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Optimizing use of multiple stars for near-infrared tip-tilt compensation at the W. M. Keck Observatory

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ABSTRACT

The implementation of a near-infrared tip-tilt sensor in the Keck I adaptive optics (AO) system is the first of its kind, and represents a substantial step forward in AO technology. Enhanced-TRICK (Tilt Removal with IR Compensation at Keck) is a project built off this implementation which will further improve performance and versatility. Currently the system is capable of using a single star for measuring image motion, but in the off-axis case this may cause elongation in the science image due to tilt anisoplanatism. The near-infrared tip-tilt sensor (NIRTTS) has been designed with the capability of using up to three stars from around the field to correct for elongation. In order for the science object correction to be optimized, the measurements from each star must be weighted based on magnitude and separation from the science object. When weighted optimally the tip-tilt error at the science object will be a minimum. The process for assigning weights is described, and results of performance modeling of the actual systems having multiple tip-tilt stars are presented.

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

1. INTRODUCTION

The current laser guide star (LGS) adaptive optics (AO) system in use on the Keck I telescope employs visible light wavefront sensing on a natural guide star to measure image motion. A dependence on natural guide stars bright enough in the visible light spectrum greatly limits the regions of the sky in which the AO system can be utilized for image correction. The ability to use the infrared (IR) would increase the sky coverage available for AO correction because the majority of stars are brighter in the IR. TRICK (Tilt Removal with IR Compensation at Keck)[1] is a new system implemented on Keck I that uses an H2RG detector made by Teledyne, built with the ability to read out in full-frame or sub-arrays (regions of interest, ROIs). The TRICK control system has the capability to switch between TRICK and STRAP, the visible light tip-tilt sensor, allowing for observers to pick the most appropriate tip-tilt sensor for each field observed.[1] TRICK can operate in either H or Ks-band, and has the built-in capabilities of using multiple guide stars for reference.

The ability to use multiple guide stars for tip-tilt measurement allows for a great degree of correction at the science target. A single guide star causes an elongation in the science target in the direction of the separation between the guide star and the science target. Multiple guide stars would diminish the degree of elongation, because the correction would be coming from multiple locations around the observed field. The image correction for each guide star is dependent on the magnitude of the guide star and the separation between it and the science target. In theory brighter guide stars, as well as closer ones, produce a better image correction at the science target.

While not every field will have enough guide stars present to use the multiple guide star capabilities of TRICK, in those that do, up to three total guide stars could be utilized at one time. This paper describes a tool for optimally weighting the measurements from multiple guide stars, combining them into tip-tilt mirror commands, and determining the predicted performance improvement for specific configurations. The next section presents how performance of individual guide stars is assessed through calculation of the error budget, followed by the weighting method in section 3. Section 4 applies this tool to potential observing configurations, and discusses performance predictions. Section 5 concludes with an analysis of the limitations of this approach, and presents steps for future work in this area.

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2. ERROR BUDGET

The tip-tilt error for a single natural guide star is calculated from three independent terms, the latency error, the measurement error, and the anisoplanatic error. The total tip-tilt variance is a quadrature sum of these terms. Tip-tilt error calculation for a star on TRICK requires inclusion of system specific factors. The code that estimates these values is described below, and was written by C. Neyman.

The latency error is dependent on the bandwidth of the TRICK system. The faster the correction speed the smaller the latency error. The TRICK system can read out at rates as high as 2 kHz, thus limiting the time in which the recorded data can be transferred and processed. The tracking frequency, f_T, depends on the tracking aperture, D, the tracking wavelength, λ, a frequency constant, K_T, zenith angle, ξ, and the wind velocity moment, v_2,[2]

$$f_T = K_T D^{-1/6} \lambda^{-1} sec^{1/2}(\xi) v_2^{1/2}. \tag{1}$$

The latency error depends on a normalization of f_T by the $3dB$ frequency, f_{3dB},[2]

$$\sigma_{lat} = \left(\frac{f_T}{f_{3dB}}\right)\left(\frac{\lambda}{D}\right). \tag{2}$$

The measurement error is attributed to the inability of the system to perfectly determine the image motion of the guide star. This is largely due to photon and detector noise. As a result, the measurement error is proportional to the signal to noise ratio, SNR, and the size of the image on TRICK, α,

$$\sigma_{mes} = \frac{1.5\pi\alpha}{8SNR}. \tag{3}$$

The final error contribution investigated is the anisoplanatic error, which occurs when the object used for tip-tilt measurement is not the same as the science target. This is often the case as the majority of science targets are not bright enough to be used for tip-tilt measurements. The separation between the guide star and the science target results in the light from each source traveling along different paths through the atmosphere. Due to variability in the atmosphere, the wavefronts of the two light sources are misshapen differently, thus causing the corrections applied from the guide star to be not identical to the correction needed at the science target. This results in a degradation of the image quality of the science object in the focal plane. The anisoplanatic error is determined by the angular separation, θ, the isokinetic angle, θ_k, and the the atmospheric coherence length, r_0,

$$\sigma_{ani} = 0.427\left(\frac{\theta}{\theta_k}\right)\left(\frac{\lambda}{D}\right)\left(\frac{D}{r_0}\right)^{\frac{5}{6}} \tag{4}$$

