Wavefront sensing in a partially illuminated, rotating pupil

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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.

Its pyramid-based layer-oriented MCAO systems are conjugated to the ground layer and to an additional layer in the upper atmosphere. The Groundlayer Wavefront Sensor optically coadds the light of up to 12 reference stars in the pupil, the Highlayer Wavefront Sensor optically combines the light of up to 8 reference stars in its metapupil. Each Wavefront Sensor has its own associated field derotator. It introduces a dependency of the sensor-actuator relation on the angle of the field derotator, which requires regular updates of the reconstructor in closed loop.

In addition, the Highlayer Wavefront Sensor has to be able to reconstruct the incoming wavefronts by analyzing an only partially illuminated metapupil. The distribution of illuminated subapertures depends on the distribution of reference stars. For each pointing, a specific reconstruction matrix has to be generated, which only considers the illuminated subapertures.

In this contribution we will present the concept of LINC-NIRVANA’s wavefront reconstruction mechanism and report on laboratory and on-sky tests.

Keywords: LBT, LINC-NIRVANA, MCAO, Wavefront Sensor

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 ambitious 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. A staged approach is foreseen to manage the complexity of the instrument. Intermediate steps include single-eye MCAO and on-axis interferometry. 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\arcsec 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\arcsec x 10\arcsec 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.

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2. MULTI CONJUGATE ADAPTIVE OPTICS FOR LINC-NIRVANA

Two identical layer oriented MCAO Systems are used for wavefront control in the two arms of LINC-NIRVANA. Each MCAO System consists of a Ground-layer Wavefront Sensor (GWS), a High-layer Wavefront Sensor (HWS) and Deformable Mirrors (DM) which are associated with each sensor. The ground-layer wavefront control loop uses the adaptive secondary mirror of the LBT as actuator, which is conjugated to a distance of 100 m. It is part of the FLAO infrastructure at the LBT. A commercial deformable mirror, conjugated to a distance of 7100 m, serves as actuator in the high-layer control loop.

LINC-NIRVANA implements the multiple field-of-view approach, in which different fields are exploited for ground- and for high-layer wavefront control. Each GWS is designed to optically combine the light of up to 12 natural reference stars in an annular field with an inner diameter of 2 arcminutes and an outer diameter of 6 arcminutes. The central 2 arcminutes will be used to optically combine the light of up to 8 natural reference stars for high-layer wavefront control. All sensors are based on the pyramid wavefront sensing technique.

One of the Ground-layer Wavefront Sensors has seen first light on sky and is undergoing daytime and nighttime testing at the Large Binocular Telescope as part of the Pathfinder Experiment (Figure 1). The other Wavefront Sensors are being integrated on the LINC-NIRVANA optical bench (Figure 2).
Figure 2. LINC-NIRVANA’s optical bench. The left of the two optical paths is fully aligned. The light of the reference sources passes through the telescope focus at the left entrance of the instrument (bottom right corner of the picture). Alternatively a calibration unit can be folded into the optical path at this position. On its way to the HWS, the light is reflected off the 349 actuator Deformable Mirror. A K-Mirror in front of the HWS is used to derotate the field.

3. PUPIL AND METAPUPIL

In pyramid wavefront sensors, the light of a reference star is focused on the tip of a four-sided pyramid. The pyramid splits the light into four beams which form four pupil images on a pixel array detector (Figure 3). Each pupil image is covered by a number of pixels, and each pixel is associated with a sub-aperture of the telescope pupil. The local tilt of the wavefront for a subaperture can be measured by comparing the intensities of the pixels in the four pupil images that correspond to this subaperture. These wavefront slopes are determined for all subapertures. The full set of subaperture slopes is used to perform a modal reconstruction of the wavefront across the pupil. Once determined, the reconstructed modes are used to calculate a compensation signal which is applied to the adaptive mirror in the loop.

The compensating device for the ground-layer loop, the adaptive secondary mirror, forms the telescope pupil. In the pupil the light coming from any direction in the field of view passes through the same circular area. The circular footprints of each of the reference sources coincide in the pupil. Hence, the light of several reference sources are optically coadded and the signal that can be retrieved by the GWS for each subaperture is uniformly increased.

In the high-layer control loop the deformable mirror is not located in the pupil. The circular footprint of each reference source only fills part of the aperture of the deformable mirror (Figure 4). Its position is dependent on the position of the reference source in the field of view. The metapupil is the area that covers the footprints from any source in a 2 arcminute diameter field of view. Its diameter is approximately 1.5 times larger than the diameter of each single footprint. In the optical design the metapupil fills the actuated area of the deformable mirror. The brightness distribution in the metapupil depends on the asterism that is used for wavefront sensing. High signals can be measured for subapertures that are covered by several bright footprints.
Figure 3. Left: Pupil images measured and analyzed by the GWS. The inner obscuration is introduced by the adaptive secondary mirror of the LBT. In the ground-layer loop, the adaptive secondary mirror is used to control the wavefront. It forms the pupil of the telescope - the footprints of all reference sources coincide and fully overlap on the CCD of the GWS, independent of their position in the focal plane.

