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Journal

Adaptive Optics for Extremely Large Telescopes 4 - Conference Proceedings, 1(1)

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Publication Date

2015

DOI

10.20353/K3T4CP1131565

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Near-infrared tip-tilt sensing at Keck: System architecture and on-sky performance

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ABSTRACT

The sky coverage and performance of laser guide star (LGS) adaptive optics (AO) systems is limited by the natural guide star (NGS) used for low order correction. This limitation can be reduced by measuring image motion of the NGS in the near-infrared where it is partially corrected by the LGS AO system and where stars are generally several magnitudes brighter than at visible wavelengths. We have integrated a near-infrared tip-tilt sensor with the Keck I telescope's LGS AO system and recently began offering it for science use. The implementation involved modifications to the AO bench, real-time control system, higher-level controls and operations software. The tip-tilt sensor is a H2RG-based near-infrared camera with 0.05 arcsecond pixels. Low noise at high sample rates is achieved by only reading a small region of interest, from 2x2 to 16x16 pixels, centered on an NGS anywhere in an 100 arc second diameter field. The sensor operates at either Ks or H-band using light reflected by a choice of dichroic beam-splitters located in front of the OSIRIS integral field spectrograph. This work presents an overview of the completed system along with on-sky performance results. Lessons learned and efforts to extend the capabilities and further optimize the system are also discussed.

Keywords: Laser guide star, adaptive optics, near-infrared, tip-tilt sensing, wavefront sensing

1. INTRODUCTION

The Keck I laser guide star (LGS) adaptive optics (AO) system began science operations in 2012 [1]. Until recently, both Keck LGS AO systems have utilized a visible-wavelength quad-cell avalanche photodiode based tip-tilt sensor (known as STRAP), which was developed by Microgate and ESO. STRAP can make use of tip-tilt stars as faint as $R=19$, and up to 60 arcseconds away from the science target. In 2015, a near-infrared tip-tilt sensor [2] was commissioned on Keck I, and is now available for shared risk-science operation. It has been demonstrated to perform well with the Ks-band dichroic, using stars as faint as $K=14$ and out to ~ 50 arcseconds off-axis. In some on-axis cases, the Strehl ratio was improved by 84% compared with what was observed with STRAP.

TRICK (Tilt Removal with Infrared Compensation at Keck) offers two main advantages: 1) improved sky coverage because stars are typically brighter at near-infrared (NIR) wavelengths, and 2) the high order correction from the adaptive optics (AO) system allows measurements on an often near diffraction-limited core which leads to improved performance. TRICK supports the science instrument OSIRIS, which is an integral field spectrograph (IFS) and imager [3]. The IFS has a choice of 20, 35, 50 or 100 milli-arcsecond (mas) spatial scales with a field of view (FOV) up to 4.8x6.4 arcseconds, and a spectral resolution of 3800 using a Hawaii-2 detector. The imager has 20 mas pixels and a FOV of 20.4 arcseconds using a Hawaii-1 detector. The IFS and imager fields are separated by 19.4 arcseconds center-to-center.

This document provides an overview of the "as-built" TRICK system architecture in Section 2, followed by presentation of results from on-sky tests and performance characterization in Section 3. The final section discusses the current status of TRICK, how its capabilities are being extended by the Enhanced-TRICK project, and what lessons have been learned in the process of commissioning.

2. SYSTEM ARCHITECTURE

TRICK is composed of five subsystems, as shown in Figure 1. Four of the subsystems represent modifications to the existing Keck I LGS AO system, while the camera is a completely new addition. The following subsections explore each subsystem with emphasis on how they are configured in the final implementation and where the most significant challenges were encountered.

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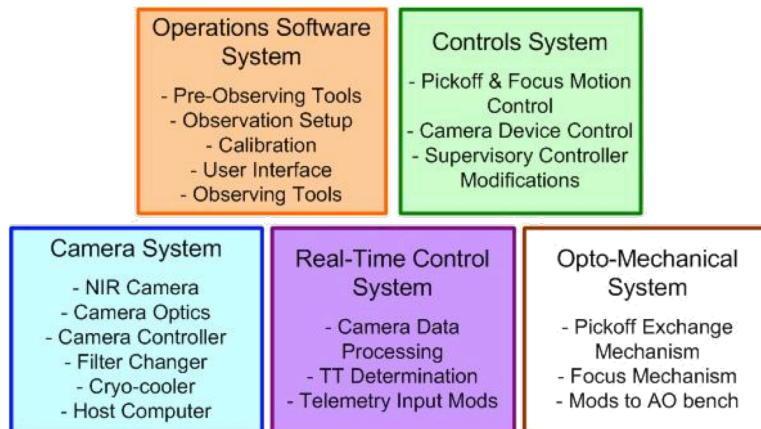


Figure 1: The five subsystems of TRICK.

2.1 Camera

A Teledyne Hawaii-2RG detector facilitates tip-tilt sensing at NIR wavelengths. With 2048x2048 pixels, and 50 milli-arcseconds (mas) per pixel, the available FOV is 102 arcseconds. The detector and reimaging optics are cryogenically cooled to 105 K to produce low noise properties out to Ks-band wavelengths [4]. An engineering grade chip was selected to reduce project costs, and has anomalies such as a dead band between lines 1361 and 1490, and clustered low-sensitivity pixels in two areas near the lower edge. Figure 2 shows a full frame image, without flat fielding, which shows these anomalies along with the mapped positions of the OSIRIS imager and IFS. In total, around 10% of the pixels are unusable due to detector issues, and another ~10% are outside the camera FOV [5]. The bad pixels and unusable regions require additional planning by the user, and/or the ability to reconfigure (i.e. rotate or offset) during the observation.

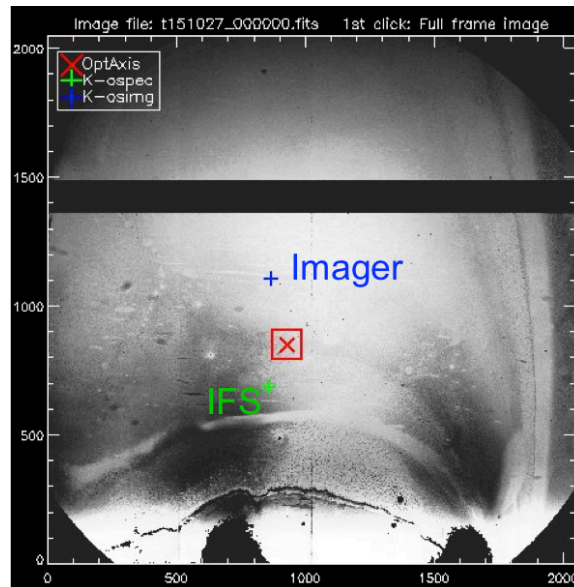


Figure 2: Full frame image (without flat fielding) showing detector anomalies and the mapped locations of the centers of the OSIRIS imager and IFS.

