# Laboratory Demonstration of Real Time Frame Selection with Magellan AO

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### ABSTRACT

The Magellan AO system combines a pyramid wavefront sensor and high-order adaptive secondary mirror, and will see first light on the Magellan Clay telescope in November 2012. With a 24 cm projected actuator pitch, this powerful system will enable good correction in the optical (0.5 to 1  $\mu$ m). Realistic laboratory testing has produced Strehl ratios greater than 40% in i' (0.765  $\mu$ m) on bright simulated stars. On fainter stars our visible AO camera, VisAO, will work in the partially corrected regime with only short moments of good correction. We have developed a form of lucky imaging, called real time frame selection, which uses a fast shutter to block moments of bad correction, and quickly opens the shutter when the correction is good, enabling long integrations on a conventional CCD while maximizing Strehl ratio and resolution. The decision to open or shut is currently based on reconstructed WFS telemetry. Here we report on our implementation and testing of this technique in the Arcetri test tower in Florence, Italy, where we showed that long exposure i' Strehl could be improved from 16% to 26% when the selection threshold was set to the best 10% of instantaneous Strehl.

Keywords: adaptive optics, visible adaptive optics, frame selection, lucky imaging, Magellan

# 1. INTRODUCTION

The Magellan adaptive optics (AO) system (MagAO) consists of a 585 actuator adaptive secondary mirror (ASM) and a pyramid wavefront sensor (WFS). MagAO is a near clone of the very successful Large Binocular Telescope (LBT) first light AO (FLAO) systems.<sup>1</sup> Though the MagAO system has 87 fewer actuators than the LBT ASMs, it is being deployed on a smaller primary mirror so it will have a higher projected actuator pitch. We therefore expect performance at H band at least as good as obtained by the LBT, where Strehl ratios (S) as high as 90% in H band are reported.

With a 24cm projected actuator pitch, MagAO should even provide good correction for wavelengths less than  $1\mu$ m. On good nights we expect to achieve S > 40% at 0.77 $\mu$ m. To take advantage of this capability, we have developed the VisAO camera.<sup>2–4</sup> VisAO is based on an e2v CCD 47 with a Scimeasure Little Joe controller, which allows both high frame rates (up to 42 fps over a 32x32 window) and low readout-noise (RON) with longer integrations (~  $3e^{-}$ ). These features are important for maintaining the dynamic range necessary to work with bright natural guide stars (NGS) while providing sensitivity to faint companions and circumstellar structure. VisAO contains two filter wheels, one loaded with sloan digital sky survey (SDSS) r', i', z', and a long pass dichroic which is essentially y band. The second wheel contains a selection of coronagraphic occulting spots, as well as custom dual filters which will be used for the simultaneous differential imaging (SDI) technique. To facilitate SDI, VisAO contains a wollaston prism beam-splitter.

On targets fainter than, say,  $R \sim 10$ , correction at visible wavelengths will begin to degrade. A well established technique for optimizing resolution in such conditions is Lucky imaging, which has been demonstrated in combination with AO.<sup>5</sup> Lucky imaging consists of recording a series of short exposures, short enough to capture

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moments of higher S, and shifting and adding (SAA) the best images. The drawbacks to high frame rate imaging are decreased sensitivity due to RON, smaller field of view (FOV) often required to achieve high enough frame rates, and large data volumes which are challenging both to store and process. There are camera technologies, notably the electron multiplying CCD (EMCCD) and the rapidly developing CMOS detectors, which mitigate or even eliminate the RON and FOV drawbacks. We have developed a novel technique which allows us to simultaneously mitigate all three of these drawbacks.<sup>6</sup> We use AO system telemetry, in real-time, to determine when AO correction is above a pre-determined threshold and select those moments by opening a fast mechanical shutter. Called real-time frame selection (RTFS), this technique allows us to integrate on a conventional CCD over its full FOV. This avoids the RON penalty and the challenges associated with high data volumes.

The MagAO system is in preparation for first light on the 6.5 m Magellan Clay telescope in November, 2012. It was first integrated in the summer of 2011 in Arcetri, Italy, where it then underwent extensive testing in the same test tower facility used for the LBT FLAO systems. Here we provide a brief discussion of some of the steps we took to validate this testing and an example of our results, which we compare to our previously reported performance predictions.<sup>6</sup> As part of this testing, we conducted proof-of-concept testing of RTFS in closed-loop. We here describe our current implementation of this technique and present our results from this first demonstration.

