LINC-NIRVANA, A FIZEAU BEAM COMBINER FOR THE LARGE BINOCULAR TELESCOPE

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ABSTRACT

Fizeau interferometry at the Large Binocular Telescope (LBT) offers significant advantages over other facilities in terms of spatial resolution, field of view, and sensitivity. We provide an update of the LINC-NIRVANA project, which aims to bring a near-infrared and visible wavelength Fizeau beam combiner to the LBT by late 2005. As with any complex instrument, a number of detailed requirements drive the final design adopted.

Keywords: Interferometry, Fizeau, Imaging, Near-Infrared, Visible Wavelength, Adaptive Optics

1. INTRODUCTION

LINC-NIRVANA is a visible-wavelength to near-infrared image-plane beam combiner for the Large Binocular Telescope. It combines the radiation from the two 8.4 m primary mirrors in "Fizeau" mode, thereby preserving phase information and allowing true imagery over a wide field of view. Using state-of-the-art detector arrays, coupled with advanced adaptive optics, LINC-NIRVANA will deliver the sensitivity of a 12 m telescope and the spatial resolution of a 23 m telescope, over a field of view up to 2 arcminutes square.

The instrument design has evolved considerably since our last report[1]. At its heart, the beam combiner uses a classical "collimator-camera" optical design with two collimators (one per input telescope) and a shared camera. A cold pupil just inside the near-IR detector cryostat suppresses thermal background radiation, allowing sensitive observations blueward of 2.4 microns. Visible-wavelength radiation reflects off the cryostat entrance window to the CCD sensor channel.

The LINC-NIRVANA interferometric beam combiner is being built by a consortium of three Institutes: the Max-Planck-Institut für Astronomie (MPIA) in Heidelberg, the Osservatorio Astrofisico di Arcetri in Firenze, and the University of Köln. Further, up-to-date, news and information about LINC-NIRVANA are available at http://www.mpia.de/LINC.

1.1 FIZEAU INTEFEROMETRY WITH THE LARGE BINOCULAR TELESCOPE

Users of conventional optical telescopes are currently in a situation similar to that faced by our radio astronomy colleagues 20 to 30 years ago. How can we improve the spatial resolution and collecting area of future telescopes? The LBT will be among the last of the 8-10 m class telescopes to come online, and the next generation of "extremely large" telescopes is at least a decade in the future. We do not currently know how to build pieces of glass much larger than 10 m across, but we do know how to combine several smaller telescopes in an interferometer. As a result, there has been significant interest and rapid growth in the field of optical interferometry in recent years, resulting in several state of the art facilities, including VLTI, Keck-I , CHARA, and the LBT.

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Essentially all current ground-based interferometers are of the coaxial or pupil-plane configuration, in which the beam combiner superposes the two (or more) telescope pupils, and, by scanning a small delay line, produces a modulated signal as the two paths pass back and forth through constructive (zero optical path difference) interference. The amount of fringe modulation, or *visibility*, is a measure of the correlated flux with spatial frequency and orientation determined by the geometry of the observation – essentially one point in the spatial frequency spectrum of the object distrubution.

Although widely implemented, amplitude interferometry suffers from a number of drawbacks. For example, in its simplest implementation, it does not produce images. Also, building up the spectrum, one spatial frequency point at a time, can consume significant observing time. Field of view (FOV) limitations are also severe for the pupil-plane configuration.

The Fizeau or image plane configuration overcomes these limitations. In a Fizeau interferometer, the wavefronts interfere in the focal plane, not in the pupil plane. Unlike their pupil-plane cousins, Fizeau interferometers are true imaging devices. In fact, the field of view can be arcminutes in size, limited only by the ability of the adaptive optics (AO) system to deliver aberration-free wavefronts over large sky angles. Perhaps the simplest way to think of a Fizeau interferometer is as a very large telescope with a 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 (see Figure 1).

There are a number of compelling reasons for aggressively pursuing image-plane interferometry on the LBT:

1. Fizeau interferometry provides high angular resolution over a wide field of view, but only if there is a geometrical similarity between the entrance and exit pupils of the optical system (this is the so-called "sine condition" or homothetic pupil constraint -- see Angel 1998[2]. This usually requires cumbersome relay optics, but on on the LBT, the two mirrors share a common, steerable mount. This means that the telescope always presents the same pupil configuration to the target, drastically simplifying the task of maintaining constant pupil geometry. This simplicity translates directly to cost savings and increased sensitivity. On the LBT, there will be three, not twenty, warm mirrors before the radiation enters the beam combiner.