The full frame readout mode can be useful for field identification during acquisition, but the standard method of operation is to read out the detector in sub-arrays. Low noise at high sample rates are achieved by only reading a small region of interest (ROI), which can be 2x2, 4x4, 8x8 or 16x16 pixels. The sub-array readout scheme for this CMOS device is shown in Figure 3, where a series of non-destructive reads are coadded and subtracted to produce frames.

Because the detector must be reset periodically to avoid saturation, there is an occasional gap in the data flow. The frequency at which the detector is reset is determined by the number of reads or cycles per reset (CPR). The optimal number of coadds for a given stellar magnitude and ROI size is calculated based on modeling of the detector noise. Increasing the number of coadds reduces the read noise, but at the expense of decreasing the tip-tilt correction bandwidth.

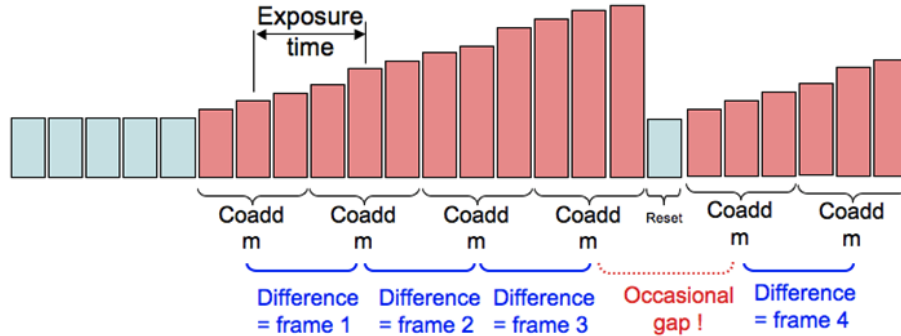


Figure 3: The detector readout takes place in a series of non-destructive reads, which are then co-added and subtracted to produce frames. Occasionally the entire chip must be reset to avoid saturation.

Two areas that presented unforeseen challenges have been the camera filter wheel and TRICK detector server. The filter wheel has three available positions: H, Ks, or open. However, the read-back of the filter wheel position has been found unreliable at detecting mechanism drift, resulting in the need to periodically re-initialize and/or home the device (about every 1-2 months). The most common symptom is having no light present on the detector, and the recovery process takes under 5 minutes. The detector server can easily be jammed if operated while improperly configured, but jams also seem to occur spontaneously about every 4-6 months. At present, recovering from the majority of detector jams requires someone at the summit to physically press a button on the back of the server. In the future, this will be automated, and recovery times should then be below 10 minutes.

2.2 Real-time computer

The existing Microgate real-time control (RTC) computer, also called the wavefront controller (WFC), was developed in 2006. The hardware and software were modified by Microgate to support the fiber interface with TRICK and the additional real-time processing steps shown in Figure 4. Beyond standard operation, the new system architecture was designed to handle up to 8 ROIs, simultaneous operation of STRAP+TRICK, image motion measurements from a correlation algorithm (as opposed to simple centroiding), and a focus calculation based on the light distribution in the TRICK pixels when some astigmatism is present. The functionality of all these items has been verified but, with the exception of parallel STRAP+TRICK operation, determination of their validity and/or usefulness is still a work in progress.

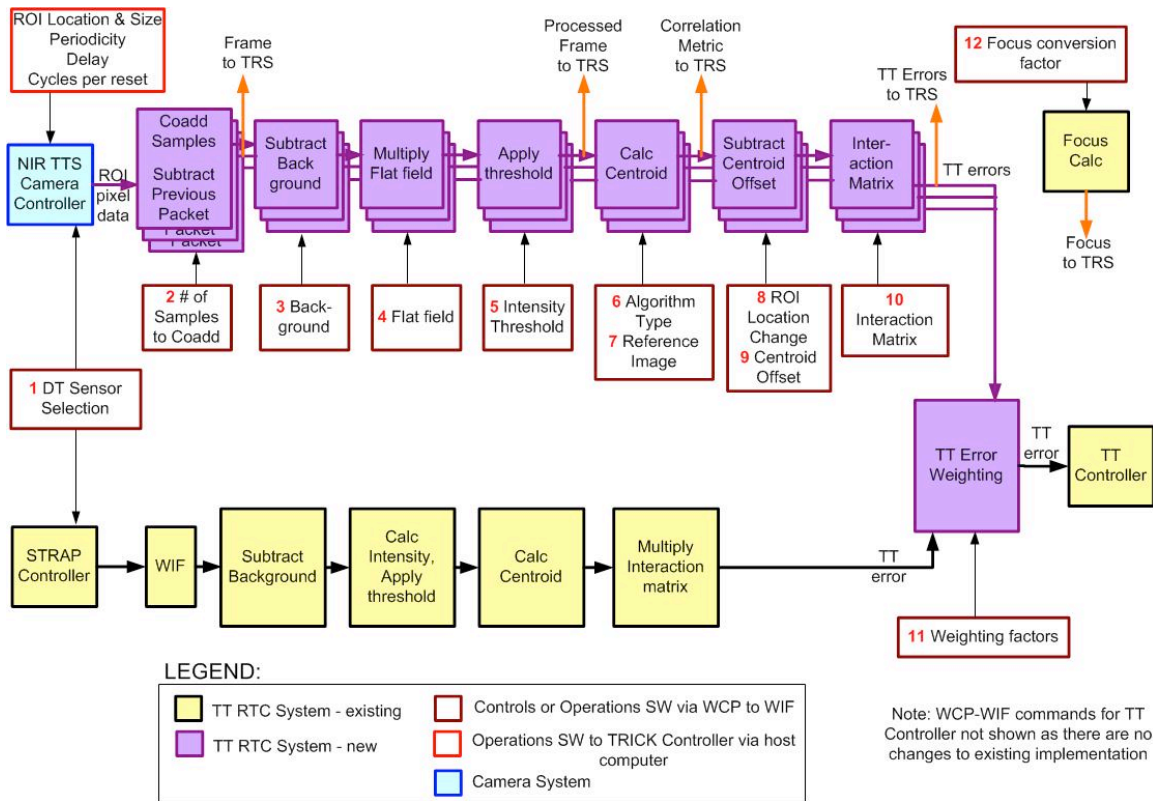


Figure 4: Significant functionality (shown in the purple boxes) was added to the existing RTC for TRICK.

