The LINC-NIRVANA Fizeau interferometric imager - final lab integration, First Light experiments and challenges

T. M. Herbst\textsuperscript{a}, R. Ragazzoni\textsuperscript{b}, A. Eckart\textsuperscript{c}, and G. Weigelt\textsuperscript{d}

\textsuperscript{a}Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
\textsuperscript{b} Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I - 35122 Padova, Italy
\textsuperscript{c} I. Physikalisches Institut, University of Cologne, Zülpicher Str. 77, 50937 Cologne, Germany
\textsuperscript{d} Max Planck Institute for Radio Astronomy, Auf dem Hügel 69, 53121 Bonn, Germany

ABSTRACT

LINC-NIRVANA (LN) is an innovative Fizeau interferometric imager for the Large Binocular Telescope (LBT). LN uses Multi-Conjugate Adaptive Optics (MCAO) for high-sky-coverage single-eye imagery and interferometric beam combination. The last two years have seen both successes and challenges. On the one hand, final integration is proceeding well in the lab. We also achieved First Light at the LBT with the Pathfinder experiment. On the other hand, funding constraints have forced a significant re-planning of the overall instrument implementation. These laboratory, observatory, and financial “events” provide lessons for builders of complex interferometric instruments on large telescopes. This paper presents our progress and plans for bringing the instrument online at the telescope.

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

1. INTRODUCTION

LINC-NIRVANA is a Fizeau-mode interferometric imager which operates at near infrared wavelengths (NIR $\sim$ 1.0-2.5 $\mu$m) on the Large Binocular Telescope. In addition to providing interferometric beam combination, LN will deliver high sky coverage, diffraction-limited, single-eye imagery, thanks to its natural guide star Multi-Conjugate Adaptive Optics. Previous papers in this conference series explain and illustrate the configuration and operating principles of the instrument. In particular, Herbst et al. 2010\footnote{herbst@mpia.de phone: (+49) 6221 528 223 fax: (+49) 6221 528 246} provide considerable detail and a bibliography of additional material. This paper reports on progress during the final laboratory integration phases and presents the results of our first light experiments at the Large Binocular Telescope. The final section lays out the modified implementation plan.

2. LABORATORY ASSEMBLY, INTEGRATION, AND VERIFICATION

The Assembly, Integration, and Verification (AIV) phase of an instrument as complex as LINC-NIRVANA requires careful planning and resource allocation. To help ensure success, we held an externally refereed review of our plans at the beginning of this phase and have spent the last two years executing the steps needed to bring the instrument to the milestone of Preliminary Acceptance Europe (PAE).

We have adopted a hierarchical approach, completing and testing sub-systems prior to system integration and testing systems prior to full instrument integration. One significant technical challenge for LN was the design, alignment, and performance verification of the science channel optics. Properly sampling the diffraction-limited field of a 23-meter effective telescope operating in the NIR requires long focal length optics and extremely high image quality, all in a cryogenic environment.

Figure 1 shows a cut-away schematic of the LN science channel opto-mechanics and a photograph of the completed cryostat in the laboratory. To produce the required sampling, the camera optics must have a focal length in excess of 11 meters and an effective input beam diameter of almost 350 mm (the shared footprint of the two 126 mm telescope input pupils). And, in order to allow sampling of a large, one-arcminute field of view for fringe tracking stars, the cryogenic camera must deliver this performance over a focal plane more than 200 mm in diameter. Clearly, a compound optical system, such as a Cassegrain telescope, is the only way to handle these dimensions while keeping the cold volume...
manageable. LINC-NIRVANA uses the off-axis portion of a single larger Cassegrain telescope. The direct focus falls onto a fringe sensor to track differences in optical path between the two arms of the instrument, while a small, exchangeable dichroic mirror directs the central 10x10 arcseconds upward to the science detector (Figure 1).

Aligning diffraction-limited optics of this dimension in vacuum cryogenic conditions is very challenging. We therefore decided to implement all-metal optics using an alloy which is compliant with the thermal expansion properties of the cryostat as a whole. This lets us align the instrument warm and achieve the required performance cold (only the tip, tilt, and piston of the secondary mirror are adjustable).

The science channel AIV comprised several sequential tests. After performance verification of the separate sides of the camera, the team demonstrated that, when illuminated by collimated light, the two channels produce high quality images which overlap. With only adjustments of the secondary mirror, this has to work correctly by construction. An initial difficulty with proper overlap was traced to a small, 5-arcsecond wedge in the cryostat entrance windows. If not properly aligned parallel to each other, these wedges can cause image decorrelation with such a long focal length camera.

