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Six Telescopes Star Tracker (STST)

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1. Introduction

As the STST name implies, its purpose is to monitor (field and pupil) and track the infrared beams and stabilize beams using labao and other actuators. The STST is contemporary concept working at the VLTI/GRAVITY acquisition and guiding camera (Anugu et al. 2018). STST is funded from the grants of University of Exeter (Prof. Stefan Kraus) and University of Michigan (Prof. John Monnier). Figure 1 shows the position of STST in the light train of CHARA.

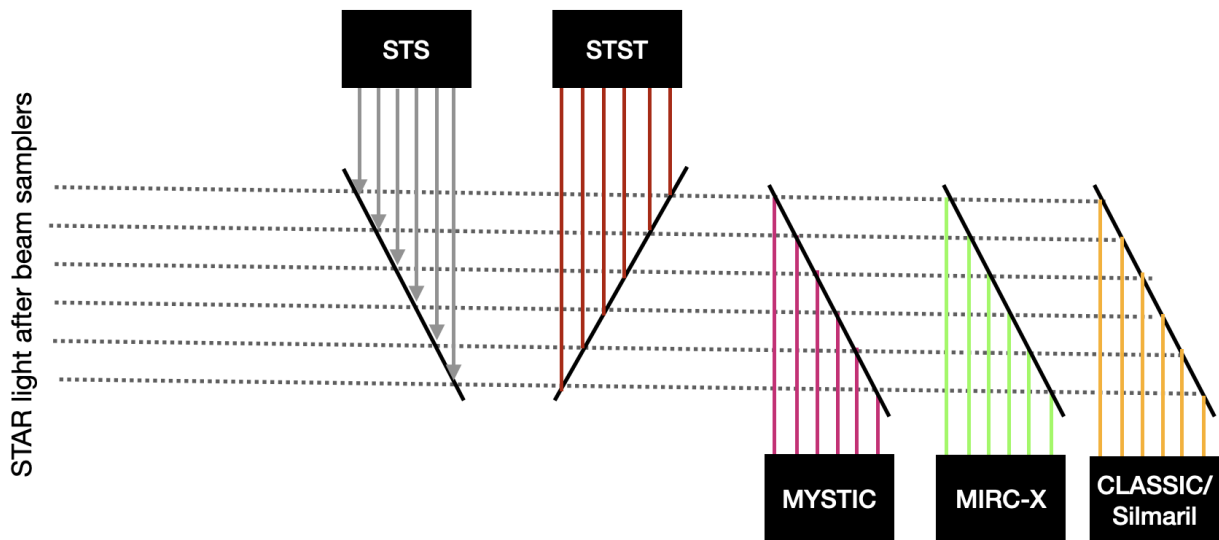


Fig. 1: The STST position in the context of the CHARA light path. The STST is aligned with the Six Telescope Tracker (STS), which simulates six telescope white light broadband beams consisting of wavelengths from visible to the near-infrared. The STST beam alignment helps the all the near-infrared beam combiners MYSTIC (Setterholm et al. 2023), MIRC-X (Anugu et al. 2020) and CLASSIC/Silmaril (Lanthermann et al. 2022).

