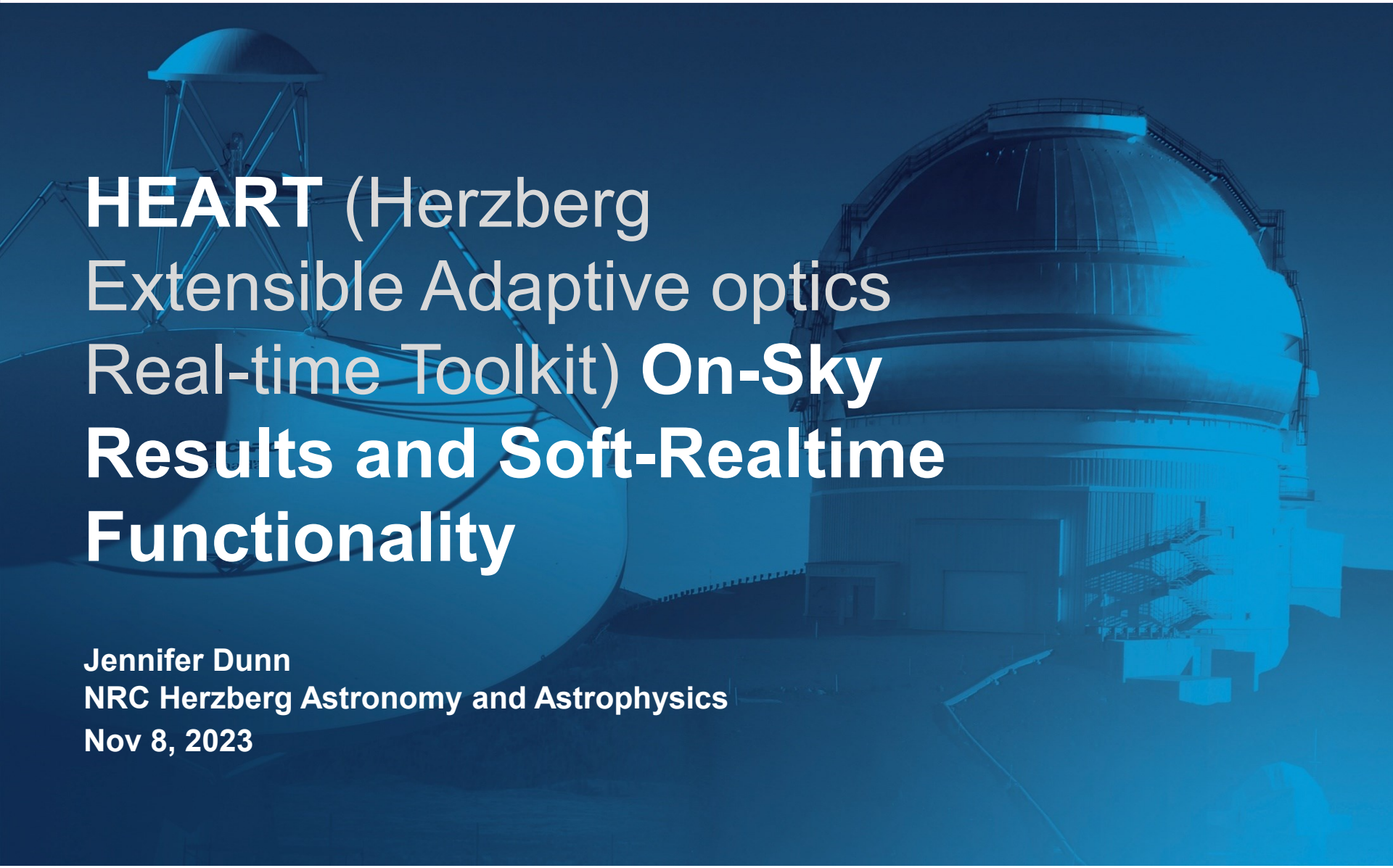


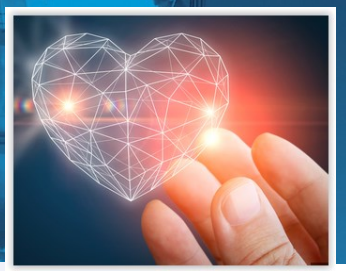
HEART (Herzberg Extensible Adaptive optics Real-time Toolkit) **On-Sky Results and Soft-Realtime Functionality**

Jennifer Dunn
NRC Herzberg Astronomy and Astrophysics
Nov 8, 2023

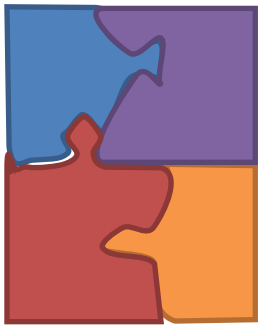
Summary

- HEART RTC and On Sky using REVOLT (the Research, Experiment, and Validation of Adaptive Optics with a Legacy Telescope)
  - Functional diagram /Timings
  - Power Spectral Density (PSDs)
  - Cleanup of uncontrolled modes
  - Psuedo-open loop (POL)
  - Open Loop
- Pyramid WFS and Pixel based reconstruction with REVOLT Copper and more
  - ANDES HEART RTC (ArmazoNes high Dispersion Echelle Spectrograph, formerly HIRES)
- MORFEO HEART HRTC (Multiconjugate adaptive Optics Relay For ELT Observations)
- Soft-Realtime functionality

HEART (Herzberg Extensible Adaptive optics Real-time Toolkit)



HEART is a framework and collection of tools that can be put together into different ways to produce different types of AO Systems



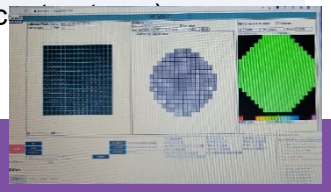
HEART is in the process of being built now!

HEART is going to be used or in the process of at least 4 different International Telescopes

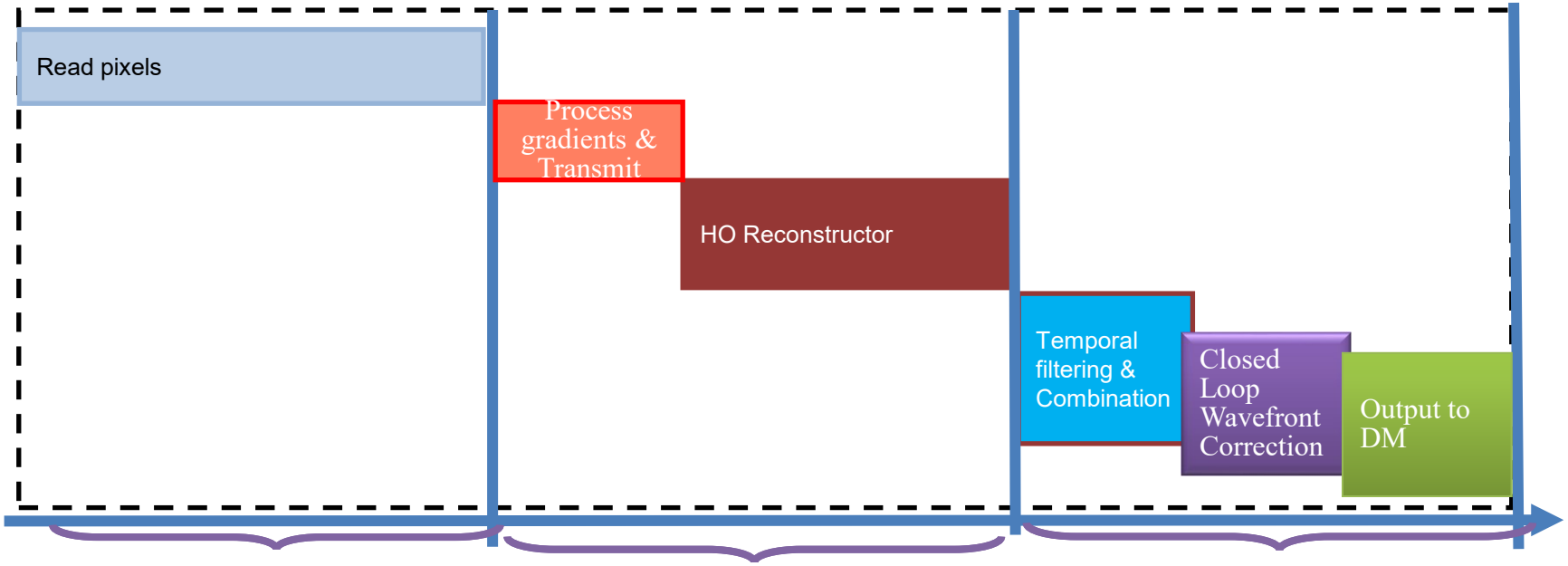
HEART can be used for many different types of AO systems :

- Single Conjugate
  - GPI2 (Gemini Planet Imager) Gemini (in progress)
  - ANDES (ArmazoNes high Dispersion Echelle Spectrograph) ELT (in progress)
  - REVOLT Copper (Canadian On-sky Platform for PWFS Experiment and Research) DAO (in progress)
- Laser Tomography AO and Ground Layer AO
  - GNAO (Gemini North AO) Gemini (in progress)
- Multi-conjugate AO
  - Gemini Future Instrument upgrade (Part of GNAO) Gemini (in progress)
  - TMT NFIRAOS (Narrow Field Infrared Adaptive Optics System) TMT (in progress)
  - MORFEO (Multiconjugate adaptive Optics Relay For ELT Observations) ELT (in contract neg)
- Multi-Object AO
  - REVOLT Gold (GIRMOS Open Loop Demonstration) DAO (on sky!!!)
  - GIRMOS (Gemini Infrared Multi-Object Spectrometer) (in c

HEART has been used on-sky with <u>REVOLT</u>



“Full Frame” Pixels



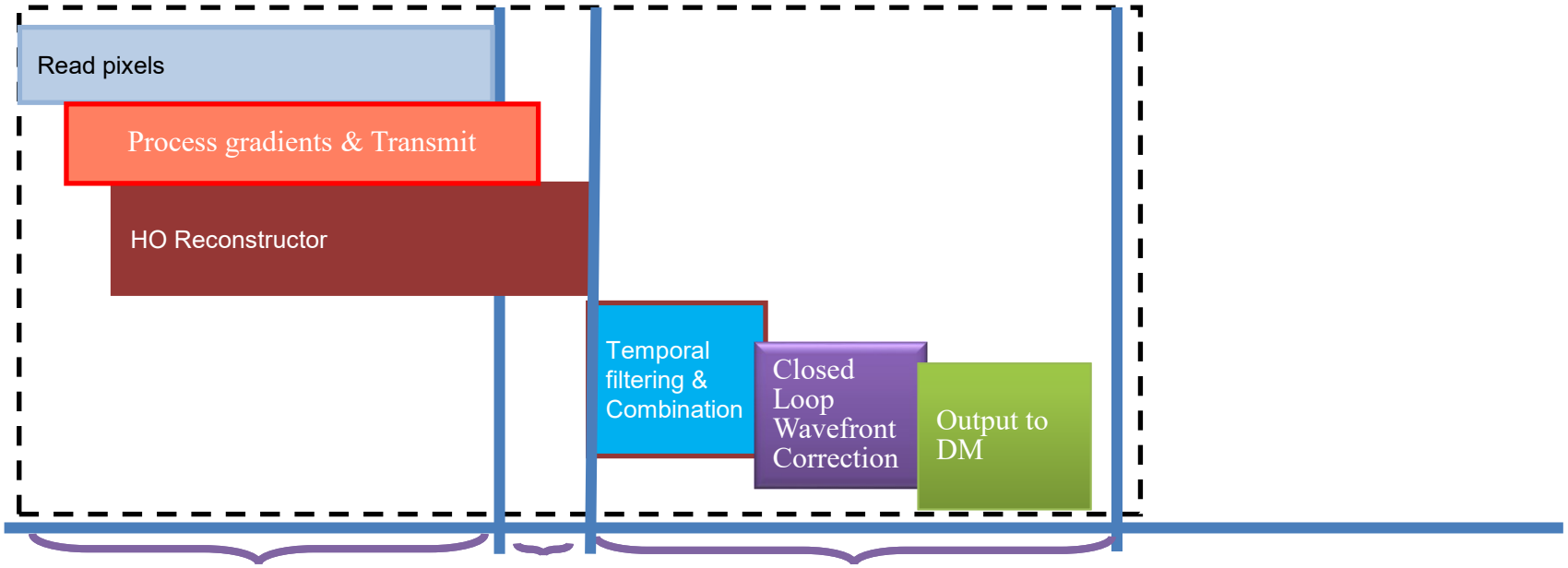
Time to read one full frame of pixels

Dependent on the time required to read out the WFS

After reading the last pixel there time to complete the reconstructor calculation

