Extreme Adaptive optics progress report from November run

For: New Development Group

Date: 12/01/2014

This document serves as a low-level/detailed overview of the highly successful results that came from the SCExAO Instrument during the November run. It will mainly focus on the wavefront sensor used to obtain extreme AO, i.e. the pyramid wavefront sensor (PyWFS).

Wavefront sensor goal:

The aim of the PyWFS as part of the extreme AO system, is to boost the performance given by AO188. In this regard the PyWFS is expected to increase the Strehl from 40% after AO188 (in good seeing) to >90% in the H-band on a regular basis. This will enable high performance coronagraphic imaging, very close to the host star, optimizing faint companions/disk detection.

How do we achieve high Strehl?

AO188 already corrects ~188 modes at a speed of 1 kHz (typical Strehl of 20-40% in H-band). To improve on this the PyWFS needs to correct more modes and/or operate at a faster pace with a better measurement sensitivity. With the 2000 element deformable mirror and the new OCAM^{2}k, SCExAO is capable of correcting up to 2200 modes at a speed of 3.5 kHz (on bright targets).

Hardware upgrades:

Prior to the November run, the PyWFS got a number of hardware upgrades, which we determined were limiting the performance. These included:

- A photon counting EMCCD (OCAM^{2}k – FirstLight Imaging): binned frame rate = 3.5 kHz, negligible latency, 0.3 e^- read-out noise at a gain of 600×.
- A fast tip/tilt mount (PI) to enable pyramid modulation on SCExAO: can be run up to 10 kHz but amplitude of modulation drops off at higher frequency.
- A pyramid optic: The pyramid optic was leant to us by MagAO (Laird Close and Jared Males). The optic consists of two pyramid optics back-to-back as shown in Figure 1. The apex and vertices at the interface of the sides of the pyramid are extremely precise (less than 5 µm wide), which minimizes the affect of diffraction (which in turn optimizes the use of photons for wavefront sensing).

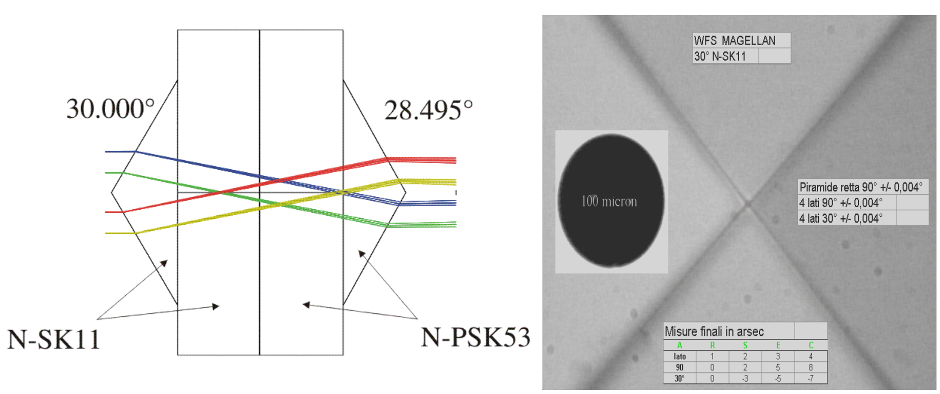

Figure 1: Pyramid optic used on November run.

The pyramid optic was needed as we determined micro-lenses were not ideal when modulating. Small micro-lenses are cheap, provide low diffraction due to their small inter—lens spaces (see Figure 2) and simplify the optical design since the prism effect and reimaging lenses are already combined in only one optic.

