Keck Adaptive Optics Note 1350

Asterism Generator: Operations Software System

Sam Ragland & Peter Wizinowich; 2020May 31

Contents

1. Introduction

The Keck I AO system is undergoing a significant upgrade as part of the Keck Precision Adaptive Optics System (KAPA) project. One of the primary technical goals of KAPA is providing a high Strehl ratio through atmospheric tomography to eliminate the "cone effect" (KAON 1210). The laser tomography uses multiple lasers projected around the science target on the sky to overcome this effect.

The asterism generator (AG) is one of the crucial subsystems for laser tomography that adds new capabilities to the existing laser steering system. It splits the recently commissioned KAPA laser (a bright TOPTICA laser) into the four beams, projects them equally spaced on a circle with an on-sky radius of 7.59", and tracks them to compensate for the Earth's rotation as needed.

The AG has four Up-link Tip-Tilt (UTT) mirrors for tip/tilt compensation and fine differential laser pointing correction of the individual laser beam, and a common rotation stage (AGR) to set and track the asterism orientation on the sky. The UTTs are controller by the wavefront sensors (WFS.)

Figure 1 shows a schematic diagram of the laser beam train. The AG will be located in between the laser beam transport mirrors KM6 and KM7 (i.e., just before the beam transfer optics bench (BTOB) and laser launch telescope.) The global laser steering device, consisting of a global UTT mirror (BM2) and BM5, is on the BTOB, which in turn is located in the telescope secondary-socket. The global on-sky pointing of the asterism and beam centering at the laser launch telescope secondary are accomplished by the coordinated movements of BM2 and BM5. In addition to pointing correction, the global UTT compensates for the fast global tip/tilt error. In contrast, the four individual UTTs compensates for the differential tip/tilt of the particular beam with respect to the global tip/tilt. As before, the global UTT offloads the pointing error to the BM2-BM5 system.

The operations software sets the AGR and configures the WFSs and the AO rotator for the mode of operation. The laser control software system (ref) controls and commands the steering devices.

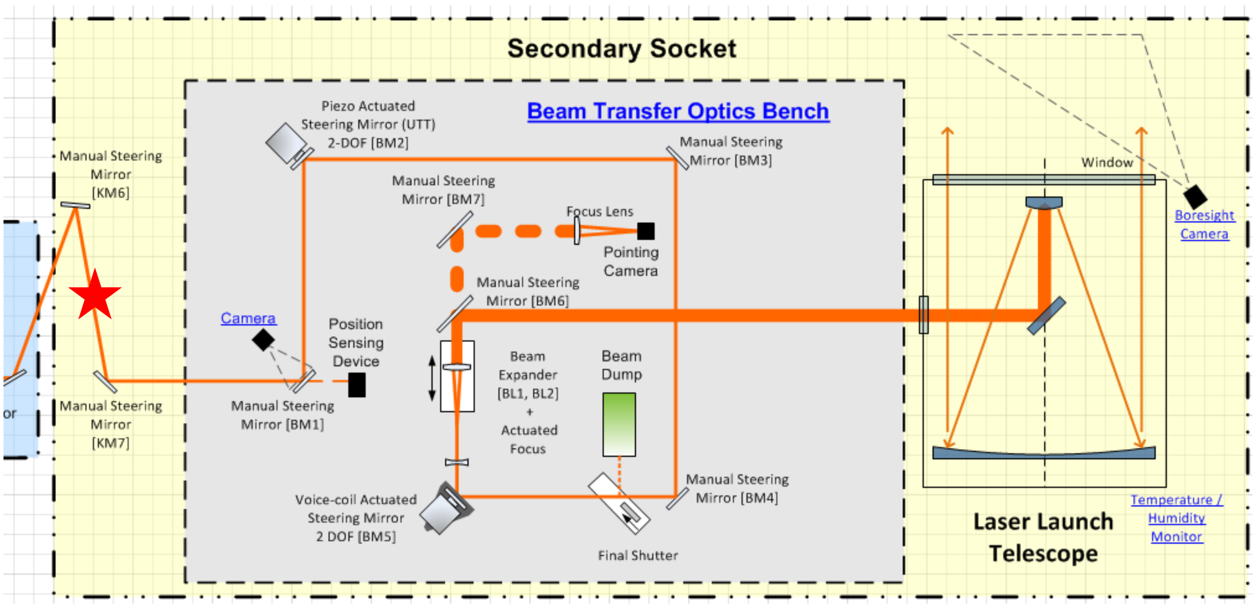

Figure 1: A schematic diagram of the laser beam path. The location of the AG is marked with a red star symbol.

