Updates on AO3k's new modules

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I. AO3k Polychromatic Calibration Source

AO188's calibration source AOCAL uses three laser diodes. One at 633 nm (red), one at 1550 nm (IR), one a 589 nm (sodium wavelength). It does not include a pupil mask, but has two wheels simulating atmospheric turbulence.

The upgrade of AO188 to AO3k includes:

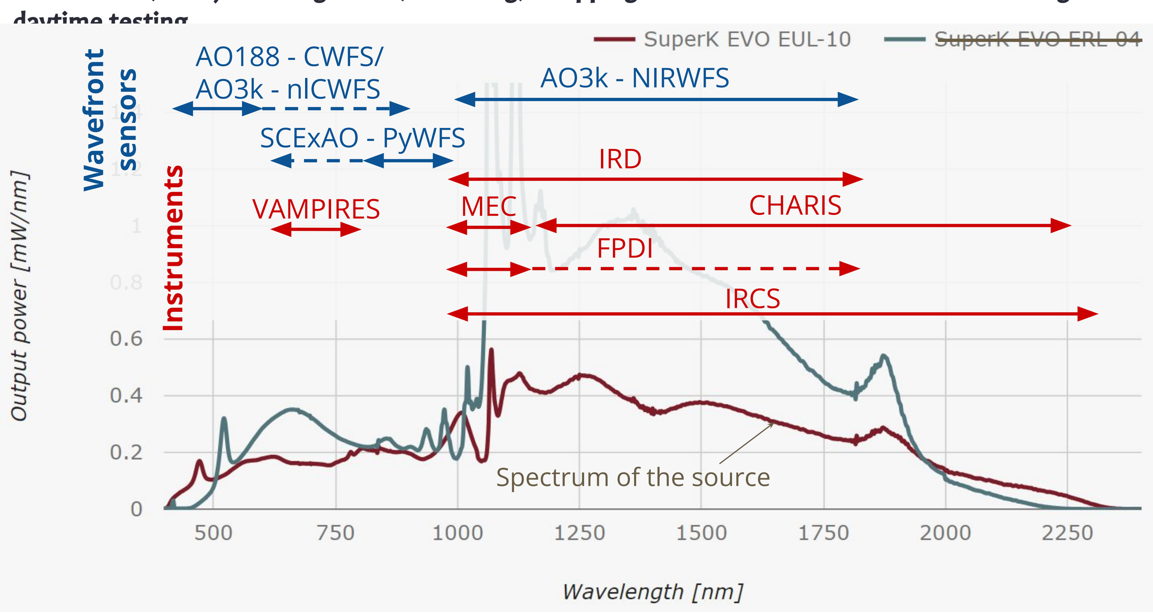
- new 3000-actuator deformable mirror (DM3k)
- new Near Infrared Wavefront Sensor (NIRWFS)
- new non-linear Curvature Wavefront Sensor (nlCWFS).

AO3k's performance is vastly superior to AO188, but it requires a precise calibration of its wavefront sensors.

A new source with the following characteristics is needed:

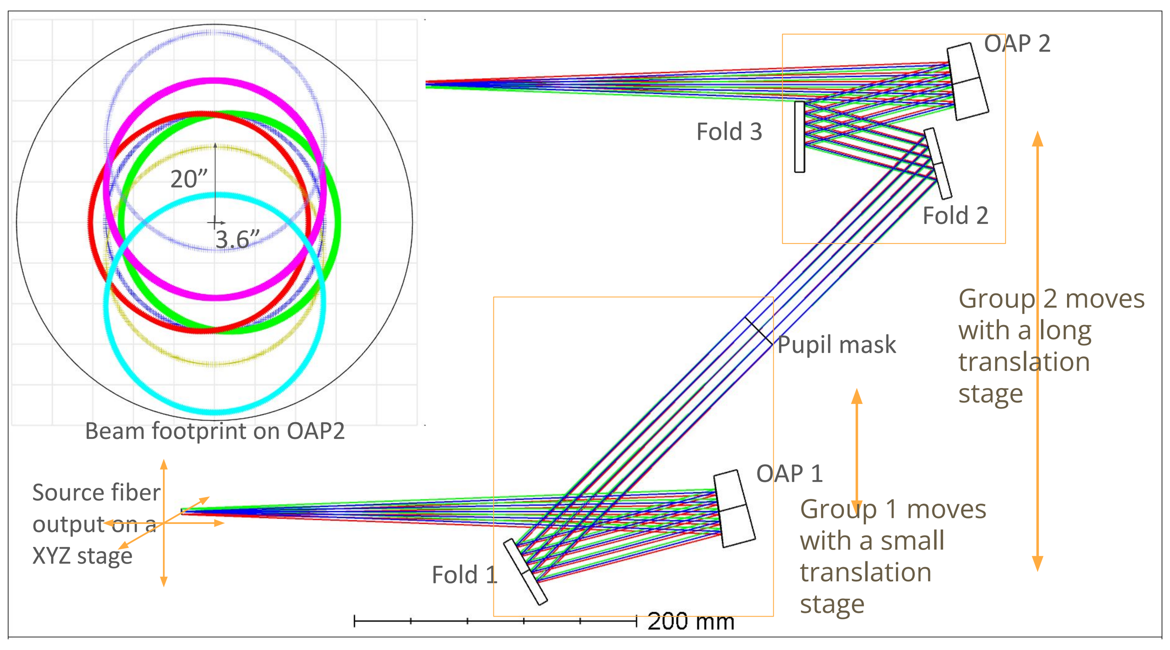
- Polychromatic instead of laser diodes, with the use of a supercontinuum laser (same as SCExAO's source). This will allow to test the polychromatic mode of the nlCWFS (dichroic beamsplitter used), and include chromatic effects in the calibration of the NIRWFS.
- A pupil mask simulating Subaru's pupil. The lack of pupil mask in the current source is creating a sub-optimal response for the calibration of the wavefront sensors. The pupil mask can be fixed, and rotation can be performed with the image rotator.

