

# LINC-NIRVANA: Optical design of an interferometric imaging camera

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## ABSTRACT

Combining the two 8.4 m telescopes of the Large Binocular Telescope<sup>1</sup> (LBT) offers the unique possibility to achieve diffraction limited images with 23 m spatial resolution. This requires an interferometric superposition of the two telescope beams in a Fizeau-type interferometer. LINC-NIRVANA delivers a 10 arcsec x 10 arcsec panoramic field of view with 5 mas pixel size. In addition to delivering diffraction limited, single-telescope images, the optics have several additional constraints imposed by interferometric operation. In this paper, we describe the evolution of the optical design and how the individual optical subsystems were developed in parallel to provide optimal combined performance. We also present an alignment strategy to setup the optics and to achieve zero optical path difference.

**Keywords:** IR optical design, interferometric imaging, interferometry, interferometric instrumentation

## 1 INTRODUCTION

This paper focuses on two issues. First, we describe the LINC-NIRVANA<sup>2</sup> optics itself. This includes a detailed report on the optical design and the performance analysis. We present a description of the alignment procedure and a verification of the design done by non-sequential ray tracing. Second, we present the outlines of an interferometric design. We address the additional features required for interferometric operation, along with the description of the design. These features, e.g. point spread function (PSF) overlap and pupil homotheticity, usually can be ignored for conventional designs but they are essential for interferometric performance<sup>3</sup> and put additional constraints to the design.

## 2 OPTICAL DESIGN

The LINC-NIRVANA optical design consists of three main parts, in addition to the LBT telescope optics: the collimators, the beam combiner, and the  $f/20$  camera optics used for wavefront sensing. Since LINC-NIRVANA is fed by both telescopes, two identical copies of the collimator and the camera optics will be built.

The collimator forms both a constant envelope beam, in order to illuminate all actuators of the deformable mirrors used for adaptive optics corrections, and a collimated beam in the pupil located near the center of the instrument. A common 45° piston mirror reflects the collimated beams in order to form a homothetic pupil inside a cryostat, which is the interface to the beam combiner optics. Before entering the cryostat, the light is split by a dichroic mirror into a NIR and a visible wavelength range. The NIR part is transmitted into the science and fringe tracking channel of the beam combiner. The visible light is reflected from the dichroic and forms a pupil, which is the interface to the  $f/20$  camera optics. The camera optics deliver a telecentric  $f/20$  focal plane, which is used for wavefront sensing.

### 2.1 Concept and interfaces

The telescope optics is fixed and forms an external interface for the LINC-NIRVANA optical design. In addition to the typical telescope parameters such as focal ratio, field curvature and exit pupil position, the absolute position of the optics and interfaces is of importance, because of the required homothetic pupil<sup>3</sup> and other interferometric conditions. For a simple approach and a fast realization of the design, all parts are designed in sequential mode. To design the

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collimator and the beam combiner optics in sequential mode, the interface must be well defined and absolute reference planes must be integrated into both optical designs. The camera optics is designed in a conventional approach.

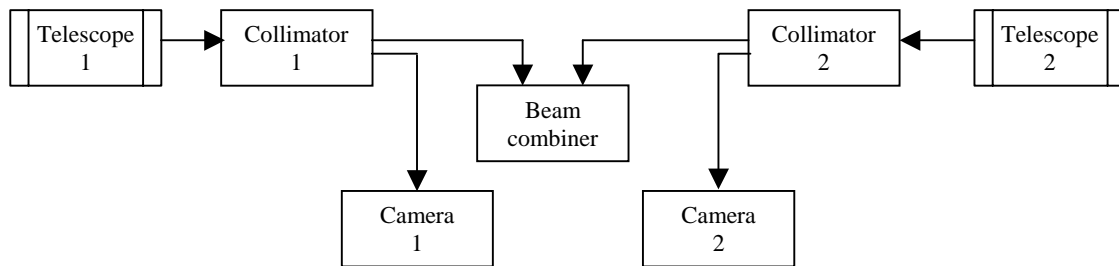


Figure 1: Schematic of the LINC-NIRVANA optics.