When configured for TRICK, the WFC is running at near maximum capacity even for the simplest case of a single ROI. The stability of the WFC has been a serious issue for the project, but has seen significant improvement during the past year with the frequency of crashes being reduced from ~5 per night, to currently averaging ~1 per TRICK night. Recovering from a crash generally takes 5-10 minutes. Erroneous warnings from the AO system fault detector that a crash may have occurred still take place 1-2 times per night, but are likely a symptom of overall system slowness.

Additionally, unexpected failures have occurred that may or may not be related to the WFC stability problems. The Hot Link board that connects the fiber optic cable from the TRICK camera to the WFC became inoperable twice within two months (in August and September 2015) and had to be replaced. The Keck I STRAP unit also failed twice during the past year, while for comparison the STRAP unit on Keck II has been issue free for ~5 years. A potential culprit is that the power supply to the RTC is allowing too dramatic of voltage fluctuations. This “dirty” power coupled with the system running at maximum capacity could have consequences of the nature we’ve observed. Unfortunately, it’s not straightforward to modify or replace the power supply.

2.3 Opto-mechanical system

The opto-mechanical components include: 1) the optical pickoff stage, 2) the camera focus stage, and 3) modifications to the AO bench covers for TRICK. The location of the pickoff stage can be seen on the right in Figure 5, just below the TRICK camera (item 19) and directly before the light enters OSIRIS. It currently holds two dichroic beam splitters, both manufactured by Custom Scientific. The Ks-band reflective dichroic transmits shorter wavelengths, thus supporting science at H, J, and shorter bandpasses. A second dichroic (which will be referred to as the H-band dichroic) is an annular gold-coated optic with a small H-band reflective/K-band transmissive central region. This design was chosen to support K-band science with the IFS, while allowing K-band tip-tilt sensing if the guide star is ≥ 35 arcseconds off-axis. Figure 6 shows a schematic of the H-band dichroic. In addition to these two positions, the optical pickoff stage also has one currently unused dichroic location and an open position.

The existing tip-tilt sensor (STRAP; item 17 in Figure 5) and low bandwidth wavefront sensor (LBWFS; item 15) are co-mounted on a x,y,z-stage (item 16) and share the visible light from the same star.

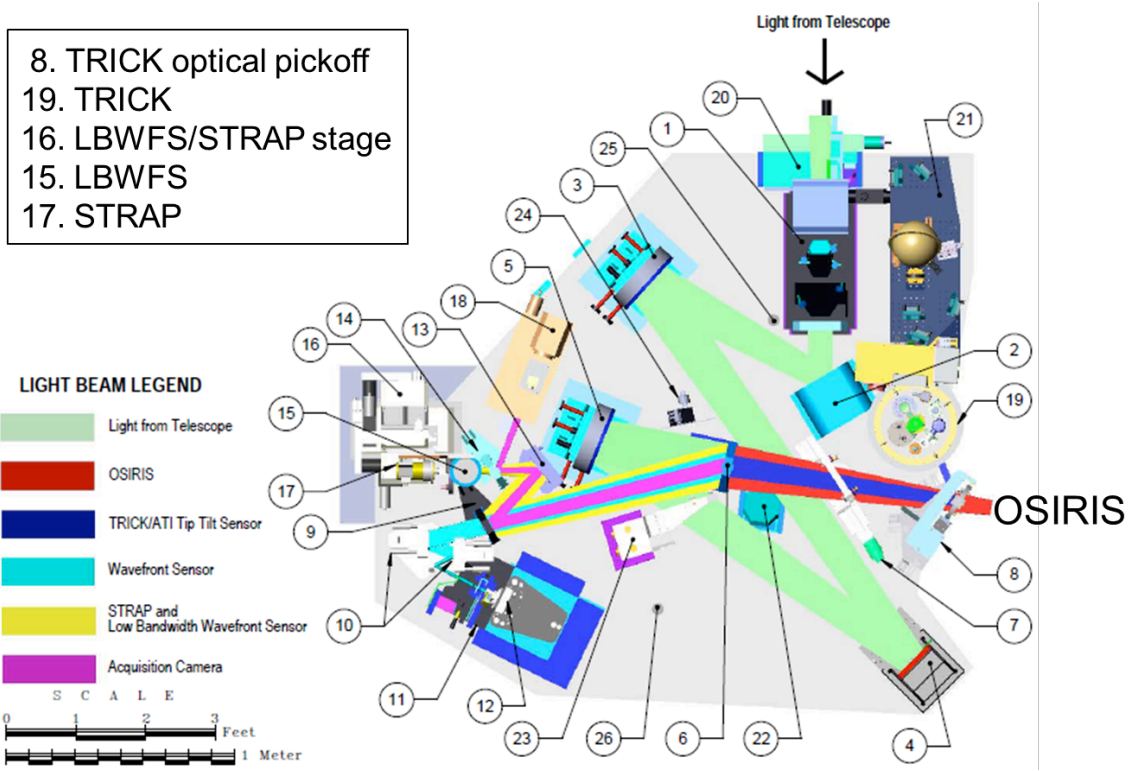


Figure 5: Schematic of the Keck 1 AO bench showing the locations of TRICK and the dichroic pickoff stage.

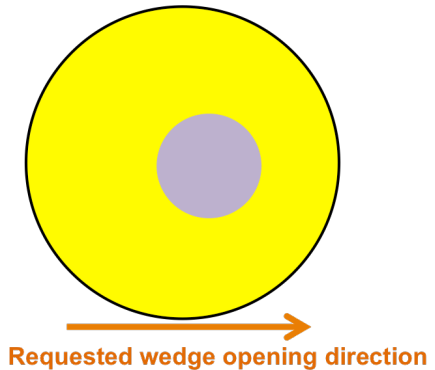


Figure 6: Schematic of the H-band dichroic, with offset central portion and requested wedge opening direction indicated. The actual wedge opening direction is opposite the direction of the offset central region.

