Monte Carlo simulations of an Adaptive Optics system for the CHARA array

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1. Introduction

This report presents adaptive optics (AO) simulations for the CHARA interferometry array. Currently, CHARA is funded to build wavefront sensors (WFS), which can be used to measure atmospheric turbulence and apply a correction to a tip-tilt mirror downstream. In the future, CHARA would like to upgrade the telescopes to include a deformable mirror (DM). A DM in the common path would have to be large and elliptical, and thus expensive. An alternative would be to place a smaller, round DM downstream. In this report, we compare the performance of the Shack-Hartmann and Pyramid WFSs for the two scenarios.

All the Monte-Carlo simulations described here were performed in YAO. YAO is a general purpose, flexible and powerful AO simulation tool written in yorick. It is free and open source and can be easily installed on Linux and Macs.[1]

2. Simulation parameters

2.1. Telescope

The telescope modeled is a 1.00 m diameter telescope with a 0.24 m central obscuration. While the obscuration by the secondary mirror is only 0.14 m, M3 obscures a larger fraction of the beam. No spiders or other obstructions are included in the model.

2.2. Wavefront sensing camera

The wavefront sensing camera is an Andor iXon Ultra 897. This has up to 512x512 pixels, but the higher the number of pixels, the lower the maximum frame rate. The maximum frame rate for the full frame is 56 Hz, with a maximum frame rate of 595 Hz for 128x128 pixels and and a maximum frame rate of 11 kHz for an unspecified number of pixels. For our purposes, we require somewhat faster operation than 595 Hz but a lot fewer pixels than 128x128, and we assume that 1000 Hz operation is possible.

The dark current is negligible and the read noise is sub electron when operated in EM mode. The read noise will be set to 0.5 e- in the simulations (as the midpoint between 0 and 1!). When simulating EM CCD devices, the electron multiplication effect is typically simulated by assuming that the effective quantum efficiency is a factor of two lower.

2.3. Photometry

All the light shorter than 1 micron will be passed to the WFS. The photometry was calculated by adding the flux in each of the B, V, R and I bands multiplied by the average quantum efficiency in each band, using the target quantum efficiency of the detector shown in Figure 5.

1 http://frigaut.github.com/yao/index.html

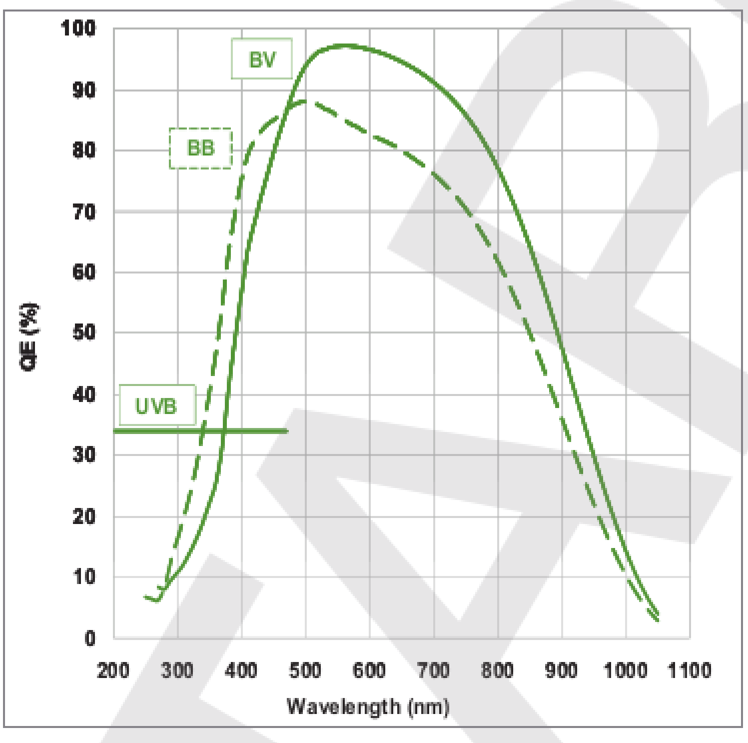

Figure 1: Target quantum efficiency for the Andor iXon Ultra 897. The BV curve is the one assumed in this study.

The photometric zero point for the sum of B, V, R and I-bands was taken to be 2.63e+10 photons/s. The average wavelength was calculated to be 580 nm. The sky background was taken to be 18.5 (mag/arcsec^2). It was found to have a negligible effect on the noise and was subsequently ignored.

There are seven reflections before the WFS, and the transmission for each one is assumed to be 88%, for a total of 41%. A figure of 30% is used to account for transmission losses in the WFS.

2.4. Atmospheric conditions

The seeing conditions on Mt. Wilson are quite variable, with r_0 measurements between 1 and 20 cm, as shown in Figure 2. The histogram of τ_0 values at 2300 nm is shown in Figure 3.

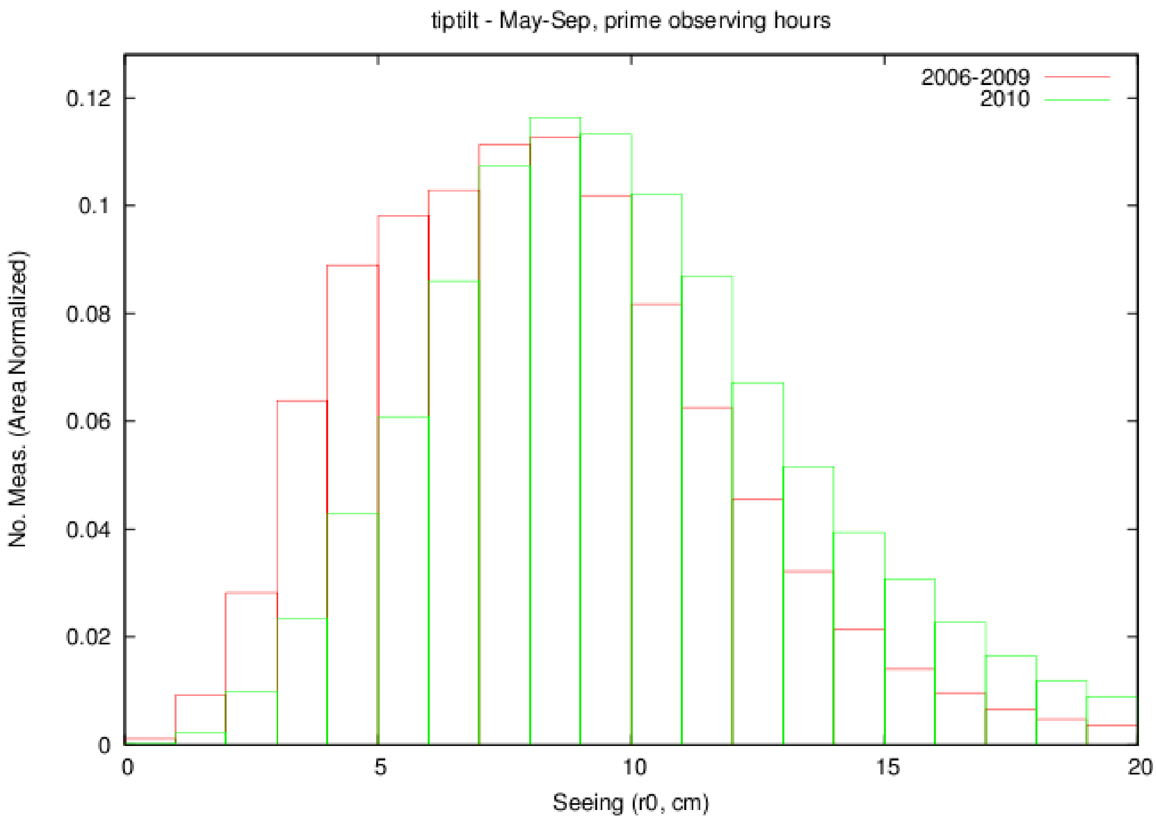

Figure 2: Measured r_0 at 550 nm.

