NGWFC Next-Generation Wave Front Controller

Keck Adaptive Optics Note #489

Performance of the Keck II AO system

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Table of Contents

TABLE OF CONTENTS 1
1 INTRODUCTION 1
2 NGS AO: PERFORMANCE ON BRIGHT GUIDE STARS 2
3 NGS AO: STREHL VS MAGNITUDE 3
4 STREHL VS ELEVATION 4
5 EXTENDED OBJECTS 4
6 DAR ACQUISITION AND TRACKING 5
7 IMAGE DEGRADATION WHEN USING TIP-TILT CONTROL OFFSETS 5
8 LGS AO: PERFORMANCE ON BRIGHT GUIDE STARS 5
9 LGS AO: STREHL VS MAGNITUDE 7
10 SKY COVERAGE 8
11 DISCUSSION 8
12 ACKNOWLEDGMENTS 9

1 Introduction

In February 2007, the AO system on Keck II was upgraded with a new wavefront controller and a new wavefront sensor, including a new wavefront sensing CCD. This project is known as the Next Generation Wavefront Controller, with the acronym NGWFC.

This report documents the performance of the AO system on Keck II using the NGWFC. Its purpose is to document the current performance of the system. Some of the more basic functionality was tested thoroughly on Keck I and simple tests were performed to ensure that they also hold on Keck II. A similar report on the performance of the NGWFC on Keck I is contained in KAON 458: Status of the NGWFC on Keck I.[1]

[1] E. Johansson, P. Stomski and M. van Dam, KAON 458: Status of the NGWFC on Keck I

Data was collected over many engineering and science nights: the data included in this report is from February 28 to June 7 2007 UT. Note that some improvements were made to the software and calibrations over that time, and improvements will continue to be made.

Most of the results and images presented here were obtained with the NIRC2 camera on Keck II. Good performance was also obtained using OSIRIS, NIRSPAO (NIRSPEC behind AO) and the interferometer.

2 NGS AO: Performance on Bright Guide Stars

The performance requirements for the NGWFC project called for a Strehl ratio of 60% on bright stars with good seeing ($r_0 \geq 20$ cm). In Figure 1, the Strehl ratio is plotted as a function of seeing for bright natural guide stars (7-8 magnitude). The r0 at 500 nm and the Strehl ratio at 2200 nm were estimated from open and closed loop NIRC2 images respectively. It can be seen that the Strehl ratio achieved on good seeing nights just meets the requirements.

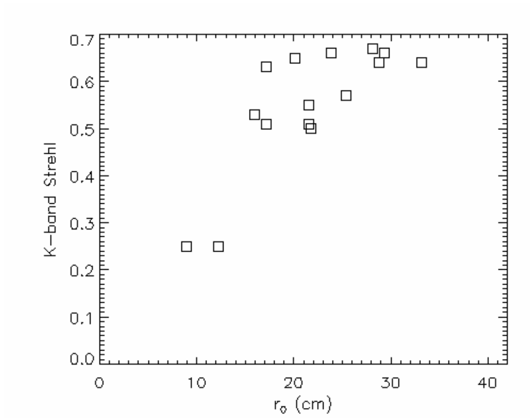

Figure 1: Strehl vs r_0 for bright NGS

One feature that will help improve the performance is using the tip-tilt closed loop mirror positioning (CLMP) system. This loop uses strain gauge feedback from the tip-tilt mirror to ensure that the tip-tilt mirror is at its commanded position and eliminates the effect of hysteresis. Although the CLMP works well, it has not been well tuned and has the unfortunate consequence of actually amplifying the oscillations of the tip-tilt mirror. Tuning the CLMP properly will allow us to operate with much higher tip-tilt bandwidths, since the hysteresis of the tip-tilt mirror is worse for high temporal frequency commands. In addition, we find that the performance degrades when we operate at the highest frame rates and have restricted the frame rates to 1054 Hz. We now believe that we can obtain better performance by running the AO system at 1700 Hz, but are still investigating why the performance suffers when using the CCD program with the fastest frame rate.