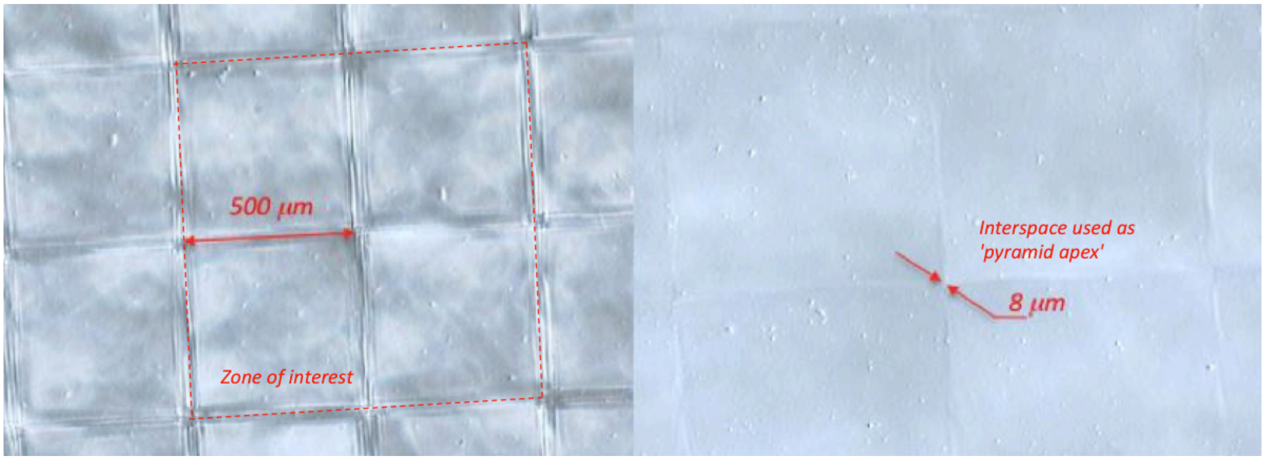

Figure 2: SCExAO first Pyramid (SUSS micro-lens array).

Unfortunately small mirco-lenses limit the filed-of-view (limited step between two lenses), which meant it was not possible to modulate with them. With a non-negligible radius of modulation, the beam tends to go out of the zone of interest (i.e. the area of four neighboring lenses which form the pyramid) (see Figure 3).

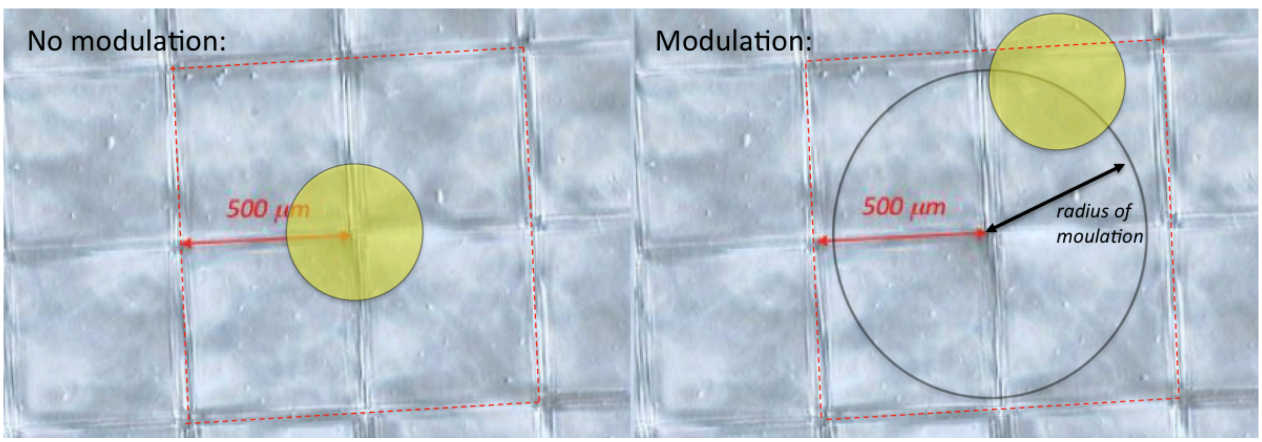

Figure 3: Limitation of the micro-lenses array when modulating

Larger lenses were tested (September 2014) which allowed the use of a larger modulation radius but the inter-lens quality was poor and led to very high diffraction effects.