The three individual errors are calculated by a program for a specific set of camera parameters and observing configuration. The input values include the size of the ROI, the number of coadds and the resulting effective frame rate, the number of cycles per reset (CPR) of the TRICK camera, the magnitude and off-axis distance of the star, its elevation, and the strength of the atmospheric turbulence. The total tip-tilt error is a quadrature sum of the individual error terms.

$$\sigma_{TT}^2 = \sigma_{lat}^2 + \sigma_{mes}^2 + \sigma_{ani}^2. \tag{5}$$

This section has described how the error budget, and total tip-tilt error, for a single star on TRICK are determined. The same program used for calculating the tip-tilt error was also employed in optimization of the camera parameters for the single star case. However, due to constraints in how the camera is utilized for multiple stars, the actual parameters often do not match the optimal values. For example, when reading out multiple ROIs, the number of coadds for each must be integer multiples of one another, and have a common CPR. Once the actual system parameters have been obtained for a given configuration the total individual tip-tilt error is calculated and used to determine how to weight the measurements from each star used. This process is described in the next section.

3. WEIGHTING

Whether or not multiple tip-tilt guide stars can be used depends on the field being observed. In the case that a field has more than one potential natural guide star, the use of multiple-ROI can be used on TRICK. However, for the measurements from each separate ROI to be combined into a single tip-tilt error correction, the ROIs must be weighted. The weights assigned to the measurements from the natural guide stars should minimize the tip-tilt error for the science target.

The weighting of the natural guides stars is taken from the tip-tilt error calculation of each guide star. The tip-tilt error calculation incorporates the star's magnitude and separation from the target. The weights assigned are calculated from the tip-tilt error, σ , and the weighting factor, w, as seen below,

$$w_i = \frac{\sigma^2_{TTi}}{\sum \sigma^2_{TTi}}. \tag{6}$$

These weighting factors are subsequently applied to the calculated tip-tilt measurement for each guide star, δ_i. The weighted tip-tilt measurement for each star are summed in quadrature to produce a single tip-tilt correction command, δ^2_{total},

$$\delta^2_{total} = \sum w_i \delta^2_i. \tag{7}$$

This section described how two or three guide stars on TRICK are optimally weighted based on magnitude and separation from the science target. Brighter stars and guide stars that are closer to the science target are weighted more heavily, thus contributing more to the total tip-tilt correction. The improvement in the tip-tilt error by using multiple weighted guide stars is described below using our most recent performance modeling.

4. TEST CASES

Two configurations were used as an initial simulation to ensure the weighting of multiple natural guide stars was minimizing the tip-tilt error. The first test case engv12_894, Figure 1, consisted of three natural guide stars of 13.57, 11.55 and 11.54 magnitude in the K-band. In order to test that our algorithm optimizes the science target's tip-tilt correction, we calculated the individual tip-tilt error for the guide stars, as well as the tip-tilt error for a two guide stars and a three guide star configuration. These simulations do not take into account the fact that when multiple ROIs are read by the TRICK system, each ROI is read less frequently which increases the latency error for a fixed number of coadds. The individual tip-tilt measurements can be found in Table 1, with the best correction coming from the 11.55 mag guide star.

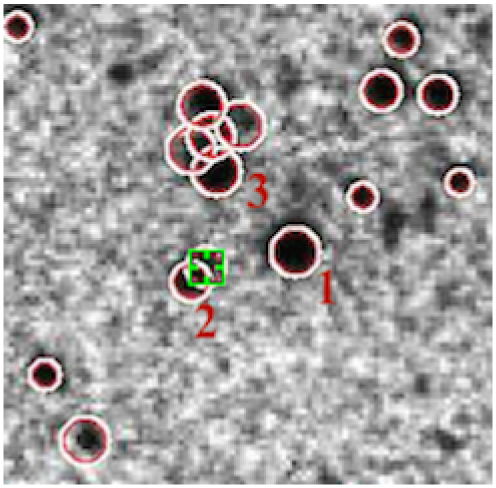

Figure 1: The first test configuration engv12_894. The guide stars used are labeled in order, as one, two and three, and the green square marks the science object.

