Status of the near-infrared wavefront sensor (NIRWFS) for AO3k

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I. AO3k: AN UPGRADE OF AO188 IN PHASES

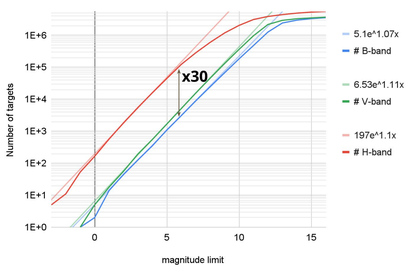
The facility adaptive optics of the Subaru Telescope AO188 (188-actuator DM, visible curvature WFS, 1 kHz) is in the process of getting upgraded to AO3k (ALPAO's 64x64 DM, ~3000 actuators in the pupil, NIRWFS @ 2 kHz, non-linear visible curvature WFS).

Phase Ia: Installation and on-sky testing of the NIR WFS (completed in 2023)

- The NIR WFS was added inside AO188 in the available space in May 2022 (open-loop testing) and May 2023 (closed-loop testing with 188 DM), compatible with SCExAO and IRCS.
- The pickoff is installed manually during the instrument exchange, in a motorized flip mount.
- The NIR WFS was successfully tested on-sky on both occasion. We successfully demonstrated operation in May 2022, and closed-loop performance in May 2023.

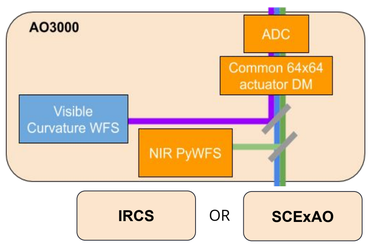
Phase Ib: Replacement of the original 188-actuator DM with ALPAO's 64x64 DM (completed May 2024)

- The new DM is a drop-in replacement of the original one.
- The new DM will not have a fast tip-tilt mount. Offloads will be sent to the telescope's M2.
- The original fast tip-tilt mount might move to another flat mirror inside AO188 in the future.

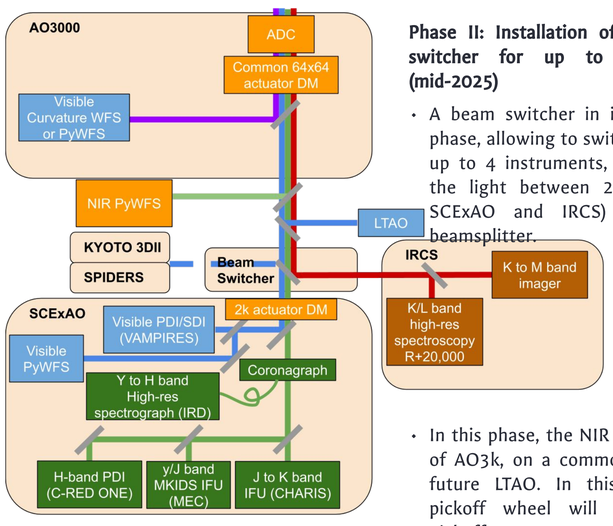


A NIR WFS can reach up to 30 times more targets, thanks to the number of stars brighter in IR than visible.

The sky coverage of AO3k will dramatically increase compared to AO188.



Top: Number of reachable targets by visible or IR magnitude limit. Right: AO3000 with the new ALPAO 64x64 DM, the new NIR WFS, and either IRCS or SCExAO behind. Bottom: phase II of the upgrade, including the NasIR beam switcher.



