Keck Adaptive Optics Note 855

Near-IR Tip-Tilt Sensor
Acceptance, Integration, Test and Commissioning

P. Wizinowich
March 25, 2011

Table of Contents

Acronyms

AO	Adaptive Optics
HQ	Head Quarters
I&T	Integration and Test
KAON	Keck Adaptive Optics Notes
LGS	Laser Guide Star
NIR	Near InfraRed
OSIRIS	Oh-Suppression near InfraRed Integral field Spectrograph
STRAP	System for Tip-Tilt Removal with Avalanche Photodiodes
TBC	To Be Confirmed

TBD	To Be Determined
TT	Tip-Tilt
TTS	Tip-Tilt Sensor
WMKO	W. M. Keck Observatory

1. Introduction

This document is intended to define the activities that will need to be performed beginning with subsystem acceptance, through lab and telescope integration and test (I&T), and through commissioning. The system design, requirements and interfaces which are relevant to these issues are defined in other Keck Adaptive Optics Notes (KAONs).

2. Subsystem Acceptance

The near-infrared (NIR) tip-tilt sensor (TTS) system is made up of the five subsystems shown in Figure 1. Each subsystem is expected to be fully assembled and tested to meet its functional requirements, as well as the relevant system requirements, prior to subsystem acceptance. A subsystem acceptance mini-review will be held for each subsystem prior its movement to lab I&T.

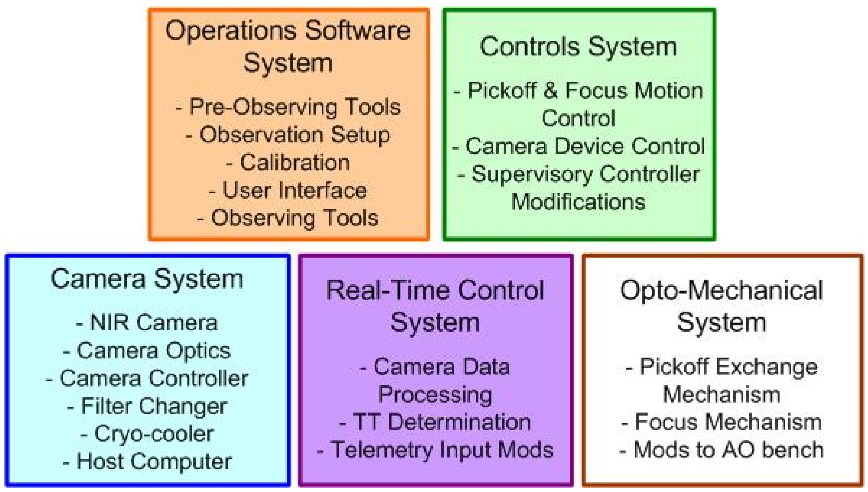

Figure 1: NIR TTS major subsystems

The existing Keck I AO facility will need to be modified to accept these systems at the telescope. Mechanical modifications, including modifications to the AO bench or to support cryo or vacuum hardware, are the responsibility of the opto-mechanical subsystem. Electrical, cabling, computer, network or software infrastructure modifications are the responsibility of the controls subsystem.

2.1 Subsystem Acceptance Review Deliverables

The following items are deliverables as part of each subsystem's acceptance:

- A functional demonstration of the system, including demonstration of key performance requirements.
- An acceptance review document including:
  - Compliance matrix for functional requirements.
  - Compliance matrix for interface requirements.
  - Compliance matrix for system requirements.
  - Documentation to support the requirements and interface compliance.
- A list of all hardware components and their relevant properties.
- A list of all software components and their function, as well as inputs and outputs.

- Vendor data and manuals for all commercial components.
- As-built changes to the mechanical and electrical drawings provided at the detailed design review.
- As used assembly, alignment, calibration and test procedures, and any associated hardware or software tools.
- Software source code and build procedures, and as-built changes to the software design documentation provided at the detailed design review.

2.2 Camera System

The camera system includes the items in the product breakdown structure (PBS) shown in Table 1.

Table 1: Camera system PBS

Level 2	Level 3
External opto-mechanics	Kinematic interface plate
	External optics cylinder
	Field Lens & Mount
	Fold Mirror & Mount
Camera	Camera Opto-mechanics
	Filter Change Mechanism
	Filter Stage Motor, Limit Switches & Cable
	Dewar Cryostat
	Detector
	Heaters/Thermistors
Readout Electronics	ARC Timing Board
	Video Card
	Interface to Dewar
	Interface to Host Computer
	Interface to RTC
Housekeeping Electronics	Housekeeping Interface Board
	Temperature Controller/Sensor
	Interface to Host Computer
External Motion Control	Stepper Motor Driver
	Interface to Host Computer
External Cryo System	CryoTiger
	Interface to Dewar
External Vacuum System	Ion Pump
	Interface to Dewar
Host Computer	Computer
	Readout Control Software
	Housekeeping Control Software
	Motion Control Software
	Keyword Interface

2.2.1 Interface Testing

The camera system will interface to the AO system mechanically via an interface plate, to the Microgate RTC via a fiber optic communication link and protocol and to the AO control system via an Ethernet interface and keywords, and to the MAGIQ system via an API. The interfaces are defined in KAON 836. This system will be delivered by Caltech.

The camera team will assemble and test a fiber link interface simulator that will be shipped to Microgate for testing prior to both systems acceptance reviews. The keyword interface will need to be tested prior to the subsystem acceptance review.

2.2.2 Optical Testing

The camera team will need to demonstrate the alignment and performance of the camera optical system including the detector. We will need to determine what level of optical testing will be done as part of the subsystem acceptance versus the lab and telescope I&T. The final optical testing will be performed once the system is integrated into the K1 AO system. It will be important to adequately test the camera system optical alignment and performance before shipping to Hawaii.