## 2.2 Collimator design

The collimator is folded by 2 plane mirrors, which in the final LINC-NIRVANA configuration are two deformable mirrors (DM) per side. The positions are conjugated to certain layers in the atmosphere. The DMs have a fixed diameter and to use as many actuators of the DM as possible, the beam for a certain field should have a constant outer diameter i.e. the two DMs are fully illuminated (Figure 2). The collimator forms a pupil, which is close to the centerline of the two telescopes. This pupil defines two interfaces, one to the cold beam combining optics and one to the camera optics. The interface to the beam combining optics considers the pupils of both collimators. The two pupils must be homothetic i.e. the diameter and separation ratio must be identical to the ratio of telescope entrance pupil diameter to telescope separation. In addition, the beams for the beam combining optics must be well-collimated in order to assure a PSF overlap of both arms in the common focal plane (Figure 3).

For the second interface, the light is split just before the cryostat windows. Dichroic substrate and vacuum windows are not considered in this configuration. The collimator transfers a 2 arcmin diameter field of view for the full wavelength range of the wavefront sensors and IR science channel from  $0.6 \mu\text{m}$  to  $2.4 \mu\text{m}$ .

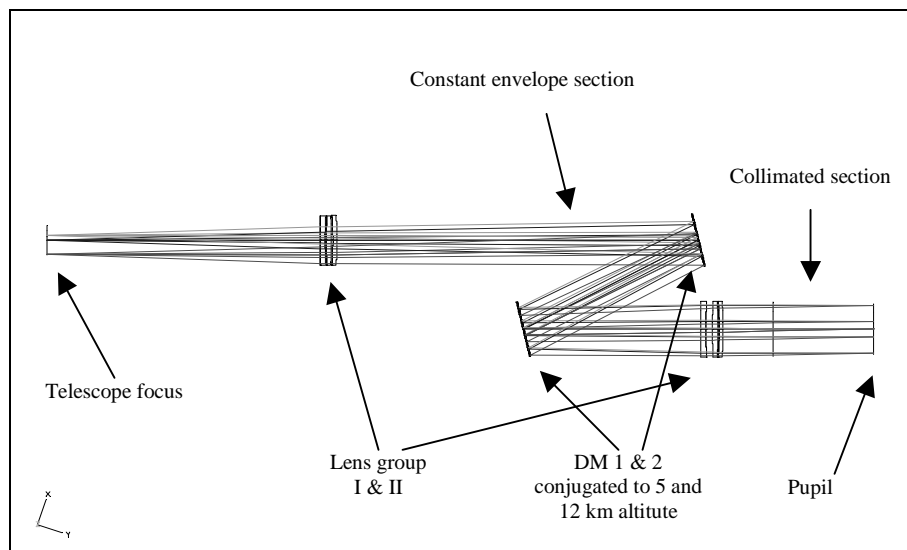


Figure 2: Layout of the collimator design.

Since the collimator operates in a telescope environment with large temperature variations, the thermal compensation is done by moving the two lens groups on motorized stages. For the thermal compensation, the identical requirements are applied, i.e. the compensation must preserve pupil position and diameter and the PSF overlap. This in particular is relevant for the specifications of the linear stages, which are used to compensate the thermal effects. The tolerances are tight, especially for long focal length optics since small angles in pitch and yaw correspond to a de-correlation of the

PSFs. Even a simple movement along the optical axis might be adjusted by a compensator, e.g. with the tilt of the DM mirror.

