Acquiring multiple stars with the LINC-NIRVANA Pathfinder

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ABSTRACT

The LINC-NIRVANA Pathfinder (LN-PF), a ground-layer adaptive optics (AO) system recently commissioned at the Large Binocular Telescope (LBT), is one of four sensors that provide AO corrected images to the full LINC-NIRVANA instrument. With first light having taken place on November 17, 2013, the core goals for the LN-PF have been accomplished. In this report, we look forward to one of the LN-PF extended goals. In particular, we review the acquisition mechanism required to place each of several star probes on its corresponding star in the target asterism. For emerging AO systems in general, co-addition of light from multiple stars stands as one of several methods being pursued to boost sky coverage. With 12 probes patrolling a large field of view (an annulus 6-arcminutes in diameter), the LN-PF will provide a valuable testbed to verify this method.

Keywords: acquisition, adaptive optics, pathfinder, asterism, wave front sensor, LINC-NIRVANA, efficiency, LBT

1. INTRODUCTION

In this article, we first describe issues and strategy for the general case of acquiring multiple guide stars with any wave front sensor (WFS). We then, after a brief introduction to the instrument, present our on-sky experience with, and future plans for, acquiring multiple guide stars with LN-PF.

2. ACQUISITION SEQUENCE

Figure 1 and table 1 outline the sequence required for multiple-star acquisition. In the sections below we give a description, and a basis for the table 1 time estimates.

Table 1. The six acquisition steps given in figure 1 are repeated here with best-vs-worst time estimates. For each step, the basis for the time estimate is given in a section of this article as indicated in column 3. In column 2 (and throughout this article) we use the acronym "SE," to refer to the LN-PF star probes. SE stands for "star enlarger" and is the term most commonly used to refer to the LN-PF star probes.

<table>
<thead>
<tr>
<th>#</th>
<th>Sequence Step</th>
<th>Section</th>
<th>Time (best case)</th>
<th>Time (worst case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slew to Field</td>
<td>2.1</td>
<td>5s</td>
<td>30s</td>
</tr>
<tr>
<td>2</td>
<td>Center Field</td>
<td>2.2</td>
<td>5s</td>
<td>&quot;several minutes&quot;</td>
</tr>
<tr>
<td>3</td>
<td>Start Derotator</td>
<td>2.3</td>
<td>1s</td>
<td>60s</td>
</tr>
<tr>
<td>4</td>
<td>Assign SE</td>
<td>2.4</td>
<td>1s</td>
<td>&quot;several minutes&quot;</td>
</tr>
<tr>
<td>5</td>
<td>Position SE</td>
<td>2.5</td>
<td>5s</td>
<td>&quot;tens of minutes&quot;</td>
</tr>
<tr>
<td>6</td>
<td>Center SE</td>
<td>2.6</td>
<td>3s</td>
<td>10s</td>
</tr>
</tbody>
</table>

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2.1 Slew to Field

The time estimates given in table 1 for slewing the telescope to the field are taken from our experience with LN-PF at LBT. Slews are fast and reliable. This step does not contribute significantly to overall acquisition time and, as shown in figure 1, can be overlapped with other acquisition steps.

2.2 Center Field

As part of target preparation, for each asterism, a mid-point* is selected which is used as the origin of a Cartesian coordinate system for specifying guide star positions within the focal plane. The location of each star in the asterism is then specified in two coordinate pairs (i.e., in both millimeters in the focal plane and arcseconds on the sky) relative to this mid-point†. The step we refer to here as “center field” then refers to performing the telescope offsets required to align the mid-point with the bearing axis of the derotator.

As indicated in table 1, this operation can be very quick, however, in difficult situations this step can be lengthy. We consider two cases: first the case in which the asterism includes one or more central reference stars visible in the patrol camera‡; second the case of a truly “blind” acquisition with no such reference stars available to guide the centering procedure.

2.2.1 Case 1: Stars Visible in Patrol Camera Field

In this case, the time required to center the field is only the time needed to offset the telescope to a predetermined pixel location on the patrol camera; i.e., the pixel location that aligns the asterism midpoint (defined above) with the bearing axis.

2.2.2 Case 2: No Stars Visible in Patrol Camera Field

In this case, two quantities have to be determined beforehand as part of the observation planning process: (1) a pixel location onto which a reference star will be placed (as described for the easy case in section 2.2.1 above) and (2) the telescope offset required to bring that star into the field of view of the patrol camera and onto that pixel location. A 3-step procedure is then required as follows:

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*For science operations, this mid-point will be chosen to best place the field of interest on the science detector. For on-sky tests with LN-PF, however, this mid-point is simply taken as the 2D average of the guide star locations.