This is the time to complete all tasks before the next frame

“Streaming” Pixels, much better



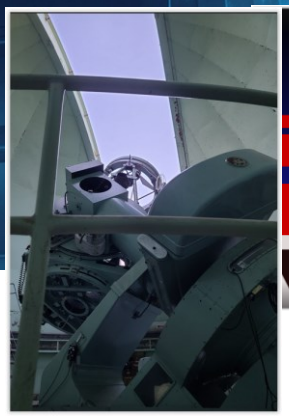
→ Time to read one full frame of pixels

Dependent on the time required to read out the WFS

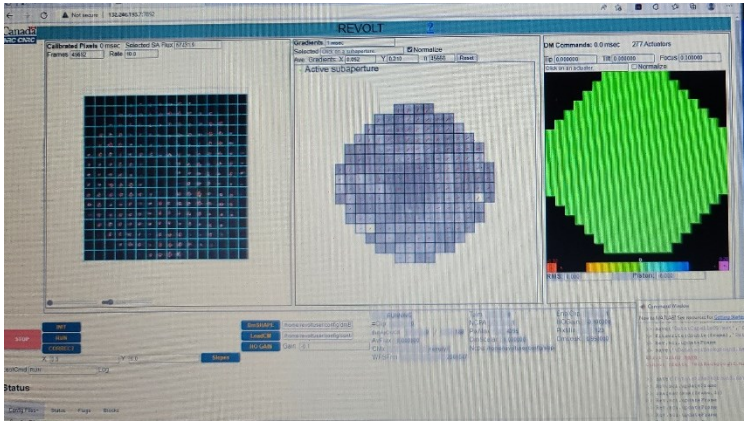
After reading the last pixel it is only a short amount of time to complete the reconstruction calculation

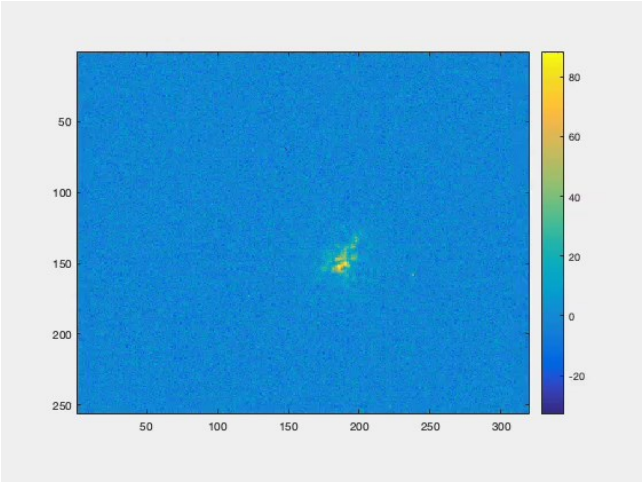
This is the time to complete all tasks before the next frame

HEART RTC On-Sky

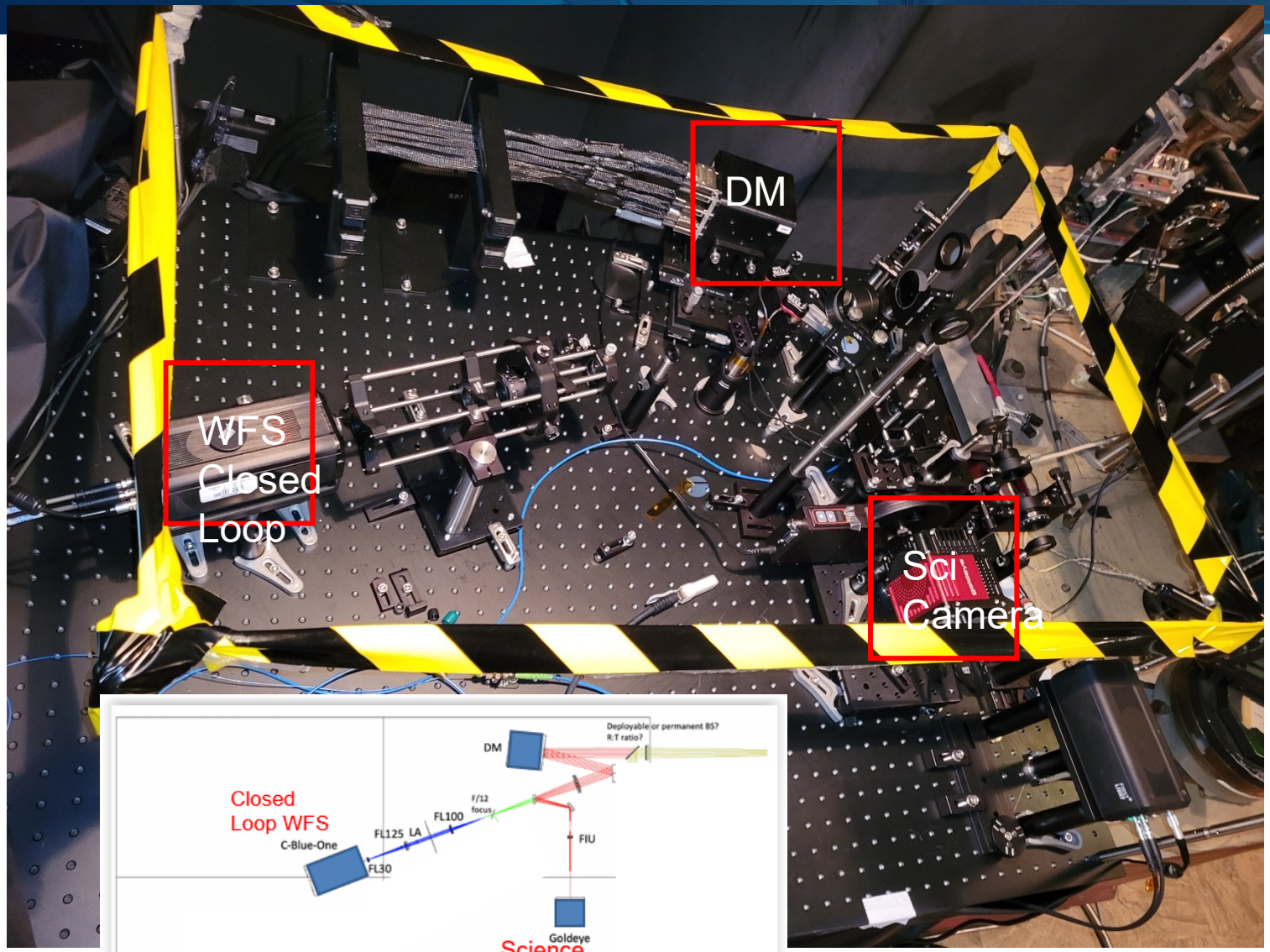


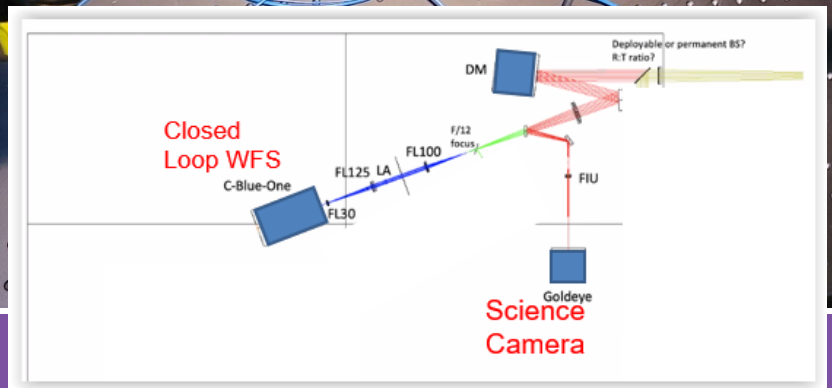
- REVOLT (the Research, Experiment, and Validation of Adaptive Optics with a Legacy Telescope)
- SCAO system for the HAA 1.2m McKellar telescope
- First Light C-Blue One 16x16 SH-WFS, 277-element ALPAO deformable mirror (DM), InGaS science camera
- Site characteristics:
  - Seeing = 1.5” (best) / 2.1” (mean) / 2.5” (90%tile) / 4.2” (worst)
- 4 successful runs so far
  - In September we had 2 runs,
  - October 2 runs with a modification to the bench to add an open-loop WFS





REVOLT Bench





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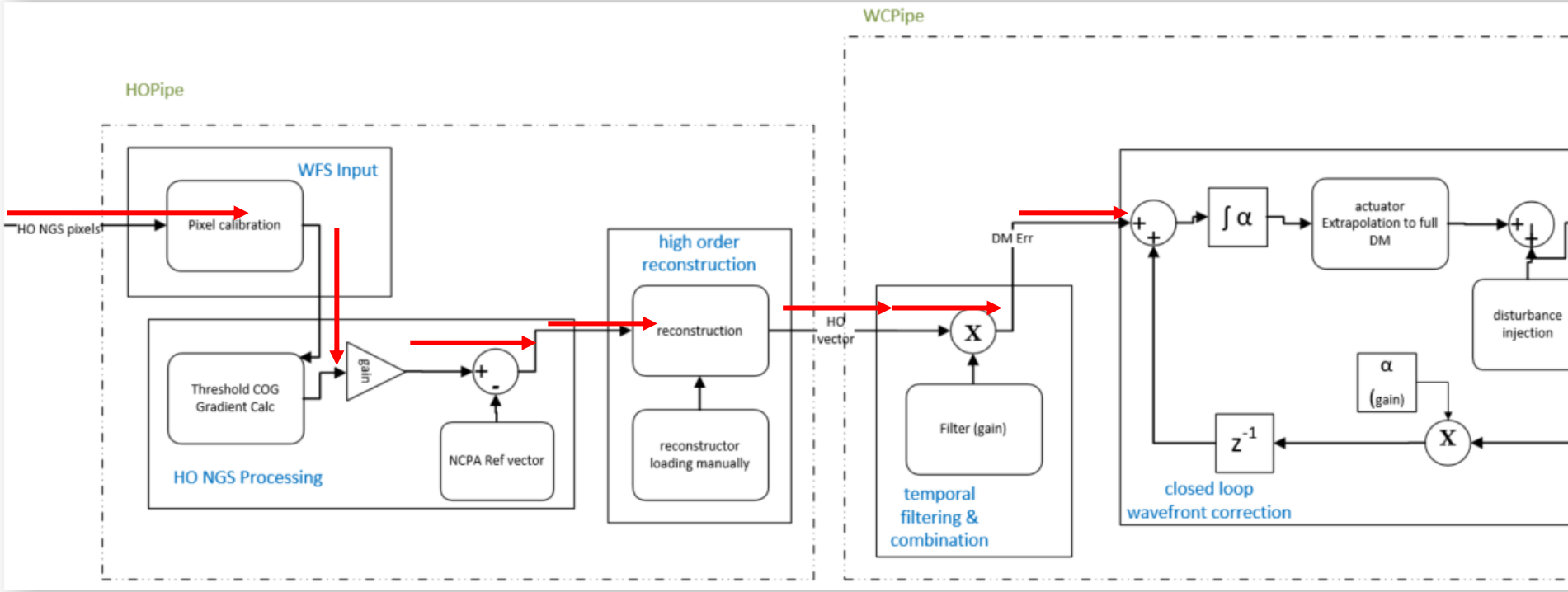
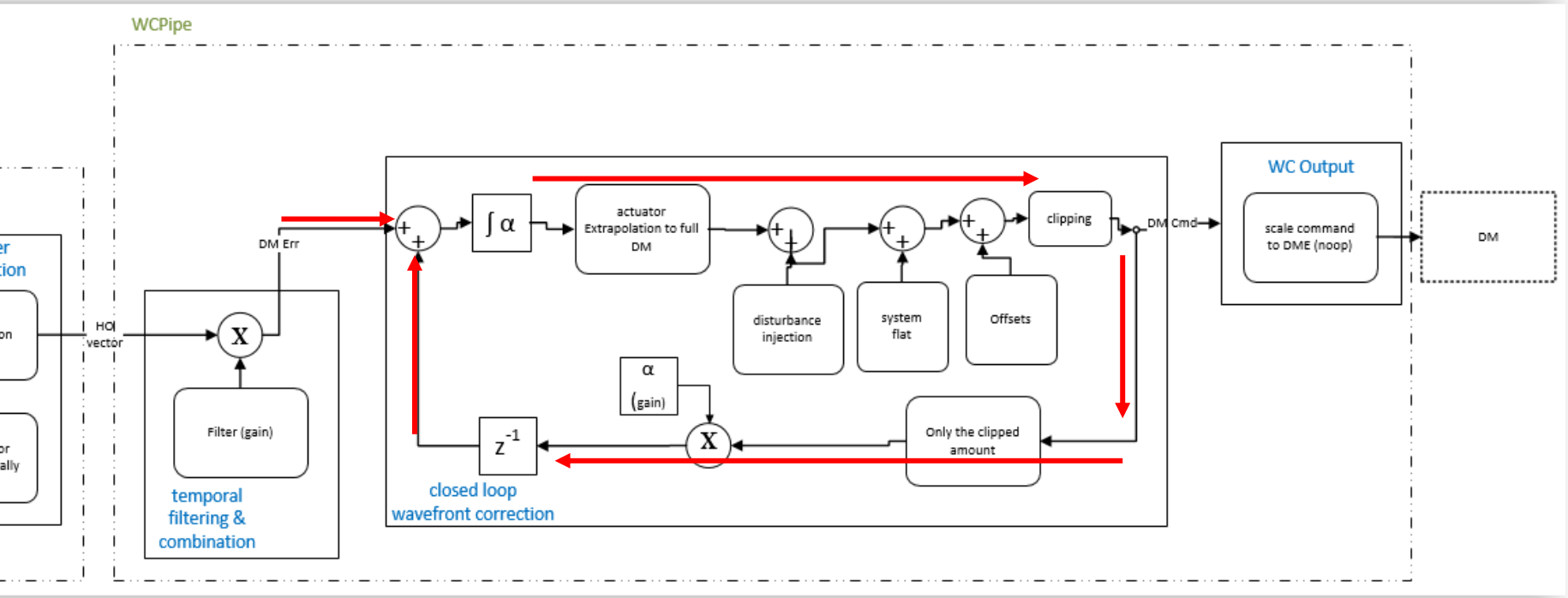
REVOLT – Functional Diagram