2. Fizeau imaging works best with compact arrays of telescopes, that is, configurations in which the separation of the mirrors is comparable to their diameter. This ensures relatively uniform spatial frequency coverage, eliminating difficulties associated with "resolving out" structures with spatial frequencies intermediate between that corresponding to the single dish diameter d and the baseline B. For example, an interferometer consisting of two 10 m telescopes separated by 100 m and operating at λ~2 μm has difficulty "seeing" structure at spatial scales between 5 mas (λ/B) and 50 mas (λ/d). The LBT, with its 8.4 m primary mirrors and 6 m separation, has no such blind spot.

3. There are also strategic reasons for focusing on LBT image-plane interferometry. In addition to being a potentially important technology for future ground and space-based telescopes, Fizeau beam combination on LBT offers a doubling of telescope collecting area and spatial resolution, compared to the largest current facilities. Almost all of the partners in the LBT consortium already have access to 8 m class telescopes and state-of-the-art instrumentation. It is a sobering thought to realize that by the time LBT is ready for science operations, there will have been more than 30,000 observing nights on other 8 m class telescopes throughout the world. Concentrating on LBT's unique aspects, in particular interferometry, will allow us to outperform these competing facilities.

4. Finally, and most importantly, Fizeau interferometry on the LBT will allow us to significantly enhance the quality and type of science we can do. Specifically, Fizeau interferometry offers a way to deploy our precious mirrors in a way that preserves sensitivity, spatial resolution, and field of view.