Figure 4 shows the new hardware installed on the top bench of SCExAO using the glass pyramid. In addition to the optical hardware control electronics were needed to control the modulation of the tip/tilt mirror and synchronize it to the EMCCD. We discovered on the September run that synchronization of the camera and tip/tilt was very important and the loop would not work without it. The control electronics work as follows:

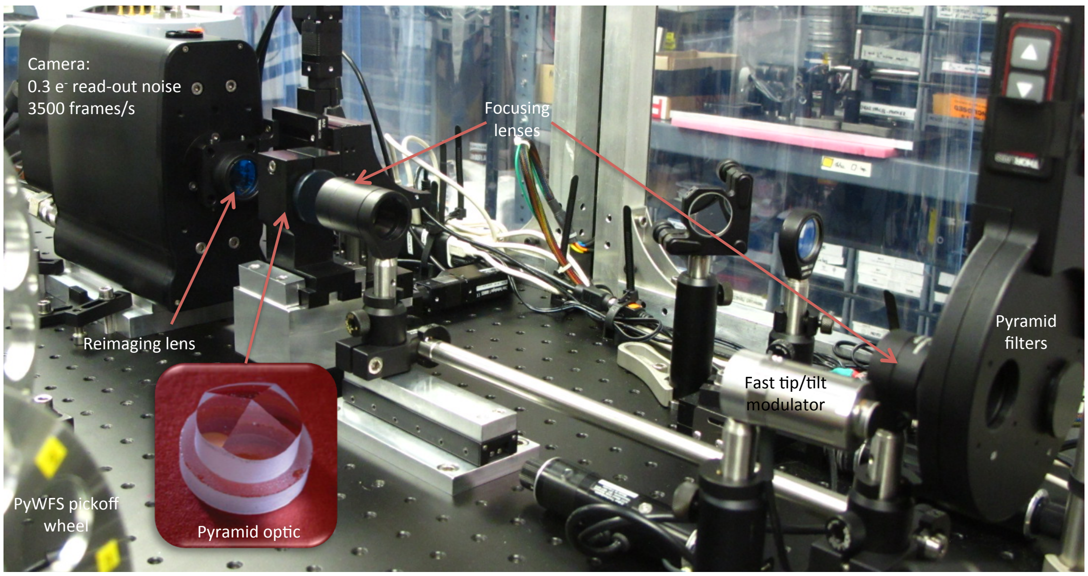

Figure 4: New pyramid wavefront sensor layout

Purpose 1: Modulating the tip/tilt mount

- The waveform generator is used to generate two low frequency (500-3500Hz) sine waves. The waves are phase shifted by 90° with respect to one another and are used to drive one axis of the tip/tilt mount respectively. In this way the tip/tilt mirror moves in a circular route on each oscillation of the waves.
- Since the maximum voltage from the sine waves is +/-1V it needs to be amplified. It is therefore passed through the Bose stereo amplifier (previously used in AO36) until it is amplified by a factor of ~4.
- As the high voltage driver for the tip/tilt mount can only be driven with an input between -2 and 12 V, then the -4-+4V sine waves must first be DC offset into the middle of the range. This is done by adding +5V DC to the sine waves by a summer circuit (an operational amplifier circuit). For this purpose two of the outputs of the analog output card were used.
- The DC offset, amplified sine wave signals are then routed to the high voltage driver for the piezo in the tip/tilt.