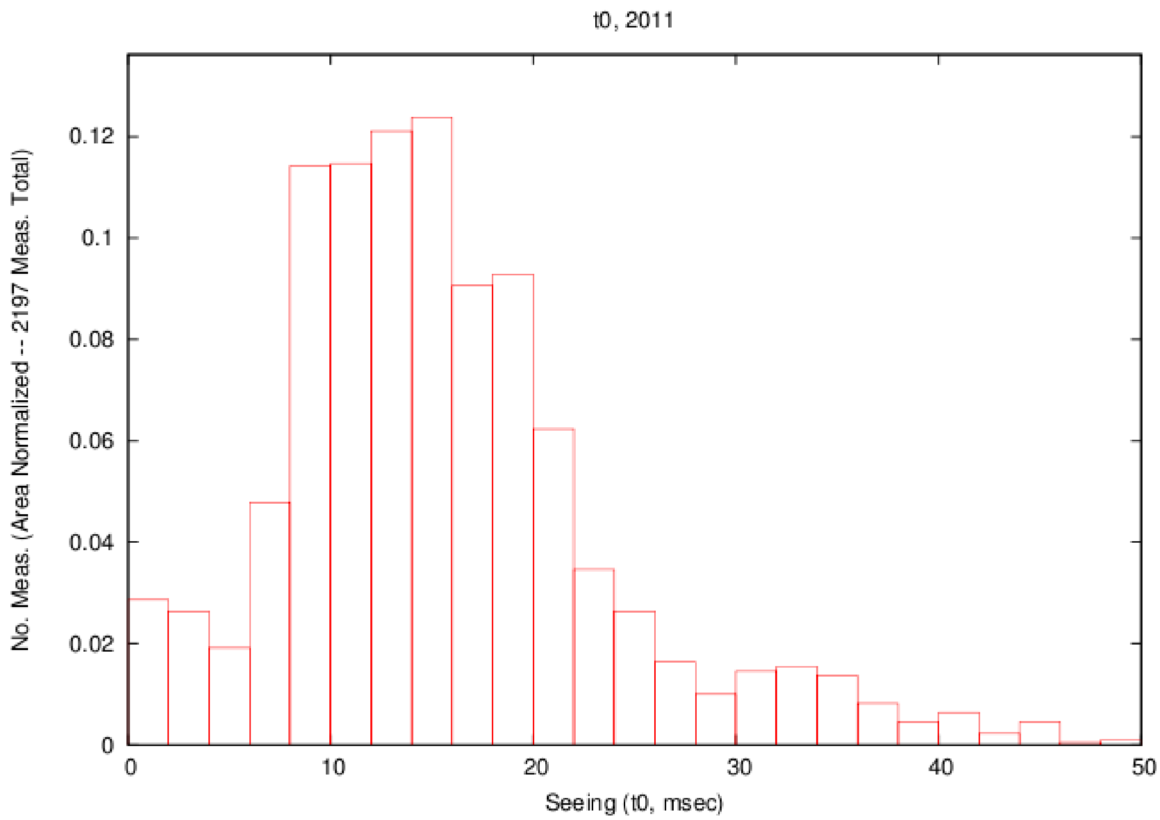

Figure 3: Measured τ_0 at 2300 nm.

The relationship between τ_0 and wind speed, v, is:

$$v = 0.314\, r_0 / \tau_0 \tag{1}$$

A typical value of r_0 at 550 nm is 0.08 m, corresponding to an r_0 at 2300 nm is 0.45 m. Taking the average value of τ_0 to be 0.013 s and inserting these values into Eq. (1) gives an average wind speed of 11.65 m/s, which is used in the simulations.

Kolmogorov turbulence is assumed in these simulations, as the outer scale is not really relevant to 1 m telescopes. Since all the science target is typically the AO guide star, the vertical distribution of turbulence is not important. Five atmospheric layers with the same speed blowing in random directions will be used in the simulations.

2.5. Shack-Hartmann WFS

A detailed design of the Shack-Hartmann WFS is beyond the scope of this report. In this section, we derive reasonable parameters for the purposes of the simulation.

There are six subapertures across the pupil, with a pupil sampling, *d,* of 0.167 m.

It is well known that the best noise performance is obtained using a quad cell (2x2 pixels per subaperture), especially if there is significant read noise. However, quad cells suffer from a changing "centroid gain" when the seeing changes.[2-3] This has two negative effects: the effective loop gain in the control loop changes, and the reference centroids obtained in the calibration of the AO system are no longer valid. In addition, this makes it impossible to operate the AO system in open loop, since the overall gain is not well known. Since the AO system will be operated over a large range of seeing conditions, a well sampled spot is preferable.

In order to maintain a linear relationship between the centroid measurement and the displacement of the spot, the pixel size must be equal to or less than the FWHM of the spot. For a wavelength of 580 nm, the diffraction-limited FWHM is

$$FWHM=\lambda/d=0.72'' \quad (2)$$

And the pixel extent was set to be this size. If r_0 is 5 cm, then the size of the spot is approximately

$$FWHM=\lambda/r_0=2.2'' \quad (3)$$

So a 6x6 pixel detector spans 4.3" and detects almost all of the light, even in the bad seeing case.

The standard center-of-mass algorithm is the simplest to implement and has a number of good properties, and this is used here. However, there are other algorithms, such as the correlation algorithm, which reduce the noise in the centroid measurement.[4]

2.6. Pyramid WFS

The pyramid WFS was also selected to be have 6x6 "subapertures" across the pupil. Note that the number of subapertures can be decreased simply by binning the pixels. However, in this case the read noise is negligible so binning pixels does not reduce the noise very much.

The modulation was set to be circular with an amplitude of 0.4 arcseconds. The optimal value depends on the seeing and the guide star magnitude, but it was not practical to optimize it for every simulation. Instead, it was optimized for a bright star with an r_0 of 0.10 m.

2 J.-P. Véran and G. Herriot, "Centroid gain compensation in Shack–Hartmann adaptive optics systems with natural or laser guide star," J. Opt. Soc. Am. A 17, 1430–1439 (2000).

3 M.A. van Dam, "Measuring the centroid gain of a Shack-Hartmann quad-cell wavefront sensor by using slope discrepancy," JOSA A 22, 1509-1514 (2005).

4 L.A. Poyneer, "Scene-Based Shack-Hartmann Wave-Front Sensing: Analysis and Simulation," Applied Optics 42, 5807-5815 (2003).

2.7. Deformable mirror

For the purposes of the simulations, there are two types of mirror to be used:

- A tip-tilt mirror, that corrects only tip-tilt
- A continuous phase sheet 7x7 actuator deformable mirror, with the actuators conjugate to the corners of the subapertures

2.8. Control law

The simulations are run in one of two modes: open-loop or closed-loop. Open-loop refers to the case where the DM or tip-tilt mirror is located in the science path but not in the path of the WFS. Hence, the WFS cannot see the applied correction. In closed-loop operation, the correcting element is in the common path.

In open-loop, the measurement on the WFS is applied to the DM. In closed, loop we use a simple integrator with a loop gain set to 0.4 in all the simulations. The frame rate is optimized depending on the each guide star magnitude and the seeing conditions.

Since the simulations are run in discrete time, we apply a delay of two cycles to account for the WFS stare, the DM zero-order hold, the read-out of the detector and the compute delay. In practice, the compute delay and sometimes the read out time is independent of frame rate.

2.9. Science metric

It is assumed that the science target of interests are always on-axis. The results are computed at the central wavelengths of the R, J, H and K bands, which are 0.640, 1.215, 1.654 and 2.179 microns respectively. The Strehl ratio is computed as the output of the simulations.

3. Shack-Hartmann WFS simulation results

In this section, we document the performance of the different modes when sensing the wavefront using a Shack-Hartmann wavefront sensor.

3.1. Performance of an open-loop tip-tilt only system

Initially, the WFSs is used to drive a tip-tilt mirror downstream of the wavefront sensor pick-off. The contribution of tip-tilt coming from the telescope is neglected.

A screenshot of the simulations in progress can be seen in Figure 4.

