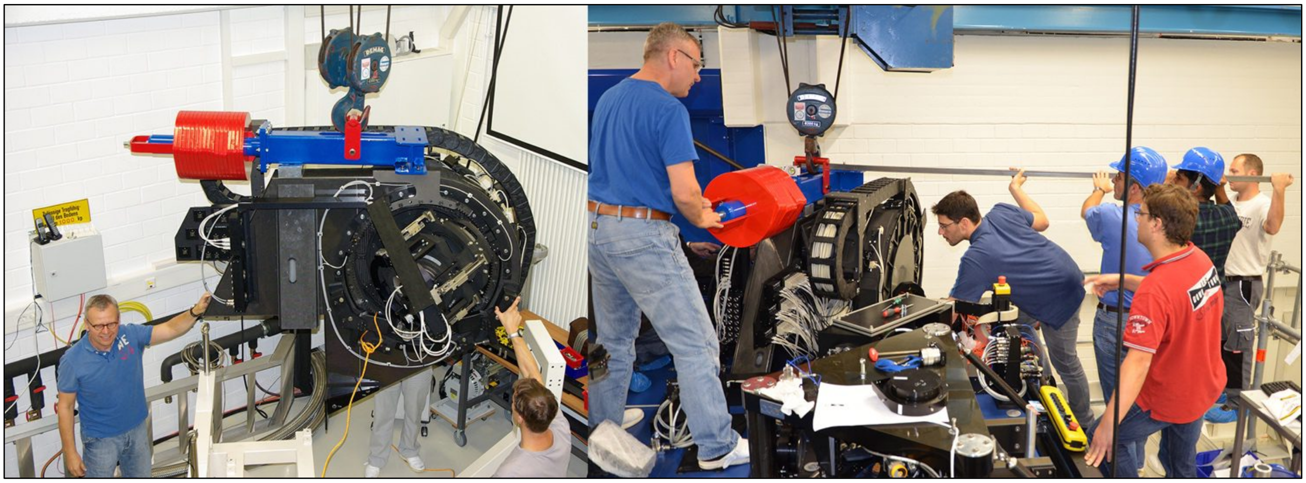

Figure 4. Special handling equipment. In the left panel, one of the two ground-layer wavefront sensors is being lifted off its transport cart (white structure at bottom, and itself a special piece of handling equipment). The blue structure is a custom traverse with adjustable counter-weights (red) to allow the GWS to swing into position outside of the footprint of the overhead crane (right panel). Note also that the crane must operate very close to its vertical limit in order to place the GWS on the top of the optical bench, which is approximately 3.4m above the laboratory floor.

4.4 Complexity

Perhaps the greatest challenge in successfully operating an instrument such as LINC-NIRVANA lies in managing complexity, and this challenge extends to the shipping and re-integration phase as well. The chart below attempts to summarize the ingredients that make up LN and breaks down just one of those ingredients into its component parts. Experienced instrument builders will recognize the potential for trouble that comes with almost a thousand cables, and as a consequence, more than two thousand connectors – at the observatory, it is always connectors that cause problems.

LINC-NIRVANA Ingredients

- 4 wavefront sensors
- 4 deformable mirrors (2042 actuators total)
- 8 science-grade detector systems (6 visible, 2 infrared)
- 250+ optical elements, many with active control
- 2 calibration units with selectable sources
- science channel cryostat with remote cooling
- stiff mechanical support for subsystems
- electronics and cabling →

Electronics and Cabling

- 7 electronics cabinets – 6 onboard + 1 for AIV
- 53 invidual 19-inch modules
- active air and water-glycol cooling
- 134 motors
- 67 separate network ports
- 988 separate cables
- 2000+ connectors

To confront this, the team decided more than a year before shipment that we would not try to re-cable the instrument at the mountain. Instead, we built up the electronics infrastructure, including all the cabinets and internal modules, in the lab at Heidelberg and shipped the instrument with everything tested and in place. Note that the complex routing often called for custom-length cables that were manufactured in-situ during layout. While this strategy resulted in a working instrument "out of the box" after shipment, it did have additional logistical and cost penalties (see "Shipping Challenges" above).