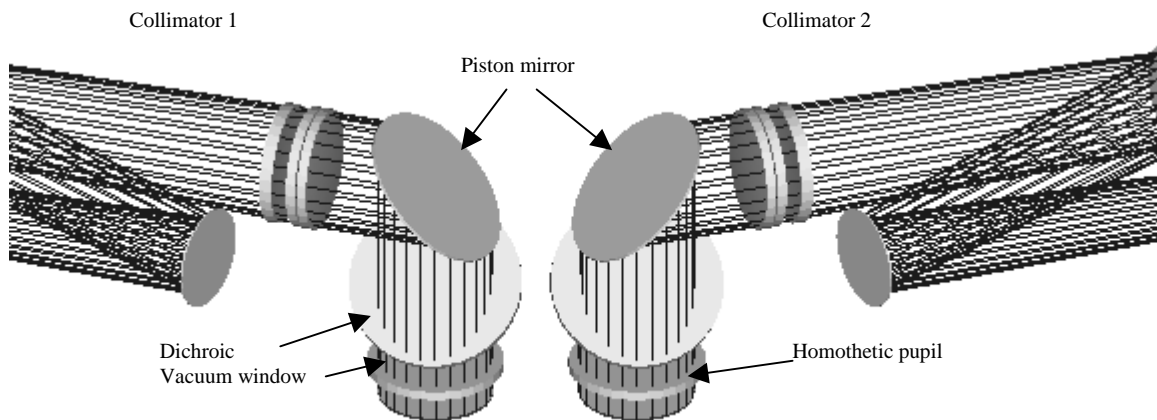


Figure 3: Arrangement of both collimators forming the cold pupil interface.

### 2.3 Camera optics

The camera optics interface to a single collimator and can be done independently since the collimation and optical performance of the collimator is sufficient to be assumed as perfect. No corrections of the previous optics is required. The camera focuses a 2 arcminute field of view to a telecentric  $f/20$  image plane, which is again the interface to the wavefront sensors<sup>4,5</sup>. In order to compensate the field rotation, an optical field rotator (K-mirror) is included in the  $F/20$  optics (Figure 4).

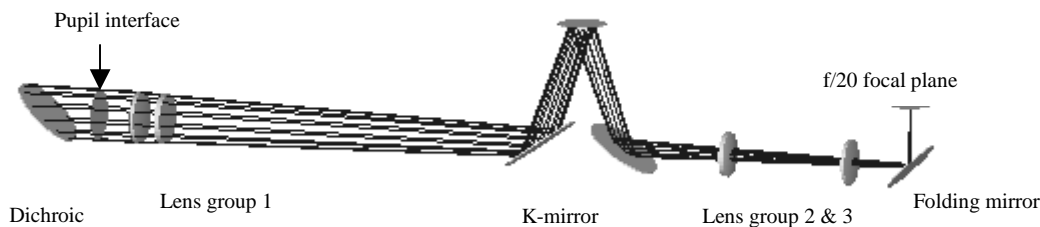


Figure 4: Layout of the  $f/20$  camera optics.

### 2.4 Beam combining optics

The cryogenic beam combining optics<sup>6</sup> deliver two focal planes, one for the science detector and one for the fringe tracker (FFTS), split by a second dichroic mirror (Figure 5&7). This dichroic mirror reflects the center of the field of view to the science detector. The fringe tracker field of view is in transmission through the dichroic in this central region. The outer fields are accessible directly (Figure 7). There is some vignetting for intermediate fields, due to the mounting of the dichroic mirrors. The split between the science and fringe tracking field is done after the powered elements, very close to the final focal plane to minimize non-common path aberrations including OPD. The science field of view is defined by a HAWAII2 detector. This focus delivers diffraction limited optical performance, usable for interferometry. For obvious reasons (best quality, field de-rotation), this field of view should be centered in the total field, which is used for fringe tracking. The fringe tracking field of view is optimized for a field of 1 arcmin x 1.5 arcmin, with slightly reduced performance outside the 1 arcmin diameter.

The interface for the beam combiner optics is the homothetic pupil, delivered by both collimators. For the design and optimization process, both beams must be considered in order to judge the optical performance. Therefore, a sequential

design is only possible for the beam combiner optics without the telescopes and collimators, with a user defined pupil interface.

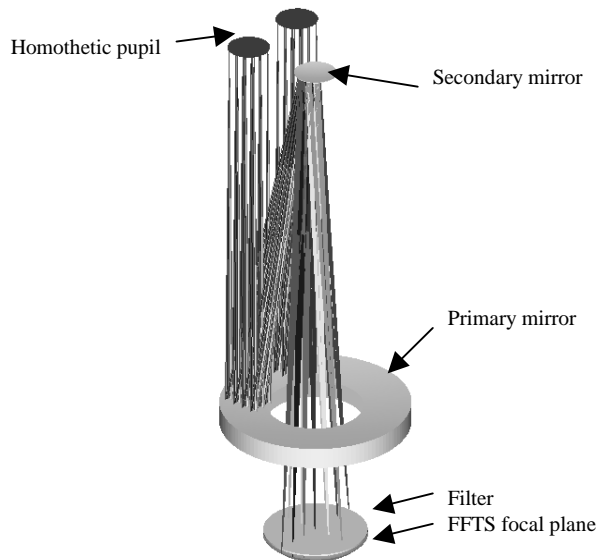


Figure 5: Layout of the beam combiner optics.