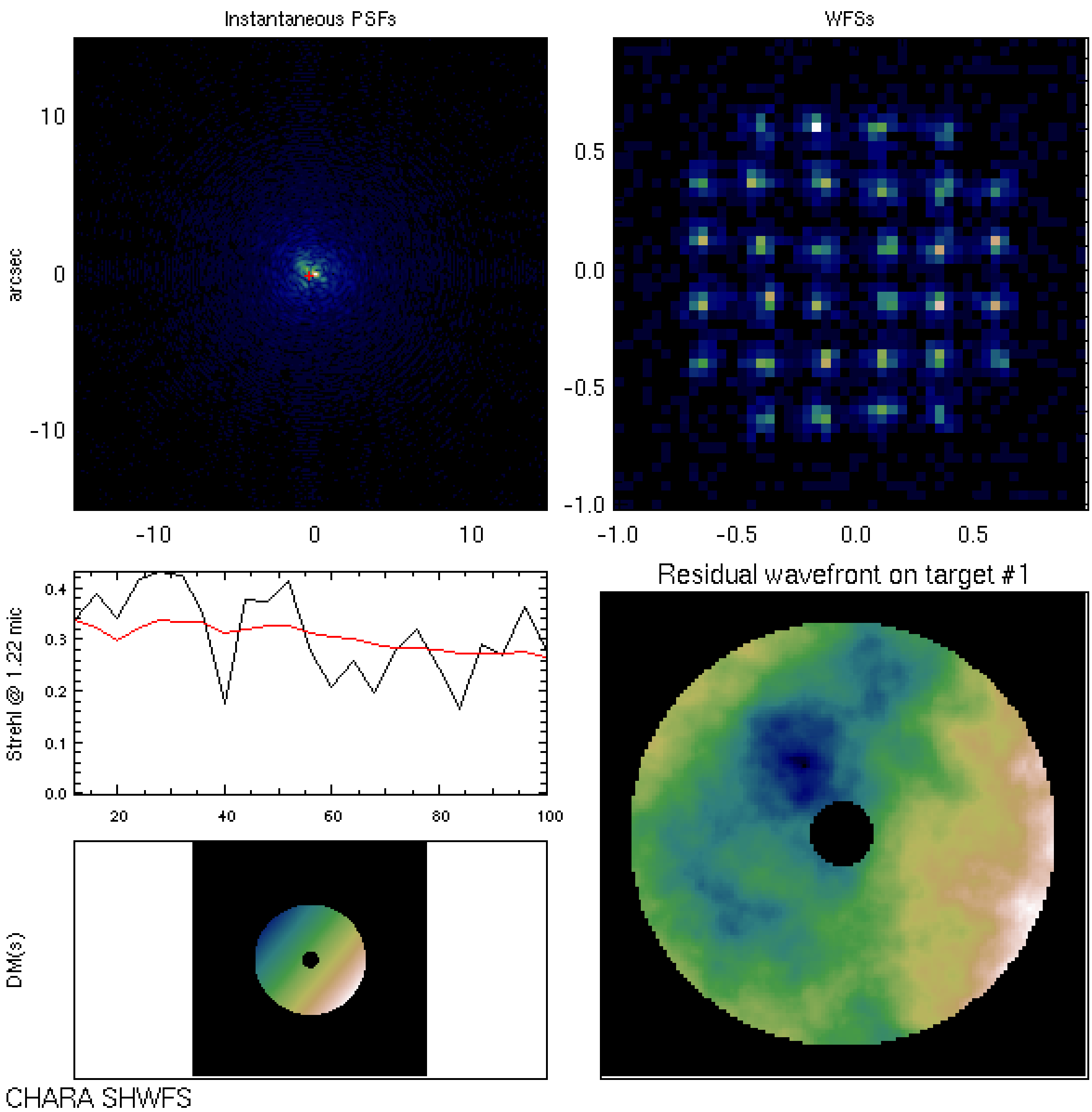

Figure 4: Screenshot of the simulations in YAO

Simulations were run for a variety of seeing conditions, and the results are plotted in Figures 5, 6 and 7. 5000 iterations of the simulations were run at various frame rates, ranging from 31.25 Hz to 500 Hz. The Strehl rations for the frame rate that produced the best performance for each star was kept. Because the frame rates were optimized coarsely, the Strehl versus magnitudes curves are somewhat jagged.

It can be seen by the dashed lines in the plots that the system produces a significant improvement in Strehl ratio up to 13th magnitude stars, and there is essentially no correction on 15th magnitude stars.

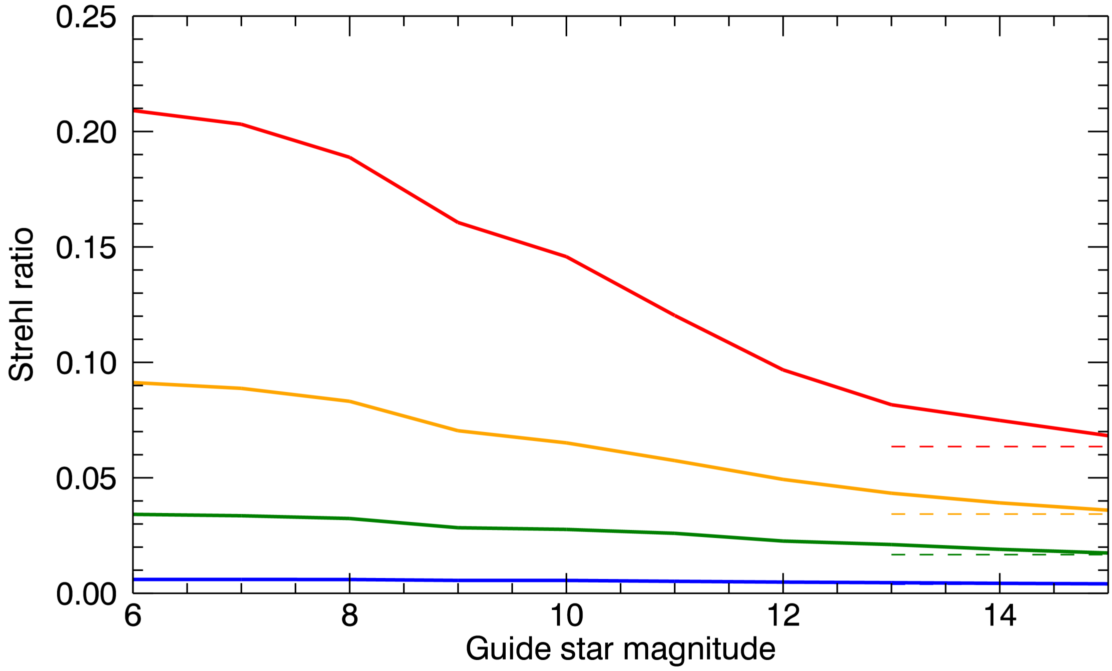

Figure 5: Strehl versus guide star R-magnitude for an open-loop tip-tilt system with an r_0 at 550 nm of 0.05 m. The four colors represent R (blue), J (green), H (orange) and K (red) and the dashed lines show the performance with no correction.

