The Fringe and Flexure Tracking System for LINC-NIRVANA: Basic Design and Principle of Operation

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ABSTRACT

LINC-NIRVANA is the interferometric near-infrared imaging camera for the Large Binocular Telescope (LBT). Operating at JHK bands LINC-NIRVANA will provide an unique and unprecedented combination of high angular resolution (~ 9 *milliarcseconds at* 1.25 μm), wide field of view (~ 100 *arcseconds*^{2} *at* 1.25 μm), and large collecting area ($\sim 100\ m^2$).

One of the major contributions of the I. Physikalische Institut of the University of Cologne to this project is the development of the Fringe and Flexure Tracking System (FFTS). In close cooperation with the Adaptive Optics systems of LINC-NIRVANA the FFTS is a fundamental component to ensure a complete and time-stable wavefront correction at the position of the science detector in order to allow for long integration times at interferometric angular resolutions.

Using a dedicated near-infrared detector array at a combined focus close to the science detector, the Fringe and Flexure Tracking System analyses the interferometric point spread function (PSF) of a suitably bright reference source at frame rates of several hundred Hertz up to 1 kHz. By fitting a parameterized theoretical model PSF to the preprocessed image-data the FFTS determines the amount of pistonic phase difference and the amount of an angular misalignment between the wavefronts of the two optical paths of LINC-NIRVANA. For every exposure the correcting parameters are derived in real-time and transmitted to the respective control electronics, or the Adaptive Optics systems of the single-eye telescopes, which will adjust their optical elements accordingly.

In this paper we present the opto-mechanical hardware design, the principle of operation of the software control algorithms, and the results of first numerical simulations and laboratory experiments of the performance of this Fringe and Flexure Tracking System.

Keywords: LBT, instrumentation, interferometry, fringe tracking, piston

1. LINC-NIRVANA - THE NEAR-INFRARED INTERFEROMETRIC IMAGER FOR THE LARGE BINOCULAR TELESCOPE

Regarding its optical design and physical dimensions the Large Binocular Telescope (LBT) represents a revolutionary and fascinating new type of astronomical interferometer. In contrast to all other large-scale interferometric telescopes (either already operational or currently under construction) the optical layout of the LBT resembles a Fizeau interferometer, with both primary mirrors sharing a common mount (Hill & Salinari 1998; Angel et al. 1998).

The baseline of a Fizeau interferometer is not fixed with respect to the ground (e.g. like at VLTI* (von der Luehe et al. 1997; Eckart et al. 1997; Glindemann & Lévêque 2000) or Keck I & II (Booth et al. 1999; Swanson et al. 1997) where the baselines are defined by the relative geographical locations of the individual telescopes),

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*VLTI - Very Large Telescope Interferometer but is fixed with respect to the movable common mount of the two mirrors. Therefore, while the pointing of the telescope follows the apparent nightly motion of an observed astronomical source, the length of the geometrical projection of the baseline onto the plane of the incoming wavefront (i.e. perpendicular to the line of sight) remains constant in time at 14.4 metres. Since the angular resolution of an interferometer is a linear function of this baseline it remains constant, too, what allows for direct interferometric imaging of an astronomical source without the need of sensitive optical delay lines to compensate changing baseline projections.

The beam combiner of LINC-NIRVANA is specifically tailored to preserve the exact pupil geometry of the LBT (i.e. the output pupil is a scaled model of the input pupil), what allows for homothetic imaging at interferometric resolutions over a wide field of view. Using Multi Conjugate Adaptive Optics (MCAO) (Berkefeld et al. 2001; Diolaiti et al. 2001) both optical channels of LINC-NIRVANA will be operated at the diffraction limit of the 8.2 metres primary mirrors - a mandatory requisite for time stable interferometric observations. However, for successful long term integrations of the science detector at highest interferometric angular resolutions, the lengths of the two optical paths of the instrument have to be controlled, too. This important task will be fulfilled by the Fringe and Flexure Tracking System of LINC-NIRVANA, which is presented in the following sections of this paper.

For an in-depth discussion of the overall design and functionality of the LINC-NIRVANA camera system please refer to the contribution of T. Herbst to this conference.

2. THE NEED OF A FRINGE AND FLEXURE TRACKER FOR INTERFEROMETRIC IMAGING CAMERAS

To allow for direct imaging at interferometric telescopes, i.e. to obtain two-dimensional images of interferometric angular resolution from focal plane arrays after long integration times of several seconds up to minutes, two fundamental physical conditions have to be fulfilled at all times: all contributing telescopes must be operated at their respective diffraction limit, and a flat wavefront coming in on the optical axis of the system must not show any phase difference between the two channels of any interferometric baseline.

The first criterion is a well known and extensively studied problem, which faces all kinds of ground based optical telescopes that shall deliver astronomical images of maximum angular resolution. The common approach to its solution is the implementation of Adaptive Optics (AO), i.e. deformable mirrors, wavefront sensors and fast numerical closed-loop algorithms, to correct the image degrading phase aberrations in real-time and in parallel to an ongoing exposure of the science detector. Besides of static or only slowly varying contributions from non-perfect telescope optics, most of these aberrations are due to the turbulent atmosphere of the earth with characteristic timescales of fractions of seconds to milliseconds. Using current generation real-time computers and detector technologies the obtained closed-loop frequency of an AO system can reach several hundred Hz up to 1 kHz, and therefore can be higher (or at least of the same order) than the characteristic timescale of atmospheric turbulences. As a result, the point spread function of an individual telescope can be brought close to its diffraction limit at most atmospheric conditions, what allows for long integration times of the science detector at the highest possible angular resolution of the telescope.

