Status of the DKIST Solar Adaptive Optics System

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DKIST: Daniel K. Inouye Solar Telescope

- 4 m solar telescope: off-axis Gregorian, clear aperture
- Formerly ATST: Advanced Technology Solar Telescope (until Dec. 2013)
- Under construction at Haleakala in Maui, Hawaii
- Collaboration of 22 institutions

Night median seeing:

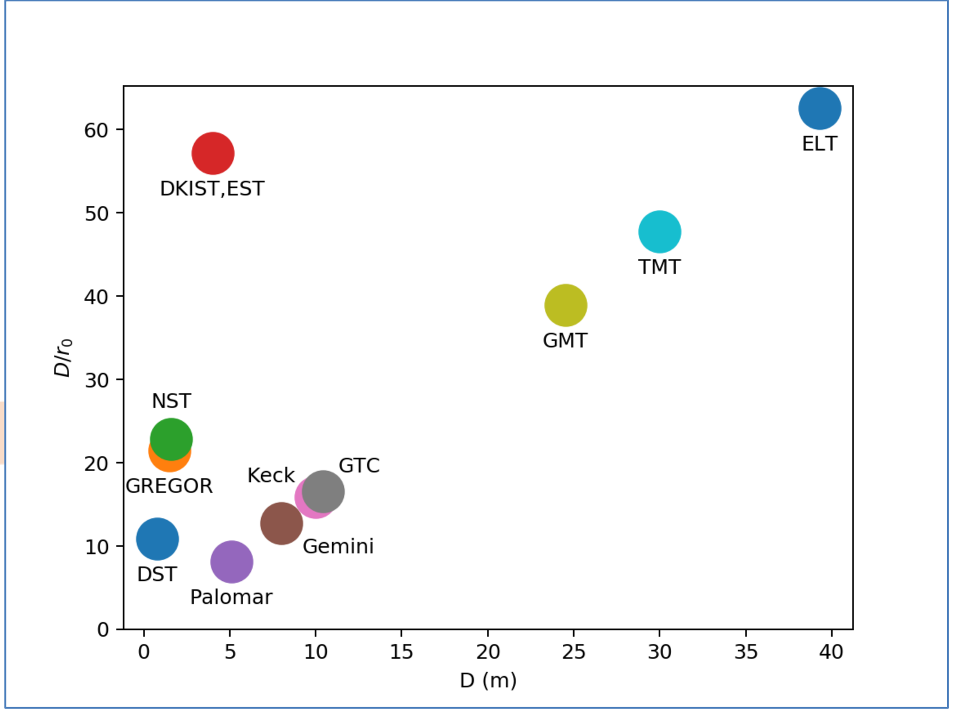
r_0 (0.5 µm) = 15 cm

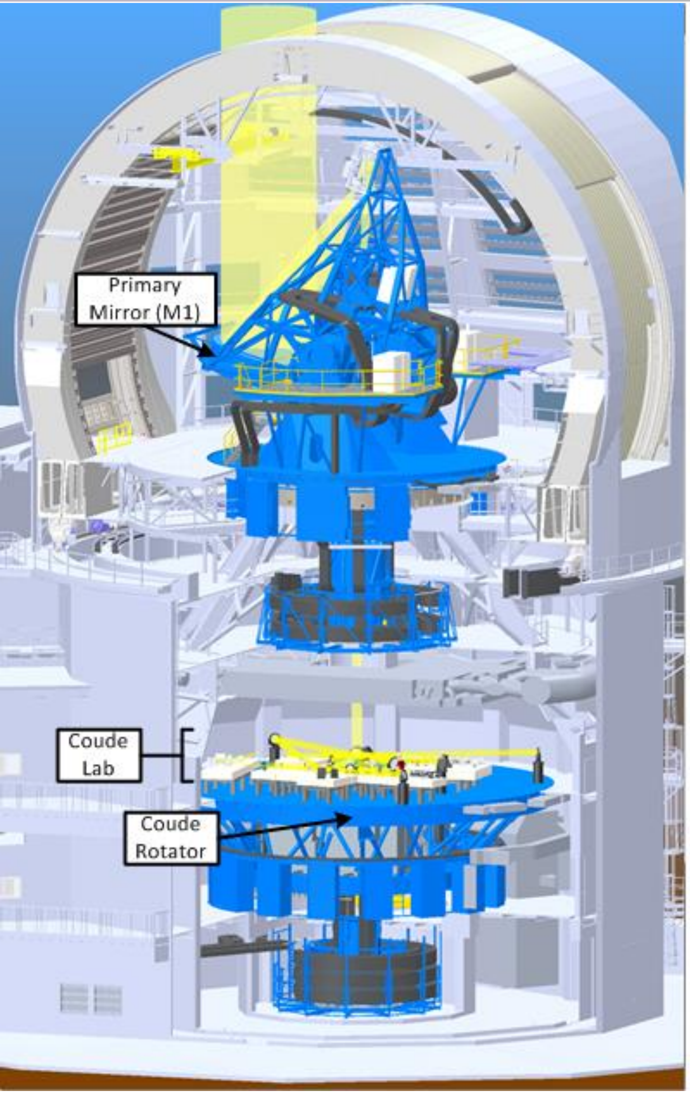
λ = 1.65 µm

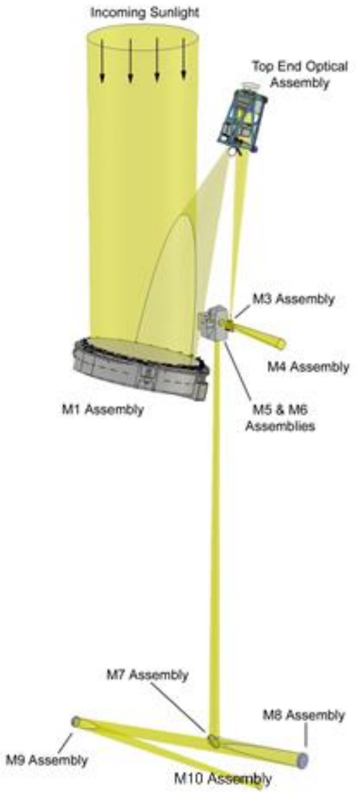
Day median seeing:

r_0 (0.5 µm) = 7 cm

λ = 0.5 µm







Actively controlled mirrors

Mirror	Degrees of freedom
M1	118 actuators – active surface control
M2	6 - x, y, z, Rx, Ry, Rz (hexapod)
M3	2 – pupil positioning in x and y
M6	2 – image positioning in x and y

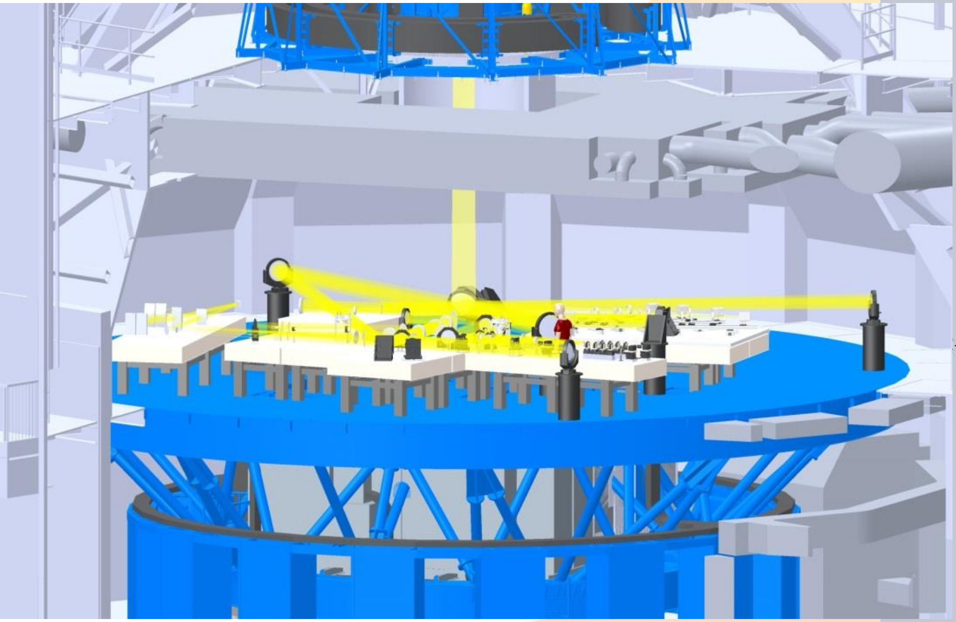
Adaptively controlled mirrors

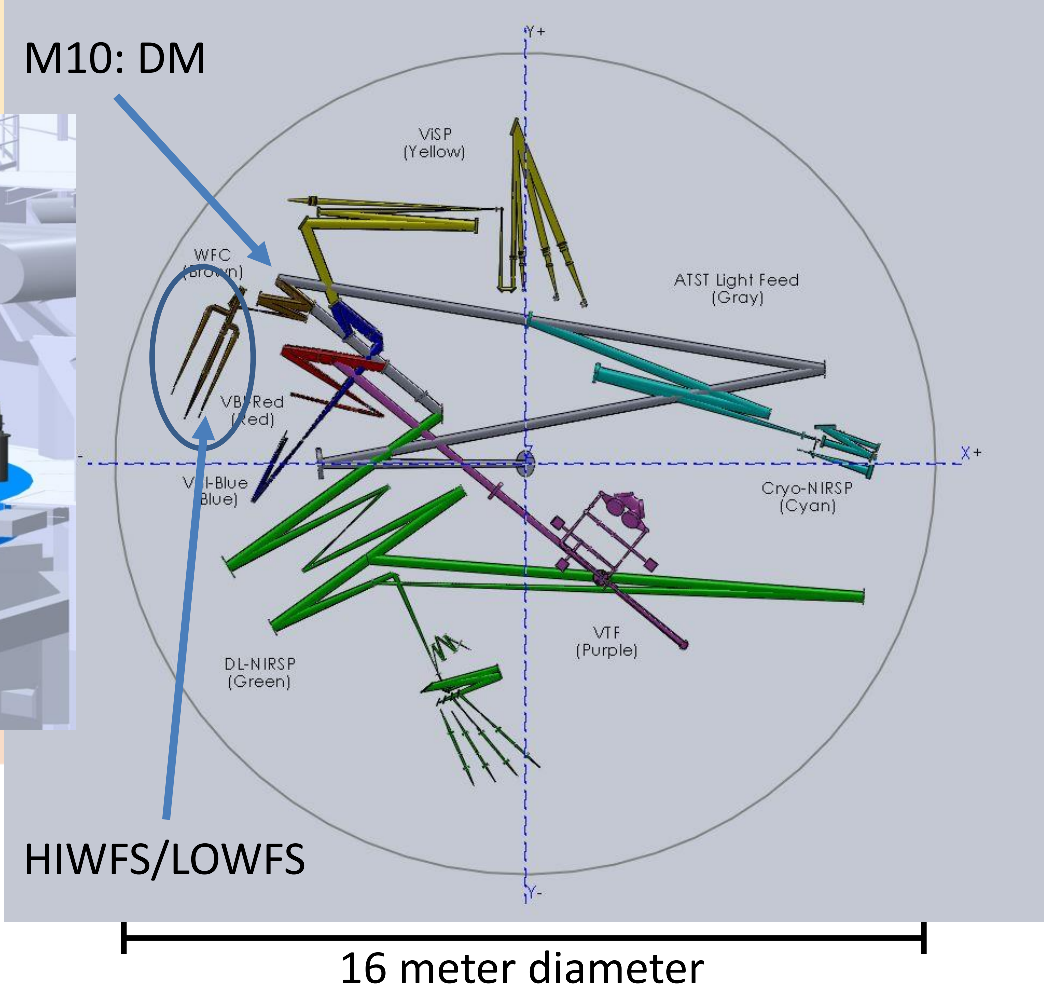
Mirror	Degrees of freedom
M2	θx, θy - fast tip-tilt (Limb Tracker only)
M5	θx, θy - fast tip-tilt
M10	1600 actuators – surface control