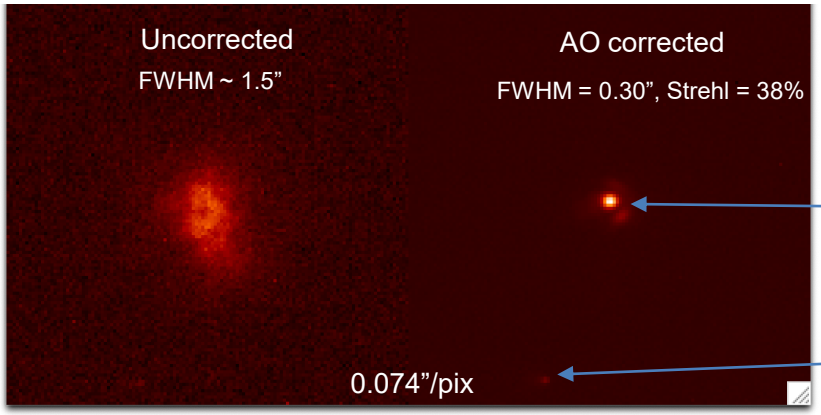


REVOLT – Functional Diagram



Alpha Persei (Mirfak) observed with REVOLT on Aug 12 in “H-Band” (1600nm ± 50nm) on the DAO 1.2m Telescope
Using C-Blue One and HEART RTC @ 1 kHz AO frame rate (Sept/22)

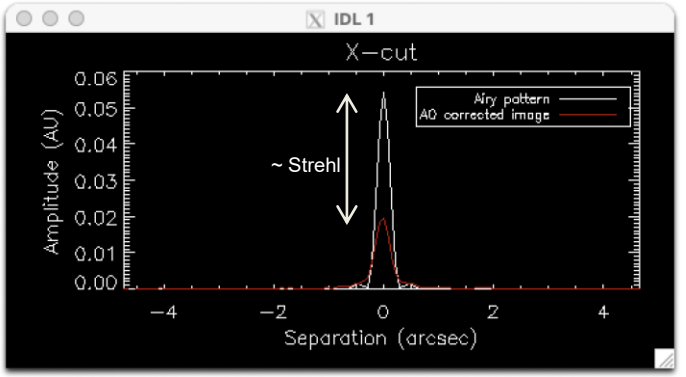
Long-exposure images normalized to maximum



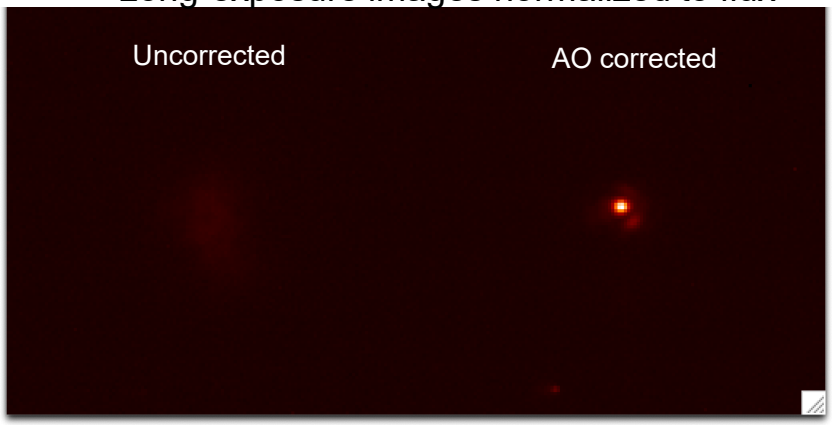
Airy
FWHM = 0.28”
Strehl = 100%

First Airy ring

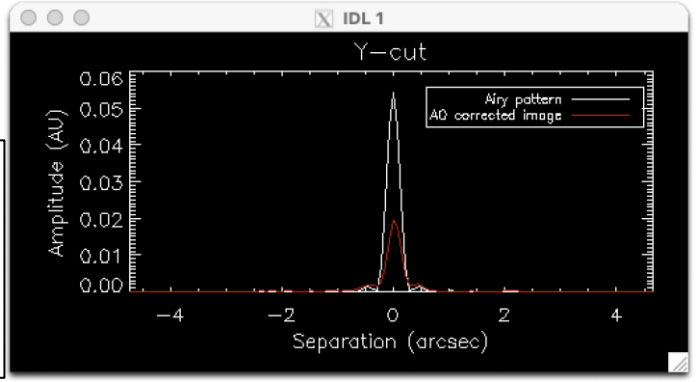
Fiber return



Long-exposure images normalized to flux



Seeing:
1.5” @ 1.6um
1.9” @ 0.5um
Median @ DAO:
2.1” @ 0.5um

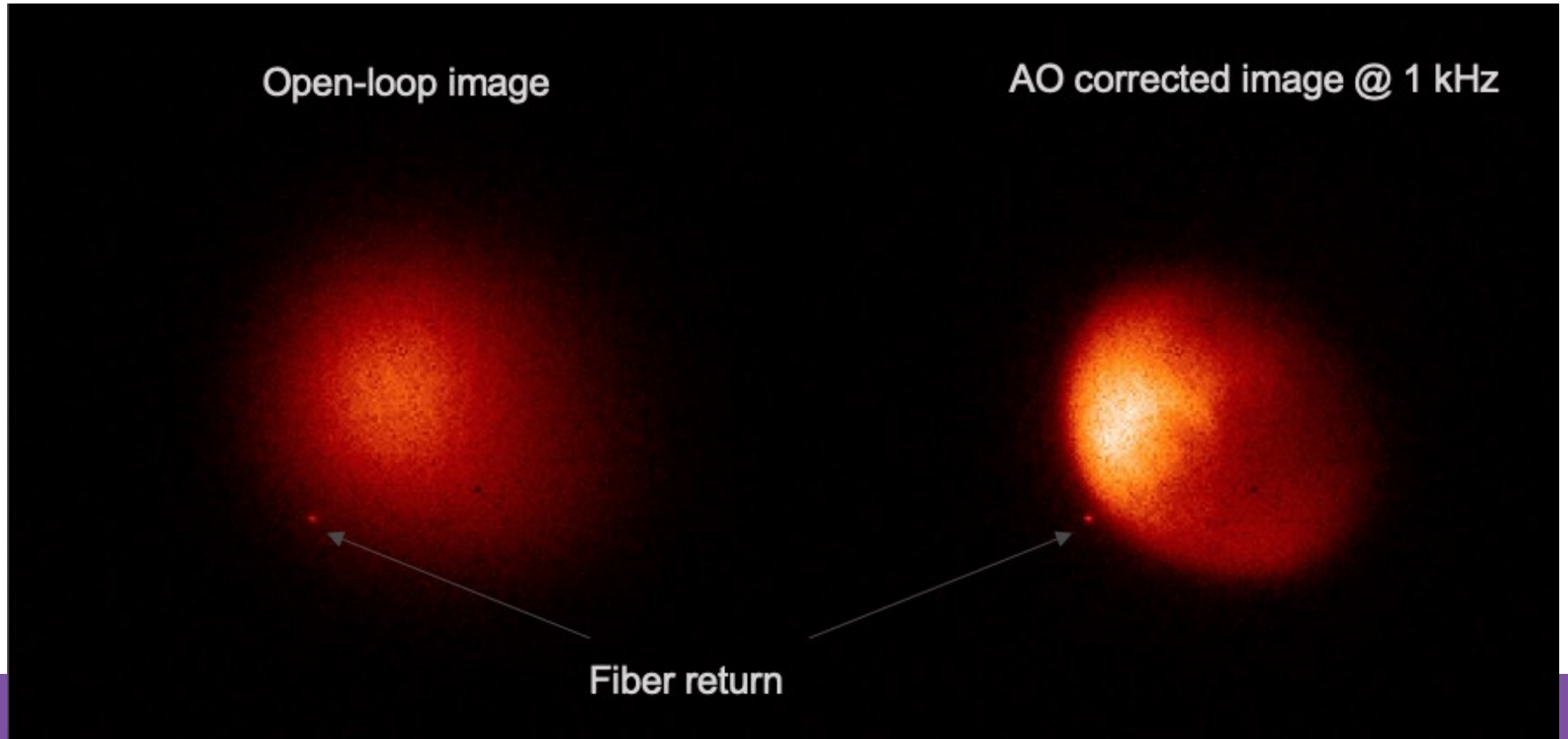


With calibration source, best Strehl = 66%

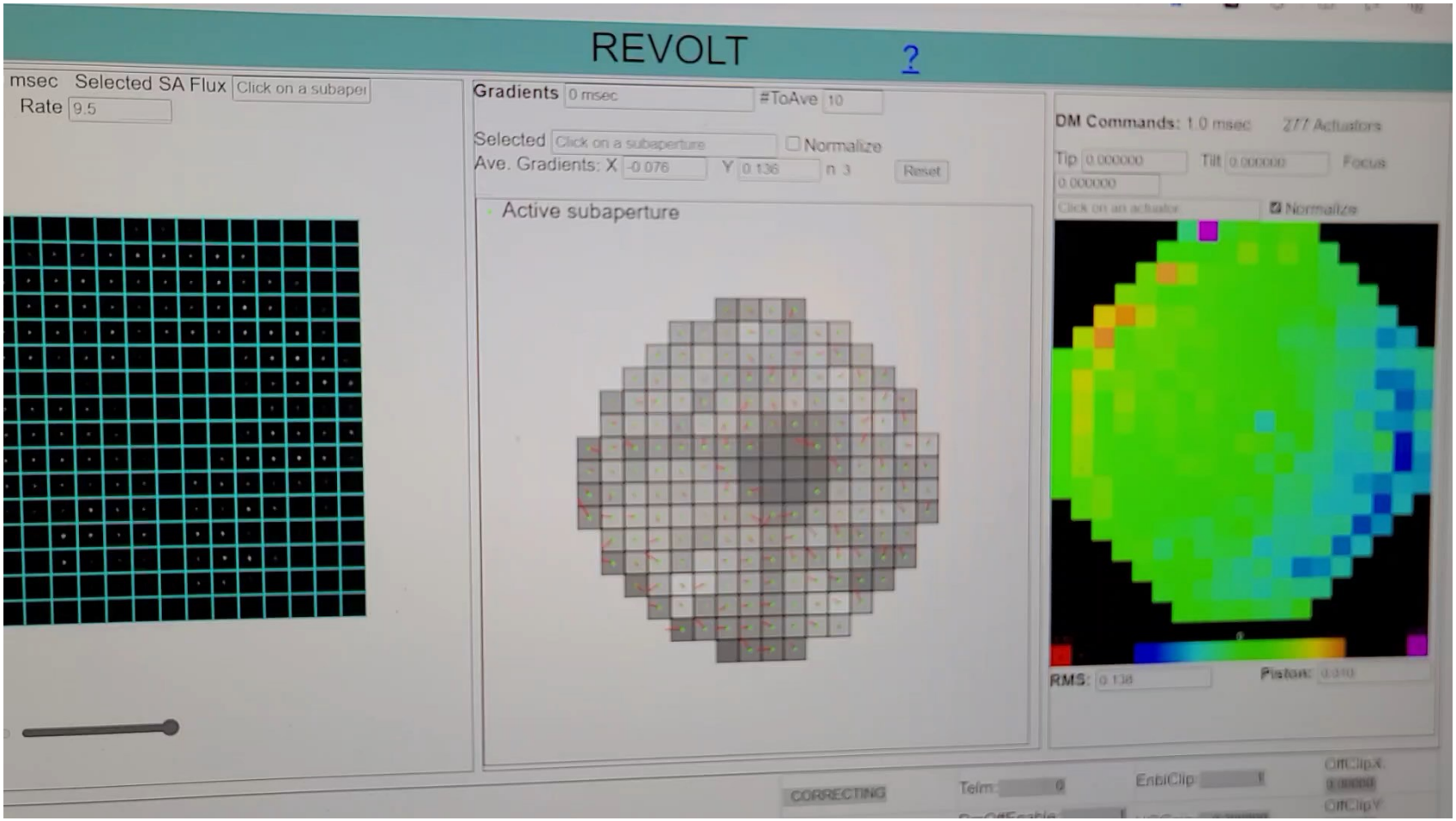
Slide provided by Jean-Pierre Véran

MARS !

