Novel AO on the Pathway to ELTs: MCAO with LINC-NIRVANA on LBT…Lessons Foreseen?

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Abstract. LINC-NIRVANA is a near infrared interferometric imager that will achieve ELT-like spatial resolution for panoramic imagery on the Large Binocular Telescope (LBT). The LBT is a unique platform since its two, co-mounted 8.4-meter primary mirrors, coupled with fully adaptive secondary mirrors, present a time and view-direction independent entrance pupil. This allows Fizeau-mode beam combination, giving 23-meter equivalent spatial resolution and the collecting area of a 12-m telescope. In order to achieve diffraction limited image quality and maximum sky coverage, in particular for finding fringe-tracking reference stars, LINC-NIRVANA employs unique multi-conjugate adaptive optics (MCAO). The NIRVANA system comprises a total of five control loops for atmospheric turbulence: sequential ground and high-layer NGS AO correction for each telescope, coupled together through a common delay line to remove differential atmospheric piston and vibration. The MCAO operates in layer-oriented, multiple field-of-view mode with up to 12 ground-layer and 8 high-layer natural stars per telescope. LINC-NIRVANA is a pathfinder for ELT instrumentation and AO systems in more ways than merely spatial resolution: in terms of physical size, complexity, alignment tolerances, and integration challenges, LINC-NIRVANA serves as an instructive precursor for future efforts. In this paper, we provide an update on the integration and testing of the instrument, and attempt to foresee and forestall future lessons learned.

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1. Introduction

LINC-NIRVANA (LN) is a Fizeau-mode interferometric imager for the Large Binocular Telescope (LBT). Operating in the near-infrared J-H-K photometric bands, LN will produce two-dimensional, panoramic imagery with the spatial resolution of a 23-meter telescope over a field of view approximately 10-arcseconds square. This corresponds to 10-milliarcseconds at the shortest operating wavelength, a resolution comparable to state-of-the-art observing facilities over a broad range in wavelength (ALMA, VLBI, etc.). In addition to synergy with other telescopes, this spatial scale opens up some very exciting scientific domains. For example, 10 mas resolution will allow direct imagery of the surfaces of evolved stars, and it corresponds to AU scales in the nearest star forming regions.

To achieve this level of performance, LINC-NIRVANA must maintain exquisite control over atmospheric turbulence, including not only the delivered wavefront shape, but also the differential arrival times at the two telescopes. LN does this using separate adaptive optics systems and a shared fringe tracker. Because the ultimate scientific performance of the instrument is driven by the availability of reference stars for fringe tracking, LN must deliver a very large AO corrected field: 1 x 1.5 arcmin. For this reason, LINC-NIRVANA employs multi-conjugate adaptive optics (MCAO).

Specifically, the LINC-NIRVANA MCAO is a layer-oriented, multiple field-of-view system using natural guide stars and optically-combined pyramid wavefront sensors. In the context of LN, these terms have the following meanings and specifics:

layer-oriented	The system contains one optical sensor per atmospheric layer, not one sensor per guide star. This is closely related to the concept of optically-combined (see below)
multiple field-of-view	The fields conjugated to the two deformable mirrors are of different size. For LN, the ground-layer sensor patrols an annular region between 2 and 6 arcminute diameter, while the high-layer sensor locates stars in a 2 arcminute diameter field.
natural guide star	Only natural star beacons are used in LINC-NIRVANA. There are 12 star probes for the ground layer loop and 8 for the high layer loop.
optically-combined	Each CCD sensor accepts the light from all of its associated star probes. This has the benefit of reducing the requirement on brightness of the individual stars and hence increases sky coverage.
pyramid wavefront sensors	LINC-NIRVANA uses pyramid wavefront sensors [1]. Each of the star probes contains a local field magnifier and glass pyramid. See [2] and references therein for details.

2. LINC-NIRVANA Optical Path

Figure 1 shows a three-dimensional computer rendering of the LINC-NIRVANA warm optics. Light from the two, 8.4 meter telescopes enters the instrument and immediately strikes an annular mirror. This element is located near the telescope focus and can thus redirect part of the field – that with radius 1-3 arcminutes – into the Ground Layer Wavefront Sensors (GWS), while allowing the central 2 arcminute diameter to continue into the instrument.