Nevertheless, the performance is much better than that obtained using the OWFC, as can be seen by looking at the one of the best recorded images in Figure 2. The scale and stretch is different; nevertheless, the improvement in image quality is obvious and quantifiable! The highest Strehl ratio obtained with the NGWFC is 71%, compared with 58% with the old system.

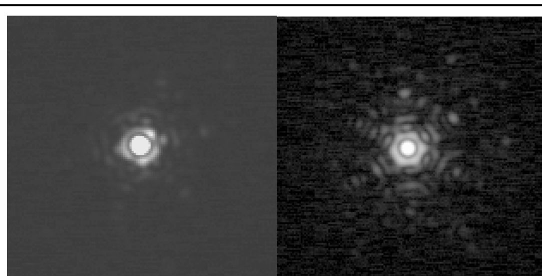

Figure 2: Some of the best images of a 7^{th} magnitude star taken with the OWFC (left) and the NGWFC (right). The images have K-band Strehls of 58% and 66% respectively.

Figure 3 shows the PSF as a function of wavelength for the same bright star.

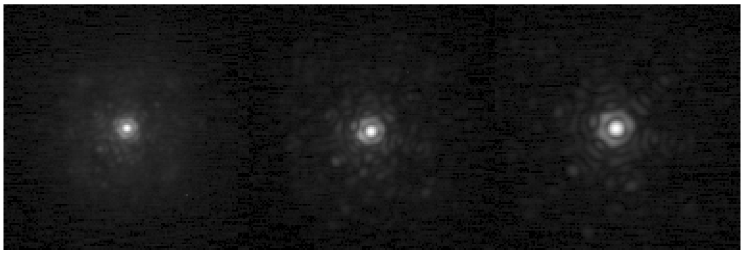

Figure 3: J, H and K images of the same bright star. The Strehl ratios are 22%, 41% and 62% respectively.

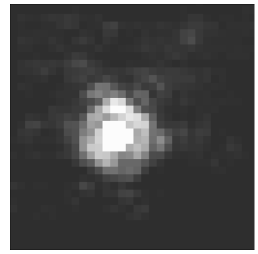

Figure 4: Best image obtained with OSIRIS

The performance has been equally impressive when using OSIRIS, as can be seen by an image of a bright star taken with the spectrograph and reproduced in Figure 4. The image quality on OSIRIS is still limited by the ability to correct for non-common path aberrations, so imperfections in the PSF are still present.

I believe this star has the best image quality seen in OSIRIS to date. The NGWFC is a major step forward in AO performance at Keck. – James Larkin

3 NGS AO: Strehl vs Magnitude

Since not all astronomers like to use bright natural guide stars, it is important to characterize the performance as a function of guide star magnitude.

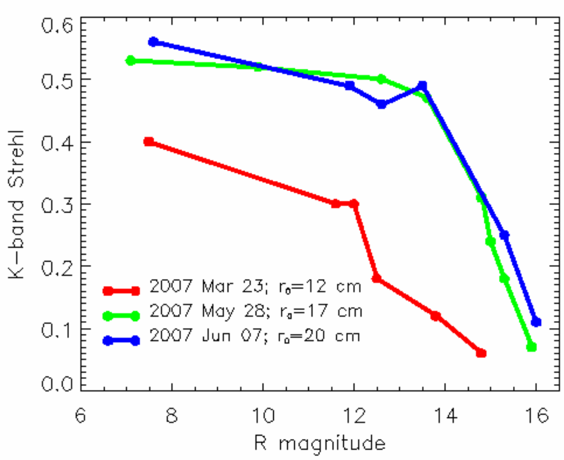

Figure 5: Strehl vs R-magnitude in NGS AO mode

First, it is important to define the guide star magnitude. The wavefront sensor has a response most similar to an R filter. But since it is not the same as an R-filter, the counts on the wavefront sensor depend not only on the R-magnitude but also on the spectral type of the star. Ultimately, the wavefront sensor does not care what the R-magnitude or spectral type of the star is, but how many counts it sees. In what follows, we use the term R-magnitude in place of the number of counts measured by the wavefront sensor equivalent to the counts measured if guiding on a K0 star with that R-magnitude. The actual R-magnitude could be higher or lower, depending on the spectral type.

