Beam control for LINC-NIRVANA: From the binocular entrance pupil to the combined focal plane

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ABSTRACT

LINC-NIRVANA is the near-infrared interferometric imaging camera for the Large Binocular Telescope. Once operational, it will provide an unprecedented combination of angular resolution, sensitivity and field of view.

To meet the tight requirements that result from long exposure interferometric imaging over a large field of view, active control beyond fringe tracking and adaptive optics has to be in place in the telescope and in the instrument domain. The incoming beams of the binocular telescope have to be controlled along the entire optical path, from the entrance pupil to the combined focal plane. The beams have to coincide in the focal plane of the science detector, their pointing origins, offsets, orientations, plate scales, and distortions have to match each other and must not change during the observation. Non-common path effects between AO and science channel, flexure and thermal effects have to be compensated and offloading requests from the adaptive optics and fringe tracking systems have to be arbitrated without introducing unwanted optical path length differences or changes in the geometry of the binocular entrance pupil.

Beam Control aspects include pointing, co-pointing and field derotation, active optics and collimation control. In this presentation, the constraints for coherent imaging over a 1.5 arcminute field of view are discussed together with a concept for a distributed control scheme.

Keywords: LBT, LINC-NIRVANA, beam control, telescope control, interferometry, instrument control

1. INTRODUCTION

1.1 LINC-NIRVANA

LINC-NIRVANA\textsuperscript{1} is the NIR homothetic (“Fizeau”) imaging camera for the Large Binocular Telescope\textsuperscript{2} (LBT) and combines two ambiguous technologies in ground-based instrumentation in one instrument: cophased imaging and Multi Conjugate Adaptive Optics (MCAO\textsuperscript{3,4}). Initially introduced as LINC, the LBT INterferometric Camera, LINC is now the first step in the implementation towards the final goal: NIRVANA, the Near-IR/Visible Adaptive iNterferometer for Astronomy. The difference between the two phases of implementation are the capabilities (and the complexity) of the adaptive optics (AO) systems. LINC incorporates a single on-axis wavefront sensor per telescope while NIRVANA provides full MCAO capabilities. The realization of LINC-NIRVANA is a joint undertaking by German and Italian institutes.

LINC-NIRVANA is designed to provide a diffraction limited, interferometric Field of View (FoV) with a diameter of more than 60” and with an angular resolution of, in the best case, less than 10 mas. The full interferometric field will be exploited for off-axis fringe tracking, whereas only the central 10”x10” will be observable with the science camera. The scientific FoV is merely limited by the cost of NIR focal plane arrays. The left and the right 8.2m beam of the LBT are combined by a Cassegrain telescope within the cryostat of LINC-NIRVANA.\textsuperscript{5} The instrument will be installed in one of the bent Gregorian focal stations provided by the LBT and will be subject to an elevation variant gravity vector.

1.2 Constraints for Cophased Imaging

Long exposure cophased imaging instruments, such as LINC-NIRVANA, have to obey a number of additional constraints compared to single aperture AO assisted instruments. A qualitative comparison of the effects to be considered by different exemplary LBT instrument types is given in Table 1.

\begin{table}[h]
\begin{tabular}{|c|c|c|c|}
\hline
Instruments & LINC-NIRVANA & LBT Project Camera & LBT Project Camera \hline
Constraints & & & \\
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\end{tabular}
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Table 1. Relevance of different effects on the incoming wavefronts for different instrument types.

**Beam Combination in the Image Plane:** LINC-NIRVANA will combine the incoming wavefronts in a combined focal plane. This is achieved by superposition of the left and the right image in the same focal plane. To achieve a satisfactory superposition over the required field, the two images have to be very similar. This includes (within tolerances):

- the **coincidence** of the pointing origins.
- **Identical offsets** for both images. In standard operation, both pointing origins will have to coincide with the intersection of the science detector derotation axis and the combined focal plane. The offsets then have to be zero.
- **Identical orientation** of the two images (no differential rotation).
- **Identical plate scales and distortions** of the two images.

