Performance of the Keck TRICK sensor

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GMT

1. Introduction

This document records the results of YAO simulations which were run to assess the performance of the WM Keck Observatory TRICK sensor. In particular, we are interested in the performance when the tip-tilt star is far away from the optical axis. We find that the performance degrades a lot more than is expected from the anisokinetism. This can be mitigated by using the centroid algorithm and a larger number of pixels (~10x10), but this solution is not satisfactory due to the penalty hit in the noise.

2. Simulation results

2.1. Simulation details

The simulation parameters used here are the same as those used in *FWN 15: Tip-tilt tomography for TRICK at Keck Observatory*. They are reproduced here for convenience.

We use the median turbulence profile for Mauna Kea, tabulated in Table 1. The value for r_0 was taken to be 0.15 m at 500 nm, with no outer scale.

Elevation (m)	0	500	1000	2000	4000	8000	16000
Turbulence fraction	0.517	0.119	0.063	0.061	0.105	0.081	0.054

Table 1: Turbulence profile used in the simulations

The wind speed for all layers was 10 m/s with each layer having a random orientation. The frame rate for all sensors was chosen to be 500 Hz; this is too high for faint tip-tilt stars, even running with a reduced loop gain, but the implementation of running wavefront sensors at different frame rates in YAO is not well-understood by the author, so this was avoided. 2500 iterations (5 seconds) of the simulations were run; this is not enough for quantitative results of tip-tilt, since there is more smearing out of the image than occurs over 5 s. Nevertheless, it is long enough that the results are meaningful. The pixel size on the tip-tilt sensor was 50 mas and the loop gain was roughly optimized for each case.

3. Simulation results

3.1. Strehl ratio as a function of anisokinetic angle

Figure 1 plots the K-band Strehl ratio as a function of anisokinetic angle. As can be seen, for anisokinetic angles larger than 15 arcsec, the Strehl ratio degrades more when sensing in the infrared than one would expect, especially at H-band. By contrast, a visible light quad cell with large pixels experiences almost the same degradation as a perfect, mean-slope sensor, as shown in Figure 2. Unfortunately, having a large infrared quad cell is not really an option for TRICK for two reasons: the sky background would dominate the signal, and one would not be able to compensate for DAR by using centroid offsets.

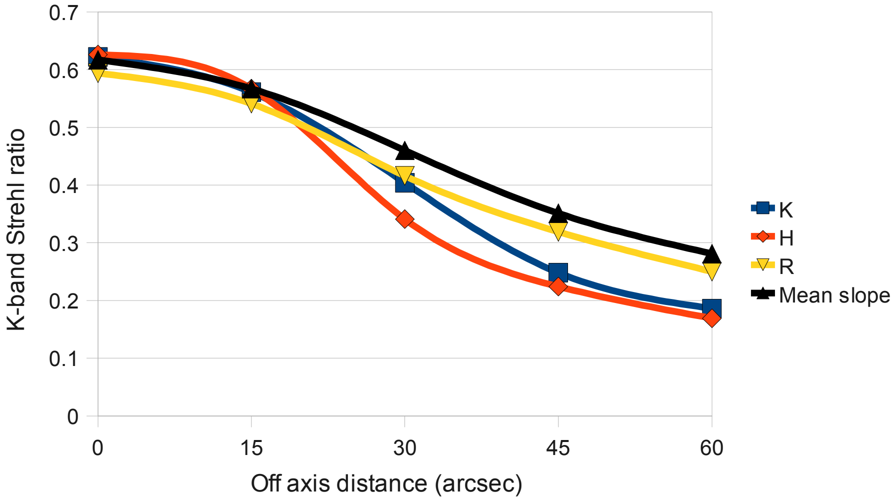

Figure 1: K-band Strehl ratio as a function of anisokinetic distance for three different tip-tilt sensing wavelengths. The H and K bands were sensed using a 4x4 centroider with 50 mas pixels. The R band comparison consists of a quad cell with 500 mas pixels. The guide stars were magnitude 14 at the respective tip-tilt sensing wavelength.