Table 1: Test Case 1

Guide Star	K mag.	Sep. (arcsec)	TT error single (arcsec)	TT error cumulative (arcsec)	% reduction in TT error	% Strehl estimate*	# coadds	CPR	ROI weights (1,2,3)
1	11.55	17.68	0.0104			20.0**	12	1500	(1, 0, 0)
2	13.57	3.88	0.01341	0.00823	20.9	23.3	12	1500	(0.62, 0.38, 0)
3	11.54	18.92	0.01096	0.00658	36.8	25.5	12	1500	(0.4, 0.24, 0.36.)

*Assuming 25% of the total (squared) WFE in the error budget is from TT errors.
**Assumed based on measured performance data.

In the two guide star configuration we added the 13.57 mag star weighing it with $w = 0.38$ and the 11.55 mag had $w = 0.62$. The total tip-tilt error was reduced by 20.9%. The percent change in Strehl was calculated on the assumption that tip-tilt error accounted for 25% of the total squared wavefront error, and performance data allowed us to extrapolate an estimated 20% Strehl for a single guide star. Using these assumptions the two guide star configuration increased the Strehl to 23.3%. For the three star configuration the 11.54 mag star was added. Our algorithm yielded the heaviest weight, w=0.4, for the K=11.55 mag star which is the second brightest guide star used. The other two natural guide stars were weighted more evenly, with w=0.24 for the 13.57 star and 0.36 for 11.54 star. The resulting total tip-tilt error was 36.8% smaller than the tip-tilt error for the smallest individual tip-tilt error calculated from a single guide star. The resulting Strehl percent estimated was an improvement of 25.5% from one to three guide stars.

The second configuration used to simulate the weighting optimization was eng548, Figure 2, which consisted of star with K-band magnitude of 10.70, 14.65, and 13.52. The tip-tilt error for each guide star was calculated, as well as in a two and three star configuration. In the two star configuration the percent reduction in tip-tilt error was 19.9% and the Strehl estimate, using the same assumptions as stated above, was 23.1%. In the three star configuration the brightest guide star, despite not being closest to the science target, was weighted most heavily, while the other two guide star's weights were dominantly determined by proximity to the science target. The cumulative tip-tilt error correction reduced the total tip-tilt error by 22.7% and the Strehl increased to 23.5%.

Table 2: Test Case 2

K mag.	Sep. (arcsec)	TT error single	TT error cumulative	% reduction in TT error	% Strehl estimate*	# coadds	CPR	ROI weights (1,2,3)
10.70	23.59	0.01399			20.0**	10	700	(1, 0, 0)
14.65	12.33	0.01870	0.01120	19.9	23.1	35	700	(0.64, 0.36, 0)
13.52	24.26	0.04165	0.01082	22.7	23.5	25	700	(0.60, 0.33, 0.07.)

*Assuming 25% of the total (squared) WFE in the error budget is from TT errors.
**Assumed based on measured performance data.

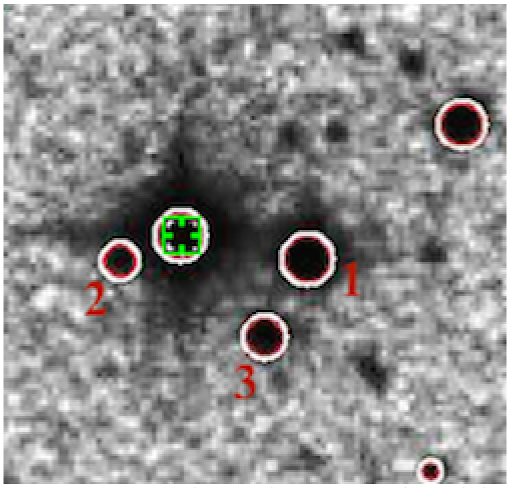

Figure 2: The second test configuration eng548. The guide stars used are labeled in order, as one, two and three, and the green square marks the science object.

5. CONCLUSIONS

TRICK was created with the capabilities of utilizing light from up two three guide stars in order to make a single correction. The tip-tilt error calculation has been updated and now is capable of calculating the tip-tilt error from three guide stars. The tip-tilt algorithm produces a single tip-tilt error correction by weighting the individual tip-tilt errors from each guide star based on magnitude and separation from the science target.

We tested the tip-tilt error calculation algorithm on two test configurations, in order to obtain a performance model to predict on sky performance. The first test configuration produced a 20.9% reduction in tip-tilt error correction with only two guide stars, and a 36.8% reduction with three guide stars. The second test configuration produced a 19.9% reduction in tip-tilt error with two guide stars and 22.7% reduction with three. Thus, we can conclude from the performance model that using more guide stars to calculate the tip-tilt error is advantageous. The tip-tilt error is smaller when using more guide stars, therefore the correction at the science object is better. The improved correction with multiple guide stars indicates the possible advantage that could be had when the TRICK system is used on sky in the future.

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