Figure 5 plots the K-band Strehl as a function of R-magnitude for data taken on three different nights. The requirement stated that the Strehl should be 30% when guiding on a 14^{th} magnitude star on a night with good seeing ($r_0 \geq 20$ cm); clearly, this requirement has been exceeded. In fact, the best images when guiding on a 14^{th} magnitude star have had Strehl ratios in the range of 60-67%, as can be seen in Figure 6.

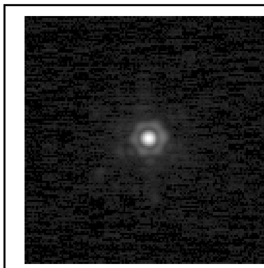

Figure 6: Image of a 14^{th} magnitude star

Figure 7 shows the PSF as a function of guide star magnitude:

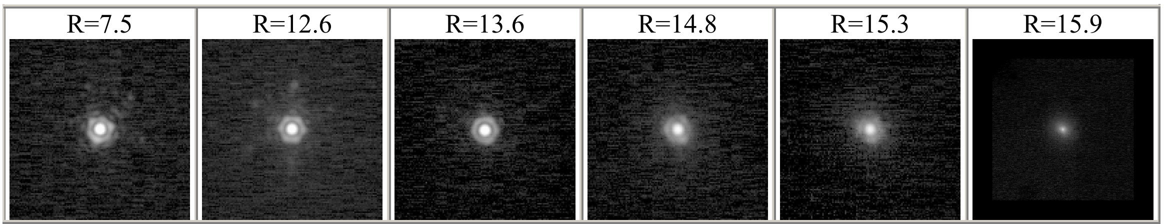

Figure 7: PSF as a function of guide star magnitude taken on 28 May 2007 UT

4 Strehl vs Elevation

We captured data on a bright guide star at three different elevations. A narrowband filter was used to mitigate the effect of dispersion, for which the AO system is unable to compensate. We found that the performance is very good, even at low elevations.

Elevation (degrees)	80	41	32
K-band Strehl ratio	55%	50%	47%

Table 1: K-band Strehl ratio as a function of elevation.

5 Extended Objects

We have successfully guided on three extended objects: Titan, Neptune and Uranus. The AO system automatically accounts for the large angular extent of these objects if the target name is included in the target list. Figure 8 shows images of Uranus, Neptune and Titan. The PSF on Uranus, which is the most challenging of these objects due to its large (4”) extent, can be seen by the inset of Miranda. The measured K-band Strehl is 40% with a corresponding FWHM of 53 mas. Assuming that Miranda has an angular extent of 35 mas, then the true Strehl ratio is 54%. From the PSF, we can tell that there are no artifacts induced by the fact that we are guiding on an extended object.

Figure 8: J, H and K’ color composite of Uranus (left), H and K’ color composite of Neptune (middle) and K’ image of Titan (right). The inset on the top left is an enlarged image of Miranda at K’.

The images look great! – Emily Schaller

6 DAR Acquisition and Tracking

Tests were performed to see whether the functionality to compensate for differential atmospheric refraction is intact. This was confirmed by taking an image at a position angle, changing the demanded angle by 180 degrees and taking another image. For DAR acquisition, where DAR compensation is achieved using the field steering mirrors (FSMs), there was no change in software.

The performance of DAR tracking was measured by acquiring a star at a low elevation and setting. DAR tracking was turned on and the elevation changed from 40.82 deg to 38.59 deg over a period of 15 minutes, with a corresponding change in air mass of 1.492 to 1.601.