This document provides the design of the operations software for the asterism generator subsystem. The operational software changes for the upgrade will be implemented under ECR 3105.

2. Overview of the Operational Software System

The OSS consists of six major components. Figure 2 shows a block diagram of the OSS. A brief description of the six components is given below from the perspective of the changes needed for the AG sub-system.

Figure 2: The major components of the Keck AO Operational Software. The software components with significant changes are shown in orange.

The main changes are:

- Introducing a new operational mode for laser tomography (LT)
- Moving the AG in or out of the beam for the LT and single beam LGS configurations, respectively
- Setting the AG rotator to the desired orientation
- Monitoring the AG
- Informing the user on the available range for tracking the guide star
- Reacquiring the guide stars after offsetting the AG rotator by 90 degrees to continue observing the science target
- Monitoring the four additional UTT in addition to the global tip/tilt control.

2.1 Pre-observing Tools

The pre-observing tools include (1) AO Guide Star tool for target selection, (2) Keck AO web pages for the observers, and (3) AO science instrument pre-observing web pages. The last two items require an update in terms of performance numbers and the limiting magnitudes of the operational modes. These updates will be performed at the end of the on-sky performance validation of the LTAO implementation.

The following are the changes to the AO Guide Star tool.

- The FSM field layout of the AO Guide Star tool will be updated for the OSIRIS instrument as the off-axis laser beams will take some of the field of view of the FSMs.
- The AO Guide Star tool shows the parallactic angle plot with hour angle. The AG rotator position for the input position angle could be shown with hour angle. The expression for estimating the AGR angle is the following:

  AGR angle = Position angle – Parallactic angle – Instrument angle (1)

  The Instrument angle is 312 degrees for the OSIRIS.

  The AO rotator angle with an elevation term:

  AO rotator angle = AGR angle + elevation (2)

2.2 Observation Setup Software

The ‘aoacq’ sets the mode of AO for night time operation. The OSIRIS instrument software or user scripts set the AO rotator mode and the rotation angle.

The AGR angle is controlled through the laser control software using equations (1) and (2). The operations software homes the stage when needed.

2.3 Calibration Software

This session covers the routine calibrations required to prepare the AO system for nightly operation. The main changes to the calibration software are (1) Field steering mirror (FSM) calibrations, (2) DM-to-lenslet array registration, (3) reference slope calibration, and (4) interaction matrix calibration for the new four UTTs.

2.3.1 Calibration Setup routine

The modifications to the calibration setup script, “calsetup.pro” (Figure 3) include (1) introducing an option to select LTAO in the top-level GUI (Figure 4), (2) setting the WFS for the NGS, single LGS or LTAO configurations, (3) setting the optical stages, and (4) setting up the fiber source based on the mode of operation.

The LTAO configuration will use the pupil simulator. The light source will be turn on, and the pupil similar fold mirror will be inserted for this mode of operation. For the other operations mode, the SFP stage will be inserted, the pupil simulator mirror will be moved out of the beam, and the SFP source will be turned on.