### 2. TOWER TESTS

MagAO was integrated and tested in Arcetri, Italy, between March 2011 and March 2012. This period culminated with a successful pre-ship review (PSR) by an external panel in late February 2012. Here we provide a brief overview of our results from this testing and describe our attempts to validate the simulated atmospheric turbulence and how we correct our results to produce estimates of on-sky performance.

### 2.1 Seeing Validation

In the test tower, atmospheric turbulence is generated using the ASM itself. A pre-calculated phase screen is applied to the mirror in parallel to the AO corrections. A full description of how turbulence is generated using the ASM has been provided elsewhere.<sup>1</sup> To provide a baseline for evaluating performance we took data with AO off but the phase screen propagating across the ASM, that is we took simulated seeing limited data. We then used this data to test whether the seeing produced by the ASM matches expectations from theory. We typically used a phase screen generated to have a seeing limited full-width at half-maximum (*FWHM*) of 0.8" at 0.55 $\mu$ m, or  $r_0 = 0.14$ m. For SDSS i', with central wavelength  $\lambda_0 = 0.765\mu$ m, we have  $r_0(0.765\mu$ m) = 0.21m. So in the SDSS i' bandpass, assuming Kolmogorov turbulence, we expect the seeing limited PSF to have *FWHM* = 0.75".

We must also consider that outer scale was set to  $L_0 = 40$ m (which doesn't depend on wavelength). Assuming von Karmen statistics on a large aperture, this causes a reduction in FWHM by a factor 0.8159 at 0.765 $\mu$ m.<sup>7</sup> So our expected  $FWHM(0.765\mu m) = 0.611$ ". In Figure 1 we show a cut through the seeing limited PSF generated by this phase screen, recorded at SDSS i' with the CCD 47. The best Moffat profile fit to the seeing limited data is FWHM = 0.617", assuming a plate scale of 0.0080", corresponding to f/52.6. Of note, the Moffat index of the fit was  $\beta = 3.9$ . It has been reported that  $\beta = 4$  provides a good match to a telescope seeing limited PSF using on-sky data.<sup>8</sup> We conclude that the seeing generated in the test tower using the ASM does a very good job of producing the expected image at the CCD 47.

# 2.2 Fitting Error

The MagAO ASM influence functions were measured in the Arcetri test tower using an interferometer. The best fit projection of these into a Karhunen-Loeve (KL) basis set was then computed. As is done at the LBT, these KL modes will be used during on-sky closed-loop operations at Magellan. To determine the fitting error of our modal basis, 500 independent Kolmogorov phase screens were generated and fit with progressive numbers of our KL modes. The residuals for each number of compensated modes were computed, and these points were fit with a function of the standard form:

$$\sigma^2 = A(j_{max})^B (D/r_0)^{(5/3)} \tag{1}$$



Figure 1. A cut through a seeing limited image, showing the best fit Moffat profile. We also show the best fit Gaussian for comparison. The fits were conducted in two dimensions.



Figure 2. Fitting error of the MagAO ASM after correcting  $j_{max}$  modes. We show the measured residuals after fitting with the KL modes that will be used on-sky, the residuals expected using Zernike polynomials, and the best fit of Equation 1 to the KL mode residuals. Note that our KL modes become less efficient than Zernikes after about mode 400.

with

$$A = 0.232555$$
  
 $B = -0.840466$ 

A comparison of this function with the fitting error expected from a pure Zernike polynomial basis is shown in Figure 2. The MagAO basis is less efficient than Zernikes for modes greater than number 400, a different result than obtained for the LBT ASMs with an identical procedure. We speculate that this is due in part to the asymmetry caused by the machined slot at the outer edge of the shell.

As discussed above, in the test tower atmospheric turbulence is simulated using the ASM itself, so the phase screen contains only a limited number of spatial frequencies corresponding to the maximum degrees of freedom of the mirror. In the case of MagAO this means that only the first 495 modes of turbulence are simulated, so we must correct our laboratory results for the wavefront variance caused by modes  $496 - \infty$  which will be present on-sky. We can use Equation 1 to estimate the correction factors to apply to our results. Table 1 lists the corrections for our standard VisAO filters.