We plan to use the existing Caltech Offner relay test system to test the camera. This is a large system (~ 6 foot) on an optical bench. The features of this system include the following:

- 457 mm diameter primary with 1500 mm radius of curvature.
- Secondary mirror provides a f/8 output when using the full aperture.
- Pupil masks are interchangeable. At present these are all circular at f/8, f/11. f/16 and f/32.
- Very good images over a 40 mm field of view with ~1% ellipticity.
- Diffraction-limited images at 600 nm.
- Assortment of 50x50 mm target masks, chromium on glass with ND5 extinction, with a range of circular and elliptical apertures. The smallest is a grid of 3 μm apertures. Apertures have 50 nm edge placement accuracy.
- Target masks are mounted on a 6-axis stage which nominally has 50 nm resolution, however 1 μm scatter is observed for centroid motions when requesting linear motion (under investigation).
- Secondary position is controlled manually in 5-axes with micron accuracy in tip, tilt and focus, and conventional stages in x, y.
- At present illumination is with LEDs shining into an integrating sphere. Near-IR LEDs could be procured. For K-band we would use an incandescent lamp.
- A 150 mm diameter, λ/100 fold mirror can be used to relay the beam upwards or sideways.

The camera system would be installed on this bench for optical testing. The f/8 system could be stopped down to f/15 for the testing and a pupil mask could be located at the Keck telescope equivalent position.

The simplest method to test optical quality on the H2RG detector would be to measure the spot size by moving the source in x or y across an inter-pixel boundary. To check for off-axis aberrations the spot size could be measured as a function of position on the detector. The source could also be moved through focus to qualitatively check for aberrations.

Distortion can be measured with the grid by measuring the actual position on the H2RG versus the actual grid spacing or by using the fiber source on a precision positioner. In order to remove any centroid offset effects it would be best to move the source to the intersection of 4 pixels and measure how much the source was moved.

The size, alignment and repeatability of the pupil masks within the camera could be checked with a multi-hole pupil mask in the Offner (1 hole at the center and 4 off-center holes at the same radius to match the edge of the correct pupil). With the camera out of focus to separate the images from the 5 holes check the relative flux of the four off-center holes. If the relative flux is not the same then the Offner pupil mask could be laterally displaced to measure the decenter of the camera pupil mask.

Potentially an interferometer could be used to measure the wavefront quality in double pass with reflection off the H2RG. The interferometer would be focused at the input focus to the camera system.

As a backup approach, another hardware option for testing the optical performance of the camera system, but not the pupil size or alignment, is an illuminated pinhole mask, or a fiber source, on a precision movable stage at the input focus. A possible astrometric grid pinhole mask design is discussed in section 4.3 of KAON 745. This proposed mask for Keck's Next Generation AO system had an 80x80 grid of holes with a diameter of 3.6 μm on a 360 μm spacing, corresponding to 5 milli-arcsec diameter spots on a 0.5 arcsec grid. We would want to double the size of this pinhole mask to at least 80x80 mm; a 1 arcsec grid would be adequate. The proposed light source was a woven fiber optics panel (http://www.lumitex.com/machine_vision.html; available in 4"x4" panels) placed behind the grid supplied by an arc lamp source (50-200W, F/2.2 fused silica, 0.5-3 mm focus, available from Newport Optics, http://search.newport.com/?q=*&x2=sku&q2=66476; $6161).

2.3 Opto-mechanical System

The opto-mechanical system includes the items in the product breakdown structure (PBS) shown in Table 2. The opto-mechanical system will be assembled and aligned in the same lab that will be used for system lab I&T. This system will be delivered by WMKO.

Table 2: Opto-mechanical PBS

Pickoff Exchange Mechanism	AO Bench Extension
	AO Bench Modified Cover
	Pickoff Stage Mount
	Pickoff Stage
	Pickoff Stage Motor, Encoder & Cable
	Pickoff Mount
	K'-Band Dichroic
	H-Band Dichroic
	Annular Mirror (option)
Focus Mechanism	Riser for Focus Stage
	Focus Stage
	Focus Stage Motor, Encoder & Cable
	Mounting Plate to Camera Interface Plate
AO Modifications	Modifications to Support Camera System

2.4 Real-time Control System

The real-time control (RTC) system includes the items in the product breakdown structure (PBS) shown in Table 3. The requirements on this system are defined in KAON 824. This system will be delivered by Microgate and will be tested with the existing spare Microgate controller in the WMKO lab.

Table 3: RTC system PBS

Microgate HW Mods	Camera Interface
Microgate Software Modifications	Camera Interface & Readout
	Wavefront Controller Interface Mods
	Wavefront Processor Mods
	Telemetry Recorder/Server Mods
	Downlink TTM Controller Mods

2.5 Controls System

The real-time control (RTC) system includes the items in the product breakdown structure (PBS) shown in Table 4. This system provides the controls functionality at the level of the existing AO optics bench subsystem (OBS) and supervisory controller (SC). This system will include the motion control for the opto-mechanical subsystem, the device control for the camera and real-time control subsystems and the software that resides at the OBS and SC levels. This system will be delivered by WMKO.

Table 4: Controls system PBS

OBS Modifications	Pickoff Stage Motion Control Hardware
	Pickoff Stage Motion Control Software
	Camera System Hardware Implementation
	Camera System Control Software
SC Modifications	Modifications to RTC Interface
	DAR Compensation Modifications
	Focus Compensation Modifications
	Non-Sidereal Tracking Modifications (goal)
	Rotator Control Modifications (long term)
RTC Modifications	Wavefront Controller Command Processor Mods

2.6 Operations Software System

The operations software system includes the items in the product breakdown structure (PBS) shown in Table 5. This system provides the higher level control functionality needed for observing. This system will be delivered by WMKO.

Table 5: Operations software PBS

Pre-Observing Tools	Acquisition Planning Tool Software
	Acquisition Planning Documentation
	Performance Estimation Tool Software
	Performance Estimation Documentation
Observation Setup Software	OBS Setup Software
	SC Setup Software
	Camera System Setup Software
	RTC Setup Software
Calibration Software	Camera Calibration Software
	Focus Calibration Software
	Distortion Mapping Software
User Interfaces	Engineering GUI Additions/Modifications
	Observing UI Additions/Modifications
Observing Tools & Sequences	Acquisition Software
	MAGIQ Software Modifications
	Nodding Script Modifications
	Dithering Script Modifications
	Repositioning Script Modifications
	Background Measurement Script Mods
	FITS Header Modifications
	Telemetry Data Recording Modifications
	TT Control Loop Parameter Optimization

3. Laboratory I&T

Laboratory I&T at WMKO headquarters (HQ) involves the assembly, alignment, integration and test of the four subsystems. The integrated system must be demonstrated to meet the system requirements that can reasonably be demonstrated off of the telescope. A pre-telescope readiness review will be held prior to moving the integrated system to the telescope.