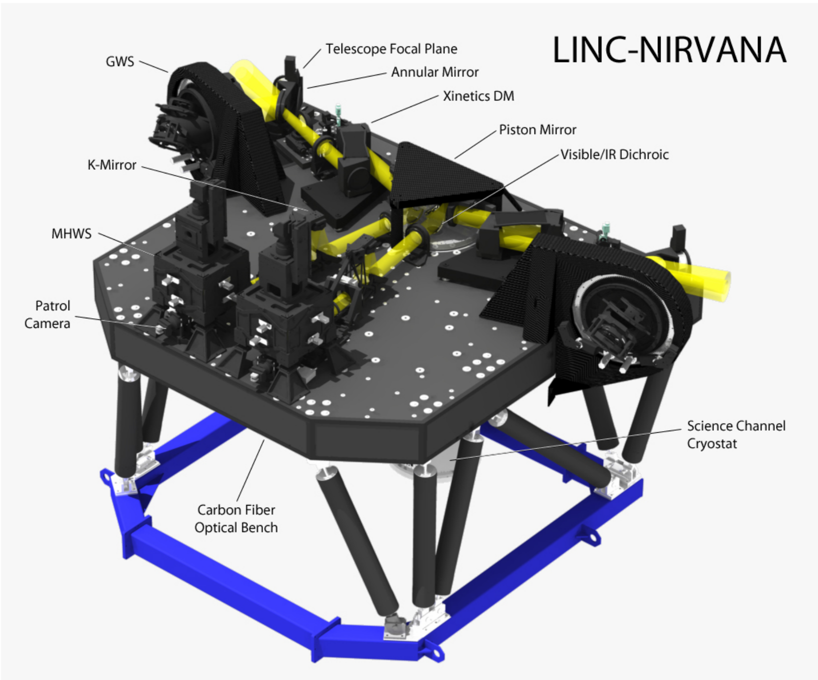

Fig. 1. The LINC-NIRVANA warm optics

Each GWS unit contains twelve “star enlargers” (SE) on motorized X-Y stages. The SE magnify the 1.2 arcsecond field of view around each natural guide star by a factor of ~12 and cause the light to fall on a shallow, four-sided glass pyramid. This pyramid then redirects aberrant wavefronts into one of four quadrants, in a manner identical to the classic Foucault knife-edge test. An f/0.9 optical system then combines the light from all the star enlargers and produces four pupil images conjugated to the ground layer on a 128x128 CCD-50 detector.

Exactly as with a simple quad cell, the pixel-by-pixel signal differences between the four pupil images gives the wavefront slopes, which are fed to the facility adaptive optics secondary mirrors. These deformable mirrors feature 672 voice coil actuators across their 90 cm diameter active surfaces. Reference [2] contains more information on the pyramid wavefront sensors, while reference [3] describes the LBT adaptive secondaries.

After passing the annular mirror, the light from the central 2 arcminutes continues into the instrument, passes through a pair of lenses, then bounces twice off flat mirrors in a symmetric "Z" configuration. This lengthens the optical path without introducing any change in beam direction. The second of these mirrors is a Xinetics 349-actuator piezo-stack deformable mirror conjugated to the "high layer" at an altitude of 7.1 km.

The light from the two telescopes then continues toward the midline of the instrument, where it passes through a third lens then is directed downward to the science channel cryostat by a pair of 45° mirrors joined as a single assembly. This critical component is the "piston mirror" or delay line, which compensates for differential arrival time of the wavefronts from the two sides. Constructed of light-weighted, diamond-turned aluminum and mounted to a high-stroke piezo-electric stage, the piston mirror can move rapidly back-and-forth along the line joining the two telescopes, shortening one optical path while simultaneously lengthening the other.

Two visible-reflecting, infrared-transmitting, dichroic mirrors mounted directly above the cryostat windows direct the shorter wavelengths parallel to the optical bench. This light passes through twin f/20 optical systems and "K-mirror" field derotators before being re-directed upward by 45° mirrors into the Mid-High Wavefront Sensors (MHWS). The upfold mirror can be exchanged with a beamsplitter, giving the two Patrol Cameras a share of the visible light for field identification and star enlarger placement.