DKIST first light instruments

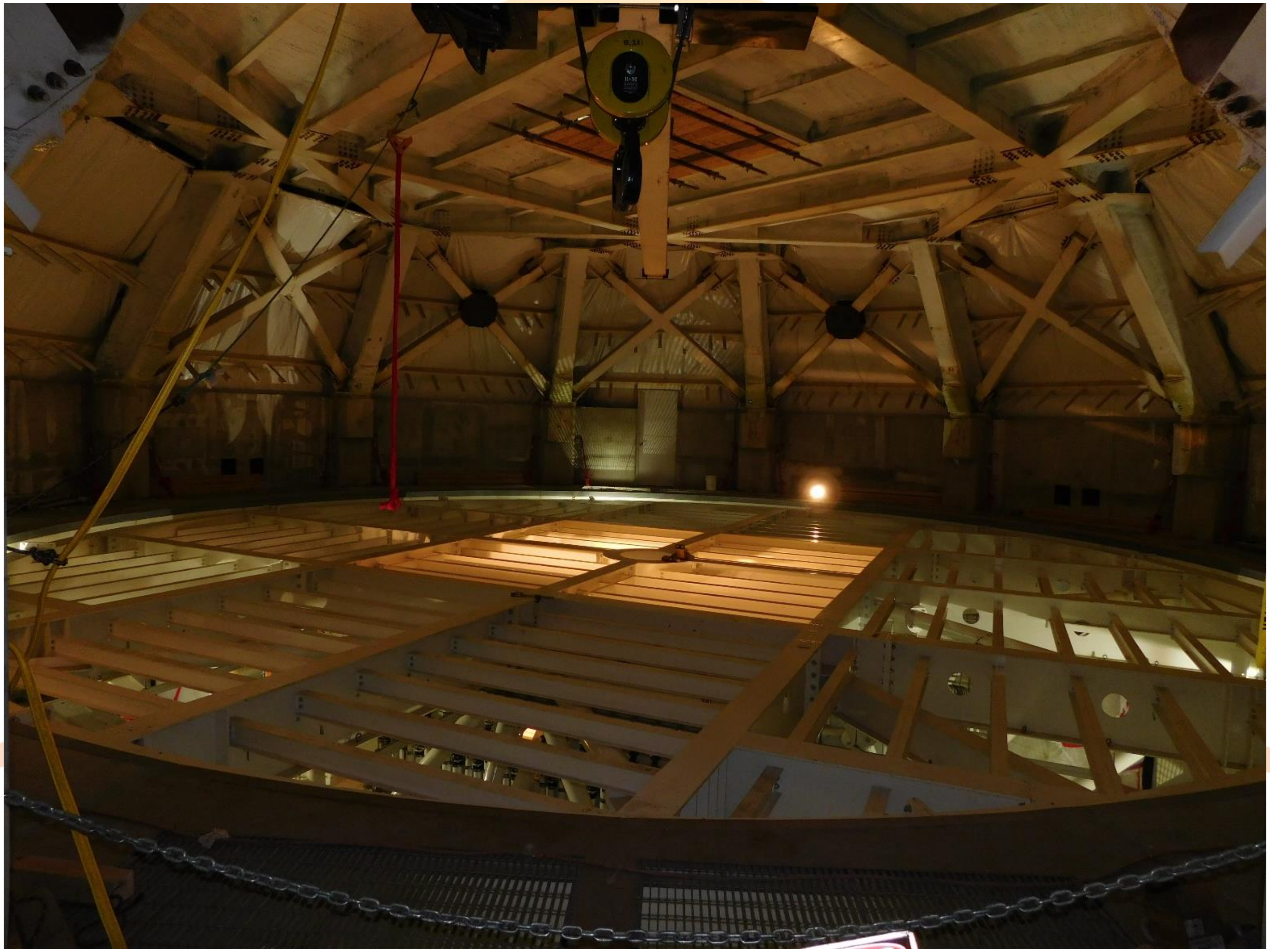
Instrument	Instrument type	Wavelength	Resolution	Field of View	Cadence
VBI Blue	Imager	393 – 486 nm	0.022″	45 x 45″	0.033 s (raw) 0.366 s (multi-λ) 3.2 s (reconstructed)
VBI Red	Imager	656 – 706 nm	0.034″	69 x 69″	0.033 s (raw) 0.366 s (multi-λ) 3.2 s (reconstructed)
VTF	Tunable filter	520 – 860 nm 3 lines per obs.	0.028″ 6 pm@600 nm (R=100,000)	60 x 60″	0.8 s imaging 10^{-3} I_{cont} in 13 s
ViSP	Spectropolarimeter	380 – 900 nm	0.07″ 3.5 pm@630 nm (R=180,000)	2 x 2′	10^{-3} I_{cont} in 10 s
DL-NIRSP	Spectropolarimeter multi-slit Spectrograph and IFU	0.5 – 2.5 µm	0.03″ R=50,000 – 250,000	2 x 2′	1 s
Cryo-NIRSP	Spectropolarimeter multi-slit Spectrograph or 2D imaging capability	0.5 – 5.0 µm	0.15″/pixel (disk) 0.5″/pixel (corona) R=100,000 (disk) R=30,000 (corona)	4 x 3′	0.1 s