†While the coordinate given in arcseconds on the sky is invariant, the pair given in millimeters in the focal plane depends on the time of the observation and the bearing angle (see figure 2).

‡For LN-PF we use a commercial camera at the direct focus for field acquisition (see left hand panel of figure 5). This is not the true “patrol camera” which will be commissioned with the full instrument, but we use this term here to refer to this commercial camera being used temporarily as a patrol camera only during the LN-PF commissioning phase.
1. Move the telescope as per the predetermined offset.

2. Correct the pointing by moving the star to the predetermined pixel location.

3. Position the asterism in the correct position for the observation by making the step 1 reciprocal offset.

2.3 Start Derotator

As with telescope slews (see section 2.1 above), the act of simply enabling the instrument derotator, and keeping it tracking in accordance with received trajectories, is taken from our experience at the telescope. This step is quick and straightforward as indicated by the best case time given in the table. The worst case time given in table 1 stems from the need to specify a starting point for the rotator. In the default case, in which all star probes are performing equally well and symmetrically cover the WFS field of view, this starting point will simply be computed as that point which starts the rotator at the favorable end of its travel limits. However, for situations when (due to, for example, a technical problem with one or more of the SE) the probes cannot be assigned equally well at all rotator angles, then this step can take more time. To some level, this value can be predetermined beforehand during the observation planning process, however, since it varies depending on the exact time of the observation, some during-acquisition compute time will be required for this operation. See figure 2 for an example.

2.4 Assign SE

The times given in table 1 for this step range from very quick, corresponding to automated assignment, to up to several minutes for manual alignment. The automated method, referred to as the “solver” has been described in a previous article. A prototype GUI for visualizing the automated assignment mechanism is shown in figure 3. This method will be available for LN science operations. However, for the commissioning phases (including LN-PF) we rely on a manual method that employs a GUI for visualization (see figure 4). The GUI shown in figure 4 will also serve as a prototype for a pre-observing planning tool to be used after science operations begin.

<table>
<thead>
<tr>
<th>#</th>
<th>Error Source</th>
<th>Description</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Positioning Errors</td>
<td>Due to mechanical imprecision in either the SE or rotator bearing mechanisms.</td>
<td>These error sources are small, and for many cases negligible, but can continue as potential problem sources even after commissioning.</td>
</tr>
<tr>
<td>2</td>
<td>Tracking Errors</td>
<td>Tracking errors originating from either the telescope drive servo; or stemming from problems (e.g., latency) with the trajectory being communicated to the WFS rotator.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Astrometry Errors</td>
<td>Errors with coordinates derived during the observation preparation process (e.g., omitting proper motion or using the wrong equinox).</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mapping Errors</td>
<td>Errors in the focal-plane positioning to mechanical positioning coordinate system transformation (e.g., sign flips, scale errors, etc).</td>
<td>These error sources can be large during early commissioning, but do not persist into science operations.</td>
</tr>
<tr>
<td>5</td>
<td>Interface Errors</td>
<td>Miscommunication across the telescope-instrument interface (e.g., incorrect mode settings).</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Visualizing the WFS to Sky Mapping. A sequence of focal pane visualizations for a given asterism in a special case in which only 3 of the 12 SE are selectable is shown. This sequence was worked out using the tool shown in figure 4 as part of the observation preparation for the most recent LN-PF run. The two-star asterism (indicated by the green squares labeled B and C) is the same as that shown in figure 4. The sequence shows the bearing rotation as the field transits and then eventually, as seen in the lower right panel, reaches its limit (as depicted by the yellow diamond encountering the black bar that depicts the rotator travel limit).
Figure 3. **SE GUI Snapshots.** Four snapshots of the SE GUI are shown. In panel (a) 5 of the 8 SE have been assigned to their respective target stars in the asterism. In panel (b) all 8 have been assigned. In panel (c) the probes have begun moving toward their respective targets. Finally, in panel (d), all 8 probes are in the correct position and ready for the fine centering step (see section 2.6).
Figure 4. **SKY to Focal Plane Tool.** A prototype GUI for visualizing the LN-PF focal plane with respect to on-the-sky positions of stars in the selected asterism is shown. This GUI serves as a compliment to the GUI shown in figure 3 by presenting more detail of the factors that determine the sky-to-focal-plane mapping. For example, in planning mode, the user can specify the time of the observation and then manipulate the bearing angle with respect to its travel limits (indicated by the yellow diamond traveling between the two black bars separated by 120°). This mode is especially useful when one or more SE are not available due to, for example, a technical problem with the mechanism.
2.5 Position SE

In this step the SE are moved along trajectories that have been pre-computed to be collision free\(^4\) (see figure 3) to the positions in the focal plane that were pre-determined (using the coordinate system described in section 2.2) during observation planning.