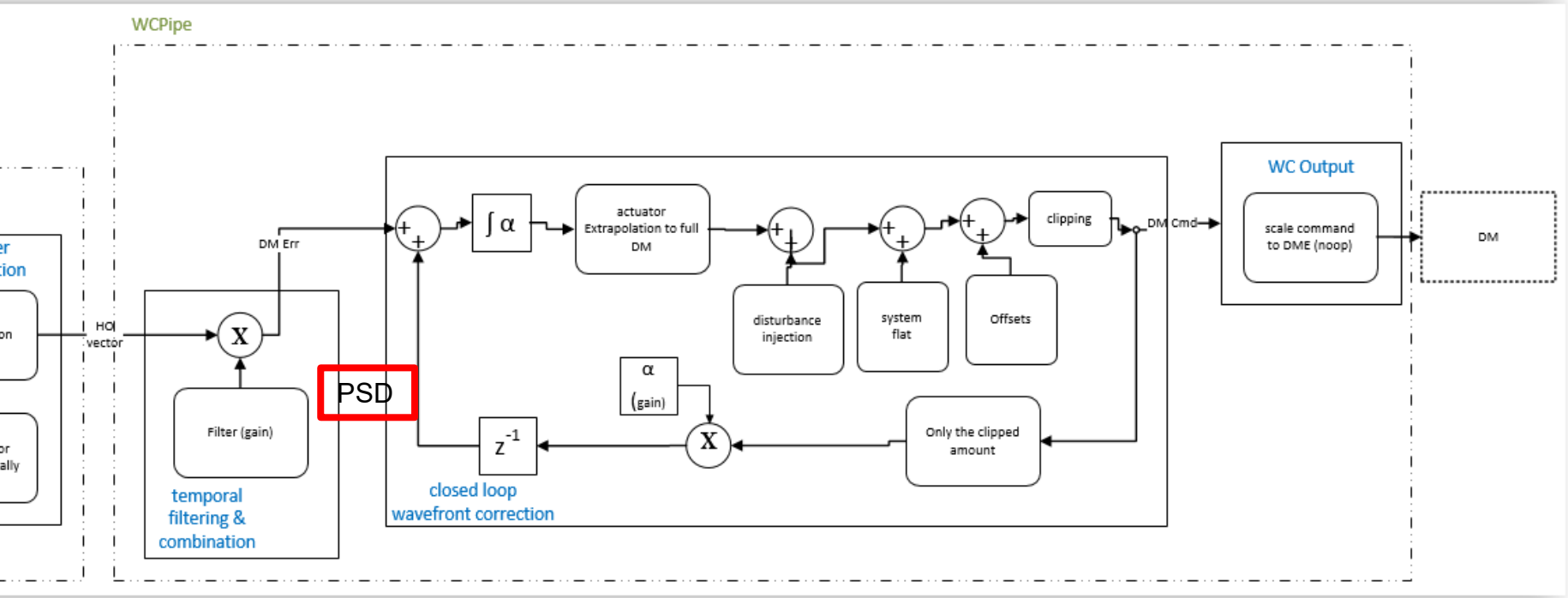
- Mars (10.29” diameter – Sep 9, 2:45am PDT)
  - Sub-aperture FOV: 15.3”
- 50 images, 75ms per image H-band



500 Hz, Gain 24, Oct 25/23



Power Spectral Density (PSD)



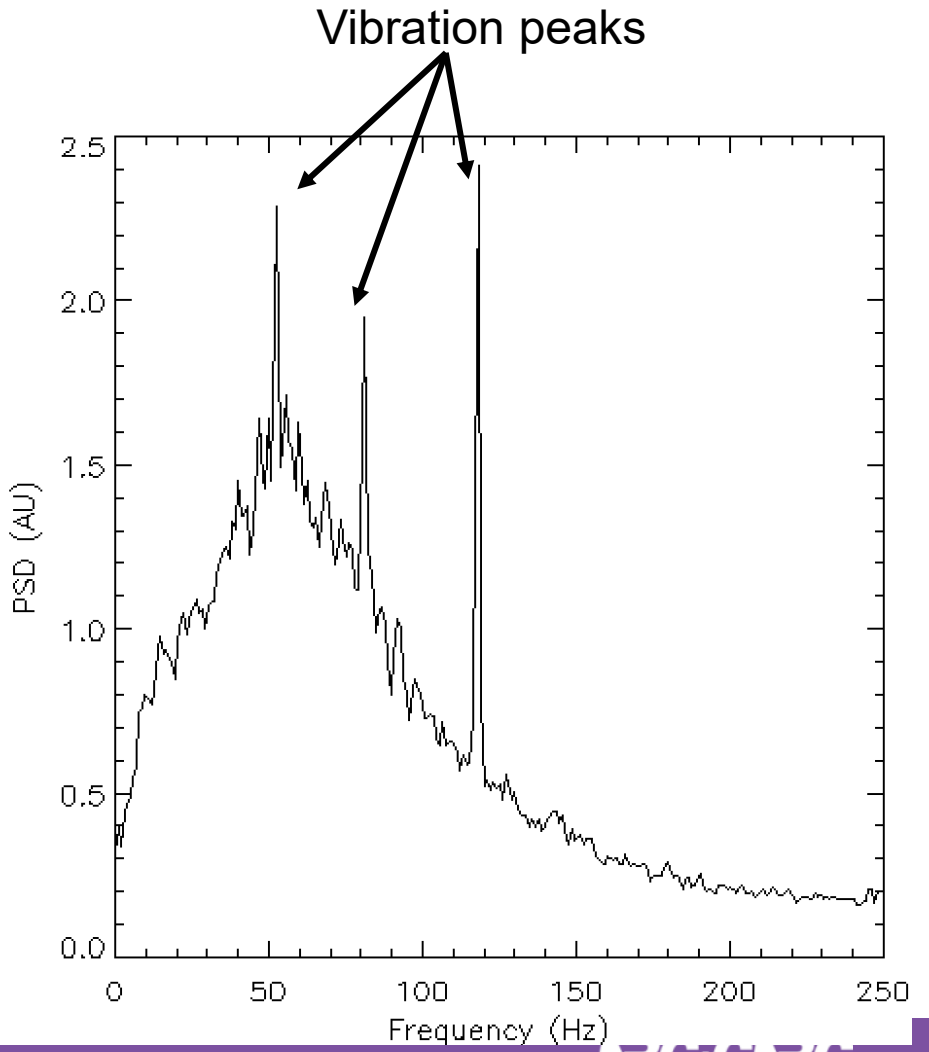
Added ability to optionally collect PSD's using HEART

Power Spectral Density (PSD)

- HEART creates a window each time segment with a Bartlett apodization function, take the FFT^2 and average them together both spatially and over time
- Output is a single PSD estimate every time M segments are accumulated
- For this test on 8 actuators were selected. Of those 2 were actively controlled

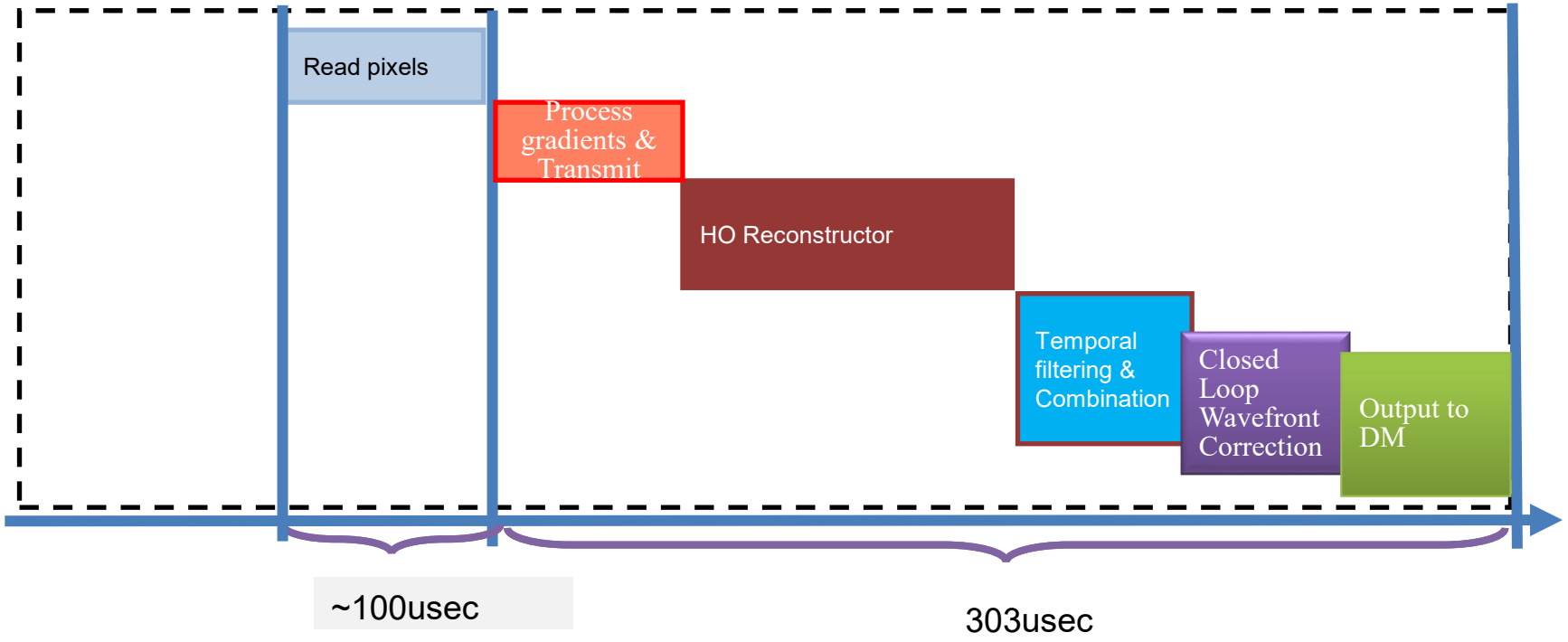
Continuously compute AO residual PSDs to optimize correction

- PSDs can be used to optimize AO loop gains (integral control)
- PSDs can be used to pick out vibrations line and design advanced controllers to cancel these vibrations
- PSD computed by HEART on REVOLT @ 500 Hz frame rate, Oct 25, 2003



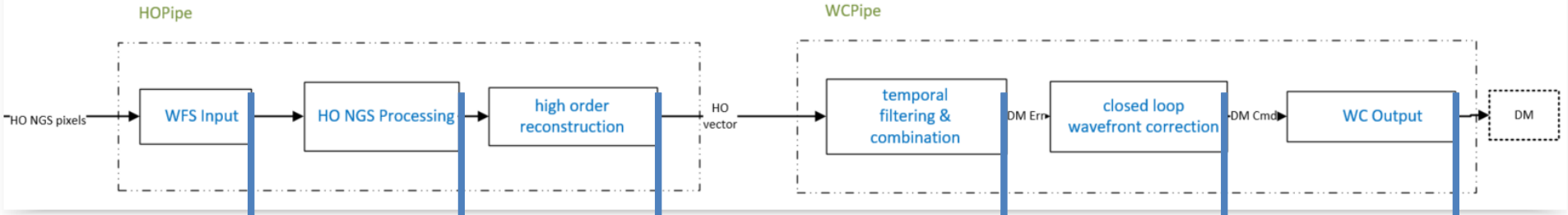
… Exposure Time takes 891 + deadtime=103usec + Readout takes 1000usec (frame rate is 1Khz) get the frame to the RTC

Exposure Time = 891usec, Readout = 891usec when at 1KHz, For 1896usec when at 500Hz



After the WFS is done exposing, it is then read out, and then it takes the RTC ~ 400usec for the correction to be seen on the DM