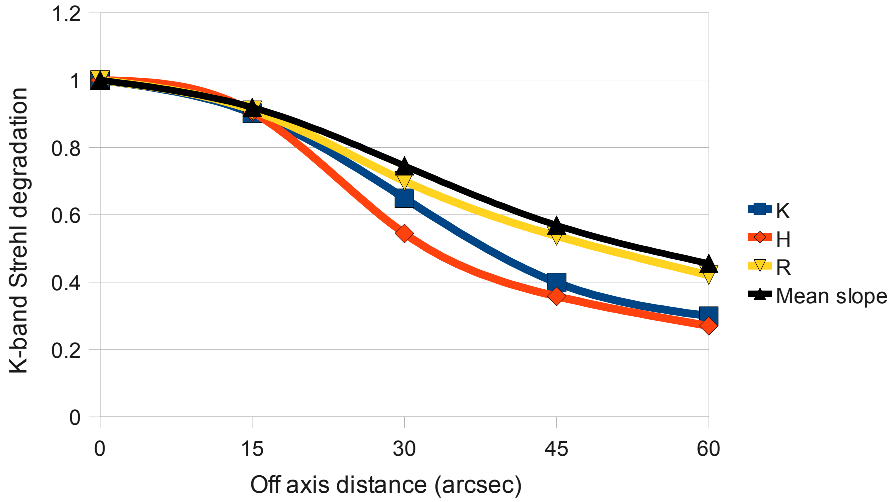

Figure 2: K-band Strehl degradation as a function of anisokinetic angle. The values are scaled relative to the on-axis Strehl ratio.

Figure 3 compares the performance of the correlation algorithm with the centroid algorithm. It shows that the performance is approximately comparable, with small gains for one algorithm with respect to the other depending on the anisokinetic distance.

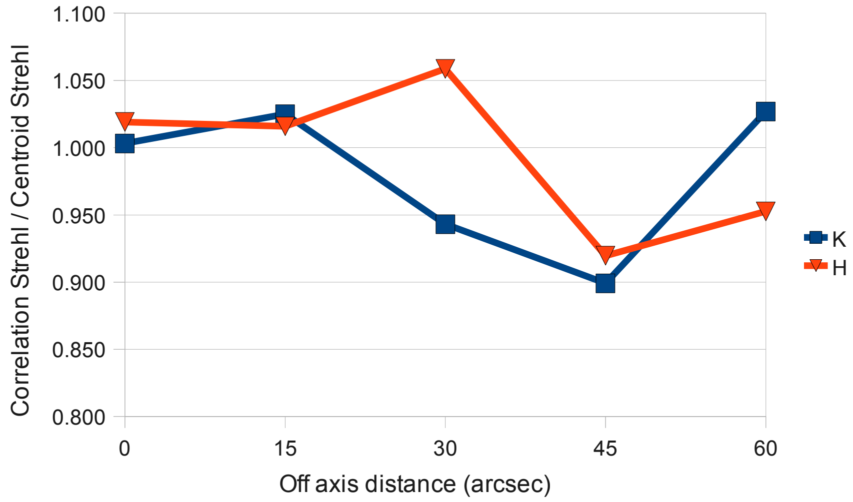

Figure 3: Comparison of the correlation algorithm with the centroid for a 14th magnitude star.

3.2. Faint guide star performance

The simulations were repeated for a faint guide star: an m_R = 18.5 M_0 star, which corresponds to m_H = 16.5 and m_K = 16.0.[1] However, the optical throughput for the R-band star was adjusted to match the measured photometry from the Keck II STRAP system (see Appendix A: Photometry and noise parameters). This corresponds to a total throughput of 16%, including the quantum efficiency of the detectors. For the TRICK sensor, the throughput used was a higher, at 34.4% and 39.7% for H- and K-band respectively.

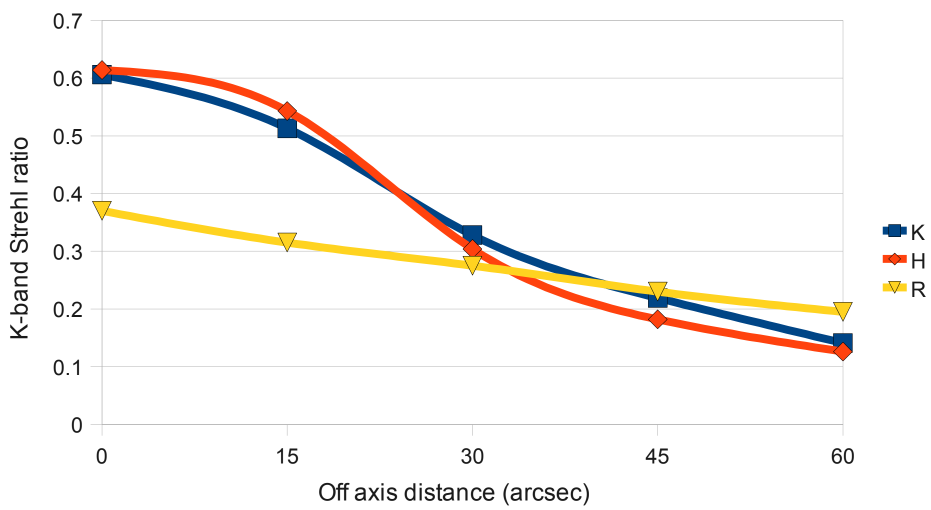

Figure 4: K-band Strehl ratio as a function of anisokinetic distance for three different tip-tilt sensing wavelengths. The H and K bands were sensed using a 4x4 centroider with 50 mas pixels. The R band comparison consists of a quad cell with 900 mas pixels. The guide stars were magnitude 16, 16.5, and 18.5 at K, H and R respectively.

