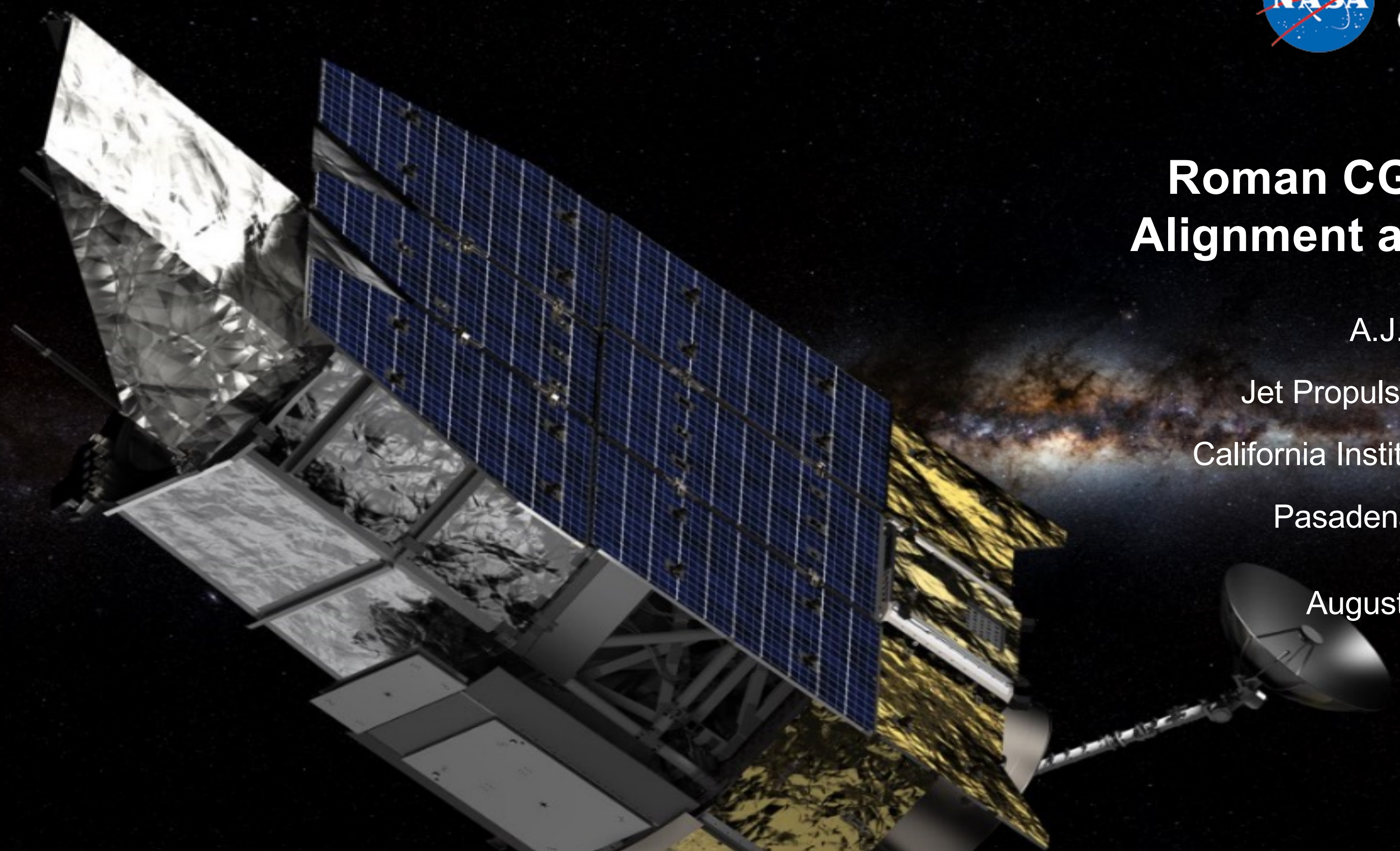

Roman CGI Automated Alignment and Calibration

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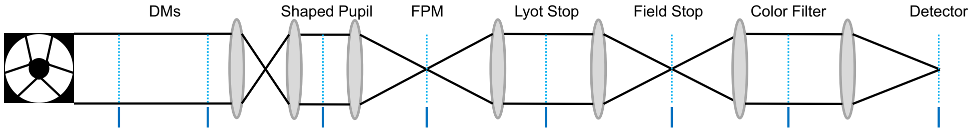
Background



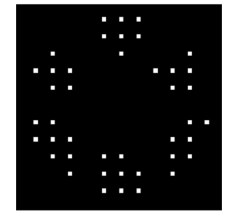
- We use model-based high-order WFSC.
- Before we can begin HOWFSC, we must build an accurate model.
- This requires calibrations of all key optics and the stellar E-field:
  - Magnification, clocking, and translation of the deformable mirrors.
  - Magnification and clocking of all the masks
  - Magnification and translation of the PSF.
  - The E-field at the entrance pupil
- In addition, the masks must be aligned to the beam to within some small tolerance.
- Unlike with our early CGI testbeds, we used automated routines for the first time with CGI itself. (A person still had to run the software but not do “by-eye” alignments or “by hand” calculations.)

