Natural Guide Star Acquisition for LINC-NIRVANA's MCAO systems

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Abstract. This paper describes the positioning routine for the pickup optics of LINC-NIRVANA's wavefront sensors which is executed during the acquisition of multiple natural guide stars. The near-infrared interferometric imaging camera for the LBT, LINC-NIRVANA, incorporates layer oriented multi-conjugate adaptive optics systems. They can use up to 20 natural guide stars within a 6 arcminute field of view for wavefront sensing. Each guide star is used to sense the turbulence in one of two discrete atmospheric layers. To be able to combine the wavefront information from each natural guide star, opto-mechanical pickup units have to be positioned in the physically large focal planes of the wavefront sensors. These pickup units contain the pyramids of the wavefront sensors. They will be moved in parallel and have to be accurately positioned on the targets. Collisions have to be prevented. The exploitation of large fields of view for multi-object Adaptive Optics is a challenge that will become more and more prevalent with increasing aperture sizes, especially for the upcoming generation of extremely large telescopes.

1 Introduction

With the increasing size of ground based optical telescopes sophistication increases but also the complexity of the Adaptive Optics (AO) systems, which are mandatory for long exposure diffraction limited imaging through the turbulent atmosphere. This development continues with the next generation of extremely large telescopes (ELTs). The correctable field of view (FoV) of traditional on-axis AO systems is very limited. Sky coverage, the fraction of the sky for which sufficient correction can be achieved, is also limited. To overcome these limitations, a number of advancements in AO technology are discussed, which are based on the use of multiple guide stars. Multi-conjugated adaptive optics (MCAO) [1] and multi-object adaptive optics (MOAO) [2] are developments in this direction. The acquisition of the natural guide stars (NGS) plays an important role in these concepts.

LINC-NIRVANA [7] is the NIR homothetic ("Fizeau") imaging camera for the Large Binocular Telescope (LBT) and combines two ambitious technologies in ground-based instrumentation in one instrument: cophased imaging and MCAO. The realization of LINC-NIRVANA is a joint undertaking by German and Italian institutes. The instrument is designed to provide a diffraction limited, interferometric FoV with a diameter of more than 60 arcseconds and with an angular resolution of less than 10 mas in the best case

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Its multiple FoV layer-oriented MCAO systems (one for each arm of the interferometer) are conjugated to the ground layer and to an additional layer in the upper atmosphere, at ~7100 m above the telescope. The ground layer wavefront sensor (GWS) can acquire up to 12 NGS in an annular shaped FoV with a diameter of 6 arcminutes, the high layer wavefront sensor (HWS) can acquire up to 8 additional NGS within the central 2 arcminutes FoV. Ground layer correction will be applied via the adaptive secondary mirrors [6]; an additional Xinetics-349 deformable mirror (DM) on each side is used to apply high layer corrections.

2 High layer Wavefront Sensor Testbed

The HWS and most of its fore optics were integrated in a laboratory testbed (figure 1), which allows for extensive verification of all hardware and software components, for testing calibration methods and for testing new concepts for closed loop operation. Valuable hands-on experience is gained from the work on the testbed. A more detailed description can be found in a separate paper [10].

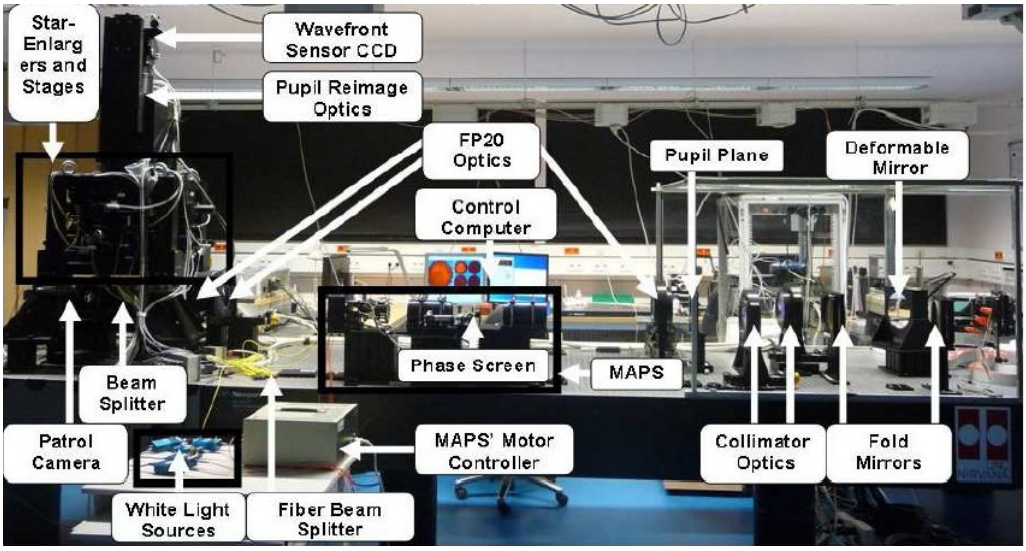

Fig. 1. LINC-NIRVANA's High layer Wavefront Sensor testbed.