The results plotted in Figure 4 show that these results for the TRICK sensor are substantially better than the results obtained by STRAP when the guide star is near the science target. The cross-over point is about 35-40 arcseconds, when the STRAP performance overtakes that of TRICK. It should be noted that, in practice, the Strehl ratio obtained with STRAP on such a faint star is nowhere near the simulation results (more likely around the 10-15% range). The discrepancy probably stems from

1 P. Wizinowich, private communication (17 Feb 2011).

the fact that the tip-tilt error is dominated by vibrations, and not by atmospheric turbulence. Likewise, we would expect the results with TRICK to be much worse than these idealized simulations. Nevertheless, the relative actual performance between the two sensors is likely to be the similar to that yielded by these simulations.

3.3. Strehl ratio as a function of number of pixels for a bright off-axis star

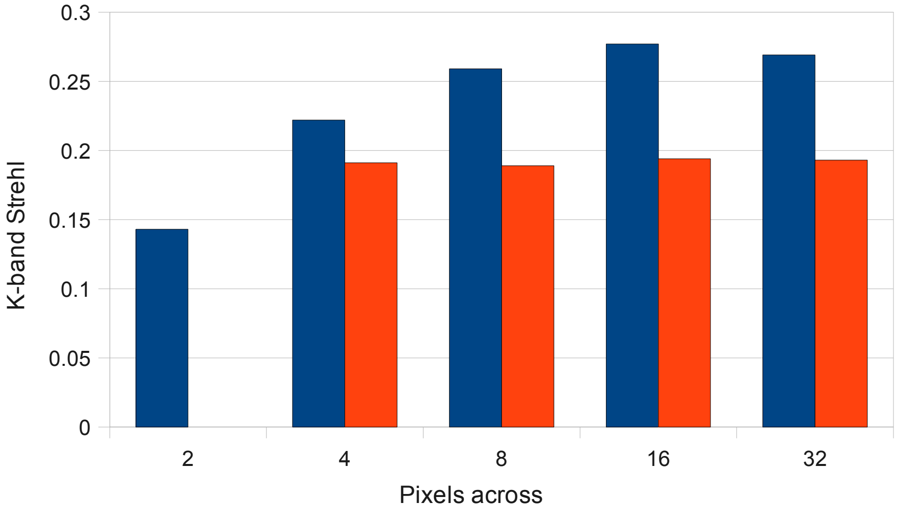

Figure 5: K-band Strehl ratio as a function of number of pixels for a tip-tilt star 60 arcsec away *from the science target using the centroid (blue) and correlation (red) algorithms. No noise is applied to the tip-tilt sensor. The pixels are 50 mas in extent and the sensing is at K-band.*

Tip-tilt sensing far away from the optical axis requires a larger number of pixels, as can be seen in Figure 5. There are three problems with increasing the number of pixels. The first is that the sky background increases as the square of the number of pixels across. The second is that the read-out noise of a pixel will increase. The third is that the error in the centroid also increases with increasing number of pixels (even if the only noise source is photon noise). The correlation algorithm does not improve with increasing number of pixels, since it is only trying to track the brightest peak. Its performance is hampered by the fact that there is more than one peak, as can be seen in Figure 6. Note that for a relatively bright star (14^{th} magnitude) the performance of the centroid drops below that of the correlation algorithm for a 4x4 pixel array, and drops further with increasing number of pixels.

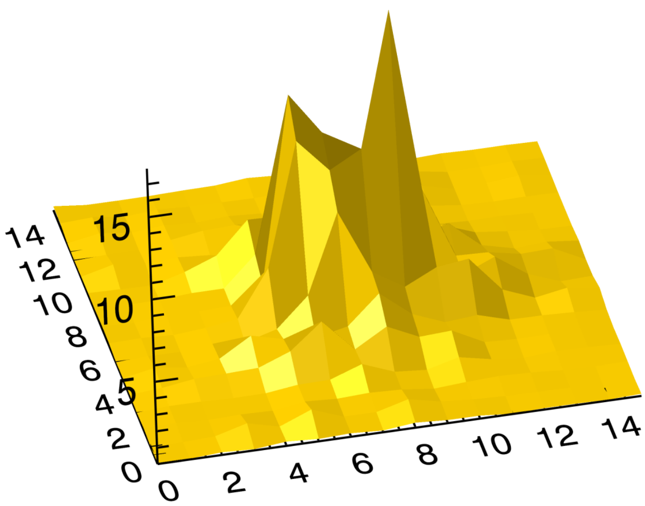

Figure 6: Typical K-band image at 60 arcsec. Note the presence of two large peaks and three smaller peaks over a region of about 6x6 pixels.