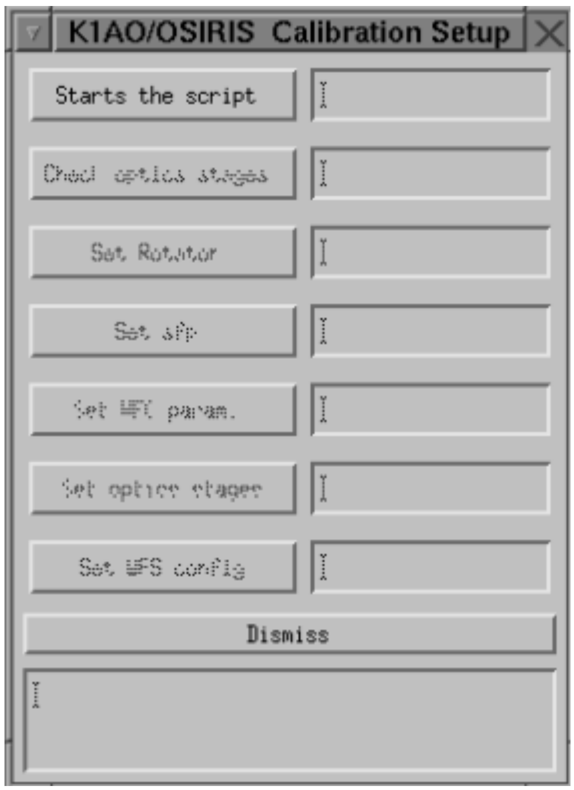

Figure 3: The currently used calibration setup.

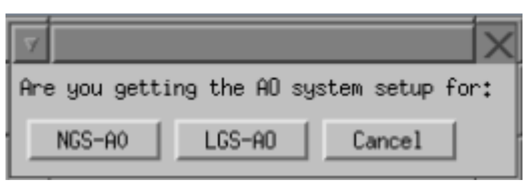

Figure 4: The mode selection GUI of the current calibration setup script.

A new Python GUI for the AG simulator control will replace the currently used IDL light source control GUI (Figure 5).

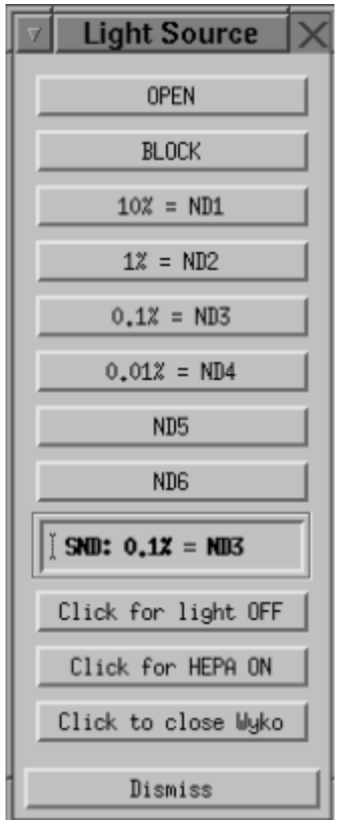

Figure 5: The SFP light source control.

The neutral density references in the following IDL routines need to be modified for the new fiber source.

- aoacq.pro
- calsetup.pro
- check_device.pro
- lbwfscals_subs.pro
- lightcontrol.pro
- makedarks.pro
- move_dev.pro
- set_light_level.pro
- take_wfs_bkg.pro
- wfs_focus.pro

The set optical stages include the FSMs and lenslet array based on the previous calibration of these stages. The FSM position for the LTAO mode are defined in the 'fsm_origin.dat' and the calibration of this is discussed in the next subsection.

2.3.2 FSM origin calibration

The operations software sets the FSM to pick off the portion of the field that will be visible to the AO WFS and hence sets the field of view of the science instrument and the location of the laser guide stars on the sky. Accurate calibration of the FSM for different modes of operation is crucial to make sure that the return laser light would fall on the corresponding WFSs irrespective of the FSM position.

The LTAO mode involves four wavefront sensors (WFS) operating off-axis (~ 7.6” from the optical axis of the WFS) to receive the four laser guide stars.

As a side effort of the implementation, the single beam LGS and the NGS modes, too, use an off-axis WFS. However, the guide star in the case of single beam LGS and the NGS modes is on-axis with respect to the AO rotator axis (unlike in the case of LT where the guide stars are off-axis.) The daytime calibration accounts for the difference in the FSM offsets for the different modes.