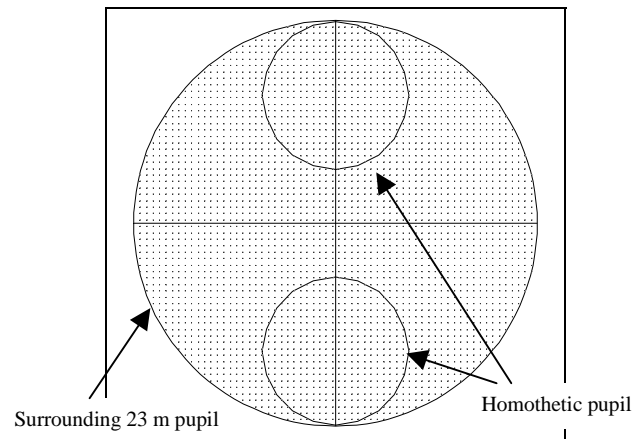


Figure 6: Pupil integration method, 64x64 array of rays.

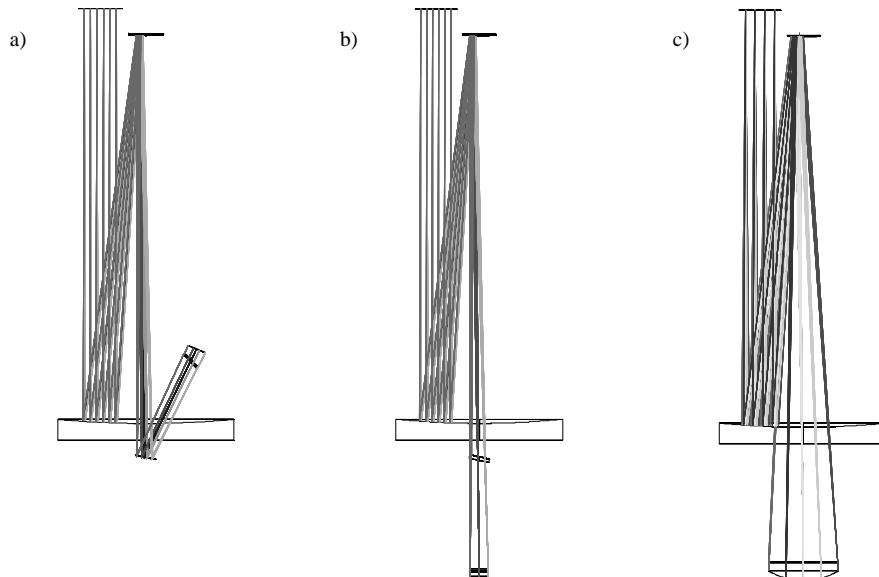


Figure 7: The three configurations of the beam combiner optics: a) science channel in reflection off the cold dichroic, b) FFTS through the dichroic (center fields) and c) FFTS outer fields.

In the sequential case with the user defined pupil, the pupil is not radially symmetric and the center is blocked. Hence, a Gaussian quadrature method of filling the pupil is not appropriate, and a rectangular array algorithm is applied. This algorithm traces a grid of rays (64 x 64) through the pupil as indicated in Figure 6. The rays outside the two user defined circles are clipped and are not used for the calculations.

### 3 OPTICAL PERFORMANCE ANALYSES

The optical performance analysis focuses on the interferometric mode. We do not give a complete analysis here. Rather, we show an example to demonstrate the key performance of the optical design. We present the f/20 camera optics analysis only briefly for completeness.

#### 3.1 Performance analysis for the sequential mode

In sequential mode, there are two main analysis configurations:

- Analysis of the single arm configuration. One telescope, one collimator and the beam combiner optics. In this configuration, only the single telescope diffraction limited performance can be investigated. If both single arm configurations are simulated, some interferometric requirements can be demonstrated, e.g. PSF overlap.
- Analysis of the beam combining optics only, without telescope and collimator as used for the optimization process. Since the optical quality of the collimator design is superb, this can be assumed as perfect and useful results for a real pupil geometry can be calculated.