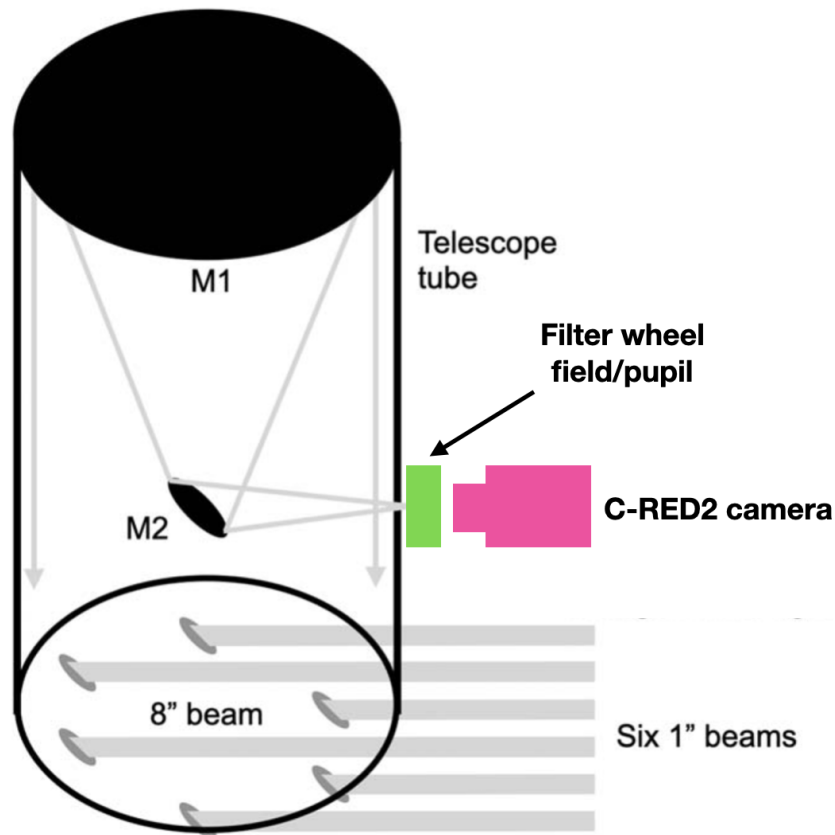


Fig. 2: The STST works in reverse to the Six Telescope Simulator (STS), i.e., it collects six CHARA beams with ~5% reflection of light using a beam splitter and images the field and pupil of each beam using a 8-inch telescope on a C-RED 2 camera.

2. How to start STST:

(1) Move STST beam splitter fold into the CHARA on-sky beams path

Open *shutgtk* and click on “STST” button, which should turn yellow while moving and turn green once reached its final position.

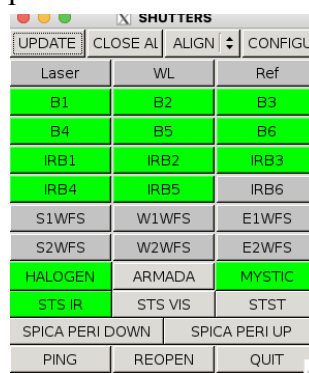


Fig.3 shutgtk, enables to move the STST IN/OUT of the light path

(2) Start server and GUI

Now let's learn how to start its server and GTK interface.

Generally the server runs always. However, if you start, it can be started with `mircx_bootLaunch` from either `spooler@stst` or `spooler@mircx` or `mystic`. Its server name is "`stst_server`". The server log can be accessed from `spooler@stst:/home/spooler/LogData/stst_server.log`.

Steps for restarting stst server:

```
ssh -X spooler@stst
killall mircx_stst_server
mircx_bootLaunch
```

Its GUI can be accessed with `ststrtd_gtk`, as shown below. One GUI has access to all controls. Let's start with first control,

1. To use STST with low dark current, the chiller needs to be set to 5°C and the camera set to -40°C. The camera temperature can be changed on the `ststrtd_gtk` gui.
2. Configure the detector integration time (DIT) per frame seconds and number of coadd frames (COADD). A minimum total integration DIT x COADD allowed is 1sec. Default is 1 sec detector integration. Feel free to experiment with long exposures or more number of coadds for fainter stars. The status of current DIT and COADDs are shown on the GUI adjacent to the DIT entry label.
3. Once configured the camera parameters, Start Camera and Start RTD.
4. If you change camera parameters, you need to take Backgrounds as this is an infrared camera. There are two types of backgrounds implemented (i) Backgrounds – backgrounds done inside the camera firmware, which is only required if DIT is changed. (ii) Use Bkg – takes background inside the server and applies. It is quick and works if camera DIT is not changed. In both cases, the backgrounds are taken automatically by moving the filter wheel with a blocker in front of the camera. The filter wheel should be in the CLOSED position to take backgrounds.
5. FILTERS – selection button allows to select the IMAGE field or PUPIL. This action moves the Thorlabs FW102C filter wheel. The pull-down menu lets you select the filter, while the current status of the filter wheel is written next to the pull down menu.
6. You can adjust the scaling of the display by changing the maximum number in the “Flux” box on the GUI.
7. “Filter wheel focus” and “camera focus” can be adjusted using the Zaber linear translation stage. Filter wheel focus – can be used to adjust the pupil focus. First select PUPIL in the filter wheel and next move the filter wheel focus to adjust its focus.

8. The STST box size needs to be < 20 pixels for centroiding and setting reference box positions (“Set ref” button) to work. The “adjust box” button opens the “ststrtd_gtk_adjust” box where you can select the beam and move the corresponding reference box to center the reference box on the star. Reference boxes should be centered on STS positions. The “Load ref” button will load the last saved reference box positions. The “Set ref” button will adjust the center of the boxes to the center of the light in the box. The “Save ref” button will save the current reference box positions to the defaults.
9. “Save fits” button will save fits files in /ctrscrut/chara/data with file names like stst_2023-01-24T06-34-48.fits
10. When you are finished using STST, click the “Start Camera” button to turn off the camera (the button will go from green to gray). Then change the filter wheel to the closed position. Using the shutter gtk, remove the STST stage from the beams. For now, the daytime alignment is done without STST in the path.