3.1 Laboratory versus Telescope I&T

The AO system on the telescope has the advantage that it is already fully set up for experiments. The AO system has a fiber source that can be moved around the field, a pupil simulator, a tip-tilt mirror, the deformable mirror (that can be used as a pupil stop) and flat field lamps.

The advantage of the lab is that we can more easily physically manipulate the NIR TTS if needed. This comes at the expense of preparing a lab system to test the NIR TTS system at whatever level we feel is appropriate prior to the move to the summit.

The risk of being at the telescope is that we could interfere with science observations. At minimum we need to ensure that the NIR TTS system is sufficiently checked out before moving to the telescope that we can insure we will not impact science observations.

The risk of going to the telescope too early is that we might have to do more work on the hardware within the AO system or remove the hardware, which puts the existing system at risk.

What do we really need and want to do in the lab or to add to the pre-subsystem acceptance work? The interfaces are an area of risk. This has been minimized by testing these interfaces prior to subsystem acceptance.

The optical performance of the camera system will already have been tested prior to the camera acceptance review, as will have been the performance of the dichroics as part of the opto-mechanical acceptance review.

The camera to RTC interface will have largely been tested at Microgate with the camera emulator provided by Caltech. The most at risk area is the combined operation of the real camera and RTC, and the layering of the controls and operations software on top of these systems. These interactions are the ones that will be the focus of the lab I&T.

3.2 Laboratory Preparation

An optics bench will be identified for lab I&T in the clean room at WMKO HQ. There are two vibration isolated optics benches in this clean room and an electronics rack set up for motion control. The spare Microgate controller is set up just outside this clean room (along with a spare STRAP unit and SciMeasure camera). A WYKO interferometer and two alignment telescopes are available.

The systems optical alignment and performance should already have been tested at Caltech. At minimum we would want to move an illuminated pinhole mask or fiber source by a known small amount to test the RTC output. A source with a tip-tilt mirror in the path could allow tests of closed loop tip-tilt operation.

3.3 Subsystem Installation and Testing

The opto-mechanical, controls and operations software will already have been set up in the WMKO HQ lab as part of their subsystem development.

The RTC system is currently also set up in the HQ lab but will be shipped to Microgate for subsystem development. The RTC system will need to be reinstalled in the WMKO lab and the acceptance test performed at Microgate will be repeated to ensure that this system is ready for lab I&T. In addition the systems operation with the spare STRAP unit will also be tested.

The camera system will be set up in the HQ lab and the acceptance tests performed at Caltech will largely be repeated to ensure that this system is ready for lab I&T.

3.4 Interfacing and Testing

Subsequent to subsystem testing all interface connections should be made and tested. These include:

- The mechanical interface between the camera and the opto-mechanical system.
- The data interface between the camera and the RTC.
- The keyword interface between the controls and camera system.
- The full frame acquisition interface between the camera system and MAGIQ.
- The keyword interface between the controls and RTC system.

3.5 System I&T

All system-level functionality should be tested including:

- Observation setup
- Calibrations
- Acquisition
- Tip-tilt loop parameter optimization
- Nodding, dithering and repositioning
- Sky background measurement
- Telemetry recording

3.6 Pre-Telescope Readiness Review

A readiness review will be held before the system is moved to the telescope. This review will include summary results from the subsystem acceptance reviews, the results from lab I&T, the engineering change request results, the summit preparedness, the system and functional compliance matrices and the telescope I&T plan.

4. Telescope I&T

Telescope I&T will include system installation and alignment prior to both daytime and nighttime testing of system functionality. This will be followed by multiple nights of system performance characterization. We will also work with our science team to ensure that one or two science verification programs are performed to ensure that the system is working as an overall effective science facility.

All system requirements must be verified at the telescope to ensure that the system is ready for handover to operations. An operations handover review will be held.

Prior to any modifications to the existing K1 AO system or the installation of any new hardware or software with the summit system engineering change requests (ECRs) must be submitted to the AO change control board (CCB) and approved.

4.1 Telescope Preparation

4.1.1 Bench Modifications

A hole will need to be cut in the AO bench cover. New side panels will also need to be manufactured and installed. A riser supporting the AO bench cover must be removed from the area needed for the NIR TTS hardware, and replaced. The cover, side panel and new riser work should be done prior to the installation of OSIRIS into the AO enclosure, or possibly during the same week.

The bench cover is made of a 2 inch thick aluminum honeycomb structure sandwiched between two 0.032 inch aluminum plates with a 0.25 inch thick aluminum plate to seal the edges. Newport reports that this operation is just like cutting through aluminum, however care should be taken to not be too aggressive in order to not cause local delamination of the honeycomb from the facesheet around the cut edge. A circular saw would be used for the straight cuts and a reciprocating saw for the corners. Some clean up of the cut with files will likely be necessary. To finish the cut edge a piece of aluminum can be bond to the existing aluminum (the edges on the bench cover are finished with 0.25 inch thick aluminum).

There are two options that are being considered to cut a hole in the cover: one is in-situ and the other is to remove the cover from the AO enclosure. The former approach is preferred if it can be done in a clean and low vibration way. We will endeavor to obtain a sample of this material from Newport during the detailed design phase to allow us to practice the cutting procedure and to determine whether option 1 is feasible.

Option 1: Cut the cover in-situ.

In this scenario it is critical that the cutting be done in a clean way so as not to contaminate the AO optics and in a low vibration manner so as not to impact alignments. The process would include the following steps:

1) Cover the optics on the AO bench.
2) Cover the area around the region to be removed by cutting using heavy plastic and thorough taping.
3) Install a vacuum to remove debris from the cut.
4) Install a hose and fan to the outside of the AO enclosure to draw air from the covered area while cutting.
5) Perform the cut and clean up of the cut.
6) Remove the equipment setup for the cut.
7) Clean the AO bench.
8) Uncover the AO optics and CO2 clean the optics.