Using the formulas from Roe,[2] the atmospheric differential refraction, R, between two wavelengths is:

$$R_{vis} - R_{ir} = 206265\left(\frac{n_{vis}^2 - 1}{2n_{vis}^2} - \frac{n_{ir}^2 - 1}{2n_{ir}^2}\right)\tan(z)\ \text{arcsec},$$

where z is the zenith angle. n_{ir} and n_{vis} are the refractive indices of air for infrared and visible light respectively and take values of 1+ 2.7290e-4 (at 2.73 μm) and 1+2.7579e-004 (at 0.7 μm).

The amount of DAR correction applied from the formula is about 64 mas; the FITS headers unfortunately did not contain all the AO parameters, including the tip-tilt control offsets applied. The residual motion of the spots was less than one NIRC2 pixel (10 mas) away from the initial position throughout the experiment. This indicates that DAR compensation works well.

7 Image Degradation when Using Tip-tilt Control Offsets

Tip-tilt control offsets (also known as DT control offsets) are used to compensate for changes in DAR while an exposure is being taken (DAR tracking) and for the position of the image on the Keck Angle Tracker (KAT)in NGS AO. They work by changing the control point of the tip-tilt controller: the tip-tilt mirror is driven so that the average centroid is equal to the control offset, specified value in arcseconds. Unfortunately, when the tip-tilt control offsets are large, the image degrades. A test was run to see how much the Strehl ratio degrades with increasing tip-tilt control offsets, and the results are plotted in Figure 9.

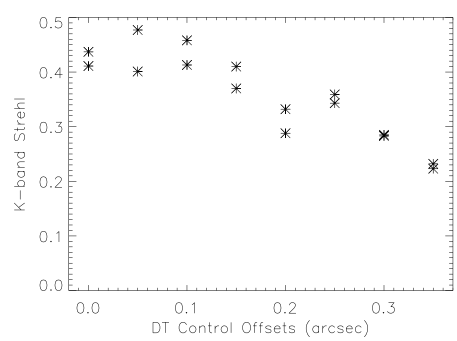

Figure 9: Strehl as a function of DT control offsets for the 2.4” plate scale

Knowing how the Strehl degrades with increasing tip-tilt control offset is important in determining how often we need to offload the offsets to the field steering mirrors when using DAR tracking or the KAT.

8 LGS AO: Performance on Bright Guide Stars

Since there is no laser guide star on Keck I, Keck II was the first opportunity to measure the correction using LGS AO. We were pleasantly surprised by the improved performance, especially at the shorter wavelengths. The reason that the performance appeared to improve most at shorter wavelengths is that the

[2] Henry G. Roe, “Implications of Atmospheric Differential Refraction for Adaptive Optics Observations,” PASP **114**: 450-461 (2002).

low order correction (tip/tilt/focus) did not change much, while the high-order correction did. The best ever Strehl ratio at K-band improved from 44% to 51%.

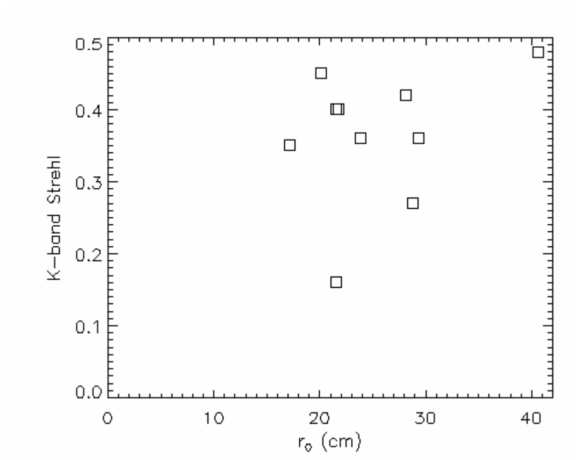

Figure 10: Strehl vs r_0 for bright tip-tilt guide stars

Figure 10 plots the Strehl achieved as a function of seeing. During the commissioning period, we had problems with the stability of the beamsplitter cube that splits light between STRAP and the LBWFS. As a consequence, the performance was degraded during some nights, since the LBWFS correction was very poor. Nevertheless, we can see that excellent performance was achieved regularly.