However, reaching the diffraction limit at all contributing telescopes is only a first (nevertheless fundamental) step for the successful and time-stable operation of an imaging camera at the combined focus, but it is not sufficient in order to obtain interferometric fringes.
Even if the wavefronts from all telescopes are corrected to perfection (within their independent reference frames), there are still two factors left, which may introduce image degrading aberrations at the combined focus, and which cannot be sensed and corrected by the AO systems of the individual telescopes:

- a fast varying part, which is due to atmospheric turbulences, and which manifests itself in highly variable pistonic phase differences between the wavefronts from the individual telescopes
- a constant or only slowly varying part, which is due to misalignment of the optical axes (e.g. arising from mechanical flexure) of the individual telescopes before the interferometric combination. This misalignment may result in different optical path lenghts of the interferometric baselines, as well as in different intersections of the optical axes with the detector array in the combined focal plane.

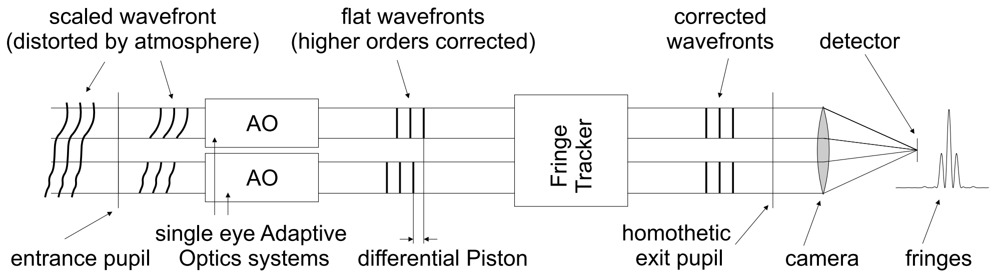

Figure 1. The sketch above illustrates the two consecutive stages of Adaptive Optics (AO) systems, which have to be invoked in order to obtain time-stable interferometric fringes at the combined focal plane of an interferometer.
The left hand side of the diagram shows the incoming wavefront of the observed target after its passage through the turbulent atmosphere of the earth. This wavefront is severely distorted on all spatial frequencies, but nevertheless, it does not exhibit any discontinuities in the mathematical sense. However, after the entry pupil of the interferometer (i.e. the spatially separated primary mirrors) several discrete pieces out of the formerly continuous wavefront are entering the beam-combiner optics.
Since the single-eye AO systems are operating mostly independent of each other, these sensors are only sensitive to wavefront distortions within their own reference frame (i.e. the single-eye pupils). The best correction that can be obtained by these systems will therefore result in wavefronts, which are perfectly flat over the diameter of a single-eye pupil, but which may show a time dependent pistonic phase difference between each other. This low order aberration can only be measured by a sensor (a fringe tracker) at the combined focus of the interferometer, where it can observe the incoming wavefronts of all optical paths simulateously.

Both of these aberrations can only be detected by a sensor at the combined focal plane of the interferometer, i.e. by a dedicated Fringe and Flexure Tracking System. Similar to all other aberrations, a non-perfect correction of either of both effects may reduce the fringe contrast to zero at long integration times of the science detector (i.e. several seconds to minutes), and therefore may preclude interferometric observations.

It is therefore imperative to sense and correct these aberrations in a real-time closed-loop operation in order to ensure a time-stable image quality at highest interferometric resolutions, and to allow for deep integrations with an imaging science detector at the combined focus of any optical interferometer.

3. THE FRINGE AND FLEXURE TRACKING SYSTEM OF LINC-NIRVANA

The general design and principle of operation of the Fringe and Flexure Tracking System (FFTS) of LINC-NIRVANA are based on the following list of specifications:

- Located at an interferometric focus of LINC-NIRVANA, the FFTS analyses those aberrations, which are not detectable by the Multi Conjugate Adaptive Optics systems (MCAO) of the two single-eye telescopes. These two aberrations are the pistonic phase difference between the wavefronts collected by the two primary mirrors, and the misalignment of the optical axes of the two optical paths. All other (high order) aberrations of the wavefront from the observed source are assumed to be corrected to best extent by the MCAO systems of the single-eye telescopes. The two incoming wavefronts of the FFTS can therefore be assumed to be flat within their respective reference frames, i.e. they are free of tip-tilt or higher order aberrations.

- Besides of slow changes of the optical path lengths within LINC-NIRVANA and the LBT (e.g. due to thermal gradients or mechanical flexure), most of the pistonic aberration between the wavefronts of the two telescopes is introduced by the turbulent atmosphere of the earth. The characteristic timescale of these phase variations will therefore be tenth of seconds to milliseconds. The FFTS has to analyse and correct both effects in real-time in parallel (and independently) to an ongoing long term integration of the science detector.

- Mechanical flexure within LINC-NIRVANA itself, as well as within the LBT and the LINC-NIRVANA - LBT interface, give rise to the need for continuous control of the alignment of the optical axes of the two optical paths in the interferometric focal plane. The characterisic timescale of these alignment variations is expected to be tens of seconds to minutes. The FFTS will determine possible misalignment in real-time and relay the respective parameters to the MCAO master control system.

- Before the fringe tracking loop of LINC-NIRVANA is closed (i.e. at the begin of an observing night, or after repointing the telescope), the instrumental pistonic phase difference between the two optical paths may be unknown and off by several micron due to mechanical flexure or temperature gradients. The FFTS must be able to provide sufficient information to initialise the telescope-instrument assembly to zero optical path difference and well aligned optical axes as quickly as possible.
- In order to reduce potential non common path aberrations, the detector of the FFTS shall be located at an interferometric focal plane close to the science detector.
- The FFTS shall be useable on reference stars in a field of view (FOV) as wide as possible, i.e. the FOV shall be limited by the interferometric image quality provided by the MCAO systems of the single-eye telescopes and the beam combiner, and not by the physical size of the used detector array.
- Similar to the science detector of LINC-NIRVANA, the FFTS shall operate at near-infrared wavelengths. Depending on the wavelengths of the science observation the FFTS shall monitor adjacent JHK bands.

