Keck Adaptive Optics Note 1069

Tip-Tilt Sensing with Keck I Laser Guide Star Adaptive Optics: Sensor Selection and Performance Predictions

DRAFT to be updated as more performance data becomes available

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Contents

1. Summary Recommendation

Summary recommendation for when to use the near-infrared tip-tilt sensor (Vega magnitudes are used):

- For K-band OSPEC science when you have an H<14 star within 15″ of the science target. *(not yet available)*
- For all science short of K-band when you have a K<16 star within 30″ of the science target.
- These off-axis distances can be increased when the available tip-tilt stars are R-K > 2.5 (possibly due to dust) or when the isoplanatic angle is large.

2. Introduction

The energy within an AO-corrected image depends on the performance of the wavefront sensor control loop. The angular size of this image depends on the performance of the tip-tilt sensor control loop. For LGS AO the wavefront sensor loop performance is independent of the nature of the science object. However, the tip-tilt performance is highly variable depending on the magnitude and off-axis distance of the tip-tilt star.

The Keck I laser guide star (LGS) adaptive optics (AO) system offers a choice between visible and near-infrared (IR) tip-tilt sensors: STRAP (System for Tilt Removal with Avalanche Photodiodes) and TRICK (Tilt Removal with Infrared Compensation at Keck) (Wizinowich et al., 2014). In both cases a visible guide star is needed for the low bandwidth wavefront sensor (LBWFS), which provides focus corrections to the wavefront sensor focus stage and centroid offset corrections to the wavefront sensor.

The purpose of this document is to support observers by providing information on: (1) selecting between STRAP and TRICK, and (2) TRICK performance.

There are three potential benefits of sensing in the near-IR for LGS AO: (1) the average star is considerably brighter in the near-IR than in the visible; (2) closing the LGS loop provides sufficient correction in the near-IR to allow tip-tilt sensing on a near-diffraction limited, rather than seeing-limited, image; and (3) allowing or improving LGS AO observations of dust obscured regions. TRICK will offer higher performance and sky coverage in many, but not all, cases.

3. OSIRIS Science Modes Supported

All OSIRIS modes are supported by STRAP. TRICK does not support K-band imaging. TRICK must be reconfigured between OSIRIS science at wavelengths shorter than K-band and spectrograph science at K-band. For science short of K-band a K-band reflective dichroic is inserted into the path to OSIRIS. For K-band spectrograph science a gold annular mirror with an H-band reflective dichroic at its center is inserted into the path to OSIRIS. Both dichroics reduce the light to OSIRIS by 7% (and thereby increase the thermal background to OSIRIS) but do not degrade the image quality.

TRICK uses Ks-band light for tip-tilt sensing when the K-band reflective dichroic is in the OSIRIS path. When the H-band reflective dichroic is in the beam TRICK can use Ks-band light from stars > 35” off-axis or H-band light from stars anywhere in the field. The Strehl ratio of the AO-corrected tip-tilt star will be higher at Ks-band than H-band.

4. Keck LGS AO and STRAP Performance

Figure 1 and Figure 2 provides some performance references from the Keck II LGS AO system. The Figure 2 data are from after a wavefront controller upgrade that increased the typical Strehl ratio from 0.35 to 0.39 under good condition. For reference, a K-band Strehl ratio of 0.4 corresponds to an H-band Strehl ratio of 0.2. The Keck I LGS AO performance is higher due to center launch and a brighter LGS. Some data for this system is plotted in Figure 3. Tip-tilt performance noticeably degrades for R > 16.