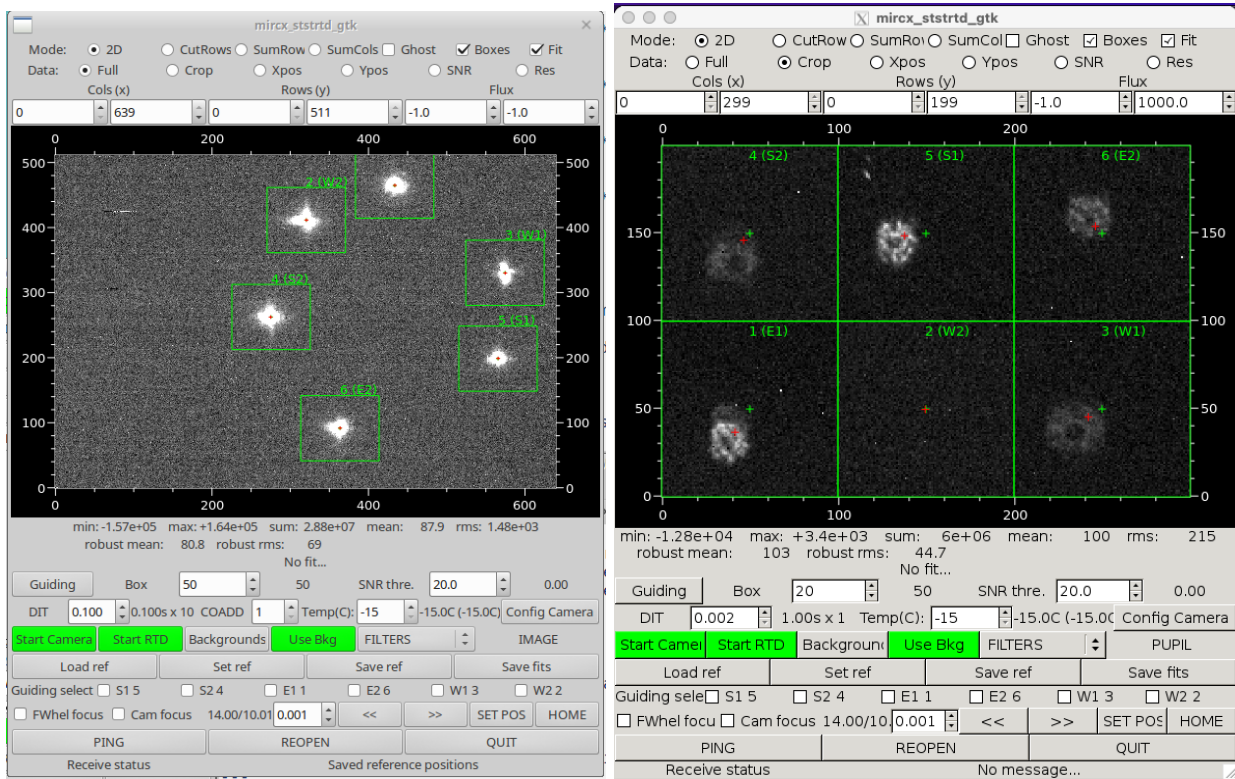


Figure 4: ststrtd_gtk. (Left) The image display is the field images of STS and (Right) pupil images on-sky CHARA beams