According to the specifications listed above, the design of the Fringe and Flexure Tracking System (FFTS) of LINC-NIRVANA is based on a near-infrared detector array (HAWAII 1) of similar pixel size than the science detector (HAWAII 2), what reduces the necessity of optical elements in the non common path to a minimum, since no additional refocussing components are needed. The optical paths towards the science detector and the detector of the FFTS are separated by an observer-selectable dichroic about 100 mm in front of the interferometric focal point of LINC-NIRVANA. This dichroic reflects the selected J, H, or K-band onto the science detector and transmits the respective remaining spectral bands towards the detector of the FFTS. In order to expand the area of operation of the FFTS (i.e. the maximum angular distance of a usable reference star to the optical axis of the science detector) over the physical size of affordable NIR detector arrays, the detector of the FFTS is mounted on a three-dimensional positioning device (see discussion of the mechanical concept in Sect. 3.1). Using this concept the FFTS can pick a reference source from a much larger field of view than the one of the detector array itself.

With regard to the list of specifications given above, the wavefront aberrations which have to be analysed by the FFTS can be divided in two different components: a fast varying part which is due to atmospheric turbulences and a constant (with respect to the integration time of the science detector) or at most very slowly varying part, which is due to mechanical flexure of the telescope - instrument assembly.
The FFTS of LINC-NIRVANA will process these independent aberrations in two dedicated sub-systems: the closed-loop for piston control (see Sect. 3.2) and the closed-loop for flexure control (see Sect. 3.4). Both control loops use the same input data, i.e. the fast sequence of two-dimensional images of the reference source provided by the FFTS detector, but are based on completely different analysis algorithms, time constants, and opto-mechanical hardware elements for correction. For a more detailed description of the principles of operation of these sub-systems please ronfer to the respective chapters of this paper.

The Fringe and Flexure Tracking System of LINC-NIRVANA is a contribution of the I. Physikalische Institut of the University of Cologne.

3.1. opto-mechanical design

A driving specification of the mechanical design of the Fringe and Flexure Tracking System (FFTS) of LINC-NIRVANA is its ability to monitor reference stars which might be located at a distance of up to 30 to 45 arcseconds from the optical axis. On the other hand, the angular resolution of the FFTS has to be at least at the Nyquist limit of the interferometric point spread function, what yields a pixel-scale of the used detector array which corresponds to about 5 $milliarcseconds$. Even large scale near-infrared detector arrays of $2k \times 2k\ pixel^2$ would therefore be able to cover only about $10 \times 10\ arcseconds^2$, a small fraction of the desired area of about $1 \times 1\ arcminutes^2$.

However, since only one reference source has to be monitored at a time, and regarding the high costs of near-infrared detector arrays, the chosen solution to this problem is to mount the detector array on a large scale multi-dimensional positioning stage, which can position the detector to any location within a volume of $30 \times 20 \times 7\ cm^3$. Given a focal ratio of $\sim F/32$ the xy-extension of this volume corresponds to about $1.5 \times 1.0\ arcminutes^2$. The implemented z variance of 7 cm is necessary since the large scale focal plane of LINC-NIRVANA exhibits a significant amount of field curvature.

Unfortunately, the mechanical realisation of this movement is not a trivial task, since near-infrared detector arrays operate at cryogenic temperatures of about 77 K, and since there exists only limited experience in designing and operating large-scale mechanical devices at these temperatures.

In a first attempt to solve this problem the I. Physikalische Institut of the University of Cologne in close cooperation with commercial companies evaluated fully cryogenic designs of such devices, with all moving components operating at 77 K. However, while first laboratory experiments at the I. Physikalische Institut proved that it indeed is possible to achive a reliable operation of such devices in terms that there are no lock-ups, the same experiments showed that the necessary positional repeatability of better than 10 μm (i.e. half the pixel size of a HAWAII 1 detector arry) won't be guaranteed. Furthermore, the development of such a device proved to be far more expensive than it was foreseen in the budget plan of LINC-NIRVANA.

As a result of these persisting questions, the design of the three-dimensional positioning device of the FFTS was modified towards a semi-cryogenic concept. In this new design especially the most critical mechanical components (in terms of tolerances, positional accuracy, positional repeatability and lock-ups) of the positioning stage are operated close to ambient temperatures (however still within the vacuum of the camera dewar), and only a platform carrying the near-infrared detector array and the filter wheel of the FFTS is fed through the internal cryo shields of the camera dewar to the cryo-vacuum environment.

The major advantage of this concept is that the incorporated linear stages operate at (or at least close to) ambient temperatures, what allows the implementation of off-the-shelf devices that easily meet the constraints on mechanical precision at a fraction of the cost of a custom made cryogenic device. Since, nevertheless, the detector array has to be operated at cryogenic temperatures, it is located on top of a cooled detector platform, which is mounted to the positioning device via a 20 cm high and thermally insulating carbon-fiber pole. In addition to the thermal insolation of the pole, the detector platform of the FFTS is separated from the ambient temperature regime of the dewar by two layers of cryo shields. The detector pole is fed through a movable area of these cryo shields, which allows for two dimensional movement over the full area of operation of the FFTS (i.e. $30 \times 20\ cm^2$), while providing a complete thermal and radiative separation of the cryogenic and ambient temperature regimes of the dewar at all positions and at all times.