Purpose 2: Synchronization

- To trigger the cameras exposure time and make sure its synchronized with the revolution of the tip/tilt modulator, the sine wave signal needed to be converted to TTL and then LVDS.
- The signal from one of the sine waves was injected into a comparator circuit. Initially another output of the analog output card was used to drive the comparator (i.e. the DC level at which the comparator switches to generate a TTL signal). However, we learnt at the summit that the analog output card unfortunately did not have a high frequency filtered output (i.e. it was noisy). For this reason it we used remotely controllable DC power supply. Low pass filter circuits will be added by January so it can be once again be used. A trace of the original sine wave and the TTL pulse train created are shown in Figure 5.
- The output pulse train was a 5V TTL signal synchronized with the sine wave. To accommodate the LVDS signal required by the OCAM, the TTL signal was injected into a LVDS convertor chip before being sent to the camera.

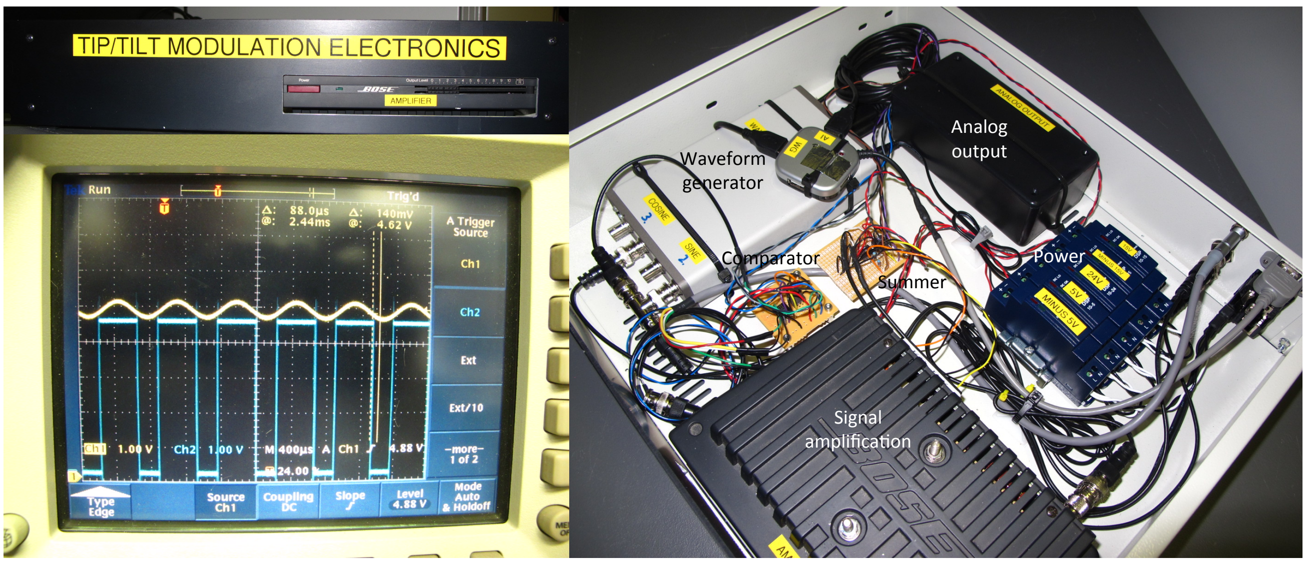

Figure 5: Tip/tilt control electronics. Image of the wavefrom trace on the oscilloscope.

Run format:

The November run consisted of 2 engineering nights (8 and 9th), 2 IfA science nights (10 and 11th) and 1 staff night (12th). The first 4 nights were clear and the seeing was favorable (0.6-1”). Only the 5th night was fully clouded out (bar the first 45 minutes).

In the days leading up to the engineering nights considerable effort was put into

- Preparing the new hardware: aligning optics, getting camera to integrate with the SCExAO computer, fixing issues with the control electronics, calibrating the modulation amplitude.
- Upgrading the AO loop code/debugging and
- Testing the system.