The currently followed procedure is to have the FSM origin for each mode is saved to a separate file in ASCII format. For instance, the FSM origin for the NGS and LGS are calibrated and saved to fsm_origin.datOSIRIS-N and fsm_origin.datOSIRIS-L, respectively during the AO calibration. The appropriate file is copied to fsm_origin.dat during the AO operations for the given mode of operation. If we were to follow the same procedure, the FSM origin calibration would create a file called, fsm_origin.datOSIRIS-LT and the operations tools will be modified to use this file for LT operations. A sample fsm_origin.dat is shown below:

```
12.204800      8.2180675      -1.2951213      0.83197570
```

We would use this opportunity to consider using an alternate file format identified below as O-01.

O-01: Have a single file with multiple rows for different modes and as a (first) column to identify the mode. This would avoid having to copy the files for mode changes.

Another side effect is additional restrictions on the field of view of the FSM in a specific direction. The field of view of the FSM is ~ 30” and relatively tight for off-axis AO observations and sky measurements at least in one direction because of field vignetting.

The items that require a decision to be made are referred to as “D-#”, where # refers to the serial number.

D-01: Should we continue supporting the single LGS mode? Unclear why would anyone want to use the single LGS when LT is available. A decision not to support single LGS would simplify the software changes needed to support LT.

2.3.3 DM-to-lenslet registration

The IDL routine, ‘calc_dm_reg.pro’ (Figure 6) performs the DM-to-lenslet registration. The calibration involves (1) applying a checkerboard pattern on the DM, and (2) performing the least-square fit estimate the error in translation, magnification, and rotation of the lenslet stage.

The IDL tool will be modified to set the pupil simulator for LTAO and move the FSMs to the LTAO values. The WFS settings and the light level settings are modified in the code for different modes.

The lenslets will be optimized to minimize the error in all the WFSs at the same time for the LTAO configuration. We plan to update the existing IDL routine to read the centroids of all four WFSs. The matrix used for least-square estimation remains the same as there is no change to the DM configuration. The mode settings from the ‘calsetup’ tool will be passed to ‘calc_dm_reg’ in the form of a keyword to not make any changes for the existing modes of operation.

We would use this opportunity to write a Python GIU for this calibration identified below as O-02.

O-02: Consider rewriting this tool Python.

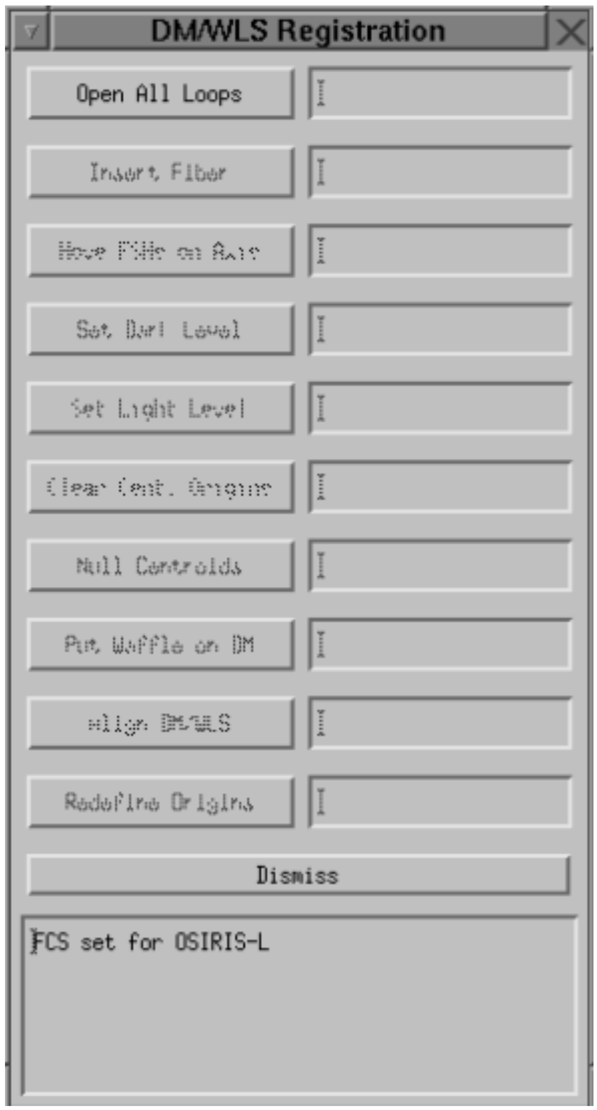

Figure 6: The DM-3-lenslet registration GUI.