In order to have the H-band reflective/K-band transmissive region of the H-band dichroic aligned to the OSIRS IFS, this part needed to be offset by ~5 mm from actual center of the optic. Additionally, both dichroics have a wedge designed to reduce chromaticity when oriented properly. For the H-band dichroic, the requested wedge opening direction was the same as the offset direction of the central portion, as indicated in Figure 6. During testing in August 2015, it was discovered that the actual wedge direction is opposite what was requested, although the labels on the optic indicated otherwise. With the central region aligned to the IFS, the astigmatism has increased from ~250 nm to 380 nm. It is still possible to remove the majority of the additional aberration using the deformable mirror (DM), but the final PSF is still ~20% larger on OSIRIS. The consequences of using the DM to accommodate aberrations of this magnitude are: 1) reduced actuator stroke available for correcting atmospheric turbulence, meaning performance can be expected to degrade faster in poor seeing conditions, and 2) the PSF on TRICK is severely aberrated which also reduces performance. Figure 7 shows the PSF on TRICK when the DM shape has been optimized to produce the smallest spot on OSIRIS. Besides being clearly astigmatic, the full width at half maximum (FWHM) is ~1.7 pixels, compared to <1 pixel

when the wedge is in the correct orientation. Measurements also confirmed the presence of additional chromaticity in the IFS.

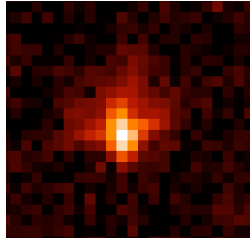


Figure 7: With the H-band dichroic aligned to the IFS and the DM shape optimized to give the smallest spot on OSIRS, the PSF on TRICK has FWHM of ~ 1.7 pixels and is visible astigmatic.

Nevertheless, on-sky testing of the H-band dichroic was performed during October 2015. The seeing conditions were approximately median but variable, and an on-axis tip-tilt star was used to facilitate H-band image motion measurements on TRICK and K-band performance measurements on the OSIRIS IFS. Tip-tilt correction was observed to be on average slightly better when using TRICK compared with STRAP, verifying that performance gains are possible with H-band tip-tilt sensing. In both cases, the H-band dichroic was present in the optical path so this was not a comparison to typical STRAP operation. Procurement of a new H-band dichroic is planned for the near future.

2.4 Controls system

The operation of TRICK requires increased data flow between the AO bench components and the telescope. Figure 8 shows the control loop signal paths in green, and the light path in red. A notable change in the interaction between the telescope and AO system with the addition of TRICK is that the supervisory controller (SC) no longer handles reclosing the AO loops after a telescope offset (or dither, or nod). This responsibility has been passed to the operations software, as discussed in Section 2.5. The SC does reposition the ROI to correspond to the star location after a telescope move when SC tracking is enabled. To accurately do this requires precise knowledge of the distortion in the TRICK camera, which has been determined through daytime testing.

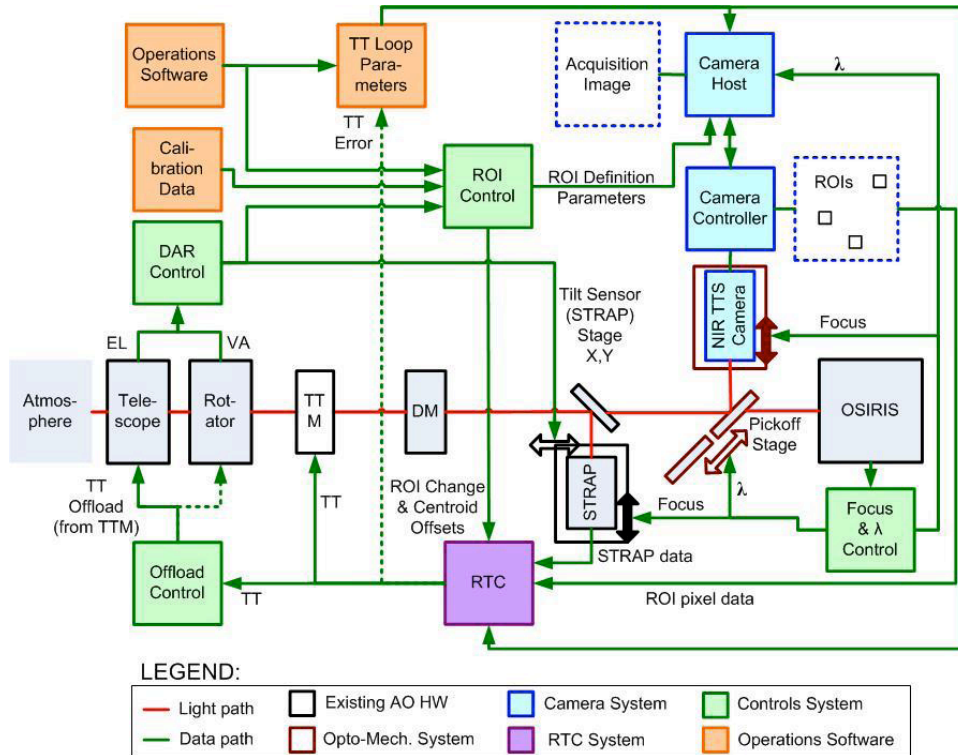


Figure 8: The tip-tilt control loops have increased complexity due to the addition of TRICK.

2.5 Operations software

Successful science operation of TRICK has required creation of new graphical user interfaces (GUIs) and tools for monitoring and interacting with the new devices, as well as substantial modifications to existing AO system tools. These latter have included MAORI (the AO operations GUI), SC GUI, STRAP status, and AOAcq (the acquisition GUI), of which AOAcq has undergone the most dramatic changes. The three new tools for operating the system are the TRICK manager, the ROI GUI, and TODA (TRICK Offset Detection and re-Acquisition).

Figure 9 shows the updated version of AOAcq on the left. The externally visible changes include a new row of fields near the top for the H and K magnitudes of the infrared tip-tilt star (IRTT) and its distance from the science target, two new modes in the “AO Mode” drop list for LGS and NGS TRICK operation (the latter is mainly used for daytime testing and calibrations) with the suffix “-ST/IR”, new pointing origins for both the H and K dichroic, a display of the effective position of the ROI in millimeters on the AO bench with respect to the other relevant AO bench devices, and the selection of background options (which is currently not activated).

The flow chart in the middle of Figure 9 displays the steps added to the process of setting up the AO bench. The “Setup bench” script now checks that the new devices are properly positioned and configures the TRICK camera for the stellar magnitude indicated in the star list. To accomplish this, AOAcq parses star lists with flags that identify which tip-tilt star to put on TRICK and which to have on STRAP (i.e. “irtt=1” and/or “vistt=1”). Magnitudes can also be entered manually in the fields near the top of the GUI. When a non-TRICK mode is selected, the script will check that no dichroic is in the beam path, and will remove it if necessary.