**Field Access:** The size of superposed images in the combined focal plane will correspond to a field on sky with a radius of up to 45°. The resolution element corresponds to ~5 mas – resulting in a field radius of up to 9000 resolution elements! This FoV is used to acquire a fringe tracking reference star. The quadratic Science FoV is centered on this fringe tracking FoV and has an edge length of ~ 10°.

**Adaptive Optics:** A complex “Multiple field - Multi Conjugate Adaptive Optics” (MCAO) system will be used on each side. It is intended to provide a medium Strehl correction with a high degree of homogeneity across the entire exploited FoV.

**Cophasing:** The images must not only match each other in their spatial parameters. It has also be guaranteed, that the wavefront segments which belong together arrive at the combined focal plane at the exact same time. Optical Path length Differences (OPD) have to be controlled to remain at zero. A fringe tracker takes care of the closed loop control of OPD. However, the instrument internal range for OPD correction is limited to ~100µm. It has to be possible to offload OPD to the collimation of the telescope.

**Telescope induced OPD:** Another constraint for OPD control is, that the other key control loops (cf. Section 1.3) must operate OPD neutral. If this is not possible for some reason, any telescope (or key control loop) induced OPD must be compliant with the fringe tracker in terms of range and frequency response.
**Long exposure diffraction limited interferometric imaging:** The acceptable tolerances for image superposition and OPD control are driven by the need to do science exposures over time scales that are much larger than the characteristic timescales of the atmosphere (LINC-NIRVANA does not do speckle imaging).

**Field dependent OPD:** As mentioned before, LINC-NIRVANA intends to make use of the large interferometric FoV that is possible with the common-mount design of the LBT. For off-axis fringe tracking and also to ensure a homogeneous PSF morphology across the science FoV, it is important to fulfill the “homotheticity” condition: The exit pupil of the Telescope+Instrument system has to be a homothetic transformation of the entrance pupil. If this is not the case, the OPD will be field dependent. Active Optics and collimation control have an effect on the geometry of the entrance pupil. Hence, they have to consider the required invariant entrance pupil geometry in their control logic.

### 1.3 Key Control Loops in the Telescope and Instrument Domain

The Telescope Control System (TCS) and the Instrument Control System (ICS) contain a set of subsystems with key control loops (open and closed) that have a direct influence on the incoming wavefronts and that provide compensations for most of the aforementioned effects.

- Pointing Control
- Active Optics
- Collimation Control
- (Instrument) Beam Control
- Adaptive Optics
- Phase Control

Figure 1 provides an overview of the most relevant hardware and software subsystems and their associations with either the Telescope or with the Instrument domain. There are several other subsystems which are not mentioned in this context but which are mandatory to operate the telescope. Table 2 shows the task division of the various control loops in the case of LINC-NIRVANA.

<table>
<thead>
<tr>
<th>key control loop</th>
<th>relevant effect</th>
<th>image pos./motion</th>
<th>field rotation</th>
<th>slow aberration</th>
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Table 2. Which control task deals with which focal plane effects

The constituent parts of the control loops (sensor hardware, control software, actuators) can be associated with either the Telescope or the Instrument. A common approach is that the telescope services the focal station.
of the instrument by providing the image quality in the focal plane that is required by the instrument. The instrument then concentrates on obtaining the product without any further active correction of the incoming wavefronts. For LINC-NIRVANA, the task division is not so clear. Several sensors are located in the instrument domain, such as the MCAO wavefront sensors. OPD information can only be obtained in a combined focal plane, which is only realized in the instrument domain.
2. THE BEAM CONTROL SYSTEM OF LINC-NIRVANA

LINC-NIRVANA adopts a distributed control scheme, in which the subsystems (LAOS for Adaptive Optics, LFFTS for Phase Control, LIRCS for camera control) each maintain their own logic. Every control task that can be exclusively associated with a subsystem is realized within the corresponding subsystem. These are the main control loops (fringe tracking, wavefront control) as well as supporting tasks such as positioning of opto-mechanical components. In many cases, however, a coordination between subsystems is necessary. Whenever a task affects more than one subsystem, e.g. if a compensation is seen by a couple of subsystems which are linked in the optical path optical path via photons, the task is assigned to LINC-NIRVANA’s Beam Control System. LBCS is a superordinate system within LINC-NIRVANA’s Instrument Control Software. A software centric view upon LBCS is provided elsewhere. Its tasks can be grouped in four categories:

- **Slow image motion control loop**: Non-common path flexure, atmospheric differential refraction (ADR) and the limited alignment accuracy of the field derotators of the wavefront sensors will cause slow individual motions of the two images in the combined focal plane. Beam control will compensate these slow motions and assure the coincidence of the two pointing centers in the combined focal plane with the center of the science detector. This will be done in closed loop (cf. Section 2.1).

- **Offloading to the Telescope**: Beam control is the central instance within LINC-NIRVANA which requests offloads to the collimation to the Telescope (cf. Section 2.2). These include AO related offloading requests, such as tip/tilt or other low order terms for the individual sides of the telescope, but also requests that have to be balanced between the two sides of the telescope: OPD and the position of the binocular entrance pupil.

- **Instrument internal collimation**: Beam control manages the collimation within the instrument (cf. Section 2.3). It controls critical optical parameters such as focus, pupil and image position (see below) and non-common path effects between AO and science channel. An open loop focus model is required for temperature compensation within the instrument. Whenever possible, flexure will at least be partially compensated in open loop by the component at which it occurs.

- **Parallactic angle distribution**: Six instances within LINC-NIRVANA require parallactic angle information: the four wavefront sensors, the science camera and the fringe tracker each have their own field derotator. The parallactic angle trajectory will be determined by the pointing kernel of the telescope and then distributed within the instrument by the Beam Control System.

2.1 Image Motion Control

The tip-tilt control scheme for LINC-NIRVANA involves several subsystems and control loops:

1. **Adaptive Optics**: The AO systems are sensing and correcting tip-tilt for each side individually with the bandwidth required to deal with any source of tip-tilt.

2. **LN Beam Control**: The coincidence of the two pointing origins in the combined focal plane has to be controlled. Furthermore, non-common path tip-tilt (cf. Figure 2) has to be compensated within the instrument. Only tip-tilt that is seen in both, the science channel and the AO channel, should be compensated by AO.

3. **Collimation Control**: To remain within the actuation range of the deformable mirrors, accumulated tip-tilt has to be offloaded regularly to the collimation of the telescope.

4. **Pointing Control**: Tracking errors or flexure that is common to both sides introduce tip-tilt that is common for both sides. Such a common tip-tilt should be offloaded to the mount rather than to the collimation of the telescope. This requires a central tip-tilt arbitrator, which acts upon the tip-tilt offloading requests of both sides.
Figure 2. Tip-tilt /co-pointing control scheme for LINC-NIRVANA. Fast tip/tilt will be sensed and compensated for each side individually by the MCAO systems. The Highlayer Wavefront Sensors (HWS) sense fast tip/tilt. LINC-NIRVANA’s AO Software Subsystems (LAOS) process the sensors’ signals and send tip/tilt slopes to the so called slope computing “Basic Computational Units (BCU)”. These are integral parts of the FLAO systems. The computed slopes, which consider the tip/tilt signals from LAOS, are then reconstructed and corrections applied with the help of the Adaptive Secondary Mirrors.

The MCAO system of one side does not know about the other side nor about the non-common path between AO and science channel. To maintain the coincidence of the two images in the combined focal plane, the position of each image has to be sensed. This is done with the Fringe and Flexure Tracker, which operates in the same combined focal plane as the Science detector. The position of each image is sent to the Beam Control System. It combines the measured data, flexure and ADR models and sends slope offsets to the left and right LAOS subsystems. They have to consider these offsets in their tip/tilt solutions.