The same source can also be used by science instruments downstream (IRD, IRCS, SCExAO and its modules, etc.) for alignment, focusing, mapping and other characterizations during daytime testing.

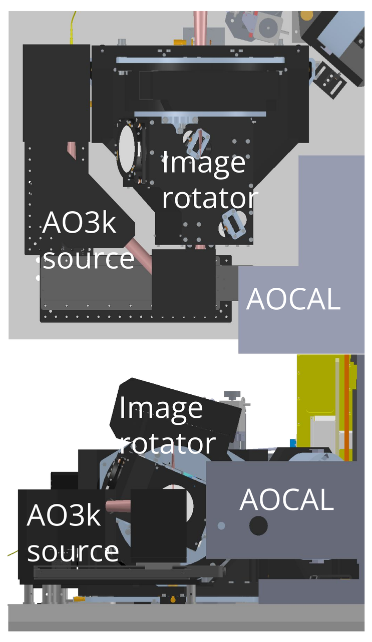


Due to the large wavelength coverage of the polychromatic source, the optical design is based on off-axis parabolas (OAP) and flat mirrors.

- Since the focal plane is inside the image rotator, The OAP's focal length has to be large enough to clear the IMR, but short enough to have a reasonable beam size for the f/13.9 beam. The only off-the shelf solution is the Thorlabs MPD2151-P01. It has a 2" diameter, a 381 mm focal length, and 15 degrees of off-axis angle. With this focal length, the beam diameter is 27.4 mm.
- The source is collimated by OAP 1, then through a series of fold mirrors, the collimated beam goes through a pupil mask at a distance f_{OAP}, and the focusing OAP 2 at a distance $2f_{OAP}$.
- 3 fold mirrors are necessary to fit in the available space. Fold 3 is designed to be as close as possible to the IMR, and due to the shallow angle of the OAPs, the beam reflects close to the edge of the mirror.
- The OAPs are oriented in such a way so that they compensate for each others astigmatism.
- Moving the fiber in X and Y allows a range of ±20" vertically and ±3.6" horizontally, due to the position of Fold 3. But by moving all the components horizontally instead, we can get a range of ±22.5" horizontally.
- The optical quality is almost perfect over the whole range of wavelengths and all positions in the field.