Filter	$\lambda(\mu m)$	$\sigma^2(\mathrm{rad}^2)$	$S_{corr}$
SDSS r'	0.624	0.60	0.55
SDSS i'	0.765	0.40	0.67
SDSS z'	0.906	0.28	0.75
950 LP (y)	0.982	0.24	0.78

Table 1. Tower Test fitting error corrections for 0.8" seeing. Any S measurement made in the tower can be multiplied by the appropriate  $S_{corr}$  to determine an estimate of the on-sky S.



Figure 3. Example tower test results. In this case the system was correcting 400 modes at 800Hz, and data were taken in the SDSS i' bandpass. At upper left is a theoretical Airy pattern. At upper right is the MagAO PSF with no simulated turbulence applied, so that the system was correcting only the small amount of turbulence present in the test tower tube. At lower left is the PSF with 0.8" simulated turbulence applied. At lower right is the result with the AO correction off, showing the seeing limited PSF in the same simulated atmosphere. Note that S values quoted in the figure do not have a fitting error correction applied.

# 2.3 Tower Test Results

Over the course of the Arcetri tower testing we took data in many different system configurations, including different magnitude guide stars and different VisAO filter selections. A typical experiment involved taking measurements without simulated turbulence to capture the small amount of turbulence present in the test tower tube, due to internal convection and tip/tilt from flexure caused by the outside wind. We then took an identically configured data set with the ASM simulating turbulence as described above. Finally we nearly always took seeing limited data. Figure 3 shows an example of results from such an experiment conducted on a bright star with the loop operating at 800Hz. There we compare the three measurements to a theoretical Airy pattern. Figure 4 compares the same experiment to the simulation based performance predictions made earlier,<sup>6</sup> and also shows the magnitude of the fitting error correction which we apply to form an on-sky performance prediction. See the paper by Close et. al., in these proceedings, for additional tower test results.<sup>4</sup>

# **3. REAL TIME FRAME SELECTION**

Here we describe our implementation of RTFS. This technique, essentially a form of Lucky imaging, requires us to identify moments of bad AO correction and reject them by closing a fast shutter. In previous work we provided an analytical comparison of the trade-offs between resolution and efficiency one needs to consider with



Figure 4. A comparison of predicted performance and our SDSS i' test tower results. The solid curves are from our previously reported simulations of MagAO performance.<sup>6</sup> The data points connected by a vertical line show the raw measured SDSS i' S from our results shown in Figure 3 and the value obtained after applying the correction for fitting error from Table 1. We also highlight the predicted value for an 8th magnitude guide star.

RTFS, and demonstrated the impact of these trade-offs using simulated data.<sup>6</sup> In the experiments reported here, we for the first time tested our RTFS system in closed-loop using the MagAO system in the test tower. To do this we monitored correction quality using WFS slopes which were used to reconstruct an estimate of S. If this estimate of S was below some threshold, the shutter was closed, and likewise opened when reconstructed S exceeded the threshold.

Below we formally describe the algorithm used to determine whether to open or close the shutter, discuss some calibration issues with reconstructing wavefronts with a Pyramid WFS (PWFS), discuss a few other implementation details, describe our experimental setup, and finally present results from our first closed-loop test of RTFS in the laboratory.

# 3.1 WFS Telemetry Based RTFS

RTFS uses a fast shutter to block moments of bad correction, causing only periods of high S to be recorded by the science camera. We previously developed a notation to describe a generic frame selection algorithm, including conventional Lucky imaging.<sup>6</sup> Here we adapt that algorithm and notation to the specific case of using only WFS telemetry to reconstruct S.

We record a slope vector at time  $t_i$  with *n* elements,  $\vec{X}(t_i)$ . The wavefront is reconstructed by multiplying the slope vector by the reconstructor matrix **R** (the same one in use in the main AO loop).

$$\vec{A}(t_i) = \mathbf{R}\vec{X}(t_i)$$

where  $\vec{A}(t_i)$  is the vector of reconstructed mode amplitudes at time  $t_i$ . The orthogonal KL modal basis is normalized such that each mode has unit variance, so we can calculate the wavefront variance by summing the amplitudes in quadrature

$$\sigma^2 = (4 \times 10^9)^2 \vec{A}(t_i) \cdot \vec{A}(t_i)$$

where the factor of 4 accounts for the double pass of the ASM in the test tower, and  $10^9$  converts to nanometers. We then calculate the reconstructed S using the extended Marechal approximation

$$S_{rec}(t_i) = e^{-\left(\frac{2\pi}{\lambda}\right)^2 \sigma^2}.$$

Next we apply an empirical calibration, using two parameters.

$$S_{cal}(t_i) = aS_{rec}(t_i) + b.$$

See below for further discussion of this calibration step and the interpretation of these parameters.