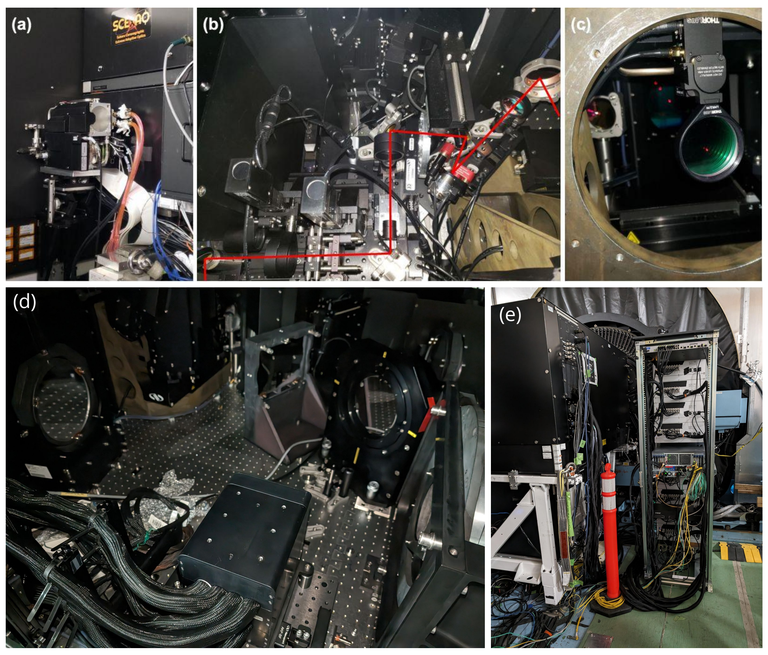
Phase II: Installation of a NasIR beam switcher for up to 4 instruments (mid-2025)

- A beam switcher in in the final design phase, allowing to switch rapidly between up to 4 instruments, and even splitting the light between 2 instruments (e.g. SCExAO and IRCS) with a dichroic beamsplitter.
- In this phase, the NIR WFS will move out of AO3k, on a common platform with a future LTAO. In this configuration, a pickoff wheel will host the various pickoffs.

II. AO3k - NIRWFS AVAILABLE FOR OPEN-USE

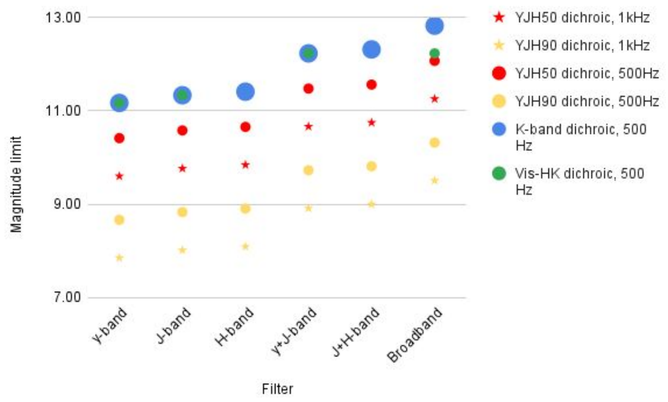
The NIRWFS v1 was installed in AO188 in 2023. We started Open-Use observations in S24A, with the original 188-actuator DM.

The new ALPAO 3000-actuator DM was installed in May 2024. With the new DM the NIRWFS provided ExAO-level of correction right away.



a) NIRWFS's C-RED ONE mounted outside the AO188 enclosure. (b) NIR WFS core optics integrated inside of AO188 for the first engineering night. (c) Dichroic pickoff in a flip mount at the output of AO188. (d) DM3k installed in AO188 (bottom) and modified TTM2 (top). (e) electronics rack for the DM3k installed next to AO188.

The NIR WFS has different dichroics that can be used to split the light between wavefront sensor and science, each dichroic has a range of magnitude limits that can be accessed, depending on the speed of the camera, the filter used, but also the spectrum of the guide star. Red stars have lower H-band magnitude limits than A-type stars for example.

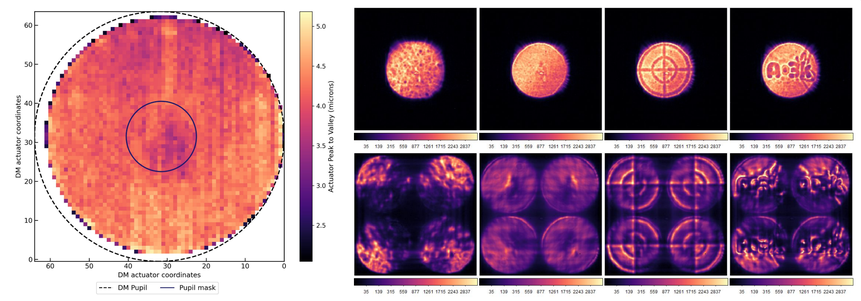


Magnitude limits for the various dichroic pickoffs available, for two loop speeds and for various band filters. These assume flat spectra for the guide stars, i.e. A-type stars.