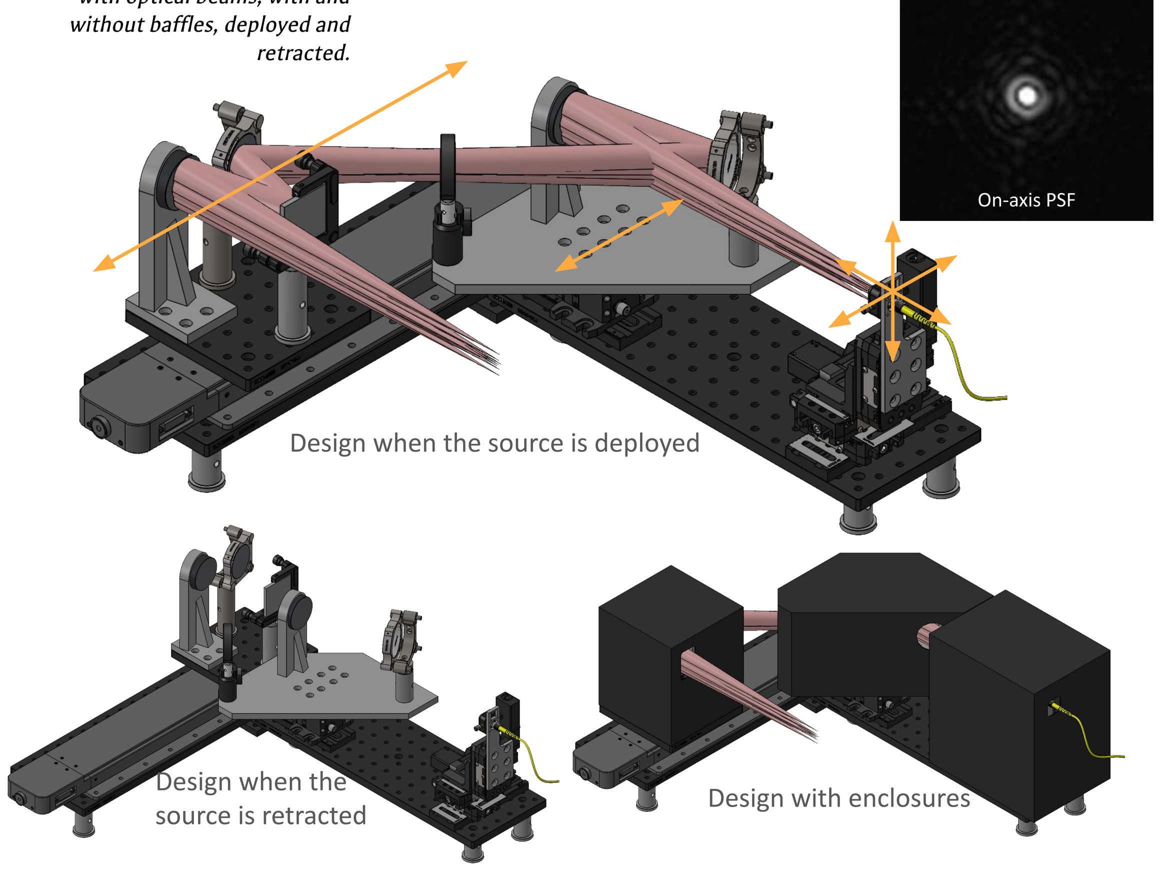
Zemax optical design. The optics are grouped in two groups that will not collide when the source is retracted. Each group is motorized on one axis separately, and the fiber itself is on a separate XYZ stage.



Top: CAD model of AO3k when the source is inserted and AOCAL is retracted.
Down: CAD model of the source with optical beams, with and without baffles, deployed and retracted.

The mechanical design has to fit inside a L-shaped footprint next to the image rotator, and take into account the motion of AOCAL when it is used or retracted.

- It is using off-the-shelf parts as much as possible. Two 150x450 mm raised plates arranged in a L shape constitute the base. A 300 mm OptoSigma translation stage is used for group 2, while a Thorlabs 25 mm translation with a Zaber motor moves group 1. The source uses a Thorlabs 3-axis 25 mm stage, also powered by 3 Zaber motors.
- The three optics of group 2 are attached to a 150x150mm plate, while the three optics of group 1 are attached to a custom plate. OAPs are mounted in fixed custom mounts, while the others are mounted in off-the-shelf adjustable holders.
- When the original source is retracted, the new source can be inserted by moving group 2 in front of the image rotator.
- Interlocks are necessary for the operation of both sources: one can only be used if the other one is retracted completely .
- The design includes baffles to avoid any stray light when in use.
- Clearances were checked to avoid any collisions with the IMR and AOCAL when they are in motion.



The source will be realigned and reinstalled inside AO3k in the next few weeks. It will also be used for other PI modules like LTAO and NINJA, and experimental setups like SPIDERS.

II. AO3k - NIRWFS: ON-SKY RESULTS

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.