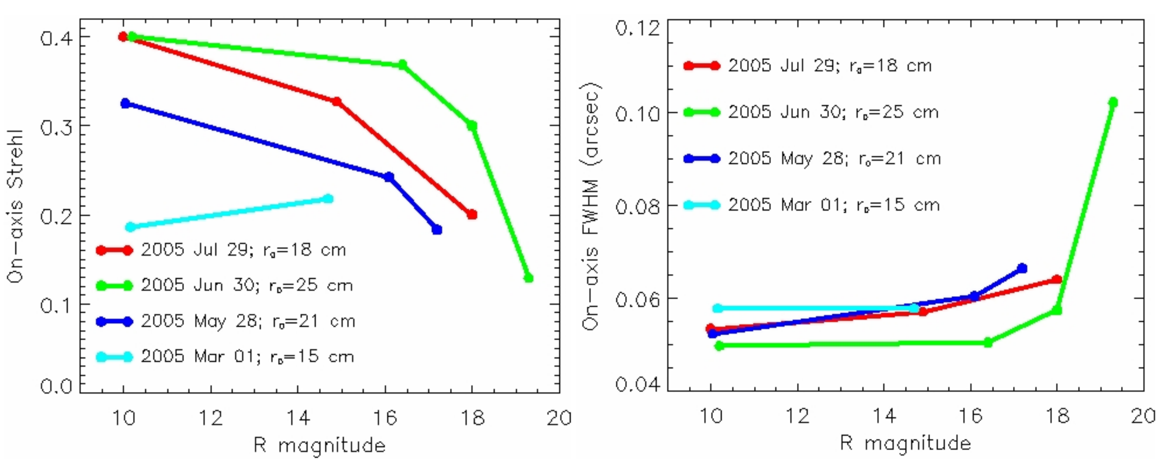

Figure 1: Keck II LGS AO performance measured in 2005. K-band Strehl ratio (left) and FWHM (right) versus seeing conditions and tip-tilt star R-magnitude.

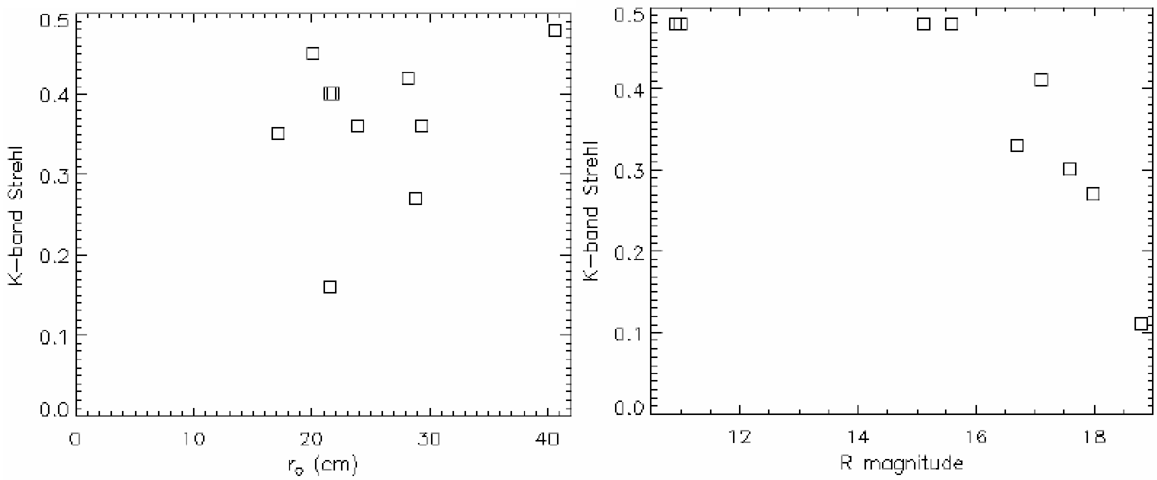

Figure 2: Keck II LGS AO performance measured in 2007 as documented in KAON 489. Left: K-band Strehl versus seeing for a bright tip-tilt star. Right: K-band Strehl versus tip-tilt star magnitude in very good seeing conditions.

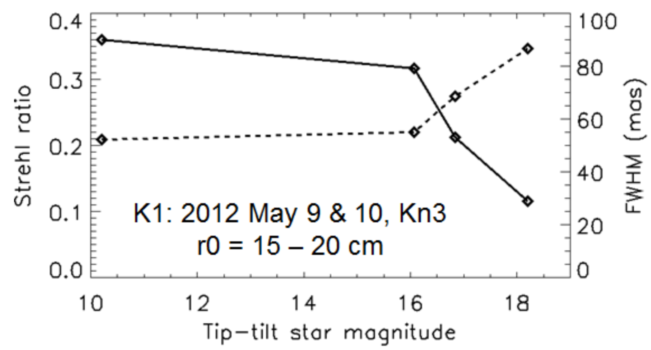

Figure 3: Keck I LGS AO K-band Strehl ratio and FWHM as a function of tip-tilt star R-magnitude (KAON 925).

5. Demonstrated K-band TRICK versus STRAP Performance

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 (Rampy et al., 2016). The on-sky performance data taken with TRICK and the K-band dichroic consistently show improvement in the Strehl ratio and FWHM compared to STRAP. The extent of improvement depends both on the absolute and differential magnitudes in R-band and K-band.

Figure 4 contains plots of the H-band Strehl ratio versus seeing for three different observations where 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 seeing conditions the Strehl ratio increased 84% when using TRICK. Table 1 lists the average values of Strehl ratio 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. Only the 4x4 ROI case is considered since this mode displayed the most clear and consistent performance gains.