3.2. closed-loop piston control

As already mentioned in the introduction of the Fringe and Flexure Tracking System (FFTS) of LINC-NIRVANA in Sect. 3, the closed-loop piston control algorithm uses a fast sequence of two-dimensional images of a reference source as input data. Depending on the brightness of the chosen source and the encountered atmospheric conditions the frame rate of the image sequence can be up to about 1 kHz. Assuming the availability of a bright enough reference source, the obtained image frequency can therefore be faster than the characteristic timescale of atmospheric turbulences at all atmospheric conditions.

Out of several promising concepts for the detection of pistonic phase difference in the 2-D images, the algorithm described in the following was chosen to be implemented first. A more detailed discussion of the algorithm can be found in the contribution of Bertram et al. to this conference (#5491-167).

After copying the image-data from a shared memory section (where it was placed by the readout electronics of the FFTS detector array) to a memory region dedicated to the piston control loop, the first step is to determine the vertical (i.e. perpendicular to the interferometric baseline) centre of the 8.2 metre Airy distribution of the single-eye telescopes. Depending on the brightness of the observed reference source (and therefore the signal to noise ratio -SNR- of the image) two different scenarios are possible. In case of a bright source, this can be done directly from the obtained image by collapsing (e.g. averaging or taking the median) the image along the horizontal axis and determining the location of the brightest pixel along the resulting vertical line profile. For

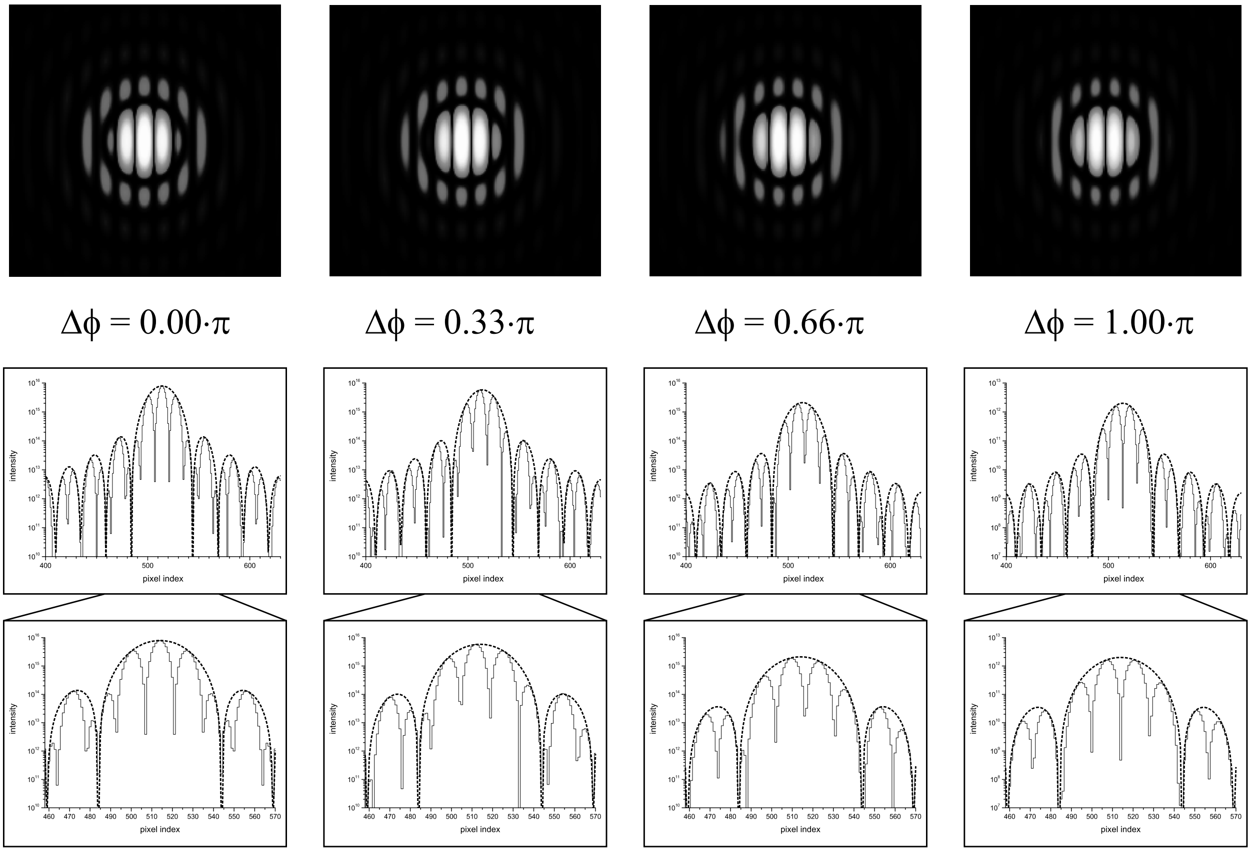

Figure 2. This figure presents the result of numerical simulations of the monochromatic interferometric point spread function (PSF) of LINC-NIRVANA under the assumption of different values of pistonic phase difference (i.e. from left to right $\triangle\phi = 0.00\pi, 0.33\pi, 0.66\pi$ & 1.00π respectively). The simulation is based on a single-eye aperture of 8.2 metres and an interferometric baseline of 14.4 metres.

The upper row of the figure shows the two-dimensional intensity distribution of a reference source (using a logarithmic color map) like it is observed by the imaging detector of the Fringe and Flexure Tracker. Although the graphical representation of the huge intensity differences of the maxima of more than four orders of magnitude can be only partially successful, the images give a fine impression of how the interferometric PSF of LINC-NIRVANA is combined from the superposition of the circular Airy distribution of the individual 8.2 m telescopes, and the interferometric *cos*-based variation of the 14.4 m baseline along the horizontal axis of the image.