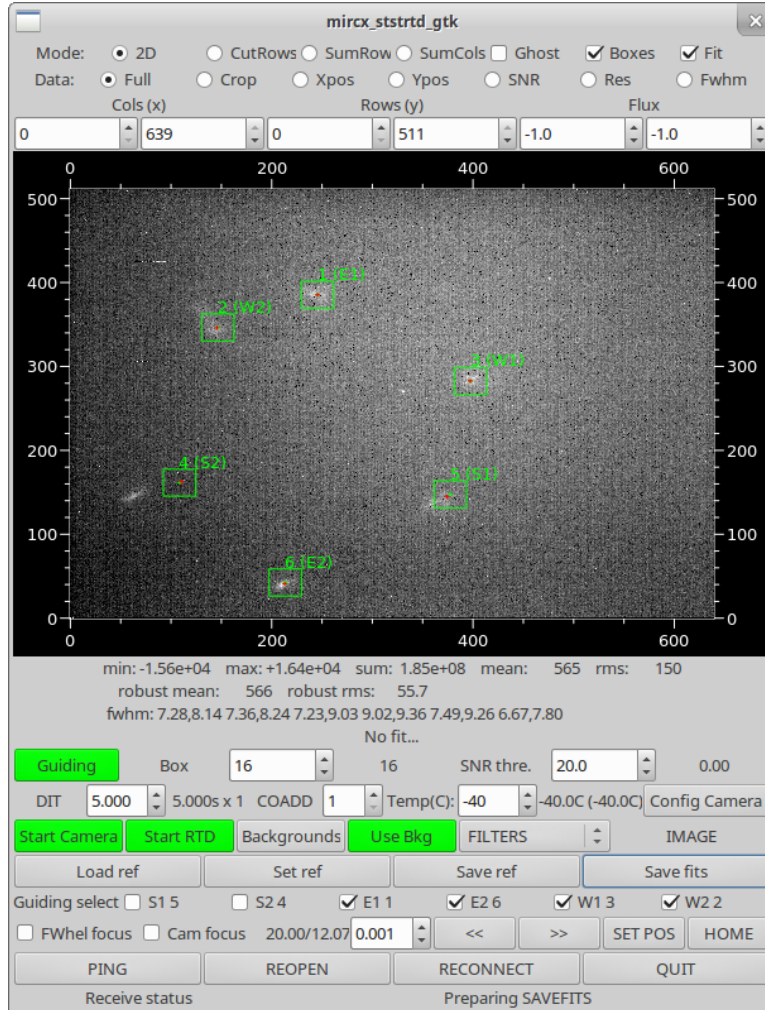


Figure 5: STST observation of a faint H=6 star with 5 sec exposure.

Shutting Down STST at the End of the Night

When you are finished using STST, click the “Start Camera” button to turn off the camera (the button will go from green to gray). Then change the filter wheel to the closed position. Using the shutter gtk, remove the STST stage from the beams. For now, the daytime alignment is done without STST in the path so it is important to remove STST at the end of the night.

3. The STST camera:

The STST uses the C-RED2 camera from the first light with the sensitivity to 0.9 - 1.7 μm wavelengths. The datasheet of the camera can be found from this datasheet.

https://www.first-light-imaging.com/wp-content/uploads/2019/02/Datasheet_C-RED-2_10.09.2021.pdf

C-RED 2 PERFORMANCES

FEATURES*	Result	Unit
Maximum speed Full Frame	600	FPS
Readout Noise at high gain, Tint @ 50 μs , 600 FPS Full Frame	< 30	e-
Dark Current @ -40°C	< 600	e/p/s
Quantization	14	bit
Flat Quantum Efficiency 1.0 to 1.65 μm	> 70	%
Operability due to signal response / pixels with signal ± 0.3 *median at 20°C	99.5	%
Image Full well capacity at low gain, 600 fps	1400	ke-
Image Full well capacity at med gain, 600 fps	128	ke-
Image Full well capacity at high gain, 600 fps	33	ke-
Maximum speed in 32 x 4 (min)	32066	FPS
Maximum speed in 320 x 256	1779	FPS

* Average values observed

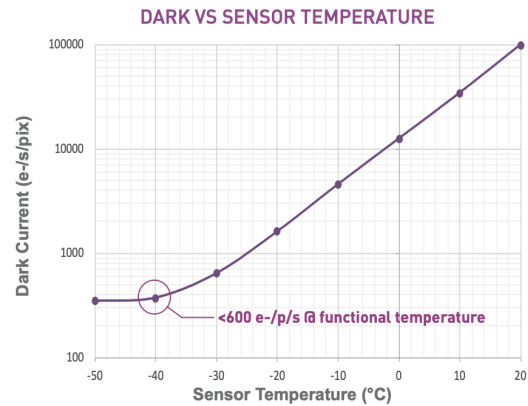
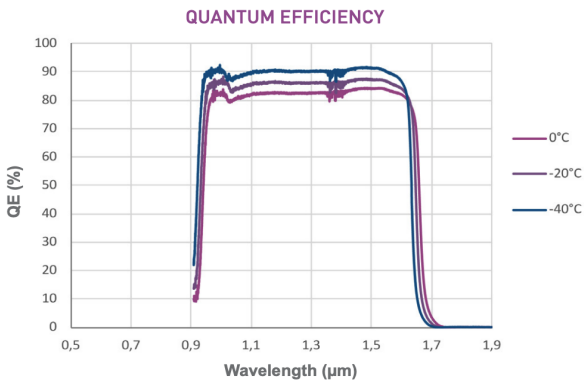


Figure 7: The quantum efficiency and dark noise performance of the C-RED2 camera being used inside the STST.

The camera comes with <math><30 \text{ e- RON}</math> and low dark when the camera is cooled.

3.1 Procedures to turn on water chiller for low dark (usually for engineering, water chiller always runs):

In order to use the chiller, follow the below instructions:

Step 1: Turn the unit's power on.

Step 2: Set temperature and time by pressing the SETTING button (Gears). NOTE: If you want the unit to run continuously, DO NOT enter the time or change the time to 00:00.