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

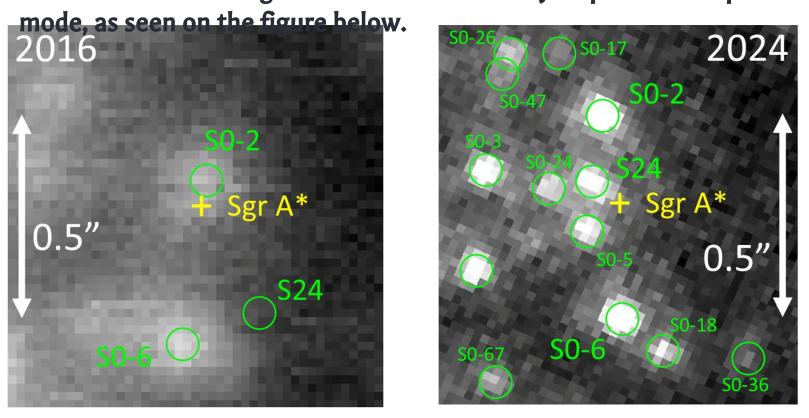
- Data was taken simultaneously with VAMPIRES and CHARIS for analysis.
- CHARIS results showed very high Strehl in J, H and K-band, even for high airmass targets.
- The second level of correction from SCExAO improves even further the Strehl, but mostly improves the stability of the speckle halo around 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.

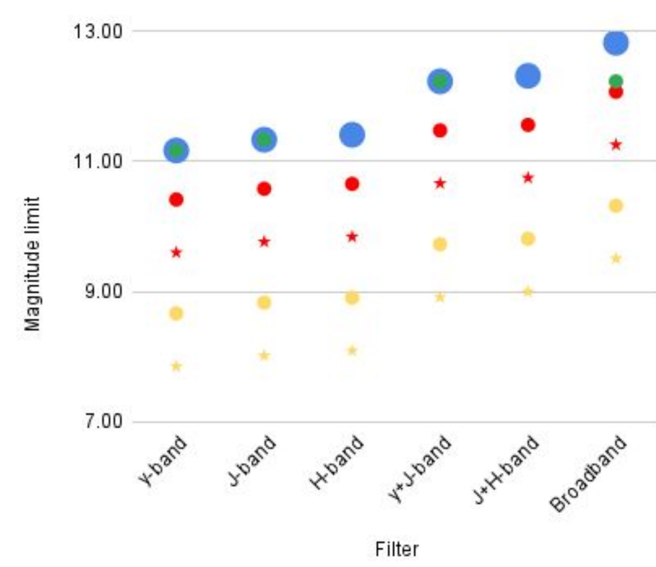
The NIRWFS showed good performance with IRCS as well, despite the lack of ADC.