The middle and lower rows of images display linear intensity profiles (using arbitrary units) along the horizontal (i.e. interferometric) axes of the 2-D images, with the lower row showing the central regions of the PSF only. While the stepped curves represent the results of the numerical simulations, the dashed lines indicate the Airy distribution of a 8.2 m aperture in absence of interferometric modulation (e.g. perpendicular to the interferometric baseline, or after a loss of coherence).

Comparing the images from left to right one can see how the sinusoidal interferometric intensity modulation shifts along the horizontal axis with respect to the centre of the Airy distribution. For the case of no pistonic phase difference the centre of the 0^{th} order (i.e. white) fringe coincides with the Airy centre, while for the case of 1.00π of differential piston the first interferometric minimum is located at that position.

By the analysis of the intensity line profile and the offset of the interferometric intensity modulation with respect to the centre of the underlying Airy distribution it is therefore possible to derive the amount of pistonic phase difference that was present at the time of the exposure.

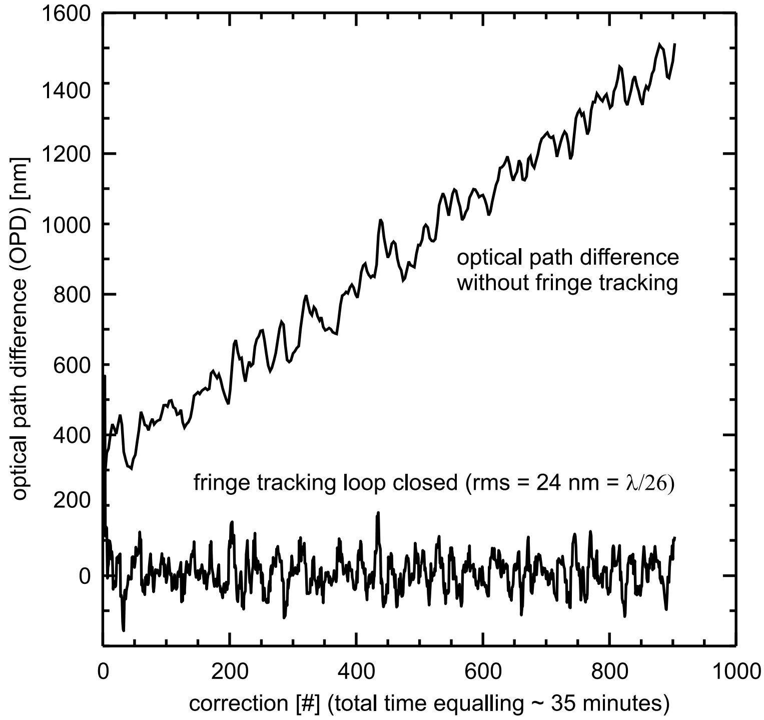

Figure 3. The graph presented above shows the result of a joint laboratory experiment of the Max-Planck-Institute for Astronomy (MPIA) and the I. Physikalische Institut of the University of Cologne (image courtesy of D. Andersen).
Under the lead of Dave Andersen the MPIA built a scaled model of the warm optics of LINC-NIRVANA from the two outside focal points up to a (warm) interferometric focus. (For an indepth discussion of this laboratory setup please refer to the contribution #5491-207 of D. Andersen to this conference.) In combination with a coherent light source (for this example a laser beam of $\lambda \sim 620\ nm$ was used) and a coherent fibre based beam splitter this setup can be used to obtain interferometric fringes at its focal plane, and to study the temporal evolution of the pistonic phase difference (i.e. the shift of the fringes with respect to their Airy envelope) between the two optical paths. The result of such a measurement is presented as upper curve in the figure above, and although the experiment was performed at as stable environmental conditions as possible, it can be seen that the differential piston nevertheless sums up to about one λ during about half an hour.
In a combined effort with LINC-NIRVANA team members of the I. Physikalische Institut of the University of Cologne the MPIA laboratory setup was modified to allow a first experimental test of the piston analysis algorithm of Thomas Bertram (for more details on the used algorithm please refer to Sect. 3.2 of this paper or to the contribution #5491-167 of T. Betram to this conference). For this test the image-data of the CCD camera at the interferometric focal plane were fed to the piston analysis software, which then derived the phase difference from the observed fringe offset, and passed the respective value to a piezo controlled linear stage within the setup to correct the offset. The residual piston after the applied correction is shown as lower curve in the figure above, and although the obtained loop frequency of this first test was only of the order of about 0.2 Hz because of limitations of the used computer hardware (loop frequencies of up to 1 kHz were already successfully obtained with faster computers at the University of Cologne), the obtained piston correction of better than $\lambda/25$ is very encouraging.
Further tests with different loop frequencies, signal to noise ratios, pixel scales, spectral bandwidths etc. will follow in the near future to improve the performance of the applied piston analysis algorithm.

fainter sources, the centre of the Airy distribution is provided by the flexure control loop of the FFTS. Operating at a much slower characteristic timescale (i.e. being able to sum up several individual low SNR images), the flexure control loop is able to determine the centre of the Airy distribution with high precision even in faint images.

As a second step the central rectangle of the 2-D image is collapsed (again by averaging or taking a median) along the vertical axis. The vertical position of this rectangle is centered around the previsously derived vertical centre of the Airy distribution, and its height is selected automatically by the fringe control loop in order to obtain a maximum SNR of the line profile. The width of the rectangle is set to the full width of the 2-D image.