The additional steps taken by the “Acquire star” script are shown in the flow chart on the right in Figure 9. These were added to the end of the original sequence, when the state of the system is to have the DM loop closed on the LGS, and tip-tilt loop closed on STRAP. If the IRTT star is not the same as the star on STRAP, the ROI will be moved to a new location based on the star list coordinates and current position of the AO system field rotator. At this point, a pop-up message will ask the user if they are ready to acquire on TRICK. This operator interaction is currently required to ensure the LGS has been successfully acquired on the fast wavefront sensor (WFS), and that the low bandwidth wavefront sensor (LBWFS) is converging. Both are necessary to have sufficient high-order correction for stable closed-loop operation with TRICK. Once the user gives indication to proceed, the script will verify that the light level in the ROI is above a background threshold and switch control of the tip-tilt mirror to TRICK. The alignment/registration between STRAP and TRICK is then verified and adjusted if necessary, and the user is asked to select the final ROI size. After the camera has been reconfigured for the final ROI size, tracking of the ROI by the SC is enabled.

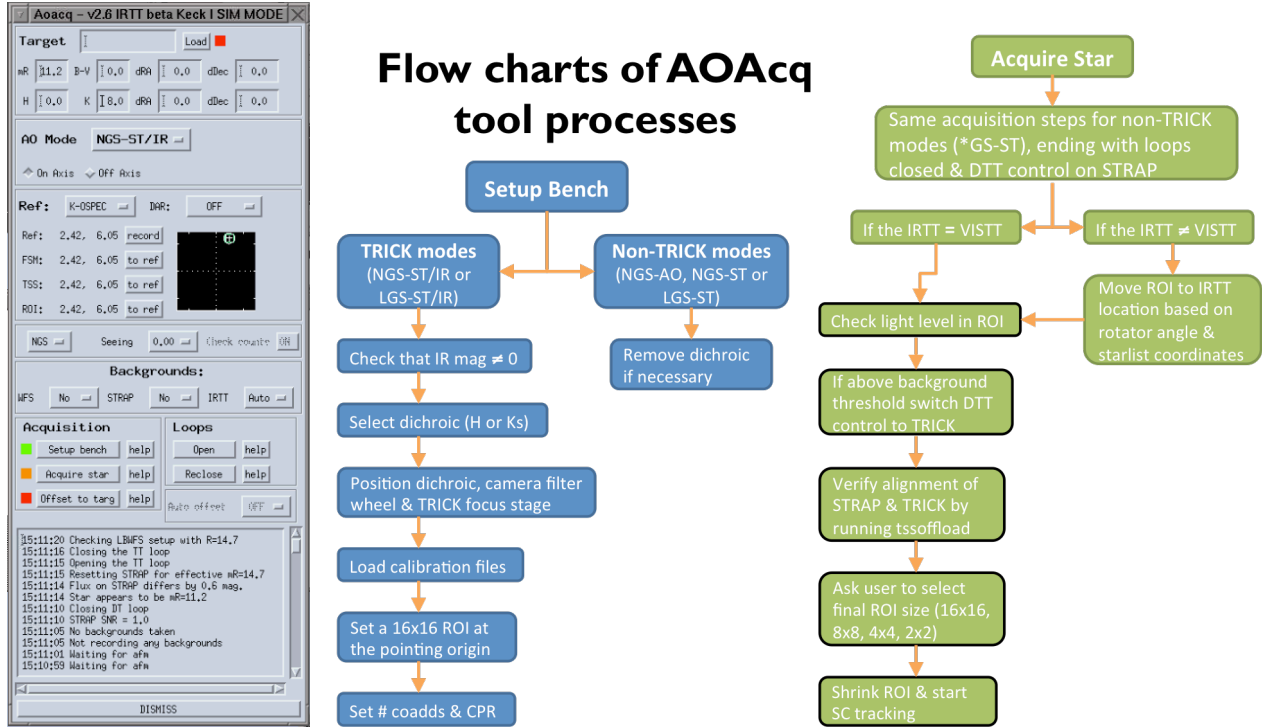


Figure 9: AOAcq was substantially modified for TRICK operations. The updated GUI is shown on the left, and the flow charts of revised processes for setting up the bench and acquiring a star are displayed to the right.

The TRICK manager GUI and ROI GUI provide the user with information about the TRICK system and resources for interacting with it. These are shown on the left and center of Figure 10. The TRICK manager displays a video feed from the ROI, along with information on the camera read mode, status, filter, whether STRAP or TRICK is controlling the tip-tilt loop, ROI position and size, centroid offsets, and effective frame rate. Its interaction features include saving a cube of frames as a FITS file, switching control between STRAP and TRICK, a drop list for selecting a different star from the star list to be the IRTT, and accessing the ROI GUI (as indicated in the figure with the red circle and arrow). The ROI GUI allows manual control of the size and position of the ROI, adjustment of the CPR and number of coadds, the ability to turn off/on the video feed and SC tracking, and provides a method for taking full frame images on TRICK. This latter procedure is occasionally required during acquisition due to errors in stellar coordinates, which result in the star being outside the 16x16 ROI FOV of 0.8 arcseconds.

On the right in Figure 10 is a screenshot of TODA with its associated IDL session. This tool is necessary to monitor for telescope offsets, re-close the AO loops (since this is no longer handled by the SC), and re-acquire on TRICK. In addition, TODA monitors the light levels on the WFS and in the ROI. Losing light on the WFS means the high-order correction has been lost, and control of the tip-tilt loop will switch to STRAP since this device is stable under seeing-limited conditions. The most common case where this occurs is when the laser must be shuttered for a space command closure. Monitoring of the light intensity in the ROI is required to automatically recover if the star is lost, which can happen due to the very small FOV (only 0.1 arcseconds with the 2x2 ROI) and/or poor seeing conditions. Recovery involves switching tip-tilt control to STRAP (which has a much larger field-of-view), increasing the ROI size, and then switching control back to TRICK if the intensity is above the background threshold.