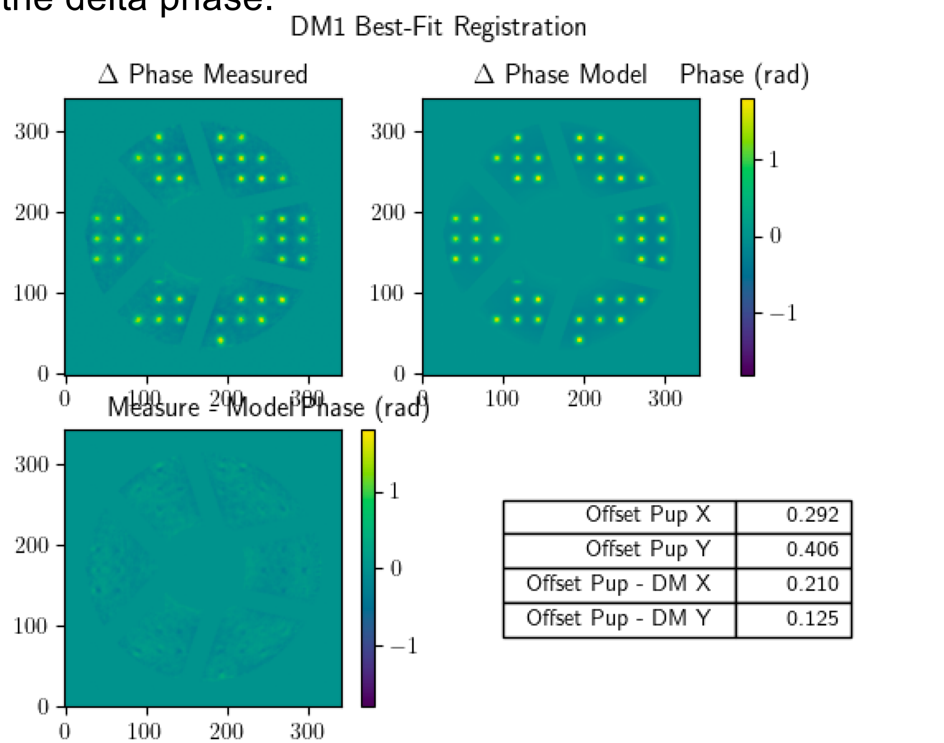
Much of this software has been open-sourced: https://github.com/nasa-jpl/coralign

DM Registration

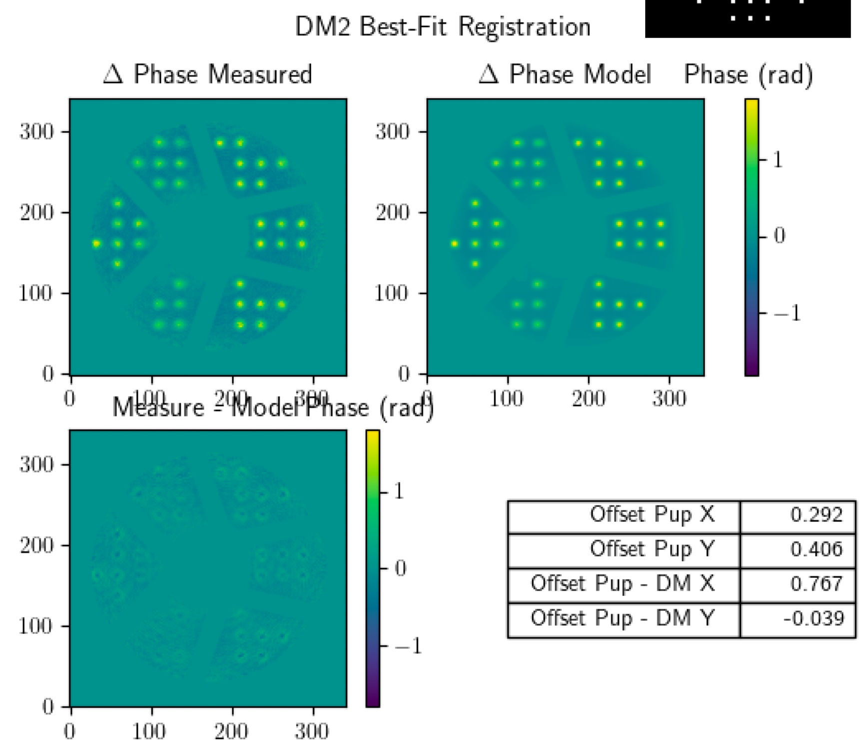
- Phase retrieval gives us the wavefront with/without a sparse grid of poked actuators on each DM.

- The rotation, scaling, and translation of the DM actuator grid are then computed all at once from the delta phase.





Offset Pup X	0.292
Offset Pup Y	0.406
Offset Pup - DM X	0.210
Offset Pup - DM Y	0.125



Offset Pup X	0.292
Offset Pup Y	0.406
Offset Pup - DM X	0.767
Offset Pup - DM Y	-0.039

Line-of-Sight Selection

- Have to choose the line-of-sight (i.e., beam position) that works for both the LOWFSC and HOWFSC paths.