Figure 11 shows a brown dwarf binary pair with separation of 80 mas.

Wow!! The J-band performance is much better than I have ever gotten from LGS - Michael Liu

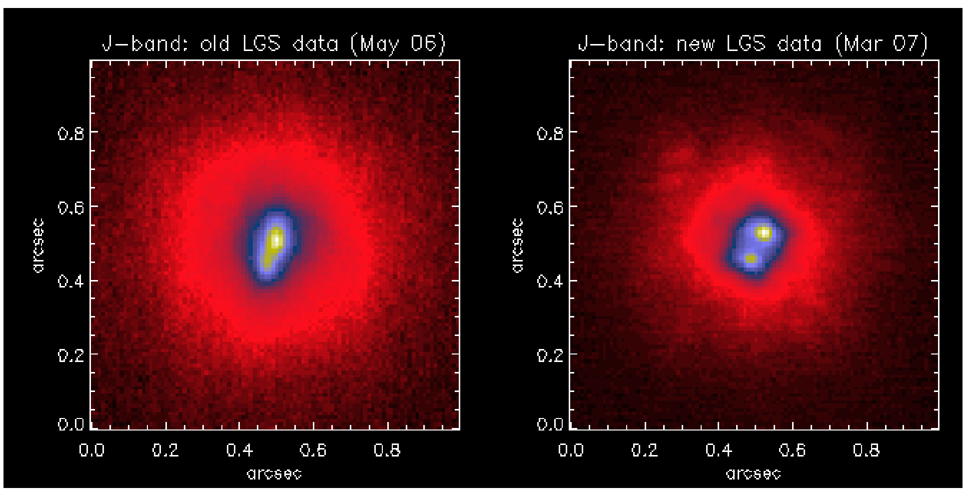

Figure 11: J-band image of a brown dwarf binary pair with separation of 80 mas (Michael Liu, 26 March 2007).

Figure 12 displays the Galactic Center imaged at K-prime using LGS and NGS AO. The images are the best ever captured for both of those AO modes, and they demonstrate the power of NGS AO for targets using guide stars that could only previously be used to provide good LGS AO correction. For average conditions, NGS AO provides better on-axis image quality than LGS AO for guide stars brighter than R-mag=13.5-14.0.