The closed loop tip-tilt control on each side is realized via the adaptive optics systems. The co-pointing will be controlled by LBCS – cf. Figure 2. It receives information on the position of each of the two images in the combined focal plane from the (Fringe and) Flexure Tracker (F)FTS and controls these positions by generating slope offsets which are to be considered by the AO systems on each side.
Figure 3. Collimation/Active Optics Control scheme for LINC-NIRVANA. The net shapes of the Adaptive Secondary mirrors are determined and sent as offloading requests via the Beam Control System to the PSF subsystems. The PSF subsystems in the Telescope Control System will consider the requests in their range-balanced arbitration scheme and offload it to the positions of the bulk optics of the LBT and/or the shape of the Primary Mirror (M1).

By channeling the offloading requests through LBCS, LBCS becomes aware of the slowly changing low order modes the AO systems sense. It can consider this information for the instrument collimation task and sense effects that are common on both sides of the Telescope.

2.2 Offloading to the Telescope

The AO offloading scheme is outlined in Figure 3. On each side, the LAOS Subsystems will receive the command vectors for the Adaptive Secondary Mirrors. The average shape of the shell (the integral of the wavefront, including tip-tilt) will be provided to the LN Beam Control Subsystem. It sends offloading requests to the left and right PSF respectively. The PSF subsystems consider these offloading requests in their collimation tasks.

Figure 4 outlines the OPD offloading scheme. In principle, OPD offloading to the collimation of the telescope could be done by sending different piston term requests to one or both PSF subsystems (left and/or right). The difficulty is in the distribution of piston between the two sides. The PSF arbitrators try to find the most adequate range balanced collimation solution for each side, but they are not aware of each other. To range-balance piston on both sides, a superordinate instance has to be aware of the piston ranges on each side. Based on this information it can issue piston requests to each of the PSFs. Since this is a telescope collimation task, such an instance should be part of the TCS. In Figure 4 this superordinate instance is called “OPD” subsystem. It receives OPD offloading requests from the instrument and sends piston requests to the left and the right PSF,
Figure 4. OPD offloading scheme for LINC-NIRVANA. The Fringe and Flexure Tracker (FFTS) senses OPD in the combined focal plane and corrects it with the piston mirror. The range of the piston mirror is limited to 100µm. Slow, instrumentally induced OPD with a large stroke has to be offloaded to the collimation of the Telescope. The offloading request is sent via LBCS to Telescope Control System. A subsystem within TCS (here called “OPD”) will arbitrate the offloading request and generates piston requests for each side of the telescope. These piston terms then will be considered by the PSF Subsystems on each side.

which consider them in their collimation solutions.

OPD balancing is part of an extended arbitration scheme for the LBT. The positioning solutions for M1, M2, M3, and telescope mount are much more constrained for the Interferometers at the LBT. A revised scheme could be as sketched in Figure 5.
2.3 Instrument Collimation

The Beam Control System can control the position of all critical optical elements in the optical path of LINC-NIRVANA:

- Most lens mounts in the fore optics can be moved along the optical axis to compensate temperature induced focus changes.
- A fold mirror in each arm of the interferometer can be controlled in tip/tilt to maintain the geometry of the binocular exit pupil.
- Dichroic fold mirrors, which direct the visible wavelength domain to the Highlayer Wavefront Sensors and the Near-Infrared domain to the science camera, can be remotely adjusted in tip/tilt. This allows to compensate for non-common path tip/tilt errors between the AO channels and the science channel.
- Annular mirrors in front of the Groundlayer Wavefront Sensors (GWSs) can be remotely adjusted in tip/tilt and linearly in one direction. This allows to adjust the focal planes of the GWSs.
- The cold secondary mirror of the beam combining telescope in the cryostat can be adjusted in tip/tilt to compensate flexure effects of the cryostat.

In addition to directly influencing the position of optomechanical components, the Beam Control System can set slope offsets for the MCAO systems. This is used to control the co-pointing (see Section 2.1), but also to compensate for higher order non-common path effects between MCAO channels and science channel. A Calibration Unit in each arm of the interferometer allows to determine the non-common path aberrations; an NCP model within the Beam Control System then supplies slope offsets depending on the observing conditions.
REFERENCES