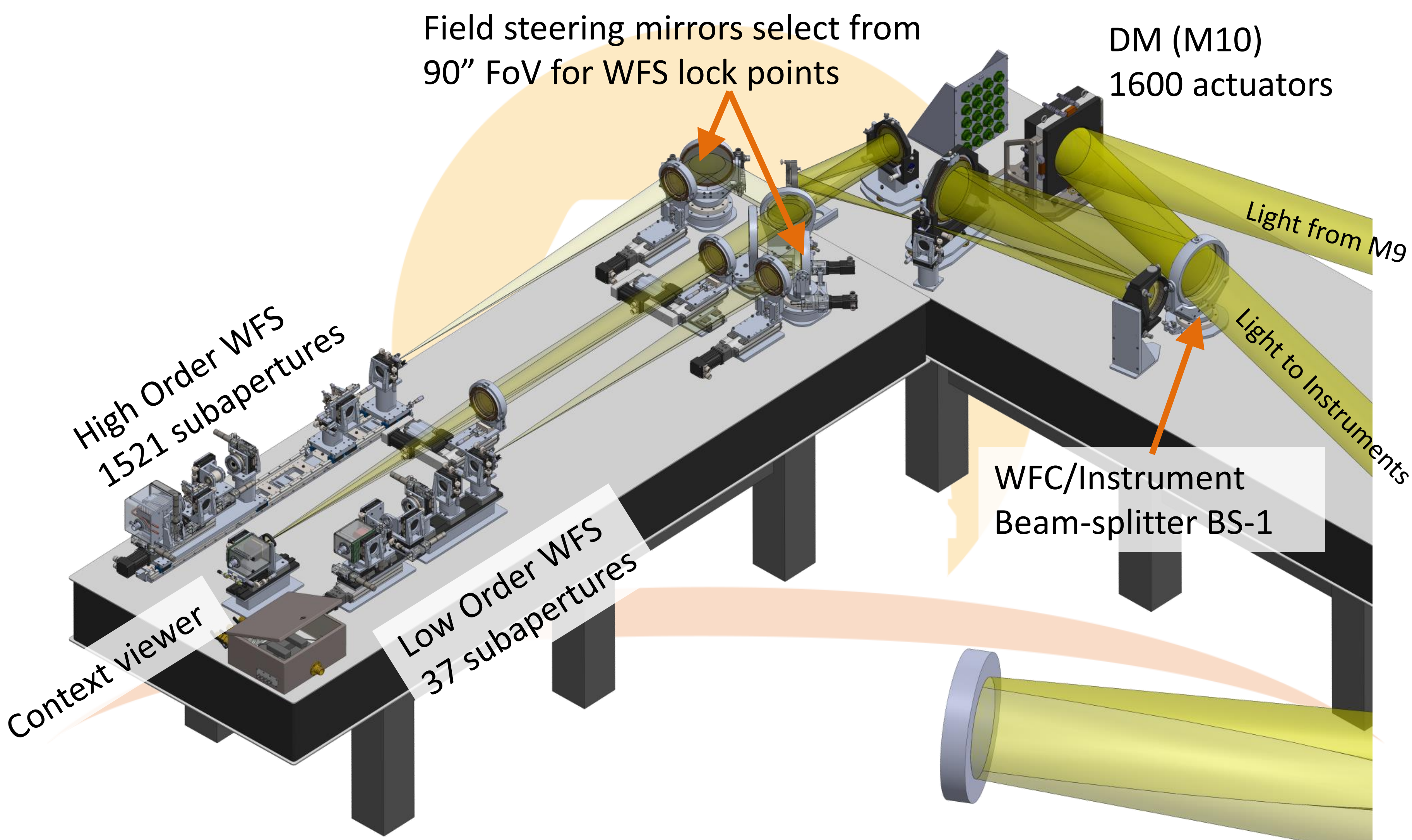
DKIST Coude Lab



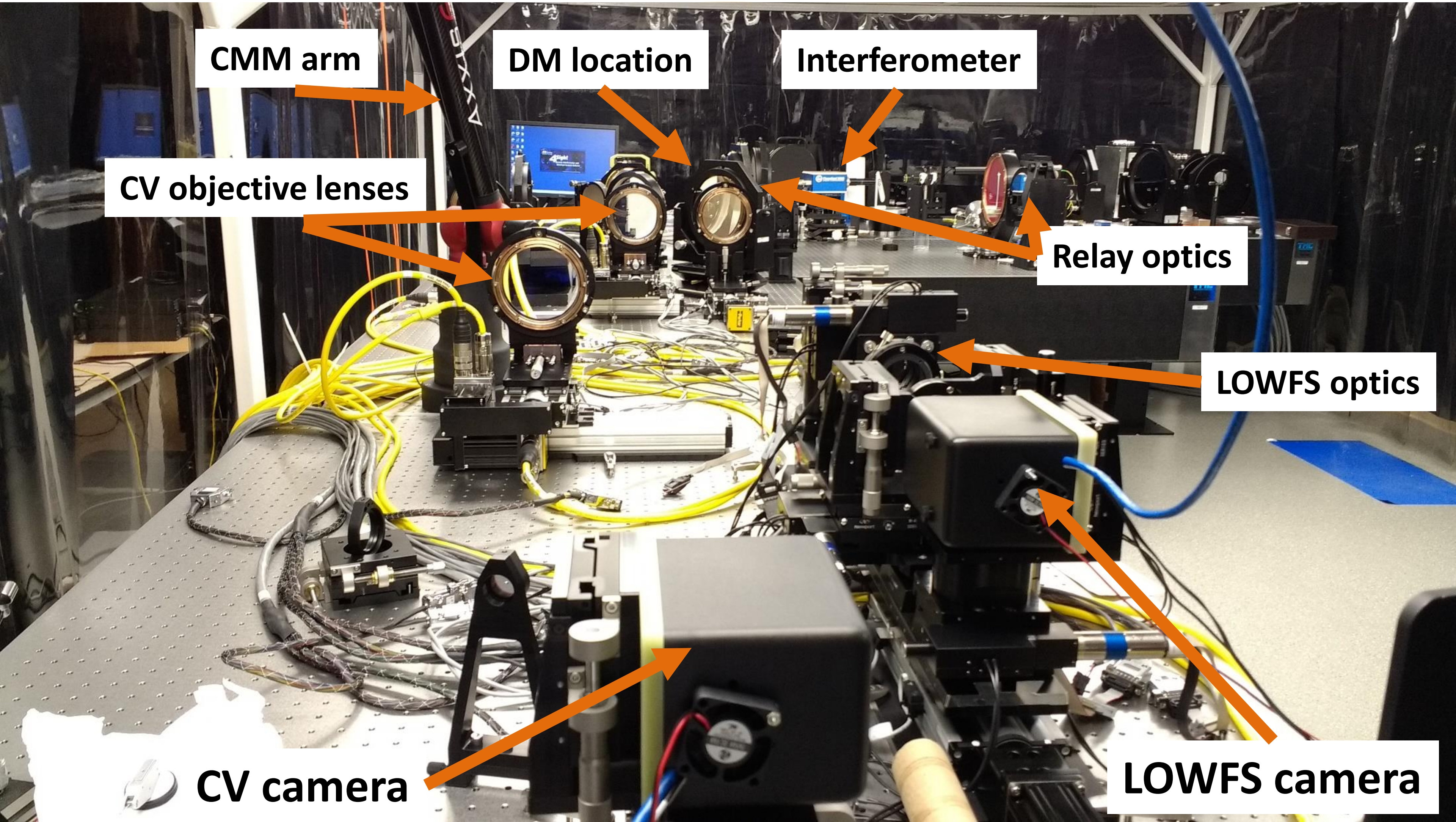


Coude Platform Installation – 10/27/2016

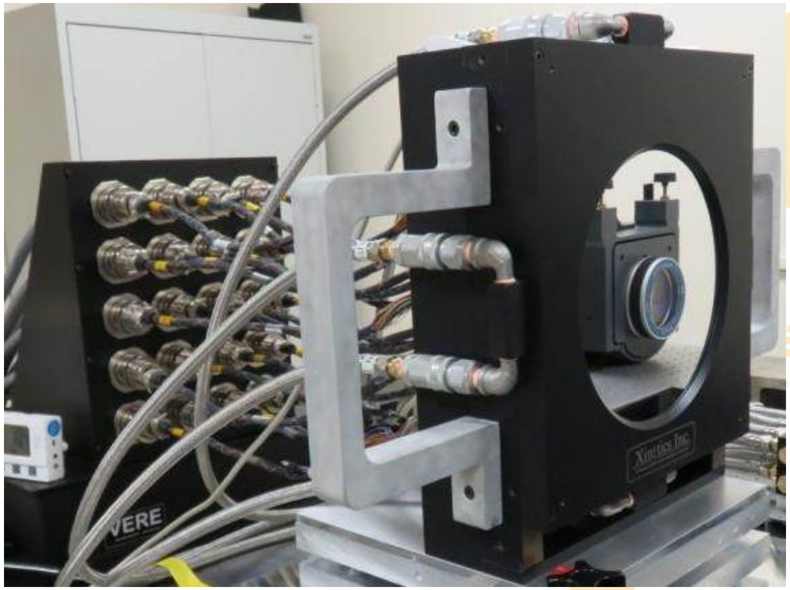


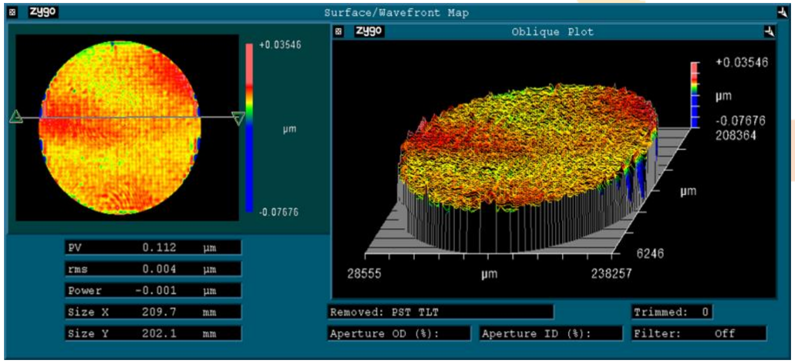

Field steering mirrors select from
90" FoV for WFS lock points
DM (M10)
1600 actuators
Light from M9
Light to Instruments
High Order WFS
1521 subapertures
WFC/Instrument
Beam-splitter BS-1
Low Order WFS
37 subapertures
Context viewer

DKIST WFC Lab, Boulder CO



M10 Deformable Mirror

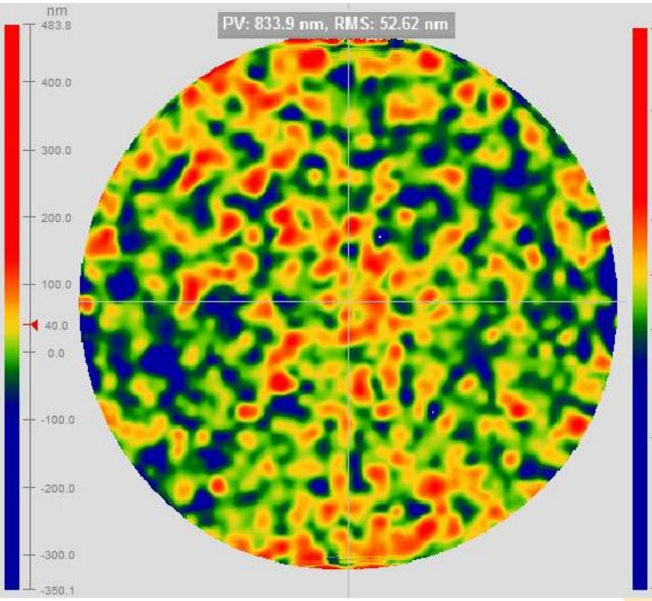




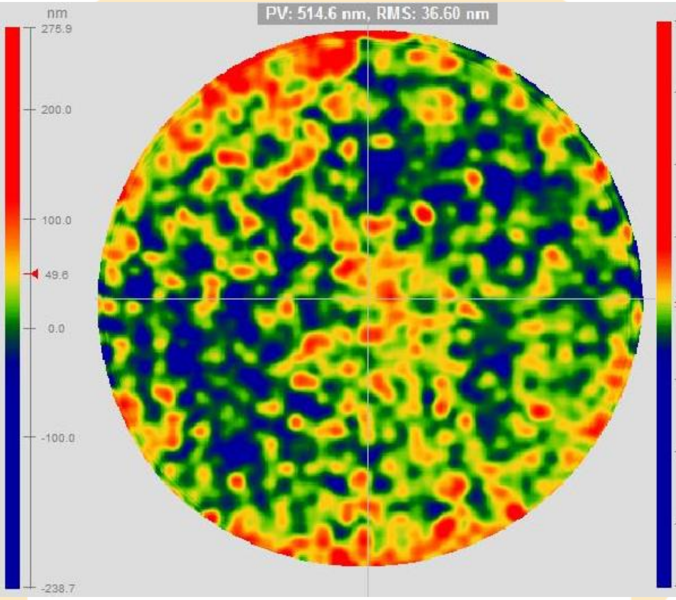
Specification	Requirement	FAT result
Clear aperture	210 x 202 mm elliptical	Pass
Actuator count	1584 minimum (44 across) No defective actuators	1600 actuators No defective actuators
Actuator spacing	4.87 mm Horizontal 4.70 mm Vertical	Pass
Total stroke	5.0 µm	5.17 microns minimum
Interactuator stroke	2.0 µm	2.0 microns
Actuator coupling	20%	16.7% max
Flat shape	15.8 nm RMS	6.1 nm RMS
Rise time	100 µs	88.98 µs max
Settle time	200 µs	136.8 µs max
Non-linearity	5.0%	4.9% max
Hysteresis	5.0%	3.08% max
Update rate	3 kHz	5 kHz
Surface temp	+0/-2C from ambient (20C) 100 W/m^2 absorbed heat	Pass

Fabricated by AOA Xinetics, FAT in May 2015, delivered in September 2015

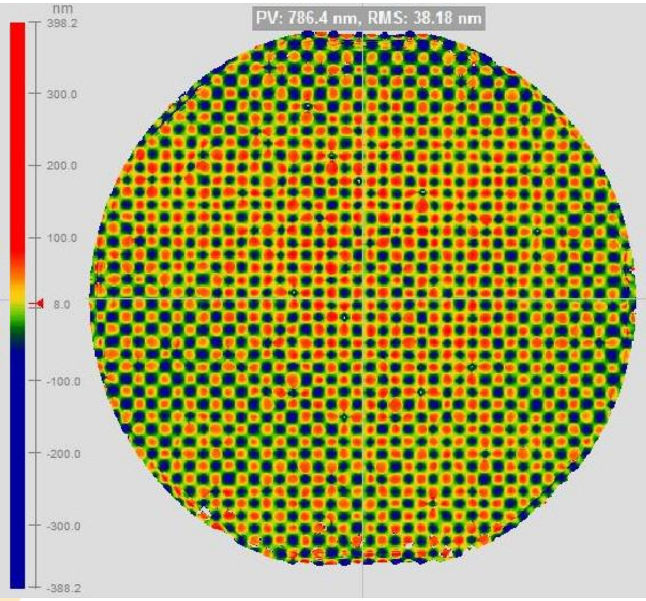
DM driven by DKIST RTC



Unpowered shape
52.62 nm rms



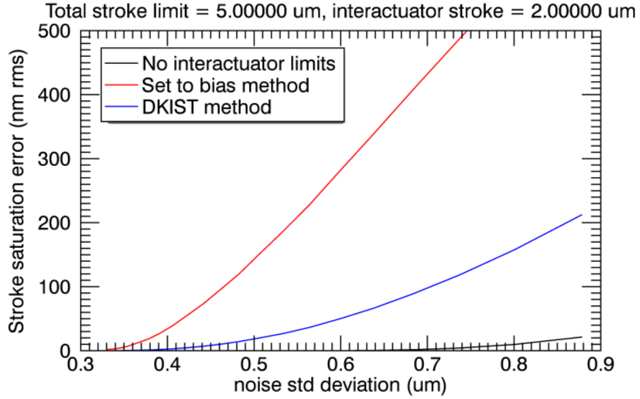
Bias shape
36.60 nm rms

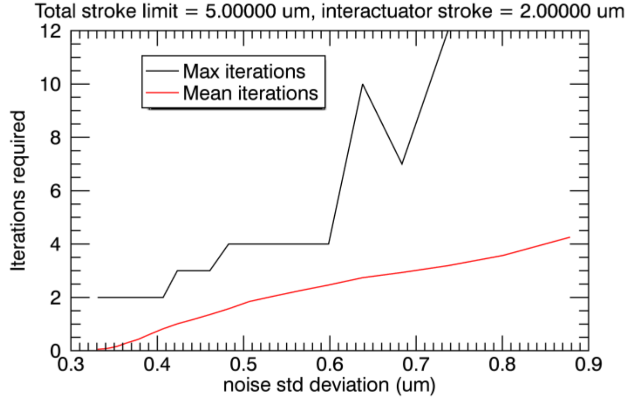


Waffle poke

Due to polishing at bias voltage, bias shape is flatter than unpowered shape!