The optical path of the setup is shown in figure 2. The Multiple Atmospheric Phase screens and Stars simulator (MAPS) [3] allows us to simulate realistic conditions. The stars are simulated with white light sources, which are connected to a fiber plate in the focal plane of MAPS. Turbulence is introduced by two rotating phase screens. The pupil plane follows MAPS and the collimator optics with the Xinetics DM in the optical path. Additional lens groups then form an F/20 beam. A beam splitter divides the light path. One path is going to the Patrol Camera, which images the entire accessible FoV and is used for guiding and acquisition. The other path leads to the wavefront sensor, where the focal plane is formed and 8 opto-mechanical pickup units, the "Star Enlargers" (SEs) [5] are positioned at the images of the guide stars. Their light is optically combined on the wavefront sensor CCD by the pupil reimaging optics.

3 Star Enlargers

Each SE consists of two lenses and the pyramid itself (figure 3). The lenses reimage the guide star on the tip of the pyramid and introduce a local change of the the F ratio in order to get a suitable PSF size

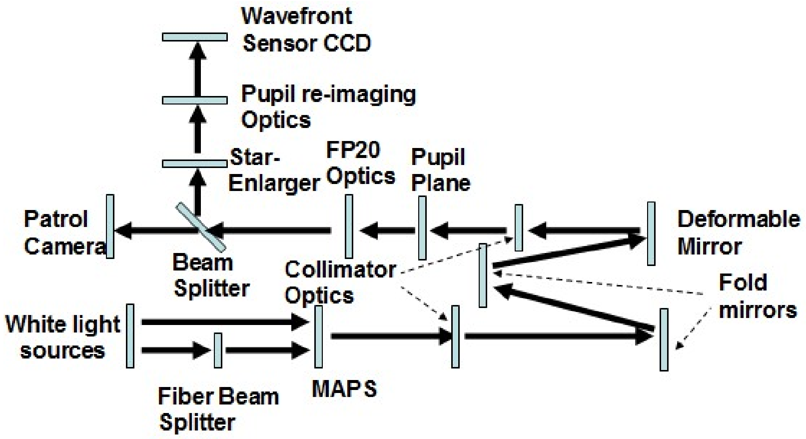

Fig. 2. The optical path of the laboratory setup.

for the pyramid and the suitable size of the pupil images on the CCD. Each SE Unit is mounted on xy micro-positioning stages, which allow it to be positioned in the focal plane. The SEs of the HWS are shown on the right side of figure 3.

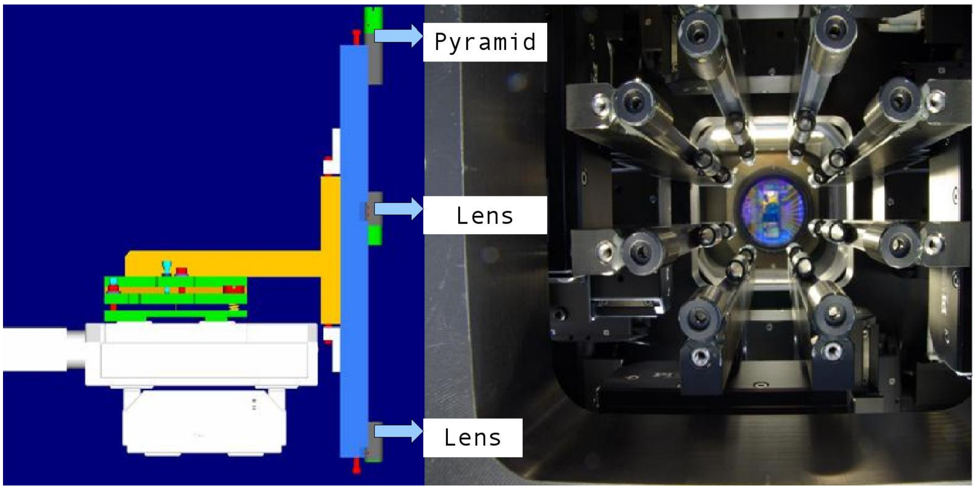

Fig. 3. Left panel: The opto-mechanical design of the Star Enlarger, the micro-positioning stages on the left side are used for the x-y movement in the focal plane. The vertical (blue) bar holds the two lenses and the pyramid. **Right panel:** All 8 Star Enlargers in the High layer Wavefront Sensor.