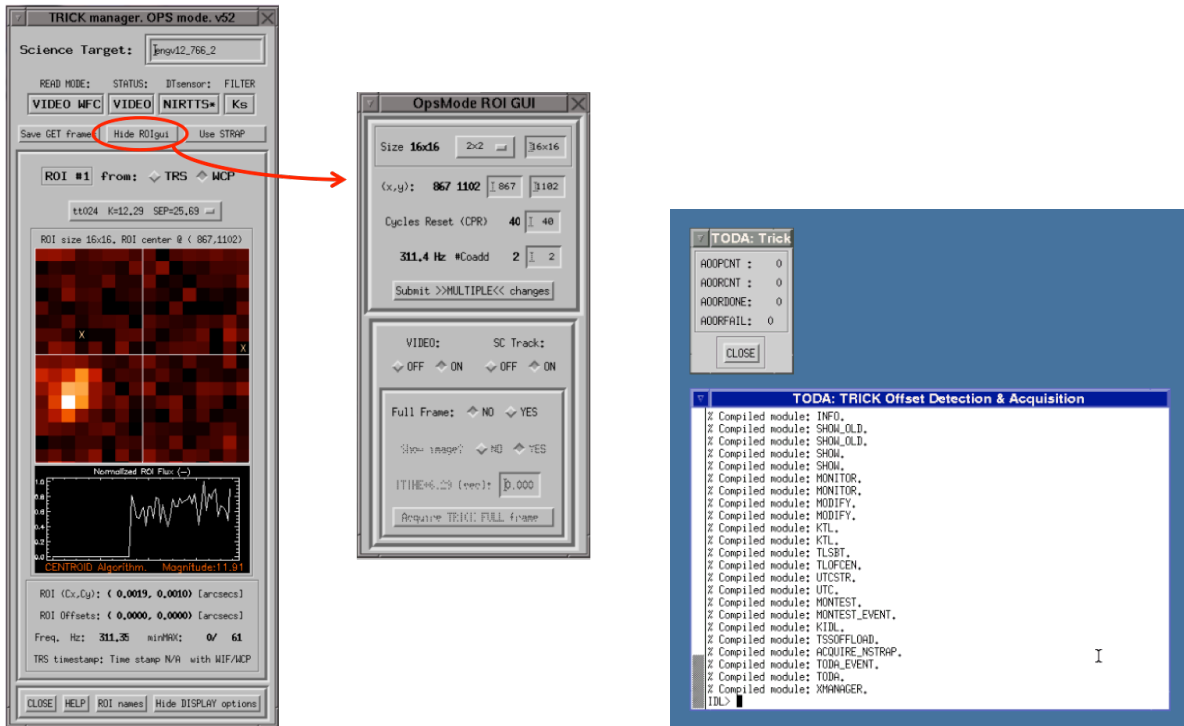


Figure 10: Three new tools were developed to allow the user to interact with and monitor TRICK. From the left, these are called TRICK manager, the ROI GUI, and TODA.

While running the new tools for TRICK, CPU usage on the Keck I AO system server has been found to be consistently at 100%. The cause of this was traced to a problem with the IDL libraries and their interaction with system parameters. Mitigation efforts thus far have been unable to reduce the CPU load without causing catastrophic failures in other parts of the system. More laborious strategies, such as purchasing a dedicated TRICK server or rewriting the operations software in Python, are a current topic of discussion. The most notable consequences of having the server taxed to full capacity include reduced efficiency due to overall slowness, reconstruction matrix file load failures, false alarms that the WFC may have crashed, and reduced communication speeds which could potentially be a culprit in the ongoing WFC stability issues.

3. ON-SKY PERFORMANCE RESULTS

Once operability of the TRICK system was achieved, the focus during on-sky engineering turned to performance characterization. This was done for both on- and off-axis configurations, with the latter going up to nearly 50 arcseconds off-axis. Measurements were taken on multiple nights, and in a variety of seeing conditions. Optimization of parameters such as the tip-tilt loop gain and number of coadds was also investigated. All performance data presented here were taken with the OSIRIS imager, using a narrow H-band filter and exposure times of around 30 seconds, and were background subtracted before processing with IDL tools to determine FWHM and Strehl ratios.

The on-sky performance data taken with TRICK and the K-band dichroic consistently show improvement in the Strehl and FWHM compared to STRAP. The extent of improvement depends both on the absolute and differential magnitudes in R-band and K-band. Figure 11 contains plots of the H-band Strehl versus seeing for three different observing configurations. In all these cases STRAP and TRICK were on the same on-axis star. In the first two cases, the tip-tilt star was saturating the OSIRIS imager so performance was measured on a nearby star. The plots to the right have increasing difference between the R and K magnitudes, as well as fainter absolute magnitudes. The combination of these circumstances results in larger performance enhancements when using TRICK. In the far right plot, under similar conditions the Strehl increased 84% when using TRICK. The average values of Strehl and FWHM for each case and for data points having similar seeing conditions, along with the percent improvement (either increase in Strehl or decrease in FWHM) when using TRICK with a 4x4 ROI, are tabulated in Table 1. Only the 4x4 ROI case is considered since this mode displayed the most clear and consistent performance gains.

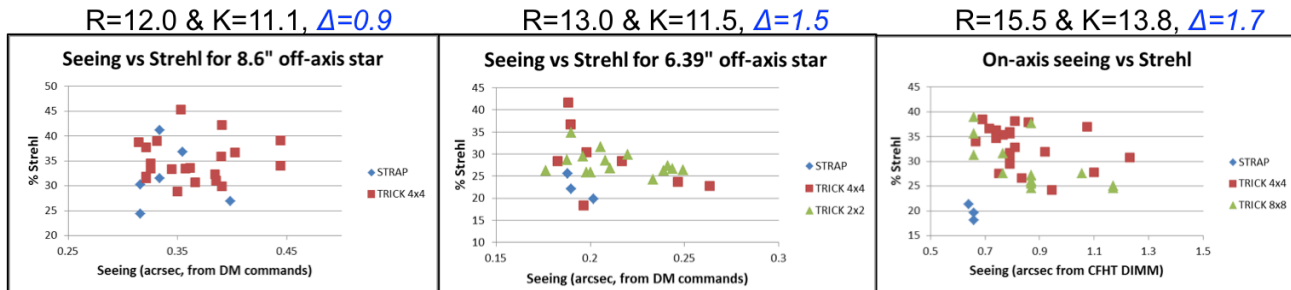


Figure 11: Comparisons of seeing versus Strehl between STRAP and TRICK for three different on-axis stars. In these examples, the performance gain when using TRICK is most notable when the difference between the R and K magnitudes is greatest, and when the R magnitude is faintest.

Table 1: The % Strehl and FWHM for the cases shown in Figure 11, averaged over data points taken under similar seeing conditions. The % improvement (either increase in Strehl or decrease in FWHM) when using TRICK is shown in the bottom row.