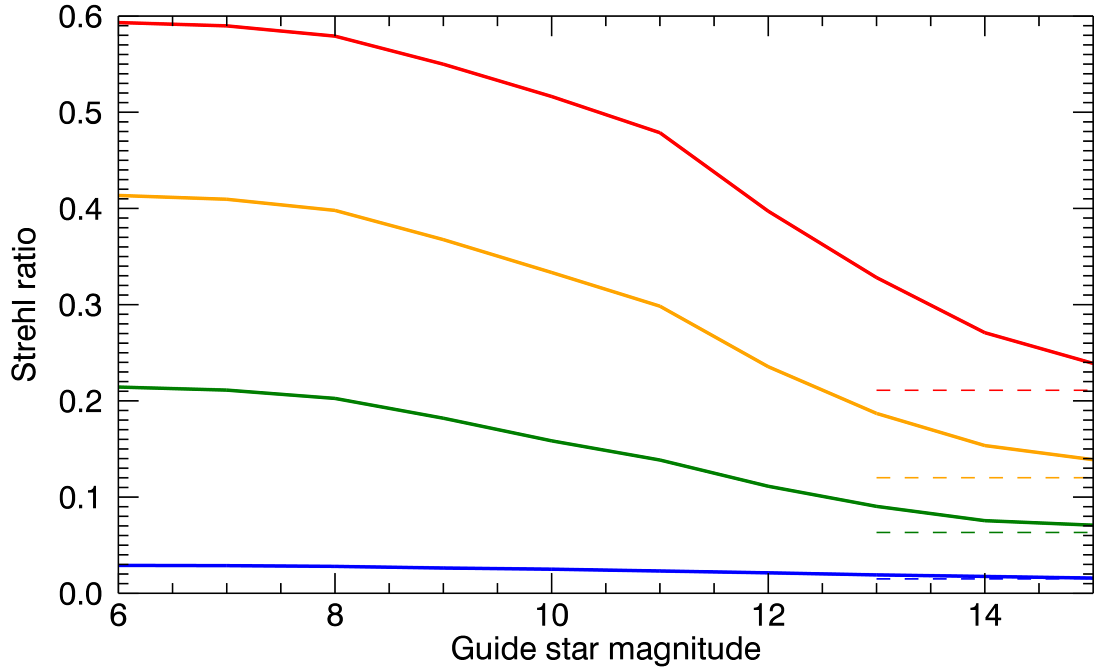

Figure 6: Strehl versus guide star R-magnitude for an open-loop tip-tilt system with an r_0 at 550 nm of 0.10 m. The four colors represent R (blue), J (green), H (orange) and K (red) and the dashed lines show the performance with no correction.

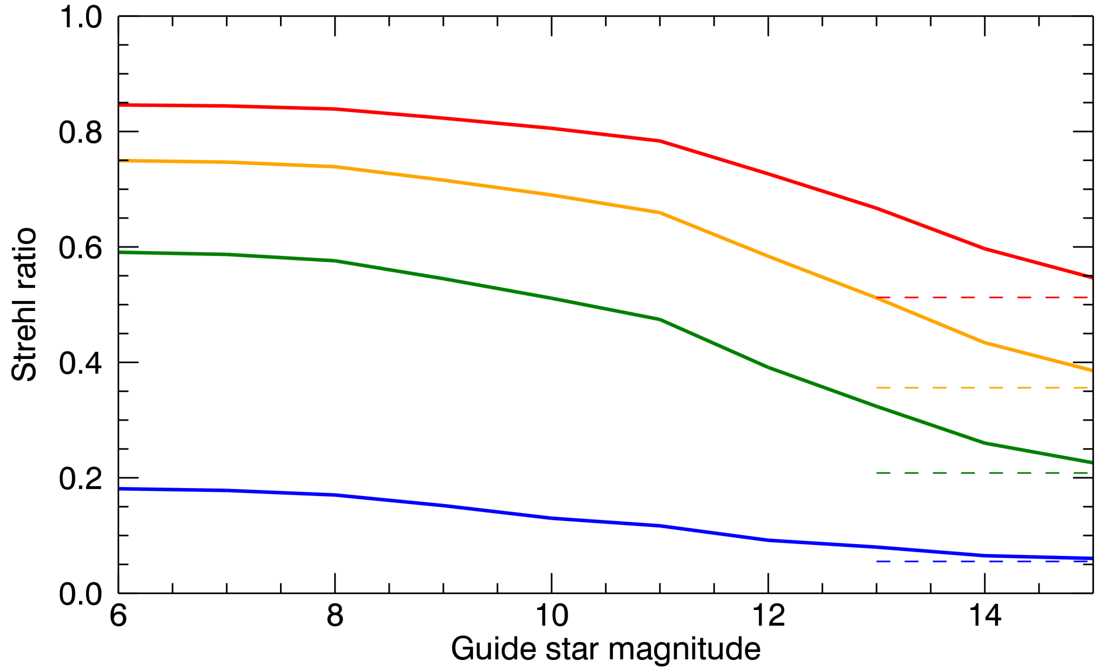

Figure 7: Strehl versus guide star R-magnitude for an open-loop tip-tilt system with an r_0 at 550 nm of 0.20 m. The four colors represent R (blue), J (green), H (orange) and K (red) and the dashed lines show the performance with no correction.

3.2. Performance of an closed-loop, tip-tilt only system

The simulations were repeated with the tip-tilt mirror in the common path. The results, plotted in Figures 8, 9 and 10, show that the closed-loop performance is better than the open-loop performance.

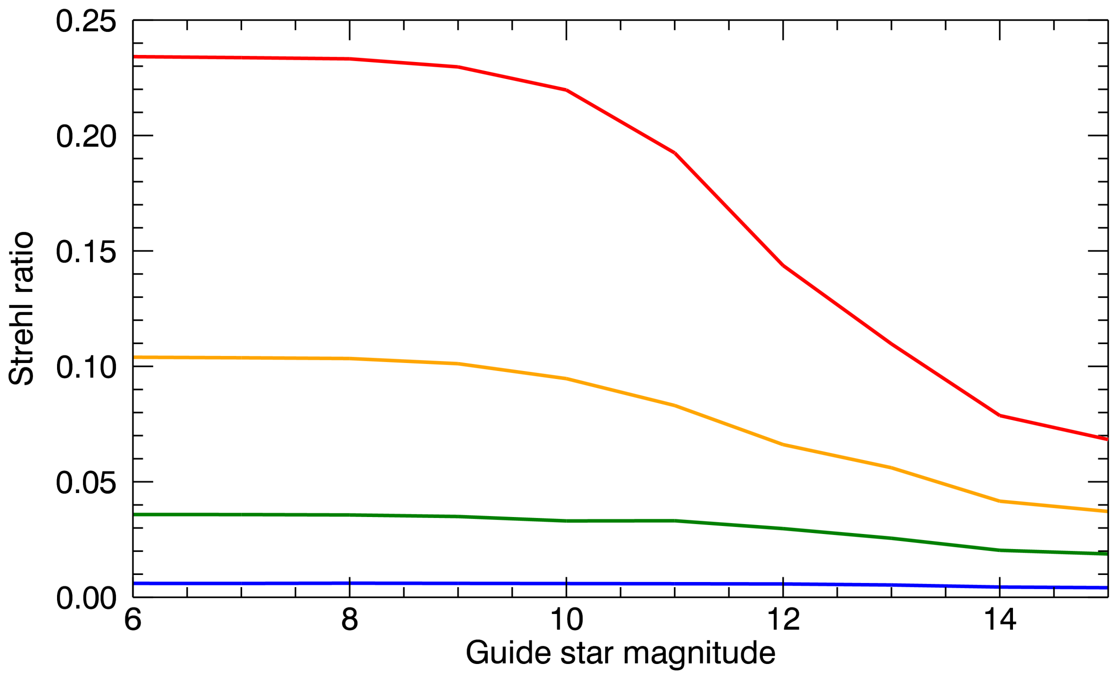

Figure 8: Strehl versus guide star R-magnitude for a closed-loop tip-tilt system with an r_0 at 550 nm of 0.05 m. The four colors represent R (blue), J (green), H (orange) and K (red).

