LINC-NIRVANA Pathfinder: Testing the next generation of wave front sensors at LBT

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ABSTRACT

LINC-NIRVANA[1] will employ four wave front sensors to realize multi-conjugate correction[2] 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. 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[3,4] 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 coadding light from multiple stars[5] has been previously demonstrated;[6] and the ability to achieve correction with an adaptive secondary has also been previously demonstrated.[7] Pathfinder will be the first system at LBT to combine both of these capabilities.

Since reporting our progress at AO4ELT2,[8] we have advanced the project in three key areas: definition of specific goals for Pathfinder tests at LBT, more detail in the software design and planning, and calibration. We report on our progress and future plans in these three areas, and on the project overall.

Keywords: adaptive optics, GLAO, LBT

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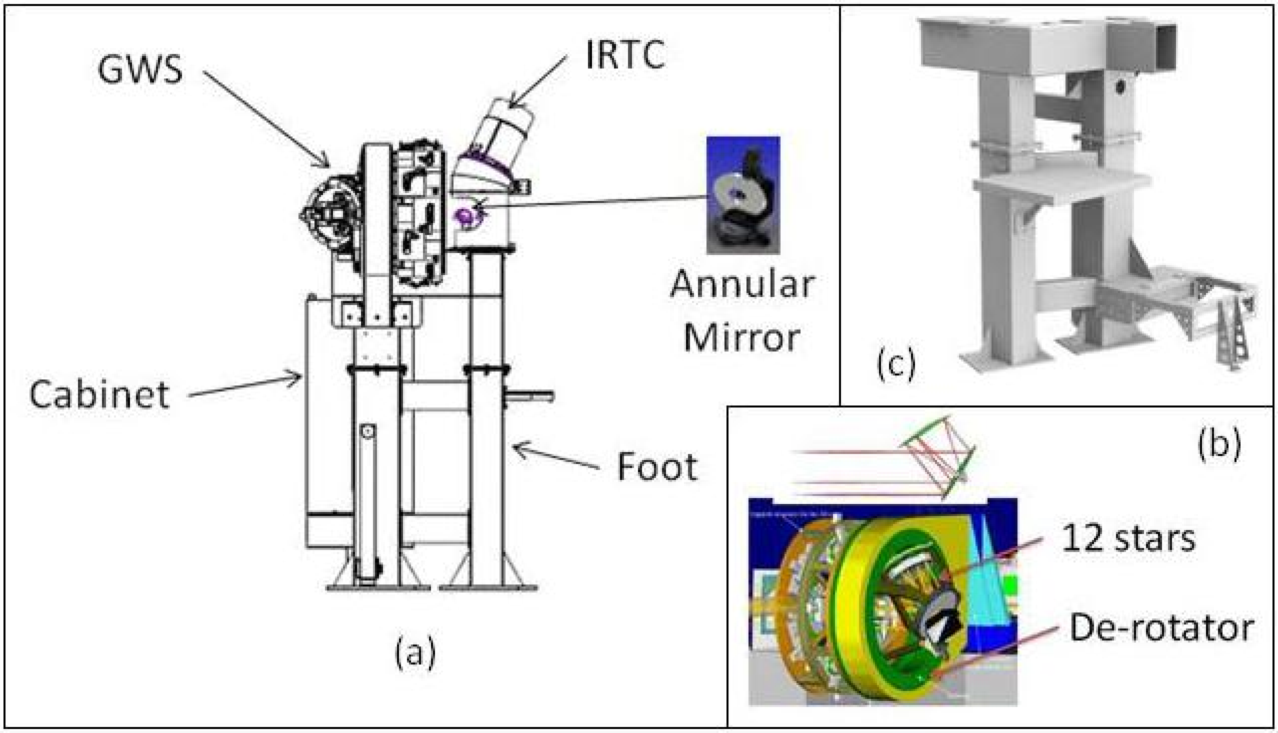