What was tested:

Here is breakdown of what was tested:

- Limited success on the 8th and 9th on-sky. Determined that our calibration technique was not optimized and hence not allowing the loop to be closed.
- On the 10th (first science night), the loop was closed on the first 5 Zernike modes (low order modes, tip/tilt, right astigmatism, 45° astigmatism and focus). This loop was stable and stabilized the PSF, which was ideal for the long exposures taken by the PI with a coronagraph and HiCAIO. It ran successfully all night.
- On the 11th (second science night), the loop was closed on 5 first Zernike modes and on 9 additional Fourier modes. Again it ran all night long showing some improvement to the PSF. In the final 30 minutes, we closed the loop on 120 modes (Fourier and Zernike). Loop converged and stayed stable but without offering much wavefront error improvement.
- On the 12th, a lot of engineering tests were done off-sky with the internal calibration source and the turbulence simulator because the weather was bad. We closed the loop on 5-1030 modes with and without modulation on a realistic wavefront error expected downstream of AO188.!

What we learnt about calibration?:

Quality and stability of the response matrices are the key element for successful operation. Over the course of the 5 night run and especially during the engineering nights, we improved our understanding of the new pyramid behavior on SCExAO. This experience also permits us to identify issues and optimize the different routines for the AO loop control (best protocol to collect sensitive and stable response matrices and construct control matrices).

The following list summarizes the major improvements we implemented that led to the successful results presented below.

- *Compensating for low response amplitude at low spatial frequencies: Variable optical gain*
  As expected, the modulated pyramid wavefront sensor has a different sensitivity depending on the calibrated modes (sensitivity depends on calibrated spatial frequency). For this reason the modes with the weakest response are rejected automatically when the control matrix is formed (rejection of the smallest singular values during the SVD). This was causing instabilities in the loop operation initially especially due to the main rejection of low spatial frequency modes. To solve that problem a variable gain for the weaker modes has been implemented in the loop control to keep them in the modal reconstruction.

- *Calibrating modulation amplitude*: It was discovered that the response matrices collected before the 8th and 9th observing nights were done using a large radius of modulation (tip/tilt mirror amplitude too high). We determined we were modulating the mirror by 9 λ/D. This amplitude made the response matrix very insensitive to tip/tilt, the key modes to correct (for the pyramid WFS, the tip-tilt sensitivity is directly proportional to the radius of modulation). With an accurate measurement of the radius of modulation vs voltage applied on the tip/tilt mount, we successfully reduced the amplitude to 1.7 λ/D which is very similar to other pyramid WFS systems such as MagAO.

- *Keeping probe amplitudes small to stay in linearity range (amplitude of the mode applied to the DM when calibrating the RM)*: Again it was determined that using a large probe amplitude to construct the response matrix limited performance. This was because a large probe amplitude modulated the image to the point where some parts of the image were saturated or in the noise floor driving a nonlinear response. This point still needs further investigation (pyramid linearity and saturation domain analysis) and is also linked to the amplitude applied to flatten the DM (see next paragraph below). Therefore, the probe amplitude was reduced while collecting response matrices for the remainder of the run.

- *Maintaining a flat illumination in the pupil images*: We determined it was extremely important to have a flat illumination across the pupil images in the PyWFS prior to collecting a response matrix (note a flat illumination on the PyWFS corresponds to a flat wavefront). This is because if it is not flat and some parts of the pupil are darker, then a probe mode can drive the signal in that portion of the pupil low enough that the response becomes nonlinear. In other words it is important for the signal in the pupil on the camera to stay in the middle of the range for the camera. For this a loop was written which iterates and applies Zernike modes until the illumination as seen by the PyWFS is flat. This helped tremendously.

- *Masking out edges for increased stability*: We discovered that pixels around the edges of the spider were giving anomalous values. This was causing phase discontinuities (piston error) between adjacent segments of the pupil (on either side of the spiders). This could come from a potential mismatching between our internal spider used for RM acquisition off-sky and Subaru telescope pupil (investigation on going). The temporary solution was to apply masks (see Figure 6-b) to the data that basically ignored any pixel values around the spiders and secondary. This worked very well and allowed the loop to close on a higher number of modes.