After single-eye verification, the team illuminated the entrance to the science channel optics using a single mono-mode fiber placed at the focus of a large parabolic mirror suspended several meters above the cryostat windows (Figure 2). This produces a common, coherent, collimated beam, exactly like starlight at the LBT. After demonstrating high quality, visible wavelength fringes with a 632 nm laser, the team replaced the fiber with a broadband infrared source and produced fringes with more than 90% contrast (Figure 3). Bizenberger et al. 2014 provide considerably more detail on the verification testing of the science channel cryogenic optics.

Additional AIV tasks accomplished since our last report include successful alignment of the first warm optics arm of the instrument (Moreno-Ventas et al. 2014), the delivery and acceptance of the second Ground-Layer Wavefront Sensor (Radhakrishnan et al. 2014), completion and handover of the OPD and Vibration Monitoring System (Kürster et al. 2010), cold testing of the Fringe and Flexure Tracking System (FFTS - Horrobin et al. 2014), and delivery and acceptance of the FFTS detector system. Despite multiple challenges and setbacks, we remain on track for completion of AIV in early 2015.

![Figure 1. Cutaway schematic of the LINC-NIRVANA science channel cryostat (left). Laboratory warm testing of the all-metal optics (right). Two Fisba interferometers coaligned and mounted to the top of the dewar (inset) allow simultaneous testing of both channels.](http://proceedings.spiedigitallibrary.org/)

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3. FRINGE AND FLEXURE TRACKER STATUS

The LINC-NIRVANA Fringe and Flexure Tracking System (FFTS) has the dual responsibility of providing wavefront arrival time information to the “piston mirror” delay line (fringe tracking) and of monitoring slow, gravity induced twisting of the overall instrument (flexure tracking). To ensure signal fidelity, the FFTS sits next to the science channel in the cryostat (Figure 1). In the original design, the FFTS sensor explored a 90 x 60 arcsecond oval field for reference stars. This required high precision positioning and tracking in X,Y,Z and unfortunately, cryogenic linear stages could not meet the performance specification. As a result, we pursued a design with warm stages and a moving set of baffles between the cold and warm sections of the cryostat.

After extensive laboratory testing, this scheme proved unworkable, and in the last two years, we have modified and simplified the baffle design. The new FFTS sensor covers a more restricted 45 arcsecond field of view (Figure 3). Of course, exploiting distant fringe tracking reference stars requires a wide delivered coherent field, and this in turn, depends on establishing and maintaining homotheticity, the condition in which the wavefronts for all field positions at the entrance pupil of the science channel cryostat are an exact, scaled copy of the corresponding wavefronts entering the telescope. At this time, neither the LINC-NIRVANA software nor the telescope software and infrastructure support the delivery of such a homothetic pupil. The FFTS will therefore be used initially on-axis only.

Figure 3. The original FFTS baffle mechanism (left) proved unworkable. The detector and filter wheel assembly mounts to the top of the larger circular “pin” (just cabling shown here). The simplified baffle with detector and filter wheel assemblies in place (right). Note the flexible copper straps to maintain proper operating temperature.
All of these changes have delayed the delivery of the FFTS, and it is currently the only sub-system of LN that has not been integrated. We are currently examining options for performing the FFTS AIV in the Fall-Winter 2014 time frame. This will have a direct influence on the revised implementation plan described in section 5. Nevertheless, the FFTS detector system is working well and has formally been accepted, and the opto-mechanics show full functionality in laboratory tests (Figure 4). Horrobin et al. 2014\(^6\) provide more information on the AIV status of the Fringe and Flexure Tracker System.

![Figure 4. Laboratory tests of fringe detection with the FFTS. Note the different PSF size for the three bands.](image)

### 4. FIRST LIGHT EXPERIMENTS AT THE LBT

LINC-NIRVANA is a complex, interacting system, which includes a large cryogenic camera, four wavefront sensors, a half-cryogenic fringe tracker, two CCD patrol cameras, two calibration units, two multi-layer turbulence and one piston simulator, as well as a host of infrastructure, software, and support elements. In all, there are eight detector systems (6 visible and 2 near-infrared), over 250 individual lenses and mirrors, 133 motors, 40 control systems, 964 separate electrical cables, and more than a third of a million lines of control software.

Proper management of this complexity is a prerequisite of success for LINC-NIRVANA. As mentioned in section 2, we have attacked this issue on the laboratory AIV side via a hierarchy. Telescope deployment brings with it a whole series of additional challenges, such as calibration strategies and software compatibility with the observatory. To address these challenges, we initiated the Pathfinder experiment, an effort to bring one of our wavefront sensors, as well as some of our electronic and software infrastructure, to the LBT well in advance of the rest of the instrument.