The MHWS operate on the identical principle as the GWS. In this case, however, eight star enlargers patrol the two-arcminute field and the pupil image is conjugated to 7.1 km altitude. This results in partial overlap of the natural guide star footprints, the so-called "meta-pupils," which fall on an 80x80 pixel CCD-39 detector. The output slopes of the MHWS drive the Xinetics deformable mirror upstream on the optical bench. The two AO loops of LINC-NIRVANA are thus fully sequential and de-coupled – the high-layer DM and sensor come after the ground-layer DM and sensor in the optical path. This configuration was pioneered by the MAD experiment on VLT [4] and simplifies control enormously.

Figure 2 shows a cutaway of the science channel cryostat. The infrared light enters the dewar through a pair of windows and is focused by a relatively conventional Cassegrain two-mirror telescope. An infrared-infrared dichroic immediately above the focus reflects the selected wavelengths through a filter wheel onto the 2048x2048 Hawaii2 science detector. The remainder of the light passes through the dichroic into the Fringe and Flexure Tracker (FFTS), a device which measures the optical path difference (OPD) and applies corrections via the piston mirror. The FFTS can operate in the shadow of the IR-IR dichroic or patrol a larger elliptical field of 60x90 arcseconds.

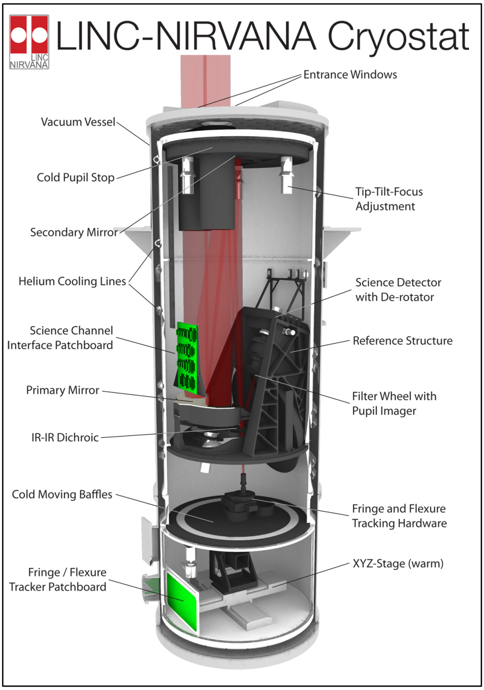

Fig. 2. Cutaway figure of the LINC-NIRVANA science channel cryostat.

3. On the Pathway to ELTs: Lessons Foreseen

In terms of size and complexity, LINC-NIRVANA is very much an ELT instrument. It thus provides a useful laboratory for identifying and solving problems before the big glass comes along. The following sections describe three "lessons foreseen" for ELT instrumentation and how we have addressed them in the context of LINC-NIRVANA.

3.1. Everything is Harder on the Mountain…

Admittedly, this is hardly a new lesson, but the increased cost and complexity of ELT instrumentation will impose serious challenges on any mountain commissioning and operation effort. Opinions vary, but most experienced instrument builders will claim that a particular task takes two to three times longer under the difficult circumstances (fatigue, altitude, temperature, etc.) of the mountain environment. With one night of ELT time valued in the hundreds of thousands of dollars, the instrument teams should attempt to identify and solve as many problems as possible in the laboratory prior to shipment.

In the case of LINC-NIRVANA, we confront the difficulty in commissioning a total of five atmospheric wavefront control loops: two ground layer, two high layer, and one piston. Testing, debugging and optimizing these loops in the laboratory has hence been a priority.

One of the great advantages of developing an interferometric instrument is that you have two (or more) copies of everything. This means that while one half of the instrument sits in the lab for alignment, software development, and optimization, the other half can be mounted on the final optical bench for flexure testing and other system-related verification.

For the MHWS, we have assembled an optical testbed containing one complete arm of the interferometer (Figure 3). This includes a two-layer turbulence simulator using rotating phase screens and a variable constellation of fiber "stars." During summer 2010, we closed the loop with 200 modes on four reference targets [5].