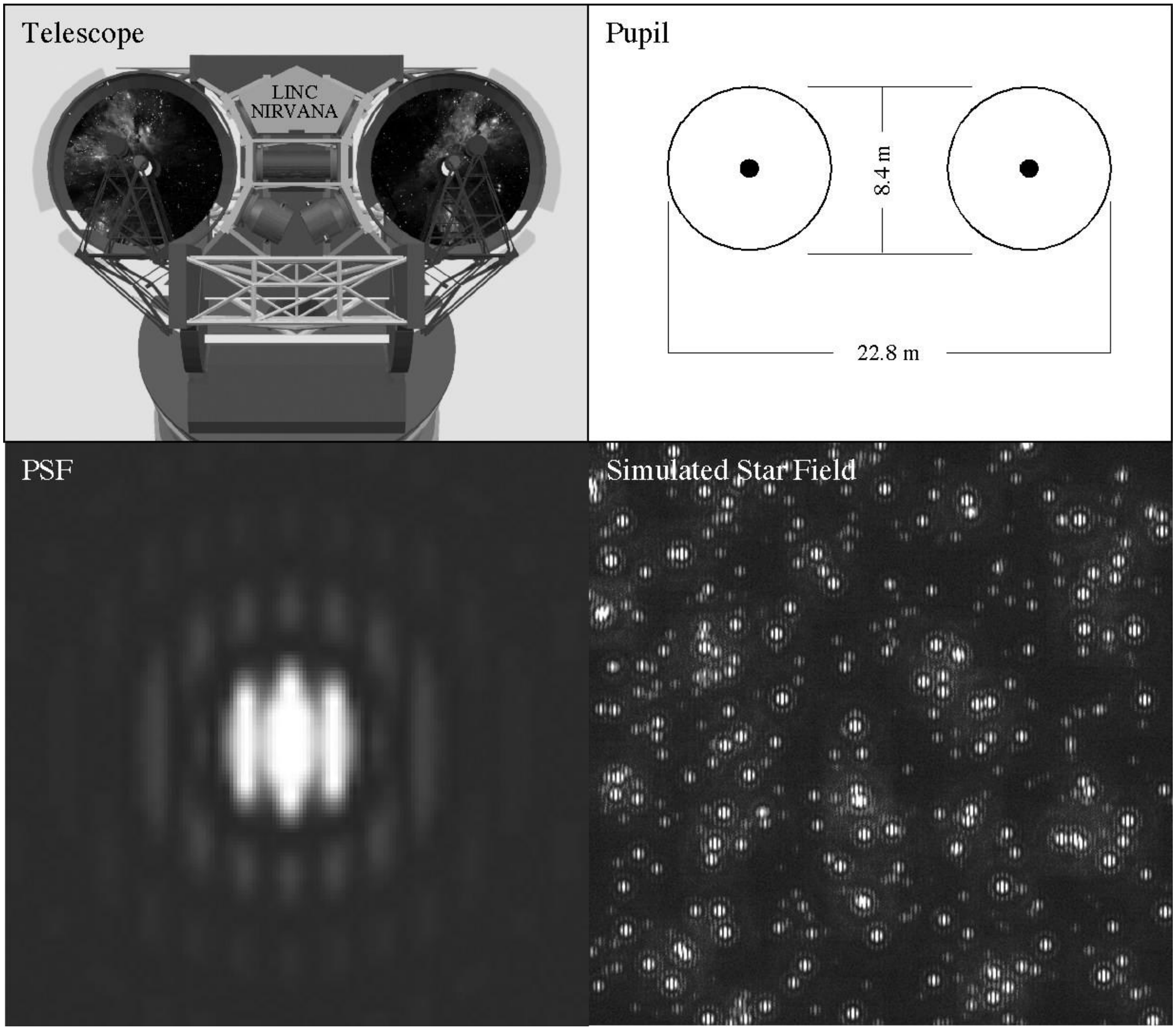

Figure 1: Configuration and Interferometric PSF of the LBT. The presence of two, phased apertures imposes a fringe pattern on Airy function diffraction of a single, 8.4~m diameter telescope. Note that all objects within the field display this PSF. The width of the central fringe is the synthesized spatial resolution λ/B, where B is 22.8 m, the longest "baseline."

2. THE LINC-NIRVANA INSTRUMENT

In order to develop and exploit the opportunities of Fizeau interferometry at the LBT, a consortium of three research institutes is building LINC-NIRVANA, a near-infrared and visible beam combiner. This instrument will sit at one of the shared, offset bent foci of the Large Binocular Telescope, combining the radiation from the two telescopes onto a single final focal plane. The beam combiner will be implemented in two stages. The first, called LINC, will employ a variant of the facility adaptive optics system and simplified control structure, in order to guarantee scientifically useful fringes as soon as possible. The final implementation stage, called NIRVANA, will harness the full power of Multi-Conjugate Adaptive Optics to increase the size, quality, and sky coverage of the corrected field of view. Both versions will have shared (*i.e.* near-infrared and visible wavelength) collimator optics, with the wavelength division occurring near the pupil. Separate NIR and visible channels then convey the radiation to the two detector subsystems (see section 2.2 below).

In the following, we describe the LINC-NIRVANA optical design, with an emphasis on the interferometric channel. Effective adaptive optics is a prerequisite for wide field interferometry on the LBT. Ragazzoni *et al.* 2002[3] present a detailed description of LINC-NIRVANA's multi-conjugate adaptive optics (MCAO).

2.1 OPTICAL DESIGN DRIVERS

This section summarizes the optical design requirements for the LINC-NIRVANA beam combiner. See Herbst *et al.* 2000[1] and references therein, for a discussion the science drivers. In the following, we list the specific design constraint and provide a short justification. The boldface letters, *i.e.* **NVS**, refer to the origin of the requirement: **N** is the near-infrared channel, **V** is the Visible wavelength channel, and **S** refers to wavefront Sensing constraints. Occasionally, only a specific sub-band has special requirements, denoted in parentheses , *i.e* **N(J)**, refers to the near-infrared J band.

1. *Optimized for all science and wavefront sensor λ.* The instrument will operate between 0.6 and 2.4 µm with a single set of fore-optics for simplicity. **NVS**

2. *Excellent optical quality.* We hope to be limited by the (excellent) performance of the AO system only. This will require Strehl >90% at all science wavelengths over the science field and at all sensor wavelengths over the sensor fields. **NVS**

3. *Operation at an offset, bent focus.* Although the central bent focal station has some advantages, there is no guarantee of long-term access to this location. **NVS**

4. *Mirror solutions preferred.* Mirrors are inherently achromatic, and they avoid difficulties associated with inhomogeneities in bulk optical glasses. Unfortunately, simple reflective optical designs violate other requirements. **NVS**

5. *Homothetic pupil.* This preserves the field-of-view. See item 1 in section 1.1. **NVS**

6. *Transmissive pupil preferred*. Transmissive pupils are "cleaner" for thermal background control. **N**

7. *Pupil near beam-combining mirrors*. This minimizes cross talk between the channels. The wide field of view implies a significant spread of angles passing through the pupil. If the beam-combining mirrors are not immediately before or after the pupil, there can be mixing of the two optical paths for objects at the edge of the field. **NVS**

8. *ADC location near pupil*. Placing an atmospheric dispersion compensator (ADC) near the pupil prevents undesirable wavelength-dependent pupil shifts. Note: an ADC is not necessary for near-IR operation, and we are helped by the fact that the fringes are always perpendicular to the dispersion. **V**

9. *Pupil just inside cryostat.* Having a cold pupil dramatically improves the infrared performance of the instrument. Placing it just inside the window minimizes the total length of cold optical path, thereby reducing accessibility, alignment, and flexure issues. It also means a relatively small (and therefore thinner) vacuum window. **N(HK)**

10. *Short as possible cold optical path*. This simplifies the beam combiner and makes more components accessible for alignment, replacement, and tests. It also implies a smaller cryostat which can be cold-cycled more rapidly and is less likely to cause flexure. **NS**

11. *Intermediate mirrors at interesting conjugates.* Multi-Conjugate Adaptive Optics will require one or more deformable mirrors in addition to the LBT secondary. The mirror locations should conjugate to 4 and 10 km altitude (adjustable) and have a minimum tilt to the optical axis: (less than 20°). **NVS**

12. *Beamsize ~150 mm at conjugates.* Deformable Mirrors (DM) are not currently available in sizes larger than this, and smaller DMs may have too few actuators.