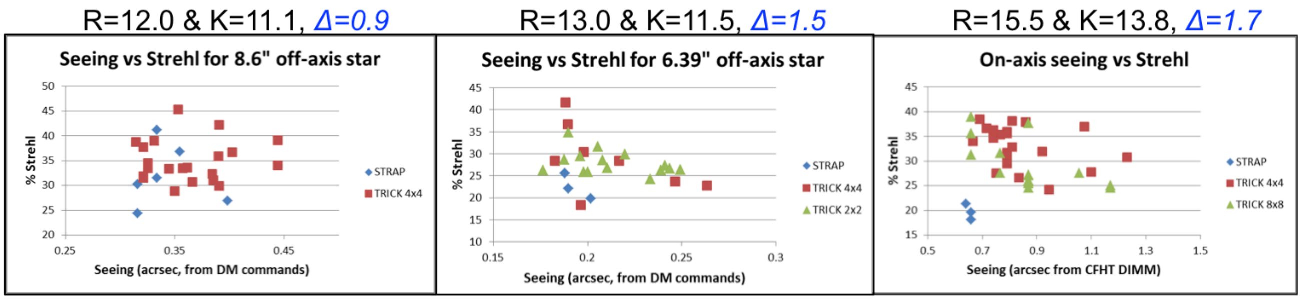

Figure 4: % Strehl ratio with STRAP and TRICK versus seeing for three different on-axis stars. The performance gain when using TRICK is most notable when the difference between the R and K magnitudes is greatest, and when the R magnitude is faintest.

Table 1: The % Strehl ratio and FWHM for the cases shown in Figure 4, averaged over data points taken under similar seeing conditions. The % improvement with TRICK (i.e. increase in Strehl ratio or decrease in FWHM) is shown in the bottom row.

	R=12.0 & K=11.1, *Δ=0.9*		R=13.0 & K=11.5, *Δ=1.5*		R=15.5 & K=13.8, *Δ=1.7*	
	% 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 observed regions presented enough stars within the 20.4″ OSIRIS imager field that performance could be sampled across the field. Figure 5 provides plots of FWHM and Strehl ratio versus off-axis distance 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 4); four stars were used for FWHM measurements, but only three for Strehl since the ~13 arcseconds off-axis star was too close to the edge of the chip. 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 ratio values do not show the same trend, but do show consistently improved performance when TRICK is used.

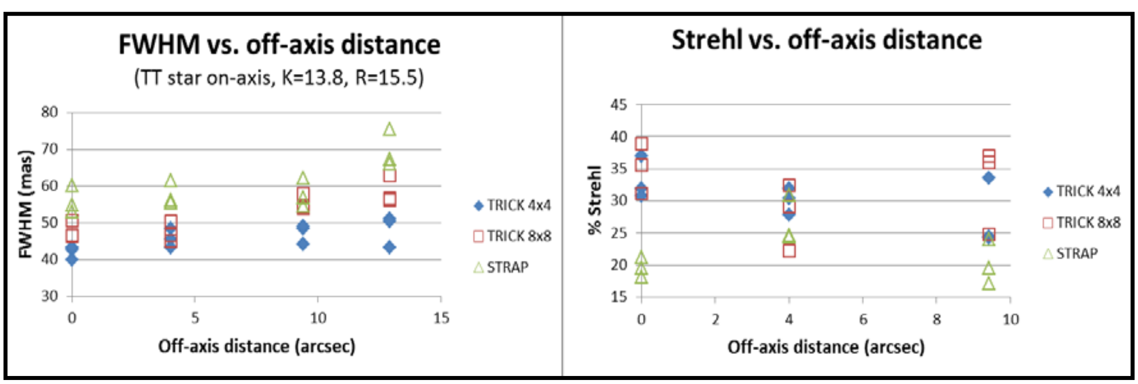

Figure 5: These plots of performance versus off-axis distance show improvement across the OSIRIS imager field with TRICK, indicating the tip-tilt values being measured with this device are more accurate.

In the previous measurements the LGS was pointing at the center of the OSIRIS imager and hence at the tip-tilt star. The Strehl ratio of the tip-tilt star is lowered as the tip-tilt star moves away from the LGS.

Beyond a certain off-axis distance STRAP will outperform TRICK, since STRAP performance is independent of high-order correction. This distance depends on the relative R and K-band magnitudes and seeing conditions.