Option 2: Remove the cover for cutting.

In this scenario the cover would be removed from the AO enclosure to perform this cutting. A potential, preferably 1 day, process would be to:

1) Cover the optics on the AO bench.
2) Remove all hardware on the AO bench cover and the bolts connecting the cover to the risers.
3) Remove the appropriate AO enclosure roof panels with the crane.

4) Remove the AO bench cover using the dome crane and move it to a suitable location for cutting and cleaning.

5) Temporarily replace the roof panels or cover this area with plastic (it will be important to minimize the entry of dirt and dust into the AO enclosure).

6) Perform the cut and clean up of the cut on the AO bench cover.

7) Return the AO bench cover to the AO enclosure and reconnect all bolts. The bench cover should have a temporary cover for the new hole.

8) Reinstall the roof panels.

9) Reinstall hardware on the AO bench cover.

10) Clean the AO enclosure before removing the AO bench covers (e.g., wipe down and vacuum the enclosure and run the HEPA filter to remove dust).

11) Uncover the AO bench optics and CO_2 clean the optics.

4.1.2 Facility Modifications

There are two spare PMAC channels and servo amplifiers with the existing system that will be used for the additional 2 degrees of freedom provided by the opto-mechanical system. Two cables will need to be run to the NIR TTS location on the AO bench.

Space must be made for the camera electronics in a thermally insulated box close to the camera. Space must be made for the camera host computer in an existing AO electronics rack.

The CryoTiger compressor will be located in the AO electronics room. A hanging bracket will be installed to support the compressor. Lines must be run from this room to the camera on the AO bench. If flammable gases need to be used for the CryoTiger then the appropriate safety equipment and procedures must be put in place and a safety check should be performed before filling the lines and operating the CryoTiger.

4.2 Installation

OSIRIS will already have been installed in Keck I AO prior to the arrival of the NIR TTS.

4.2.1 RTC Installation and Test

The modified RTC system will be the first NIR TTS system to be installed at the telescope (the replaced unit will be similarly upgraded). The acceptance tests performed at Microgate will be repeated to ensure that this system is ready for testing with the K1 AO system. The system will also be tested to ensure that K1 LGS AO performance with STRAP has been in no way impacted.

The replaced RTC system should be left in the electronics enclosure and preferably in the electronics rack until the modified unit has been demonstrated to meet its functional requirements after installation. The installation plan should include a plan to quickly swap back to the removed RTC unit if necessary.

4.2.2 Controls and Observing Software Installation

The appropriate servo parameters will need to be loaded for the two spare channels to be used to position the optical pickoff and focus stage. Cables will need to be run to the appropriate position on the AO bench. The servo control parameters for the stages may need to be adjusted and new named positions may need to be defined once the hardware has been aligned on the AO bench.

New keyword libraries will need to be put in place at the summit.

The new controls and operations software will need to be installed in the summit system.

4.2.3 Camera Controls Installation

In addition to the camera dewar installation described in section 4.2.4 the camera system will need the installation of the following items:

- A detector controller electronics box to be installed in a thermally insulated box on the AO bench cover. The thermally insulated box will be connected via a hose to the existing air-to-glycol heat exchanger.
- The cryocooler compressor will be installed on a hanging platform in the AO electronics room and the hoses will need to be run to the camera dewar.
- A Lakeshore temperature controller will be installed in a rack in the AO enclosure.
- The camera host computer will be installed in a rack in the AO enclosure.
- The camera electronics will be connected to an existing Pulizzi remote power switch.
- The Lakeshore and pressure gauge will need to be connected to an existing terminal server.

4.2.4 Opto-Mechanical and Camera Installation and Alignment on the AO Bench

The installation of the NIR TTS on the AO bench could be potentially difficult due to the tight physical constraints between the AO bench and OSIRIS, plus the size and weight of the camera system.

The installation process will include the following steps:

- The covers on the OSIRIS side of the AO bench will be removed.
- The pupil simulator may need to be removed for the installation of the following items from the side of the AO bench.
- If not previously installed the baseplate on which the optical pickoff will be mounted should be installed (we may have already installed it at the same time as the new covers).
- The optical pickoff assembly will be installed and checked out for alignment and functionality.
- The riser under the focus stage will be installed next.
- The focus stage will be installed on the riser, along with the bottom half of the interface plate. The focus stage will be checked out for functionality.
- The portion of the camera system containing the field lens and fold mirror will be installed next.
- The pupil simulator will be reinstalled (if it was removed) and used to check the alignment. The alignment procedure is documented in section 3.5 of KAON 838.
- Install a hoist on an I-beam straddling the hole in the AO bench cover through which the camera dewar will protrude (see Figure 2). The I-beam will be supported from the AO enclosure floor. One end will be located next to the pupil simulator location and the other in the dual star module location. The end at the dual star module location must be far enough from the AO bench that a cart, holding the camera dewar, can be moved under the hoist. If necessary the hoist could also have been used to install the components listed above.
- Install the lifting jig on the top of the dewar camera (see Figure 3).
- Lift the camera off the cart with the hoist and then position the hoist, with camera attached, over the hole in the AO bench cover.
- Lower the dewar. Existing defining pins between the dewar and the cylinder containing the field lens and fold mirror will be used to properly position the dewar.
- The dewar can now be connected up to its electronics and cryocooler.
- The alignment procedure is documented in section 3.5 of KAON 838.
- Replace the side covers.