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

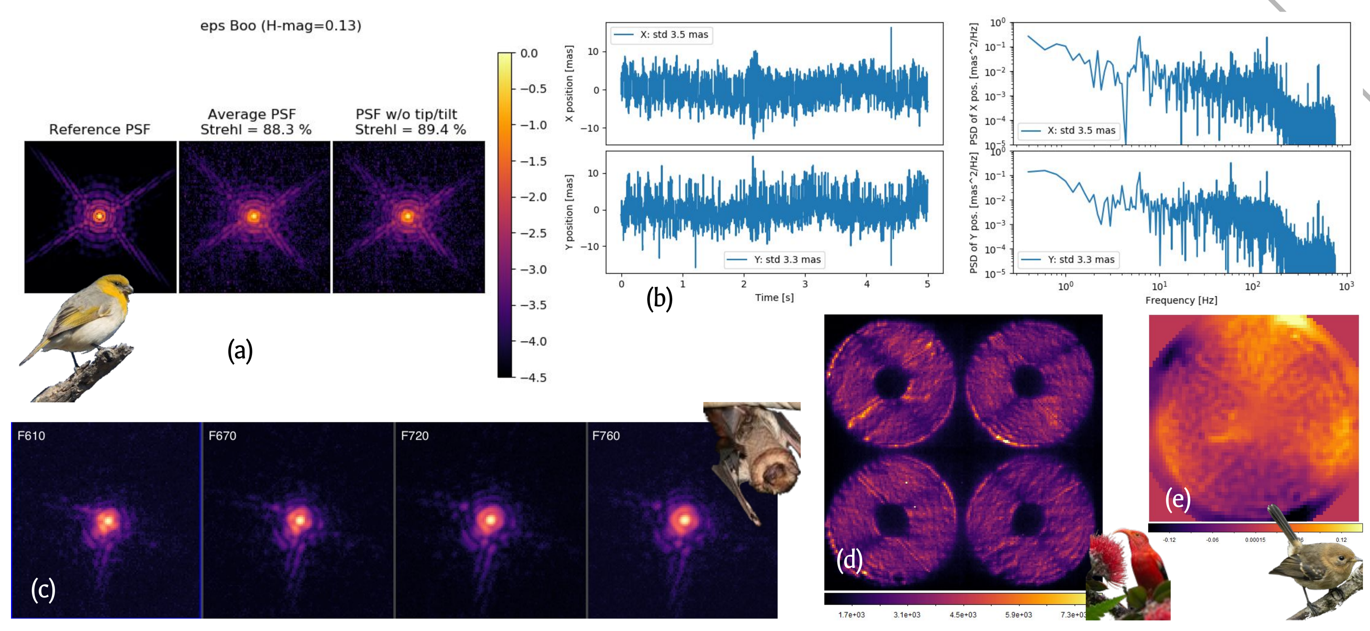


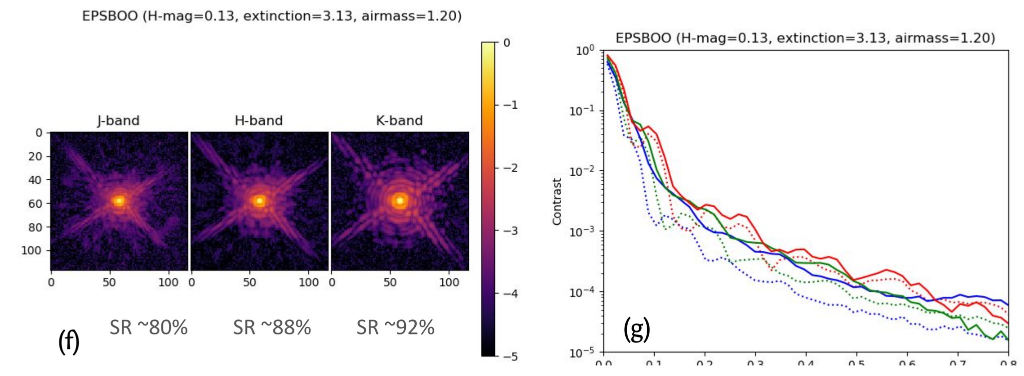
Comparison of the galactic center observations in AO188 - LGS mode in 2016, and AO3k - NIRWFS mode in 2024.

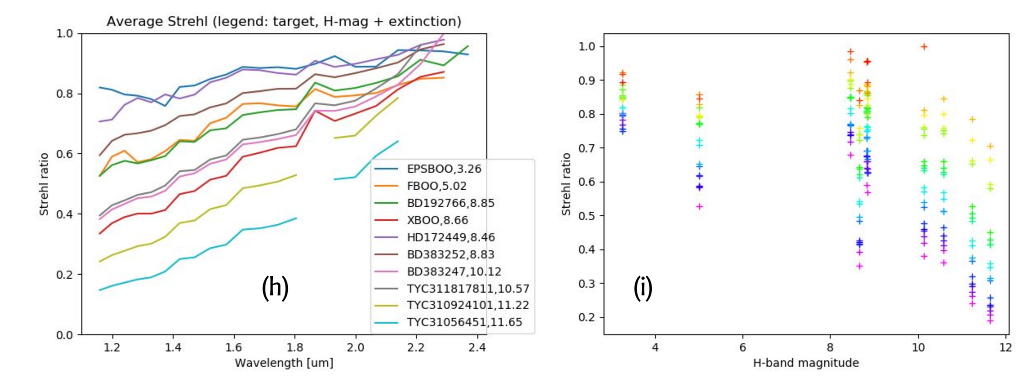
The NIR WFS has different dichroics that can be used to split the light between wavefront sensor and science, each dichroic has a range of magnitude limits that can be accessed, depending on the speed of the camera, the filter used, but also the spectrum of the guide star. Red stars have lower H-band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



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





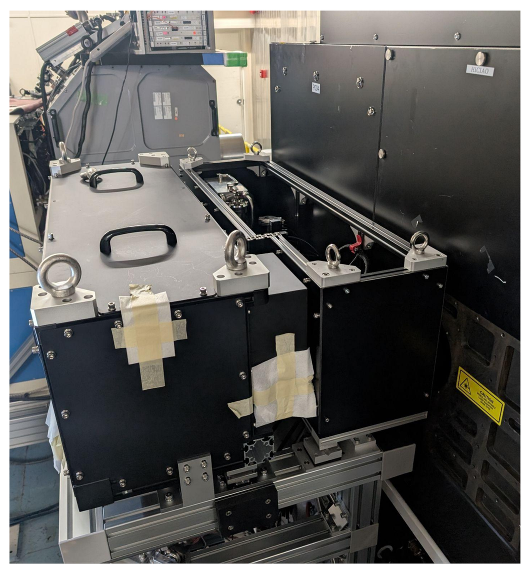


a) Palila camera images (H-band) showing high Strehl compared to the reference PSF. b) Temporal data and PSDs of the tip/tilt showing a residual of ~3 mas RMS, mostly from a few mechanical vibrations. c) VAMPIRES images in multi-band imaging mode. d) Pyramid mode of the NIRWFS used for wavefront correction. e) DM3k command applied. f) CHARIS data with AO3k - NIRWFS and SCExAO - PyWFS loops closed. g) CHARIS measurements with the AO3k-NIRWFS loop only. h) and i) Strehl measurements for various stellar magnitudes.