III. AO3k - DM3k: 3000 ACTUATORS FOR PRECISE ATMOSPHERIC CORRECTION

Timeline for the delivery of the DM3k:

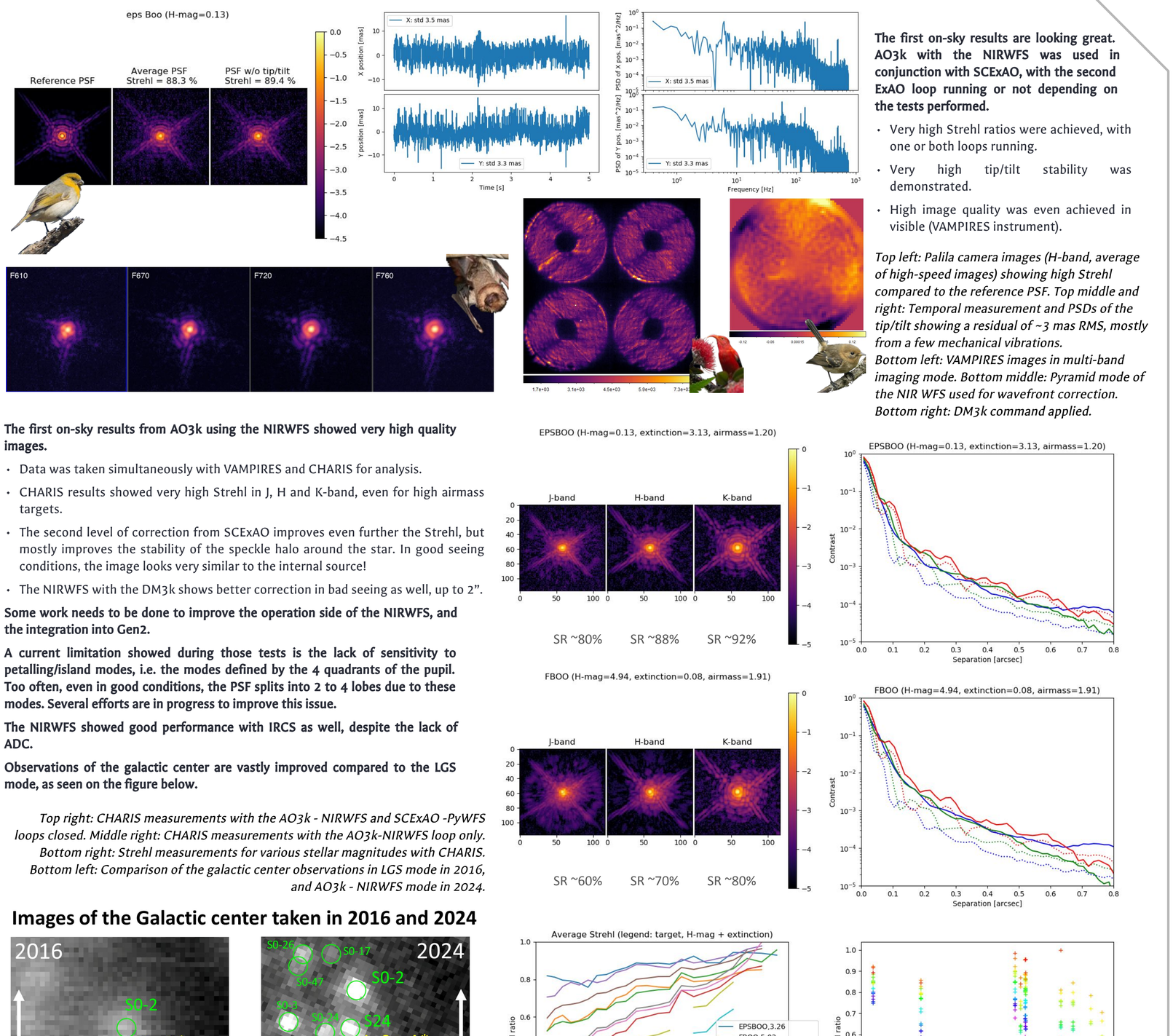
- Sept 2019 - Oct 2021: Order of the various DM subsystems
- Mar 2022: First DM received despite some known issues, due to the end of fiscal year.
- Summer 2022: First tests in the lab (Alicia Chun, University of Chicago). We found a lot of missing actuators and a rest shape that could not be flatten without using all the stroke.
- The DM was sent back to France in August 2022.
- 2022-2023: ALPAO team rebuilds the DM head and finds similar issues, leading them to change their process and quality control. Additional delays due to parts supply chain issues.
- mid-end 2023: The final DM is rebuilt and tested. Completed in December.
- Jan 25-31 2024: DM is received, plugged and controlled for the 1st time. We immediately notice a bad actuator... The tip of the iceberg.
- Jan 31 - Mar 1 2024: troubleshooting, back and forth with ALPAO to assess and plan repair (100+ emails, many tests). Repair scheduled.
- Mar 11 - 17 2024: ALPAO on site to repair the DM. DM opened twice.
- Mar 18: Start of characterizations (Blue, SCExAO intern & Maria Vincent, IfA PhD student). Some lazy actuators, but overall the DM is fixed!