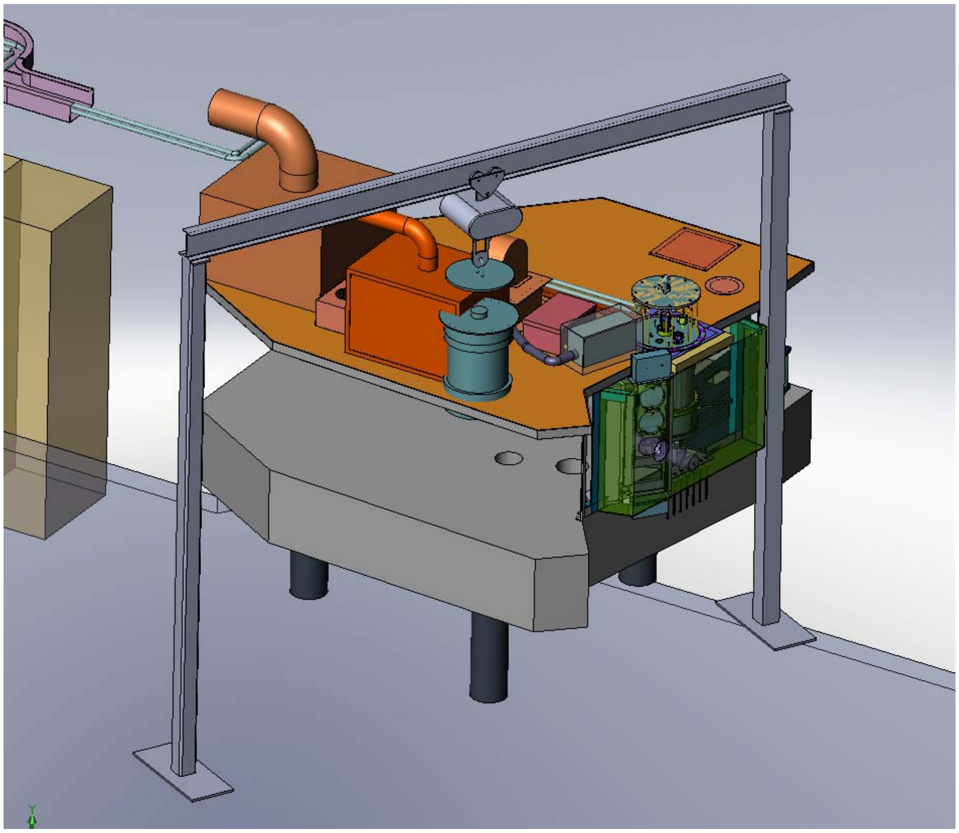

Figure 2: Temporary gantry installation used to install the camera

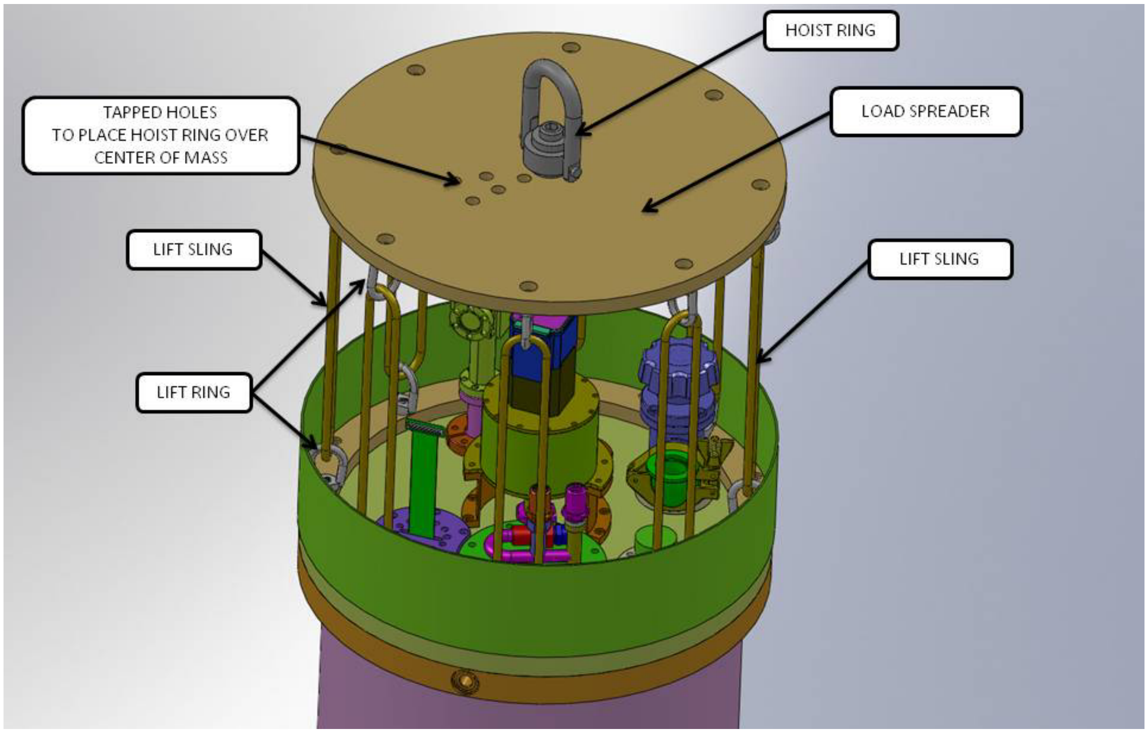

Figure 3: Camera with lifting fixture

4.3 Daytime I&T

The subsystem acceptance tests will be re-performed to verify performance. All system functionality will be tested during the day. It will be especially important to check items that may have changed in the telescope environment (e.g., detector noise, CryoTiger performance, etc.).

The AO system will offer new testing capabilities not provided in the lab. In particular, the following new tests will be able to be performed:

- Pupil alignment check. Aperture masks can be placed in front of the deformable mirror to check the centering and size of the camera pupil masks.
- Distortion map. A distortion map can be produced by moving the fiber (SFP) around the NIR TTS camera.
- Flat field calibration using the dome flats.
- Closed loop TT operation. The TT loop can be closed on the fiber. A fast disturbance can be injected into the TT mirror and the NIR TTS system can be used to correct this TT disturbance. Performance can be checked by also measuring the TT with the wavefront sensor or STRAP and/or OSIRIS. The performance for different TT offsets can also be measured. We can also consider installing an illuminated pinhole mask on the SFP stage in front of the rotator so that multiple TT stars can be used.
- Dithering, nodding and repositioning using the fiber.

4.4 On-sky I&T

All functionality should be checked with the full LGS AO system on the sky. In particular this will be the first time that the functionality of the observing software tools will be able to be fully tested.

