The LINC-NIRVANA Interferometric Imager for the Large Binocular Telescope

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ABSTRACT

We describe LINC-NIRVANA, a 1-2.5 micron interferometric imaging instrument for the Large Binocular Telescope. Operating in Fizeau beam combination mode, LINC-NIRVANA will deliver the sensitivity of a 12-meter telescope and the angular resolution of a 23-meter telescope. Unlike traditional interferometers, LINC-NIRVANA will be a true imaging device, with a field of view of ten arcseconds on a single HAWAII-2 detector array.

LINC-NIRVANA employs a number of state-of-the-art technologies, including multi-conjugated adaptive optics (MCAO), innovative cooling systems, and complex software for instrument control and data analysis. We report on overall project progress and highlight some unique aspects of LINC-NIRVANA that should be of wider interest to the near-infrared instrument-building community.

Keywords: Interferometry, infrared, imaging, Fizeau

1. THE LARGE BINOCULAR TELESCOPE AS AN INTERFEROMETER

The Large Binocular Telescope, currently nearing completion on Mount Graham in eastern Arizona, will be the next large telescope and interferometry facility to come online. It differs from other interferometric arrays in having both feed telescopes on a single, steerable mount (Figure 1). This has an enormous impact on the types and complexity of interferometric observations that can be made.

Fig. 1. (left) The LBT in May 2004. (right) LINC-NIRVANA on the central, shared-focus instrument platform (light gray box). Note the human figure for scale
Specifically, the single mount configuration offers considerable advantages over separated telescope arrays, including significantly reduced thermal background due to fewer reflections, and elimination of long delay lines to remove tracking geometry effects. The single mount also greatly simplifies imaging or Fizeau interferometry.

**Fizeau Interferometry on LBT**

LINC-NIRVANA combines the radiation from the two 8.4 meter primary mirrors of the Large Binocular Telescope in Fizeau mode. In a Fizeau interferometer, the wavefronts interfere in the focal plane, not in the pupil plane, as with essentially all current interferometric instruments. Unlike their pupil-plane cousins, Fizeau interferometers are true imaging devices. Perhaps the simplest way to think of a Fizeau interferometer is as a very large telescope with diameter equal to the baseline, but with a mask corresponding to the configuration of component telescopes placed in the entrance pupil. The Fourier transform of this pupil layout is the point spread function (PSF), and all objects within the field display this PSF.

Figure 2 shows the LINC-NIRVANA PSF, along with a simulated exposure of a galaxy. The point spread function can be understood as the diffraction-limited Airy disk of a single 8.4-meter mirror, crossed by fringes resulting from the presence of two such apertures in the entrance pupil. The maximum spatial resolution of such a configuration – that is, the width of the central fringe – is about 10 mas in the J band.

![PSF and Simulated Galaxy](image)

**Fig. 2.** The LINC-NIRVANA point spread function and a simulated image of a galaxy.

The single mount arrangement of LBT is ideal for image plane beam combination. In order to deliver a wide field of view, a Fizeau interferometer must produce a scaled-down version of the entrance pupil of the telescope (this is the so-called homothetic pupil constraint, or “sine condition”). For interferometry with separated telescopes, the projected entrance pupil changes continuously as the target moves across the sky, and any Fizeau beam combiner must therefore include complex opto-mechanics to track the changing pupil geometry. Because the LBT always presents an identical pupil to the target, no such remapping is necessary.

The field of view of a Fizeau interferometer such as LINC-NIRVANA is limited in theory by the ability of the adaptive optics to deliver flat wavefronts over a range of sky angles, but in practice, the cost of near-infrared detector arrays is a more powerful constraint. A single 2048x2048 pixel, properly sampled, HAWAII-2 detector array covers approximately 10x10 arcseconds on the LBT. Filling the entire 2x2 arcminute potential science field delivered by LINC-NIRVANA’s MCAO system would be a costly venture indeed.

LINC-NIRVANA is an interferometer, and it should thus remain fixed with respect to the telescope entrance pupil. The LBT has an alt-azimuth mounting, however, resulting in rotation of the sky on the detector. The image extraction software relies on this effect, equivalent to earth rotation synthesis in radio astronomy, to allow reconstruction of true, high-resolution imagery.
THE LINC-NIRVANA INTERFEROMETRIC IMAGER

Introduction

LINC-NIRVANA is a near-infrared image-plane beam combiner with Multi-Conjugate Adaptive Optics (MCAO). The instrument is being built by a consortium of four institutes: the Max Planck Institute for Astronomy (MPIA) in Heidelberg, the INAF - Osservatorio Astrofisico di Arcetri in Firenze, the University of Köln, and the Max Planck Institute for Radioastronomy (MPIfR) in Bonn.

LINC-NIRVANA began as two projects proposed separately by the German and Italian LBT partners. The original designs called for relatively small field-of-view beam-combination, using the facility-standard adaptive optics system. The two efforts were combined in 2001, and soon thereafter, the team realized the potential of using the LBT adaptive secondaries, in combination with one or two additional deformable mirrors, to allow multi-conjugated adaptive optics. MCAO not only increases the available field of view, but also in the LINC-NIRVANA “optical co-addition” incarnation, allows much fainter individual guide stars to be used. This has the salutary effect of significantly expanding the observable fraction of sky.