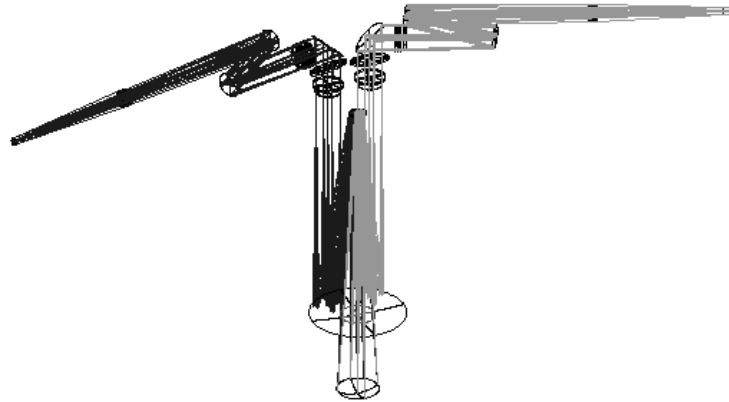


Figure 8: Analysis of two single arm configurations. Left arm (black) and right arm (grey) are simulated with the multi-configuration feature. Telescopes are not shown but included.

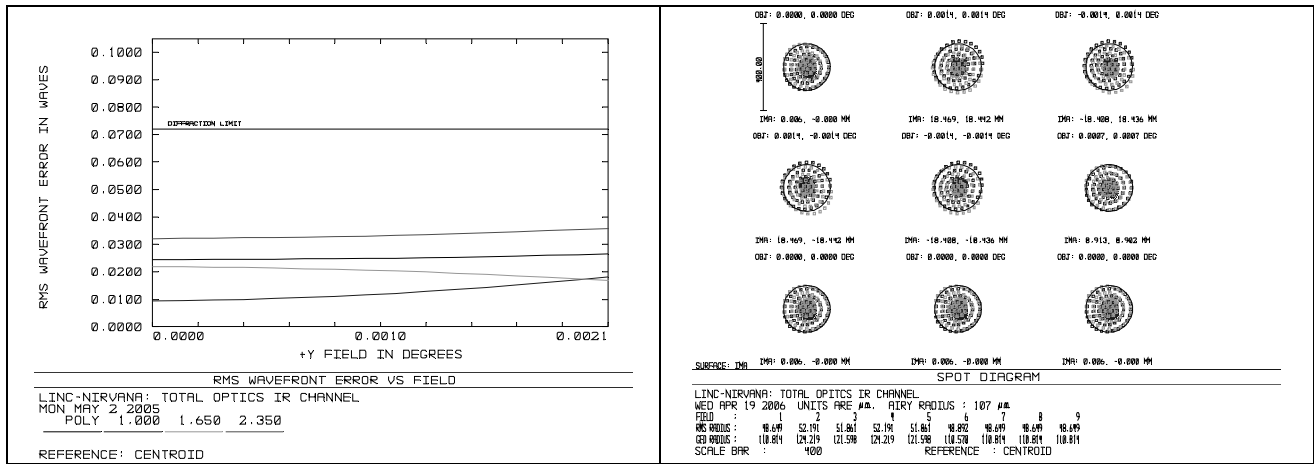


Figure 9: Performance of the single arm configuration for the science fields. RMS wavefront error for a single combination of telescope, collimator and beam combining optics. In the spot diagram, both arms are plotted. The PSF overlap can be calculated. Note: Airy discs are given for the single telescope (8.4m) pupil.