4.5 Performance Characterization

Performance on the OSIRIS science instrument will be the primary metric. The OSIRIS imager will primarily be used to measure performance (e.g., positioning accuracy, Strehl ratio, etc.). The OSIRIS spectrograph should be used to make ensquared energy measurements.

In general the following parameters should be recorded: r0, TT star magnitude in the NIR TTS band, TT star off-axis distance, NIR TTS integration time, TT gain, TT rms residual, laser signal on the wavefront sensor, zenith angle, galactic latitude and science integration time. Data from the Mauna Kea seeing monitor should be recorded in parallel with these performance characterization observations. Ideally the AO system would also provide a Greenwood frequency measurement however this tool does not currently exist (and won't be developed under this project).

On-sky data should be collected to document the following items:

- A photometric calibration of the NIR TTS as an acquisition camera. This will be immediately useful to verify the system transmission. It would be useful to have a similar photometric calibration of STRAP and the LBWFS.
- Emissivity measurement for the NIR TTS, and for OSIRIS through the NIR TTS pickoffs, on the sky. This will be immediately useful to verify the system background.
- Acquisition time (from the end of a slew to the start of a science observation).
- Dither and offsetting time.
- Repositioning accuracy.
- Strehl ratio on the NIR TTS as a function of r0 in the pointing direction and off-axis distance.
- Number of suitable TT stars and their off-axis positions as a function of galactic latitude as measured on the NIR TTS.

- Ensquared energy in a 50 mas OSIRIS spaxel as a function of r0 in the pointing direction, TT star magnitude and off-axis distance in both H and K-band.
- Strehl ratio on OSIRIS as a function of r0 in the pointing direction, TT star magnitude and off-axis distance in both H and K-band.
- We should have previously collect similar ensquared energy and Strehl ratio performance data for STRAP with the K1 LGS AO system which could be used for comparison.
- If not already measured then we need to characterize the performance of the LBWFS so that we understand to what extent it limits the system performance, especially on faint TT stars.

4.6 Science Verification

Science verification will include, at minimum, observations of gravitational lenses and the Galactic Center based on the science team's existing observing programs. Some of this science verification will be performed during engineering time but the majority will be performed during TAC-allocated shared-risk science time.

A gravitational lensing science verification program is attached as Appendix I. A galactic center science verification program will be developed during the detailed design phase.

5. Commissioning and Handover

A handover review will be held prior to transferring the NIR TTS system from the AO development team to the AO operations team. The system will be handed over to the AO operations team responsibility either at the handover review or subsequent to the completion of any liens on the review. The key elements of the handover include personnel training and complete documentation of the system.

In support of training the AO operations lead will have been involved in all design reviews and the change control process. At least one support astronomer will have been trained in the operation and optimization of the system and will take over the system, user and performance documentation. This support astronomer will have participated in the engineering nights and shared-risk science nights. Presentations on the system, with an emphasis on its operation, will have been made to both the support astronomer and observing assistant groups (preferably at the same meeting).

The AO operations team optical, electronics and software engineers will have been introduced to the system and will take over control of the engineering documentation, and will have been trained in any required maintenance procedures using documented procedures.

All documentation will be complete (as defined in the design manual and requirements) and posted in the appropriate locations, primarily on KeckShare. The LGS AO web page will have been updated with the measured NIR TTS performance.

Appendix I. Science Verification Case: Flux Ratio Anomalies and the Substructure Problem

Provided by T. Treu.

Scientific Justification

In the standard cosmology, dark matter (DM) halos host a hierarchy of sub-halos, also known as DM substructure. The number of subhalos above a given mass is expected to scale approximately as the total mass of the parent halo, and the logarithmic slope of the subhalo mass function approximately as $dN/dM_{sub} \propto M^{-\alpha}_{sub}$, with $\alpha = 1.9 \pm 0.1$ (Diemand et al. 2008; Springel et al. 2008). Remarkably, if the DM is cold, the normalized distribution of substructure depends very little on the overall scale of the halo, and we would expect approximately the same abundance of satellites around clusters and galaxies. The statistical properties of the substructure inferred from N-body simulations are believed to be robust enough to allow for a direct comparison with observations (see, e.g., Kravtsov 2010 and references therein). For these reasons such a comparison may provide one of the most stringent and direct tests of the paradigm at subgalactic scales.

Figure 4: The substructure problem. In simulations (top, from Kravtsov 2010), galaxies and clusters are self-similar and should have the same amount of satellites. In reality, this is not observed: galaxies have many fewer (luminous) satellites than expected based on dark matter substructure. Does this mean they are dark, or that they do not exist? Answering this question is the goal of this program.

At variance with the results of simulations, the abundance of luminous satellites observed around real clusters and galaxies are very different. Whereas clusters of galaxies host thousand of galaxies, many fewer satellites are found around galaxies (Figure 4). In particular, the mass function of the luminous satellites of the Milky Way differs dramatically from that of the subhalos of a typical simulated halo of comparable mass. At the high mass end of the distribution (virial Msub ~ $10^9 M_{Sun}$) the observed number of satellites is comparable, or perhaps even slightly larger, than expected. However, the mass function of the halos of the observed satellites is found to be much shallower than that predicted for subhalos, resulting in a dramatic shortfall at lower masses, below $10^8 M_{Sun}$. This discrepancy between theory and observations has been known for over a decade (Klypin et al. 1999; Moore et al. 1999), and has not been solved by the discovery of low luminosity satellites of the Local Group, nor by advances in numerical simulations.

There are two classes of possible solutions to this so-called "substructure problem". One possible explanation is that substructure exists, but it is dark, i.e. subhalos do not form enough stars to be detected. This explanation would imply that the conversion of baryons into stars is inefficient for small halos. It is hard to explain this inefficiency with the known mechanisms of supernovae feedback or the effect of the UV ionizing background (Kravtsov 2010). Alternatively, it is possible that subhalos are not as abundant as predicted by numerical simulations. This explanation would require a major revision of the standard Cold Dark Matter (CDM) paradigm, by either reducing the amplitude of fluctuations on the scales of satellites, or changing the nature of DM from cold to warm (Miranda & Macciò 2007). Either explanation would have far reaching implications. In order to be viable, the first explanation requires a clear improvement in our understanding of galaxy formation. In its most extreme version, the second explanation may require a re-thinking of the CDM paradigm.