In a final step of the analytical part of the piston control loop, a thereoretical model of the one-dimensional interferometric point spread function is fitted numerically to the observed horizontal intensity line profile (see Fig. 2). Based on fixed and known optical parameters (i.e. the 8.2 metres single-eye apertures, the 14.4 metres interferometric baseline, and the centre of the Airy distribution) the theoretical model depends on only two parameters: the amount of pistonic phase difference between the two optical paths of LINC-NIRVANA, and the overall intensity of the reference source.

After applying an eventual damping parameter to avoid unwanted resonance frequencies the derived pistonic phase offset will be transmitted to the control electronics of the piston control elements (i.e. the piston mirror on top of the camera dewar, and/or the deformable mirrors of the Multi Conjugate Adaptive Optics) of the warm optics of LINC-NIRVANA.

To get a first impression of the performance of this piston control algorithm under at least partially realistic conditions, the piston control loop described above was tested with the LINC-NIRVANA testbed interferometer (Andersen et al. #5491-207) at the Max-Planck-Institute for Astronomy (MPIA). Under the lead of Dave Andersen the MPIA constructed a scaled model of the warm optics of LINC-NIRVANA from the two outside focal points up a (warm) interferometric focus. In a combined effort of team members of the MPIA and the I. Physikalische Institut of the Unversity of Cologne it was possible to combine the laboratory experiment (including the implemented linear stage for piston control) with the piston detection algorithm. The result of this experiment is shown in Fig. 3, and although the reached loop frequency was only of the order of 1 Hz, the obtained piston correction of better than $\lambda/25$ is very encouraging.

In the near future the laboratory setup will be upgraded to faster loop frequencies (computer simulations at the I. Physikalische Institut already successfully demonstrated closed loop frequencies of up to 1 kHz), and the experiment will be repeated with lower SNR, coarser pixel scales, and wider spectral bandwidths in order to improve our knowledge on the performance of the piston control algorithm.

3.3. broadband operation and system alignment

Besides of the closed loop piston control operation of the Fringe and Flexure Tracking System (FFTS) during an ongoing integration of the science detector, the FFTS is also a crucial component for the initial setup and alignment of LINC-NIRVANA at the begin of an observing night, or after a repointing of the telescope, i.e. at times when the closed piston control loop was not active for some time. At these conditions the difference between the two optical paths of the LINC-NIRVANA - LBT assembly is unknown and may sum up to several micron due to mechanical flexure or temperature gradiants. Therefore, before a time-stable observation at interferometric angular resolution the system has to be realigned to zero optical path difference. Assuming a successful operation of the Adaptive Optics systems of the single-eye telescopes (a mandatory condition for all tasks of the FFTS) this alignment will be controlled by the FFTS, too.

To demonstrate this function the I. Physikalische Institut performed numerical simulations of the interferometric point spread function (PSF) of LINC-NIRVANA with different spectral bandwidths (i.e. $\triangle\lambda = 1\%, 16\%\ \&\ 46\%$) and different pistonic phase differences (i.e. $\triangle\phi = 0.00\ \mu m, 1.25\ \mu m\ \&\ 2.50\ \mu m$). The results of these simulations are presented in Fig. 4 of this paper.

Comparing the images of different spectral bandwidths (i.e. rows) it can be seen that the 0^{th} order fringe, i.e. the location of no pistonic phase difference, can be identified by the fact that this fringe shows the maximum intensity contrast between its intensity maximum and its adjacent minima of all fringes in the image. This criterion is due to the physical condition that only for zero phase difference between the two optical paths the