2.3.4 WFS Reference-slope and focus calibration

The 'wfs_cal.pro' (Figure 7) sets the WFS, takes centroid measurements, and saves the reference slopes for on-sky operation. The tool would save the reference slopes for all four WFS.

The four images from the AG simulator unlikely to fall at the center of all four WFS simultaneously. In the case of NGS and LGS modes, the FSM lenslet array and/or the FSMs are adjusted to remove pointing errors. As the individual spots cannot be moved with respect to each other, we are likely to have relatively large tip/tilt errors in all four WFSs. The pointing errors are subtracted from the reference slopes before saving them to a file. The cog files are written to new WFS files: 24OSIRIS-LT2x2.cog, 24OSIRIS-

LT2x2_TRICK.cog, 24OSIMG-LT2x2.cog & 24OSPEC-LT2x2.cog and the corresponding files for the unbinned modes.

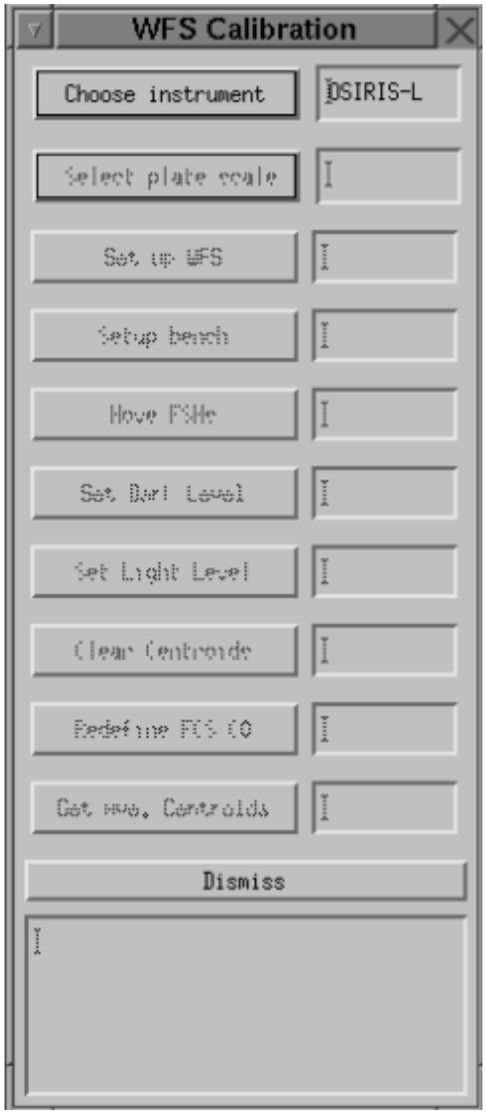

Figure 7: The WFS reference-slope calibration tool.

The WFS focus position is file, 'inst_fc0.dat.' The following is the current values of the inst_fc9.dat.

INSTRUMENT FCS C0

SHARC 6.906

SHARC-N 2.586

SHARC-L -2.332

IF 14.692

IF-N 7.591

IF-L 14.692

OHANA 14.051

OHANA-N 13.070

OHANA-L 14.051

ASTRA-N 7.532

ASTRA-L 3.010

OSIRIS 0.500

OSIRIS-N 4.937

OSIRIS-L 0.208

The rows for obsolete instruments such as ASTRA-N, ASTRA-L, OHALA-N, OHANA-L, IF, IF-N & IF-L will be deleted and a new item LTAO will be added. The reference to these obsolete instruments will be removed from 'wfs_cal.pro' and 'set_fcs_for_inst.pro.'

2.3.5 Non-common path aberration calibration

The image-sharpening algorithm estimates the non-common path aberration between the WFS and the science instrument. No changes needed for this tool.