DM interactuator stroke limiting algorithm





2 µm maximum inter-actuator stroke
Iterative algorithm
Computationally simple
Typically 10 µs compute time or less
Improved performance vs. "set to bias" method
Maximum 17 iterations needed in testing

For each actuator pair in violation:

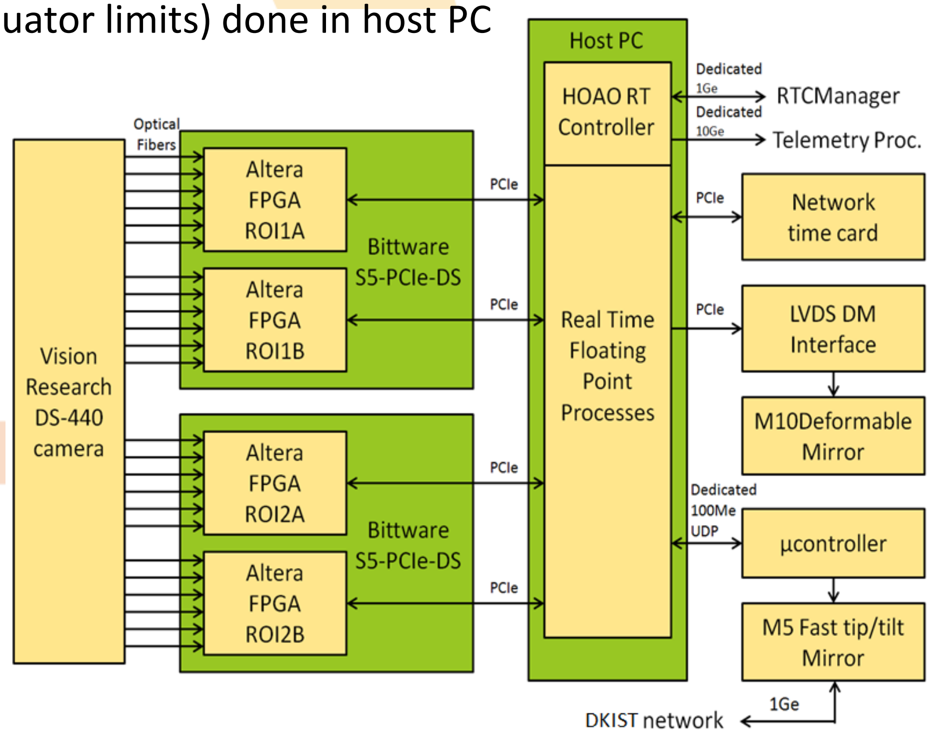
$$a_1 = a_1 + \frac{\delta a - a_{max}}{2} + 1$$

$$a_2 = a_2 - \frac{\delta a - a_{max}}{2} - 1$$

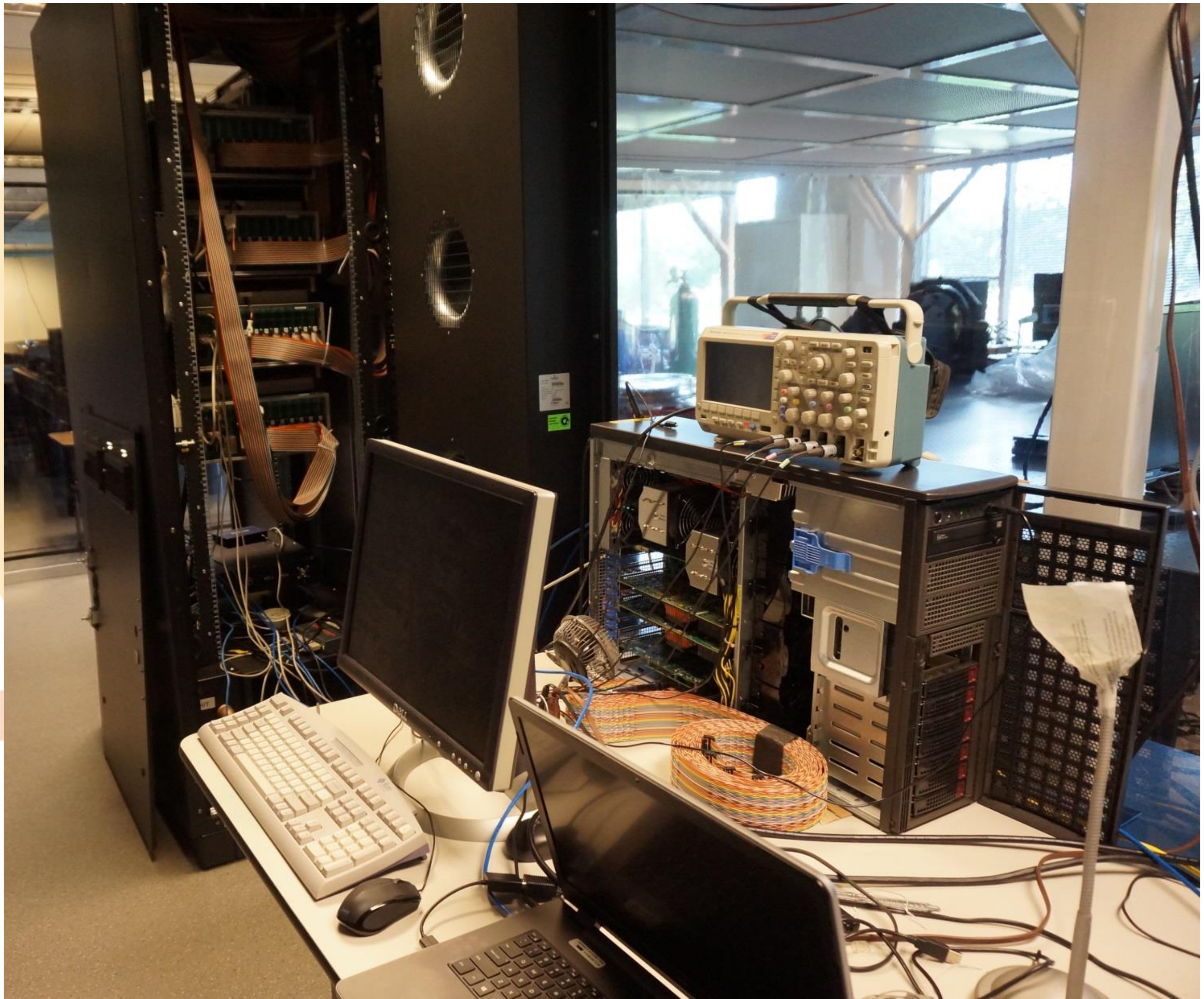
a_1: Smaller value actuator command
a_2: Larger value actuator command
$\delta a = a_2 - a_1$
a_{max}: Maximum allowed interactuator difference

Real-Time Controller

- CMOS camera, 960 x 960 pixel active region, 10-bit pixels, 1975 Hz update rate
- 20 x 20 pixel subaperture images
- As soon as a full row of subapertures arrives, cross-correlations begin
- FPGAs calculate dark, flat, cross-correlations, interpolation, reconstruction matrix
- Final processing (PI control loop, interactuator limits) done in host PC
- Full-frame telemetry:
  - slopes
  - reconstructed residuals
  - DM commands
  - subaperture images (10 Hz update)
  - 12 kB / frame (~24 MB / sec)