Opto-Mechanical Design

Figures 3 and 4 show the LINC-NIRVANA opto-mechanical design. The beam combiner sits at one of the shared, bent focal stations on the central instrument platform (Fig. 1). The telescope focal planes lie just inside the instrument enclosure. At this location, an annular mirror redirects the field from 2 to 6 arcminutes diameter into the Ground-Layer Wavefront Sensors (GWS – not shown, see Herbst and Hinz). These devices measure the turbulence directly above the telescope by sensing up to 12 natural guide stars in this annular region. The GWS send their correction signals to the adaptive secondary mirrors, each of which has 672 actuators.

Fig. 3. The LINC-NIRVANA optical path. See text for details
Light from the central two arcminutes of the field of view continues further into the instrument to a six-lens “quasi-collimator.” This device produces a nearly collimated beam with the characteristic that the ray bundles from the two arcminute field produce an envelope of constant diameter. The optical path is folded back on itself twice in a “Z” configuration – one (and eventually perhaps both) of these fold mirrors is a Xinetics 349 actuator deformable mirror with conjugation altitude in the range 8-15 km (4-8 km for the second one, if installed). The constant-diameter beam configuration takes maximum advantage of the available actuators on these devices, and the entire “Z” structure can be moved back and forth to find and/or track the optimal altitude of turbulence. After the double reflection, the beams from each telescope strike the down-folding beam combination mirror (Fig. 4).

Dichroic mirrors between the beam combination mirror and the cryostat windows redirect visible radiation through a four-element camera lens to the Mid-High Layer Wavefront Sensors (MHWS). These devices select up to eight natural guide stars in the central two arcminute field, and measure the turbulence arising at one, and eventually perhaps two, additional higher altitude layers. The corresponding correction signals drive the one (or two) Xinetics deformable mirrors.

The near-infrared radiation continues through this dichroic, forming the required scaled-down pupil image just inside the window of the cryostat, where a cold mask suppresses excess thermal background. A reflective Cassegrain camera inside the dewar produces the final interferometric focus. The science sensor, a 2048x2048 HgCdTe HAWAII-2 array, sees this radiation in reflection off an infrared-infrared dichroic beam splitter. The fringe tracking sensor exploits the NIR light outside the reflected band, or from outside the science field, to determine the differential atmospheric piston. The fringe correction signal drives a piezo-electric actuator connected to the down-folding beam combination mirror. Small displacements of this mirror shorten one telescope’s optical path while lengthening the other, effectively doubling the dynamic range for piston correction.

 Needless to say, LINC-NIRVANA will be complex both opto-mechanically and in terms of control. For example, there are three atmospheric correction loops: ground layer turbulence, mid-high layer turbulence, and differential piston. The hardware and software design allows effective separation of these loops, however, considerably simplifying the controller architecture.
**Project Status**

LINC-NIRVANA’s schedule is closely tied to that of the telescope and other instruments. For example, installation of the second primary mirror in the LBT will not occur before late 2005, and it will require several months thereafter to achieve the “coherent combination” milestone – that is, when both telescopes act as one.

LINC-NIRVANA passed its Preliminary Design Review in April 2003, and the Final Design Review is scheduled for fall, 2004. Several long lead-time items, such as the science detector, large optical bench, and special glasses for lens blanks, are already in the procurement phase. Prototyping of critical components, especially cryomechanics and elements of the MCAO system has been underway for several months (Fig. 5).

![Prototypes of cryomechanisms. (left) Filter wheel (right) Harmonic drive for detector rotation](image)

Integration of LINC-NIRVANA on the shared instrument platform will take place during the summer monsoon shutdown in 2006. We anticipate early science results, using single guide star adaptive optics, to begin flowing shortly thereafter. Complexity and system engineering will likely be the main challenges for LINC-NIRVANA, and the implementation plan includes phased commissioning of various components and observing modes (MCAO, wide field, faint guide stars) over the subsequent 18-24 months.

**UNIQUE FEATURES OF LINC–NIRVANA**

Although LINC-NIRVANA is more of a “super imager” than a conventional interferometer, many of its technologies and strategies are specific to beam combination and will not be germane to the general, ground-based, infrared instrumentation community. In this section, however, we identify a couple of aspects of LINC-NIRVANA that should be of wider interest, specifically the approach to cooling the instrument without vibrations and the technique for eliminating stepper motor noise from the science detector readout.

**Vibration-Free Cooling**

As a near-infrared instrument operating in the 2 micron atmospheric window, LINC-NIRVANA requires a cold pupil, optical baffling, and a cold, dark detector environment to reduce thermal background and maximize sensitivity. As described above, the optical interface of the cryostat is at the scaled-down pupil of the telescope, where a cold mask prevents radiation arising outside the f/15 entrance beam from striking the detector. Producing a cold, dark environment after the pupil mask presents a number of significant challenges, however.
First, the LINC-NIRVANA cryostat is large, approximately 2.3 meters long by 75 cm in diameter. Maintaining low temperatures throughout such a large volume requires significant cooling power – roughly 120 Watts. The second challenge is an outgrowth of the low vibration requirement for interferometry – any cooling scheme must produce close to zero mechanical disturbance, or the delicate fringe contrast on the detector will be lost.