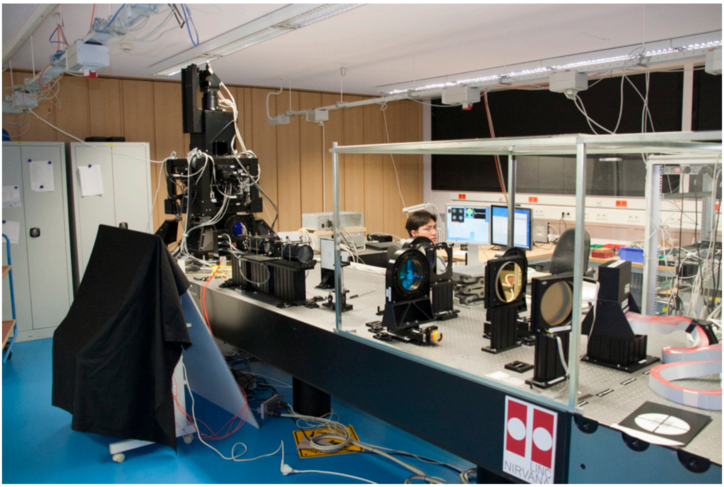

Fig. 3. Laboratory testbed for the Mid-High Wavefront Sensor.

To verify the piston control loop, we have constructed a fiber-based piston simulator with two outputs that can be plugged into the LINC-NIRVANA focal plane, including in front of the turbulence simulator [6]. The piston generator works on a woofer-tweeter basis, with piezo-electric fiber stretchers providing large, relatively slow OPD excursions, and a pair of electro-optic phase modulators for high-speed, low amplitude control (Figure 4).

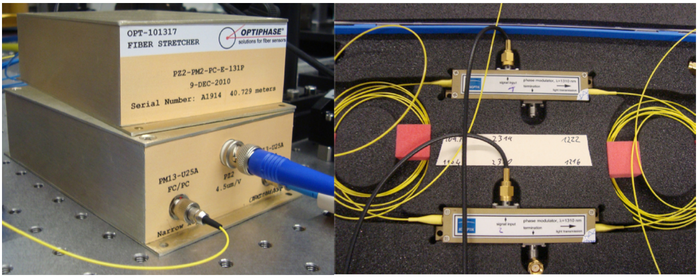

Fig. 5. Fiber stretchers (left) and electro-optical phase modulators (right) for the piston simulator.

3.2. Complexity is Your Enemy…

LINC-NIRVANA is a complex beast. In addition to the aforementioned five atmospheric control loops, the instrument contains 8 detector systems (6 visible and 2 infrared), over 250 individual lenses and mirrors (8 of them cryogenic), 4 deformable mirrors with more than 2000 actuators total, over 130 motors (10 of them cryogenic), and 40 different control systems.

Managing this complexity is central to the success of the instrument. We have adopted a “divide and conquer” approach to this situation. For example, LINC-NIRVANA has four separate implementation phases of increasing complexity:

“LINC” mode	small field interferometry with a single, on-axis reference source for both adaptive optics and fringe tracking
GWS mode	verification of ground-layer control via adaptive secondary mirror
MCAO mode	multi-conjugate AO correction of a single telescope using both GWS and MHWS
“NIRVANA” mode	full MCAO interferometry using off-axis reference stars

The implementation plan foresees significant periods of science exploitation between commissioning of the various modes.

In order to address the system complexity of operating such an instrument at LBT, we have initiated a “Pathfinder” experiment to verify telescope and AO secondary communication, wavefront sensor calibration strategies, field acquisition, rotating interaction matrix strategies, and software compatibility.

The Pathfinder experiment consists of one GWS unit, including its annular mirror, an infrared test camera, and a simple mounting “foot” interface to the telescope. This foot is the only component unique to Pathfinder; the remainder are existing hardware. The current plan anticipates shipment of the Pathfinder to LBT in late 2012, with experiments beginning in early 2013 [7].

3.3. Everything Moves…

The final foreseen lesson is that everything moves. Specifically, large telescopes and large instruments are prone to flexure, and all the fancy design and material science in the world is not going to change that.

Success with LINC-NIRVANA, and indeed with large instruments on ELTs, depends on understanding, characterizing, and where needed, compensating for this flexure. As mentioned in section 3.1, we have reaped the benefits of having dual optical systems by using one for alignment, software development, and optimization in a small lab, while the other half can be mounted on the final optical bench for flexure testing.