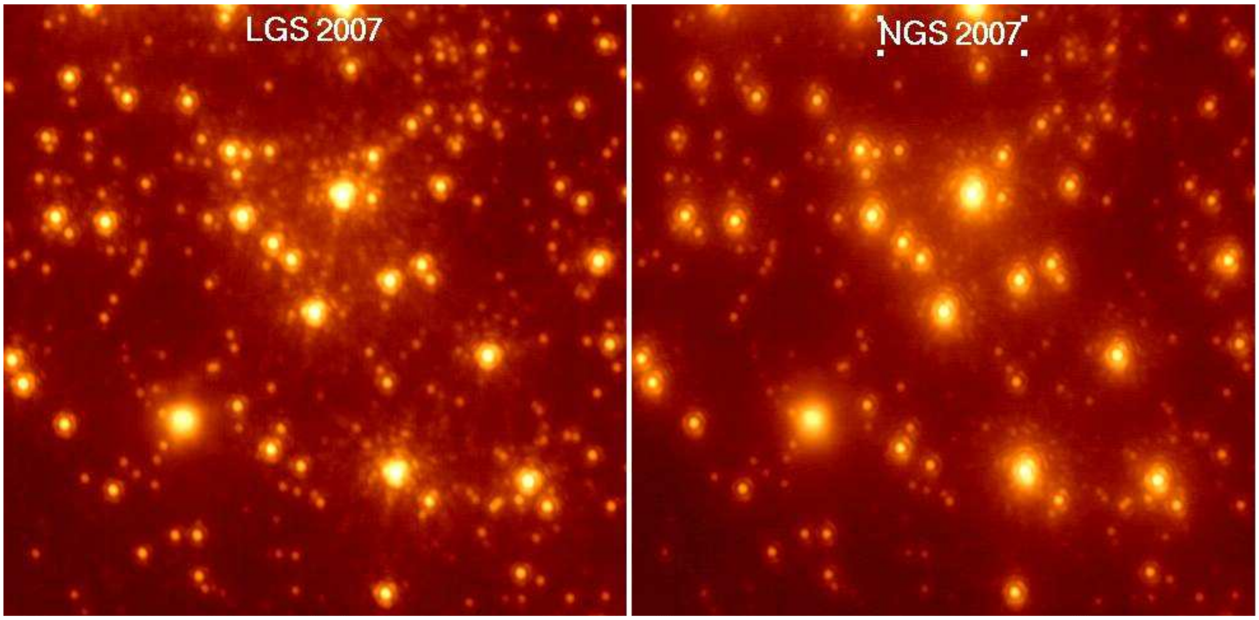

Figure 12: K-band image of the Galactic Center in LGS AO (left) and NGS AO (right)

It definitely seems like this year was better than last year! We're just thrilled about this. – Andrea Ghez

The images look amazing!!! I can hardly believe it is NGS. – Jessica Lu

9 LGS AO: Strehl vs Magnitude

Since both the LBWFS and STRAP function exactly as they did before, the expected degradation in Strehl with increasing tip-tilt guide star magnitude is expected to be the same as it was before the NGWFC upgrade. However, there are two minor differences. First, the fact that the pixels on the fast WFS are larger (3.0" vs 2.1") means that the LGS aberrations are reduced by about 30% (see KAON 479). This is especially beneficial on faint guide stars, where the LBWFS does not do a good job of correcting for the LGS aberrations. The other difference is that the NGWFC is equipped with the capability of using denominator-free centroiding on STRAP. This feature, which has been tested but not yet fully implemented, is expected to yield a measurable performance improvement on faint tip-tilt stars. However, we will not be able to take full advantage of this feature until we also implement the upgrade to the LBWFS that allows us to measure the low-order modes only, since the magnitude limit is imposed by the LBWFS. We have only measured the degradation in performance with tip-tilt magnitude once, with very good seeing (r_0 varied between 25 cm and 40 cm) and no wind. The results, which are not typical, are presented in Figure 13. At least, they reassure us that the faint guide star performance has not degraded, since results like these are completely unprecedented!

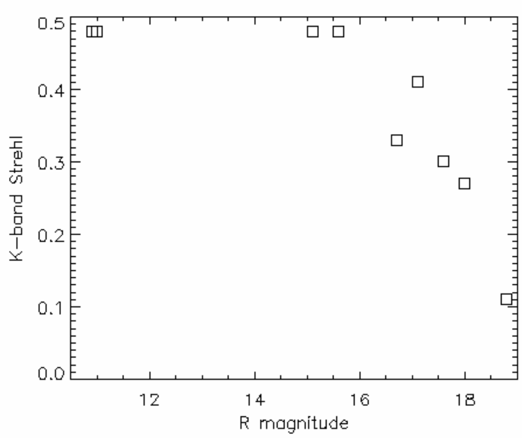

Figure 13: Strehl vs R-magnitude in LGS AO mode

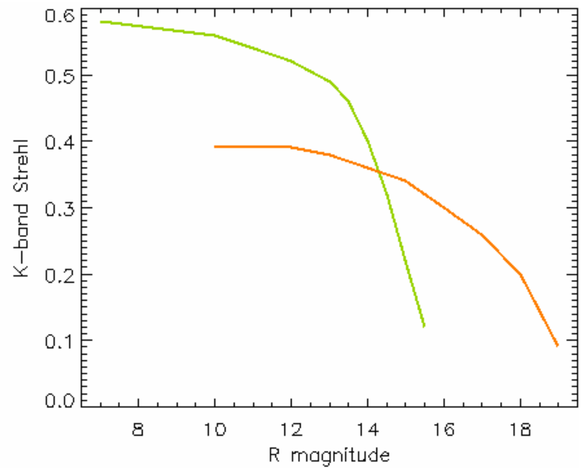

Figure 14: Strehl vs R-magnitude for NGS AO (green) and LGS AO (orange)

Figure 14 plots representative values of the on-axis K-band Strehl versus guide star magnitude for average conditions. This plot shows that the on-axis performance is the about the same for NGS AO and LGS AO when the guide star is 14th magnitude. Observing off-axis targets favors the use of LGS AO. On the other hand, the acquisition time and other overheads are reduced by the use of NGS AO.

