Extreme Adaptive optics progress report from November run

For: Subaru Telescope Directorate

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

Highlight of key results:

- The PyWFS worked on-sky on a limited number of modes (up to 14) improving the PSF stability for the IfA PI's science observations. This no doubt improved the quality of his results.
- After many days of experimenting, a robust approach to operating the PyWFS was determined. The PyWFS loop was closed on the internal laser source (with realistic turbulence, similar to post AO188 values) on up to 1030 modes! HiCAIO images with the loop open and closed clearly show the improvement in the PSF/speckle quality. The Strehl ratio improved from 23% to >90% on average. This indicates that the PyWFS will be able to take a post AO188 quality PSF and improve the Strehl to ~90% as designed!

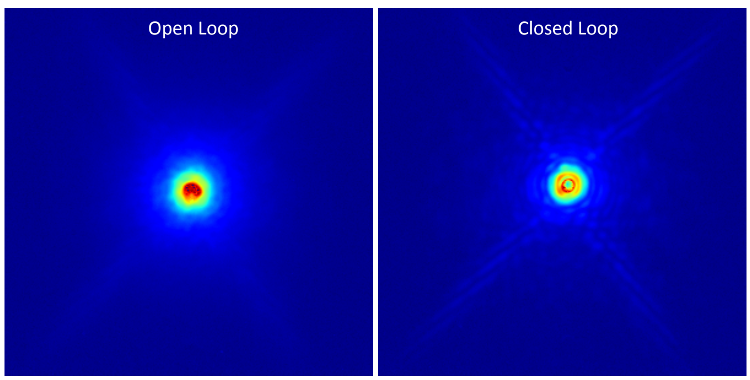

Figure 1: PSF images taken with HiCAIO with the PyWFS loop open and closed. Laser and turbulence simulator used.

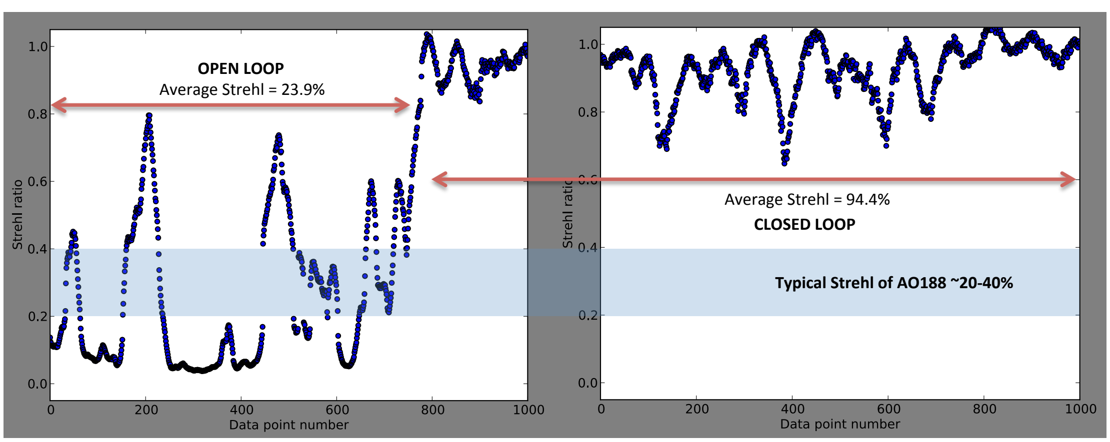

Figure 2: Strehl ratio from internal science camera images while the PyWFS loop was open and closed. The Open loop and Closed loop regime are clearly highlighted. For comparison the typical Strehl ratio achieved by AO188 is also displayed.

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 high-speed photon-counting camera (First Light Imaging OCAM2k EMCCD), SCExAO is capable of correcting up to 1600 modes at a speed of 3.5 kHz (on bright targets).

Hardware Upgrades:
We determined that the PyWFS's performance was being limited by hardware. Hence we undertook a number of hardware upgrades prior to the November run. These included a very sensitive camera (OCAM^{2}k – FirstLight Imaging) that can run at up to 3.5 kHz with negligible latency, a fast tip/tilt mount to modulate the pyramid response and a pyramid shaped optic. These are shown in the figure below.