Figure 6 shows the FWHM and Strehl ratio measurements for an on-axis star as a function of the off-axis distance of the tip-tilt star. The TRICK data were taken using a 4x4 ROI. For the case of an R=12.8, K=9.66 tip-tilt star is still slightly improved with TRICK out to at least ~40″ off-axis. The data with TRICK on a K=12.29 star has better performance than for the K=9.66 case apparently due to improved seeing conditions during that test.

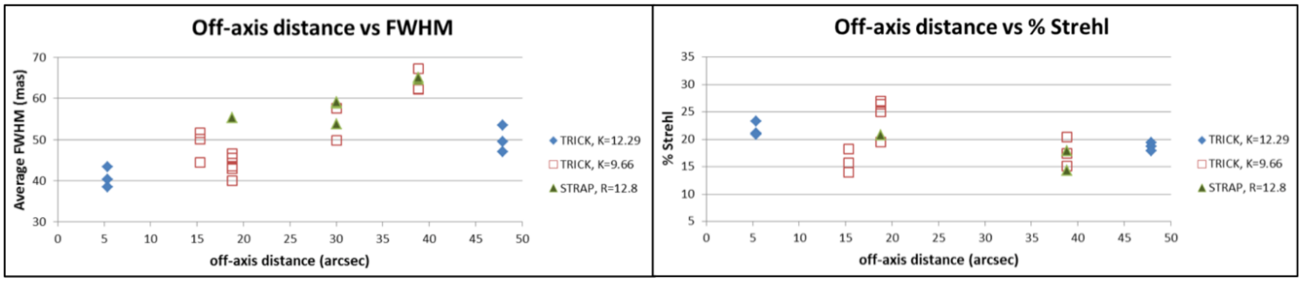

Figure 6: On-axis performance versus tip-tilt star off-axis distance, on the night of August 28, 2015. The Maunakea seeing monitor reported good and stable seeing with a mean of 0.46″. The star at 30″ was a close binary and was only used for a FWHM measurement.

A science target was observed on the night of September 3, 2014. The resultant images obtained with STRAP and TRICK are shown in Figure 7. STRAP used an off-axis star since the science target was too faint (R~20). The science object was much brighter at K allowing it to be used by TRICK. The resultant performance improvement with a bright, on-axis near-IR tip-tilt star is quite significant.

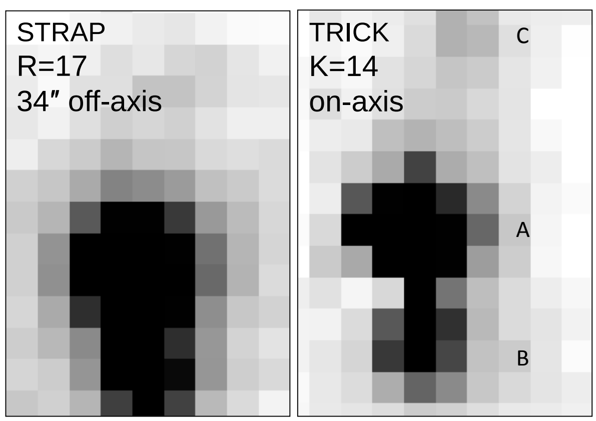

Figure 7: Science performance demonstration. A gravitational lens observed with the OSIRIS spectrograph (25 coadds, 10 minute integration, Hbb filter, 50 mas spaxels). The images are average-collapsed data cubes. A 4x4 pixel region was used on TRICK. The FWHM of an isolated source in the full spectrograph image was reduced from 101x93 mas with STRAP to 76x79 mas with TRICK; and in addition a third source is identified.

6. Expected Performance versus Angular Offset

Tip-tilt correction of the science object, at which the LGS is pointed, will degrade as the angular offset to the tip-tilt star increases. This isokinetic (tip-tilt) error will be the same for STRAP and TRICK. However, TRICK also suffers from higher order isoplanatic error which reduces the Strehl ratio of the tip-tilt star with angular separation from the LGS as shown in Figure 8.