3.1 Positioning Requirements

- The SE positions shall be represented in the focal plane coordinate system of the wavefront sensor. Focal plane coordinates shall be transformed into SE coordinates by considering the individual mount of each SE and its micro-positioning stages. Further effects that have an influence on the position of each SE or the position of the focal plane have to be considered.
- Collisions between SE units must be prevented.
- To achieve maximum sky coverage, it shall be possible to position each SE as close as possible to any neighboring SE without touching it.

- The SEs shall be movable in parallel, to reduce acquisition time.
- Before the motion of any SE, it shall be verified that all SEs assigned to the requested position of guide stars can be reached.
- A homing procedure shall be provided for initializing the position of each SE. The homing procedure has to provide a collision-free travel to the home position without the knowledge of the current position.

3.2 Arrangement, Travel Ranges, Home Positions

The stages have a travel range of 50 mm × 50 mm, which covers slightly more than a quarter of the wavefront sensor's FoV. Two SE units operate in each of the 4 quadrants. All 8 SE ranges have a slight overlap in the center of the FoV. The arrangement can be seen in figure 4. If not prevented, collisions could always occur between the SEs that share the same quadrant. In the overlap regions collisions could be possible also between SEs of neighboring quadrants and, in the central region, every combination of SEs could collide. The knowledge of the absolute position of each SE in the FoV is essential, not only for the acquisition itself but also to prevent collisions.

Each xy stage uses incremental encoders to determine its position. These require initialization when powering on the system or after a long period of operation. To initialize a stage, it has to be moved to reference switches which mark the home position and the origin of the stage's local coordinate system (cf. figure 4). The SE stages have direction sensing reference switches approximately in the center of travel. With direction sensing reference switches, it is always clear whether the home position is left or right of the current position. The limit switches, which confine the travel ranges of the SE stages, can also be used as references.

When the stages are initialized, their current positions are usually unknown. The initialization sequence, in which the stages are commanded to find their home position, must ensure that SEs with overlapping travel ranges never collide. On the other hand, the initialization sequence shall be as short as possible. Whenever it is safe, stages should be commanded to find their home position in parallel.

It is always safe to move any SE in negative y direction, as the arm that holds the SE extends in this direction and occupies the space already (cf. figure 3). For this reason, the negative limit switch was chosen as a reference for the y direction. In the initialization procedure, all SE will be moved to their y reference positions first. Once all SEs have reached the outer edge of the field, the SEs are commanded to find the direction sensing reference switches in the centers of the x travel ranges. This procedure guarantees a collision free initialization.

4 Coarse Acquisition

The coarse acquisition procedure is outlined in figure 5. The guide star PSFs are identified with the patrol camera. SEs are assigned to the guide stars, based on reachability and avoidance of collisions. The SEs are commanded to the corresponding positions in the focal plane.

4.1 Coordinate Transformations between Patrol Camera and Star Enlargers

The entire FoV of the HWS is imaged by the Patrol Camera, which can be used to determine the positions of the guide star in the focal plane. To determine SE positioning commands based on Patrol Camera images, the transformations between the Patrol Camera's pixel coordinate system and the SE coordinate systems have to be calibrated:

$$(\mathrm{SE}_{ix}, \mathrm{SE}_{iy})^T = A_i \times (x, y)^T + b_i \tag{1}$$

Where $(x, y)^T$ is a point in the Patrol Camera's pixel coordinate system and (SE_{ix}, SE_{iy}) are the corresponding coordinates in the *i*th Star Enlarger coordinate system. A_i is the static coordinate transformation between the *i*th Star Enlarger and the Patrol Camera, and b_i is the shift of the origin of the