Figure 6 shows one such flexure test for the Mid-High Wavefront Sensor. The LINC-NIRVANA optical bench sits on a large (8x6 meter, 6 tonne) tipping stage, which can simulate telescope elevation changes from zenith to horizon. By tilting the instrument and measuring deflections with an autocollimation telescope, we are able to measure the deflection of individual components, as well as the optical system as a whole. In the case of the MHWS test pictured in Figure 6, the flexure measurements indicate modest and repeatable flexures whose effects can be removed with a software look-up table.

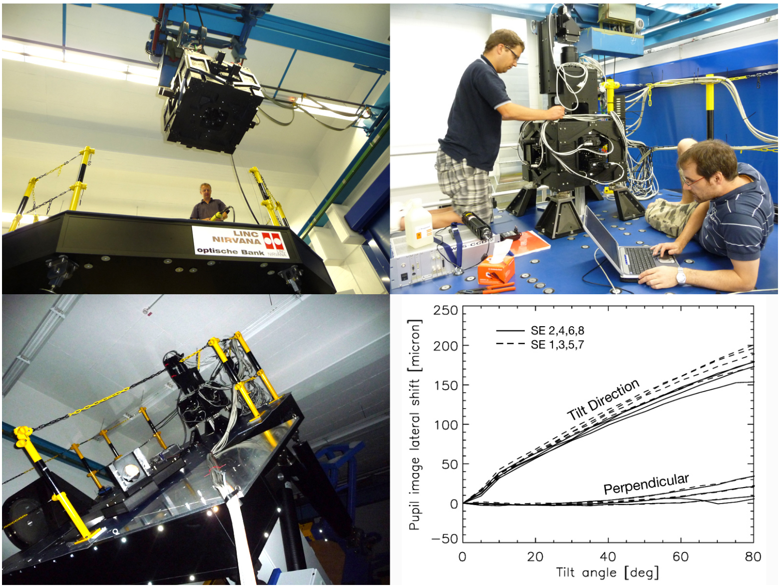

Fig. 6. Flexure testing the Mid-High Wavefront Sensor. (upper left) Hoisting the wavefront sensor into place; (upper right) installation, cabling, and testing; (lower left) tipping the optical bench to test flexure; (lower right) modest and repeatable pupil motion. The other MHWS appears in Figure 3.

4. Conclusions

LINC-NIRVANA is an ambitious project to bring the spatial resolution capabilities of ELT imaging to the current science context. It also represents an instrumentation development very much on a par with ELT efforts in terms of size and complexity.

The lessons learned – and those foreseen – with LINC-NIRVANA should help ensure that the next generation of truly giant telescopes are a success.

5. References

1. R. Ragazzoni (1996), Journal of Modern Optics **43**, 289-293.

2. J. Farinato, R. Ragazzoni, C. Arcidiacono, G. Giorgia, E. Diolaiti, I. Foppiani, M. Lombini, L. Schreiber, D. Lorenzetti, F. D'Alessio, G. Li Causi, F. Pedichini, F. Vitali, T. Herbst, M. Kürster, P. Bizenberger, F. Briegel, F. De Bonis, S. Egner, W. Gässler, L. Mohr, A. Pavlov, R.-R. Rohloff, and R. Soci (2006) SPIE 6272, 627229

3. A. Riccardi, G. Brusa, P. Salinari, S. Busoni, O. Lardiere, P. Ranfagni, D. Gallieni, R. Biasi, M. Andrighettoni, S. Miller, and P. Mantegazza, SPIE **5169**, 159-168.

4. E. Marchetti, R. Brast, B. Delabre, R. Donaldson, E. Fedrigo, C. Frank, N. Hubin, J. Kolb, J.-L. Lizon, M. Marchesi, S. Oberti, R. Reiss, J. Santos, C. Soenke, S. Tordo, A. Baruffolo, P. Bagnara, and the CAMCAO Consortium (2007), ESO Messenger, 129, 8-13

5. X. Zhang, *et al.* (2012), in prep.

6. R. Follert, T. M. Herbst, P. Bizenberger, and F. DeBonis, (2010), SPIE 7734, 77343Z.

7. A. Conrad, *et al.* (2012), this conference.