Step 3: Turn the pump switch on.

Step 4: Press the RUN/STOP or snowflake button for 3 seconds.

Step 5: When stopping the unit, press the RUN/STOP or snowflake button for 3 seconds.

Step 6: Turn off the pump by pressing the switch or the pump button on the display panel

Step 7: Turn the unit's power off.

In Steps 3 and 6 the pump should be run for at least 1-2 minutes before turning on or off the compressor. It's critical for shutting down to prevent icing/freezing.



Figure 8 Water chiller is used to cool down the camera. The photo was taken while Prof. John Monnier filled the water chiller with 50% mix of water and glycol.

3.2 Additional Metrology background reduction :

We reduced the background in two steps. In the first we used the notch filter in front of the camera. The spectral coverage of the filter is shown in Figure 9.

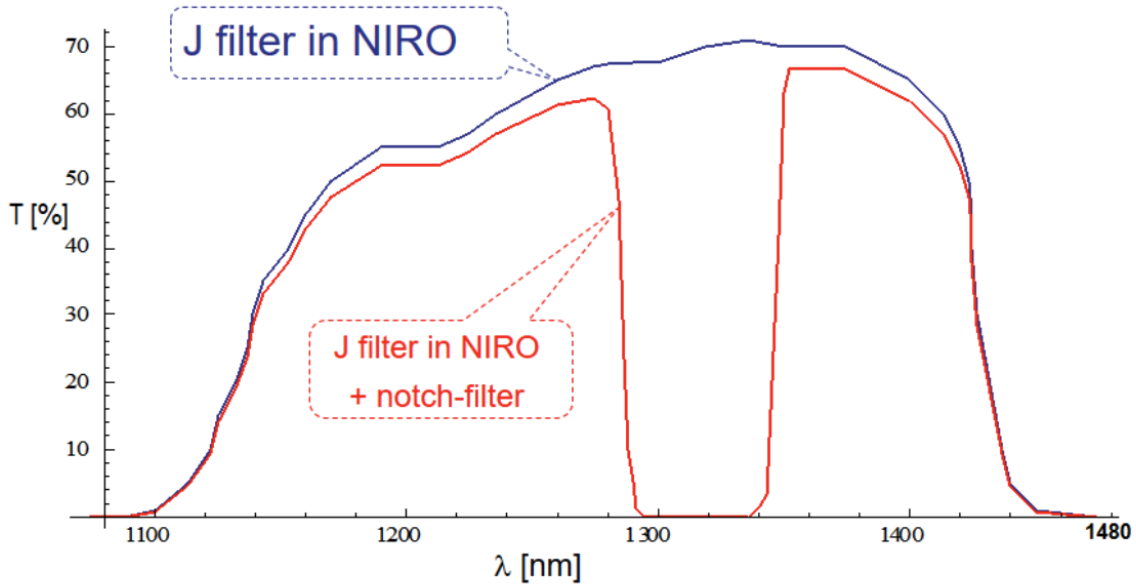


Figure 9: The spectral coverage of the notch filter. A comparison of the Classic J-band filter with and without the notch filter in place.

3. Beam combiners flux injection concepts

Here we explain how the STST could improve the sensitivity beam combiner. Lets take MIRC-X/MYSTIC as an example. They use single-mode optical fibers as a convenient solution for spatial filtering. In these beam combiners, the light from the telescopes is relayed to the combining laboratory in free space, then injected into single-mode optical fibers. In a fiber-fed image plane combiner, the outputs of the fibers are re-collimated and fed to an image plane combiner in the same format as described in (Anugu et al. 2020 and Monnier et al. 2018).

It is difficult to efficiently couple stellar light into an optical fiber. Coupling is maximised when the injection optic, such as an off-axis parabola or aspheric lens, produces a focal spot at the plane of the fiber tip that is:

- A Gaussian profile of diameter equal to the mode field diameter (MFD) of the waveguide.
- Centred on the core of the fiber.

The second condition relies on accurate beam alignment. If the beam entering the focussing optic is tilted, it displaces laterally from the ideal position. Given the narrowness of the MFD (of order 5 μm at optical wavelengths), a small angular offset can significantly reduce the coupling efficiency. Since the misalignment is likely to be uncommon between beams, this would cause their intensities to be mismatched at combination, thereby reducing fringe contrast.

4. Auto Alignments with the feedback of the STST for near-infrared beam combiners

The STST tracking works in similar terms to the CHARA/LABTT but near-infrared wavelengths. LABTT was installed in the CHARA lab, decommissioned in 2021, which used to work in the visible wavelengths using a CCD camera (see Laszlo et al. 2006). The STST camera can be comparable to the VLT/GRAVITY acquisition and guiding camera, which also provides star tracking, pupil monitoring and guiding (see Anugu et al. 2018).