4. Temporal decorrelation of speckles

A question of interest is whether the multiple speckles persist long enough to for previously recorded and averaged wavefront sensing images be used as reference images in subsequent wavefront slope estimates. Figure 7 shows the correlation coefficient as a function of the number of frames of separation. The images decorrelate too quickly to be useful in a practical correlation algorithm, especially if the guide stars are faint. Unfortunately, they do not decorrelate quickly enough that increasing the integration time on the WFS improves the performance by blurring out the speckles.

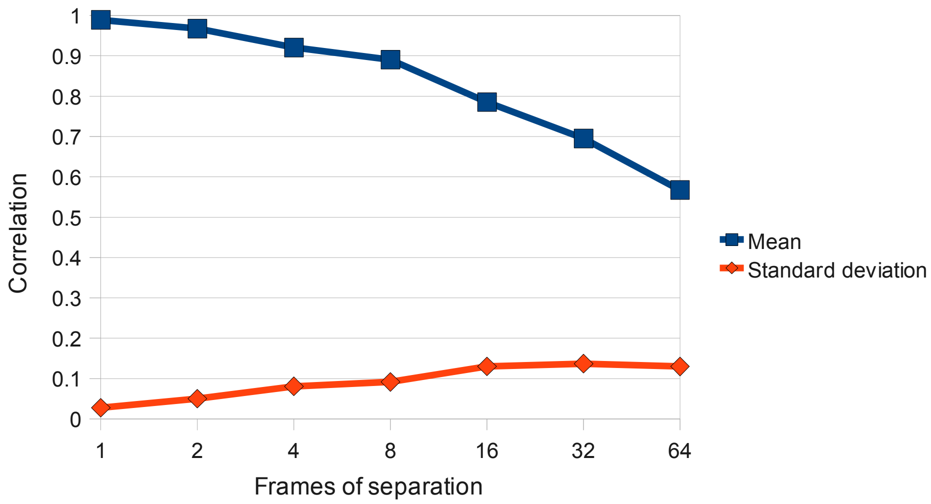

Figure 7: WFS image decorrelation as a function of the number of WFS frames of separation. The correlation was calculated using FFTs to be shift invariant. The frame rate was 500 Hz and the K-band guide star was 60 arcsec off-axis.

5. Further work

The TRICK sensor has a problem when sensing tip-tilt stars that are a long way off-axis. Currently, there are two options, none of which are satisfactory:

- we can use the correlation algorithm and pay the penalty for only tracking the brightest speckle or
- we can use the centroiding algorithm with an increased detector size with the accompanying severe increase in noise

Further work should concentrate in finding algorithms that have noise performance comparable to the correlation algorithm but estimates something more similar to the mean slope, like the centroid algorithm. Two possibilities that jump to mind are using phase retrieval to estimate the slope, and using a correlation algorithm that detects multiple peaks and finds the center of gravity of the peaks.

Appendix A: Photometry and noise parameters

The star and sky photometry parameters used in the simulations are tabulated in Table 2.

	K	H	R (STRAP)
Photometric zero point (photons/s)	1.10×10^{11}	1.76×10^{11}	6.4×10^{11}
Sky background	14.6	13.8	22.0
Optical throughput	0.5	0.5	0.1625
Read-out noise (e-)	4	4	0
Dark current (e-/pixel/s)	0	0	200

Table 2: Photometry and noise parameters used in the simulations

I cannot find the source for the numbers corresponding to the H and K columns, but they appear to be inconsistent with the values we are using for the GMT telescope.[2] The photometric zero point for GMT at K and H is 7.0×10^{11} and 1.1×10^{12} respectively. Assuming a telescope area of 76 m^2 for the Keck telescope and 368 m^2 for the GMT, we get 1.45×10^{11} and 2.27×10^{11} respectively, which is about 30% higher.

Using Antonin's R-band photometry calculations, the number of photons at R band for the GMT is 4.0×10^{12} photons per second. Taking the relative telescope areas gives 6.4×10^{11} photons per second for Keck. However, the recorded photometric zero point per APD for STRAP is 26.0 (from readbackrmag.pro), implying that there are $2.512^{26} = 2.51 \times 10^{10}$ photons/APD/s or 1.04×10^{11} photons/s for the entire detector. This means that only 16% of the photons arriving at the telescope are detected by STRAP.

2 Antonin Bouchez, "Photometry for AO Simulations," GMT-02274, Rev. 1 (08/26/2010)