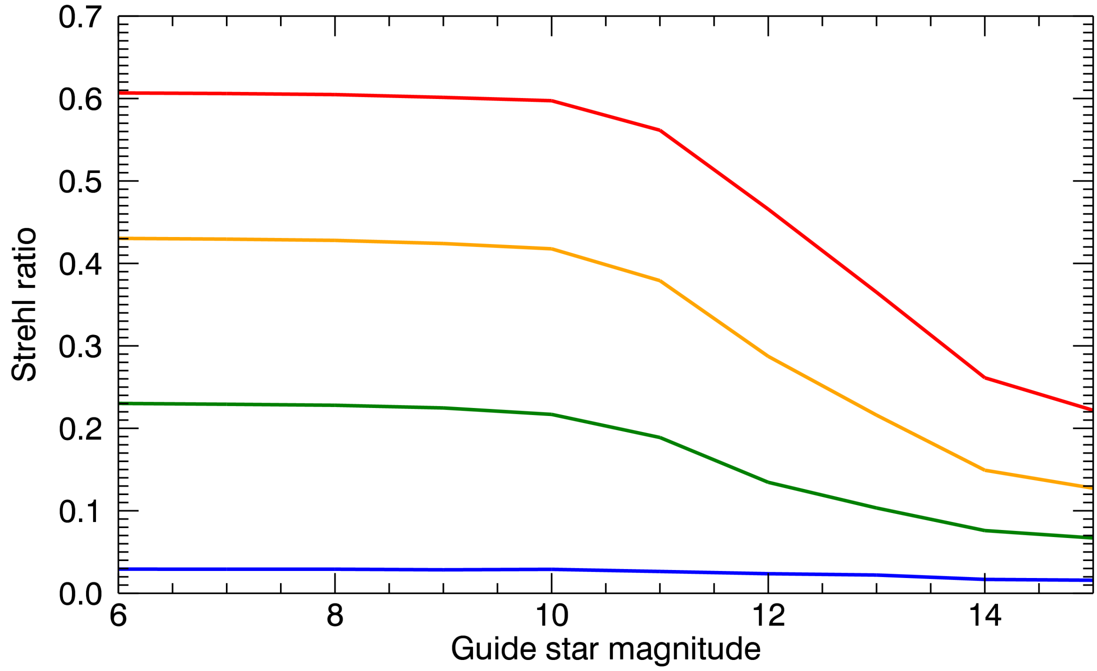

Figure 9: Strehl versus guide star R-magnitude for a closed-loop tip-tilt system with an r_0 at 550 nm of 0.10 m. The four colors represent R (blue), J (green), H (orange) and K (red)..

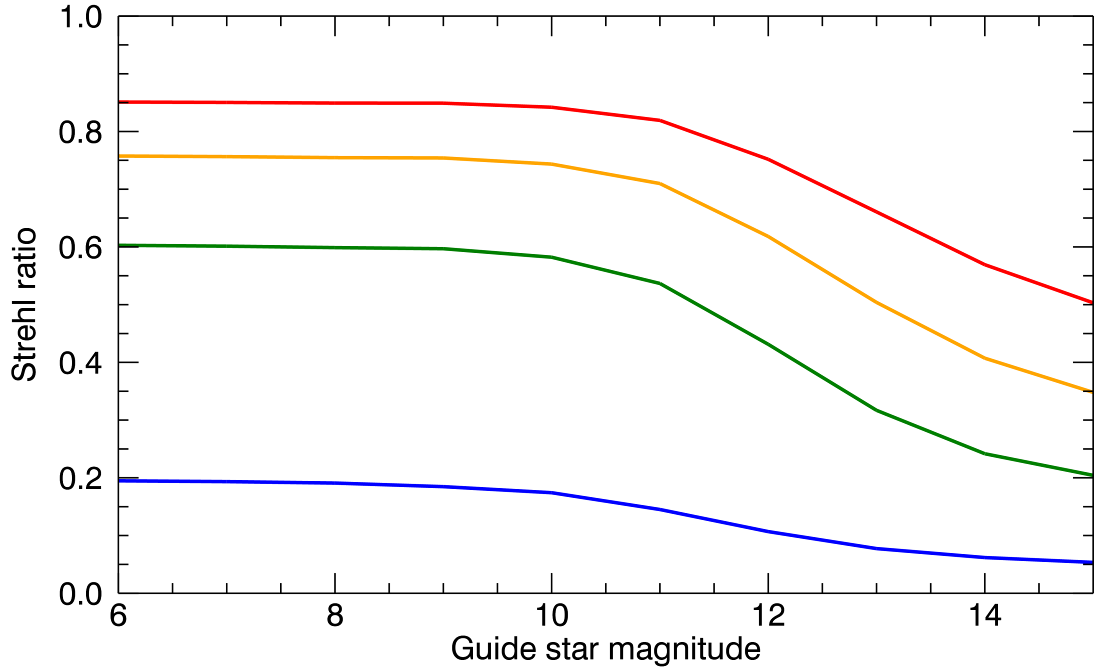

Figure 10: Strehl versus guide star R-magnitude for a closed-loop tip-tilt system with an r_0 at 550 nm of 0.20 m. The four colors represent R (blue), J (green), H (orange) and K (red).

3.3. Performance of an open-loop, high-order AO system

In this section, we replace the tip-tilt mirror with a 7x7 actuator deformable mirror.

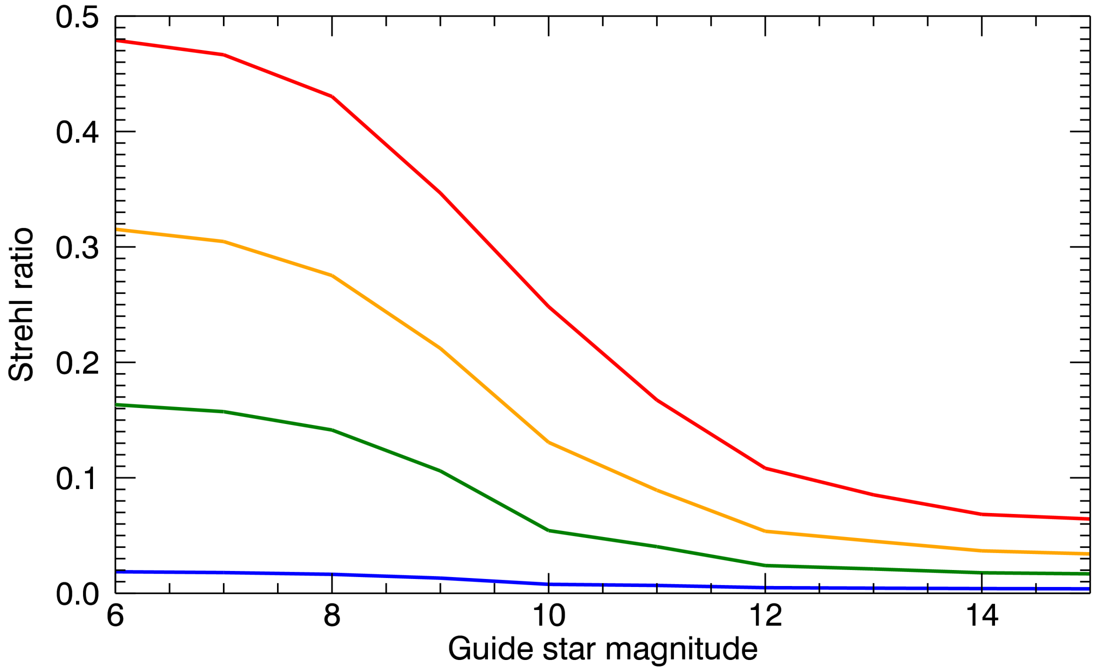

Figure 11: Strehl versus guide star R-magnitude for an open-loop 7x7 actuator DM system with an r_0 at 550 nm of 0.05 m. The four colors represent R (blue), J (green), H (orange) and K (red).

The actuators are located conjugate to the corners of the subapertures. A regularized least-squares zonal wavefront reconstructor is used.[5] The Strehl versus magnitude curves are displayed in Figures 11, 12 and 13.