Timings



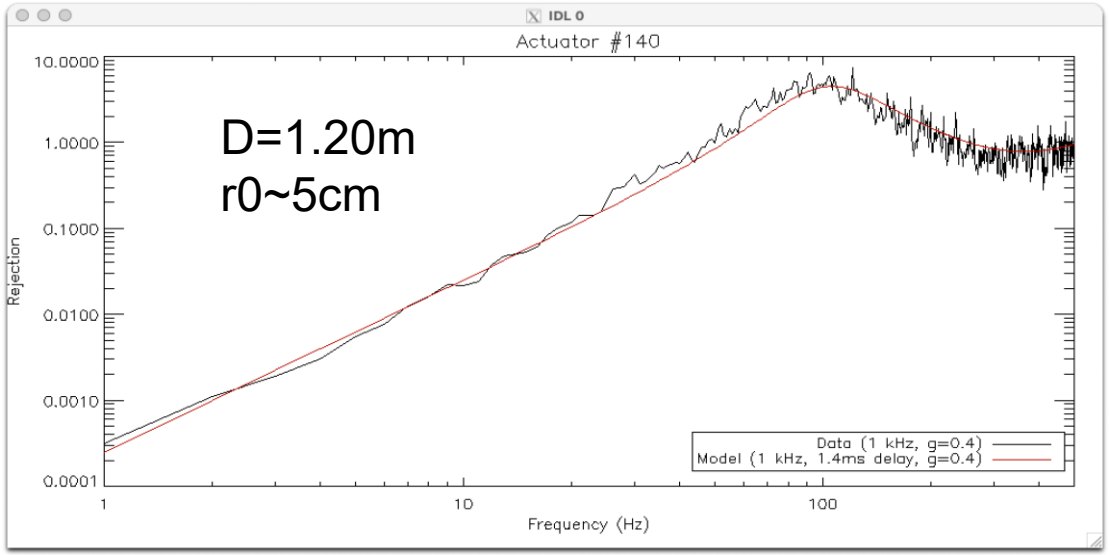
	WFS Input	HO NGS Proc	HO Recon	Temporal Filter & Combo	Closed Loop WC	WC Output
Mean	~100	99usec	163usec	20usec	6.2usec	16usec
StdDev		0.1usec	2usec	2usec	2usec	2usec

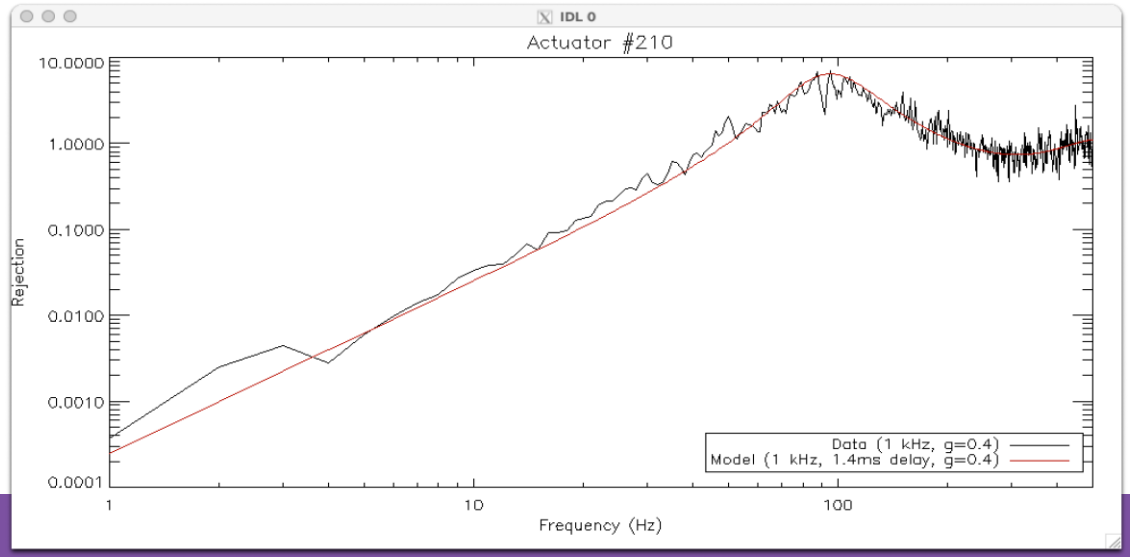
Revolt has 1 CPU (not using Numa), have ability to pin cores, but not doing that – in fact have not done any optimization on the CPU
Uses low latency version of Ubuntu, 24 cores

RTC : WFS Input to WC Output: Mean: 303usec (+time to transfer from frame grabber to RTC, ~100usec (TBC))

Camera Exposure time: 1896, Camera Gain: 24, Frames per second: 500

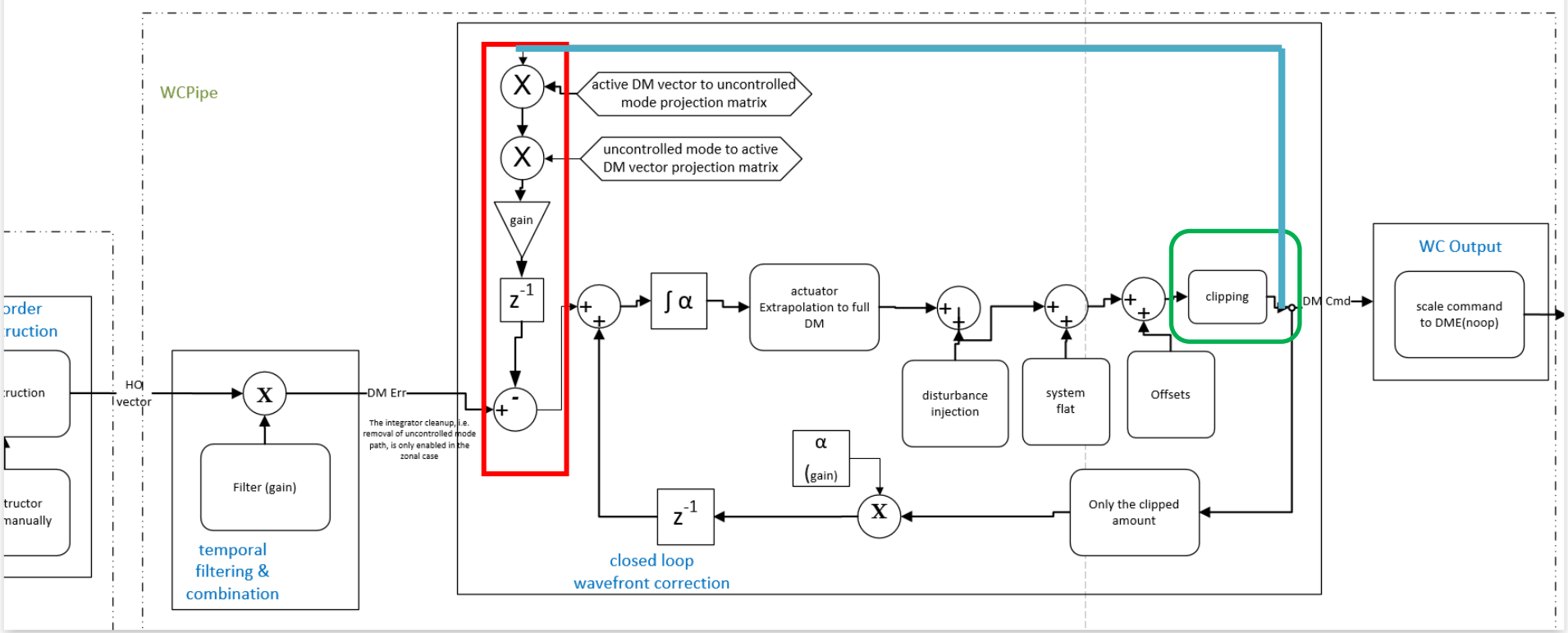
Use Power Spectral Density's (PSDs) to compute AO rejection transfer function (Sept'22)





- Revolt AO loop running at 1 kHz (integration time = 891 us)
- C-Blue One ROI 352x352 pixels
- CoaXPress 2.0 interface
- Using open-loop and closed loop PSDs obtained on-sky (bright guide star)
- Model is fitted by adjusting latency
  - Best fit: 1.4ms
  - Very clean fit
- Interface to C-Blue One is CoaXPress 2.0
  - No pixel streaming – frame must be complete to be available

Cleanup of Uncontrolled modes



In normal operation, there are uncontrolled modes, but the reconstructor removes these.

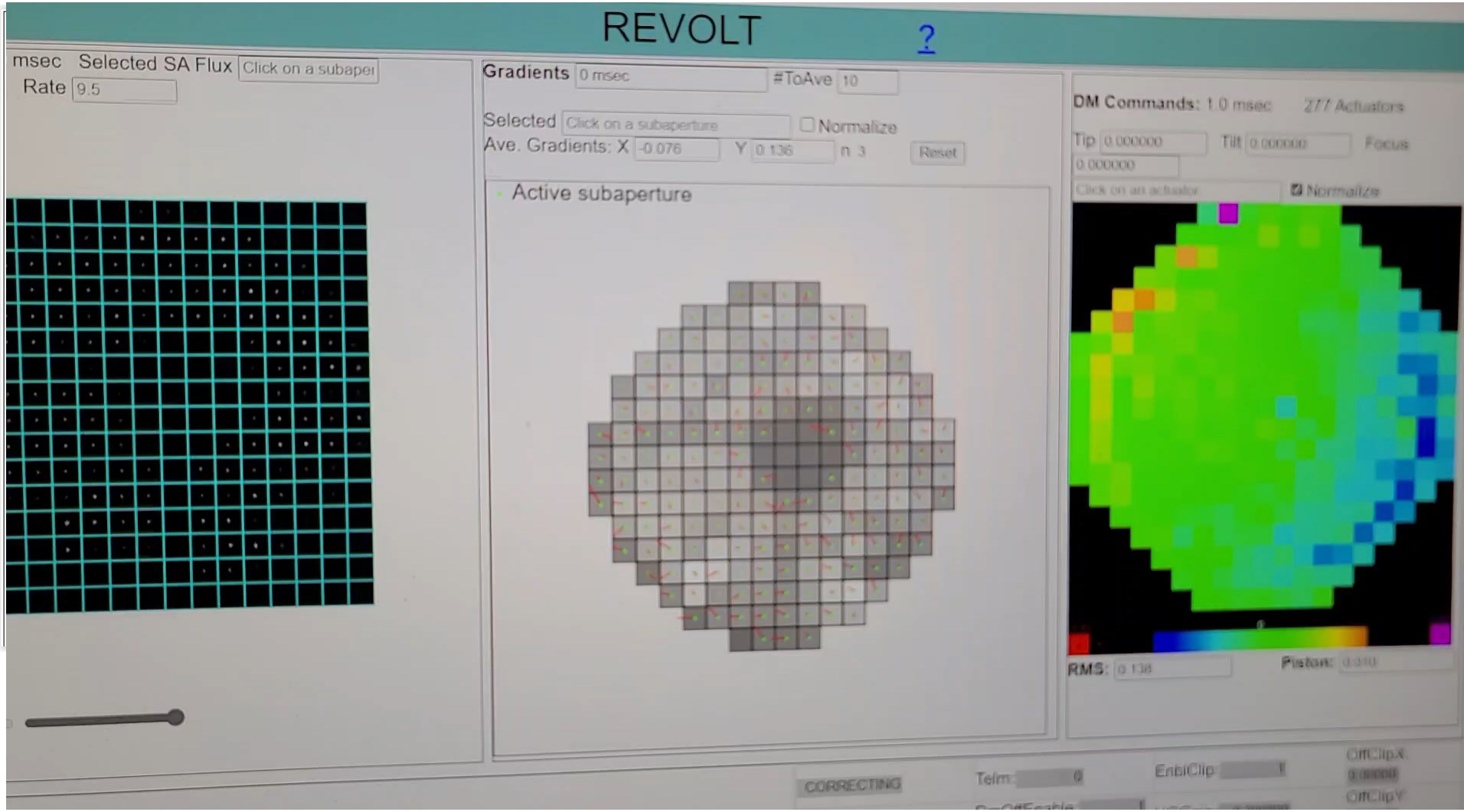
But they appear again when clipping occurs (shape changes).