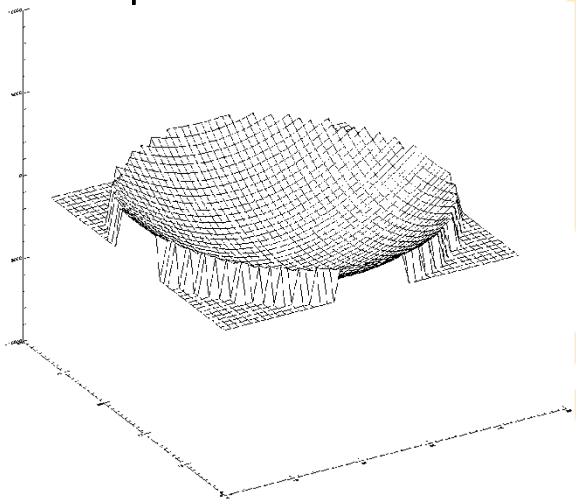


Real-Time Controller

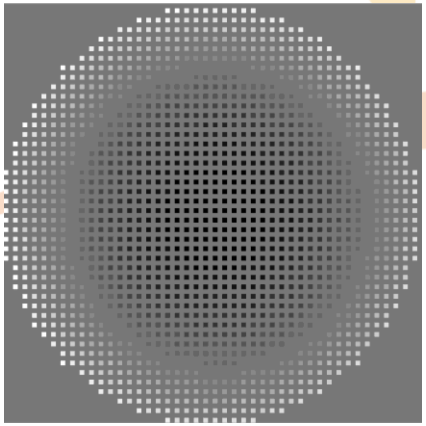


Real-Time Controller

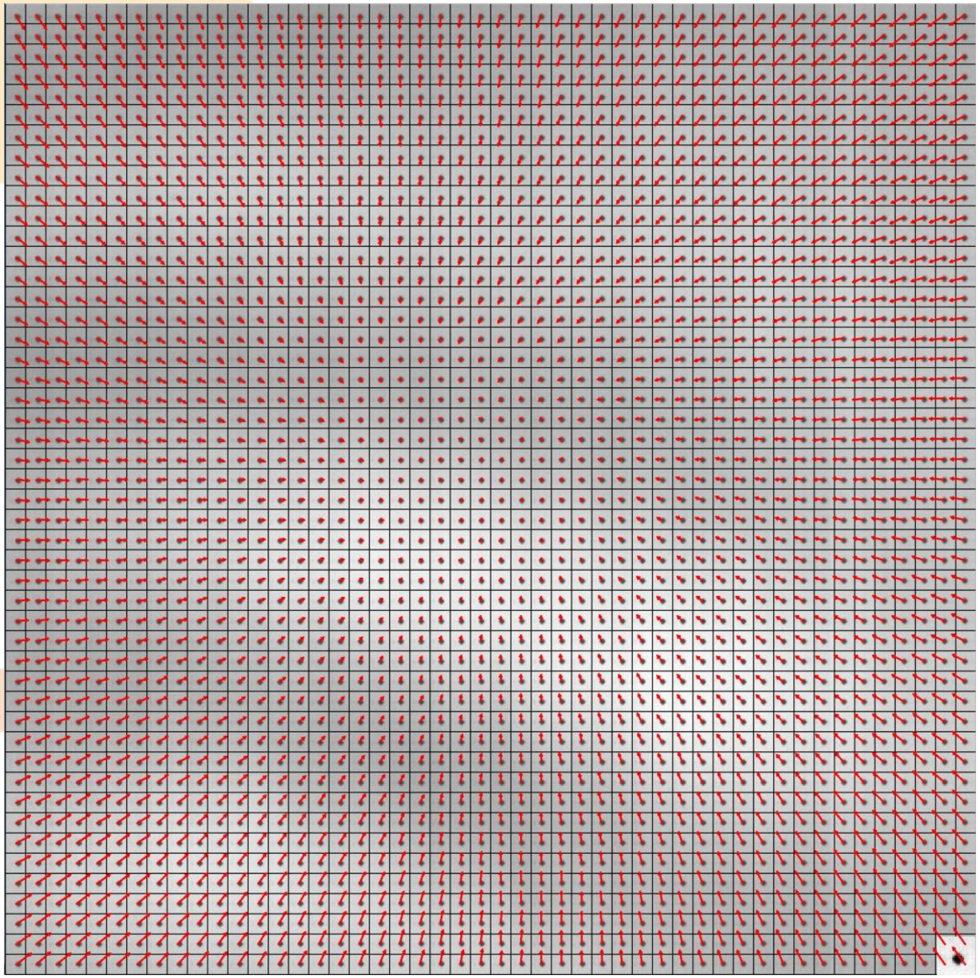
Input wavefront



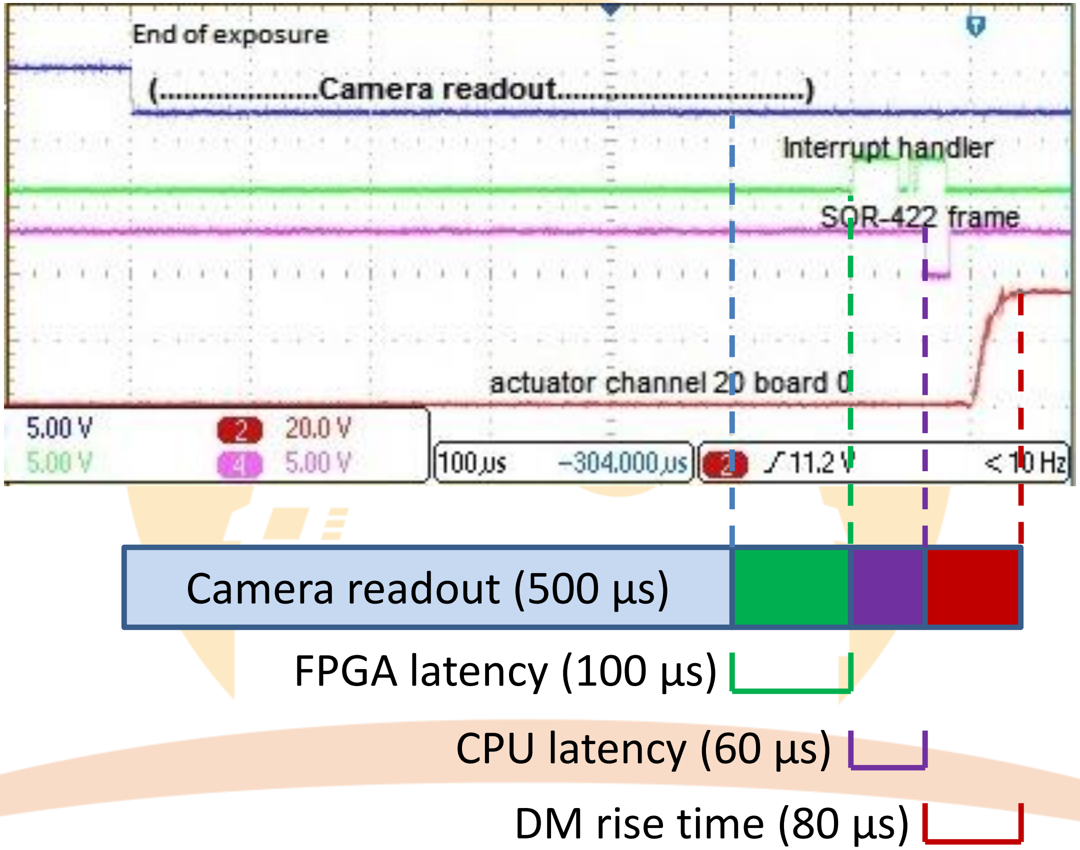
DM commands



Shift measurements



RTC Timing



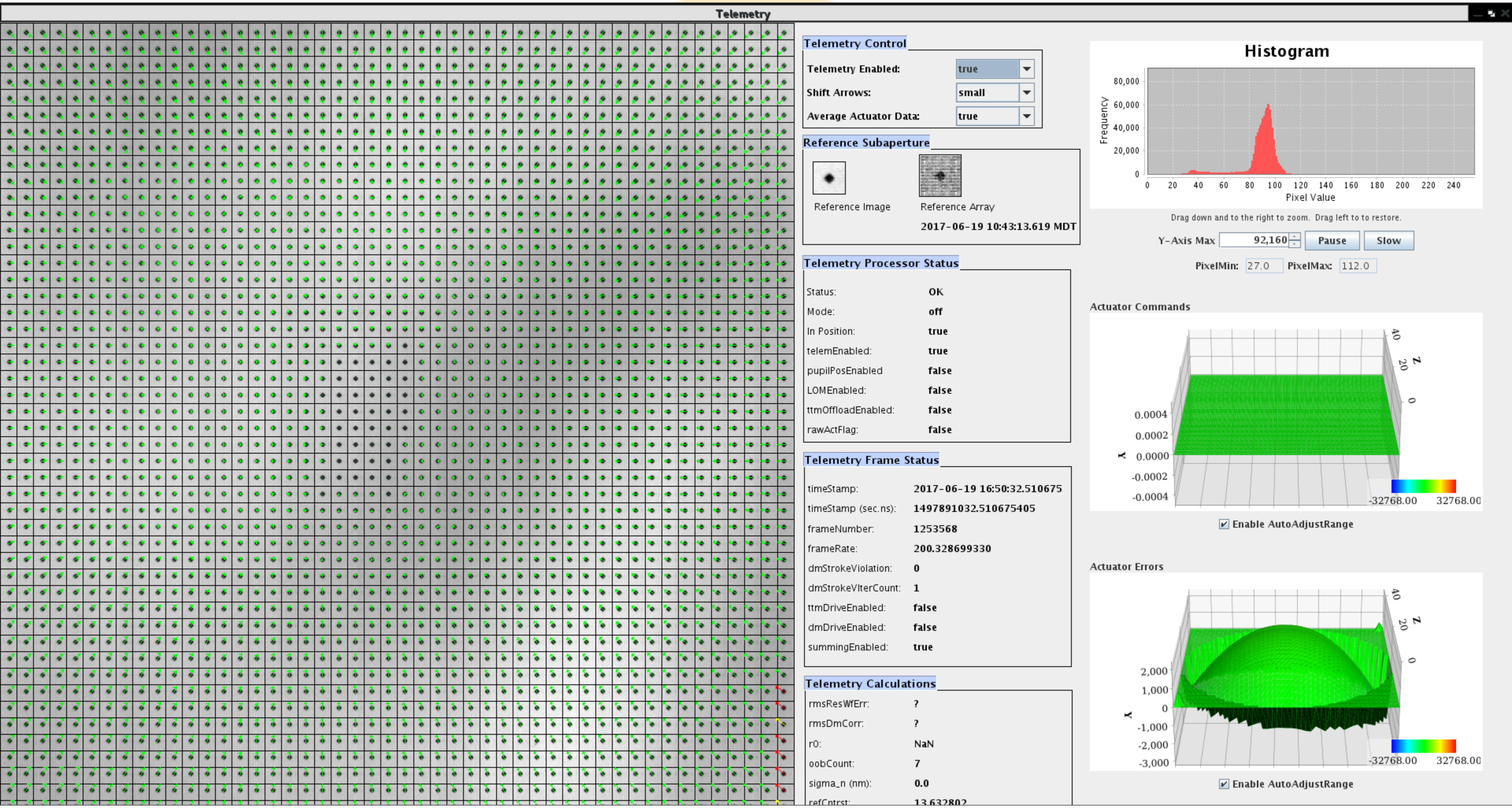
Total Latency: 730-750 µs
Closed loop bandwidth: 150 Hz

HOAO Telemetry

Dedicated Telemetry Processor

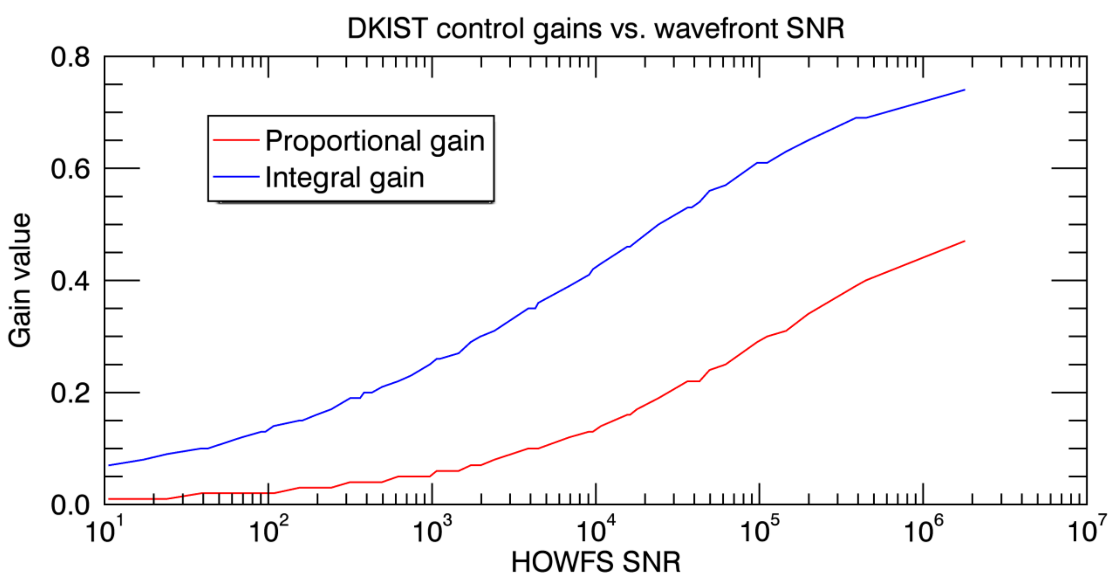
- Receives stream of raw slopes, DM commands, subaperture images
- Estimates r_0, sensor noise, illumination levels
- Tunes control loop gains and reconstruction matrices based on seeing conditions and wavefront sensor noise
- Computes pupil position on wavefront sensor
- Auto-adjusts camera exposure times
- Auto-updates reference image when correlation degrades
- Publishes telemetry data with delay <100 ms for use in speckle reconstruction

HOAO Telemetry Screen



Automatic PI Gain Tuning

- HOAO telemetry processor estimates wavefront sensor noise using method described by Poyneer[1]
- HOAO telemetry processor also keeps a running estimate of r_0
- Wavefront variance (estimated from r_0) and sensor noise can be used to estimate the "wavefront SNR"
- Integral and proportional gains in the control system are a function of the wavefront SNR
- Telemetry processor will use a look-up table, initially populated by values obtained in simulation, to update the control loop gains based on its r_0 and noise variance estimates.
- Gain updates happen between 10 and 100 Hz.



[1]Poyneer, L.A., "Scene-based Shack-Hartmann wavefront sensing: analysis and simulation", Applied Optics, 42, 29, 2003.

Automatic reconstruction matrix update

- Reconstruction matrices will be constructed from the Karhunen-Loeve[2] (K-L) basis set
- Each K-L mode has an expected SNR, calculated by dividing its expected atmospheric variance by its noise propagation coefficient through the DKIST HOAO system.

$$SNR(i) = \frac{\sigma_{wf}^2(i)}{p(i)}$$

$\sigma_{wf}^2(i)$ is the expected atmospheric variance of the i^{th} K-L mode

$p(i) = \left[\left(\mathbf{T}_{\text{wfs}}^T \mathbf{T}_{\text{wfs}}\right)^{-1}\right]_{i,i}$ where $\mathbf{T}_{\text{wfs}}$ is the system sensitivity matrix in the K-L basis.