13. *Appropriate image scale(s)*. The optics should properly sample the full operating wavelength range – 2.5±0.5 pixel per (λ/B). Different detector pixel sizes for the visible and NIR channels can help. **NVS**

14. *Effective sensor locations*. LINC-NIRVANA will require sensors for the wavefront shape, differential phase, and tip-tilt. Note that the differential phase (or piston) must be measured in the combined beam, whereas wavefront shape and tip-tilt must be sensed separately for the two telescopes. Ideally, all sensors should be as close as possible to the science detectors. The optical design must accommodate these needs. **S**

2.2 THE LINC-NIRVANA DESIGN

After considerable exploration and comparison, we have arrived at a detailed instrument concept for LINC-NIRVANA which satisfies most, if not all, of the science and optical design drivers. And, despite being a large, complex instrument, the mechanical and control problems seem tractable. In this section, we present the LINC-NIRVANA opto-mechanical layout, with an emphasis on the NIR science channel and only brief mention of the adaptive optics. In a companion paper, Ragazzoni et al. 2002[3] focus on the AO components.

Figure 2 shows the LINC-NIRVANA instrument mounted at one of the shared foci of the LBT (this is the “rear” focus, since in non-zenith operation, the telescope tips away from the viewer). The LBT is a Gregorian telescope, with a real focus approximately a meter below the adaptive secondaries. Each secondary is equipped with 672 voice coil actuators (see Riccardi *et al.* 2002[4]). Light from the secondaries is reflected by the tertiary mirrors to one of the three shared focal stations on the central platform. The middle bent focus offers the advantage of perfect optical symmetry: the rays entering the beam combiner strike all mirrors at an identical and symmetric angle for each arm of the interferometer. This is not the case for the two, offset, bent foci, and some polarization-induced degradation will occur. Nevertheless, such losses are not large, particularly when traded off against the larger instrument volume and easier access at the offset locations.

2.2.1 Optical Layout

The overall optical layout appears in Figure 3. LINC-NIRVANA uses a “classical” collimator-camera design, with separate collimator optics for each telescope and a shared camera. All of the optical components are mounted on, or referenced to, a large optical bench that spans the 6 meters between the primary mirrors. Due to weight and flexure considerations, this will not be a traditional optical bench. Rather, we plan for a custom, lightweight reference table tuned to LINC-NIRVANA’s load and tipping requirements.

The telescope foci lie just within the instrument envelope. At this location, the total field of view is six arcminutes in diameter. The central two arcminutes continue on into the interferometer, while the annular region between two and six arcminutes diameter is used by the Ground Layer Wavefront Sensors (GLWFS). These devices place pyramid wavefront sensors on multiple reference stars and interface with the adaptive secondary mirrors to correct the lowest turbulent layer.

Radiation from the central two arcminutes diverges after the telescope foci and is collimated by fore-optics consisting of three lens groups. Two pairs of fold mirrors are located at the optical conjugates of atmospheric layers at 4 and 10 km altitude (see item 11 in section 2.1 above). Although initially optical flats for the LINC configuration, these mirrors will eventually be replaced with 349 actuator Xinetics deformable mirrors. The first two lens groups produce a “quasi-collimated” beam, in which the beam divergence from a point source exactly follows the ray-bundle divergence due to the large field of view. This results in an optical envelope of constant diameter, a configuration which takes maximum advantage of the (very expensive) actuators on the Xinetics DMs (see Figure 4). However, the beam combiner requires truly collimated radiation: as shown in Figure 4, if the beams appear to diverge from a non-infinite conjugate, the shared camera optics cannot form a single, overlaid image in the science focal plane. We therefore included a third lens group in the fore-optics which acts as a "re-collimator" for the interferometric channel.