Cleanup of Uncontrolled modes

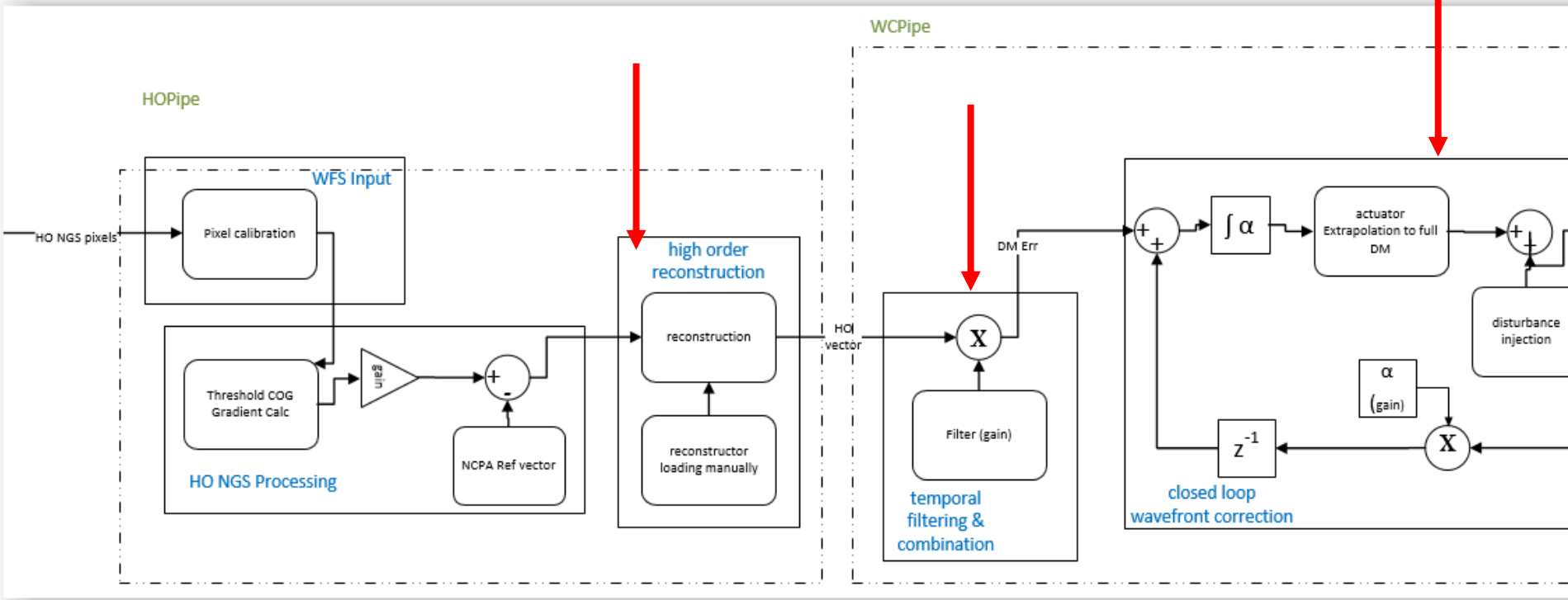
Results

- It did not break the loop!
- This was a quick test
  - next Run, change the frame rate and exposure time to saturate the DM - then the controlled modes would appear.
  - Another option is to change the clipping limit, and to include collection of PSD's at the same time.

Cleanup of Uncontrolled modes



Pseudo Open Loop (POL)

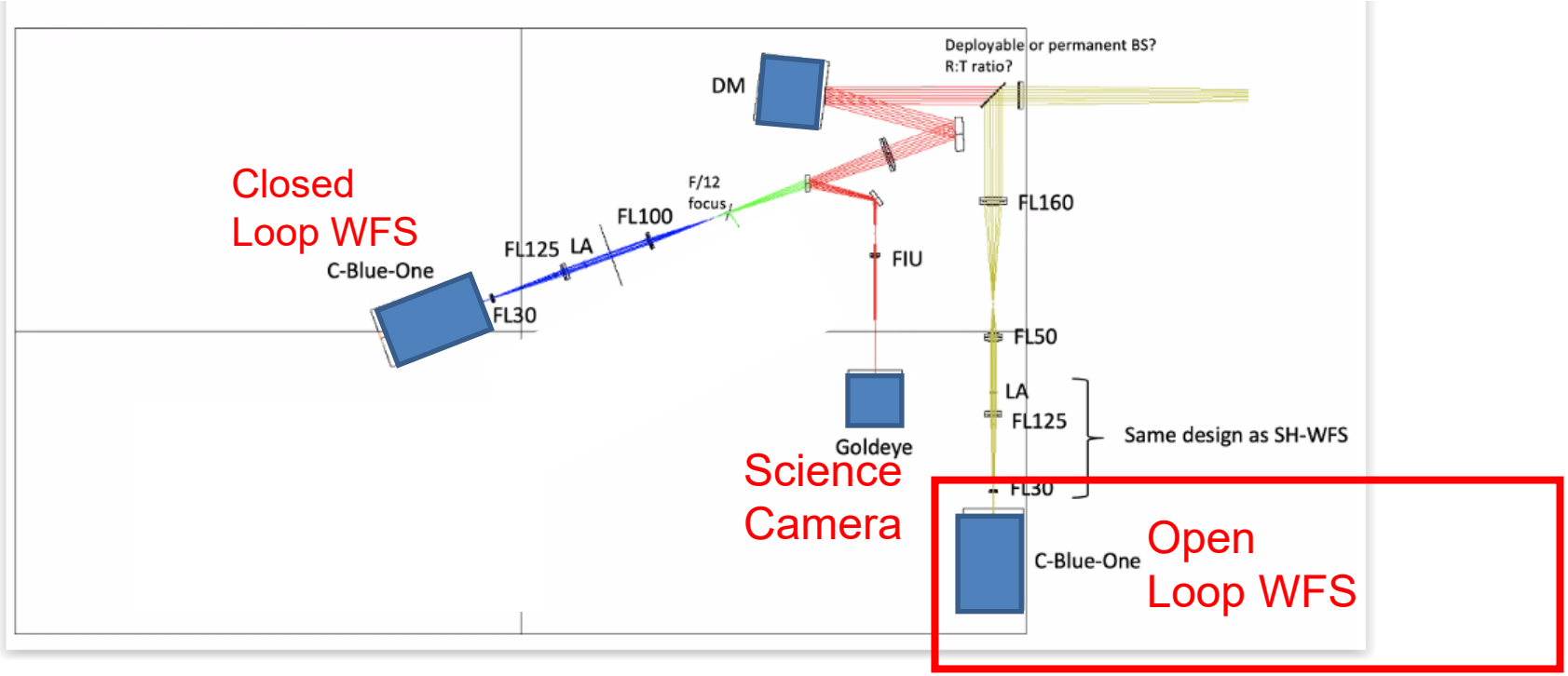


Added to HEART, but didn't have time to run and collect data this last run.

POL is used to remove visible but uncorrectable modes, such as scalloping

Adding Open Loop WFS to REVOLT

This is the first test with an Open Loop WFS and having a Closed Loop WFS to snoop on while controlling open loop



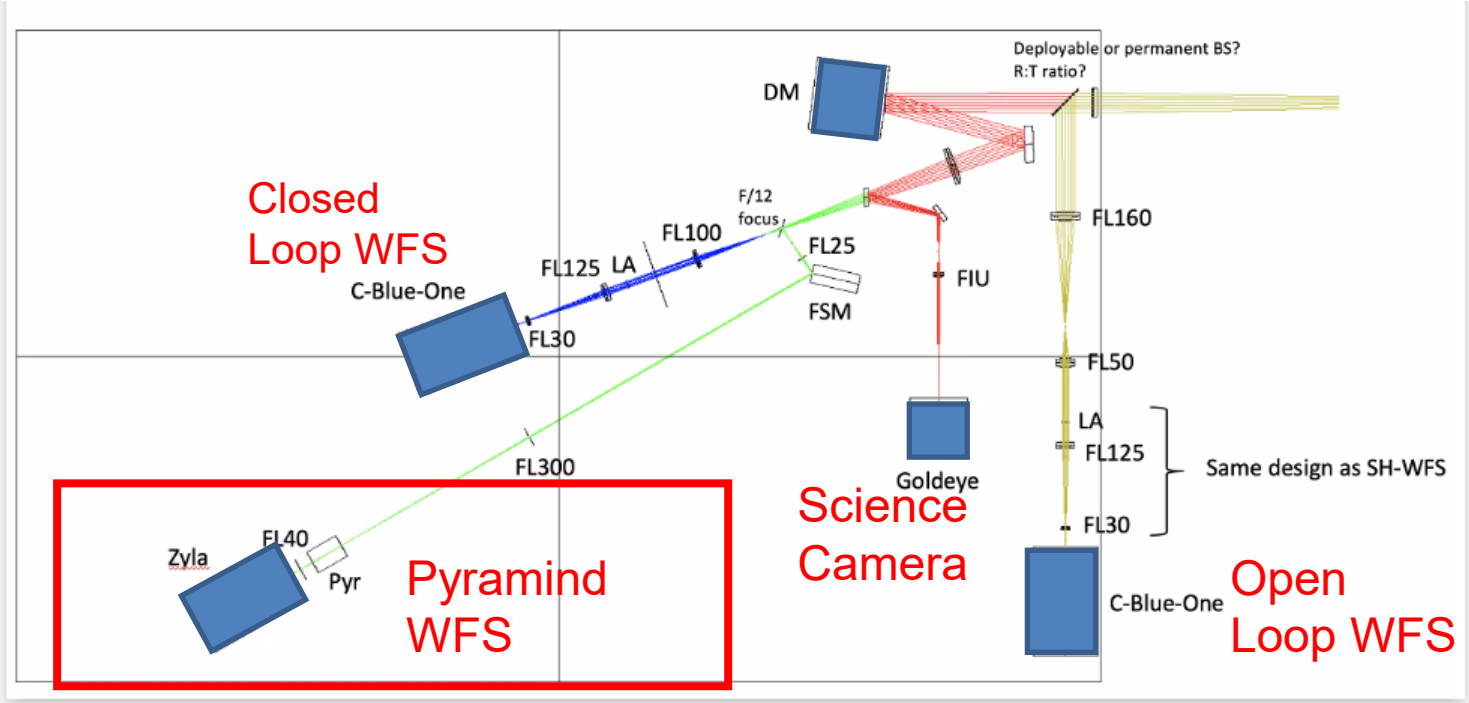
REVOLT Copper

(Canadian On-sky Platform for PWFS Experimental Research)

Andor Zyla Pyramid WFS, 128x128 pixels,

Alpao DM, 97 actuators

Pixel-based Reconstruction

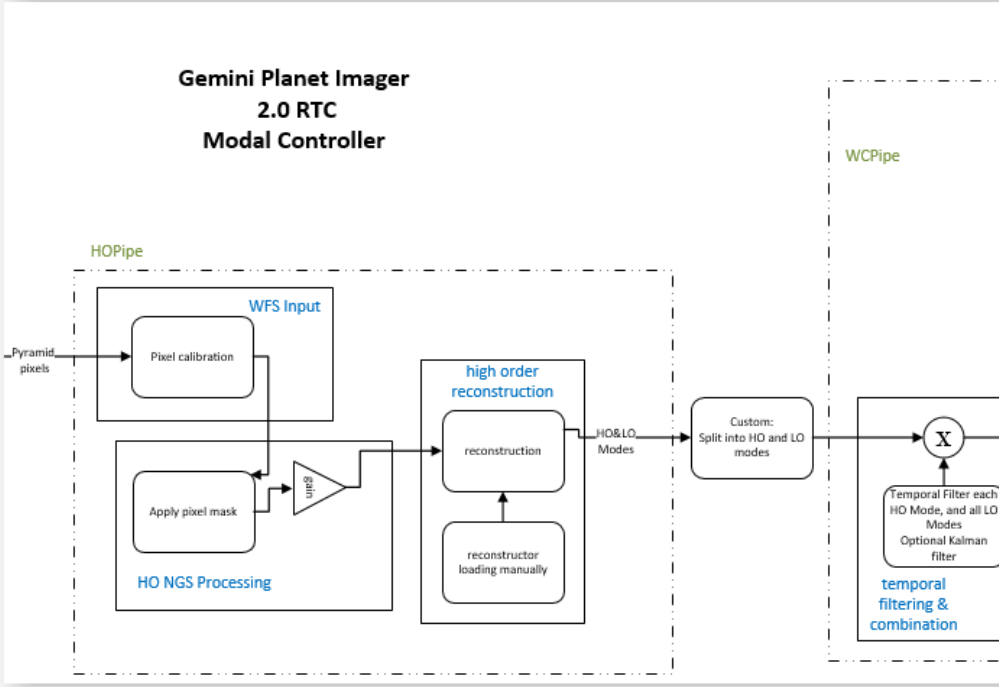


Different type of RTC also supported: Pixel Based Reconstruction

Feeding Pyramid WFS pixels directly into the reconstructor (Pixels -> Modes)