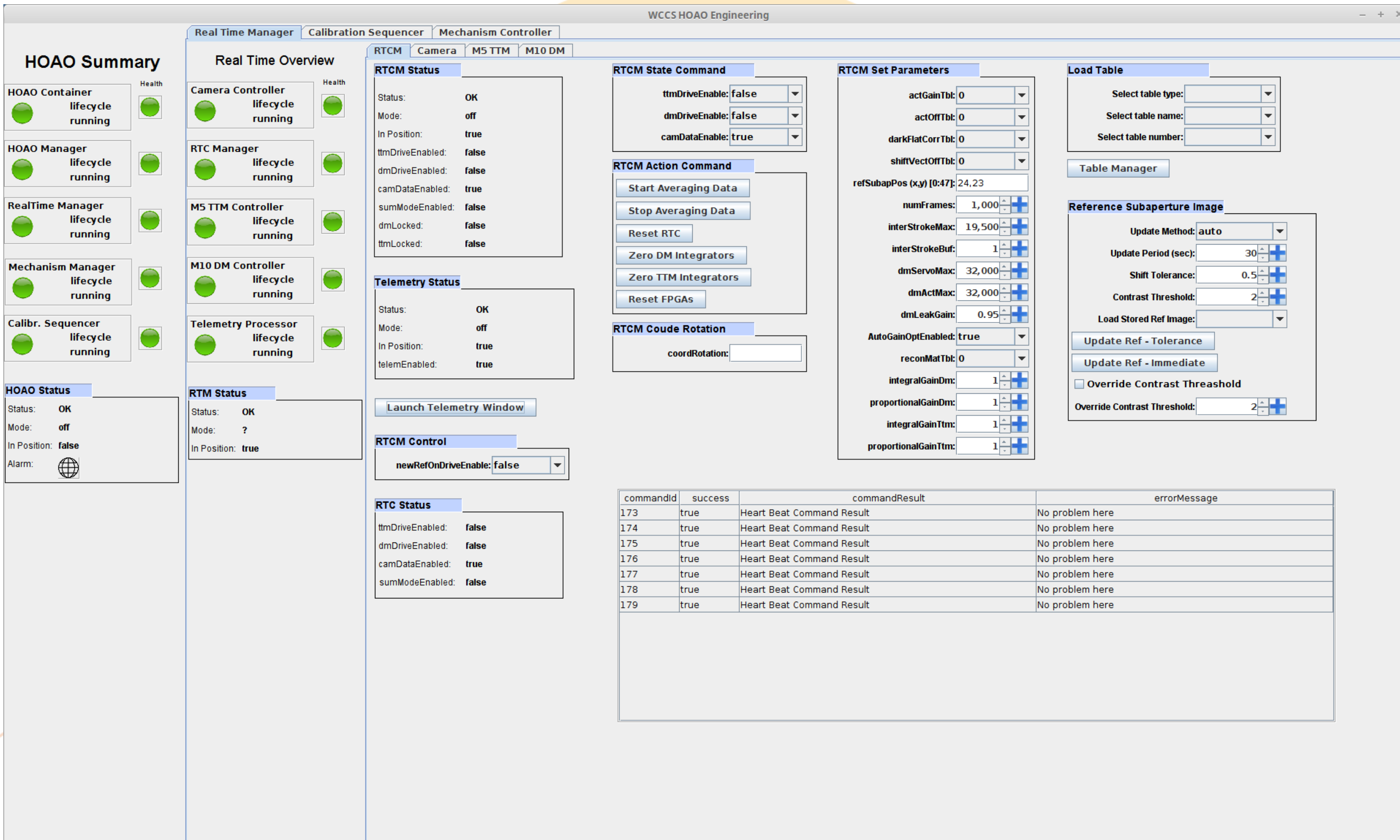
- We sort the K-L modes by expected SNR, in decreasing order, and create reconstruction matrices by setting a minimum SNR quotient between the first and last modes.

Matrix #	1	2	3	4	5	6	7	8	9	10	11	12
K-L modes corrected	3	7	18	33	74	143	256	423	663	1049	1417	1600
Relative SNR	2	4	8	16	32	64	128	256	512	1024	2048	4096

- These 12 matrices are stored in the RTC memory and can be switched between as the wavefront SNR (estimated from r_0 and measurement noise) changes. Updates at 10-100 Hz.
- The system will also change matrices to preserve stability if the number of saturated subapertures exceeds the saturation threshold.

[2]Wang, J. Y., and Markey, J. K., "Modal compensation of atmospheric turbulence phase distortion", JOSA 68, No. 1, 1978.

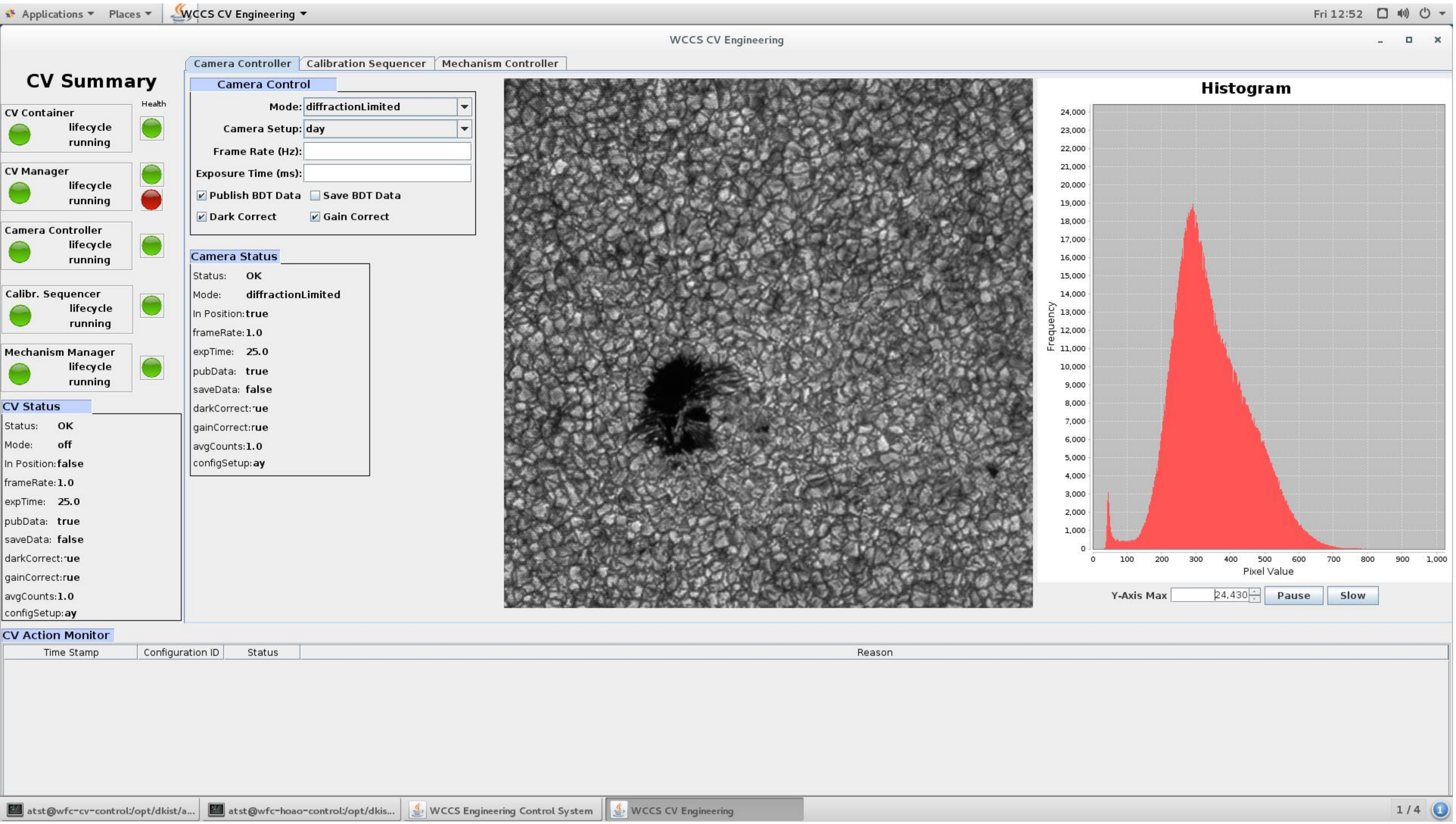
HOAO Engineering GUI



Context Viewer installed

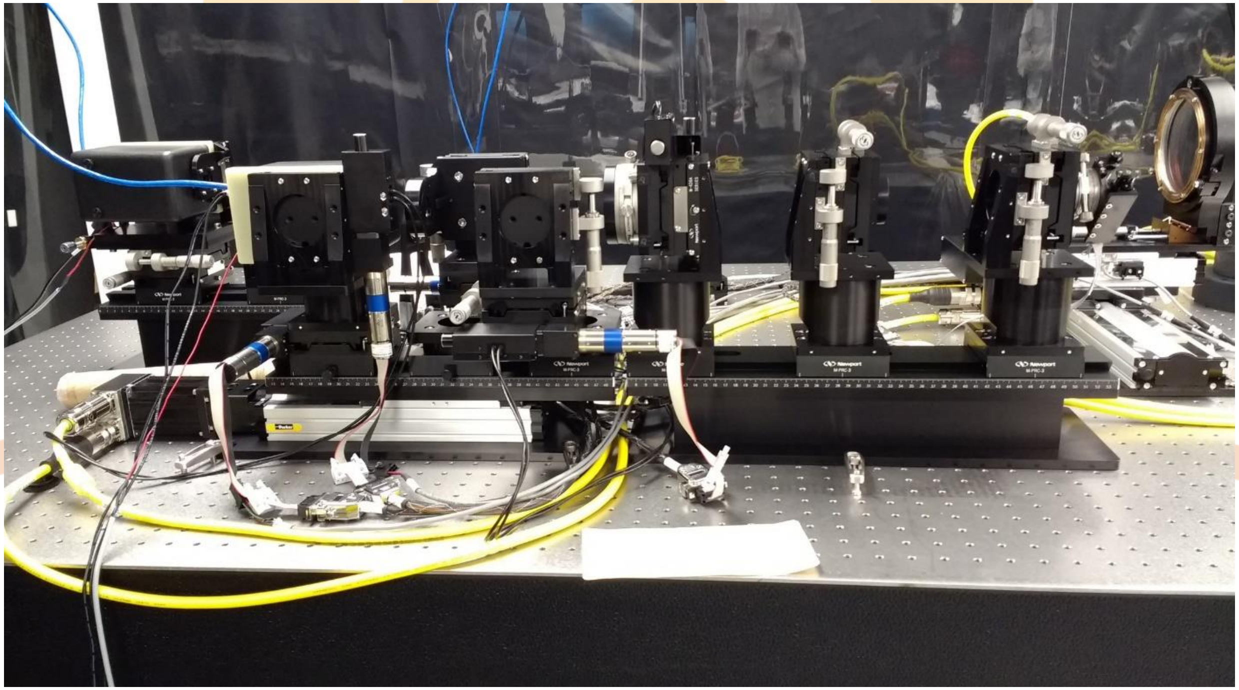
- Selectable field of view – 30" or 60"
- 10 Hz frame rate
- Motorized control of objective lens positions for focus and FoV selection
- Automated calibration scripts
  - Pixel dark and gain calibrations
  - Point source centroiding (used in boresight and pointing calibrations)
  - Focus optimization
  - Solar limb identification
  - Strehl calculation (point sources only)
  - Plate scale (using grid target as reference)