Figure 1. Five physical components comprise the LINC-NIRVANA Pathfinder. Reading counter-clock-wise from lower right in panel (a) these are: the support structure, commonly known as the *Foot*, an *annular mirror* that picks off a portion of the F15 beam for wave front sensing; the infrared test camera (*IRTC*); the ground-layer wave-front sensor (*GWS*); and the electronics *cabinet*, containing motor controllers, CCD read-out electronics, and a specialized unit for computing wavefront slopes.[9] The entire assembly is viewed as seen by a photon coming in from the LBT DX (right-hand side) tertiary mirror. A small (approximately 30 arcsecond diameter) portion of the beam is folded up to the IRTC, while the surrounding annulus, approx. 1 and 3 arcminute inner and outer radii, respectively, is folded to the GWS on the left. In the figure, the first of these two fold mirrors can be seen (near the tip of the arrowhead indicating the location for the annular mirror). The second of these two, the annular mirror, is not shown in its location on the foot, only as a small rendering near the label. This large mirror will reflect starlight from up to 12 references which are then optically coadded by the GWS as shown in panel (b). A second rendering of the support structure is provided in panel (c).

1. INTRODUCTION

Figure 1 provides a view of Pathfinder's five physical components. Because these components, and the Pathfinder project in general, have been described previously,[8] we will not provide further detail of the Pathfinder physical make-up in this report. Instead, we begin in section 2 with the Pathfinder goals. A discussion of software, with an emphasis on modular design and interfaces*, follows in section 3. Finally, we discuss calibration in section 4 and then give our conclusion in section 5.

2. GOALS

2.1 Core Goals

For Pathfinder we have six specific core goals; two to be performed in the daytime without light, two to be performed in the daytime with light (a wavefront provided by a calibration light source illuminating the LBT adaptive secondary; see figure 6 below), and two on sky. Targets for these last two tests include those given in table 1. As seen in figure 2, each of the first five core tests lies on one of three independent tracks. Goal 1

*Pathfinder is all about interfaces. By testing interfaces ahead of full LINC-NIRVANA delivery, we reduce risk and accelerate the schedule.

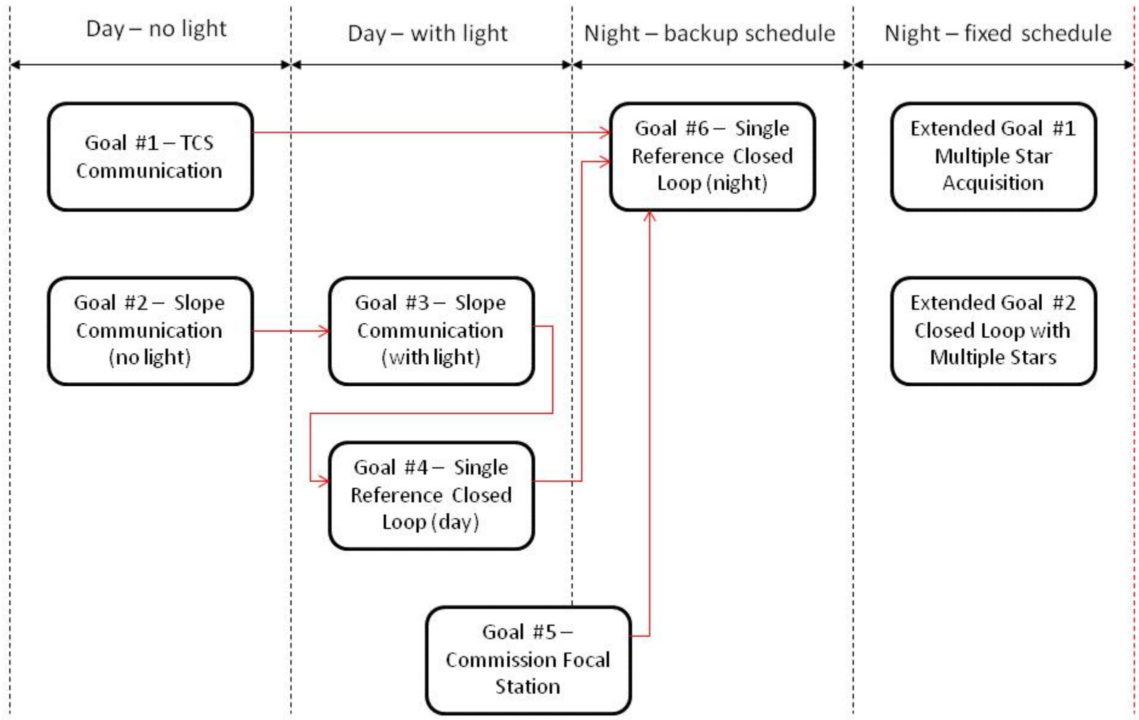


Figure 2. Flow of activity for the six core Pathfinder goals, and two of the four extended goals, to be met during commissioning at LBT.