Phase II of the AO3k / NasIR upgrade just happened this summer, with the addition of the Nasmyth Beam Switcher and the LTAO (ULTIMATE-START). In this phase, the NIRWFS was 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.

First on-sky test already demonstrated that the NIRWFS v2 performs as well as v1, with now more functionalities. Mor engineering in S25B will validate the new modes, and inform us on improved magnitude limits.

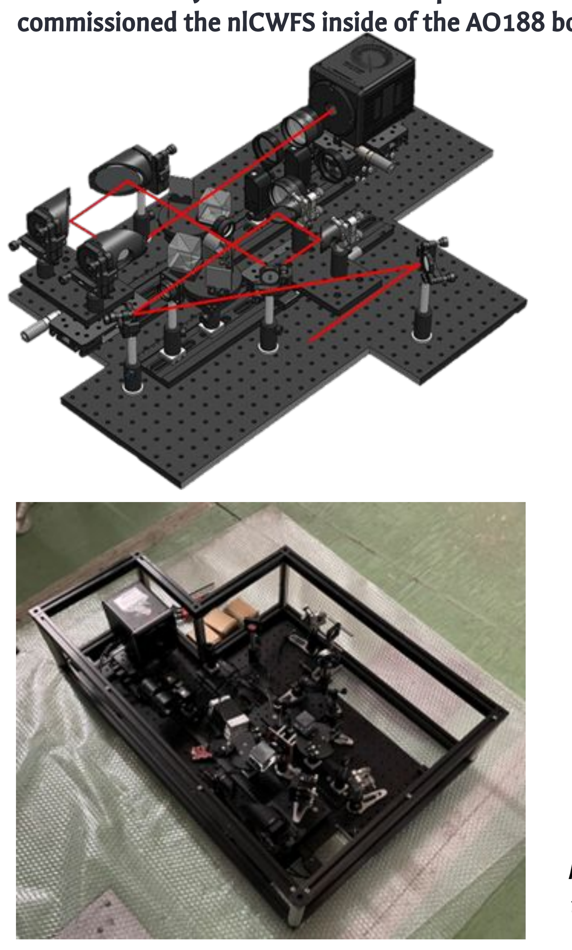


NIRWFS v2 (left) next to the LTAO truth WFS (right).

III. AO3k - nlCWFS

The non-linear curvature wavefront sensor (nlCWFS) is planned to replace the current visible WFS for the AO3k system, which is the upgraded version of the AO188.

We successfully finished the AO performance evaluations in the lab and commissioned the nlCWFS inside of the AO188 box in November 2023.



Left: 3D CAD model of the nlCWFS (top) and actual implementation inserted in AO188, just over the current visible WFS (bottom).