The DM3k was characterized and flattened in Hilo, using a Zygo interferometer.

- A flatness of 31 nm RMS was achieved
- The amplitudes of the influence functions for each actuator (Difference between a positive and negative poke) was measured (figure top left)
- Linearity, temporal stability etc. were also measured before validating the installation of the DM3k.
- Figure top right shows the first DM3k tests after installation at the summit, using the NIRWFS.

IV. AO3k - NIRWFS: ON-SKY RESULTS



The first on-sky results are looking great. AO3k with the NIRWFS was used in conjunction with SCExAO, with the second ExAO loop running or not depending on the tests performed.

- Very high Strehl ratios were achieved, with one or both loops running.
- Very high tip/tilt stability was demonstrated.
- High image quality was even achieved in visible (VAMPIRES instrument).

Top left: Palila camera images (H-band, average of high-speed images) showing high Strehl compared to the reference PSF. Top middle and right: Temporal measurement and PSDs of the tip/tilt showing a residual of ~3 mas RMS, mostly from a few mechanical vibrations.
Bottom left: VAMPIRES images in multi-band imaging mode. Bottom middle: Pyramid mode of the NIR WFS used for wavefront correction. Bottom right: DM3k command applied.

The first on-sky results from AO3k using the NIRWFS showed very high quality images.

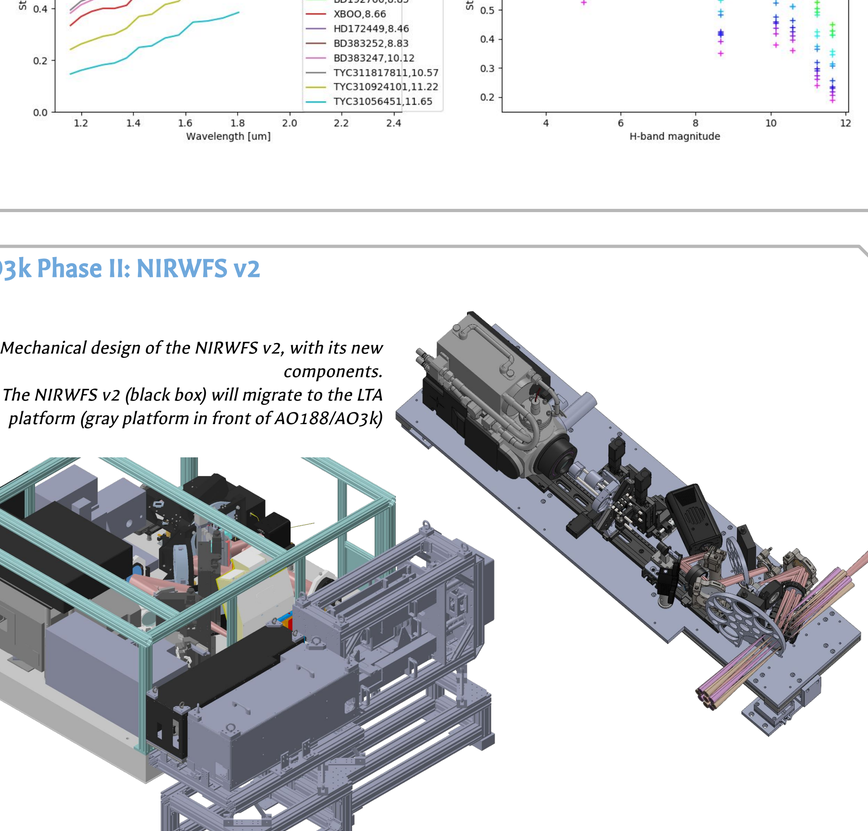
- Data was taken simultaneously with VAMPIRES and CHARIS for analysis.
- CHARIS results showed very high Strehl in J, H and K-band, even for high airmass targets.
- The second level of correction from SCExAO improves even further the Strehl, but mostly improves the stability of the speckle halo around the star. In good seeing conditions, the image looks very similar to the internal source!
- The NIRWFS with the DM3k shows better correction in bad seeing as well, up to 2".