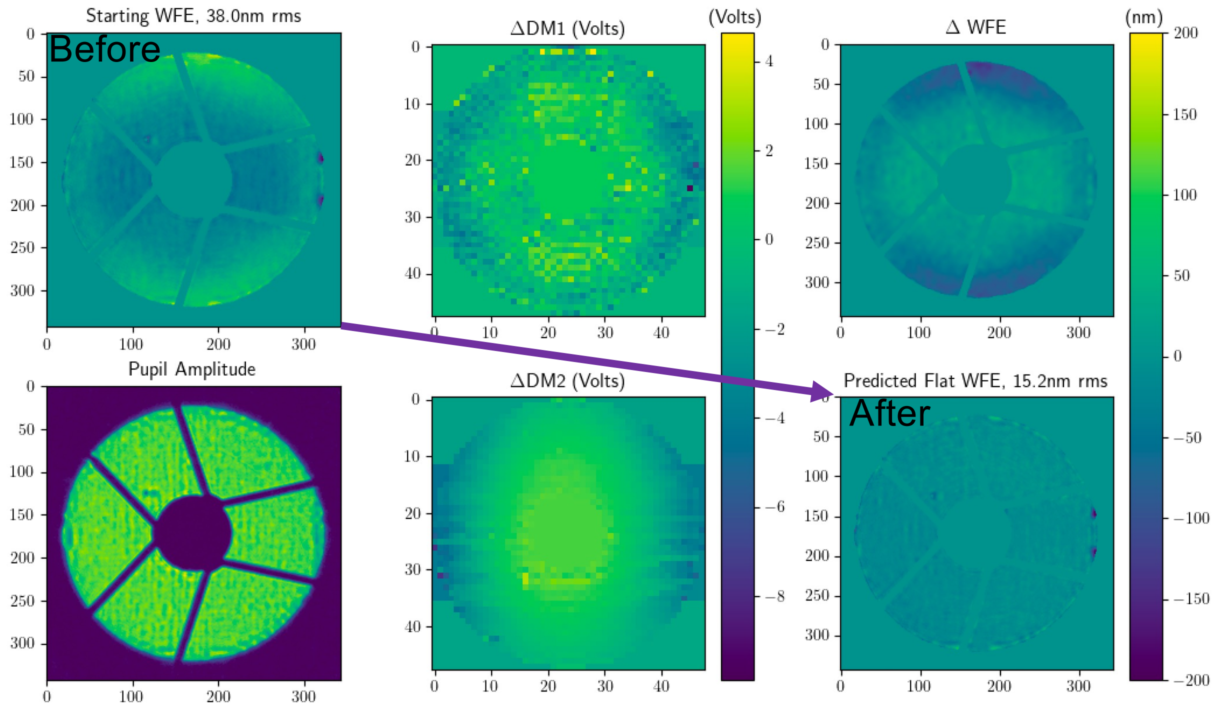
- Ideally, want:
  - DM1 centered on the pupil image → *done with periscope mirrors in TVAC*
  - DM2 centered on DM1
  - The LOWFS image centered in its separate beam path (LOBE).
    These last two are in competition if the two separate beam paths aren't exactly coaligned.

- In the end, we chose a location in between the best for LOBE and the best for the DMs.

Wavefront Flattening

- After the actuator positions are determined, the (upstream) wavefront is iteratively flattened to get the best starting point.
- We use a nonlinear model of the DM actuation for more accurate large moves.

Example of Wavefront Flattening using TVAC Data



Mask Calibrations (Magnification and Clocking)

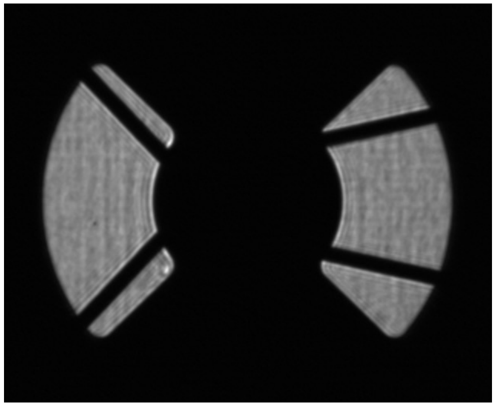
- The mask magnification and clockings are found by comparing thresholded images of far-apart openings against model-based images.

FPAM: Use two neighboring bowties.

FSAM: Use the two HLC half-dark hole openings.

SPAM: Use the two small calibration circles halfway between SPMs.

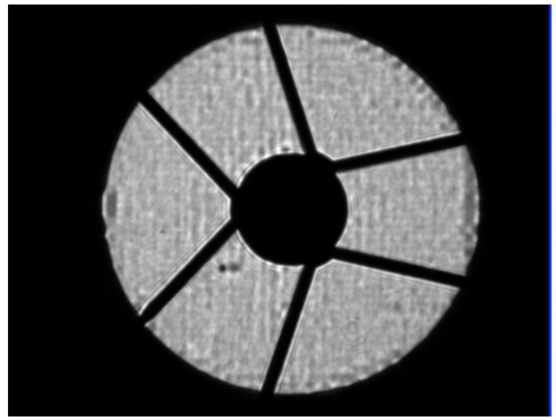
LSAM: Use the two-hole SPC Spec Lyot stop.