Right: The actuator map of the adaptive secondary mirror. The color coded actuator commands represent an astigmatism as part of a sequence of KL modes that are applied to calibrate the response of the GWS. Several successful calibration runs were executed with the GWS and the adaptive secondary mirror as part of the Pathfinder experiment.

On the other side it will not be possible to directly measure wavefront slopes for subapertures that are not illuminated by any footprint. Such cases are illustrated by the hatched regions in Figure 4. The modal wavefront reconstruction has to be able to deal with these partially illuminated metapupils. Solutions for the wavefront across the entire metapupil have to be extrapolated based on the available information. For any given asterism the interaction matrix of the HWS is reduced to the columns that represent the calibrated response of the subapertures for which slope information can actually be retrieved. This reduced interaction matrix is inverted into the reconstruction matrix, which is used in the wavefront control loop.

4. CALIBRATION OF THE INTERACTION MATRIX

The calibration of the Interaction Matrix was successfully performed for the GWS as part of the Pathfinder experiment at the LBT.

A setup with an artificial light source is used to illuminate the pupil. A sequence of modes with alternating sign is then applied to the shape of the deformable mirror (Figure 3) and the slopes response of the wavefront sensor to this push-pull sequence is recorded. As part of the processing of the recorded data, the push and the pull records for each mode are identified, extracted and combined to the mode’s row in the Interaction Matrix.

For a calibration of the response of the HWS the metapupil has to be fully illuminated. A calibration unit at the entrance of the instrument can be folded into the optical path. It provides a number of fiber coupled light sources; among them a ring of 8 sources (Figure 5, right) in the telescope focal plane with a diameter that slightly exceeds the 2 arcminute field of view. With this ring of fibers it is possible to entirely fill the metapupil (Figure 5, left). The procedure to calibrate the interaction matrix is the same as for the GWS.
Figure 4. Partially illuminated metapupil (outer red circle) of the High-layer Wavefront Sensors. The deformable mirror that is associated with the HWS is conjugated to an altitude of 7100m above the telescope. Light coming from different reference sources do not fully overlap in the metapupil, as it would be the case in the pupil. Instead, circular footprints are formed on the wavefront sensor CCD. Their distribution depends on the distribution of the reference sources in the Field of View. In this example, up to four reference sources with approximately the same brightness produce the measured intensity distribution across the metapupil. The signal in each subaperture (pixel) depends on the number of overlapping footprints in this subaperture and the brightnesses of the corresponding sources. The hatched regions between the footprints and the 2 arcminute metapupil are not illuminated by any reference source. For these subapertures a direct measurement of the wavefront is not possible.

The dot grid represents the projected location of the actuators of the HWS deformable mirror for a field derotator angle of 0 degree. To prevent large actuator strokes at the rim of the deformable mirror, the outermost ring of actuators (red dots) will be commanded to half the stroke of its neighboring actuators.
Figure 5. Almost fully illuminated metapupil. To be able to calibrate the full response of the Wavefront Sensor, the entire 2 arcminute metapupil has to be illuminated. The outer ring of fibers of a calibration unit has a diameter that slightly exceeds the 2 arcminute diameter FoV. With this geometry it is possible to fill the entire metapupil. In this example only six out of eight fibers are being used, still leaving two small regions without illumination (hatched).

5. ROTATION OF THE (META) PUPIL

As it is the case for every other imaging instrument at an Azimuth-Elevation mounted telescope, LINC-NIRVANA has to deal with changing parallactic angles while the target of interest is tracked on sky. Each wavefront sensor has its own field derotation mechanism, which is introduced between the deformable mirror and the wavefront sensor.\textsuperscript{13} In this specific configuration the field derotator changes the mapping between the actuator pattern on the deformable mirror (or subapertures of the telescope) and the pixels on the CCD of the wavefront sensor. At different derotator angles the wavefront above each subaperture is sensed by different pixels (Figure 6). This requires the usage of derotator angle dependent reconstruction matrices in the control loop. The reconstruction matrices have to be updated on-the-fly after a change of the derotator angle of 1-2 degrees.

In the context of the Pathfinder experiment Interaction Matrices were calibrated for a small number of different derotator angles. These calibrations were used to interpolate synthetic reconstructors also for derotator angles for which Interaction Matrices were not explicitly calibrated.
Figure 6. The relation between subapertures of the Wavefront Sensor and actuators of the Deformable Mirror depends on the angle of the field derotator. Because of the derotator, the distribution of reference sources in the focal plane and with that the distribution of footprints in the metapupil remains invariant. Because the field rotation is compensated in between DM and Wavefront Sensor, the projection of the DM actuators into the reimaged metapupil changes.

REFERENCES