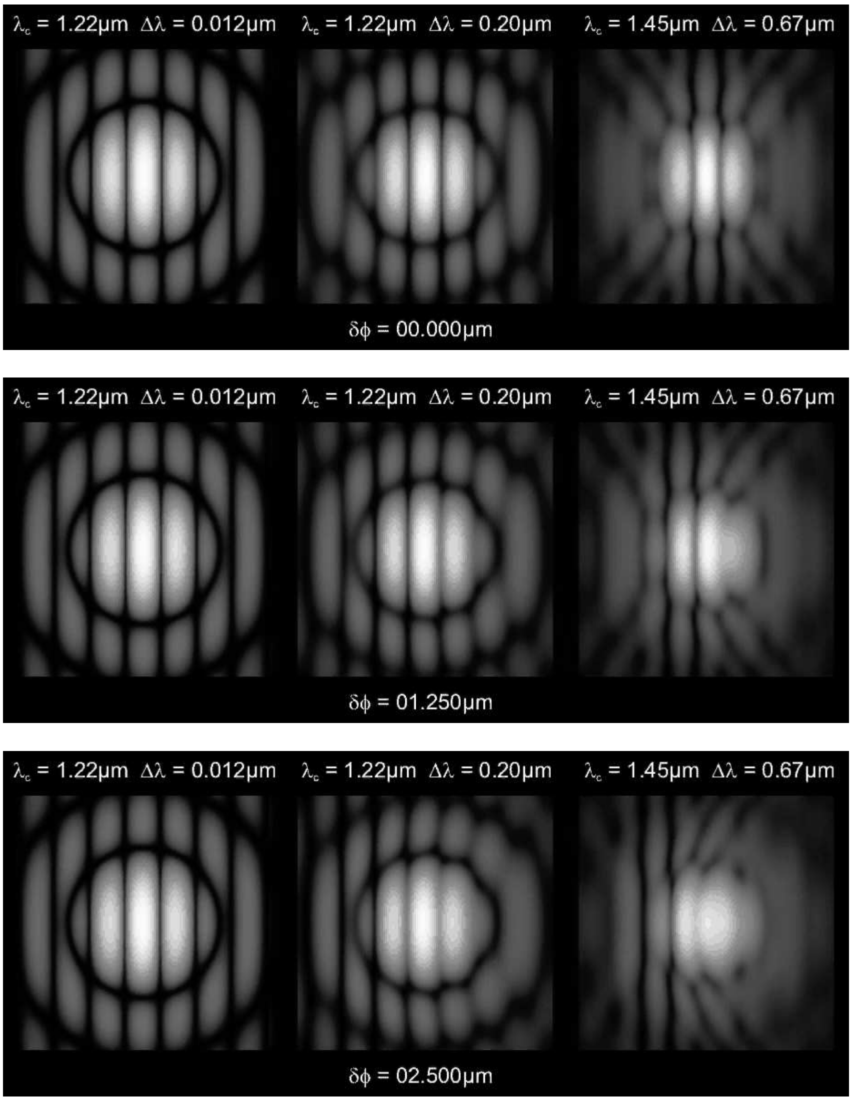

Figure 4. The images above show the results of numerical simulations of the interferometric point spread function (PSF) of LINC-NIRVANA with different spectral bandwidths (i.e. $\triangle\lambda = 1\%, 16\%$ & 46%) and different pistonic phase differences (i.e. $\triangle\phi = 0.00\ \mu m, 1.25\ \mu m$ & $2.50\ \mu m$).
Comparing the images from left to right (i.e. in the direction of broader spectral bandwidth) it becomes increasingly easier to unambiguously identify the 0^{th} order (i.e. white) fringe, which denotes the angular position of no pistonic phase difference. The identification (as well as its designation as 'white') of the 0^{th} order fringe is based on the fact, that only for zero phase difference between the two optical paths the intensity maxima of all wavelengths are located at the same position on the detector, i.e. the angular position of the fringe is achromatic. Since for a limited spectral bandwidth the condition of achromatism holds true (at least to first order) for the 1^{st} intensity minima, too, the 0^{th} order fringe is characterised by the fact that this fringe is showing the maximum intensity contrast between its maximum and its adjacent minima. In absence of high order aberrations, the white fringe is the only fringe which shows close to 100% of intensity contrast.
The unambiguous identification of the 0^{th} order fringe of no pistonic phase difference is especially important for the setup and alignment of LINC-NIRVANA at the begin of an observing night, or after a repointing of the telescope, i.e. at times when the piston control loop was not active for some time. At these conditions the difference between the two optical paths of the LINC-NIRVANA - LBT assembly is unknown and may sum up to several micron due to mechanical flexure or temperature gradiants. Based on the criterion of highest intensity contrast the Fringe and Flexure Tracker will be able to unambiguously identify the 0^{th} order fringe and align LINC-NIRVANA to zero instrumental optical path difference.

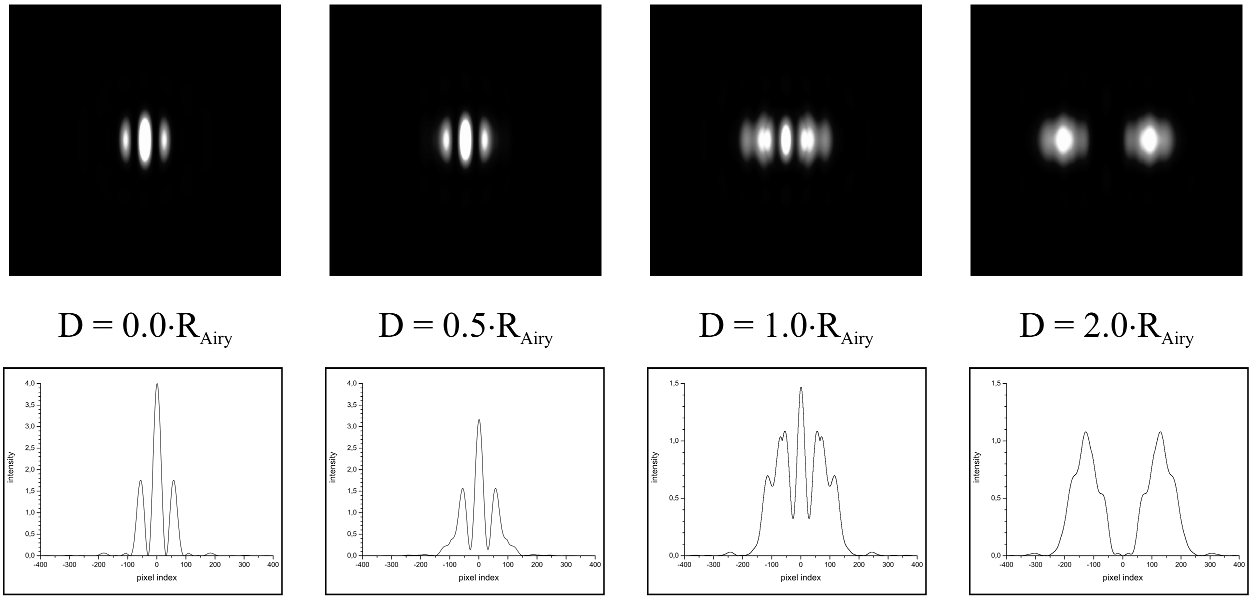

Figure 5. This figure shows the results of numercial simulations of the monochromatic interferometric point spread function of LINC-NIRVANA for the case of increasing misaligment (i.e. $\triangle\alpha = 0.0R_{Airy}, 0.5R_{Airy}, 1.0R_{Airy}$ & $2.0R_{Airy}$ with R_{Airy} denoting the radius of the Airy distribution of a single-eye 8.2 metre telescope) of the optical axes of the two optical paths of the instrument. The upper row of the figure displays the two-dimensional intensity distributions like they are observed by the detector array of the Fringe and Flexure Tracking System (FFTS). Since despite the use of a logarithmic color map a proper representation of the large intensity differences is only partially successful at the 2-D images, the lower row of Fig. 5 shows linear intensity profiles along the horiontal (i.e. interferometric) axes of the images. Comparing the images from left to right (i.e. in the direction of increasing misalignment) it can be seen that up to a separation of one Airy radius of a 8.2 metre single-eye aperture the signal of the FFTS might still be usable for a successful tracking of the position of the 0^{th} order fringe of no pistonic phase difference, since this fringe can still be unambiguously identified by showing the highest intensity contrast.