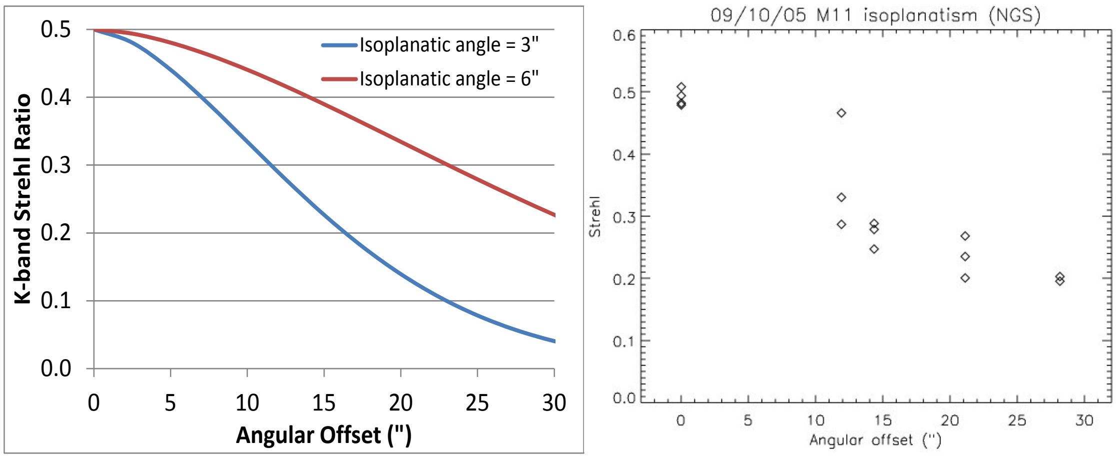

Figure 8: Left: Predicted K-band Strehl ratio as a function of angular offset from the LGS assuming particular angular offsets. Right: Measured isoplanatic performance from Keck AO data; this plot fits between the two curves in the left plot.

A decrease in Strehl ratio is equivalent to a decrease in stellar magnitude. The left plot in Figure 8 is replotted as an effective decrease in magnitude in Figure 9. For example, a 30″ tip-tilt star on TRICK should be considered to be effectively 0.9 to 2.7 magnitudes fainter than if it were on-axis, depending on the isoplanatic angle.

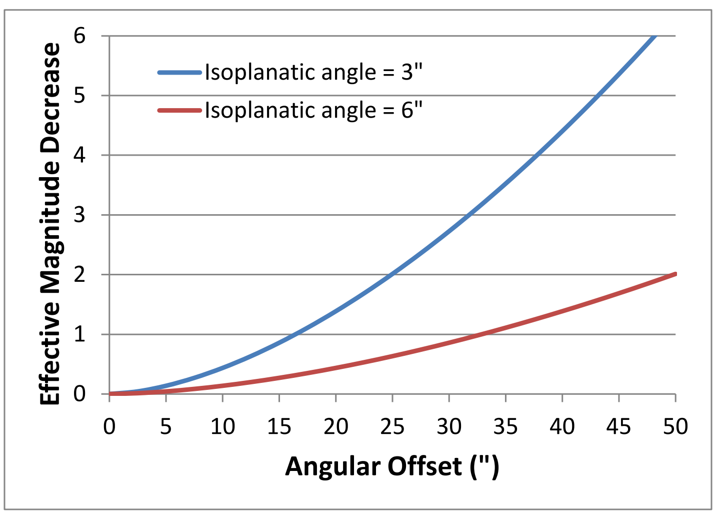

Figure 9: Effective magnitude decrease due to anisoplanatism versus angular offset.

The predicted on-axis Strehl degradation versus off-axis distance for a bright tip-tilt star is shown in Figure 10 from KAON 893 (note that since this simulation does not include all error terms the absolute Strehl is higher than we expect with Keck AO). The mean slope curve shows the degradation simply due to anisoplanatism. The performance with H and K-band tip-tilt stars further degrades due to the growing image structure as you move off-axis. In particular much of the energy in the central core extends outside the area sampled in 4x4 pixel centroiding. One could increase the number of pixels used for centroiding at the expense of increased noise (background, readout and photon).