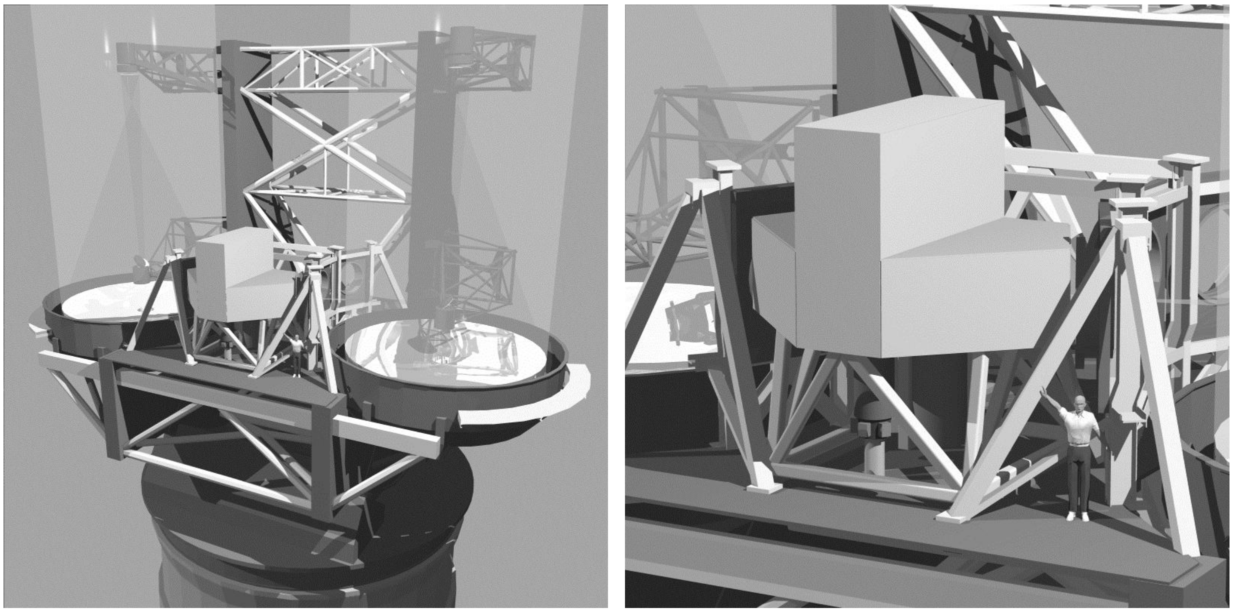

Figure 2: The LINC-NIRVANA instrument at the rear offset shared focus of the LBT. The human figure provides a sense of scale.

The geometry of Fizeau beam combination on the LBT requires that the homothetic pupil be formed in a downward traveling beam (see Hill, 1994[5]). Therefore, two 45° mirrors redirect the radiation downward toward the cryostat. These mirrors will be manufactured as a single lightweight unit. Mounting this assembly on a fast piezo-electric stage will allow rapid differential optical path length correction, in order to remove residual atmospheric piston.

Separation of the visible wavelength and near infrared channels takes place before the pupil at an inclined dichroic mirror immediately above the cryostat window (see Figure 3). An additional pair of mirrors redirects the visible light upward into the short wavelength channel. Fold mirrors and camera lenses then form the visible focus at a second location on the instrument midline offset from the NIR cryostat. This focal plane hosts both the MCAO wavefront sensor and one or two science CCDs. For further details of the visible channel, see Ragazzoni *et al.* 2002[3].

2.2.2 The Near-Infrared Channel

A large cryostat mounted below the reference optical bench houses the near-infrared channel (see Figure 5). We plan to use mechanical closed-cycle or pulse-tube coolers. Mechanical coolers simplify operations and maintenance, and our experience with the MIDI interferometer (Leinert *et al.* 2002[6]) indicates that vibration problems are tractable. The homothetic pupil lies immediately behind the cryostat window. Having a cold pupil (or Lyot stop) allows effective suppression of thermal background for NIR observations; locating it near the top of the cryostat ensures minimum flexure motion of this critical component with respect to the rest of the instrument.

One half of an on-axis classical Cassegrain telescope forms the infrared focus (see Figure 5). This allows a very large, unvignetted focal plane. A dichroic wheel, located behind the Cassegrain primary, allows a choice of photometric bands to be reflected to the science sensor. Below this wheel, an X-Y stage carries the so-called Fringe and Flexure Tracker (FFT). This device can explore a 1 x 1.5 arcminute field for a reference star to monitor atmospheric differential piston at high speed; a small fraction of this light is diverted for slow tip-tilt (*i.e.* differential flexure) measurements. Note that the dichroic holders have a minimum profile to reduce shadow effects. The FFT also has a focus mechanism. This allows it to follow the curved focal plane, as well as to compensate for focal shifts when tracking on a central object through the dichroic. Straubmeier et al. 2002[7] describe the FFT unit.