The STST feedback is used to solve two alignment problems. The CHARA laboratory AO system is fed with blue light ($\lambda < 500\text{nm}$) arriving from the beacon at the Telescope. Due to dispersion caused by passing the beam through air and transmissive optics, alignment perturbations seen at visible wavelengths might not always be shared by infrared wavelengths.

The path of the IR light will be different from the visible light because of dispersion in the telescope dichroic and atmospheric refraction. Since all the atmospheric turbulence corrections that are done by telescope adaptive optics (TELAO) and laboratory adaptive optics (LABAO) are in the visible wavelengths, the infrared beam needed to be tracked in the lab. This means, at the lab the photo centers of visible light and infrared are at different places. To compensate for this offset, we record the STAR beams on the STST and measure the offsets with respect to the STS reference and correct this offset in two levels of compensation.

- First, we correct the coarse alignment with the beaconflat actuator at the telescope, which aligns the difference in the STAR IR beam to the blue beacon used for the LABAO system.
- Second, we correct the real-time offsets, by sending offsets to the LABAO system, which eventually corrects with existing M7 actuators .

LabAO will offload STST offsets to the M7. You need to - Make sure it is **not ignoring tip/tilt**. This is still ON by default so you need to hit the IGNORE TILT button in the WFS panel and make sure you see the message “NOT ignoring WFS tilt when applying a reconstructor.” This will ensure that the labao AO servo is doing tip/tilt as well as high order corrections. In the LABAO server status window on the lower right you will see a line labeled “DM Tilt:” that will show the mean tilt of the DM with an error in Arcseconds on the sky. The range is about +/- 2.5 Arcseconds in the sky.

- You can then turn on offloading from the DM to M7 using the DM button to do it once, or the DM AUTO button in the ALIGN panel to do it whenever the range of the DM tilt goes over a specified limit. The number of tries for each iteration and limit is set in that panel. Note that this limit is in units of the DM tilt and not arcseconds in the sky (This should be fixed I guess). The relationship is $\text{DM Units} * 8.84 = \text{arcseconds in the sky}$. These numbers, and the numbers in the DM/M7 servo itself, have not been optimized but they are close. You can play with these parameters using the SERVO panel on the GUI. Note you need an engineering version of the GUI (-E flag) to get this panel.

The parameters are: Delay: Minimum number of seconds between moves of M7 Limit: Maximum allowed tilt error before servo automatically starts Step: Minimum step size for M7 motion Gain: Gain of servo I think it would be wrong to move M7 directly from STST rather than via the Labao DM servo. Moving M7 will throw LabAO alignment out, and it would be way too easy to move it so far that LabAO stops working altogether. Much safer to adjust the boxes on LabAO and let it move M7. That way both systems continue to agree on where the bore site is. In the bigger picture you need to bear in mind that moving M7 (or M10) to correct things is not optimal. In a perfect world they shouldn't actually ever move at all. We only move them to more easily correct for small errors. Motion of the beam in angle or shear is caused by mirrors that move during observations

- that is the Coude alignment is off so the beam moves when the telescope moves, or during POP changes when the POP mirrors and periscopes move which sometimes completely messes up the alignment. It's impossible to get both of these 100% right of course. We know that the Coude can be quite good and it is safe to move M7 to correct for this. POP changes can be more problematic. It should be possible to get the POPs aligned such that after a change M10 and M7 don't need to move, or at least don't need to move very much, but it's very hard to do. We've been working on that for years and more work is required. If you find that you need to move M7 fast, or a big distance, it's a sign that something is wrong in the Coude path or with the POP alignment. What would be good is to have better actuators on M10, i.e. encoded actuators, and I know this is on the long list of things to do but it hasn't happened yet.

More discussion on the alignment concepts

- **Green laser Laser fiducial from beam combining laboratory:** When directed down-stream, the fiducial helps to align the beam combiners. When directed upstream through the relay pipes towards the telescope, the fiducial shares the same diameter as the stellar beam (i.e. 125 mm). A retractable corner cube retroreflector in front of M2 sends the beam back so that it can be recorded on the acquisition camera at the telescope table. When observing a stellar target, the

telescope pointing is adjusted until the target spot overlaps with the laser spot on the acquisition readout.