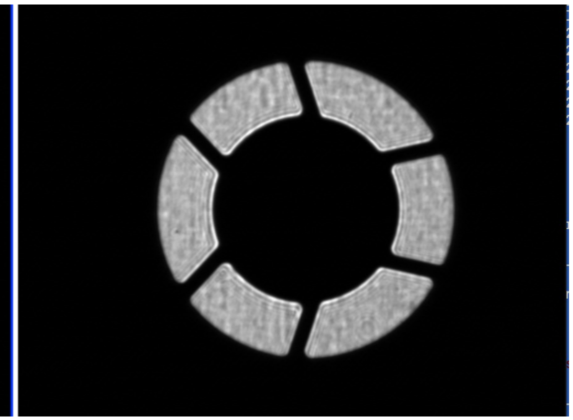
Pupil Mask Alignment

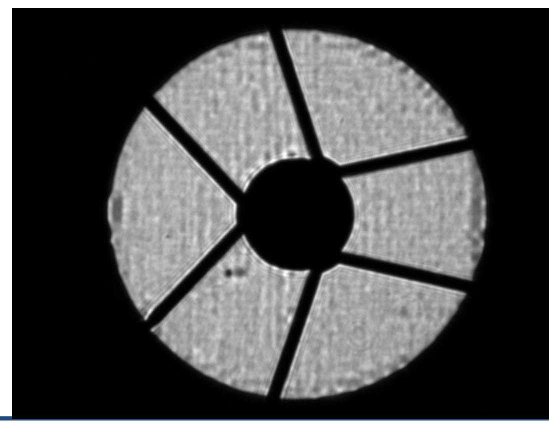
- First, the pupil location is found with an ellipse fitting routine for the outer diameter.
- The mask (shaped pupil or Lyot stop) offset is computed using a sub-pixel cross-correlation between a model-based and the measured masks, also accounting for the background obscurations of the nominal pupil.

Unmasked Pupil Image

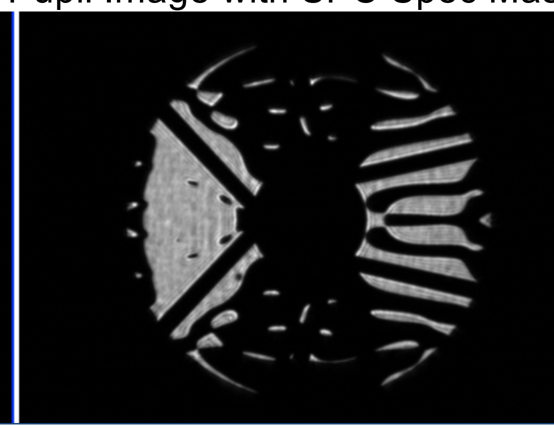


Pupil Image with Lyot Stop





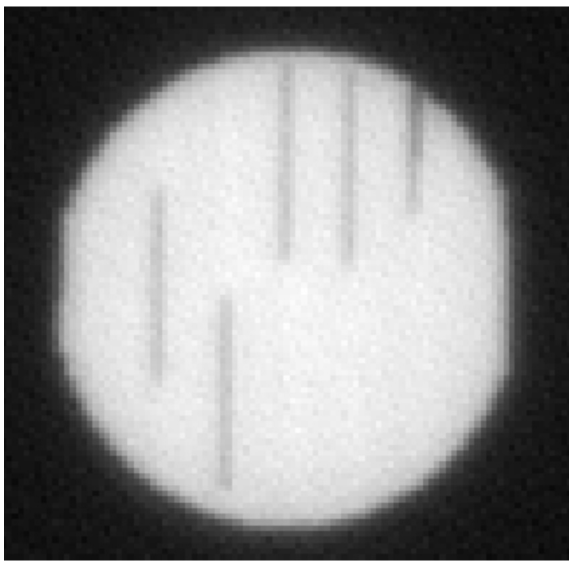
Pupil Image with SPC Spec Mask



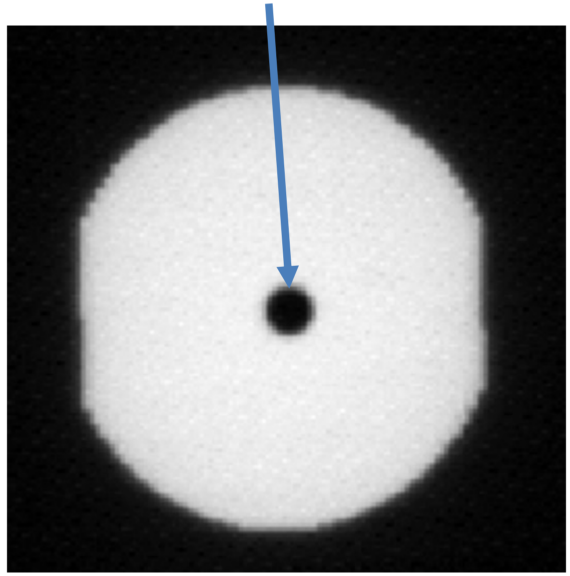
FPM and FS Coarse Alignment

- There is no diffuser in CGI.
- To back-illuminate masks in the focal plane, we can raster the PSF with the FSM.
- Basic circle fitting algorithms (*i.e., scipy, opencv*) are good to <1 pixel (<22 mas) accuracy.