Finally, we apply a finite impulse response (FIR) low-pass filter of order N to prevent high frequencies from over-driving the shutter.

$$S_{filt}(t_i) = \sum_{k=0}^{k=N} f_k S_{cal}(t_{i-k})$$

where the  $f_k$  are the filter coefficients.

We use the reconstructed filtered S to classify each moment as a good or bad according to whether it is above or below a threshold  $S_T$ .

$$G = \begin{cases} 0 \text{ if } S_{filt}(t_i) < S_T \\ 1 \text{ if } S_{filt}(t_i) \ge S_T. \end{cases}$$

$$\tag{2}$$

The value of G represents the decision whether to open (G = 1) or close (G = 0) the shutter. For the experiments reported here we did not employ any of the prediction strategies discussed in previous work.<sup>2,6</sup>

#### 3.2 Reconstructor Calibration

Due to fitting error, which is caused by the finite number of spatial frequencies sampled by the WFS, and noncommon path (NCP) errors (for VisAO primarily caused by one beam-splitter) we expect our reconstructed S to under-predict true focal plane S. Appealing to the extended Marechal approximation, we expect the combined fitting and NCP errors to be a multiplicative correction to  $S_{rec}$ :

$$S = e^{(-\sigma_{fit}^2 - \sigma_{NCP}^2)} S_{rec}$$

In our tests so far, we have found that this simple assumption is insufficient to fully describe the S time series. The logical way to proceed using the above relation is to set the combined fitting and NCP errors to match the mean  $S_{rec}$  to the mean  $S_{foc}$  measured in the CCD 47 focal plane. However, this technique underestimates the peak-to-valley variability of the true S significantly, which is unacceptable for frame-selection. To match both mean and variance, we use a simple two parameter model

$$S_{cal} = aS_{rec} + b$$

where we estimate the parameters by

$$a = \frac{\text{stdev}(S_{foc})}{\text{stdev}(S_{rec})}$$
$$b = \text{mean}(S_{rec})a - \text{mean}(S_{foc}).$$

We don't use a fitting procedure as the sampling frequencies are different between  $S_{foc}$  and  $S_{rec}$ .  $S_{foc}$  was measured in 32x32 pixel frames taken at 42fps on the CCD 47. The frames were averaged without shifting, and the ratio of this long exposure peak height to the mean short exposure peak height provided an estimate of S loss due to image motion. We then calibrated  $S_{foc}$  so that the long exposure peak height is equal to the S measured in a long exposure full frame image, and then the mean short exposure  $S_{foc}$  was set to match the image-motion corrected mean  $S_{foc}$ . This process avoids the difficulties of accurately normalizing S measurements in small format images. The results of this calibrated reconstructed S.

The parameter a retains a simple interpretation as

$$-\ln(a) = \sigma_{fit}^2 + \sigma_{NCP}^2.$$

Interpreting the parameter b is more challenging. We believe it is related to a phenomenon which has been dubbed the "optical loop gain", whereby the sensitivity of the PWFS depends on the size of the spot on the pyramid tip and hence on the instantaneous quality of correction. That is, the calibration of  $S_{rec}$  depends on the value of S itself. Work is ongoing to understand and calibrate the effect of this optical loop gain. We also note that performing these calibrations in terms of WFE instead of S requires a similar parameter.



Figure 5. Reconstructed  $S_{rec}$  compared to  $S_{foc}$  measured in the VisAO focal plane, for our SDSS i' bandpass.



Figure 6. VisAO Hardware. At left we show the as-built pyramid wavefront sensor and VisAO camera, after it was re-integrated at LCO in May 2012. At right is our Unibilitz VS-25 shutter, which is used to reject moments of bad seeing.

# 3.3 Implementation

Here we briefly discuss a few details of our current implementation of RTFS. In Figure 6 we show the as-built VisAO camera after re-integration at LCO and the Uniblitz VS-25 shutter.