on the first track demonstrates our ability to communicate with the telescope control system (TCS). Goals 2, 3, and 4 on the second track demonstrate our ability to sense the wavefront and then command the adaptive secondary accordingly. Goal 5 on the third track demonstrates we have performed the steps requisite for any LBT instrument installation (e.g., establishing correct collimation parameters). These three tracks then come together in the culminating, sixth, core goal: closed loop GLAO on a bright star.

This sixth goal subdivides into two sub-goals, closed loop with and without field rotation. For the latter we will use engineering objects like those listed in table 1 and, as that table and associated figure illustrate, we will be able to do this with bright stars (5th Vmag and brighter). This program is thus ideal for scheduling via a backup arrangement performed in conjunction with the scientific programs of our collaborators.

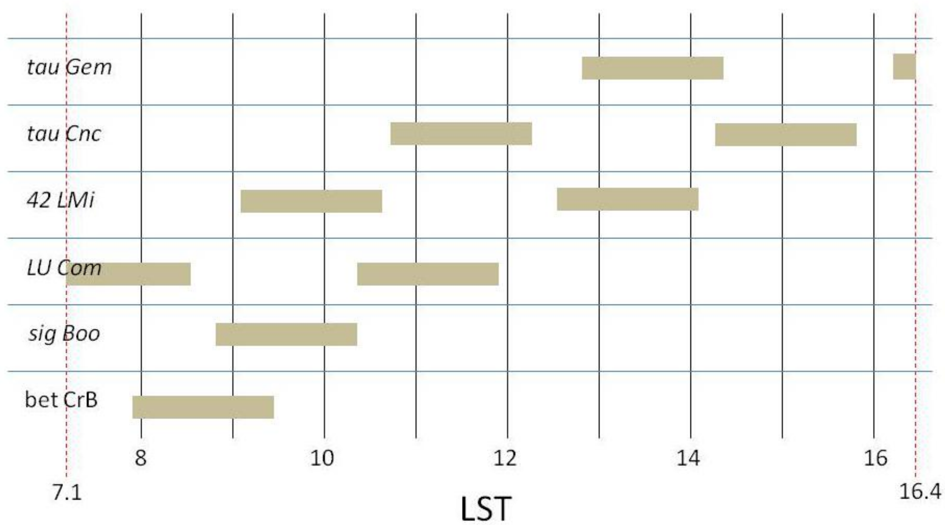
2.2 Extended Goals

Because the fundamental goal of testing interfaces is largely met by accomplishing the six core goals discussed in the previous section, the extended goals presented here are considered only as optional at this point in the Pathfinder project. Depending on the level of success achieved and time required for the core goals, these extended goals may be pursued. They probe questions of expected performance for full-up LINC-NIRVANA and will potentially tell us more about how variations in the LBT environment contribute to instrument systematic errors. Only two of the four extended goals are shown in figure 2. These first two extended goals require dedicated, scheduled, observing time. They are essentially repeats of core goals 5 and 6, respectively, but with fields more closely representing the science fields ultimately required for science operations with LINC-NIRVANA. The remaining two extended goals, a flexure test and a temperature stability test, are not shown in the figure because they have scheduling requirements that are less stringent and can be performed during the day or as part of a backup engineering program on science nights.

Table 1. As seen in figure 3, long periods of slow rotation occur at Mount Graham for objects near declination 30 degrees. See section 3.2 for details of these tables and the plot.