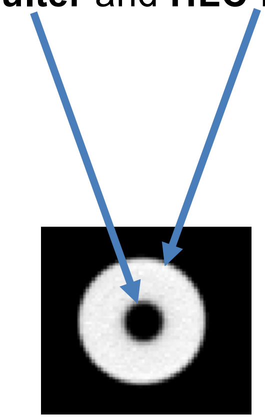
6-exposure FSM raster,
no mask



1-exposure FSM raster,
HLC occulter



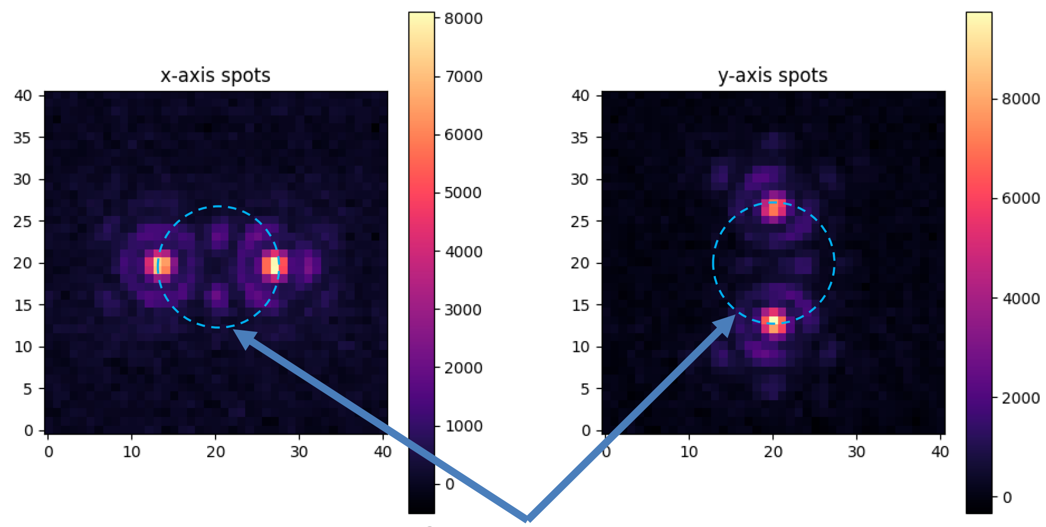
1-exposure FSM raster,
HLC occulter and **HLC field stop**



FPM and FS Fine Alignment

- The “speckle balance” algorithm is used.
  - DM-actuated sine waves in x and y are separately used to actuate spots at the edge of the mask.
  - The mask is aligned once the speckles are equally cut off on opposite sides of the star.
- Also used for field stop fine alignment

TVAC Data of HLC FPM Fine Alignment:

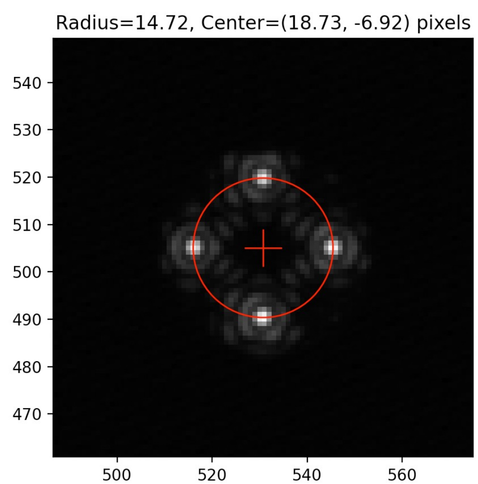


HLC FPM position
(FPM not visible because Lyot stop is in place)

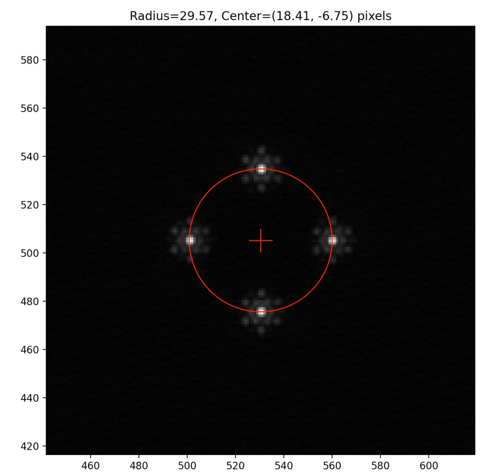
Star position and plate scale measurement

- Sine waves are actuated on DM1 to give 4 reference spots centered on the star.
  - To get rid of the cross terms with the underlying PSF, we actually do a +poke, -poke, and no poke.
- Comparing against the model, this gives us both:
  - Star position
  - Plate scale

HLC/NFOV



SPC/WFOV



Surprises!

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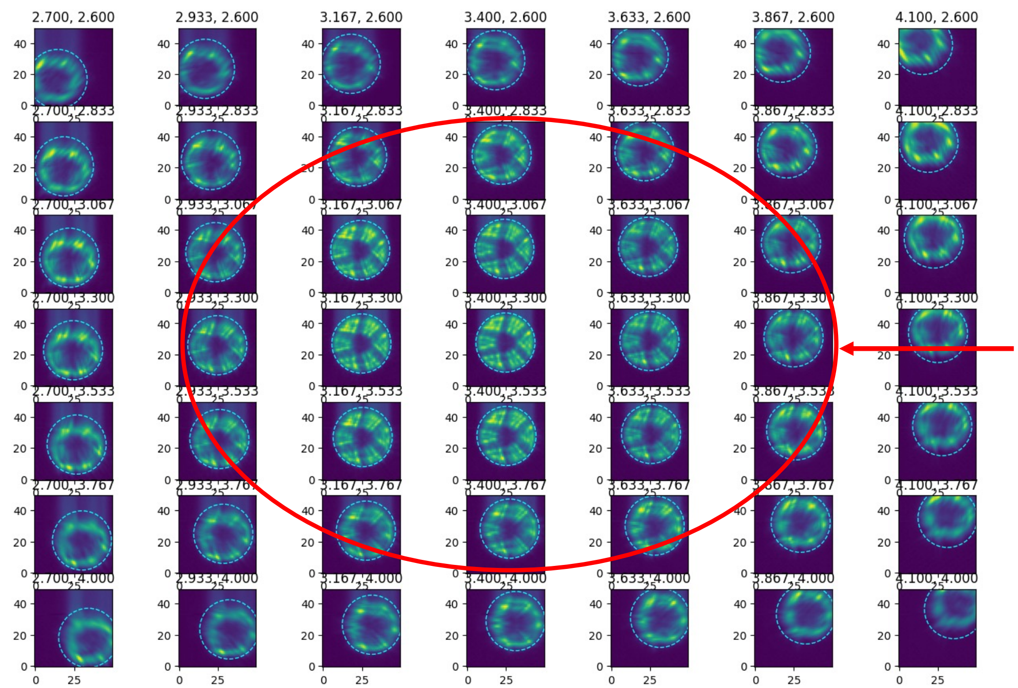
Surprise #1: LOBE FOV Smaller Than Expected