To AO workstation

Figure 7. Schematic showing the flow of data in our system. The blue lines show the path of visible wavelength light from the telescope. A selectable beam-splitter sends light to both the PWFS (left) and the VisAO camera (right). The red lines show the flow of data. The CCD 39 records the pyramid pupil images, which are processed by the BCU 39 slope computer. The slopes are sent to the ASM via a custom fast fiber link. A secondary output, for telemetry monitoring, sends the slopes over standard ethernet which we transparently intercept for use in RTFS. From there reconstruction occurs on an off the shelf GPU, which produces a real-time measure of Strehl ratio. This is used to determine whether to open or close the shutter.

# 3.3.1 Telemetry

Our system does not have a dedicated real-time telemetry system built in. For RTFS slopes are taken from an auxiliary output of the slope computer (Microgate BCU 39) so as to leave the main AO loop unaltered. This auxiliary output, a UDP broadcast over standard ethernet, is normally used to send WFS frames to the AO operator's workstation. To capture the slope output in near real-time without requiring any changes to the AO control software, we use an ethernet bridge. A bridge consists of two ethernet adapters, and a kernel software module which passes packets from one adapter to the other so as to be transparent to other devices on the network but allowing one to capture packets. We thus can transparently intercept slope computer diagnostic frames and extract the slope vector. The slope vector is then used to reconstruct the wavefront modal amplitudes as described above. See the schematic in Figure 7 which outlines how data flows from the WFS detector, through the bridge, to the GPU (discussed next), and finally becomes a command to the shutter.

# 3.3.2 GPU Based Reconstruction

We have implemented the matrix-vector multiplication step on a GPU. Our current device is an NVIDIA GeForce GTX 465, which has 352 cores. We used the NVIDIA CUDA<sup>\*</sup> basic linear algebra (BLAS) library, cuBLAS, to perform the multiplication with the SGEMV routine. For comparison, we also implemented the reconstruction on the CPU using the automatically tuned linear algebra software (ATLAS) package,<sup>9</sup> which was compiled from source to fully optimize for speed. On the GPU, time to reconstruct a single frame averages 206 msec, including slope transfer overhead. On the CPU with ATLAS the average time was 314 msec, so using the GPU results in a 34% improvement in reconstruction speed.

# 3.3.3 Digital Filter Design

After reconstruction the Strehl time series is low-pass filtered using a finite impulse response (FIR) filter. An FIR is used because of its simplicity and guaranteed stability. Filters appropriate for each loop speed (and telemetry rate) were designed in Matlab using the filter design and analysis tool, fdatool. A major concern is keeping the phase lag low to prevent inaccuracy due to filter delay. Good results have been obtained with a pass frequency of 10 Hz and a stop frequency of 50Hz, and 20 dB attenuation, using the generalized equiripple minimum order technique.

<sup>\*</sup>http://www.nvidia.com/object/cuda\_home\_new.html



Figure 8. Short exposure S statistics.

### 3.4 Experimental Setup

On bright guide stars the MagAO system performs very well, producing high and stable S down to at least  $\lambda \sim 0.7 \mu m$ . In this regime, RTFS will be counterproductive due to the small variation in S, and the relatively small improvement in signal-to-noise ratio for any corresponding reduction in total exposure time.<sup>6</sup> We therefore expect RTFS to be most useful on fainter stars, where the MagAO system no longer produces such good correction. Due to the way guide star magnitude is controlled in the test tower, both with a variable brightness lamp and by changing beam-splitters, it was challenging to create a fully realistic faint guide star simulation for these tests which also allowed enough light to reach the CCD 47 for accurate measurement of short exposure S. To compensate, we instead used a 9.4 mag guide star but ran the loop at 500 Hz and intentionally set gains to produce a large amount of variability in S. As usual, 0.8" turbulence was simulated, with a 15 m/s wind. Though artificial, this setup provided a good test of our RTFS architecture due to the large temporal variability of S while allowing accurate short exposure measurements, and produced the time series shown in Figure 5.

The statistics of our S time series are shown in Figure 8. Of note, there is negative skewness in the S probability density function (PDF). As other authors have demonstrated, we actually expect positive skewness when the mean value of S is so low.<sup>10</sup> This discrepancy is likely due to the artificiality of our test setup.

### 3.5 Results

Using the loop setup described above, we conducted a series of experiments in the Arcetri test tower to test our RTFS architecture. We set thresholds at the following selection fractions: 100%, 95%, 90%, 75%, 50%, 25%, 10%, and 5%. For example, the 5% threshold means we are attempting to select the best 5% of S. We use the term selection fraction to make it clear that we mean the amount of time the shutter will be open if it is following S with complete accuracy, or in other words the telescope duty cycle.