- **Blue Laser beacon from the telescope** Figure 10 illustrates how artificial light from the beacon is directed downstream coaxially with the stellar beam. Its purpose is to illuminate the LABAO. Light at $\lambda = 465 \text{ nm}$ is delivered to the telescope platform by an optical fiber. The expanded beam from the fiber is collimated by an on-axis parabolic mirror ($d = 152.4 \text{ mm}$, $f = 1219.2 \text{ mm}$). A flat mirror directs the collimated beam towards a dichroic splitter. In transmission, the beam arrives at the telescope wavefront sensor for calibration. In reflection, the beam passes through the beam relay and delay lines to the wavefront sensor of the laboratory AO system.

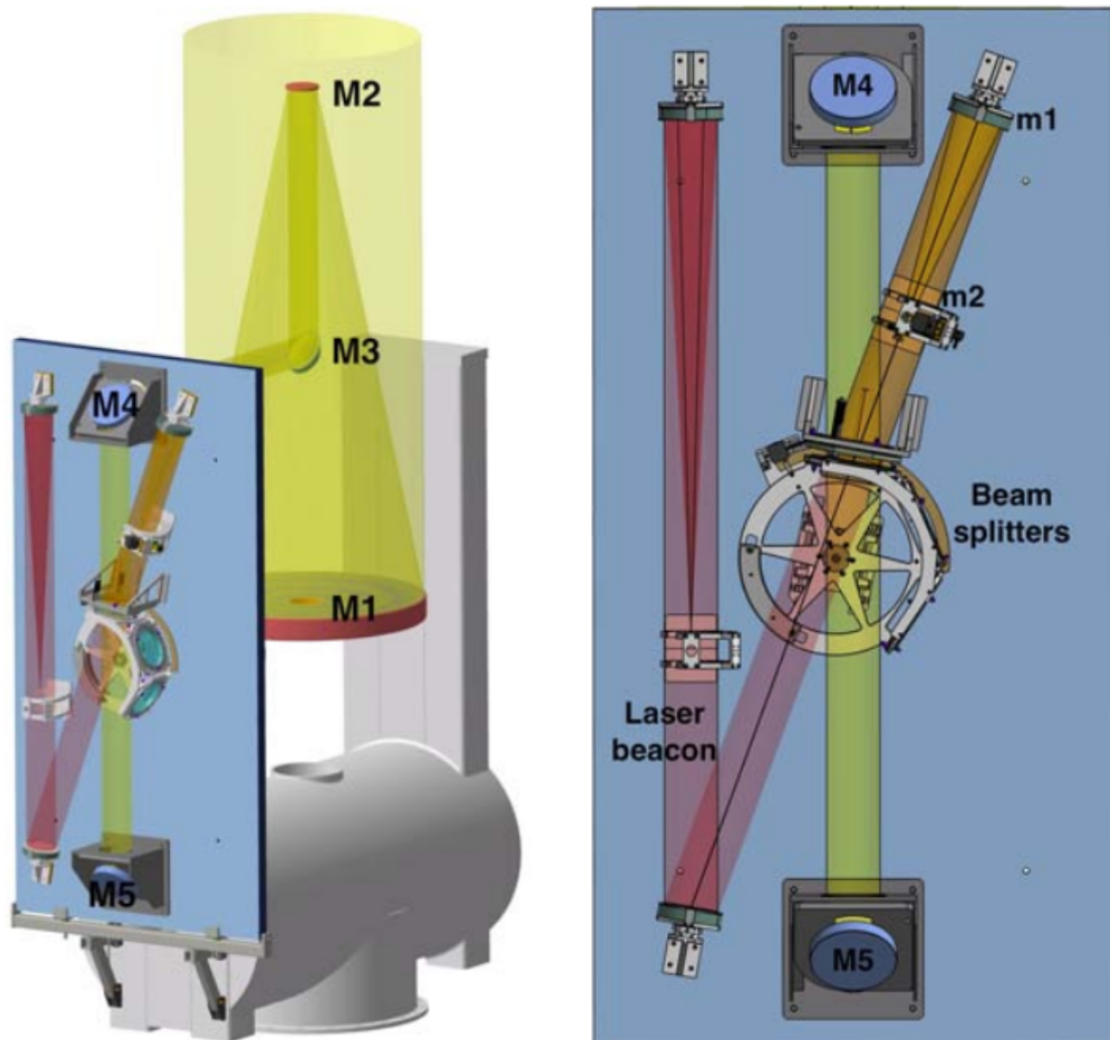


Figure 10: Components of the CHARA adaptive optics system mounted on the telescope platform. The beam splitter enables light from a laser beacon to illuminate an adaptive optics system located in the beam combining laboratory. It also passes stellar light to a wavefront

sensor that is located close to mirror m2. Mirror M4 is deformed according to measurements made by this sensor.