Flux ratio anomalies as probes of substructure

Gravitational lensing provides a unique insight into this problem, since it is arguably the only way to detect dark substructure around galaxies, measure its mass function (as opposed to a luminosity function for visible satellites), and compare it with the prediction of CDM numerical simulations.

The most direct way to detect the lensing effect of substructure is via the perturbation of the magnification pattern. Since magnification depends on the second derivative of the potential, a small local perturbation due to substructure can introduce dramatic differences in the observed surface brightness of the lensed source, without altering significantly the overall geometry of the system. For point sources, the presence of substructure results in the flux ratios between the multiple images that are significantly different than what would be predicted by a model without substructure (a.k.a. a "smooth" model). This effect is often referred to as the anomalous flux ratios phenomenon, and has been used to infer the presence of substructure in lens galaxies (e.g., Mao & Schneider 1998; Chiba 2002; Dalal & Kochanek 2002). In an influential paper, Dalal & Kochanek (2002) analyzed radio data for a sample of seven quadruply imaged sources, and measured the fraction of mass in substructure to be $f_{sub} = 0.006-0.07$. This observed fraction appears to be even higher than the mass fraction in substructure predicted by simulations (Mao et al. 2004; Xu et al. 2009).

Substantial efforts have been devoted to investigate whether satellite-size halos are the most likely explanation of the observed flux ratio anomalies. Indeed, flux ratio anomalies could also arise from other effects such as microlensing – if the source is sufficiently compact like the optical UV continuum of a quasar – or a non-uniform interstellar medium which could variously affect light propagating along different paths. However, both contaminants are wavelength dependent, while flux ratio anomalies due to the substructure are achromatic. Therefore, observations at multiple wavelengths, especially radio and mid-infrared, have been used to show that anomalous flux ratios are most likely due to substructures on scales much larger than stars (Agol, Jones & Blaes 2000; Kochanek & Dalal 2004).

Narrow line flux ratios of lensed quasars

OSIRIS on Keck is opening up a new channel for the study of galaxy substructure by measuring narrow line flux ratios of gravitationally lensed quasars. Narrow line flux ratios present a number of key advantages with respect to current methods: 1) the narrow line region is significantly larger (~kpc; e.g. Bennert et al. 2002) than the characteristic microlensing scale (the Einstein radius of a star in the deflector, 0.02pc), and therefore it is unaffected by microlensing (in contrast with continuum or broad lines). 2) (Lensed) QSOs with emission lines are more common than radio loud QSOs, and therefore larger samples are, and will be, available (many more lenses will be discovered by future optical surveys, e.g. Pan-STARRS or LSST). 3) The lines are typically observed in the infrared in the rest frame of the deflector, thus minimizing the effects of differential absorption by dust with respect to UV/optical. 4) Emission line integral field spectroscopy can be performed with much higher resolution and sensitivity than mid-IR imaging, allowing the observer to detect all images and deblend merging images. 5) Unlike continuum and broad lines, QSO narrow line flux does not vary on timescales of weeks, and therefore the time-delays between the images are irrelevant. Although this channel was suggested several years ago (Moustakas &

Metcalf 2003), it has never been properly exploited due to a lack of technology and targets. The advent of OSIRIS/LGSAO and the discovery of new lensed QSOs by SDSS now make this program feasible.

The role of TRICK

Unfortunately at this moment there are only five known quadruply-imaged quasars, with suitable narrow lines fluxes (see Figure 5), that are observable with AO from Keck. Using TRICK opens up two new avenues. On the one hand TRICK should increase the fraction of lensed quasars with suitable tip-tilt star. On the other hand, we will be able to use the lensed QSO themselves to perform the correction. With current technology very few QSO are bright enough to serve as tip-tilt stars. In the H/K band things improve substantially, especially considering that the images of the QSOs are all within a couple of arcseconds and therefore good correction should be achieved on the source used for tip-tilt correction. Higher Strehl and consequently higher sensitivity should also increase the number of targets available for this study. The current limits on dark matter substructure from quadrupled imaged QSOs are based on 7 radio-loud systems. This should be easily beatable with OSIRIS and TRICK, considering that most searches for gravitational lenses are based on optical imaging/spectroscopy (Treu 2010).