	<u>R=12.0 & K=11.1, $\Delta=0.9$</u>		<u>R=13.0 & K=11.5, $\Delta=1.5$</u>		<u>R=15.5 & K=13.8, $\Delta=1.7$</u>	
	% Strehl	FWHM (mas)	% Strehl	FWHM (mas)	% Strehl	FWHM (mas)
STRAP	31.8	45.1	22.4	47.5	19.7	56.1
TRICK 4x4	34.7	41.3	28.6	39.7	36.3	43.2
% Improvement	9.1	8.4	27.7	16.4	84.3	23.0

Some of the regions observed during commissioning presented enough stars within the 20.4 arcsecond OSIRIS imager FOV that performance could be sampled across the field. An example of FWHM and Strehl versus off-axis distance measurements across the field are given in Figure 12. This is for the case of an on-axis tip-tilt star with R=15.5 and K=13.8 (same configuration as the right plot in Figure 11). The images used to create these plots had four stars which allowed FWHM measurements, but only three for Strehl since the ~13 arcseconds off-axis star was too close to the edge of the chip. What is most interesting is that the FWHM measurements show increasingly improved performance at off-axis distances when TRICK with a 4x4 ROI is in use. This seems to indicate that the measurements of image motion on the near diffraction-limited PSF in K-band are different from, and more accurate than, the seeing-limited R-band measurements taken with STRAP. The Strehl values do not imply the same trend, but do show consistently improved performance when TRICK is used.

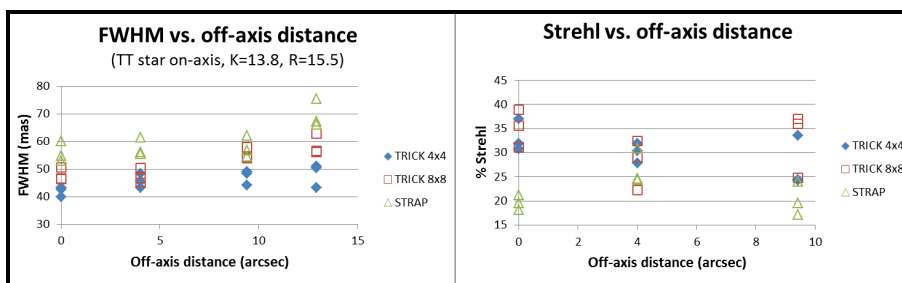


Figure 12: These plots of performance versus off-axis distance show improvement across the OSIRIS imager field with TRICK, indicating the tip-tilt values being measured with this device are more accurate.

Measurements of off-axis performance for larger distances require the tip-tilt star to be outside the FOV of the OSIRIS imager, and no longer coincident with the LGS. This results in a reduction of the high-order correction at the location of the IRTT star, therefore lowering the Strehl on TRICK and reducing performance. Thus, for cases where the star has $R < 16$ it is expected that beyond a certain off-axis distance STRAP will outperform TRICK, since performance of the former is independent of high-order correction. This distance also depends on the seeing conditions, and will be smallest when turbulence is fast and/or the isoplanatic angle is small.

Figure 13 shows FWHM and Strehl measurements for cases where the tip-tilt star was between 5 and ~50 arcseconds off-axis. The data on TRICK were taken using the 4x4 ROI, and only three of the configurations have simultaneous measurements when tip-tilt control was switched to STRAP. For the case of ~30 arcseconds off-axis, the object was discovered to be a close binary. This caused the Strehl tool to give results of questionable accuracy, so these points were omitted from the right plot. These data are from the night of August 28, 2015, and the Maunakea DIMM (differential image motion monitor) reported that the seeing conditions were good and stable, with mean of 0.46 arcseconds*. Under these circumstances, it appears performance is still slightly improved with TRICK out to at least ~40 arcseconds off-axis for the case of a tip-tilt star with R=12.8 and K=9.66. The data points with TRICK on the K=12.29 star appear to have better performance than for the K=9.66 case due to improved seeing conditions during that test.

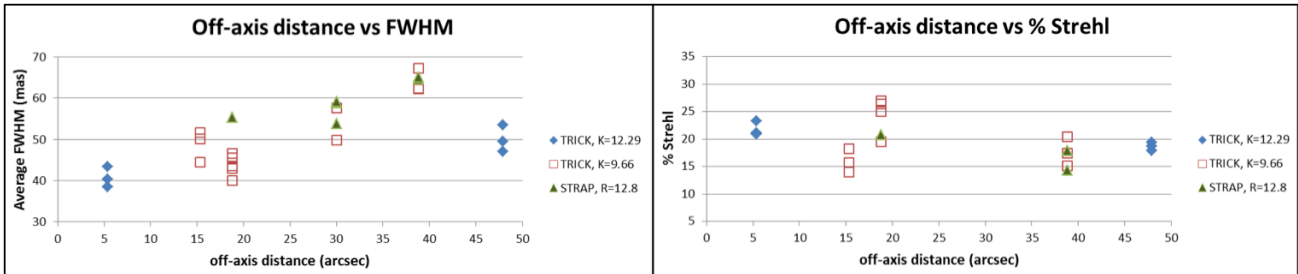


Figure 13: Performance versus off-axis distance measurements were taken with the tip-tilt star up to nearly 50 arcseconds away.

To ensure TRICK was performing optimally, some studies were done of the relationship between performance and parameters such as the number of coadds on TRICK (which determines the effective frame rate) and the tip-tilt loop gain. Reducing the number of coadds means higher bandwidth correction (up to 2 kHz possible), but increased measurement error. Due to this trade-off, the cumulative effect on performance is expected to be moderate. Default coadd values are generated for different stellar magnitudes by a simulation code that aims to balance these terms in the error budget. Optimal gain settings depend on the effective frame rate, and currently the default value is simply scaled by the frame rate to account for the repeated commands sent to the tip-tilt mirror when the system is running slower than 2 kHz. However, it is also a function of the seeing conditions, which is not actively taken into account but can be estimated with tools such as the bandwidth/optimization widget.

Figure 14 contains three plots showing results from two tests where the gain was varied, and one where the number of coadds was changed. In the left plot, the default gain of 0.046 was clearly near optimal. The example in the center shows a case where the default gain was lower than optimal, and the right plot confirms that performance is fairly insensitive to changes in the number of coadds and that the default value was fairly ideal. The overall conclusion is that default settings are adequate, but in some cases a performance boost may be possible by adjusting the gain to better match the seeing conditions.