Target:	Vmag	RA	Dec
tau Gem	4.4	07 11 08.4	+30 14 43
tau Cnc	5.4	09 08 00.0	+29 39 15
42 LMi	5.3	10 45 51.9	+30 40 56
LU Com	4.9	13 00 16.5	+30 47 06
sig Boo	4.5	14 34 40.8	+29 44 42
bet CrB	3.7	15 27 49.7	+29 06 21

Target:	RA	ha@midnight	pre-Transit		post-Transit		Total Hours of
	(as decimal)	(11.2 LST)	Start	End	Start	End	Slow Rotation
tau Gem	07.2	4.0 W	12.7	14.2	16.2	16.4	1.5 + 0.2 = 1.7
tau Cnc	09.1	2.1 W	10.8	12.3	14.3	15.8	1.5 + 1.5 = 3.0
42 LMi	10.8	0.4 W	9.1	10.6	12.6	14.1	1.5 + 1.5 = 3.0
example	11.2	0.0	8.7	10.2	12.2	13.7	
LU Com	13.0	1.8 E	6.9	8.4	10.4	11.9	1.3 + 1.5 = 2.8
sig Boo	14.6	3.4 E	-	-	8.8	10.3	0.0 + 1.5 = 1.5
bet CrB	15.5	4.3 E	-	-	7.9	9.4	0.0 + 1.5 = 1.5



3. SOFTWARE

The final software system for LINC-NIRVANA exceeds what will be needed for the Pathfinder project. For example, one of the key software systems, which performs functions associated with fringe tracking†, is not required. Primarily, Pathfinder makes use of those modules being developed for LAOS, the LINC-NIRVANA adaptive optics software system. Figure 4 provides the top-level breakdown structure for LAOS. Table 2 indicates which of the LAOS modules will be needed for Pathfinder, and to what degree those modules will be later re-used for the high-layer AO system‡. Thanks to the extremely modular nature of the LAOS software design, Pathfinder provides an indirect benefit beyond the primary goals given in section 2.1: It includes testing (in a

†called LINC Fringe and Flexure Tracking System (LFFTS)

‡See our previous report[8] for a description of how the high-layer and ground-layer AO portions of LINC-NIRVANA interact and their respective roles in the project phases: Pathfinder, then LINC, then LINC-NIRVANA.

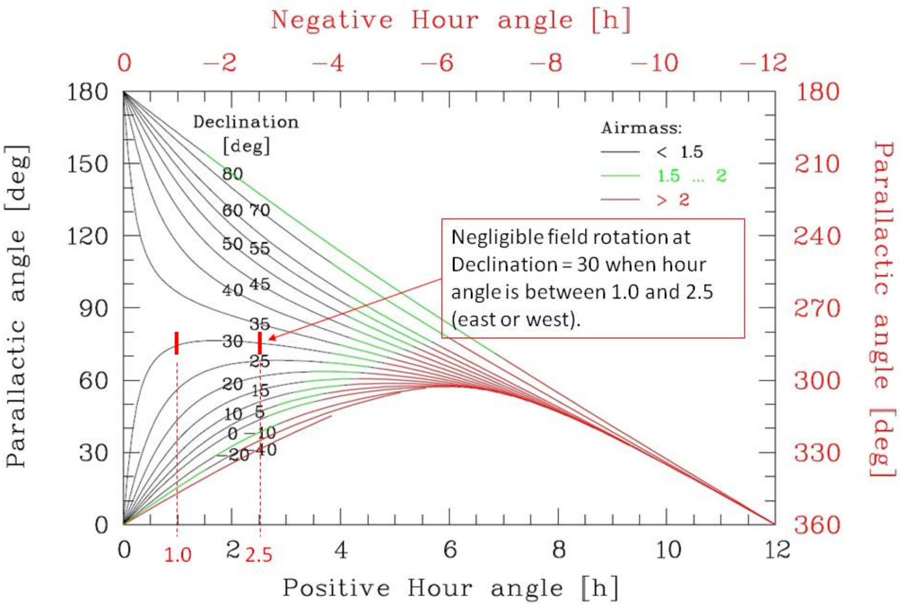


Figure 3. Parallactic angle as a function of hour angle for Mount Graham. The interval of slow change for an object at declination 30 degrees is indicated.