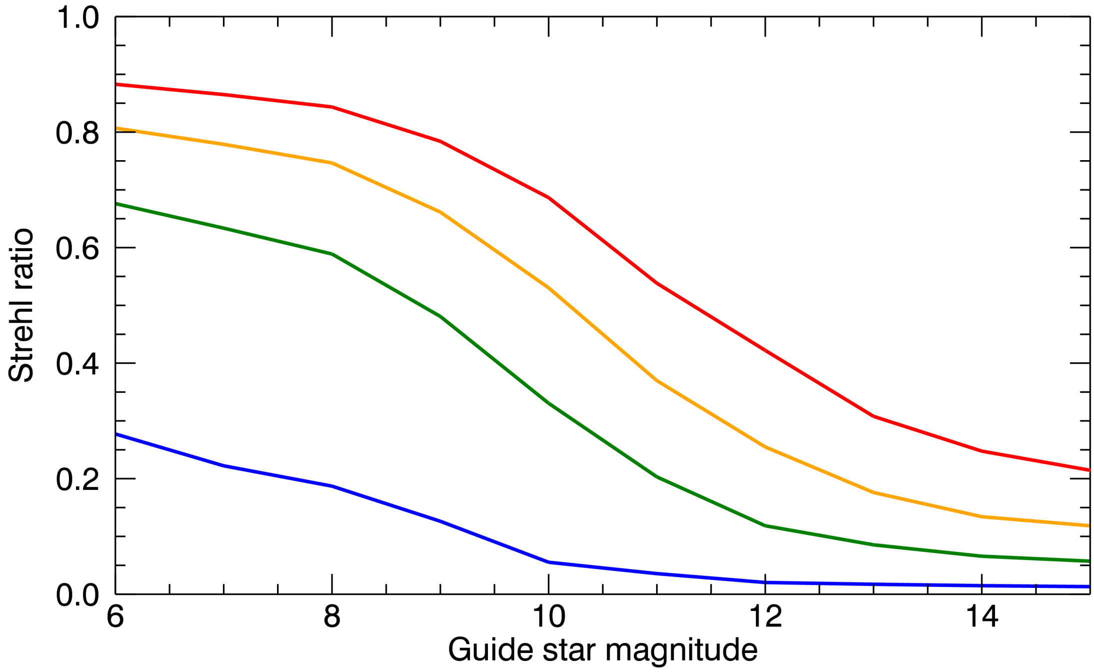

Figure 12: Strehl versus guide star R-magnitude for an open-loop 7x7 actuator DM system with an r_0 at 550 nm of 0.10 m. The four colors represent R (blue), J (green), H (orange) and K (red).

5 M.A. van Dam *et al.* "Modeling the adaptive optics systems on the Giant Magellan Telescope ," Proc SPIE 7736 (2010).

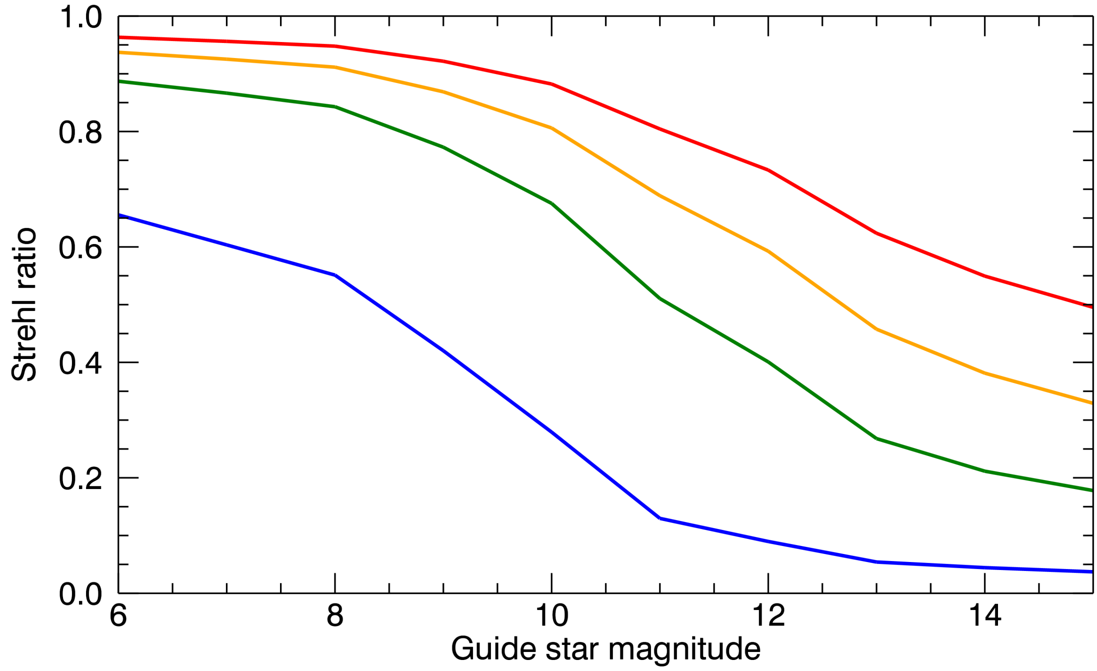

Figure 13: Strehl versus guide star R-magnitude for an open-loop 7x7 actuator DM system with an r_0 at 550 nm of 0.20 m. The four colors represent R (blue), J (green), H (orange) and K (red).

3.4. Performance of a closed-loop, high-order AO system

The simulations were repeated, this time in closed-loop. The results are an improvement on the open-loop results, as seen in Figures 14, 15 and 16.

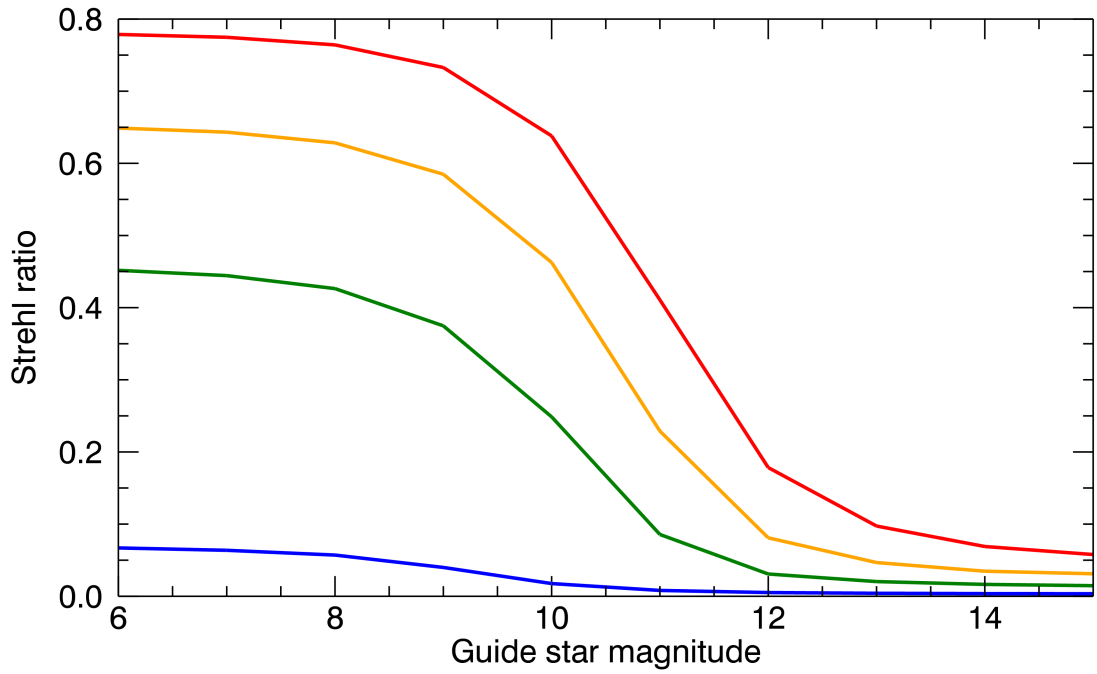

Figure 14: Strehl versus guide star R-magnitude for a closed-loop 7x7 actuator DM system with an r_0 at 550 nm of 0.05 m. The four colors represent R (blue), J (green), H (orange) and K (red).