* <http://mkwc.ifa.hawaii.edu/current/seeing/>

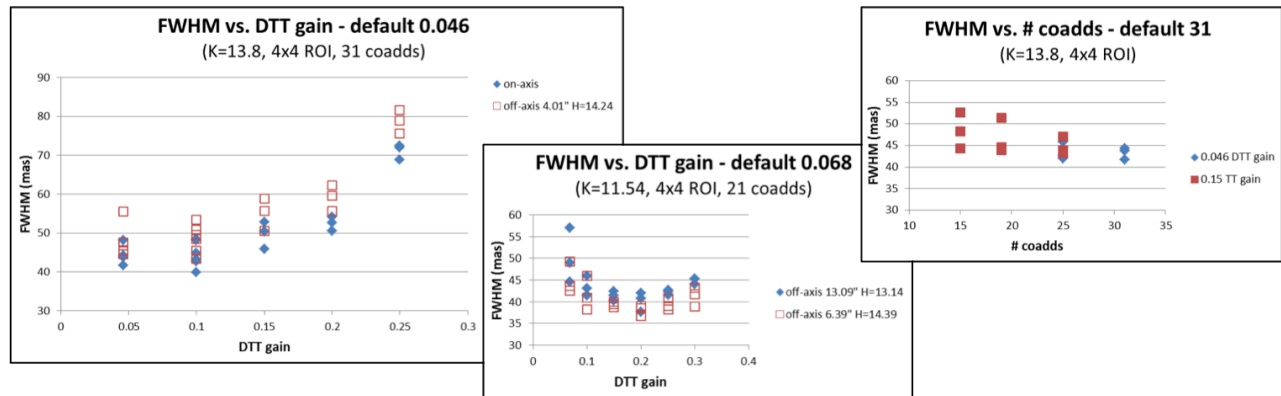


Figure 14: System optimization was investigated by looking at performance for different values of the tip-tilt gain and number of coadds. In general, the default values seemed appropriate although adjustment of the gain to match seeing conditions will in some cases yield improved performance.

4. DISCUSSION

The process of commissioning TRICK has provided valuable information into the use of a Hawaii-2RG detector for near-infrared tip-tilt sensing. This document gives an overview of the final system configuration, and discusses the areas that presented the most significant challenges. Additionally, results from on-sky performance characterization with the K-band dichroic have been revealed. In certain configurations, use of TRICK was observed to improve Strehl by 84% compared to tip-tilt sensing in the visible with STRAP. Further details on the status of the TRICK project, what are planned as the next steps, and the most relevant lessons learned, are discussed below.

4.1 TRICK project status

TRICK is available for shared-risk science use with the K-band dichroic, which supports science on the OSIRIS imager and IFS at H-band or shorter wavelengths. On-sky performance characterization has shown significant improvements are possible when tip-tilt sensing is done in K-band, so there is no doubt the science community stands to benefit from this new capability. Procurement of a new H-band dichroic will precede the ability to support K-band science with TRICK.

The main ongoing challenges of TRICK versus STRAP operation include greater user interaction during acquisition, reduced AO system stability and efficiency, and more planning to comply with new star list format requirements. The added complexity and need for greater coordination between subsystems during acquisition and offsetting results in these events taking a few seconds longer. The WFC is still witnessed to crash about once per night of TRICK use, which requires 5-10 minutes of recovery time. This may be related to the 100% CPU usage on the AO system server when the TRICK tools are running. Preparation for observing with TRICK requires identifying in the star list which object will be used for IRTT sensing, and whether or not the same object will be used for visible light tip-tilt sensing with STRAP and the LBWFS.

Determining if a particular science case could benefit from using TRICK requires analysis of the costs and benefits. Although improved Strehl and FWHM can be expected, it must be understood that both dichroics result in ~7% throughput loss in the light going to OSIRIS, and also change the distortion. This latter will need to be characterized by any campaign aiming to perform precision astrometry.

4.2 Enhanced-TRICK

Thanks to funding received from the Gordon and Betty Moore Foundation, the capabilities of the TRICK system are being tested to their full capacity. Enhanced-TRICK developments that are underway include:

- Use of multiple tip-tilt stars from around the field to reduce anisoplanatism and improve performance [6].
- Parallel STRAP+TRICK operation.
- A correlation algorithm (in contrast to the simple centroiding methods currently used).
- Implementation of a means to sense focus and higher order terms on TRICK with algorithms such as LIFT [7].
- Use of an additional ROI for real-time background measurements and subtraction.
- Improved observation planning tools for astronomers.

4.3 Lessons learned

The original plans for TRICK operation did not require the presence of a star on STRAP. However, on-sky tests determined that the 0.8 arcsecond FOV provided by the 16x16 ROI is not sufficiently large to reliably acquire the tip-tilt star. The availability of a larger ROI (such as 32x32 pixels) could potentially alleviate this issue, but would be non-trivial to implement at this stage, and since a visible light star is required by the LBWFS (which shares a portion of the light with STRAP) this does not present any new constraints. It was also found that STRAP is necessary to hold the tip-tilt star while the TRICK camera is reconfigured (for example, when the ROI size is reduced), or when high-order correction is lost (such as when the laser is shuttered during a space command closure). Furthermore, due to its much larger FOV, STRAP provides a quick and effective means of recovering the tip-tilt star in the event it is lost on TRICK.

Experimentation indicates that the 4x4 ROI is generally the ideal mode for operation. Under normal seeing conditions the star is rarely lost, and performance is observed to be near premium. For bright, on-axis, tip-tilt stars and science campaigns requiring only short exposure times, the 2x2 ROI may offer a slight performance boost combined with a greater risk of losing the star. Automatic recovery by TODA has been observed to work well in most cases, but often results in artifacts in the exposure being taken on OSIRIS. For faint stars in poor seeing, or at large off-axis distances, the 8x8 ROI may provide the best option.

The most significant challenges encountered while commissioning TRICK relate mainly to the capacity of the current Keck I AO system and its overall architecture. These factors include both the inability of the RTC to perform reliably under the increased load required with TRICK, and the problems encountered when interfacing system parameters with IDL operations software which resulted in unacceptably high CPU usage. Additionally, a significant bottleneck for this project was the need for on-sky engineering time to understand behavior and characterize performance. Having a daytime turbulence (or at least tip-tilt) simulation device could have expedited these processes.

ACKNOWLEDGEMENTS

This material is based in part upon work supported by the National Science Foundation under Grant No. AST-1007058, and by the Gordon and Betty Moore Foundation under Grand No. 4046. We would like to acknowledge the technical contributions of Andrew Cooper, Ean James, Chris Neyman, Thomas Stalcup, Jon Chock, Liz Chock, Shui Kwok, Sudha Laven, Scott Lilley, Jeff Mader, Olivier Martin, Bill Randolph, Kevin Tsubota and Ed Wetherell at WMKO, Ernest Croner, Roger Smith, Khan Bui, John Cromer, Richard Dekany, Jason Fucik, David Hale, and Hector Rodriguez at Caltech, Roberto Biasi, Mario Andrighettoni, and Dietrich Pescoller at Microgate, Marcos van Dam at Flat Wavefronts, and Antonin Bouchez at GMT. We would also like to thank our science team of Tommaso Treu at University of California (UC) Santa Barbara and Mark Morris at UC Los Angeles.

The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

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