ROMAN CORONAGRAPH

- Expected the LOBE FOV (i.e., how far off-axis for LOWFS) to be good for ~1 arcsec radius.
- Actually good out to only ~0.4 arcsec off-axis. Beyond that, no LOWFS.
  - Root cause: We had accepted the defocus in the LOBE beam path because it doesn't degrade LOWFS performance when centered, but we did not check what happens when the LOBE beam is both defocused *and* decentered.
- Means that we may have to accept some DM1-DM2 misalignment for LOWFS to work.



LOCAM images for 233 mas steps in x and y

Beyond a 400mas radius, the LOCAM pupil image rapidly degrades and goes out of frame.

Surprise #2: PIL doesn't give pupil image

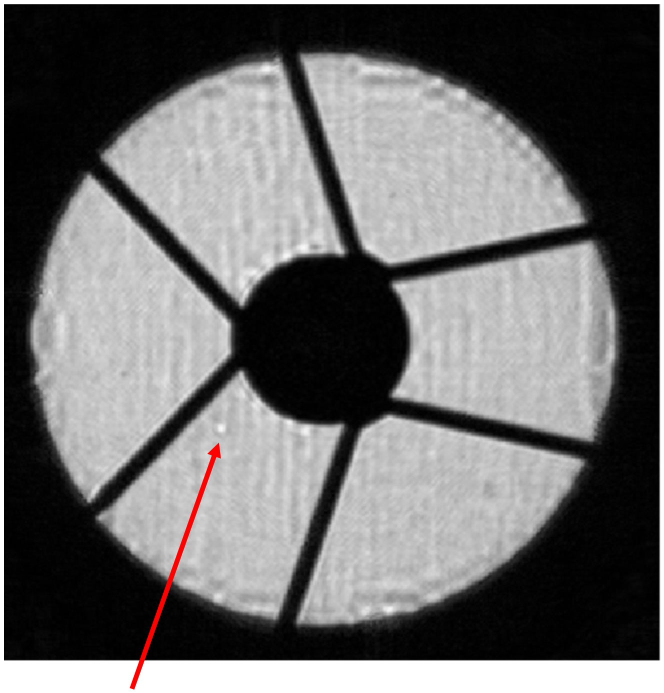


Exhibit A: The DM1 dead actuator shouldn't be visible in a true pupil image.

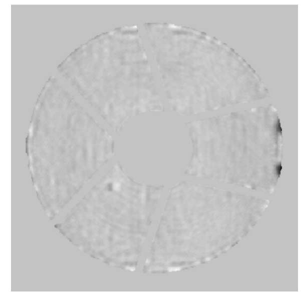
- Through several effects, we realized that the image from the pupil imaging lens (PIL) isn't quite at a pupil.
  - Also, is really for a curved surface.

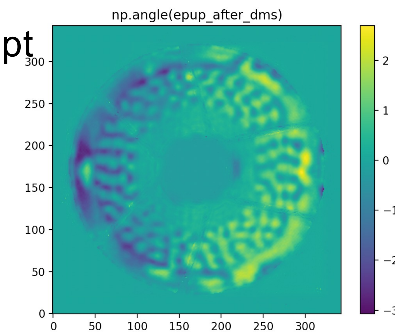
- Is OK—we can account for it now that we know about it.
  - PIL image motion when changing only tip/tilt
  - Fresnel propagate the phase retrieval answer by 0.34 meters for the HOWFSC model, which makes DM1 phase disappear.

Surprise #3: Tip/tilt building up in the HLC DM Patterns

This was a bizarre problem that we had never had in the testbeds.

1. The phase retrieval in the model needs tip/tilt/piston removed. However, because of the low points on the right, the PSF was off-center by 0.1 pixels.
2. This caused our model-based solution to try to move the PSF back-on center, and ended up 0.3 pixels off.
3. Then when applying the DM commands to the instrument, it kept building up to 0.75 pixels total (1/3 a lambda/D) → really bad!





Total HLC DM phase applied by both DMs—1/3 wave of tilt added!!!

- This caused a lot of grief and meant we had trouble getting better than ~1e-7 contrast in our first HOWFSC run.
- For the successful 2nd run, we fixed the problem by:
  - Removing tip/tilt from the phase retrieval such that the Fourier transform gives a centered PSF.
  - Removing any built-up tip/tilt in the model-based DM solution's phase before applying it to the instrument.

Summary and Conclusions

- For high contrast, coronagraph masks must be well aligned.
  - The FSM rastering was extremely useful for back-illuminating masks since we had no diffuser.
  - Having DMs helps for actuating satellite spots.

- For our model-based control, the DMs, masks, and stellar E-field must all be well calibrated.
  - Adding extra features between masks, or using a grid of masks, is very helpful for computing magnification and clocking over a long baseline.