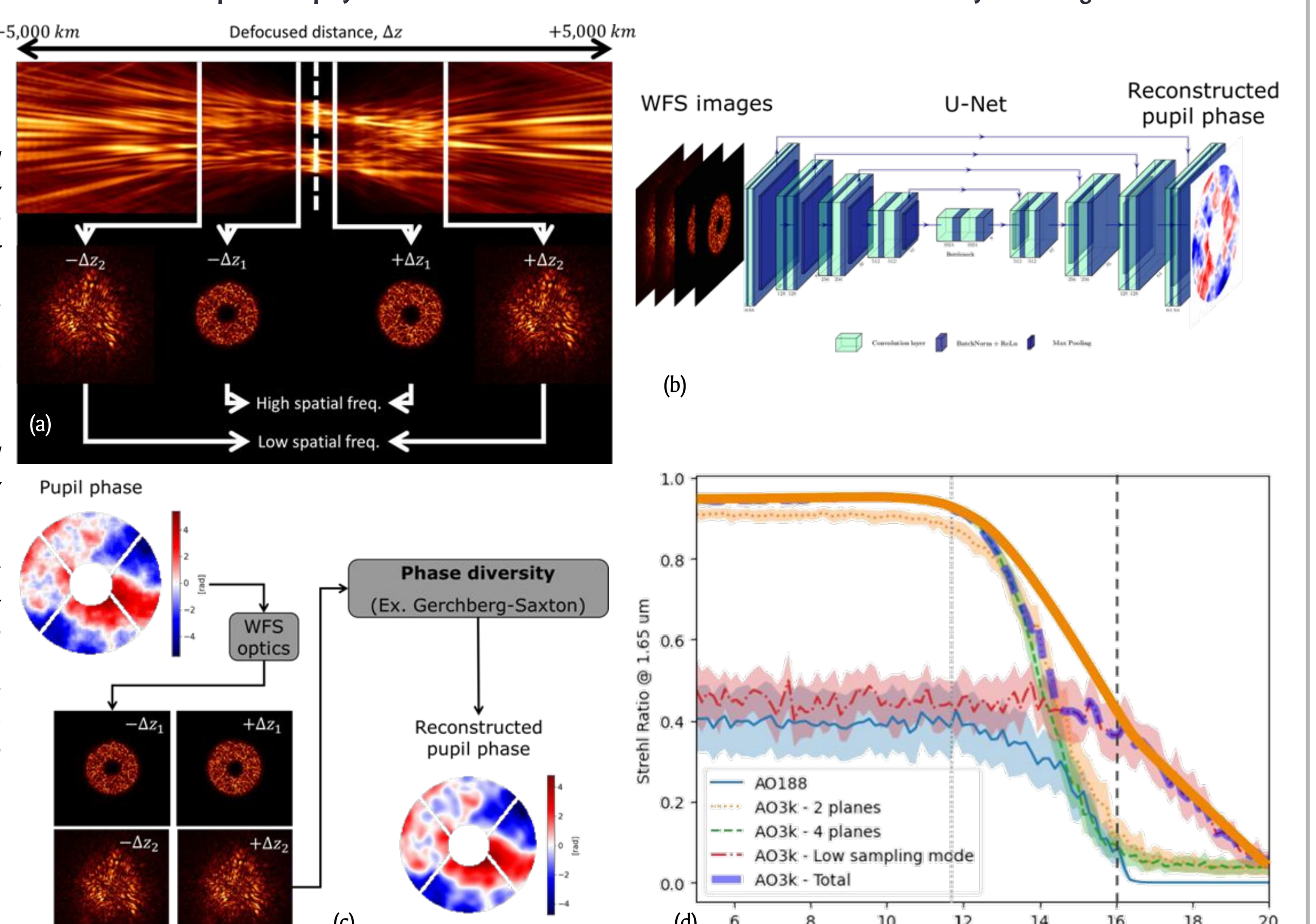
Right: a) Four defocused pupil images are used by the nlCWFS to measure the wavefront. b) A nonlinear reconstruction using a neural network is performed to go from wavefront sensor images to DM3k command. c) A nonlinear reconstruction using the more classical approach of phase diversity is another option. d) Performance comparison between AO188 - CWFS and AO3k - nlCWFS using simulations. Thanks to the higher number of actuators, the performance in Strehl is much higher, and thanks to a low sampling mode, we should be able to reach fainter magnitudes.

The current visible curvature WFS uses two defocused pupil images for WFSing.

However, the nlCWFS utilizes four defocused pupil images to have a decent sensitivity for both low-order and high-order aberrations.

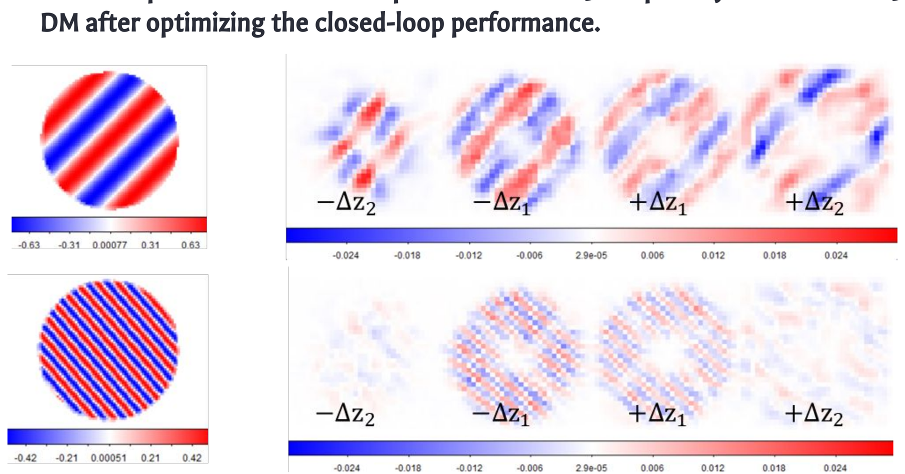
Two near-pupil images are for high-order aberrations, and two far-pupil images are for low-order aberrations.