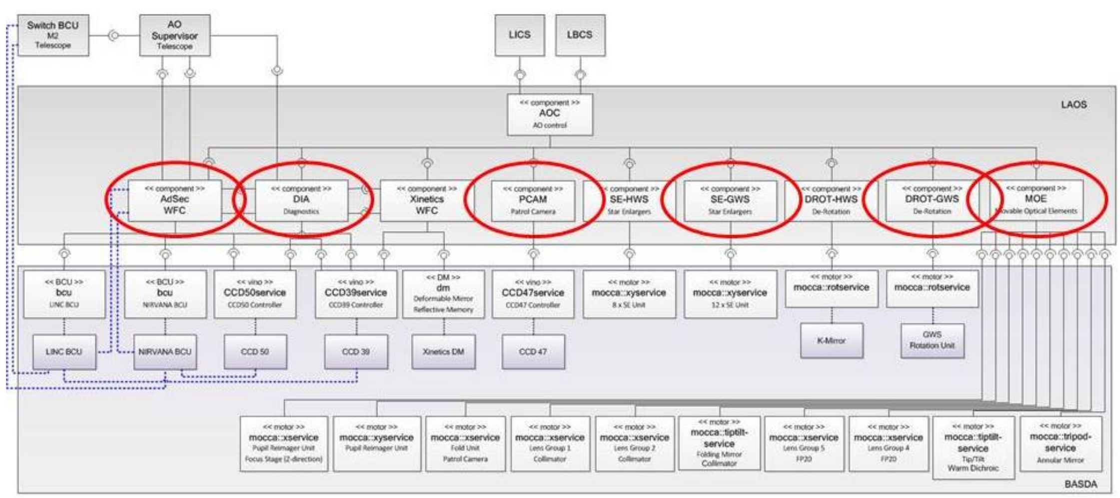


Figure 4. Top level break down structure for the complete AO software system. As described in the text, only six of the modules that appear on the second row of this figure, Adsec-WFC, DIA, PCAM (partially), SE-GWS, DROT-GWS, and MOE (partially), are required for Pathfinder.

final, at-the-telescope, environment) of software, like the high-layer AO software, that is beyond what is required for Pathfinder, but will be required for LINC when it arrives approx. 18 months after Pathfinder.

We have selected two areas of the LAOS software needed for Pathfinder that pose interesting challenges, and hence require more creative solutions. These two applications, CCD Display (see section 3.1) and acquisition (see section 3.2), fall under the AdSec-WFC/DIA and SE-GWS/PCAM portions of LAOS, respectively (see figure 4

Table 2. The function, and planned re-use for the full instrument, for each of the six LAOS modules required for Pathfinder are given. See text for discussion of re-use. See figure 4 for a view of these six modules in the context of the full AO software design.

Formal Name:	Functional Description	Re-Use with the Full Instrument
AdSec-WFC	This module provides all Pathfinder functionality associated with wave front control (WFC) and, in particular, interfacing with the existing adaptive secondary control system at LBT.	Considerable for the LINC phase; but only moderate for NIRVANA. For NIRVANA, although the same structure is used, the platform is a general purpose Linux processor instead of the FPGA platform.
SE-GWS	This module provides all Pathfinder functionality for positioning pyramids at star locations in the focal plane; including adjustments for flexure.	Very high. The software for positioning pyramids on their star enlarger (SE) mounts is nearly identical for both systems.
DROT-GWS	This module provides all Pathfinder functionality required for field derotation of the ground layer wavefront sensor (GWS). This includes communication with external modules to continuously update the reconstructor to address the effects of pupil rotation[10]	High. Although the derotation mechanisms, a large bearing versus a small K-mirror, differ; the motor controller and all the basic functionality and interaction with external modules (e.g., offloading systematic rotator errors to SE motion) will be identical.
MOE	This module provides all Pathfinder functionality for moving optical elements; for example focus and translation of the CCD in the wavefront sensor and tip/tilt adjustments of the annular mirror.	Moderate. The optical elements moved by the two AO systems differ. Although at the device layer (see figure 4) this motion control is identical, at this higher layer the unique properties of the different optical elements must be addressed.
DIA	This module provides diagnostic information from all hardware and software systems in a single stream to various clients, including an operator display.	Identical
PCAM	Field acquisition via a patrol camera. We will possibly use some PCAM software, adapted for use with the IRTC, (see section 3.2 below) to better achieve the extended goals (see section 2.2 above) for Pathfinder.	Moderate. Source extraction and automated field identification will be common.