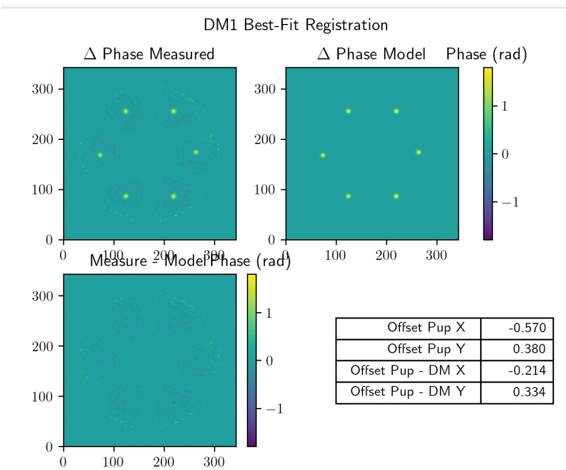
- Automating these routines was the right decision and made alignment and calibration go very smoothly.

- Algorithms we had done before in our testbeds (HCIT) tended to work well.
  - Conversely, new strategies and procedures specific to the instrument had more problems.
  - → Best to get experience with all the algorithms in a testbed first, when possible.

Back-up charts

5. (SPC only, optional) SPM-induced beam shear measurement

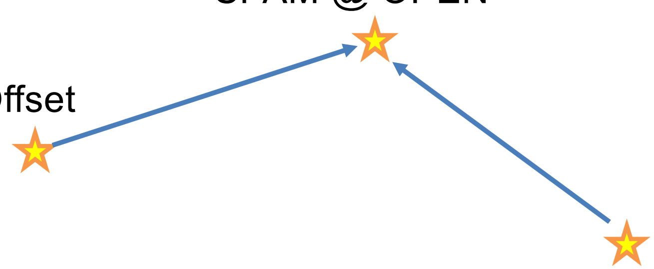
- Because SPAM has two different mirrors, any change in piston between the fold mirror and the SPM substrate causes a beam shear.
- This is problematic for calibrations (and lead to many headaches in past HCIT experiments) because we are trying to align the SPM to the pupil, but the pupil moves when you insert the SPM. So, how do you tell where the pupil is when the SPM is blocking it?
- Solution is to measure DM registration of actuators visible in SPM openings, both before and after inserting the SPM, like the grid below for WFOV:



** In TVAC, we did not have time to do this extra DM registration, so we used the Talbot effect to see intensity differences of the pokes on DM2 in the pupil image. From this, we estimated a pretty small shear of <0.2 pixels that can effectively be ignored since our SPM alignment tolerance is about 0.6 pixels.*

6. (SPC only) PSF realignment to target pixel

- SPAM's positions are all mirrors, and each gives a different star position.
  - We did not expect to see as much as we did for the SPM substrate from one position to the next, but we did. It may be from bonding stresses bowing the wafer.
- This star position shift is a problem because we must keep the LOWFSC beam path consistent for it to work (due to the nonlinearities of the 3-lens LOBE design).
- Therefore, we have to use the FSM or telescope pointing to move the PSF back to the designated happy pixel for LOWFSC.