Bergomi et al. 2014\(^7\) and Kopon et al. 2014\(^8\) describe the Pathfinder experiment in detail. Pathfinder uses the right channel (DX) Ground-layer Wavefront Sensor (GWS), along with a test camera, support electronics, and software, to correct ground-layer turbulence (Figure 5). The Pathfinder experiment is a full-up demonstrator for a number of vital LINC-NIRVANA functions, including telescope communication, wavefront sensor calibration strategies, software and electronic compatibility, and multiple star acquisition.

We brought Pathfinder to the telescope in early 2013 and after some difficulties with the facility adaptive secondary mirror, we aligned the instrument to the telescope in October. Unfortunately, bad weather forced telescope closure on all but one night of our initial four-night run. Nevertheless, we managed to get on-sky and achieved First Light with the LINC-NIRVANA Pathfinder on 16 November 2013. Figure 4 shows our first-light closed-loop operation using a single, on-axis, reference star. Although the correction was modest, the imager was operating at visible wavelengths, and the seeing at the time of First Light was approximately 2.3 arcseconds.

We returned to the telescope three weeks later to attempt acquisition and closed loop control with a single off-axis reference star. Operating in this way requires an understanding of the mapping from sky to instrument focal plane, as well as proper calibration of the X-Y motions of the individual star probes. We again had poor weather, but during our one clear half-night, we managed to acquire off-axis stars and demonstrate real-time updating of the reconstructor matrix driving the adaptive secondary mirror, a critical capability to the ultimate functioning of LINC-NIRVANA. The most recent Pathfinder run took place in early April 2014. At that time, we continued our mapping of the geometry of the LBT focal plane and made significant strides toward acquiring multiple stars. See Conrad et al. 2014\(^9\) for more information.
5. IMPLEMENTATION PLAN

At the time of this conference, the integration activities for LINC-NIRVANA are almost complete. One arm has been integrated and tested end-to-end, and full system tests should begin in September 2014. If all goes well, we anticipate Preliminary Acceptance Europe and shipment of the full instrument in the first half of 2015, with reassembly, and commissioning taking place in Fall 2015. Despite this bright outlook, completing LINC-NIRVANA has taken more time and resources than planned, and at our current rate of burn, our funding runs out before delivery. Given the instrument’s complexity, commissioning and operating LN at the telescope will consume significant manpower. While further resources in principle exist within the partnership, there has been an explicit decision to focus future funds on the European ELT.

The LN team had been aware of an impending resource crisis for some time and had been seeking solutions. Unfortunately, none of these have worked out, and as a result, we have decided to pursue a more modest initial implementation within the current resource envelope, with full capabilities following as funding and other inputs permit.

Specifically, our original goal was to implement LINC-NIRVANA in four distinct steps:

1. LINC mode (single reference star, on-axis adaptive optics, interferometry)
2. Ground-Layer Adaptive Optics (hereafter GLAO)
3. Multi-Conjugate Adaptive Optics (hereafter MCAO)
4. NIRVANA mode (Full MCAO-interferometry)

The Pathfinder experiment (Section 4) effectively swaps steps 1 and 2. Our remaining resources will allow us to complete step 3, Multi-Conjugate Adaptive Optics, along with a limited version of experimental LINC mode. The aim is to demonstrate scientifically interesting, high impact capability soon after reaching the telescope, with the longer term goal of bringing in additional resources, both financial and personal, to complete the full LINC-NIRVANA.
This decision has serious implications for the interferometric capability of the instrument. While it will be possible to perform on-axis interferometry in the initial configuration, this mode will demand that the science object act as its own phase reference as well. This has direct implications on sky coverage and the ability to perform interferometry on extragalactic sources. There is an additional challenge that all large telescope interferometers face when attempting on-axis, self-referencing interferometry: any source that is bright enough to provide a phase reference is bright enough to saturate the science detector in very short integration times. There is therefore a small “window” in brightness accessible to this mode of operation. This challenge is one of several reasons why the full NIRVANA implementation foresees off-axis phase referencing, and it is one of the main reasons we decided to focus on MCAO as the next step instead of LINC mode.

6. LINC-NIRVANA AT THIS CONFERENCE

A single short paper cannot capture the status of an instrument as complex as LINC-NIRVANA, and in fact, there are a dozen presentations and posters on LN at this SPIE. Table 1 lists the corresponding papers, organized by conference session. Interested readers are encouraged to consult these other publications, and for the latest news on the progress of LINC-NIRVANA, point your web browser to:

http://www.mpia.de/LINC

Table 1: LINC-NIRVANA publications at this conference, organized by conference session

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REFERENCES