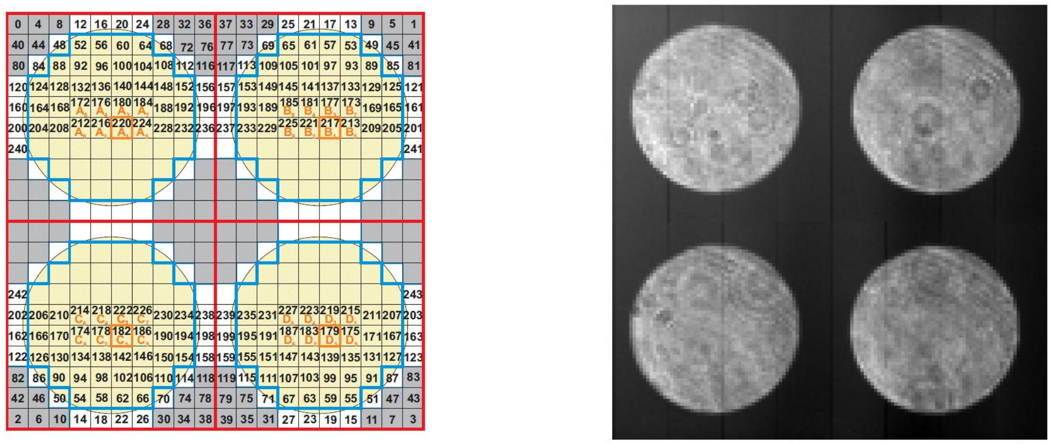


Figure 5. Two views of the pupil as it is split spatially by the pyramid into four positions on the CCD. The figure on the left shows the read-out order for a typical CCD (in this case the CCD-39 to be used for the high-layer AO system; the CCD-50 for Pathfinder has more channels (16) however the concept shown here is the same). The figure on the right (taken recently during alignment tests of the GWS as it is commissioned at MPIA) shows how pupils will appear to an operator viewing an image display of the CCD-50.

and table 2). Because these are needed for Pathfinder, developing these solutions has been accelerated on the software schedule, ahead of those LAOS modules needed later for the remainder of LINC. In the remainder of this section, we give some details of these two software modules.

3.1 CCD Display

Developing and commissioning software for controlling a deformable mirror (DM) on a telescope operating its own adaptive secondary is often considered more challenging than developing software for an AO system that can be integrated and tested with a small deformable mirror (DM) in the laboratory. But in some ways this task is less difficult. Most notably, from slopes to actuator voltages, it is possible to use existing hardware and software[11] for all but the task of providing the reconstruction matrix itself.[10] But the task of providing the measured wavefront as slopes to the LBT system for Real Time Reconstructor (RTR) computations[9] in a timely fashion, requires that CCD pixels be streamed directly to an FPGA system dedicated to the task of slope calculation. This complicates the software required for what is typically a trivial task: displaying the CCD image to the operator.

The primary function required of the software reading out the CCD within Pathfinder is getting slope information to the LBT adaptive secondary system[11] as quickly as possible, within a single kilohertz frame. To meet this speed requirement it is necessary to tap directly into the raw pixel stream emitted by the Scimeasure controller. Strictly speaking, the 2-D spatial geometry never needs to be known by the CCD software for closing loops as long as the same, per-frame, slope ordering is used for both the calibration and the loop. Typically that slope ordering is dictated by the goal to get those slopes sent out as soon as possible (see figure 5 left-hand side). However, for operations and diagnostic purposes, the AO operator needs to see the 2-D rectified image of the four views of the pupil as they appear on the CCD (see figure 5 right-hand side).