intensity maxima of all wavelengths are located at the same position on the detector, i.e. the angular position of this fringe is achromatic. Since for a limited spectral bandwidth this condition holds true (at least to first order) for the 1^{st} intensity minima, too, (which therefore are of minimum intensity of all minima in the image) the 0^{th} order (or accordingly called 'white') fringe is therefore showing the maximum intensity contrast of all fringes of the image. In absence of high order aberrations, the white fringe is the only fringe which shows an intensity contrast of close to 100%.

Using this knowledge the images of the FFTS can be used to unambiguously identify the 0^{th} order fringe out of all fringes of the image, and to align the LINC-NIRVANA system accordingly. If the instrumental optical path difference is very large, it might be possible that in a broadband image like the ones presented on the right hand side of Fig. 4 it is not possible to detect any fringes at all, since the fringe contrast is reduced to zero for higher order maxima. In this case the spectral bandwidth of the image can be reduced by switching the filterwheel of the FFTS to a more narrowband filter, what increases the coherence length of the detected signal, so that more higher order maxima get visible before they are blurred out because of chromatism.

3.4. closed-loop flexure control

In addition to the analysis and control of the pistonic phase difference between the two optical paths of LINC-NIRVANA, the Fringe and Flexure Tracking System (FFTS) has to monitor and control the alignment of the optical axes of the two optical paths. Similar to the piston control this duty can only be accomplished by the aid of a detector at the combined focal plane of the system.

As well as for the other functions of the FFTS respective two-dimensional input images of the detector array were simulated by numerical algorithms. The results of these simulations are presented in Fig. 5, and demonstrate that even for an angular misalignment of one Airy radius of a 8.2 metre single-eye aperture the signal of the FFTS might still be usable for a successful tracking of the position of the 0^{th} order fringe of no pistonic phase difference, since this fringe can still be unambiguously identified by exhibiting the highest intensity contrast. According to this finding it will be possible to keep the piston control loop closed even in cases of significant misalignment of the two optical axes.

However, the images in Fig. 5 also show the major difficulty for the analysis of the misalignment of the optical axes. To unambiguously derive the amount of a possible two-dimensional misalignment of the optical axes from an image the algorithm has to be sensitive to the spatially separated circular Airy distributions of the two single-eye telescopes. However, as can be seen best in the linear intensity profiles of Fig. 2 the intensity of the first Airy maxima is already about two orders of magnitudes fainter than the central intensity maximum. Taking into account that the exposures of the FFTS will be as short as possible in order to obtain high loop frequencies of the piston control loop (and therefore a good correction of the fast varying pistonic phase differences), the signal to noise ratio of the images will be to low to unambiguously detect the location of the faint Airy maxima. Fortunately, the characteristic timescale of possible instrumental flexure (which is the only factor leading to misalignment of the optical axes, since all concurrent high order atmospherical aberrations like tip & tilt are corrected by the Adaptive Optics systems of the single-eye telescopes) is much slower than the respective sub-second timescale of pistonic aberrations.

Due to this relaxed timescale the flexure control loop will be able to sum up several tens, hundreds, or even thousands of individual short-exposure frames of the FFTS, and increase the sensitivity to faint signals of the resulting image accordingly. By choosing an appropriate long time-constant of the flexure control loop (i.e. setting the number of individual images to sum up high enough) it is therefore possible to achieve a high enough sensitivity to determine the two-dimensional locations of the Airy distributions of the two single-eye telescopes to the necessary sub-pixel precision. The obtained values will be transmitted to the Adaptive Optics systems of LINC-NIRVANA in order to correct the positions of the optical axes to their nomial values.

4. SUMMARY

The Fringe and Flexure Tracking System (FFTS) developed at the I. Physikalische Institut of the University of Cologne is a crucial component for the proper interferometric operation of the LINC-NIRVANA camera system for the Large Binocular Telescope.

Working towards a scheduled commissioning of LINC-NIRVANA at the telescope in autumn 2006, the work on the development of the FFTS at the Cologne institute is split in two work-packages: The development of the semi-cryogenic opto-mechanics of the device (i.e. the three-dimensional positioning stage of the near-infrared detector array and the cryogenic filterwheel), and the development of the closed-loop analysis algorithms for piston and flexure control. As presented in this paper there is good progress on both fields, and the work-packages are in good agreement with the current schedule.

The design of the 3-D positioning stage was modified so that it is now based on commercial non-cryogenic linear stages, and the manufacturing of the device is sub-contracted to commercial companies.
A first version of the fringe analysis algorithm of the piston control loop is already implemented and successfully passed initial tests at the LINC-NIRVANA testbed interferometer at the Max-Planck-Institute for Astronomy.
The algorithms for the numerical simulation of the complex interferometric point spread function (PSF) of LINC-NIRVANA now take into account all orders of Zernike polynomials of the incoming wavefront, and allow to simulate polychromatic PSFs of arbitrary bandwidths.

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