Once a threshold was selected, the RTFS system was activated in closed-loop while taking data on the CCD 47 in the SDSS i' filter. To avoid saturation, we took short exposures which were then summed (after dark subtraction) without shifting to form a long exposure image. Figure 9 shows the resultant images. As we selected higher and higher thresholds, there was a clear improvement in the resultant S, and FWHM. Figure 10 plots the improvement in these values vs. threshold.

We measured the flux in each long exposure image, and compared the result to the flux in the 100% selection fraction image. This provides a measure of the net telescope duty cycle, or shutter open time, for each threshold. This also serves as a quick-look proxy for total accuracy of our RTFS system, based on how closely our system follows the y=x line. The system tends to under-select at the higher S thresholds. The shutter has an actuation delay of a few msec, and we enforced a re-actuation time of 35 msec in software as a mechanical safety measure. These delays should cause the system to miss many peaks which occur close together, though low pass filtering mitigates this to some extent.



Selected Fraction: 100% Strehl = 16.3% FWHM = 4.18 pix (30.9 mas)



Selected Fraction: 95% Strehl = 16.4% FWHM = 4.16 pix (30.8 mas)



Selected Fraction: 90% Strehl = 16.4% FWHM = 4.19 pix (31.0 mas)



Selected Fraction: 75% Strehl = 18.9% FWHM = 4.03 pix (29.8 mas)



Selected Fraction: 50% Strehl = 20.1% FWHM = 3.94 pix (29.2 mas)



Selected Fraction: 25% Strehl = 22.1% FWHM = 3.85 pix (28.5 mas)



Selected Fraction: 10% Strehl = 26.0% FWHM = 3.69 pix (27.3 mas) Selected Fraction: 5% Strehl = 20.1% FWHM = 3.77 pix (27.9 mas)



Airy Pattern Strehl = 100% FWHM = 3.28 pix (24.3 mas)

Figure 9. Long exposure images obtained with RTFS. Both long exposure S and FWHM improved as the selection fraction is changed to higher values of S.



Figure 10. At left we plot achieved S for various selection thresholds, and at right we plot FWHM. The selection thresholds correspond to the S distribution, that is a 10% threshold means that the shutter opens only when S is in the best 10%. The achieved S was lower when at the 5% threshold, compared to the 10% threshold. The shutter has a finite actuation time of about 10 msec and this drop in S at the highest threshold is possibly due to this delay compared to the width of peaks of S above the threshold. If the shutter actuates too slowly to catch the highest S, it will instead be open during lower S periods.

### 4. CONCLUSION

The 585 actuator pyramid WFS based MagAO system will see first light on the 6.5 m Magellan Clay telescope in November, 2012. At one of the world's best astronomical sites, MagAO will routinely provide some of the highest S images ever obtained on-sky. With its fine actuator pitch, the system will allow us to work at challenging visible wavelengths for the first time on a large aperture telescope.

Having just concluded a year long period of integration and testing, the results of which were briefly presented here, we believe the system will live up to its potential. In realistic laboratory testing, we achieved corrected SDSS i' S as high as 37% in 0.8" simulated seeing - a relatively poor night at Las Campanas Observatory.<sup>11</sup> In addition to many exciting VisAO science cases, the Clio2 camera<sup>12,13</sup> will be used for imaging in the near and



Figure 11. Duty cycle for the selection thresholds. Duty cycle was measured photometrically, and serves as a proxy for accuracy. A perfect system would follow the y=x line. The system is less accurate, and tends to under-select, at the most selective thresholds. This is likely due to the shutter actuation delay of 10 msec, and a software safety re-actuation time of 35 msec. These delays cause the system to miss many peaks which occur close together. Low pass filtering mitigates this to some extent.

thermal infrared (H-M bands). Clio2 will take advantage of the extremely high S that the system will provide at these longer wavelengths.

Our novel Lucky imaging technique, RTFS, has been demonstrated in closed-loop for the first time. Using WFS telemetry, we were able to reconstruct S in real time and use this knowledge to select moments of good AO correction using a mechanical shutter. This allowed us to improve S from 16% to 26% under slightly artificial laboratory conditions. There is room for further improvement in our system, as higher accuracy would permit more efficient use of telescope time.

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