The LINC-NIRVANA software for the GWS, tested first with Pathfinder, will optimize slope calculation and provide a diagnostic image display for the operator without sacrificing performance of either function. Server-side software will provide the image display, while FPGA firmware, by way of a look-up table, will provide optimal slope calculation. Further, this software will be developed in a modular fashion that ensures synchronization between the server-side C-code and the FPGA look-up table generation.

3.2 Acquisition

For initial Pathfinder tests with bright stars and slowly rotating fields we do not anticipate difficulty with acquisition. As seen in table 1 and the associated figure, long periods of slow rotation occur at Mount Graham for objects near declination 30 degrees.[§] These periods fall into 2 intervals, approximately 1.5 hours long, before and after transit. The pre-transit interval lies between 2.5 and 1.0 hours of hour angle east, and the post-transit interval lies between 1.0 and 2.5 hours of hour angle west. For this example we chose 15 March 2013[¶]. On that night the LST at midnight local time on Mt Graham will be 11.2 and thus the periods of slow rotation for an object with coordinates (11.2, +30) will be 8.7 to 10.2 LST and 12.2 to 13.7 LST. As seen in the table, objects at 30 degrees declination that are later or earlier have the LST bounds of their slow-rotation intervals shifted accordingly. Early and late objects are lopped off by the twilights, which occur at 7.1 (evening) and 16.4 (morning). The analogous windows of slow rotation for the objects from the table are given, again expressed in LST, along with the total time available for observing each object during periods of slow field rotation. This information is shown graphically in the figure below the table. From this figure, it can be seen that it will be possible at almost any time of a night to observe bright targets during their periods of slow field rotation (if, for example, Pathfinder was being used in a stand-by scheduling mode).

We have demonstrated in the LINC-NIRVANA lab at MPIA[12] that centering the X-Y stage that positions each pyramid can be performed using standard techniques when SNR is high. Moreover, the initial Pathfinder demonstrations will be conducted with a single reference; further simplifying acquisition.[‖]

On the other hand, closing loops with multiple faint stars (the raison d'etre for our WFS, but not required for Pathfinder core goals) requires an acquisition process that will be far more difficult with Pathfinder than it will be once the ground-layer system of Pathfinder is working in concert with the high-layer sensor as part of the full-up LINC-NIRVANA instrument. Full-up LINC-NIRVANA allows simultaneous images, via a beam-splitter, of the central 2 arcminute field. Software which has already been developed for this patrol camera to perform source extraction and field identification may be adopted for use with IRTC images used in place of the patrol camera. This depends on future decisions related to the extended goals, however, preliminary studies indicate that the software effort required to perform this repackaging is not great. Further, testing the patrol camera software in this way would provide a further benefit for the full-up LINC-NIRVANA system, gained from the Pathfinder experiment.

4. CALIBRATION

As for most AO systems, it will be necessary for Pathfinder to measure how characteristics of the deformable mirror interact with the complete optical system up to the wavefront sensor. This procedure, commonly referred to as calibrating the *interaction matrix* (a matrix which is then inverted to produce the matrix for reconstructing the wavefront), is a process ideally carried out during daytime with an artificial light source.[7] Recent advances have been made with the use of star light for this purpose, but these methods still require expending the scarce resource of night telescope time, a resource which is particularly precious for the Pathfinder effort.

Two significant breakthroughs have taken place since we last reported Pathfinder status:[8] an appropriate light source has become available at LBT and we have realized that an on-axis source can be used to illuminate one of our off-axis pyramids via a slight tilt of the tertiary, without significantly distorting the wavefront being measured. These breakthroughs and the full light path are summarized in figure 6.

5. CONCLUSION

As of this writing, the Pathfinder effort is on its way to achieving first light during 2013. We have provided an update on our progress in three key areas: definition of specific goals for Pathfinder tests at LBT, detail of software design and planning, and our planned methods for calibration.

[§]Periods of slow rotation exist for other declinations, as well, but at less favorable airmass. For example, the flat intervals for declination 25 are in intervals during which the hour angle is greater than 2.0 hours.