As indicated in table 1, this step will, for science operations, be quite fast, but stands as the biggest source of time lost for acquisition during the commissioning phases; and could stand as a potential for lost time due to problems even after science operations begin. First we look at what possible error sources might result in one or more of the SE not arriving within the capture range of its assigned star. Second, we look at what trouble-shooting methods can be applied, if and when this situation occurs.

2.5.1 Possible sources of error resulting in SE positioning problems

Table 2 enumerates the five potential problem sources that might result in one or more of the SE not arriving within the capture range of its assigned star. As indicated in the last column of the table, the first three of these are, in most cases, negligible but will persist into operations, while the latter two can result in large errors but are eliminated during commissioning.

2.5.2 Trouble-shooting SE positioning problems

The first step toward trouble-shooting SE positioning problems comes in determining whether or not a problem exists in the first place. In photometric conditions, it might be possible to know that “everything is fine” with the acquisition by comparing the total flux seen on the WFS to the flux expected from the combined light of all stars in the asterism. Under more typical conditions of variable extinction and seeing, however, this will not be possible. So, until complete confidence in the acquisition system has been established, the SE will have to be positioned one at a time, with a sanity check after each positioning to confirm that the flux seen on the WFS has increased by approximately the expected amount.

If the very first star does not come in, then that star will be offset to the patrol camera field of view to check for a possible astrometry error. Once the first star has been confirmed, if a subsequent star does not come in, then the corresponding SE will be moved in a raster pattern to search for the star (since an astrometry problem at this point is less likely, and the source of the problem is more likely due to one of the other four error sources given in table 2).

2.6 Center SE

In this final step, fine adjustment of each SE is made to center the star on the tip of each pyramid of the WFS. This operation requires backing-off each of the other \(n-1\) SE during the peaking-up operation. This procedure\(^4\) is nonetheless expected to be quite fast on-sky (as reflected in table 1) and has been implemented and tested in the laboratory already using the LN high-layer WFS.

3. LINC-NIRVANA

3.1 Overview

LINC-NIRVANA\(^5,6\) will employ four wave front sensors to realize multi-conjugate correction\(^7\) on both arms of a Fizeau interferometer for LBT. Of these, one of the two ground-layer wave front sensors, together with its infrared test camera, comprise a stand-alone test platform for LINC-NIRVANA called Pathfinder\(^1\) (see section 3.2 below).

3.2 Pathfinder

Pathfinder is a testbed for full LINC-NIRVANA intended to identify potential interface problems early in the game, thus reducing both technical, and schedule, risk. Pathfinder will combine light from multiple guide stars, with a pyramid sensor\(^8,9\) dedicated to each star, to achieve ground-layer AO correction via an adaptive secondary: the 672-actuator thin shell at the LBT. The ability to achieve sky coverage by optically co-adding light from multiple stars\(^10\) has been previously demonstrated;\(^11\) and the ability to achieve correction with an adaptive secondary has also been previously demonstrated.\(^12\) Pathfinder will be the first system at LBT to combine both of these capabilities.
4. ACQUISITION EXPERIENCE WITH PATHFINDER ON-SKY
Since single-star first light for LN-PF was achieved on November 17, 2013,\textsuperscript{2,3} we have worked on-sky toward the goal of multi-star acquisition. During two runs, one in December 2013 and one in March 2014, we have:

1. Verified the derotator mechanism required to fix the asterism with respect to the WFS focal plane.
2. Calibrated and confirmed the location and chirality of the vertical angle (indicated by the red arrow in figure 4) and hence (by applying the parallactic angle) the location and chirality of north and east, on the patrol camera.
3. Measured and confirmed the image scale.
4. Tested the use of small lab CCD cameras to aid in first acquisition work during the December run (see figure 5 left hand panel). These were deemed no longer necessary after coordinate systems and procedures were worked out during that run.
5. Tested the use of star probe screens (see figure 5 right hand panel) during the March run. These were useful for initial tests involving multiple-star asterisms with bright (brighter than 5th R magnitude) stars, but will not be necessary for future testing.
6. Closed loops on a single offset star, which included continuous upload of a new reconstructor to account for pupil rotation.\textsuperscript{13,14}

5. CONCLUSION
We have presented the sequence of steps for acquiring multiple guide stars on a WFS, as well as the expected times and potential pitfalls that might be encountered for each of those steps. This general approach will now be applied to LN-PF, a ground-layer AO system being used as a testbed for LINC-NIRVANA at LBT. The first steps of this process have begun and these were described in section 4.
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