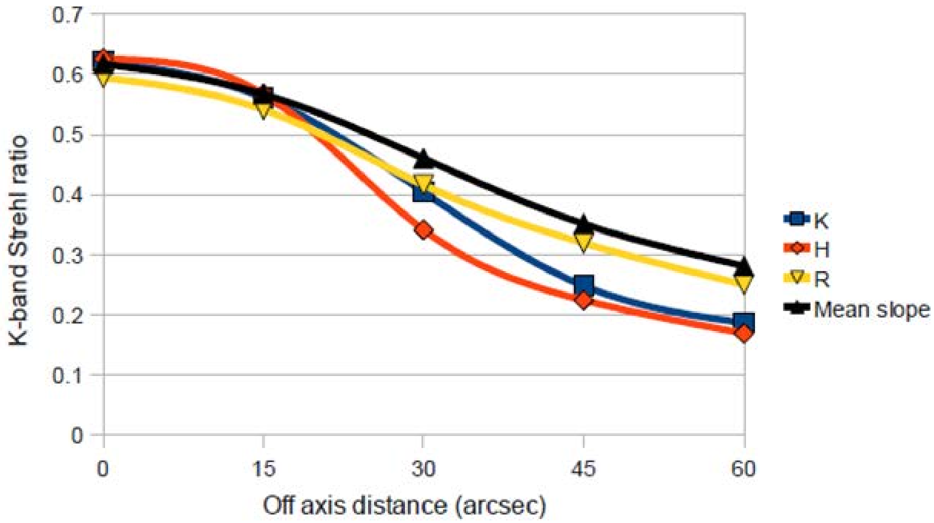

Figure 10: On-axis K-band Strehl degradation as a function of tip-tilt star off-axis distance for a 14th magnitude tip-tilt star at three different tip-tilt sensing wavelengths. H and K-band using a 4x4 centroider with 50 mas pixels. R-band using a quad cell with 500 mas pixels.

The performance improvement with K-band tip-tilt sensing is seen as we go to fainter tip-tilt stars, as shown in Figure 11. However, the performance drop off due to K-band tip-tilt image structure as a function of off-axis distance results in better performance with STRAP toward the edge of the field.

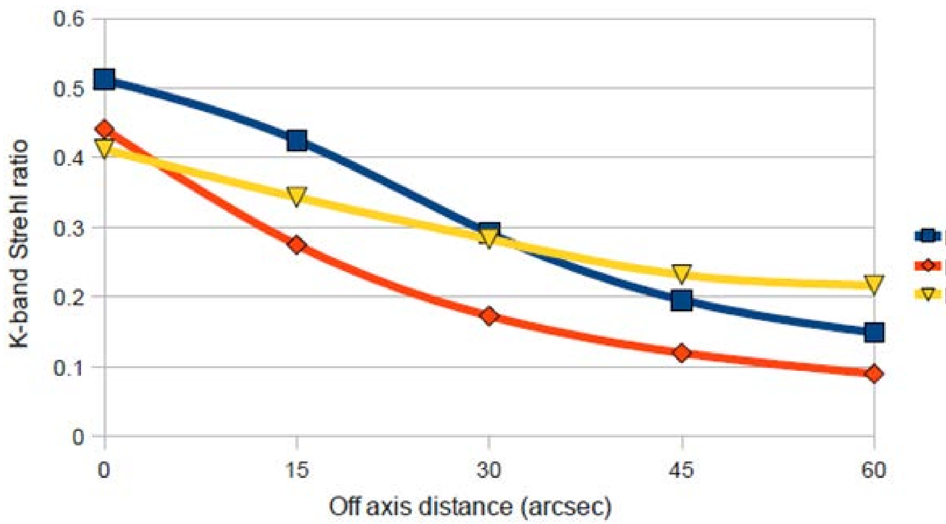

Figure 11: On-axis K-band Strehl as a function of tip-tilt star off-axis distance for a M0 guide star (R=18.5, H=16.5 and K=16). H and K-band using a 4x4 centroider with 50 mas pixels. R-band using a quad cell with 900 mas pixels.

The above two plots (once verified on sky) provide the following simple guidance as to when to use TRICK:

- For K-band OSPEC science when you have an H<14 star within 15″ of the science target.
- For all science short of K-band when you have a K<16 star within 30″ of the science target.
- These off-axis distances can be increased when the available tip-tilt stars are R-K > 2.5 (possibly due to dust) or when the isoplanatic angle is large.

7. Field of Regard

The fields of regard for the two sensors are quite comparable as shown in Figure 12 and Figure 13. The STRAP/LBWFS stage moves these detectors around its field of regard to acquire the tip-tilt star. STRAP is a 2x2 element detector with 1.4” pixels. TRICK has 0.050” pixels. A 2x2 to 16x16 pixel region of interest is read out on the stationary TRICK detector to acquire the tip-tilt star.