[¶]This night was chosen since it corresponds to our current best estimate for Pathfinder first light. Otherwise, the choice is random. We therefore believe that, on any night, bright stars can be found and observed at locations where field rotation is negligible.

[‖]When multiple stars are involved each pyramid must be isolated before it is centered; i.e., the other $n-1$ pyramids must be backed well off their respective stars so that their light does not affect the measurement for the particular pyramid being centered.

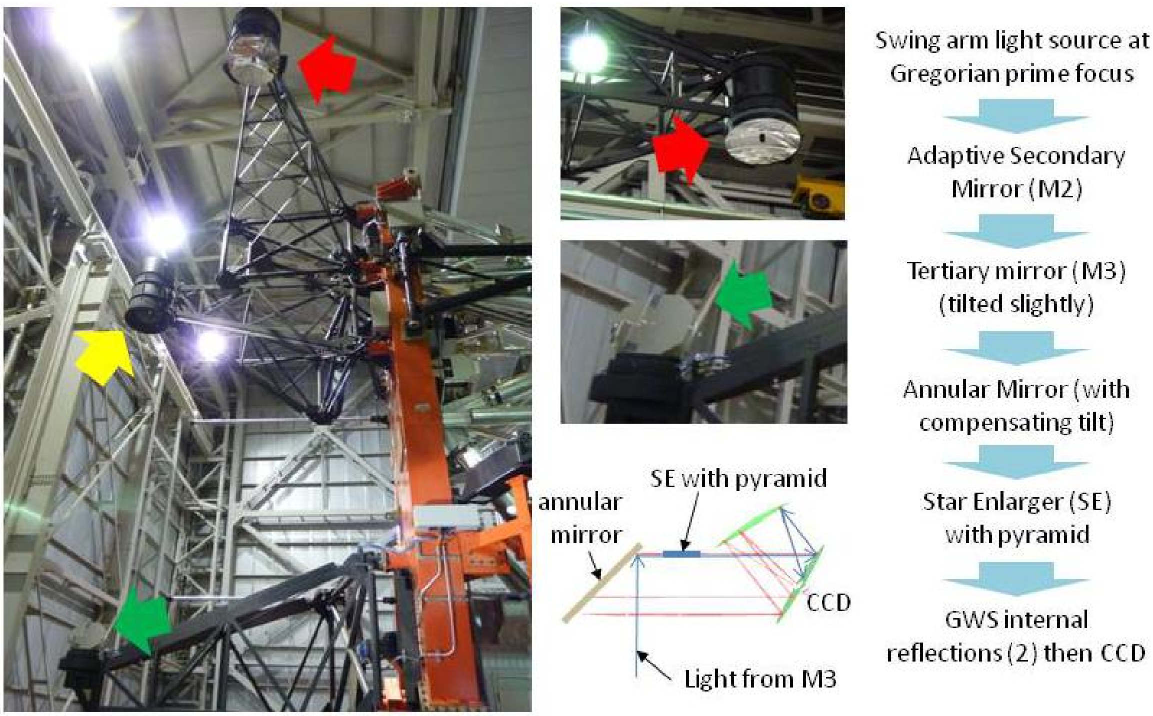


Figure 6. The optical path planned for calibrating the Pathfinder interaction matrix is shown. The left hand figure shows three of the swing arms that can be configured for use with the LBT depending on the mode of use. The primary mirror (M1) cannot be seen in this figure; it lies out of view below. Two of the three swing arms shown, the adaptive secondary (indicated by the red arrow), and the tertiary (indicated by the green arrow), will be used when calibrating the Pathfinder interaction matrix. The third swing arm (indicated by the yellow arrow), will not be used but is at the same level (the level of the Gregorian prime focus intermediate between M1 and M2) as the swing arm that will be used for the ARGOS laser system. It is this swing arm that will generate the F15 infinite-focus beam up to the secondary and ultimately to the CCD-50 within the Pathfinder GWS (see light path schematic in the right-hand panel). The center panel shows a close-up of the adaptive secondary (top), of the tertiary (middle), and a schematic showing how off-axis light is re-imaged on the CCD-50 of the Pathfinder GWS (bottom).

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