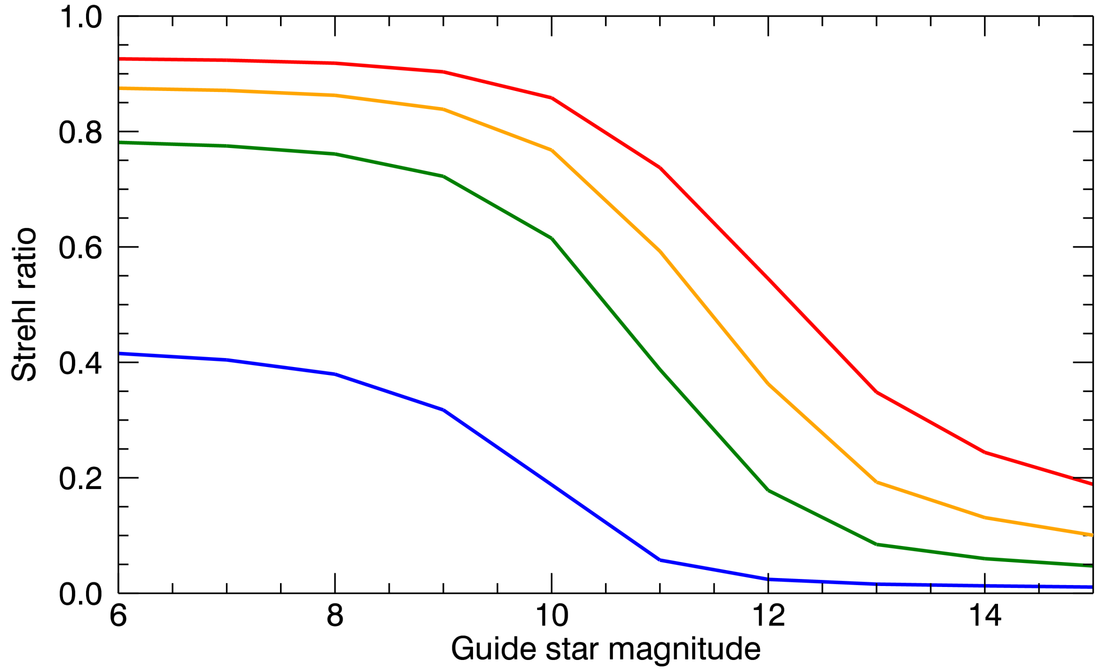

Figure 15: Strehl versus guide star R-magnitude for a closed-loop, 7x7 actuator DM system with an r_0 at 550 nm of 0.10 m. The four colors represent R (blue), J (green), H (orange) and K (red).

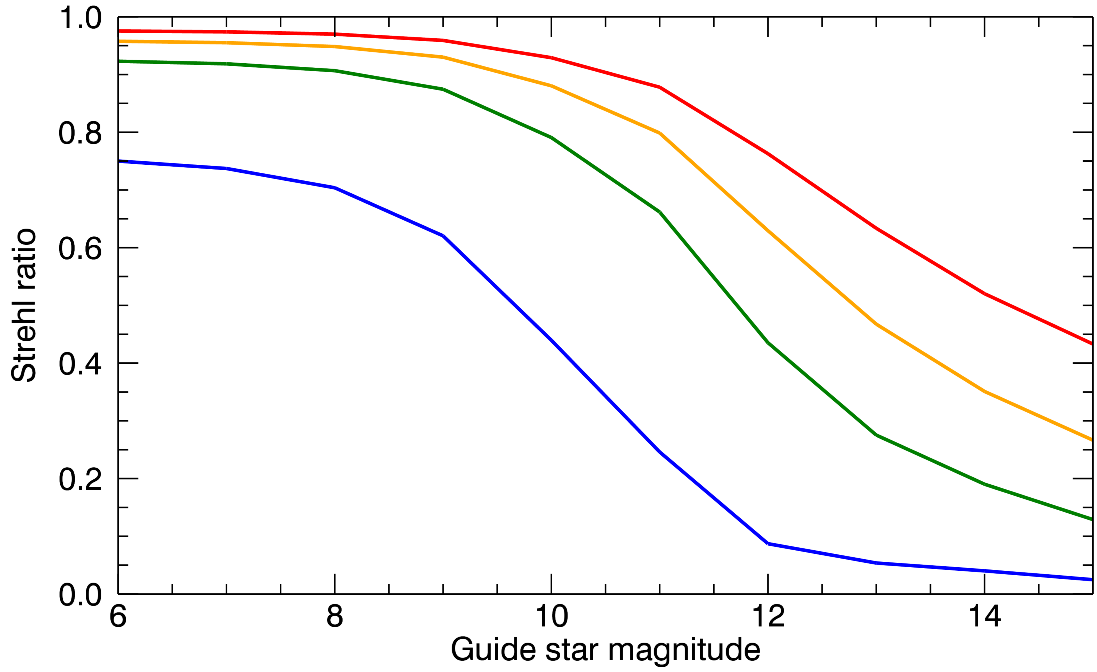

Figure 16: Strehl versus guide star R-magnitude for a closed-loop, 7x7 actuator DM system with an r_0 at 550 nm of 0.20 m. The four colors represent R (blue), J (green), H (orange) and K (red).

4. Pyramid WFS simulation results

The pyramid WFS does not work very well in open-loop, so only closed-loop results are presented here.

4.1. Performance of a closed-loop, high-order AO system

The simulation results are plotted in Figures 17, 18 and 19. In most cases, the performance of the pyramid WFS trumps that of the Shack-Hartmann WFS. However, as seen in Figure 17, the performance of the pyramid WFS is very bad when the seeing is bad and the star is faint. This could probably be improved by changing the modulation amplitude and having a modal reconstruction with variable loop gain, but such an optimization is beyond the scope of this study. A comparison of the pyramid and the Shack-Hartmann is plotted in Figure 20.

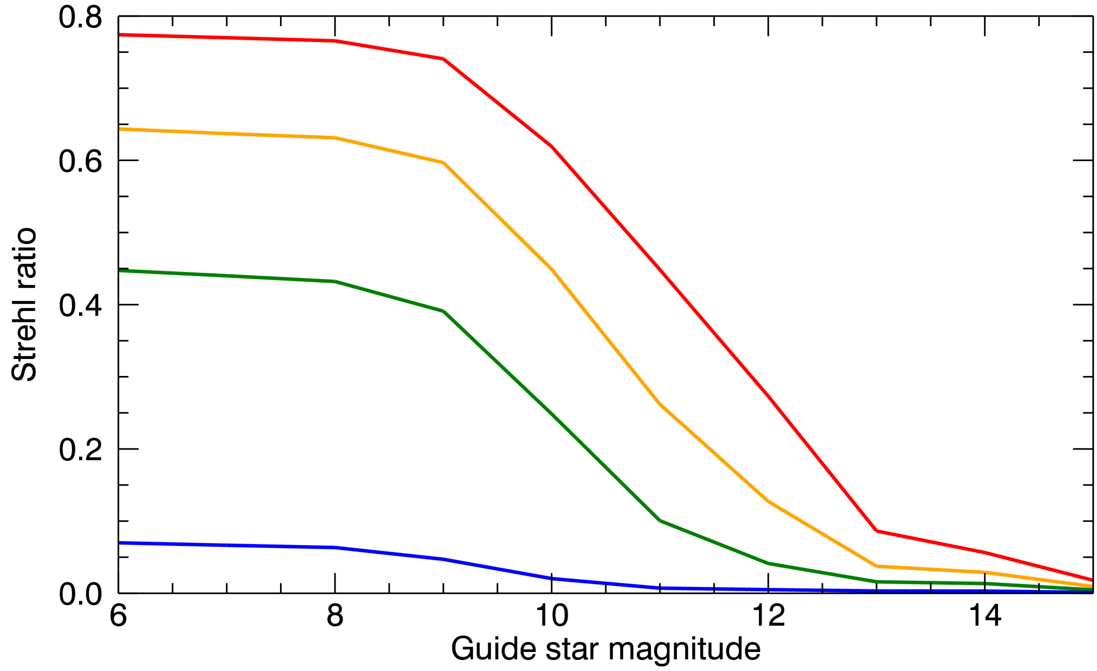

Figure 17: Strehl versus guide star R-magnitude for a closed-loop 7x7 actuator DM system with an r_0 at 550 nm of 0.05 m. The four colors represent R (blue), J (green), H (orange) and K (red).