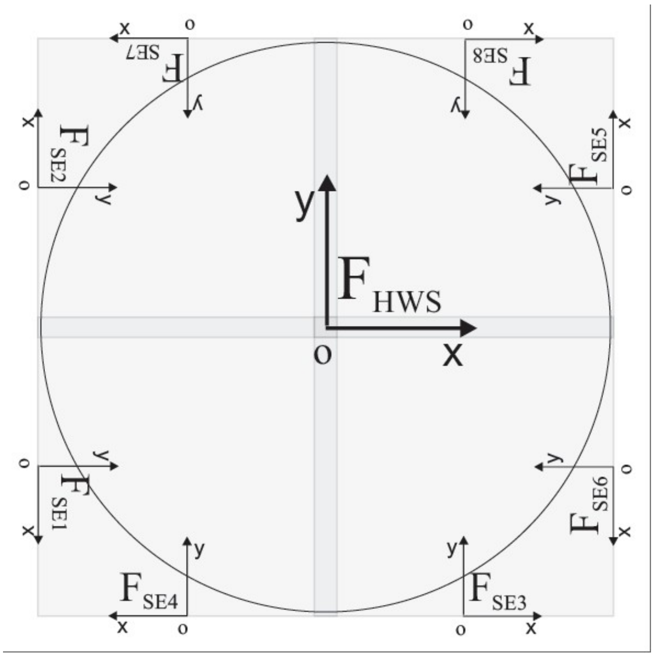

Fig. 4. Coordinate System definition for the LINC-NIRVANA high layer wavefront sensor. The origin of the local coordinate system of each Star Enlarger represents its its home position. In x direction the home position in approximately in the center of the travel range, whereas in the y direction it is always at the negative end of the travel range.

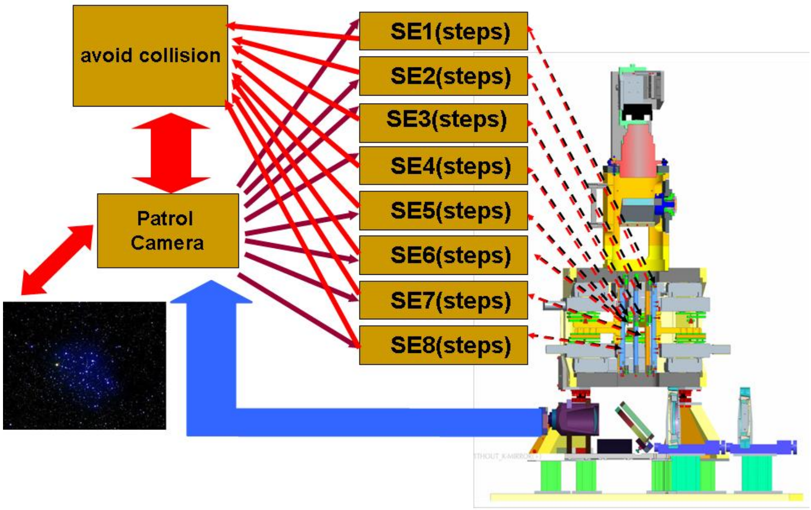

Fig. 5. Coarse acquisition procedure for the Highlayer Wavefront Sensor. The stars' positions on the Patrol Camera are converted to Star Enlarger positions in steps. Potential SE assignments are tested for collisions. The best collision free solution is chosen and commanded to the SE stages.

coordinate system. The inverse transformation is needed to convert local stage positions into the focal plane.

The calibration of A_i and b_i requires a number of light sources in each of the 4 quadrants. Each accessible source has to be acquired with SE_i and identified in the patrol camera. Then, the SE coordinates and the patrol camera coordinates have to be related to each other.

4.2 Star Enlarger Assignment

After identifying the guide stars in the image of the Patrol Camera, the current positions of SEs are converted into the Patrol Camera coordinate system. In a next step the distance between each Star Enlarger and each star is calculated and saved in a distance matrix.

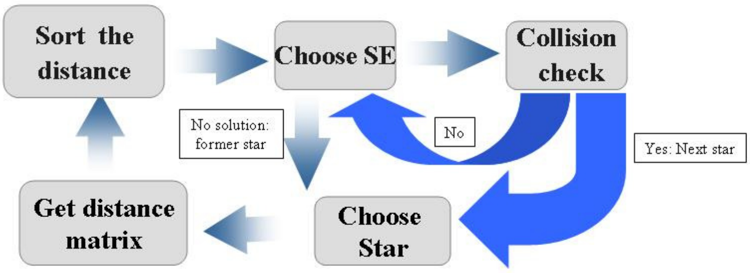

Fig. 6. The assignment of Star Enlargers to guide stars.

In this distance matrix, starting with the first star (cf. figure 6), the nearest SE is identified and assigned to the star. The distance matrix is re-calculated for the second star and the nearest of the remaining SE is assigned. This procedure is executed until all SEs are assigned. In a next step a collision check is done. If the overall assignment passes the collision check, it can be used for the acquisition. If not, the second nearest SE will be assigned to the last star and the overall assignment is checked again for collisions. If it fails again, the third nearest SE is assigned, etc. If none of the possible assignments results in a working solution, the assignment for the last star has to be changed and all combinations tested again. If this fails, the given star constellation cannot fully be used. An assignment solution has then to be found for a reduced number of guide stars.