We also plan to deploy non-linear wavefront reconstruction methods for an extensive dynamic range.

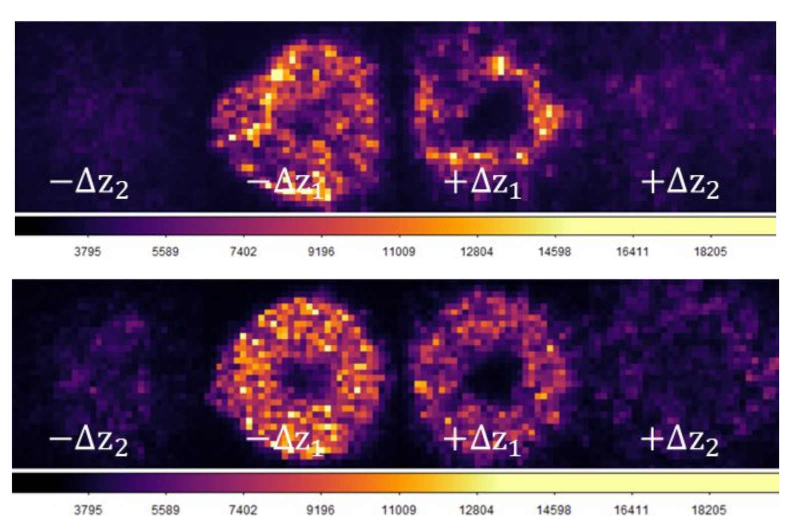


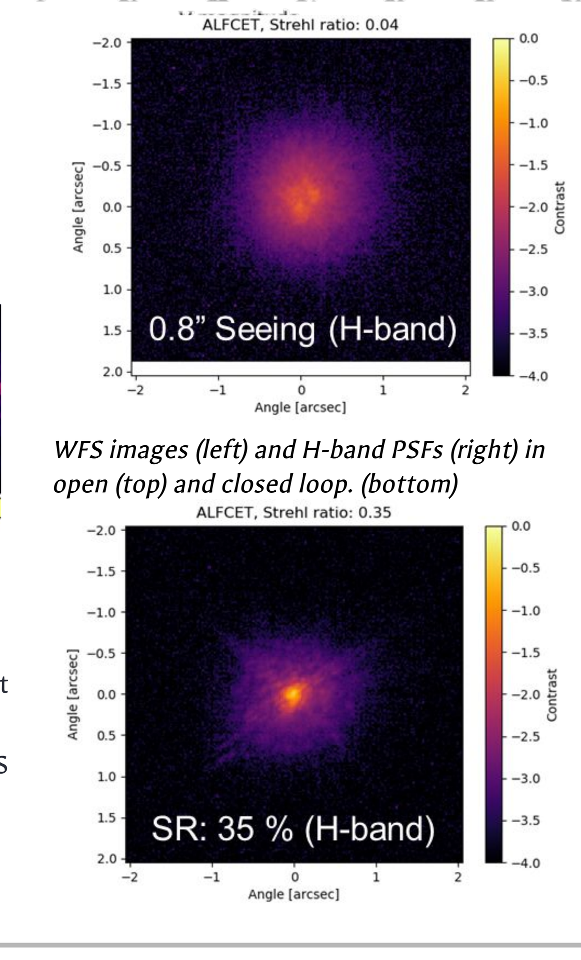
On-sky results:

- To close the AO loop, we first took an on-sky response matrix (RM) while the NIRWFS loop was closed.
- Even with on-sky RM measurement, we could get clear responses of the control modes at the deformable mirror (DM) thanks to the NIRWFS loop. (see figures below).
- After taking the on-sky RM, we tried to close the AO loop with the nlCWFS.
- Close loop was attempted for the first time in August 2024. Target: Alpha Cet, Seeing: 0.8" ~ 1" (see figures on the right).
- **We confirmed the closed-loop AO3k performance with the nlCWFS.**
- **The highest Strehl ratio was 35% at 0.8" seeing condition.**
- **We anticipate the nlCWFS will provide a full AO3k capability with the new 3k DM after optimizing the closed-loop performance.**



Left: Injected phase on the DM3k. Right: Response of the nlCWFS.





WFS images (left) and H-band PSFs (right) in open (top) and closed loop. (bottom)

More work needs to be done in the next year:

- Optimizing AO performance for various conditions.
- Quantitative comparison of the AO performance between the current visible WFS and the nlCWFS.
- Upgrading the mechanical design to provide different modes: NGS, LGS and focal plane WFS.
- Deploying the non-linear wavefront reconstruction algorithms.
- Opening the nlCWFS to the community as a PI-type module.