Using this on the REVOLT Copper Bench

Have closed the loop on this bench



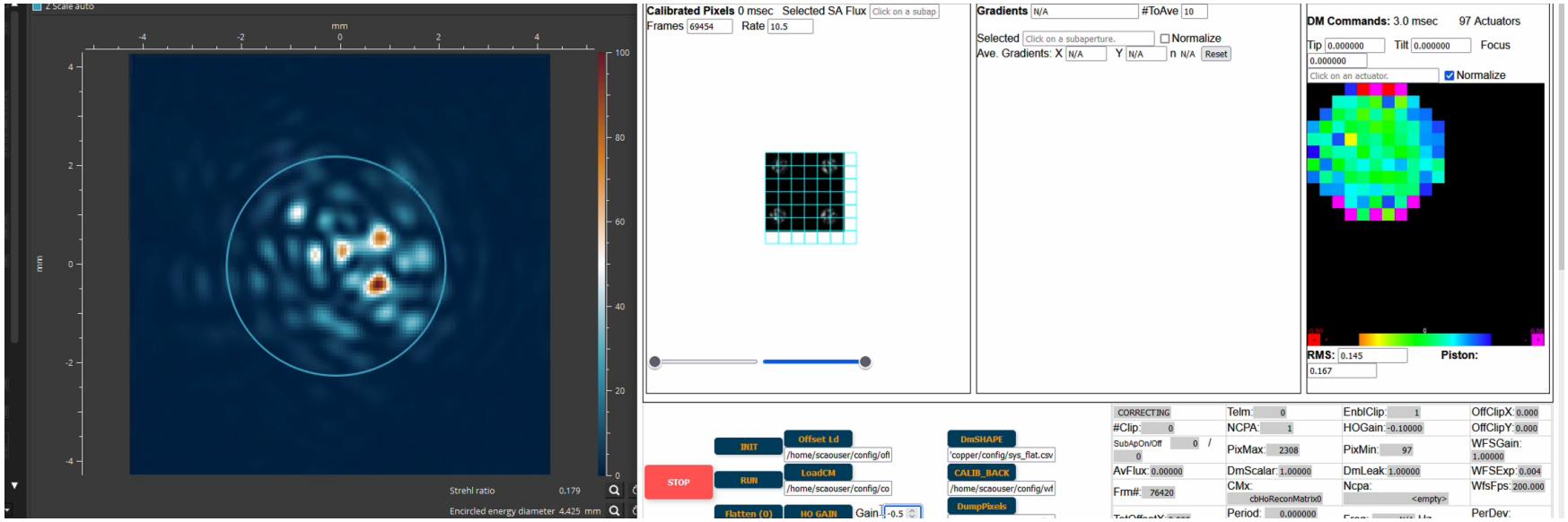
Only on the Bench, going to go on Sky this month

- Currently running on it's own bench and doing calibration
- This month to be moved to REVOLT bench and used on sky

- Using an older computer – for lab testing (2KHz, 4 cores, Ubuntu 20.04.6 LTS), not optimized

- Closed the loop without trouble at 200 Hz

Closing the Pyramid WFS Loop on the bench



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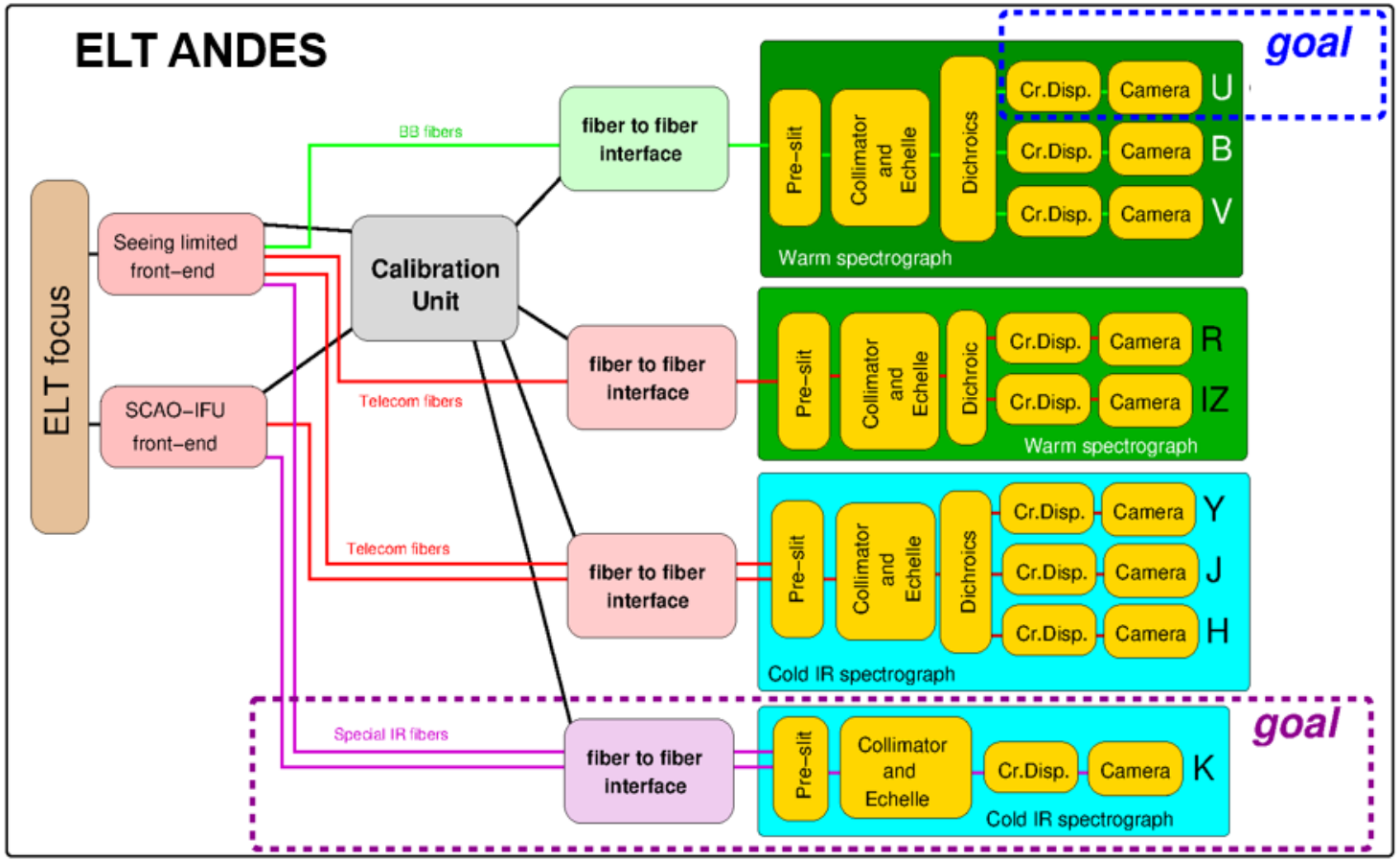
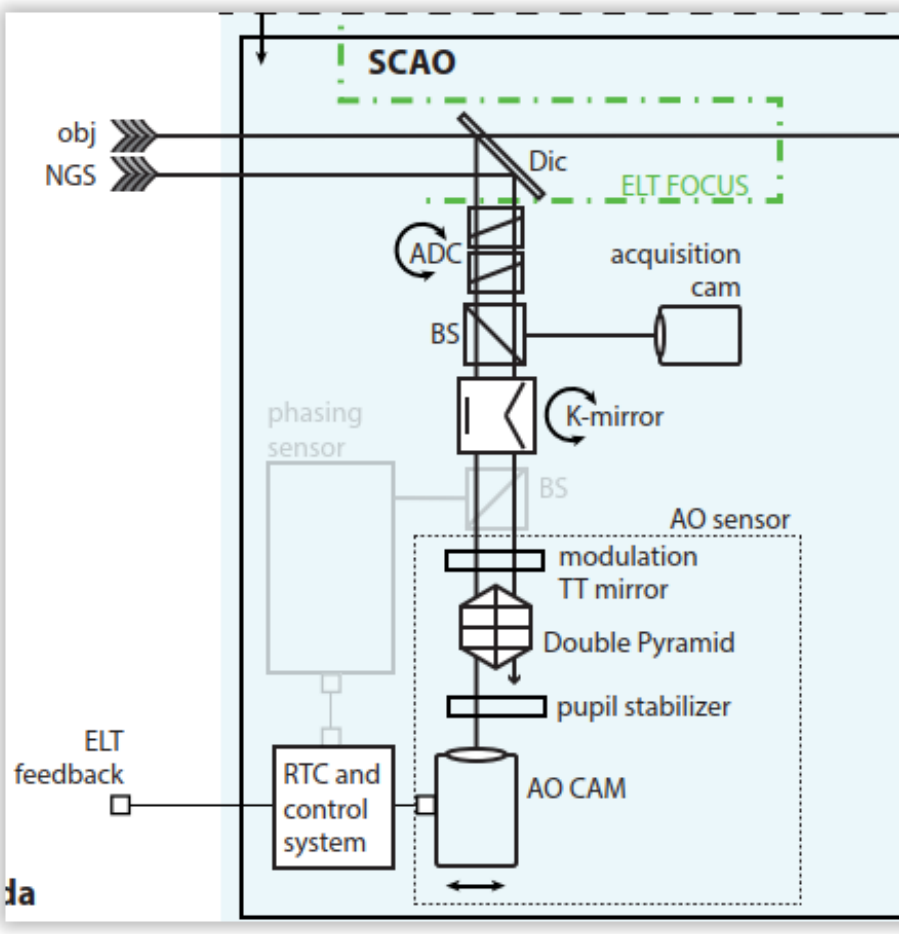
ANDES (ArmazoNes high Dispersion Echelle Spectrograph, formerly HIRES) SCAO RTC



- Second generation ELT instrument
- fibre-fed cross dispersed echelle spectrograph with 2 arms, visual and near-infrared. And IFU mode fed by a single-conjugate adaptive optics (SCAO) module to correct for the blurring effect of turbulence in the atmosphere.

SCAO (Single Conjugate Adaptive Optics System)



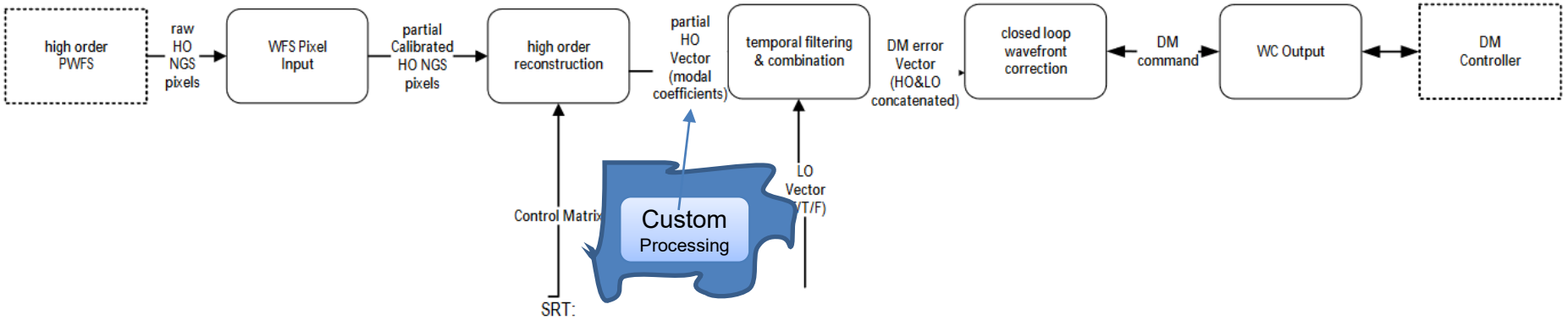
ANDES HEART Real-time Controller (RTC)

This RTC is also using the Pixel-based reconstruction and is also controlling the DM in modal space