Some work needs to be done to improve the operation side of the NIRWFS, and the integration into Gen2.

A current limitation showed during those tests is the lack of sensitivity to petalling/island modes, i.e. the modes defined by the 4 quadrants of the pupil. Too often, even in good conditions, the PSF splits into 2 to 4 lobes due to these modes. Several efforts are in progress to improve this issue.

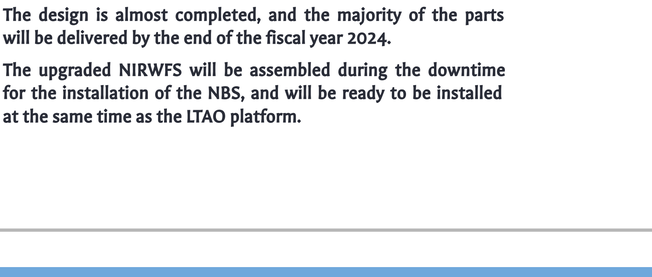
The NIRWFS showed good performance with IRCS as well, despite the lack of ADC.

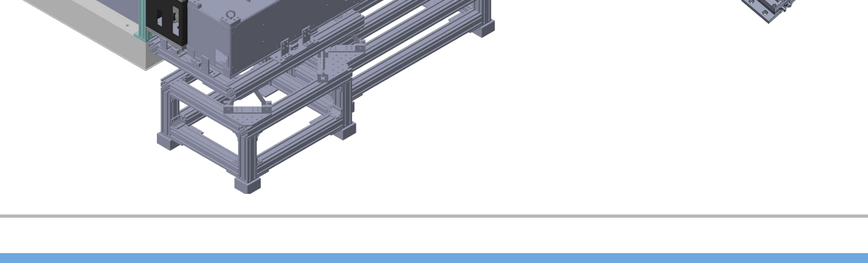
Observations of the galactic center are vastly improved compared to the LGS mode, as seen on the figure below.



Top right: CHARIS measurements with the AO3k - NIRWFS and SCExAO -PyWFS loops closed. Middle right: CHARIS measurements with the AO3k-NIRWFS loop only. Bottom right: Strehl measurements for various stellar magnitudes with CHARIS. Bottom left: Comparison of the galactic center observations in LGS mode in 2016, and AO3k - NIRWFS mode in 2024.

Images of the Galactic center taken in 2016 and 2024





V. AO3k Phase II: NIRWFS v2

Phase II of the AO3k / NasIR upgrade is happening mid 2025, with the addition of the Nasmyth Beam Switcher and the LTAO. In this phase, the NIRWFS will be upgraded and moved to the LTAO platform. The upgrade includes several additions:

- A dichroic pickoff wheel, with all the available pickoffs for an easy and automatic switch depending on the target.
- A field stop, to block stray light from other stars, especially for binaries and crowded fields. THis should improve the correction in these cases.
- A optical binning mode, where the pupils for the PyWFS modes are reduced by a factor 2, allowing to reach fainter targets, although with less corrected modes.
- An infrared acquisition camera, which should improve the overhead for the acquisition of the targets, especially for optically faint guide stars.

The design is almost completed, and the majority of the parts will be delivered by the end of the fiscal year 2024.

The upgraded NIRWFS will be assembled during the downtime for the installation of the NBS, and will be ready to be installed at the same time as the LTAO platform.

Right: Mechanical design of the NIRWFS v2, with its new components.
Bottom: The NIRWFS v2 (black box) will migrate to the LTA platform (gray platform in front of AO188/AO3k)