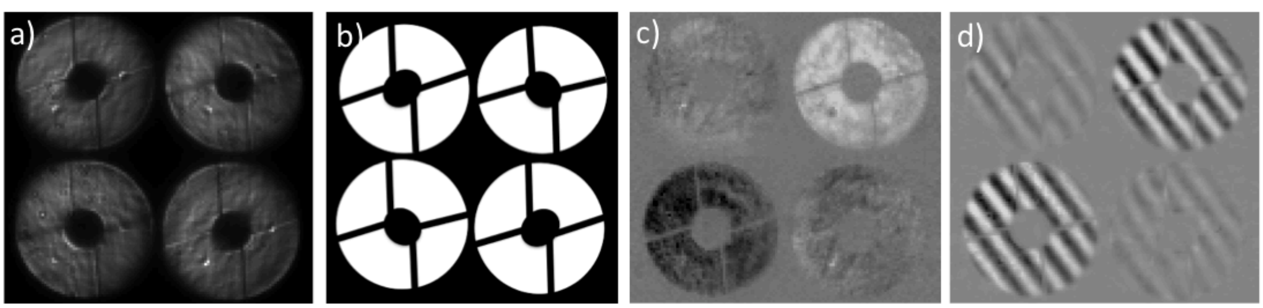

Figure 6: PWFS masking – a) reference image when modulating, b) applied numerical mask when acquiring the response matrix, c) tip saved in the RM when applying the mask, d) same as before with a high spatial frequency (Fourier mode).

Results:

On-sky

- Although the loop was closed on-sky on night 3 and 4, and was very stable, it offered very minor improvements to the PSF quality. This is because the loop was only correcting up to the lowest 14 modes, which are already corrected by AO188. In addition, the loop ran only marginally faster than the 1 kHz speed of AO188. To see larger improvements the PyWFS needs to run faster and with more modes. Note that calibration techniques 1-4 listed above were applied on these two nights and in fact made it possible to even close the loop on this limited number of modes. We attempted to close the loop with modulation on 130 modes as well. It worked but at very low gain due to the piston error between pupil segments. However the loop ran for 1 hr in this regime. Calibration technique 5 was not applied until the final night. All tests on night 3 were done in a 40 nm bandpass at 850 nm minimizing the chromatic aberrations on the WFS response. On night 4, light from 800-940 nm was used.

Internal source and turbulence simulator:

SCExAO has the ability to generate turbulence internally for testing purposes. It is possible to choose the windspeed and the amplitude of the wavefront error. For testing purposes, the PyWFS was tested with 300 nm RMS wavefront error and a windspeed of 5 m/s. Note 300 nm is larger than what we would expect to come from AO188 post correction (i.e. it is equivalent to bad correction).

- The loop was closed on 14, 400 and 830 modes during the course of the night with modulation (1.7 λ/D). The loop speed was set to 1 kHz.
- The loop was stable for all 3 sets of modes (Zernike, Fourier and Zernike+Fourier). However, one small timing bug was found which would occasionally break the loop temporarily. This has been mostly fixed during the last observation night and will be solved before January.
- Figure 7 shows the Strehl ratio in the open and closed-loop regime when the loop was closed on 830 modes. Its clear to see that when the loop is closed the Strehl improves from 23% up to 95% on average (a perfect PSF). *This is important because this demonstrates that the PyWFS can indeed start with a Strehl of the level delivered by AO188 and take it to above 90% as required!* Please see the 2 videos attached to this report for the live images of the PSF in the open loop and closed loop regime (modulated PWFS). From Marechal's approximation (inset in the figure below) we can predict to see a Strehl of 22.7% in the H-band for 300 nm wavefront error which perfectly agrees with what we measured. We can further use Marechal's approximation to determine the residual wavefront error after correction. A Strehl of 94.4% gives a 58 nm residual wavefront error post correction. At the sensing wavelength of 850 nm this corresponds to λ/15 wavefront error and λ/27 at the coronagraphic wavelength.