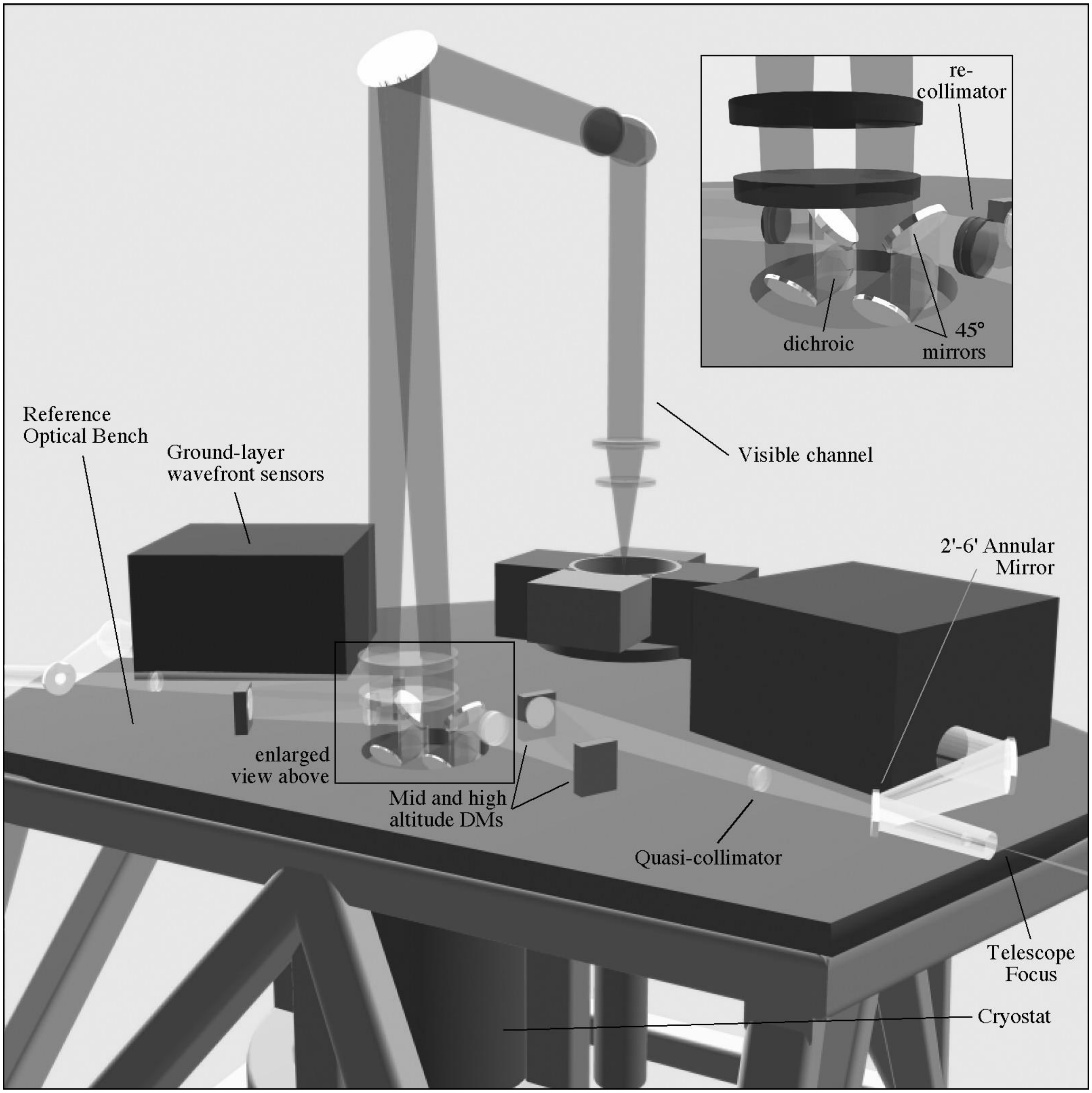

Figure 3: The LINC-NIRVANA opto-mechanical layout. This view shows the instrument, without housing, from the opposite side compared to Figure 2. The optical paths are colour-coded for clarity: light gray: Ground Layer Wavefront Sensor field, medium gray: shared NIR-visible path. dark gray: visible channel. See text for details.

The near infrared science sensor sits behind a filter wheel unit. The detector, a Rockwell HAWAII-2 device, will cover approximately 11 arcseconds square with an image scale of 5 mas per pixel, chosen as the best compromise between field of view and adequate sampling at the shortest wavelengths. Also the curvature of the focal plane does not introduce degradations over this field.

Because the LBT uses an alt-azimuth mount, the sky will rotate with respect to the entrance pupil of the telescope. In interferometric mode, the sky will also rotate with respect to the fringes on the detector. Nothing can be done about this, and in fact, we depend upon this “earth rotation synthesis” to provide complete angular “(u-v)” coverage.