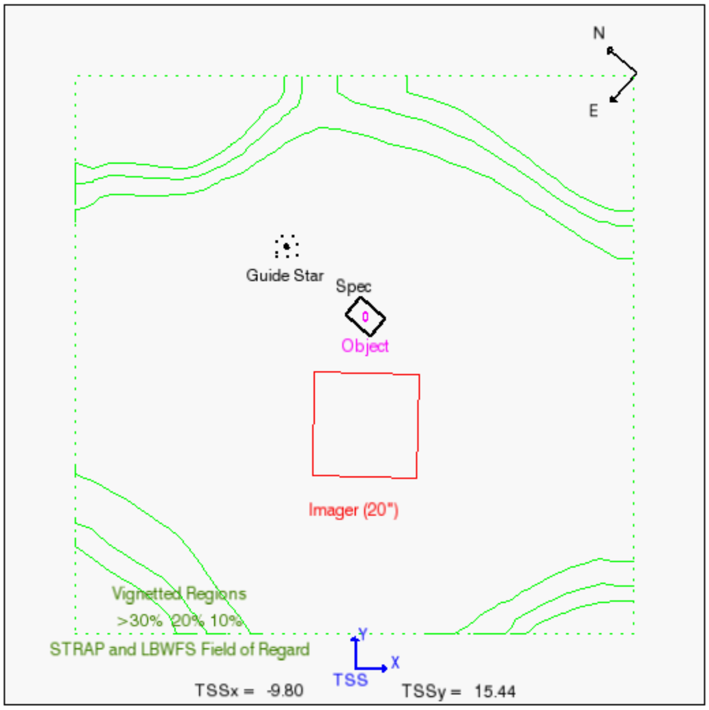

Figure 12: Field of regard within which STRAP/LBWFS can move to acquire a tip-tilt star. A 105″x105″ field is shown. The inner most contour line represents 10% vignetting. The relative location of the OSIRIS imager and spectrograph are shown.

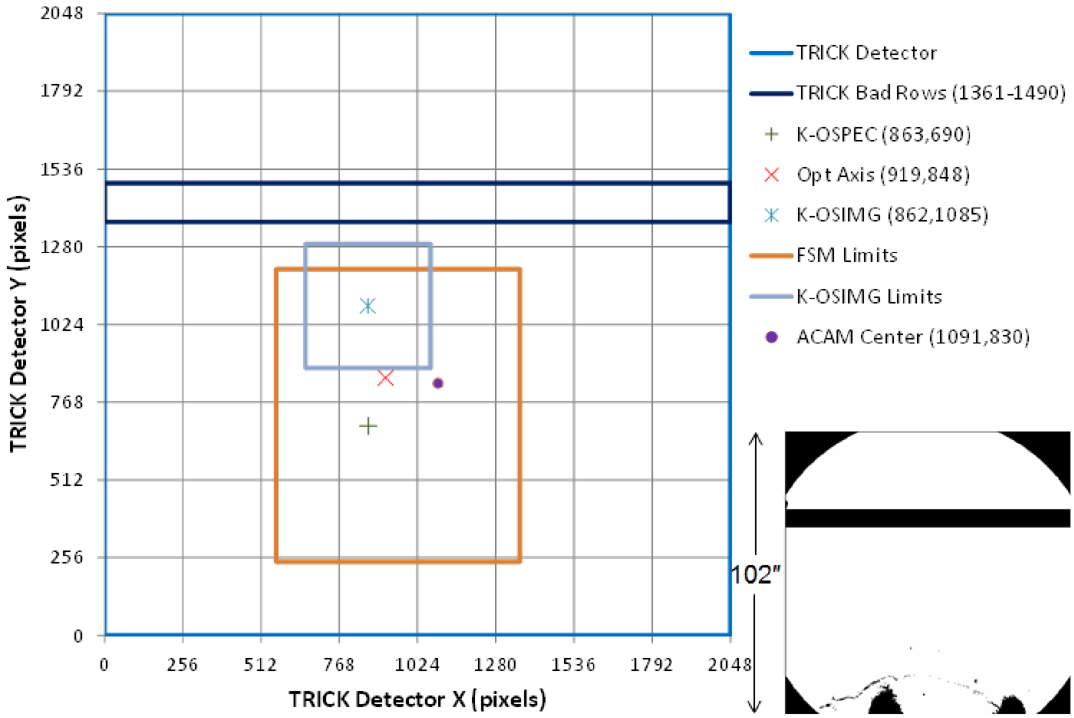

Figure 13: TRICK detector field of regard (102″x102″). The vignetted pixels and bad pixels are shown in the bottom right image. The relative location of the OSIRIS imager and spectrograph are shown.

8. Star List Format

The following two examples show (1) the current star list format to support identification of the NGS for STRAP/LBWFS and (2) the new star list format to support identification of an NGS for TRICK and an NGS for the LBWFS. In the new format the TRICK and LBWFS stars are separately identified with the designators irtt=1 and vistt=1, respectively. Backup NGS can be designators irtt=2 or vistt=2. The appropriate magnitudes are provided in each case.