2.4 Graphical user interface (GUI)

- The new GUIs for the AG upgrade include (1) replacement of the white-light source control, (2) a new GUI for setting and monitoring the AG. A version of the AG will be made available to the observers to monitor the status of the AGR and do necessary planning for the position angle settings of the observations in semi real-time.
- The main features of the AG GUI are:
    - An option to choose between simulation ('simul') and observation ('observe') to use the GUI for both monitoring and planning.
    - An option to read the currently loaded catalog in the MAGIQ GUI. We will be requesting an EPICS keyword for the presently used star catalog with full path.
    - An option to load a custom catalog for planning purposes.
    - The rotator mode and the position angle are displayed with an option to change them in the 'simul' configuration for planning purposes.
    - The AGR position corresponding to the rotator settings will be plotted with time.
    - The available observing time for the chosen rotator settings before hitting the AGR limit will also be displayed.
    - There will be an option to change the mapping of the WFS to the UTT to switching the laser beams received by a given WFS. The four possibilities will be available in a pulldown ('1 2 3 4', '2 3 4 1', '3 4 1 2' & '4 1 2 3.'
    - The setup button will set the mode and the angle of the AO rotator in the 'observe' mode. The AGR is automatically set through the laser control based on the AO rotator settings and telescope elevation.
    - We will request the highlighted target for the MAGIQ GUI to be available a writable EPICS keywords. In this case, the chosen target in the AG GUI will be automatically highlighted in the MAGIQ GUI in the 'observe' configuration.

- There will be a ‘go’ option in the AG GUI to open the AO loops and automatically run the AO bench setup script as soon as the telescope starts to slew.
- The GUI will build as consisting of different modules such as (1) telescope and AO status part, (2) AG part, (3) WFS display, (4) AGS control, etc.
- The AGS control option will disappear in the ‘observe’ configuration and will reappear when the GUI is set to ‘simul’ configuration. The use will have the option get-rid of unwanted modules.
- Switching to the ‘observe’ mode will automatically turn off the AGS and remove the pupil simulator fold from the light path and move the SFP to the ‘telescope’ position.

- The GUI will be an object-orientated code written in Python. The primary classes are (1) rotator (AO rotator & AGR), (2) WFSs, and (3) science target. All possible attributes will be added to these classes to have them more generic and reusable for the development of LTAO operations GUIs.

2.5 Observing tools

This includes the IDL tools (1) aoacq to acquire the target on the WFS and the science instruments, (2) AO optimization tools, (3) FST sequencer to acquire the laser on the WFS, (4) reconstructor tool, (5) seeing estimation tool, (6) observing tools/scripts, (7) instrument/AO setup and observing scripts, and (8) EPICS archiver visualization tool. The UTT residuals displayed on the Laser User Interface (LUI) will be updated to have the median residuals from the new UTTs as well. The EPICS archiver will be updated to include the four new UTT and the AGR position read-back channels. The operations software design document for the LTAO will address the changes needed for the LTAO mode.

2.6 Post-processing tools

The post-processing tools include the instrument fits header, KOA archival tools, instrument data pipeline software, and the PSF reconstruction tools, including the AO telemetry extraction software. The new telemetry channels for the additional WFSs need to be archived, and the PSF reconstruction tools will be updated. The operations software design document for the LTAO and PSF-R will cover these changes. The LTAO design document will address possible additions to the science fits header for the LTAO mode of operation.

3. Upgrades to the Laser Pointing Control System

The laser steering system is not part of the operations software. Nevertheless, we briefly describe the changes required for the LTAO to identify new daytime and nighttime calibrations, if any.

The laser steering software consists of two parts: (1) pointing compensation computation, and (2) pointing control. The pointing control component remains mostly the same except that the wavefront controller (WFC) would control and get UTT position feedback from AG UTTs as well in addition to the global UTT. As before, the laser pointing compensation computation software estimates the target pointing values and passes to the laser control software in AO bench image plane coordinates. All contributing terms except the flexure terms are native to AO image plane coordinates. The flexure term is converted from Projectile coordinates to AO bench image coordinates before combining with the other error terms.