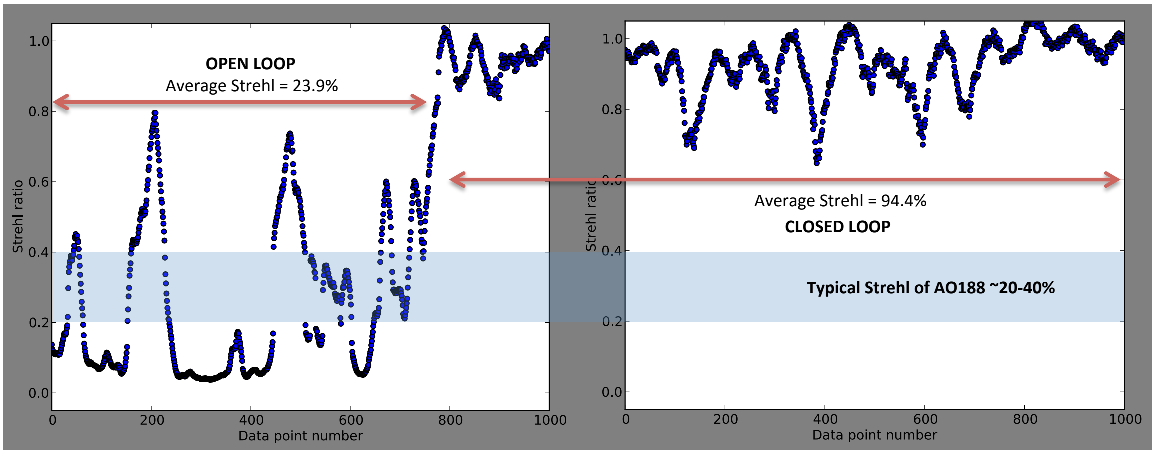

Figure 7: Strehl ratio determined from internal science camera images while the PyWFS loop was open and closed.

- The loop was also closed on 1030 modes without modulation, which is an important improvement of the pyramid use from Subaru telescope AO scientists. This is another mode the PyWFS can use when high precision correction and sensitive measurements is required (especially for coronagraphy purpose).
  The turbulence needed to be reduced to 60 nm due to the limited range of the sensor in this mode. Nonetheless the loop was successfully closed at 1.5 kHz, on 1030 modes and the speckles were held very static!
- All internal tests were done with light from 800-940 nm. The effects of running in such a broadband are not understood yet but on-sky it allowed the sensor to operate on targets between 8 and 10 magnitudes. Chromaticity is an important aspect that needs to be investigated.

Summary:

What was demonstrated?

- All hardware works as expected and the PyWFS is functioning well.
- Many small calibration and frame preparation tricks/techniques were discovered on this run, which is very important for running the sensor properly and getting the best performance.
- The AO loop software works, but there are still many upgrades to be administered.
- We demonstrated that the PyWFS can correct AO188 like PSF to >90% Strehl.
- We demonstrated that the PyWFS would operate non-modulated allowing for even greater sensitivity. We want to see if we can transition from modulated to non-modulated for the maximum possible performance.

What next?:

Before the January run we have a number of upgrades in mind:

- Upgrade the software for the AO loop to minimize set up time on-sky. This will allow more data acquisition on-sky
- Upgrade the AO loop software to run faster with fewer delays. Speed is essential if we are to improve on the performance of AO188.
- Improve calibration techniques for maximum sensitivity.
- Add more GPUs. GPUs are used for computations in the AO loop and we need to implement more to run things faster.
- Thoroughly characterize the new PyWFS with SCExAO (linearity domains etc …) before the January run. The system has stayed at the NasIR between the two runs so we have an ideal opportunity to do this.

Weather permitting, SCExAO will reach an important milestone in January!