Current star list file for Galactic Center:

```
#  Galactic Center with USNO field stars for STRAP/LBWFS
#  Either tip tilt star can be used, second is farther away use as backup
#
Sag A*      17 45 40.041 -29 00 28.12 2000.0 lgs=1
0609-0602733  17 45 40.713 -29 00 11.18 2000.0 rmag=14.0 sep=19.3 b-v=0.83 b-r=1.65 pa=45
0609-0602749  17 45 42.287 -29 00 36.80 2000.0 rmag=13.5 sep=31.2 b-v=0.68 b-r=1.40
#
```

Star list for same target with NIR TTS:

```
#  Galactic Center with IRS 7 on NIR TTS and Vis star for LBWFS
#
Sag A*      17 45 40.041 -29 00 28.12 2000.0 opsmode=lgs
IRS7       17 45 39.987 -29 00 22.24 2000.0 irtt=1 kmag=6.5 sep=5.0 b-v=2.76 b-r=1.0 pa=45
0609-0602733  17 45 40.713 -29 00 11.18 2000.0 vistt=1 rmag=14.0 sep=19.3 b-v=0.83 b-r=1.65 pa=45
```

9. Sensor Locations

A top-view schematic of the Keck I AO bench is shown in Figure 14 with the locations of the natural guide star sensor indicated by numbers. The light is sent to TRICK by a choice of optical pickoff just in front of OSIRIS. STRAP and the LBWFS use the same star and are therefore co-mounted on a stage that moves around the field reflected by the IR transmissive dichroic.

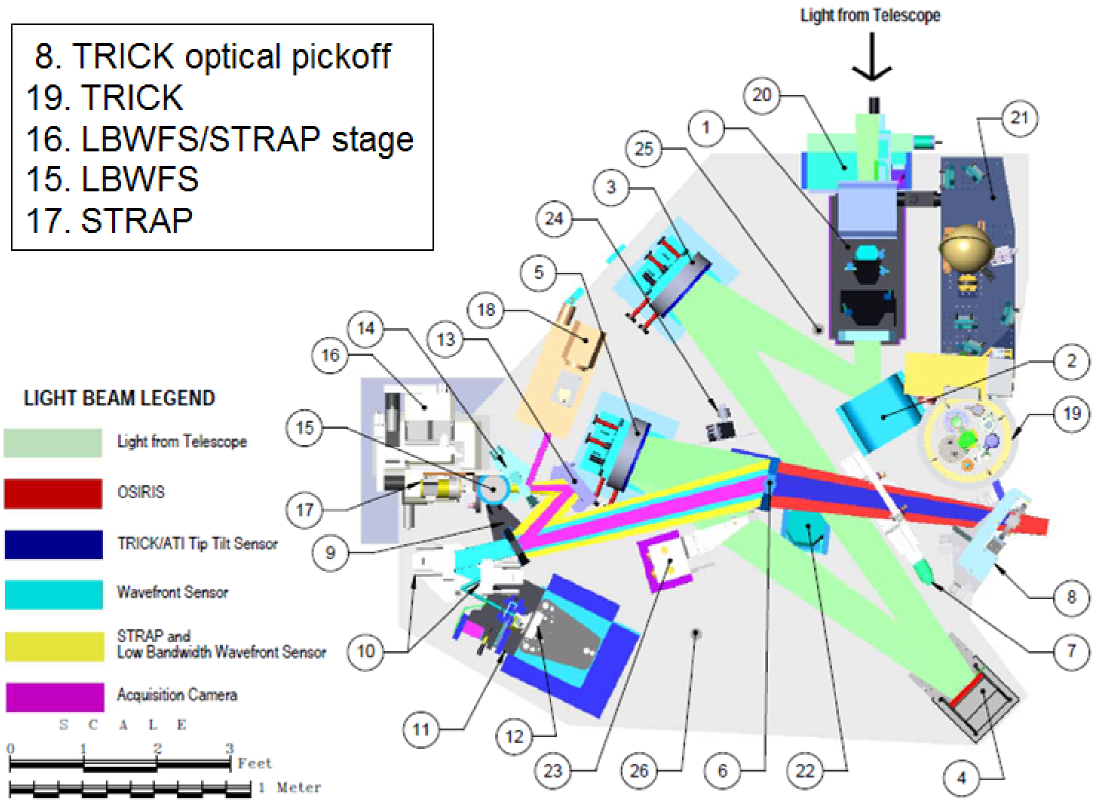

Figure 14: Keck I AO bench with the locations of the STRAP and TRICK hardware. The visible light is reflected by the IR transmissive dichroic at location 6. OSIRIS is located at the AO output at right.

10. References

Rampy, R. et al. “Near-infrared tip-tilt sensing at Keck: System architecture and on-sky performance,” AO4ELT Conference Proceeding (2016).

Wizinowich, P. et al. “A near-infared tip-tilt sensor for the Keck I laser guide star adaptive optics system,” SPIE Proc. 9148, 91482B (2014).