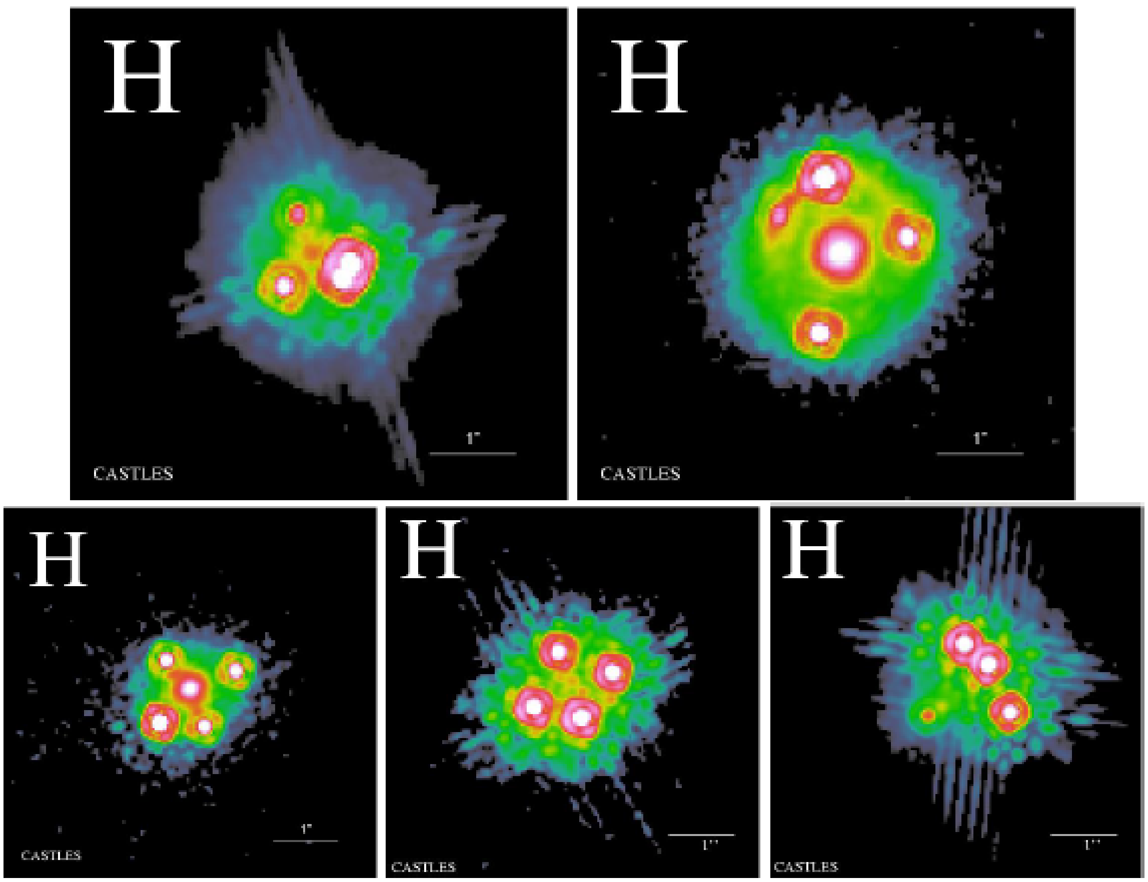

Figure 5: HST-F160W images of the targets taken from the CASTLES database, sorted by RA

We can perform two tests of the TRICK system. First, by re-observing a system that has been observed with current LGSAO, we will measure the improvement in overall performance. This will be mostly a technical test, although the improved sensitivity might be useful to obtain more precise flux ratios and therefore more stringent limits on substructure. A more ambitious test would consist of targeting a system that is not currently feasible with LGSAO. There are currently 2 such systems known (PG1115 and Q2237), and we anticipate more will be known by the time when TRICK will be tested. Interesting lines fall in both the H and K bandpasses, so this observation will provide an opportunity to test TRICK in either bandpass. The typical exposure times are 1-3 hours, and the precise target will depend on the time of the year when the verification is scheduled.

The experiment is very simple: if the narrow line flux ratios agree with those predicted by smooth models, we will conclude that the reason for the anomalous broadband optical flux ratios is microlensing; if the narrow line flux ratios do not agree with those predicted by smooth models then the cause is substructure. An individual system is a publishable result, so it would be a great showcase of the new capabilities.

Lens	RA J2000	DEC J2000	Line	Flux	z_s	λ μm	Filter	R_{TT}	$Dist_{TT}$ $''$	IMAGE
0810+2554	08:13:31.30	+25:45:03.2	NII	4	1.506	1.6521	Hn3	16.9	53.0	17.5
0924+0219	09:24:55.87	+02:19:24.9	NII	3	1.524	1.6615	Hn3	15.7	48.9	-
1115+080	11:18:17.00	+07:45:57.7	NII		1.71	1.7339	Hn5	15.4	51.2	18.1
1138+0314	11:38:03.70	+03:14:58.0	III	4	2.443	1.7239	Hn4	18.1	33.8	-
1413+1117	14:15:46.40	+11:29:41.4	NII	30	2.551	2.3376	Kn5	17.8	16.0	18.0
1413+1117	14:15:46.40	+11:29:41.4	OIII	100	2.551	1.7779	Hn5	17.8	16.0	18.0
1422+2256	14:24:38.09	+22:56:00.6	OIII	120	3.620	2.3132	Kn5	17.4	17.0	16.4
2237+035	22:40:30.34	+03:21:28.8	NII		1.69	1.7708	Hn5	-	-	16.4

Table 6: Relevant information for our targets. Narrow line fluxes for 810, 0924 and 1138 are estimated on the basis of public optical SDSS spectra and line flux ratios from vanden Berk et al. 2001. OIII line flux for 1422 has been measured by Murayama et al. 1999. Line flux for 1413 is based on OIII flux measured by Hill Thompson Elston 1993. All fluxes are given in units of 10^{-16} erg/s/cm^2. R-band magnitude and distance of the nearest tip-tilt star, as well as the R-magnitude of the brightest image, are given in the last three columns. Typical R-K colors for the lensed QSOs are ~1.5 magnitudes, so that the QSOs brighter isolated images are in the range K=15–17.

References: Agol et al. 2000, ApJ, 545, 647 • Bennert et al. 2002, ApJ, 574, L105 • Chantry et al. 2010, A&A, in press • Chen 2009, A&A, 498, 49 • Chiba 2002, ApJ, 565, 17 • Chiba et al. 2005, ApJ, 627, 53 • Dalal & Kochanek 2002, ApJ, 572, 25 • Diemand et al. 2008, Nature, 454, 735 • Goldberg et al. 2010, ApJ, 715, 793 • Hill, Thompson, Elston 1993, ApJ, 411, L1 • Keeton et al. 2006, ApJ, 639, 1 • Klypin et al. 1999, ApJ, 522, 82 • Kochanek & Dalal 2004, ApJ, 610, 69 • Koopmans & de Bruyn 2000, A&A, 358, 793 • Koopmans et al. 2002, MNRAS, 334, 39 • Kravtsov 2010, Advances in Astronomy • MacLeod et al. 2009, ApJ, 699, 1578 • Mao & Schneider 1998, MNRAS, 295, 587 • Mao et al. 2004, 604, L5 • McKean et al. 2007, MNRAS, 378, 109 • Moustakas & Metcalf 2003, MNRAS, 339, 607 • Xu et al. 2009, MNRAS, 1108 • Miranda & Macciò 2007, MNRAS, 382, 1225 • Moore et al. 1999, ApJ, 524, L19 • Murayama et al. 1999, AJ, 117, 1645 • Springel et al. 2008, MNRAS, 391, 1685 • van Dam et al. 2007, KAON 489. • van Dam et al., SPIE 2006 Proc., 6272-106 • vanden Berk et al. 2001, AJ, 122, 549