4.5 Choreography

Maneuvering large, sensitive instruments in confined spaces requires not only special tools (see above), but also careful planning. The high bay at LBT is approximately 25 meters square and 10 meters high, yet the LN shipment more than filled it, even with two-thirds of our shipping containers stored at base camp (Figure 5). Executing seemingly simple operations, such as lifting the optical bench off the pallet that formed the bottom of its shipping crate, required careful choreography and the better part of a working day. And with room for only four of our nine standard shipping containers in the high bay, this choreography extended backward in time to the packing stage in Heidelberg. Each container had to hold the exact and complete components needed for a particular phase of re-integration, after which the container would return to base camp to make room for another. There are unquestionably lessons to be learned here for the ELT's, which will have even larger instruments, but as far as we can tell, layout and integration facilities that are comparable in size or even smaller than that at LBT.

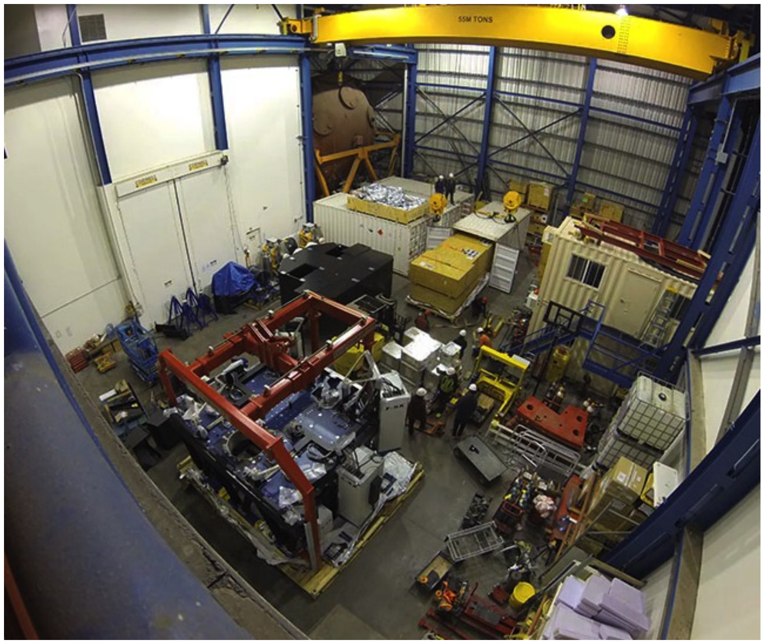

Figure 5. Wide-angle view of the LBT high bay (dimensions 25x25x10m) during unpacking of LINC-NIRVANA. The optical bench sits on its pallet at lower left. LN shipping containers, the instrument cover, and other critical components fill the available space, forcing careful choreography.

5. THE FUTURE

We are approximately halfway through commissioning, in terms of both allocated nights and tasks accomplished. Many items have taken less time than expected, but we have also "discovered" some new aspects that require attention. The focus in upcoming commissioning runs will be on improving observing efficiency and working with fainter reference stars. The planned replacement of the DX (right telescope) adaptive secondary mirror in August 2018 has delayed our work on that side, but we anticipate that our experience with the SX (left) telescope will mean more rapid commissioning.

If all proceeds as planned, we will 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.

LINC-NIRVANA's more distant future is contingent on resources and funding. An obvious first step is to replace the fine sampling of the current science camera with one more appropriate to MCAO. Ideally, this would be done with a completely separate cryostat, preserving the option to pursue interferometry.

Further information on LINC-NIRVANA appears at mpia.org/LINC. Arcidiacono et al.[3] and Santhakumari *et al.*[4] at this conference, discuss calibration procedures and MCAO challenges, respectively

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