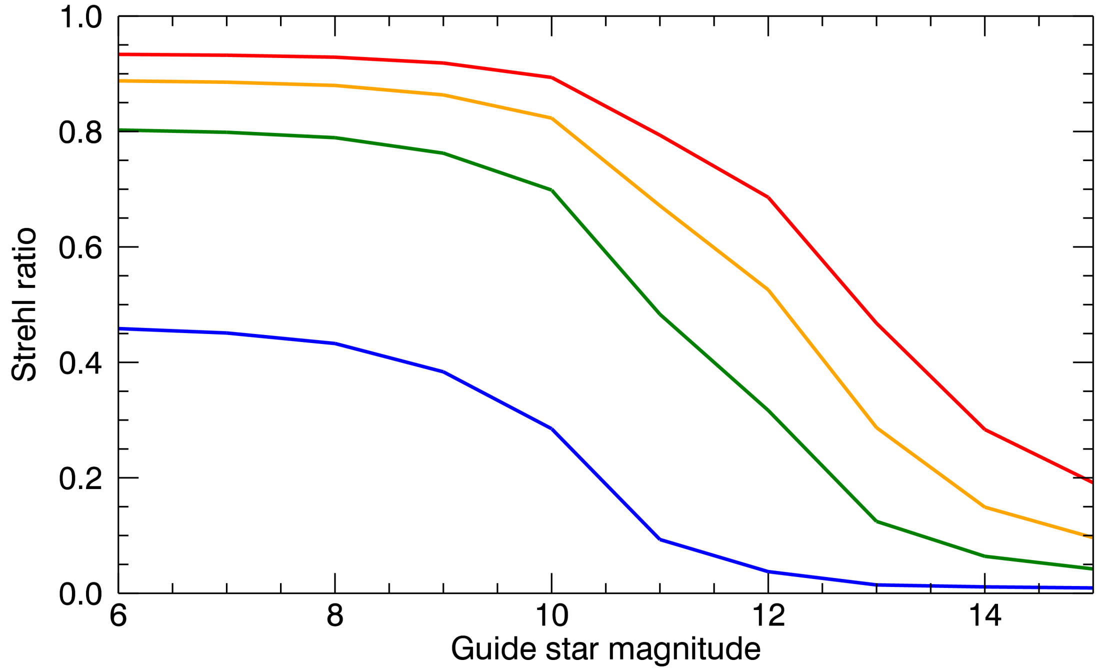

Figure 18: Strehl versus guide star R-magnitude for a closed-loop 7x7 actuator DM system with an r_0 at 550 nm of 0.10 m. The four colors represent R (blue), J (green), H (orange) and K (red).

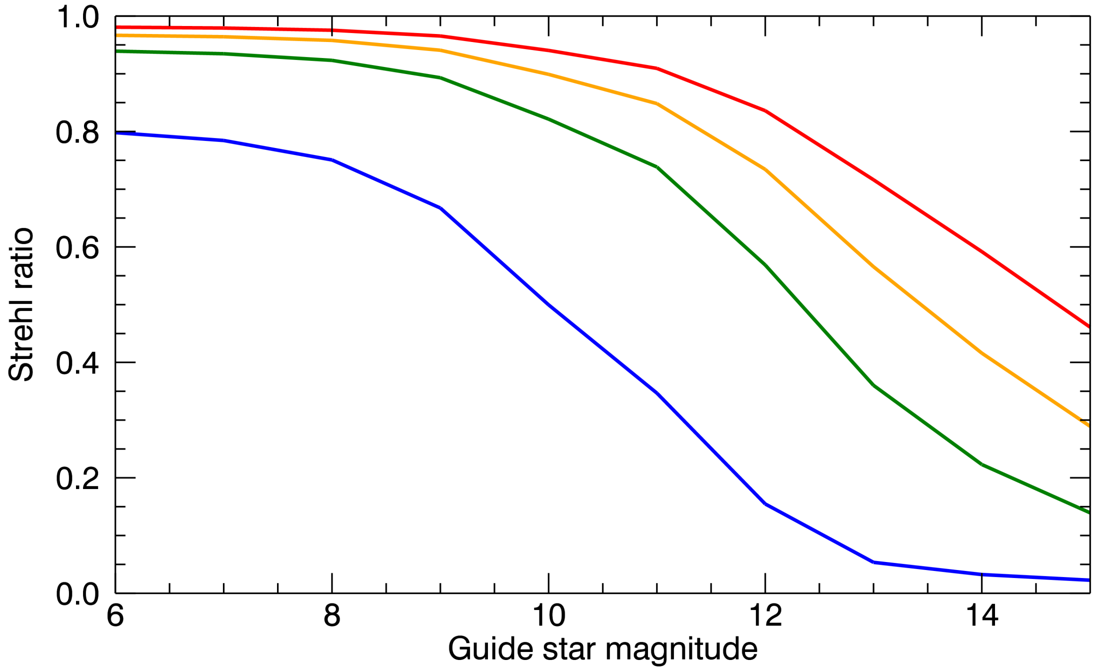

Figure 19: Strehl versus guide star R-magnitude for a closed-loop 7x7 actuator DM system with an r_0 at 550 nm of 0.20 m. The four colors represent R (blue), J (green), H (orange) and K (red).

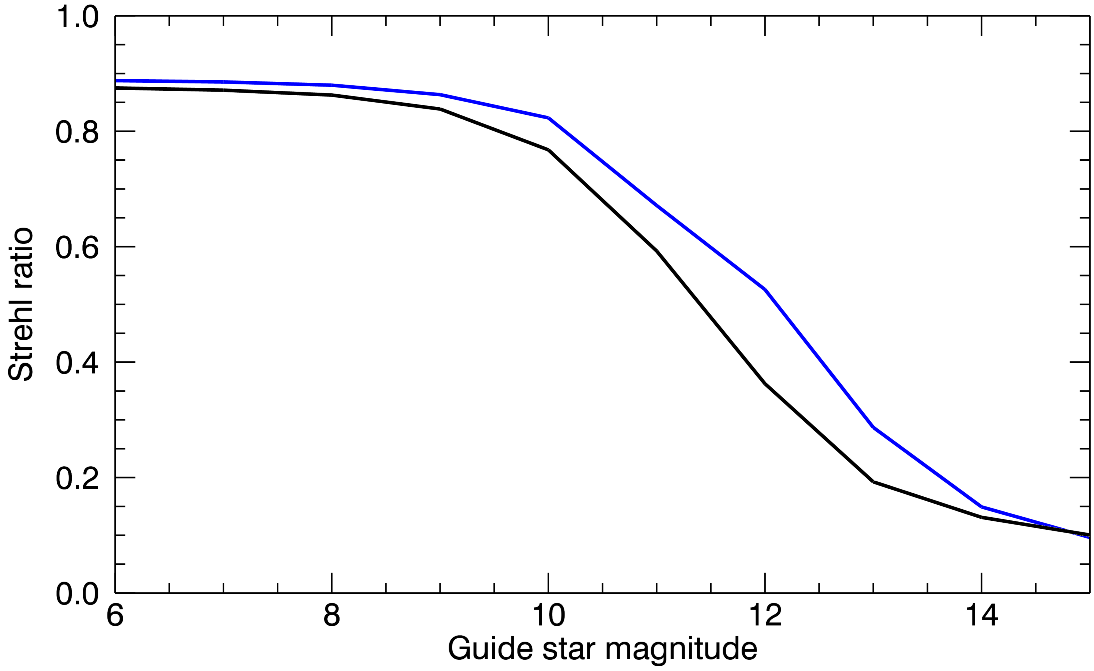

Figure 20: H-band Strehl versus guide star R-magnitude for a Shack-Hartmann wavefront sensor (black) and a pyramid sensor (blue). The value of r_0 at 550 nm is 0.10 m.

5. Conclusion and discussion

Simulations have been run for the CHARA AO system with nominal operating parameters; these parameters are all sensible but have not been optimized. The Strehl ratio delivered by the AO system improves significantly for stars of magnitude 13 or brighter. Tip-tilt correction alone provides a significant benefit. When there is a DM present excellent performance is achieved due to the small size of the subapertures (and corresponding interactuator spacing). The simulations show what is possible, but the actual performance also depends on other issues which have not been modeled here, such as non-common path aberrations and other calibration errors.

The closed-loop results are better than the open-loop results. No existing astronomical AO system operates in open-loop, although there have been on-sky demonstrators, such as the Villages project on the Lick 1-m telescope.[6] It is not recommended that an open-loop system is built, unless the cost of the DM for a closed-loop system is prohibitive.

The pyramid WFS performs slightly better than the Shack-Hartmann WFS in almost every case. The increase in complexity in implementing a pyramid WFS is probably not warranted by the performance improvement. The performance delivered by the pyramid WFS could be further improved by optimizing the modulation amplitude, loop gain and reconstructor, but this is beyond the scope of this study.

6 D. Gavel et al, “Villages: an on-sky visible wavelength astronomy AO experiment using a MEMS deformable mirror,” Proc SPIE 6888 (2008)