There are two options for countering this effect. The first is to derotate the detector to keep it fixed with respect to the sky. Of course, this causes the detector to rotate with respect to the entrance pupil of the telescope, and hence the PSF (Figure 1) will rotate *in place* and blur for all sources across the field. The second option is to do nothing – *i.e.* keep the detector fixed with respect to the pupil. In this instance, the PSFs remain sharp, but objects will track and smear across the detector during an exposure.

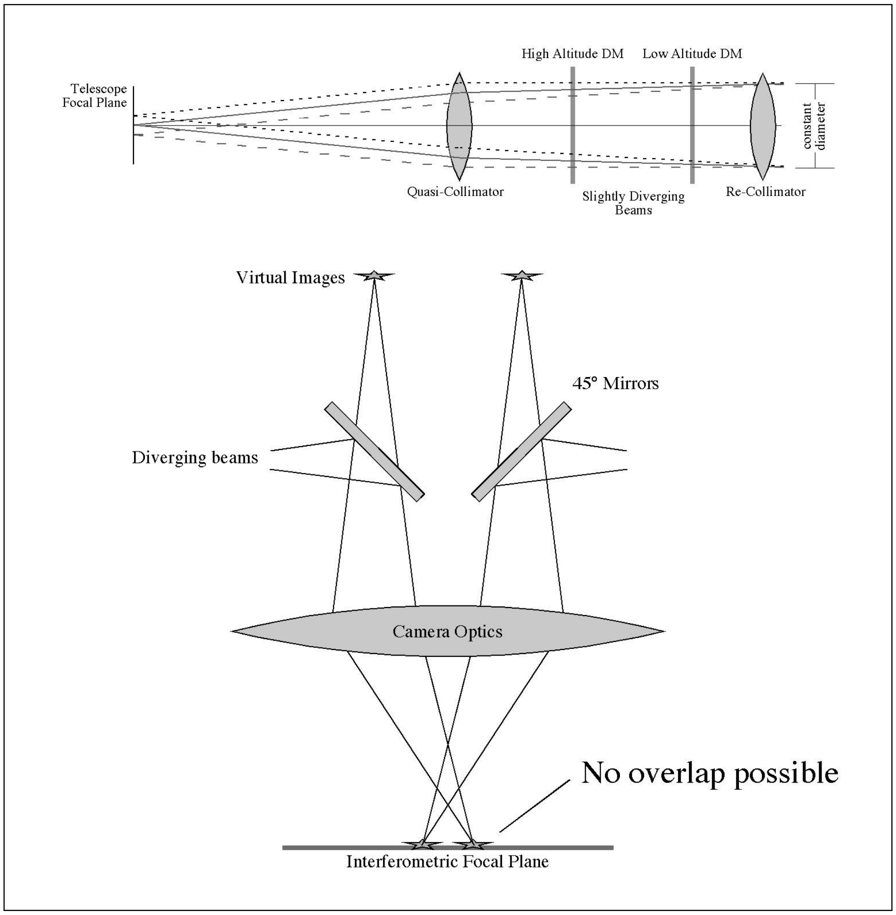

Figure 4: *Top:* The “quasi-collimator” produces slightly diverging beams to balance the spread in angles due to the large field of view. The result is a constant diameter envelope on the Deformable Mirrors. *Bottom:* If this radiation is not subsequently re-collimated, there will be virtual images at a finite distance above the 45° folding mirrors. In this instance, the single, shared camera optics cannot overlay the images, a prerequisite for interferometry.

Simple calculations demonstrate that the derotator solution is far superior. Since there are only 2-3 fringes across the Airy disk, this blurring is quite acceptable during exposures of several minutes. On the other hand, the rate of image motion in a pupil-fixed system can result in unacceptably large image motion in the corners of the field, even for modest exposure times. LINC-NIRVANA therefore includes a cryogenic mechanism for derotating the detector. This will be a simple device based on flexural pivots, since rotations of more than 30-40° are unnecessary.

3. IMPLEMENTING LINC-NIRVANA ON THE LBT

Our goal is to bring LINC-NIRVANA to the telescope in late 2005. Clearly, having all the subsystems and modes working at first light will be impossible. We are therefore outlining an implementation sequence, which breaks down the complexity into a series of incremental goals:

1. *Interferometric near-IR imaging with a pair of single, on-axis wavefront sensors (“LINC” mode).* The goal is to achieve scientifically useful data as soon as possible and to aim for performance levels suitable for routine operation.

2. *Demonstration of Ground Layer Wavefront Sensors*. This phase foresees non-interferometric, diffraction-limited observations with the GLWFS driving the adaptive secondaries, with a best effort to obtain interferometric measurements.