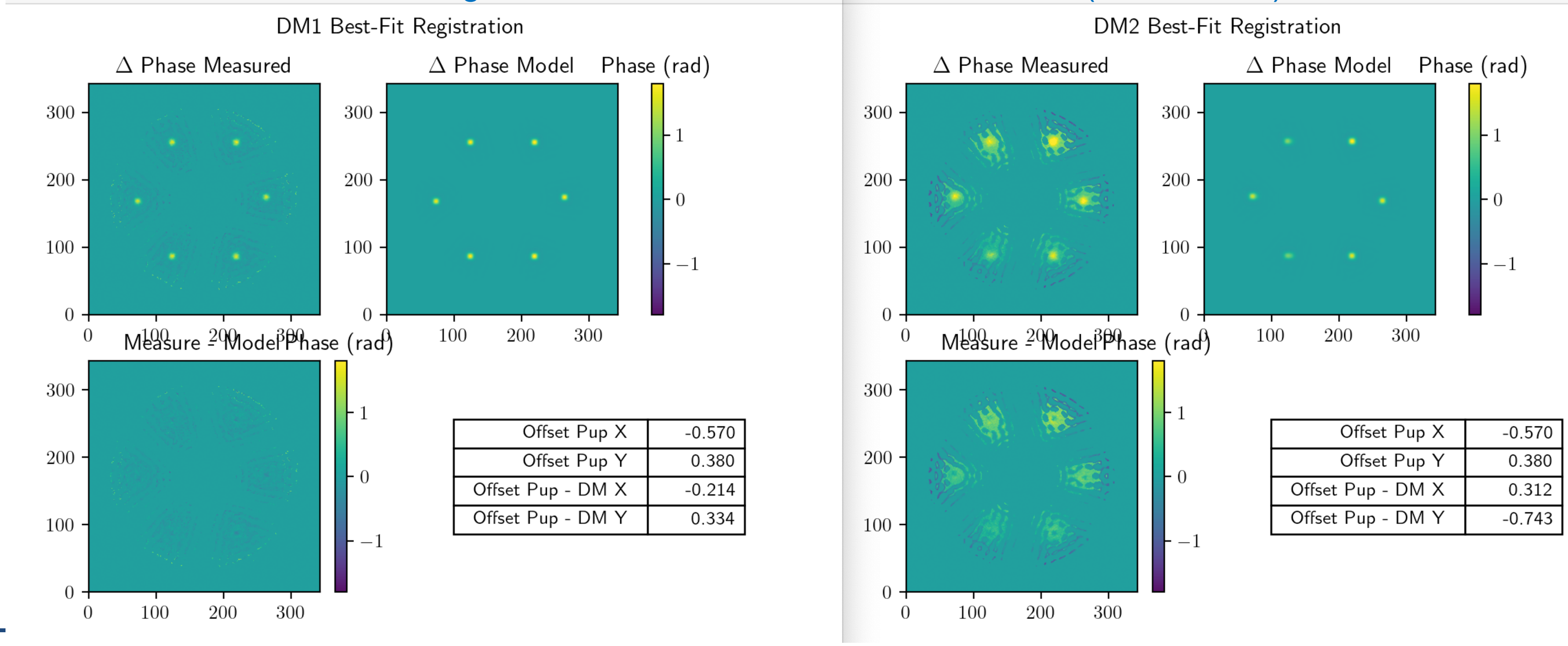


Reminder: 1 DI+EXCAM pixel = 22 mas on sky

7. (SPC only) DM re-registration with SPM in

- The FSM or telescope must be re-pointed to counteract the different pointing of the SPM compared to other SPMs or OPEN position.
- But this causes beamwalk on DM2, so DM registration (lateral check only) must be re-done.
  - Might be able to do this analytically, but safer just to do the measurement.

DM Registration with the WFOV SPM in Place (TVAC Data)



Offset Pup X	-0.570
Offset Pup Y	0.380
Offset Pup - DM X	-0.214
Offset Pup - DM Y	0.334

Offset Pup X	-0.570
Offset Pup Y	0.380
Offset Pup - DM X	0.312
Offset Pup - DM Y	-0.743

8. (HLC only) Apply HLC DM patterns

- Either from a ground seed in TVAC (Band 1) or from a model using on-orbit calibration data (Bands 2, 3, 4), the HLC needs to start from a good seed to save a ton of time getting the dark hole.
- There is GSW to add the desired delta WFE on to the DM commands found for the flattened wavefront.

DM1 WFE for Band 1 HLC

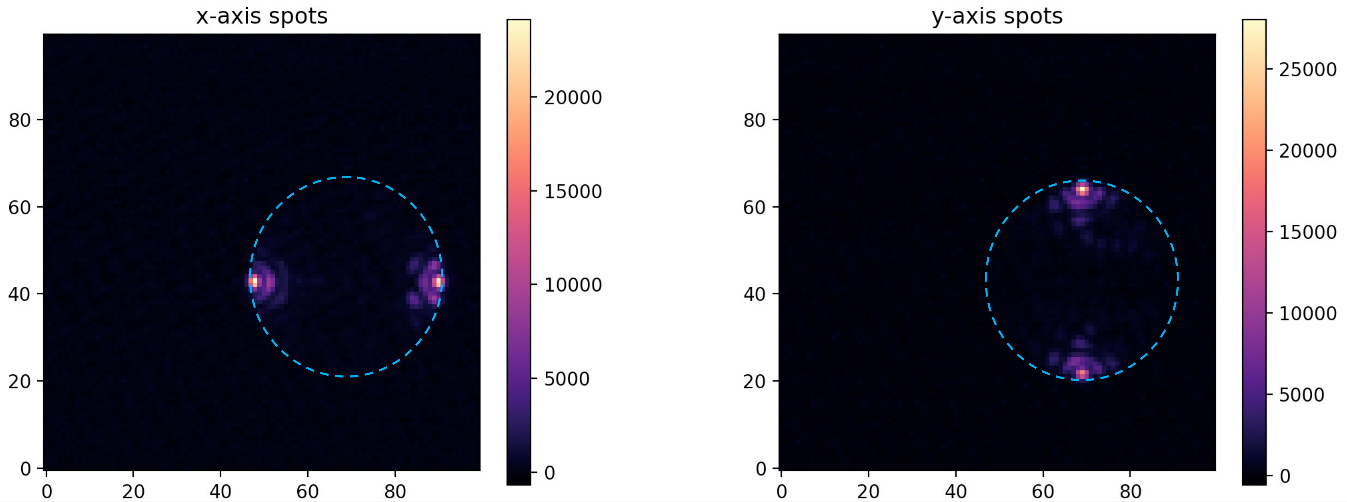
DM2 WFE for Band 1 HLC

10. LOWFS Bootstrapping and LOS Loop

- In TVAC, we empirically trained and closed the LOWFSC line-of-sight (LOS) loop for three modes:
  1. HLC NFOV for Band 1
  2. SPC Spectroscopy
  3. SPC WFOV
- Those three will be used as LOWFS estimator starting points on orbit
- For all other modes, we should be able to bootstrap from model-based LOWFS estimators
  - HLC in Band 1 was the main one that would be hard to bootstrap from the model because of the complicated FPM patterning.
  - All other modes' FPMs are much, much simpler, so the Zernike responses are much more predictable from a model.

13. (HLC only) Field stop fine alignment

- As with FPM fine alignment, the “speckle balance” algorithm is used. Separate sine waves in x and y are used to actuate spots at the edge of the mask. The mask is aligned once the speckles are equally cut off on opposite sides of the star.
- This is (mostly) only for the full HLC dark holes because those are the FSs symmetric about the star. Slits can’t be used with speckle balance because they are offset from the star and too narrow.



Dashed blued circle is the field stop outline.