Context Viewer GUI

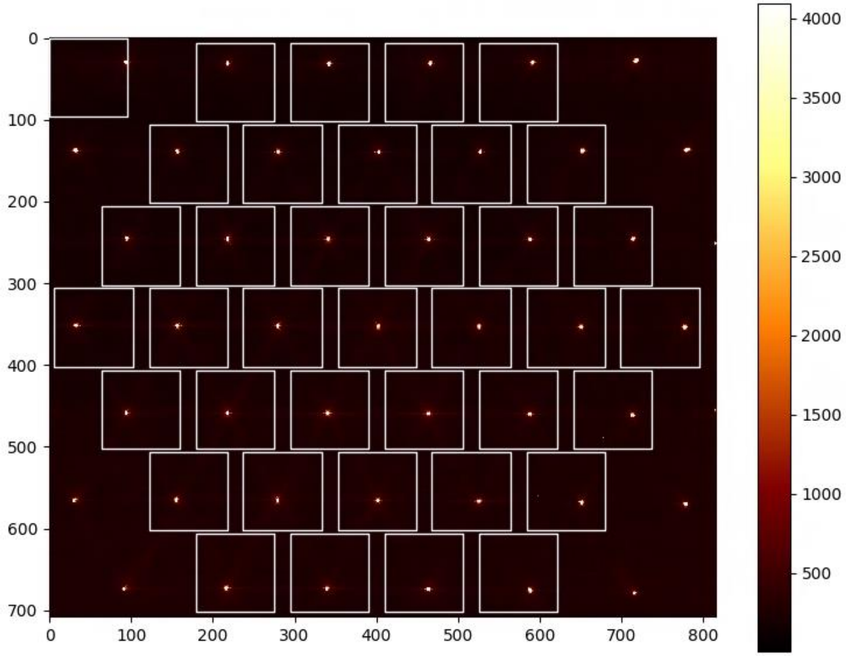


LOWFS installed and aligned

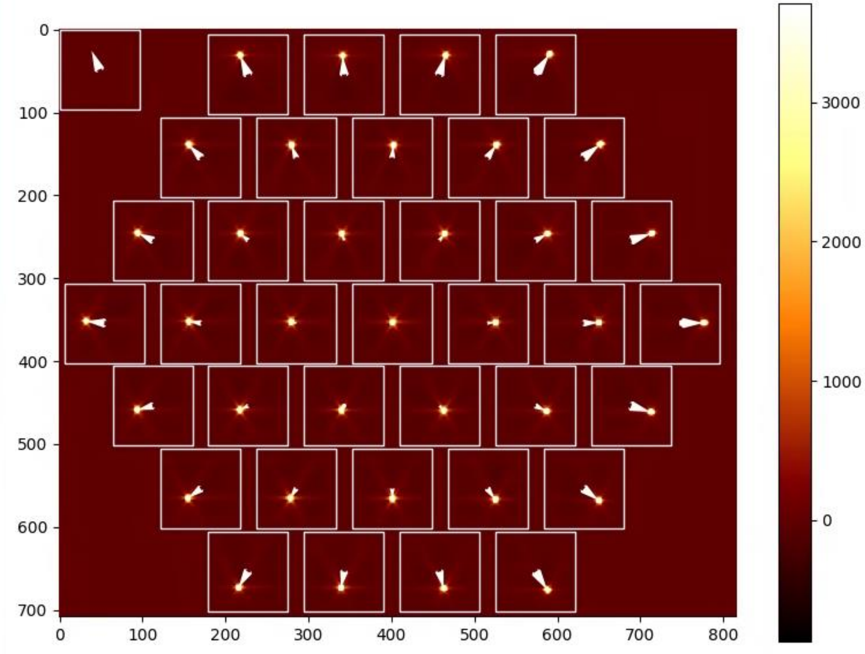
- Optics aligned on bench
- Motion control for positioning lenses, microlens array, and camera
- Software almost complete
- Working on automated calibration scripts



LOWFS images



Raw subaperture images

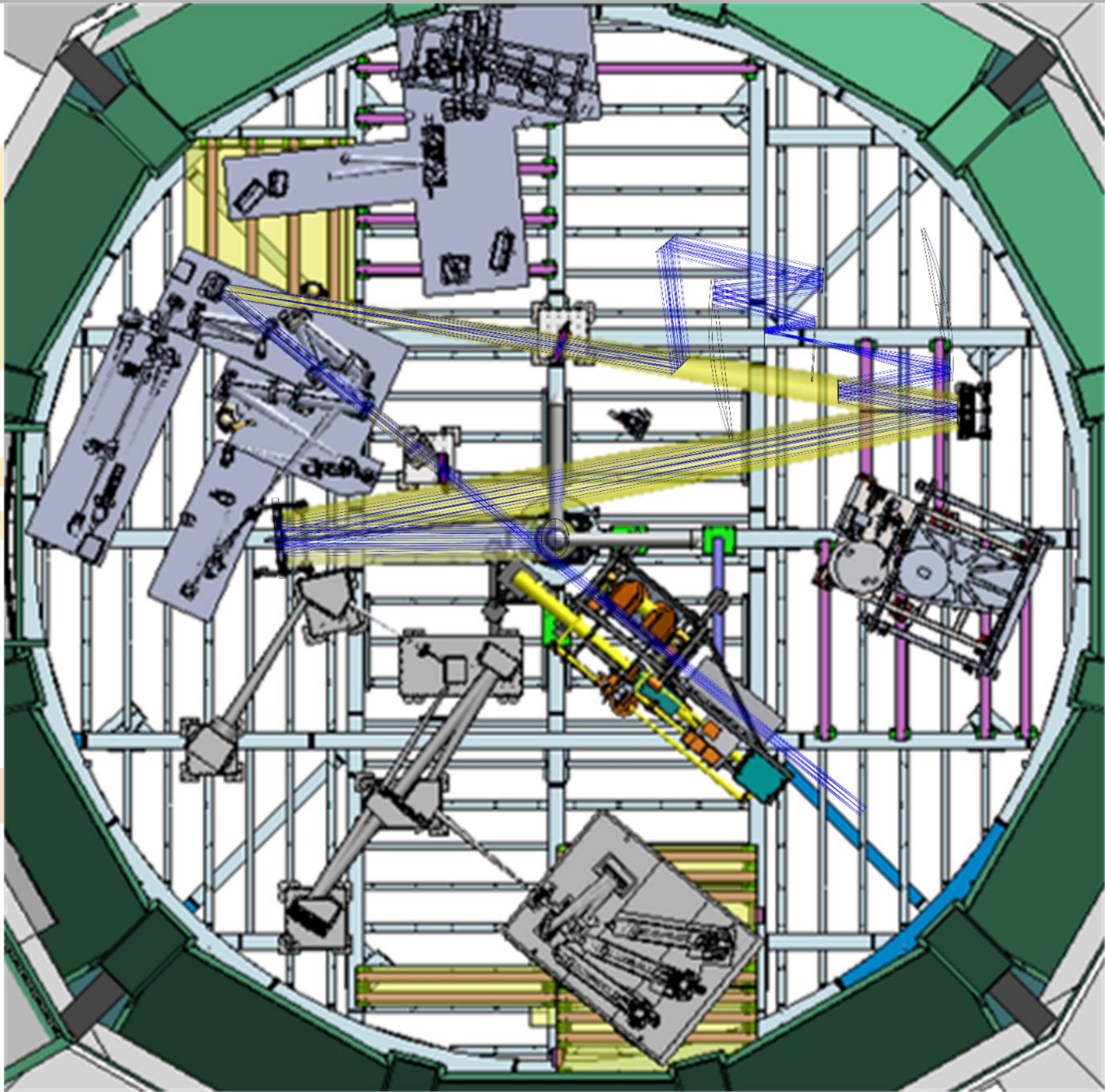


Cross-correlations

MCAO upgrade: preliminary design

- In progress:
  - Determine how many DMs, which conjugate heights needed
  - Design wavefront sensor to fit on current HOAO optical table
  - Define hardware requirements (DMs, WFS)
  - Finalize optical design of MCAO relay bench
  - Goal: MCAO to be integrated 1 or 2 years after operations
  - Clear: path finder solar MCAO experiment (see D. Schmidt talk)
- Challenges:
  - Hardware:
    - DMs must be large enough. Heating, act. density (goal: 100-300 mm)
    - Need ~10k x 10k x 2kHz camera for multiplexed WFS, not a viable option. How to optimally divide the sensing path between multiple cameras?
  - Space constraints:
    - upper layer DMs must be before ground DM due to coudé lab design
    - WFS must fit in limited space.

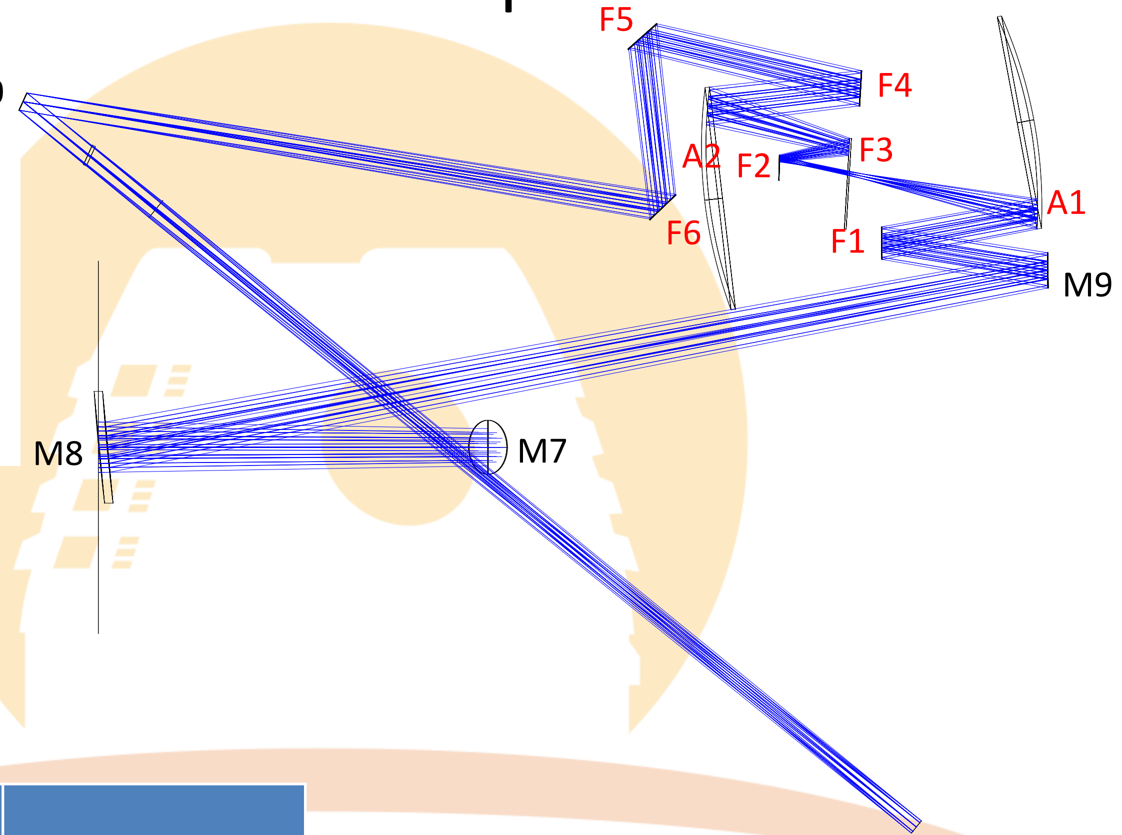
- Preliminary MCAO design concept overlaid on coudé floor.
- Current optical path in yellow, new optical path in blue (2.8 arcmin FoV)
- Pickoff mirrors insert into beam to enable MCAO
- Early concept, looking into options that would allow changing conjugate heights



MCAO concept

WARNING: not an actual design
MCAO relay adds 7 mirrors to the coudé optics (red labels)

6 flat mirrors (F1-F6)
2 Aspheric mirrors (A1 and A2)



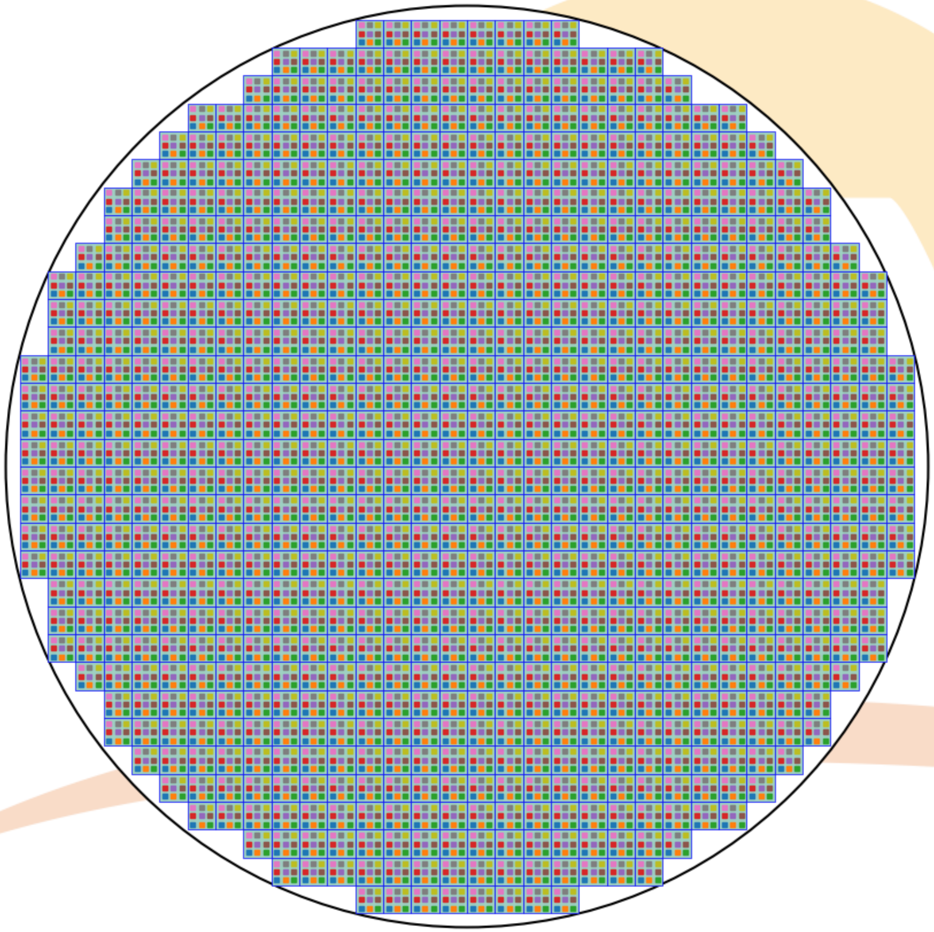
Possible DM positions:

Mirror	Diameter (mm) 2.8’	1’	Conjugate
F2	85	42	16 km
F3	200	125	7.0 km
F4	385	265	4.4 km

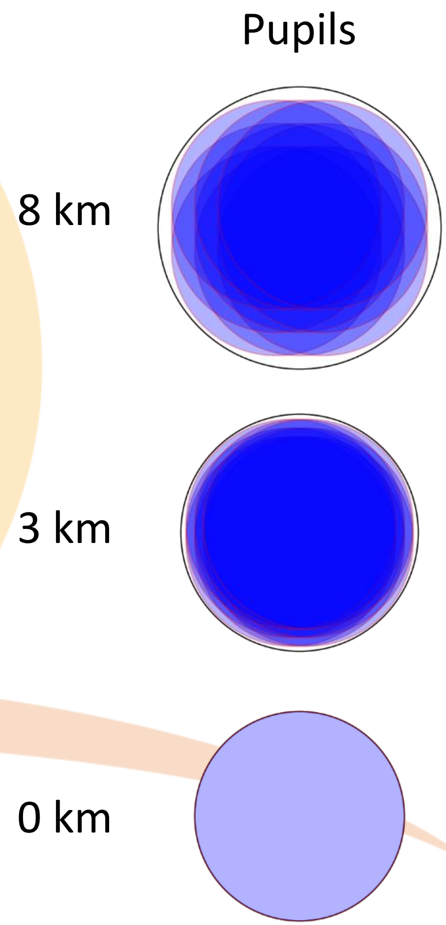
DKIST MCAO Simulation

- Using Blur+KAOS to simulate DKIST MCAO system
- Explore design parameter space over next 1 or 2 years
- Proof of concept test:
  - Adapted from Clear (BBSO pathfinder MCAO) design
  - WFS
    - 32x32 sub-apertures (804 total) with 3x3 sensing directions
    - 37.2” FOV sub-apertures (60x60 px ; 0.62 “/px)
    - 1932x1932 px camera
    - 14,472 shifts total
  - Mirrors
    - 1 TT
    - 3 DMs: 33x33 actuators (869) ; conjugated to: 0, 3 & 8 km
    - 2609 actuators total

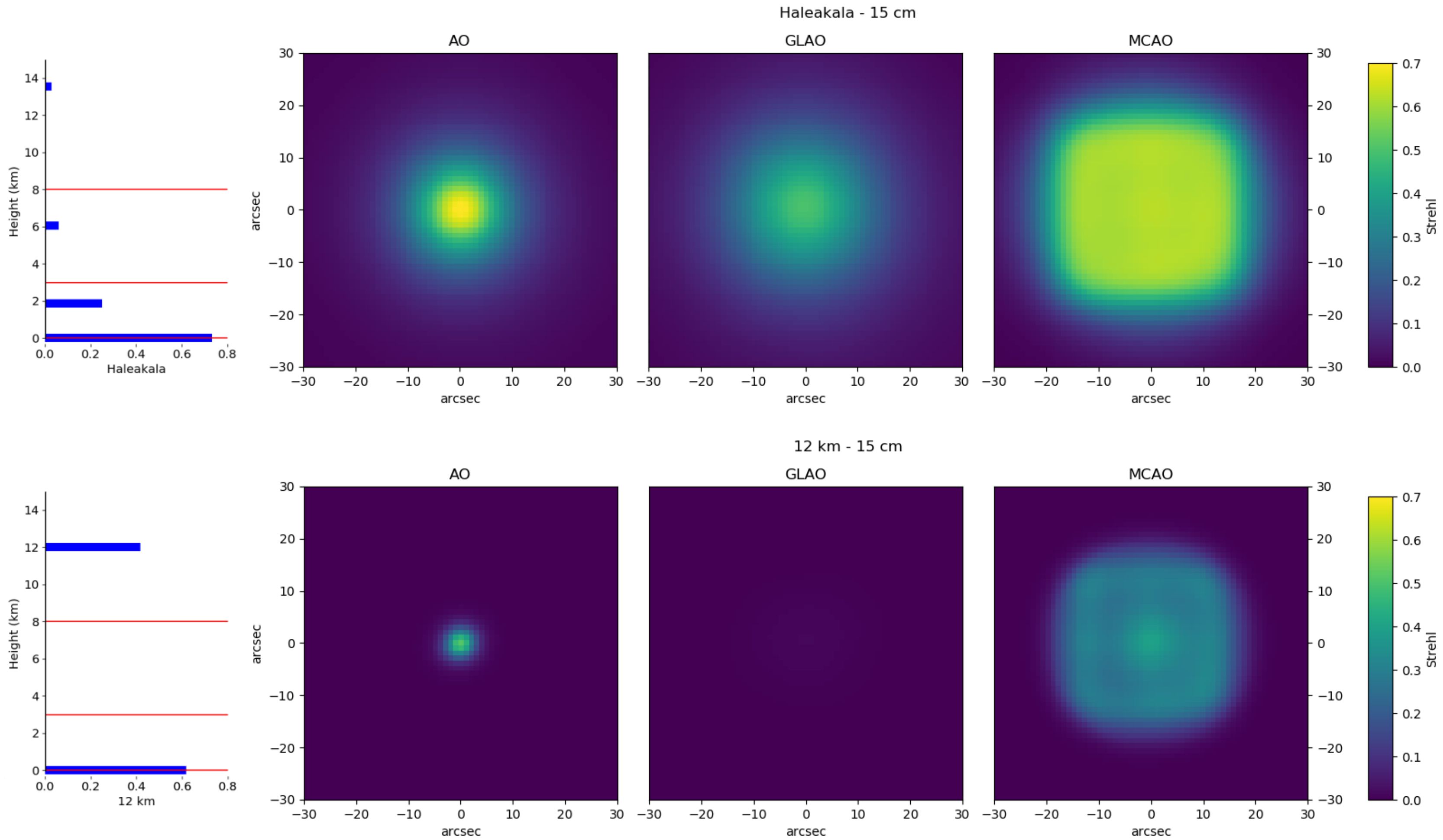
DKIST MCAO Simulation



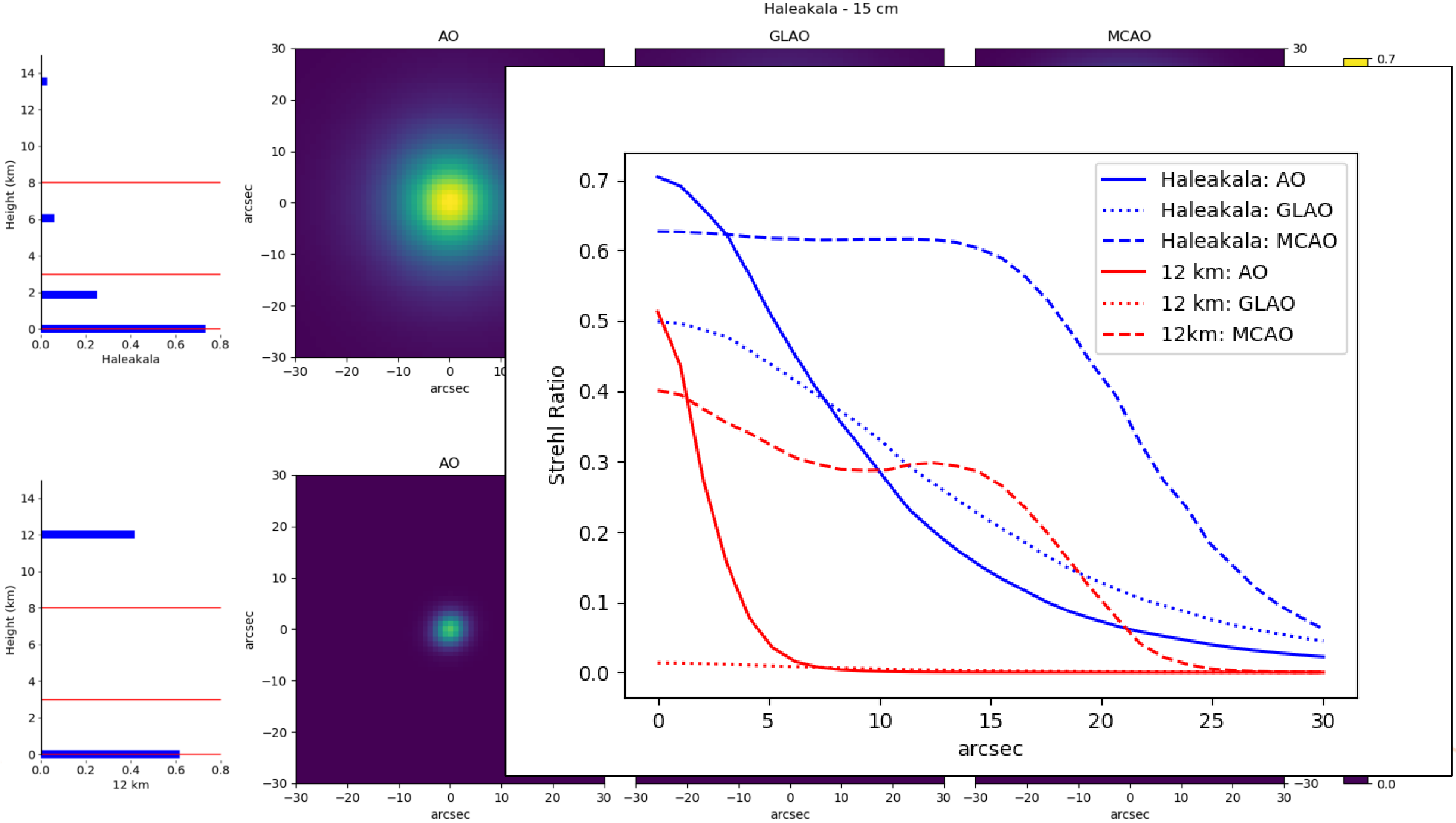
32x32+9 Multi-direction Shack-Hartmann WFS



DKIST MCAO Simulation



DKIST MCAO Simulation



Assembly, Integration, and Commissioning

Fabrication and Lab Assembly Complete	Nov. 2017
Software Complete	Feb. 2018
Laboratory Integration + Testing Complete	Apr. 2018
Full System Testing Complete	Jun. 2018
Ship to Maui Complete	Aug. 2018
IT&C at DKIST Complete	Sep. 2019
Operations	Spring 2020


Thank You!
Photo by Cathy Oleson, July 24, 2016.