3. *Multi-Conjugate Adaptive Optics using a single telescope aperture (non interferometric).* This mode uses the GLWFS and MCAO-WFS simultaneously. The goal is to demonstrate the enhanced field of view and sky coverage afforded by MCAO.

4. *Full MCAO interferometry.* This is the final NIRVANA operating mode, with interferometric observations and full MCAO with GLWFS.

At this writing (fall 2002), we are finalizing the instrument configuration and continuing with detailed design work. The optical design is essentially complete, and we are now addressing issues associated with the mechanical mount of the instrument and the software control of the various subsystems. The next significant milestone is the Preliminary Design Review (PDR), which will take place in early 2003.

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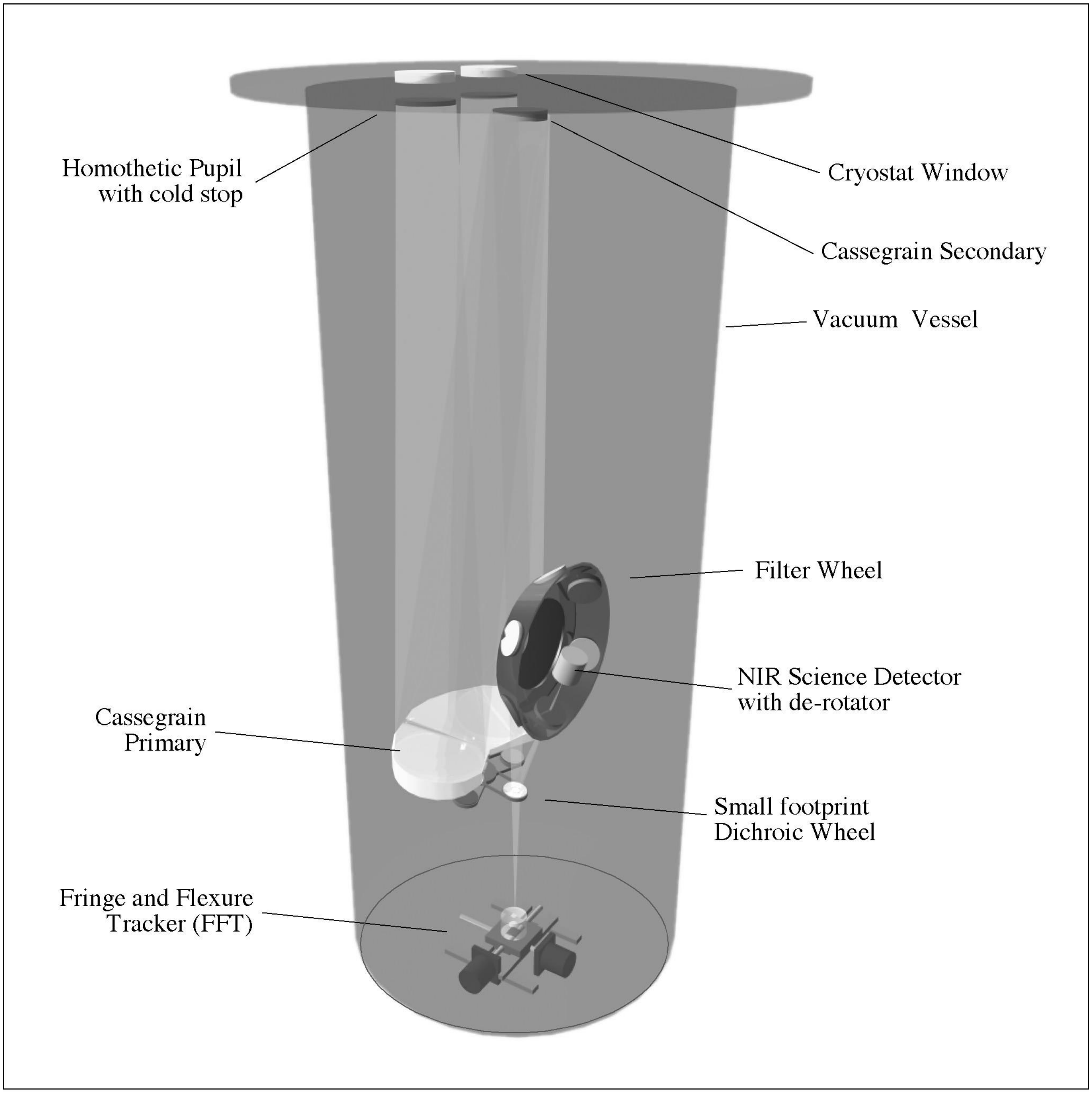

Figure 5: The LINC-NIRVANA cryostat, showing the reflective optics, Fringe and Flexure Tracker, and the HAWAII-2 sensor package.