There are, of course, a number of standard solutions for cooling ground-based, near-infrared instrumentation, including liquid cryogens and closed-cycle (Gifford-McMahon or GM type) coolers. We rejected both of these options out of hand, the first due to the operational complexity of continually re-filling the dewar, and the second because these mechanical coolers produce unacceptable levels of vibration.

Two additional, relatively recent cooling strategies offer a real prospect of achieving the high power and low vibration requirements of LINC-NIRVANA. The first of these are the so-called pulse-tube coolers. These devices resemble their GM brethren, but the cooling head contains no mechanical piston, considerably reducing vibrations. We tested a CryoMech PT-60 pulse tube cooler in the laboratory in summer 2003 (Fig. 6), and indeed, this unit achieved excellent vibration performance. Unfortunately, however, additional tests of the total cooling power available, and specifically the dependence of cooling power on cold-head orientation, demonstrated that multiple pulse tube coolers would be needed to maintain sufficiently low temperatures within the large LINC-NIRVANA cryostat.

The second strategy we pursued was a “closed-loop” cryogen cooling system. In this arrangement, a large bath of liquid or gaseous cryogen is maintained at a remote location and kept cold with a traditional GM-type cooler. A cryogenic pump then forces the liquid or gas through long vacuum lines to the instrument, which contains internal cold lines, heat-exchangers, etc. Such a system can provide kilowatts of cooling power at liquid nitrogen (and colder) temperatures, and because all the mechanical components can be located tens of meters from the instrument, this cooling power comes without vibrations.

Stirling Cryogenics and Refrigeration of Eindhoven, The Netherlands produces the actual system selected for LINC-NIRVANA. It uses gaseous helium as the cryogen, since the long feed lines and cold-strapping within the cryostat inevitably produces thermal gradients, and we want to operate the science detector below liquid nitrogen temperatures. Figure 6 shows the operating principle, and Laun et al. provides a complete description of the system.

Crystal ball gazing is inevitably a risky undertaking, but this type of cooling system offers so many advantages – high power, low vibrations, minimal hardware at the telescope foci, etc. – that it is reasonable to foresee that closed loop cryogen systems will be part of the infrastructure of future observatories. The instruments would simply be bolted to the telescope, then hooked up to the necessary electrical, dry-air, glycol, computer network, and cryogen lines.

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Fig. 6. (left) Vibration measurements of a pulse tube cooler. (right) The operating principle of a closed loop cooler.
Component Rotation while Observing

The alt-azimuth mounting of the LBT naturally provides different projections of the interferometer baseline through earth rotation synthesis. This benefit comes at the cost of field rotation, however, and there are two choices for addressing this issue. The first is to keep the science detector fixed with respect to the telescope pupil, thereby maintaining the orientation of the PSF fringes (Fig. 2) but allowing the astronomical sources to rotate around the optical axis. The second option is to rotate the detector to follow the stars, which produces rotational blurring of the PSF fringes. A quick calculation, based on the relatively short baseline of LBT and the wide field-of-view of LINC-NIRVANA, demonstrates that the second choice is almost always superior.

Rotating the detector array while observing brings its own challenges, however. Ground-based instrument builders are very familiar with the problem of stepper-motor-induced pattern noise on the detector readout. In fact, many instrument controllers actually shut off power to the stepper motors during integration and readout. This is not a luxury afforded to an instrument that must track the sky.

The success of LINC-NIRVANA depends on finding a solution to this problem, and we therefore embarked on a series of experiments to isolate and correct the source of stepper motor noise in infrared detectors. After a number of tests using actual cryogenic stepper motors and HAWAII detectors, it became apparent that the noise arises due to a combination of the traditional pulse-width modulation strategy for driving stepper motors and the relative orientation of the motor, cables, and detector.

Happily, a simple modification to the motor drive electronics can drastically improve the situation (Fig. 7). By using a sinusoidal (analog) drive pattern and careful orientation, the pattern noise can be reduced by a factor of more than a thousand, to a level where it no longer contributes significantly to the detector noise budget.

CONCLUSIONS

LINC-NIRVANA is an ambitious project to combine Fizeau interferometry with multi-conjugated adaptive optics to achieve spectacular near-infrared imaging capability on the Large Binocular Telescope. Located at one of the central, shared focal stations of the LBT, LINC-NIRVANA will deliver a 1-2.5 \( \mu \)m science field approximately ten arcseconds square. Separate natural guide star sensors and control loops for ground layer turbulence, mid-high layer turbulence, and
differential atmospheric piston will allow scientific observations over a significant portion of the sky. Despite being an interferometer, some of the technological solutions and strategies adopted for LINC-NIRVANA should be of wider interest and applicability to the ground-based instrumentation community. First light for this imaging interferometer is planned for the months immediately after the next SPIE meeting in 2006.

REFERENCES

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