4.3 Repositioning of the Star Enlargers

Once a working solution is identified, the SEs have to be moved from their current position to their assigned position. The following procedure avoids collisions during this repositioning

1. Move all Star Enlargers to their negative y limits.
2. Move each Star Enlarger to its new x position.
3. Move each Star Enlarger to its new y position.

5 Fine Acquisition

After the coarse acquisition, the Star Enlargers have reached the proximity of the guide star in the focal plane. Due to the limited resolution of the Patrol Camera and calibration inaccuracies, they still have to be fine positioned to center the tip of the pyramid on the PSF. A decenter introduces static aberration and a non-linear response of the pyramid wavefront sensor. This centering is done during the fine acquisition procedure, which is outlined in figure 7.

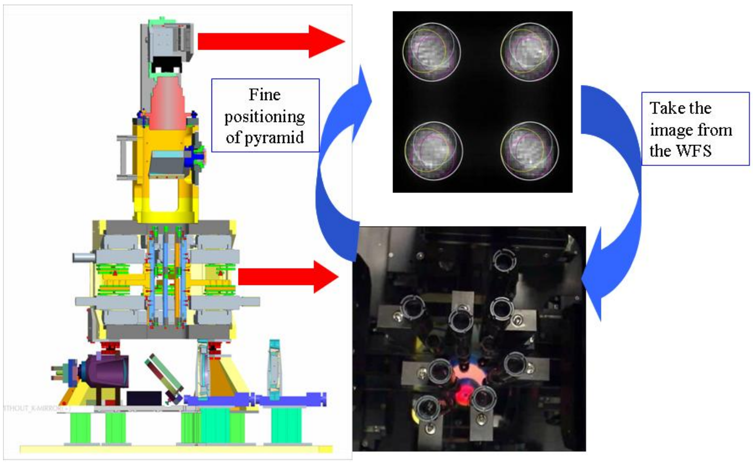

Fig. 7. The wavefront sensor is used for the fine acquisition, in which the position of each Star Enlarger is optimized separately. The wavefront slopes are analyzed and repositioning commands are derived in closed loop until the wavefront error falls below a predefined threshold.

5.1 Calibrating Star Enlargers and Wavefront Sensor

The response of the wavefront sensor to the SE position has to be calibrated for each SE individually with the following procedure:

1. Measure the initial global wavefront slope S_0 for the current SE position.
2. Move the Star Enlarger in x direction by N_x steps;
3. Calculate the global wavefront slope S_{x1}.
4. Move the Star Enlarger back and then in y direction by N_y steps.
5. Calculate the global wavefront slope S_{y1}.
6. Calculate the slopes difference $S_x = S_{x1} - S_0$ and $S_y = S_{y1} - S_0$.
7. The calibration matrix W_i between the ith Star Enlarger and wavefront sensor can be calculated from equation 2.

$$(\mathrm{SE}_{ix}, \mathrm{SE}_{iy})^T = W_i \times \left(\frac{S_x}{N_x}, \frac{S_y}{N_y}\right)^T \tag{2}$$

5.2 Fine Acquisition with the Wavefront Sensor

With equation 2 and the slopes measured by the wavefront sensor a correction to the current position of the Star Enlarger is calculated and applied. This correction reduces the overall tip/tilt sensed by the wavefront sensor. Corrections are continuously determined and applied until the tip/tilt signal is acceptable.

Since the light of the guide stars is optically combined in the wavefront sensor, the fine acquisition needs to be done for each guide star individually. To ensure that only the light of one guide star contributes to the wavefront sensor signal, all SEs except the one that is subject to the fine acquisition are moved in the negative y direction. In this way the light of inactive guide stars does not pass the their assigned SEs. The target positions of the SEs, for which the fine acquisition was already performed, have to be remembered before the position offset is introduced. Once the fine acquisition is performed for all SEs, they are all moved back to the target positions. This concludes the multi object acquisition procedure.

6 Conclusions

In this paper we have presented the multi guide star acquisition procedure for LINC-NIRVANA's layer oriented MCAO system. The procedure was successfully tested in the High layer Wavefront Sensor testbed and will be implemented also in the final AO software. The procedure is not specific to LINC-NIRVANA but might be useable also for other multiple guide star systems.

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