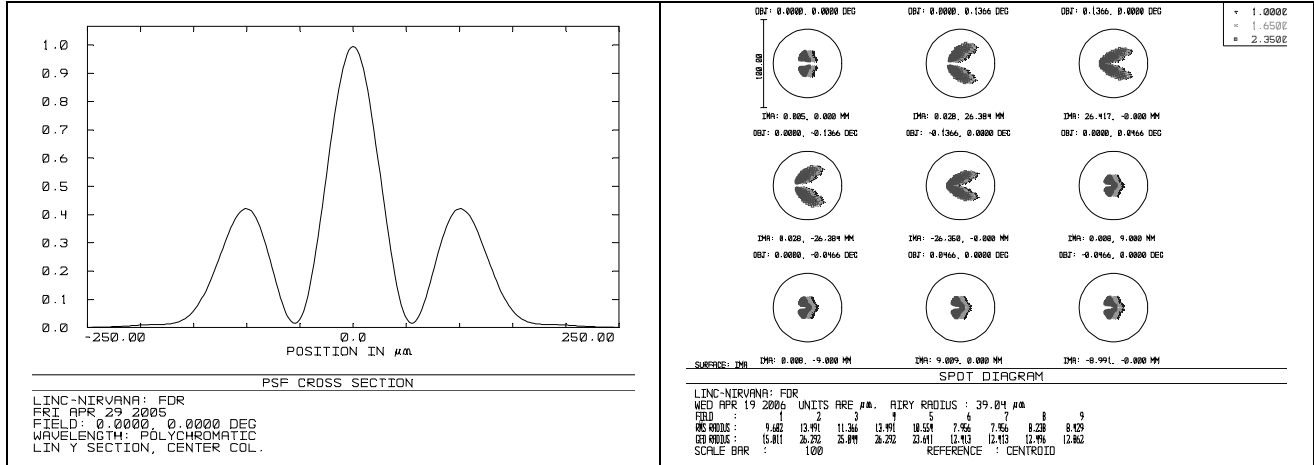


Figure 10: Performance of the beam combining optics only, with a user defined pupil. Polychromatic PSF cross-section for the K band – on axis. In the spot diagram, the effect of the two pupils is still visible. Note: Airy discs are given for a 23 m telescope pupil.

### 3.2 Non-sequential verification

The non-sequential configuration is actually setup in a mixed mode i.e. a sequential mode with a non-sequential group included. This allows the analysis of imaging features, which are not available in the pure non-sequential mode. The main advantage of this setup is the possibility of tolerancing the warm optics with an interferometric figure of merit. In case of LINC-NIRVANA, the main design goal is the amount of high spatial frequency components (Figure 11) in the modulation transfer function (MTF). This figure of merit is not usable with the previous described approach but allows e.g. the analysis of the alignment errors of the collimator optics.

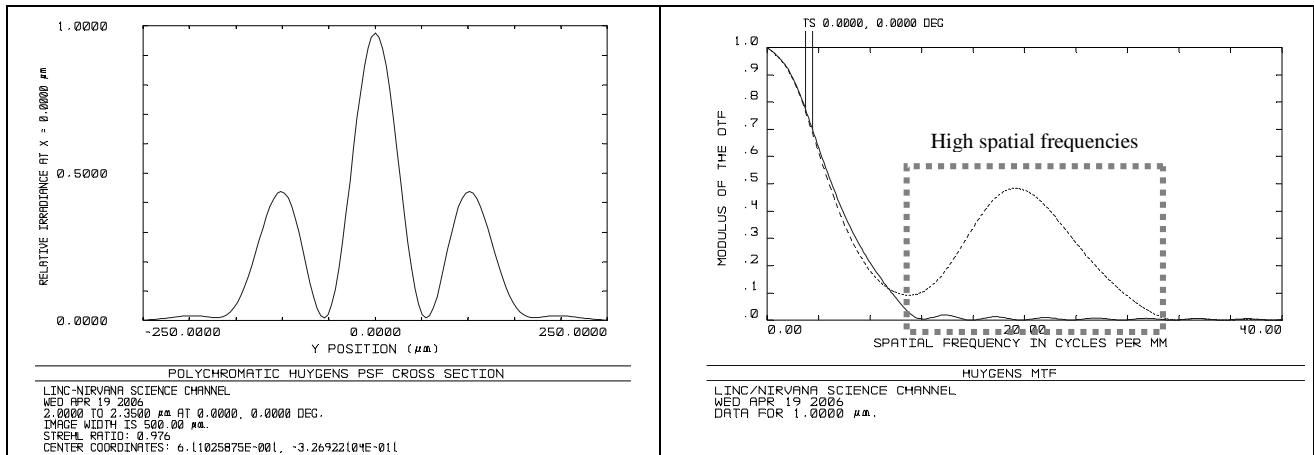


Figure 11: Non-sequential verification of all optics. Polychromatic PSF cross section for the K band – on axis. The MTF (right panel) shows the increase of the high spatial frequencies along the baseline direction with respect to a single 8.4 m telescope. This area defines the unique capability of LINC-NIRVANA in terms of resolution.