• **Six-telescope simulator at the lab (see Figure 1):** This source was commissioned to provide 6 collimated beams of broadband light with which to calibrate MIRC-X (Anugu et al. 2020). The concept is similar to ARAL and the GRAVITY Calibration Unit at the VLTI. A single mode fiber carries light from a tungsten-halogen light source to the focus of a Newtonian telescope. The telescope is upended such that its primary mirror is facing the ground rather than the sky. The collimated beam travels downwards where it is sampled by six mirrors arranged such that their centers lie on the circumference of a circle in a plane perpendicular to the propagation direction. The beams are passed to a delay-inducing stage, then subsequently injected into the beam train by mirrors mounted on a common motorized linear slide. Beam flux is controlled by blocking a fraction of the emission between the light source and fiber input with a thin metal plate. Using a photonic crystal fiber (PCF) to produce a single-mode beam for all the wavebands of interest (H-MIRC-X, K-MYSTIC and R-band SPICA).

Refer STS report:

<https://docs.google.com/document/d/1w1Ppi21b0Uh37R52btCgwsX6dNYUfEE5hUhncDlNvYQ/edit#heading=h.kg84aow1dq1a>

5. AO performance checks

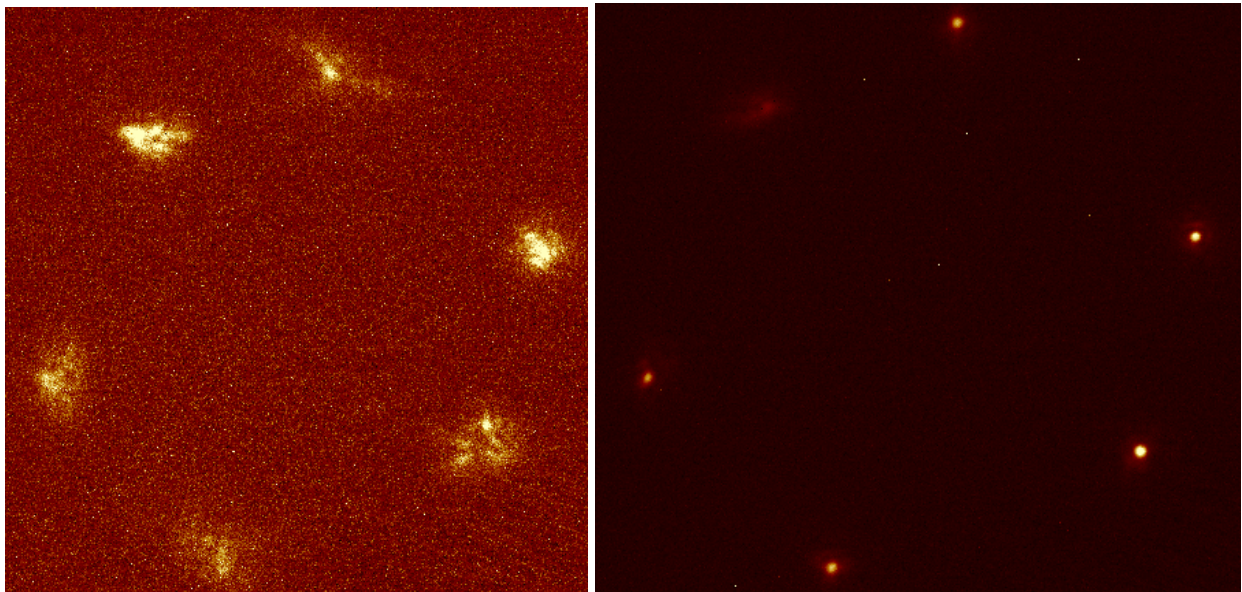


Figure 6: The performance of AO recorded on the STST. (Left panel) TELAO LOOP OPEN; (Right panel) TELAO LOOP CLOSED

Strehl ratio computation

Strehl ratio in H-band (design value is 50-70% based on how good seeing is):

E1 - 41.5%

W1 - 68.7%

S2 - 23.7%

S1 - 46.7

E2 - 66.7%

W2 - 5.4% — TELAO not in operation

The design FWHM of PSF is (5,5) pixels with pixel scale of $\sim 0.05''/\text{px}$.

For that, we measure the best $\sim (6.5, 6.5)$ pixels the on-sky.

References:

Anugu et al. 2018, <https://ui.adsabs.harvard.edu/abs/2018MNRAS.476..459A/abstract>

Anugu et al. 2020, <https://ui.adsabs.harvard.edu/abs/2020AJ....160..158A/abstract>

Laszlo et al. 2006, <https://ui.adsabs.harvard.edu/abs/2006SPIE.6268E..3TS/abstract>

Setterholm et al. 2022 <https://ui.adsabs.harvard.edu/abs/2022SPIE12183E..0BS/abstract>