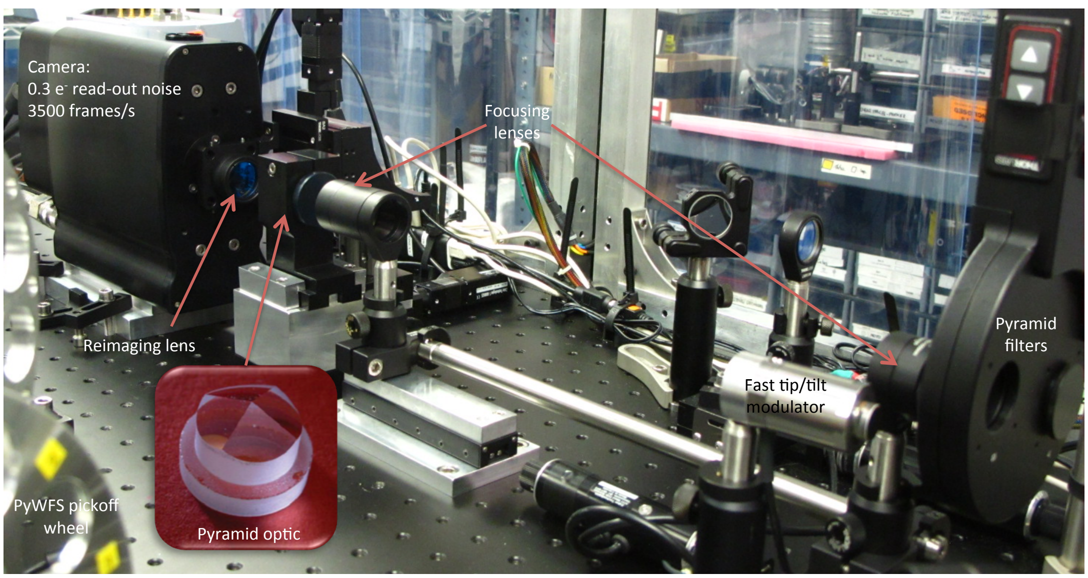

Figure 3: New pyramid wavefront sensor layout

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 etc.
- Upgrading the AO loop code/debugging and
- Testing the system.

What was tested:

Here is breakdown of what was tested:

- During daytime engineering prior to the run, we demonstrated closed loop operation with several hundred modes, and significant image quality improvement
- During first two nights (engineering, 8th and 9th), we were unable to reproduce results we had obtained in daytime engineering. We could only close the loop with a few modes. When attempting to close the loop with ~100's of modes, the loop was very unstable.
- On the 10th (first science night), the loop was closed on the first 5 modes (low order modes, tip/tilt, astig, astig 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 modes and 14 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. This worked but did not offer much improvement.
- On the 12th, there was thick cloud and hence we could not do any science on-sky. Hence we got a lot of engineering tests done off-sky with the internal calibration source and the turbulence simulator. We identified the reason for loop instability experienced on the 8th and 9th (small pupil misalignment) and implemented a software solution (ignore pupil edge pixels in wavefront control). This solution was successfully tested on the 12th. We closed the loop on up to 1030 modes with and without modulation! This test shows that SCExAO offers the highest image quality available on an 8-m class telescope, with unprecedented sensitivity and correction speed.

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.

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. The loop speed was set to 1 kHz.
- The loop was stable for all 3 sets of modes corrected. However, one small timing bug was found which would occasionally break the loop temporarily. This will be fixed before January.
- Figure 2 shows the Strehl ratio in the open and closed-loop regime when the loop was closed on 830 modes. It is clear to see that when the loop is closed experimentally, 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 ~90% as required!* NOTE: Since we create turbulence with our 2000 actuator DM, our tests using the internal calibration source do not include high spatial frequencies. The expected on-sky SR is therefore ~5% lower than the values we obtain with the internal calibration source. Please see the 2 videos attached to this report for the live images of the PSF in the open loop and closed loop regime.

- The loop was also closed on 1030 modes without modulation. The non-modulated pyramid can be used when the wavefront is already improved via modulation, and will minimize coronagraphic leaks, optimizing the detection of planets. Nonetheless the loop was successfully closed at 1.5 kHz, on 1030 modes and the speckles were held very static!

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 by using the internal source and turbulence at the Nasmyth IR platform (i.e. in realistic conditions).
- We demonstrated that the PyWFS would operate non-modulated allowing for even greater sensitivity.

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 PyWFS with SCExAO before the January run. The system is staying 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!