ANDES SCAO HEART RTC
Zonal Controller,
(No POL, No Kalman)
1 Pyramind WFS

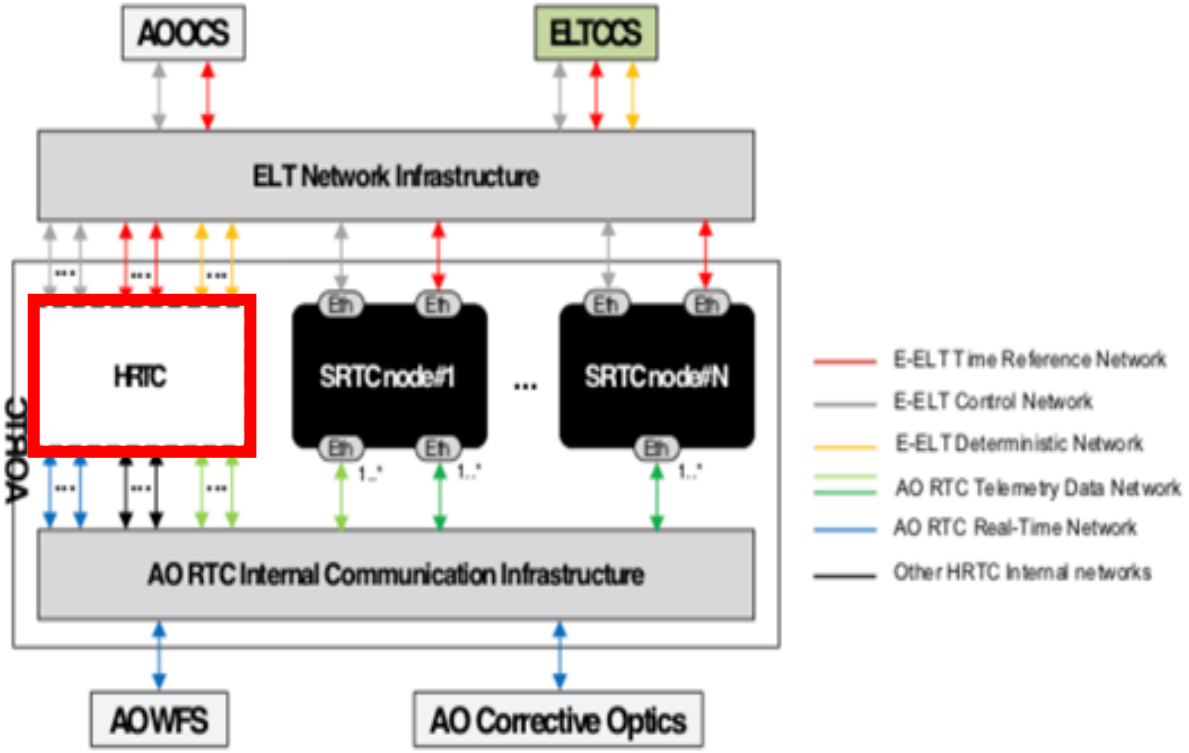
This will be tested with REVOLT Copper next month (already testing on the bench now), and in the future with the Gemini Planet Imager

camera via GigE Vision. Reads pixels, calibrates, streams



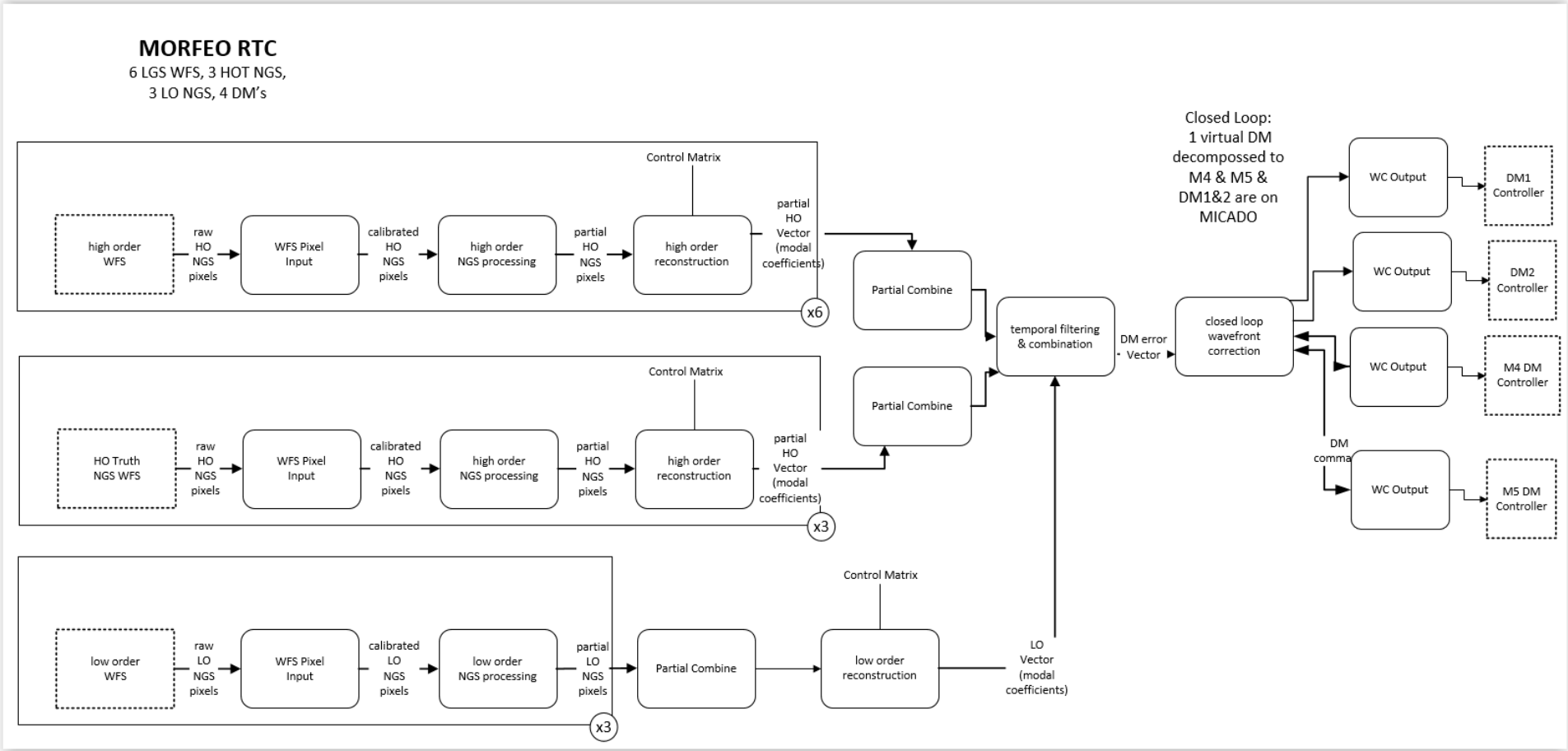
MORFEO (Multiconjugate adaptive Optics Relay For ELT Observations, formerly MAORY)

- First Generation ELT instrument

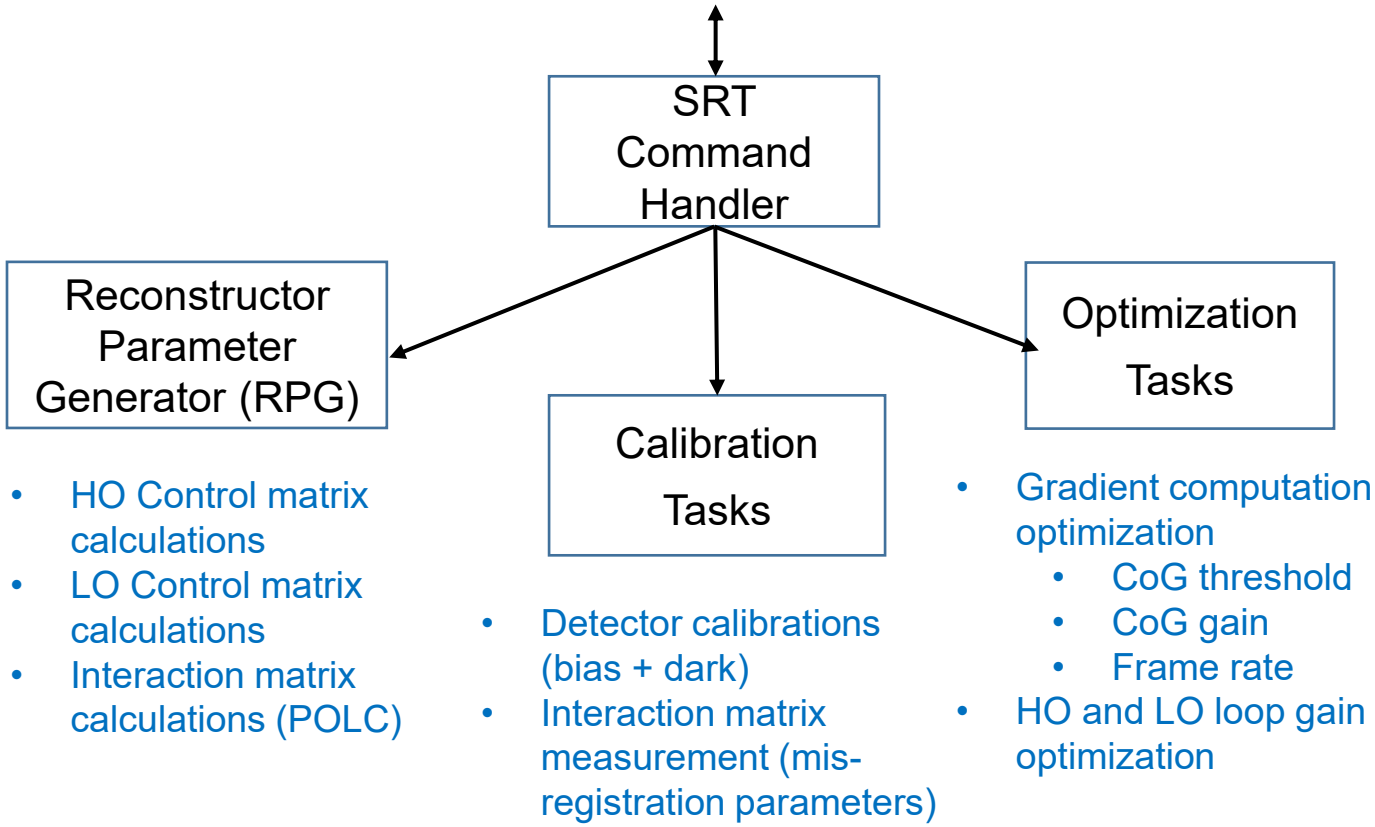


MORFEO Hard Real-time HEART RTC Diagram

6 LGS WFS, 4 Deformable mirrors,
Low-Order loop is primary running at 1kHz



HEART Soft Real Time (SRT) System



- SRT tasks are implemented in Python 3 for ease of programming / modifying / adding
- However, some underlying data / statistic gathering tasks are implemented in C as part of the HRT

4 Types of Reconstructors

- Basic Reconstruction: Pseudo Inverse of the interaction matrix, applies a eigenvalue threshold to zero out unwanted wfs noise
- Least Square (LS) Reconstructor: Uses an interaction Matrix (slope space)
- Minimal Variance (MV) Reconstructor : tomographic reconstructor, uses an influence matrix that is calculated and then the registration between the WFS and DM needs is applied
- Spatio-Angular Minimal Variance (MV) Reconstructor (future): is a tomographic reconstructor for Multi-Object AO (MOAO). Pre-multiplies the tomographic step with the projection step in the LGS direction to obtain a phase estimate directly at the pupil plane.

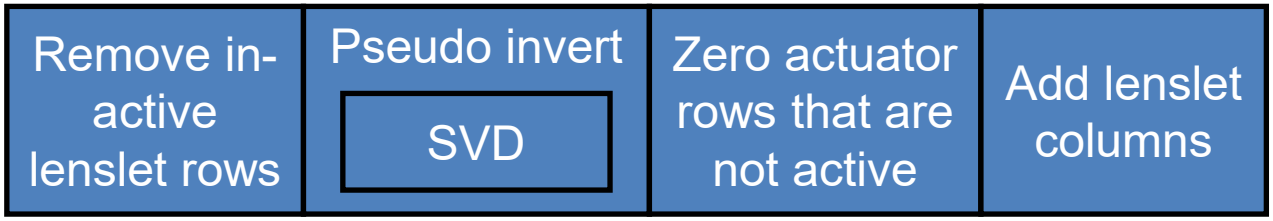
Running with HEART SRT on REVOLT on bench

Control matrix: Basic Controller

- Uses the Interaction matrix to create the control matrix. It is used to convert from WFS gradient space to DM actuator space

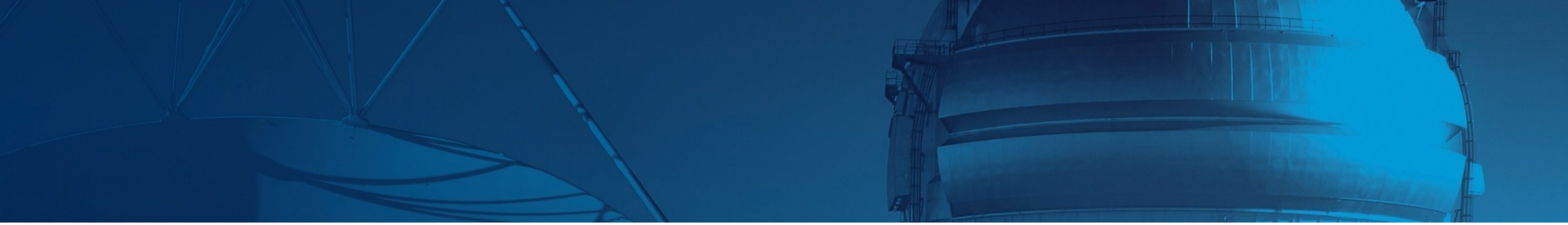
Other inputs are :

- Active Lenslet Map
- Active Actuator Map
- And Singular Value Threshold



Types of optimization

- Optical Gain Optimization: This is the value used to transform gradient values from pixels to arc sec. Or in modal space it is optimizing the optical gain for the modes.
- Pixel Threshold Optimization: This is optimizing the minimum pixel value that will be considered when calculating the gradients.
- Center of Gravity Weighted: Weights applied to the center of gravity coefficients
- Temporal Filter Optimizations: This is optimizing the loop gain and in the future temporal filter specifically the minimum and maximum loop gain given the WFS frame rate



QUESTIONS?

Thank you

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