The main difference is that the global tip/tilt will be estimated from the individual UTTs after de-rotation to account for the orientation of the AGR at a given instant. As before, the pointing control system splits the model pointing compensation into BM2 & BM5 components, converts them to the device coordinates, and applies the coordinated movement of the two mirrors.

The operations software will configure the WFC to use the appropriate UTTs for the LTAO and the existing modes of operations.

The UTT mirrors are controller by the WFC. The estimated UTT commands in the image space is converted to the projection space by the WFC real-time software. The new UTTs are not fixed on the projection space as they ride on AGR. The WFC would read the AGR position and derotate the UTT commands estimated from the WFSs to generate the UTT commands (including the global UTT) in the device space. The UTT offload to the BM2-BM5 steering system doesn't require any change.

4. AGR Range and Tracking

The AGR will be operated in two configurations: (1) vertical angle mode, and (2) position angle mode. In the vertical angle mode, the AGR doesn't move as the device is located on the telescope, but the AO rotator will be tracking compensating the telescope elevation change. In the case of the position angle mode, both rotators will be moving. The AGR will track the parallactic angle while the AO rotator will track the combination of the parallactic angle and the telescope elevation. The parallactic angle changes as much as ~ 90 degrees while tracking a target (Figure 8.) On the other hand, the user may want to observe the target at any arbitrary position angle or vertical angle. Hence, ideally, the full range of AGR will be preferable..

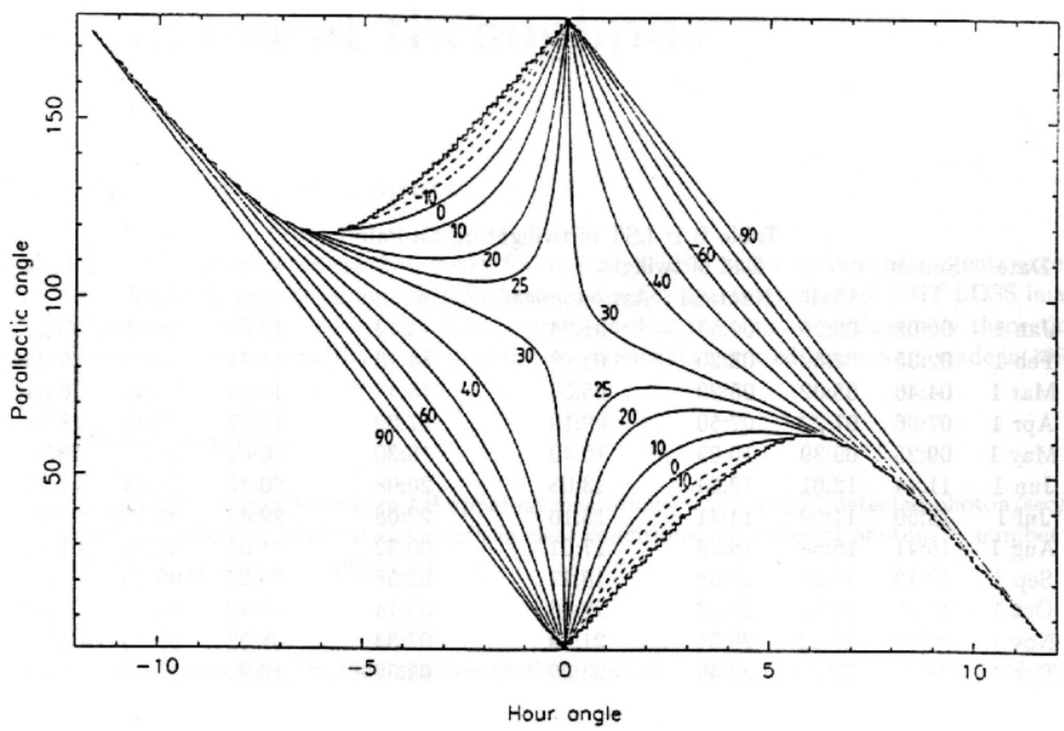

Figure 8: Parallactic angle with hour angle.