### 3.3 Camera optics analysis

The camera optics analysis demonstrates the superb optical performance of the warm optics in terms of conventional analysis (Figure 12). At least for the collimator, this is a requirement for interferometric operation.

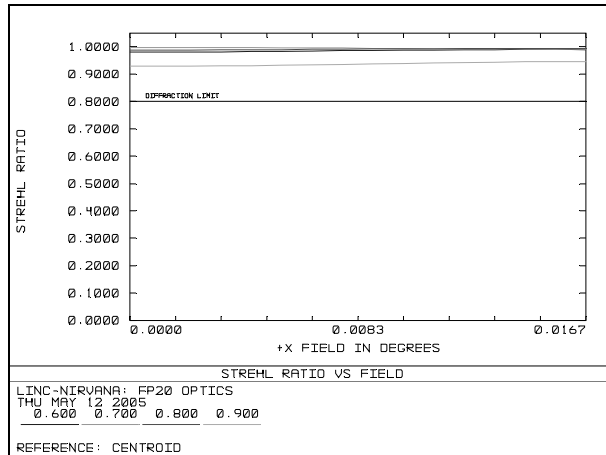


Figure 12: Strehl ratio plot for the collimator and f/20 camera optics.

## 4 ALIGNMENT STRATEGY

The initial alignment is done separately for the collimator and the beam combining optics, making use of the pupil interface with collimated beams. In a second step, the common setup for interferometric operation is achieved. The alignment procedure is only for an internal alignment of the instrument. Aligning the telescope to LINC-NIRVANA is not described in this paper.

### 4.1 Alignment of the collimators

The DM unit and the collimator optics must be pre-aligned at the component level i.e. the DM unit input axis and output axis must be parallel. The optics must be verified and fine-tuned in terms of equal focal length for both arms.

The alignment reference is a large, flat reference mirror, which covers both pupils and is mounted in the pupil plane before the cryostat is attached. This flat mirror guarantees the two arms to be parallel. The piston mirror, DM stages and an interferometer (for setup purpose only) are aligned to this reference for the optical axis. The lenses are added and adjusted with the pre-aligned interferometer.

### 4.2 Alignment of the beam combining optics

The input beams of the beam combining optics are not symmetric to the detector normal. Therefore, a reference sphere must be used in order to verify the optical performance of the NIR channel in a single reflection, double-pass measurement. Both arms are measured simultaneously. Two interferometers are aligned with a large reference mirror to be parallel. This setup is also used to verify the PSF overlap.

### 4.3 Alignment for interferometric operation

After the two previous alignments are done successfully and both parts are assembled, the remaining adjustments for interferometric operation are the following:

- **Overlap of images**  
corresponds to the alignment of the optical axis. A motorized tip-tilt unit for the DM mirrors allows a lateral shift of the single images on the detector.
- **Homothetic pupil**  
to keep the pupils diameter equal, the focal length must be tuned to be equal by adjusting the lens groups separation. This procedure was demonstrated already during the verification process of the optics. If the pupil diameters are equal, the distance between the two pupil can be adjusted by moving the piston mirror in the z direction with a motorized stage.
- **Optical path difference**  
can be adjusted with the piston mirror, which is mounted on a piezo stage. The range is limited (150 $\mu$ m) and is used primarily for dynamical control of the piston. For larger amounts of OPD between the two arms, one

collimator can be shifted closer to the pupil. This changes the focal plane position but the internal alignment occurs prior to the telescope alignment.

These procedures comprise a complete internal alignment of the instrument. For verification, testing and also calibration, a calibration unit is permanently installed on the instrument bench. This unit contains reference fibers, coherent and in-coherent, for these purposes.

## 5 CONCLUSIONS

The optical design of an interferometric instrument is possible with existing ray trace capabilities. Sequential modeling and well-defined interfaces are sufficient for calculating all necessary information. A non-sequential approach is not required for the optimization process and for the tolerancing but is very useful for verifying the achieved results. It might be necessary for tolerancing with an interferometric figure of merit e.g. the fraction of high spatial frequencies in a MTF. This is only possible by simulating the total optics in non-sequential mode. LINC-NIRVANA has an optical concept where the sequential approach generates sufficiently accurate results because of the pupil interface with collimated beams between the single path and the common path optics. This might not be feasible for any optical concept of an interferometer.

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