10 Sky Coverage

The fraction of the sky accessible to the AO system is plotted in Figure 15. Compared to the old wavefront controller, this represents a substantial increase in the sky coverage for the NGS AO system and a modest improvement for the LGS AO system. However, the fraction of the sky over which excellent (K-band Strehl of over 30%) is achieved has drastically increased for both NGS and LGS AO.

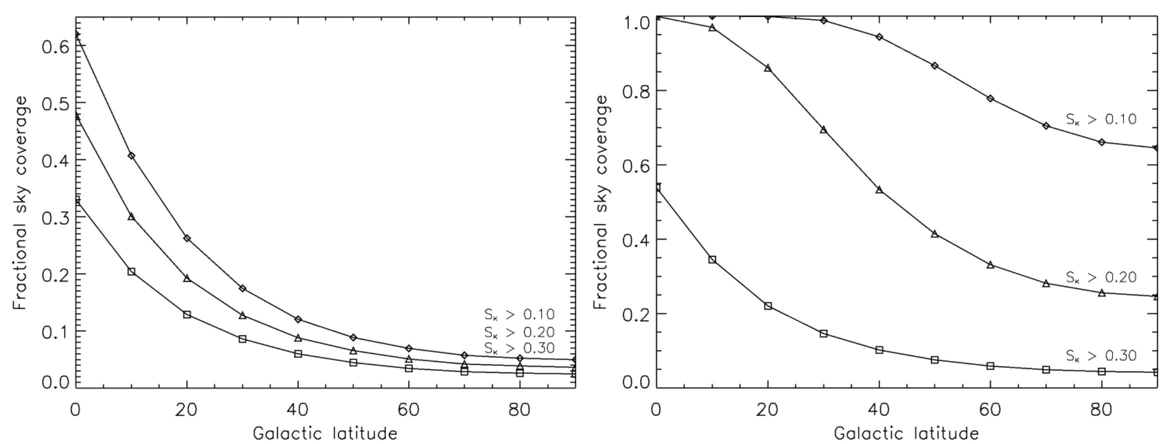

Figure 15: Sky coverage as a function of Galactic latitude and K-band Strehl ratio for NGS AO (left) and LGS AO (right).

The sky coverage was calculated using the Galactic model of Bachall and Soneira (1980) transformed to R by Simons (1995), the on-axis K' Strehl versus R magnitude in Figure 14, an isoplanatic angle of 20" (NGS) and an isokinetic angle of 72" (LGS).

11 Discussion

An upgrade to the Keck II AO system took place in February, 2007. The initial performance from the AO system has been very pleasing, and minor improvements remain to be made. The NGS and LGS bright guide star Strehl records have been smashed, going from 58% (NGS) and 44% (LGS) for the OWFC to 71% (NGS) and 51% (LGS) for the NGWFC. In addition, we have also excellent results using faint natural guide stars, with diffraction-limited images when guiding on 15th magnitude stars and partial corrections for stars up to one magnitude fainter. As a result, the faintest guide star for which NGS performance achieves comparable performance to LGS AO is for 14th magnitude stars.

12 Acknowledgments

Thanks to Patrick Fry, Andrea Ghez, James Larkin, Mike Liu, Jessica Lu, Jim Lyke, Imke de Pater, Emily Schaller, Larry Sromovsky and Shelley Wright for help with the data reduction and analysis presented here. Thank also to Randy Campbell and Jim Lyke and for help with the data collection on engineering nights.