In the absence of the 360^{o} range, either the available PA/VA range should be restricted, or the laser beams on the WFSs will have to be remapped by adding an offset angle to the AGR, which is a multiple of 90^{o}. Imposing restrictions on the PA/VA is not a significant limitation as the science images could be rotated in multiples of 90^{o} without losing any information, as there is no interpolation involved.

Once the AGR is close to the limits, either the PA/VA needs to be changed or switch the mapping of the WFS to UTT. If we change the PA/VA, we should rerun the setup bench script and reacquire the target. Switching the mapping of the laser beams to the WFSs would involve: (1) opening the AO loops, (2) configuring the WFC to remap the WFS to UTT, (3) configure the laser control software to add device offset appropriate for the WFC to UTT mapping, (4) closing the AO loop.

5. Integration Tests

The operational system will be tested in the daytime using the newly installed fiber source in preparation for the on-sky engineering for the LTAO upgrade. As the new source will be used to calibrate the existing modes of operation, the standard AO calibrations need to be tested. We expect to test most of the functionalities and calibration files through daytime tests. The remaining functionalities and AO performance will be tested through on-sky engineering.

The main daytime tests for the OSS are:

- Setup AO bench (including the RTC) for all operational modes including ACAM & LBWFS servers and verify that the positioning of the stages.
- Configure the RTC for the operational modes using the operational tools and verify the settings.
- Configure sensor(s) including the SciMeasure camera for the operational modes and verify their operation.
- Perform pupil registration for different operational modes.
- Perform OCAM2K calibrations and verify the calibration files and make sure that the new RTC uses the appropriate calibration data. (Perform these calibrations using SciMeasure Camera if it becomes necessary.)
- Perform PO calibrations for different configurations and verify using aoacq in simulation mode.
- Perform non-common path aberration calibration for different modes/instruments and verify the image quality.
- Perform OCAM2K & TRICK focus calibrations and verify that the calibrations gives diffraction-limited images on the science cameras. (Perform these calibrations using SciMeasure camera, if necessary.)
- Perform influence function calibration and compare the matrix with the data from the most recent calibration.
- Perform interaction matrix calibration for the OCAM2K, STRAP & TRICK configurations and compare the matrix with the data from the most recent calibration.
- Perform rough flux calibration for the AGS by comparing the counts from the new source with the existing one.
- The UTT interaction matrix calibrations. The UTT to the BM2-BM5 coordinate system needs to be calibrated in the daytime using the low power laser by steering the mirror while monitoring image motion on the alignment camera and the position sensing devices (PSDs.)

- Perform WFS centroid origin calibration for the SH WFS (OCAM2K) & LBWFS configurations and compare the results to the previous calibrations. (Perform these calibrations using SciMeasure camera, if necessary.)
- Verify the monitoring GUIs such as OCAM2K, SciMeasure, STRAP, and DM actuator displays, tip/tilt graphs including the UTT, SC GUI, fault detector, and AO alarm handler.
- Verify the control GUIs such as Maori, AO acquisition, ACAM Tool, FST sequencer, LB img acq, LB manager.
- Test the nighttime setup, end-of-night, switch-to-fiber, and switch-to-star scripts.

The main nighttime tests are:

- Verify again the night-time setup, end-of-night, switch-to-fiber, and switch-to-star scripts.
- Verify the AO acquisition, reconstructor, and ACAM tools.
- Verify again all the monitoring GUIs such as OCAM2K, STRAP, and DM actuator displays, tip/tilt graphs including the UTT, SC GUI, fault detector, and AO alarm handler.
- Verify the performance optimization tools such as the bandwidth widget and optical gain tracking tool.
- Verify the operation of the performance verification tools such as the Strehl tool and the seeing tool.
- Verify all the laser operations tools such as FST sequencer, LUI, TBAD, LB img acq, LB manager.
- Perform on-sky AO functionality tests making sure that the tools perform as intended.
- Perform on-sky AO performance tests and compare the results with expected performance.
- Perform flux calibration of the AGS using photometric standard stars.
- Regression test the post-observing tools.

6. Summary

This document presents the operations software changes required for the AG subsystem integration for the LTAO operations. The LTAO operations software design document will cover the broader system and the tools to acquire and observe the science targets.