Polarimeter to Unify the Corona and Heliosphere


# WFI Instrument Status

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WFI Instrument Lead

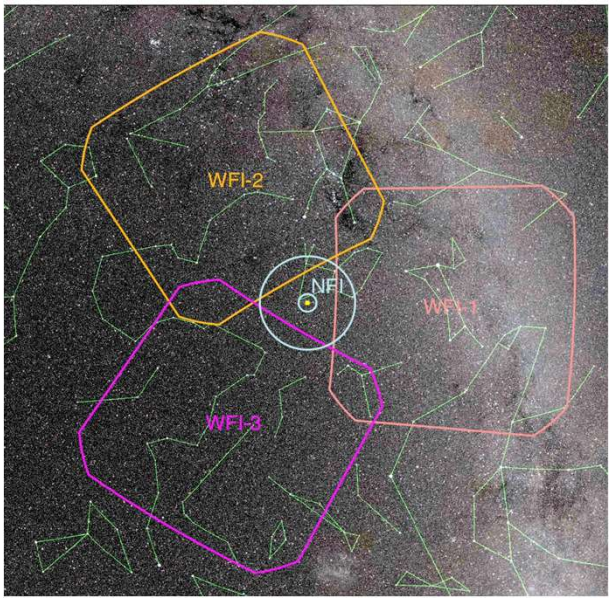
**PUNCH 6 Science Meeting**

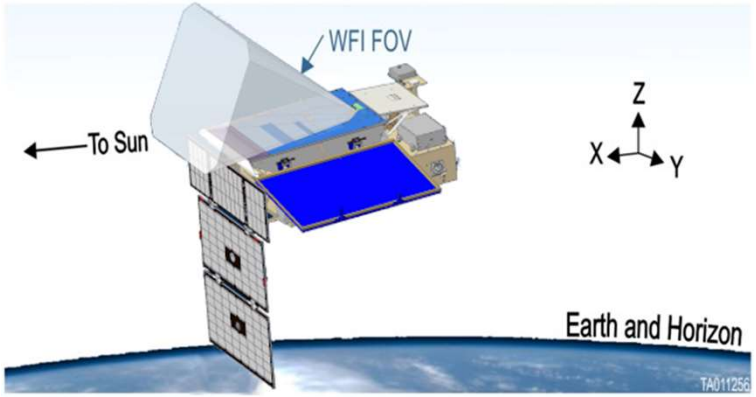
February 25-26, 2025

Cal Poly

# WFI Overview

- WFI/NFI provide first complete, photometric, high resolution views of corona/solar wind transition.
  - WFI 5-45°, NFI 1.5-8°
- WFI provides first wide-field polarimetric solar wind images.
- Design based on STEREO/HI, SoloHI - heliospheric imagers.
- 3 observatories in 620 km polar orbit (95.95 min)
- Rotating trefoil pattern orbit separated by 120° ±30°.
  - Continuous observations 4 min observing cadence (2x per roll)
  - Full coverage in 32 min
  - 30° roll every 8 min

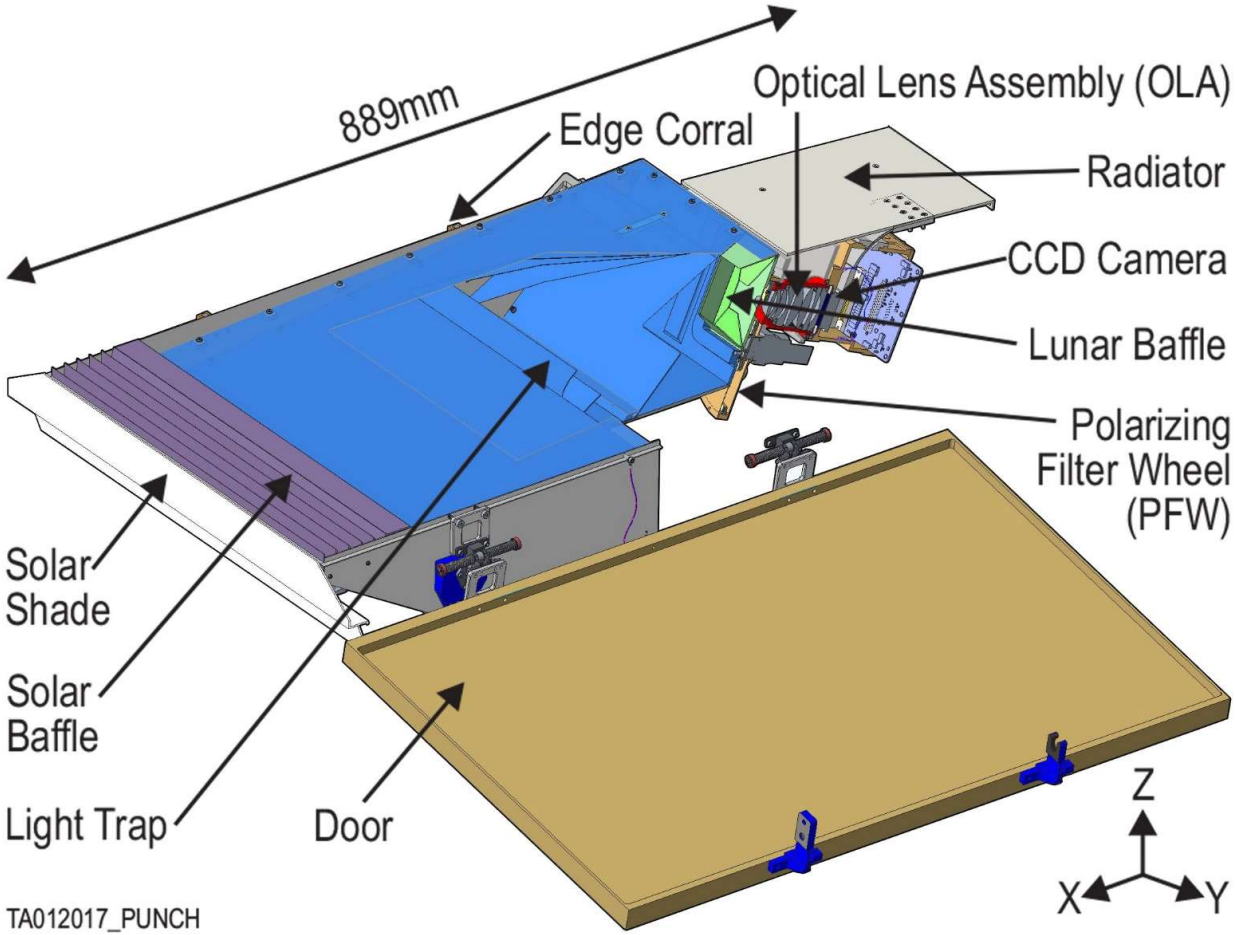


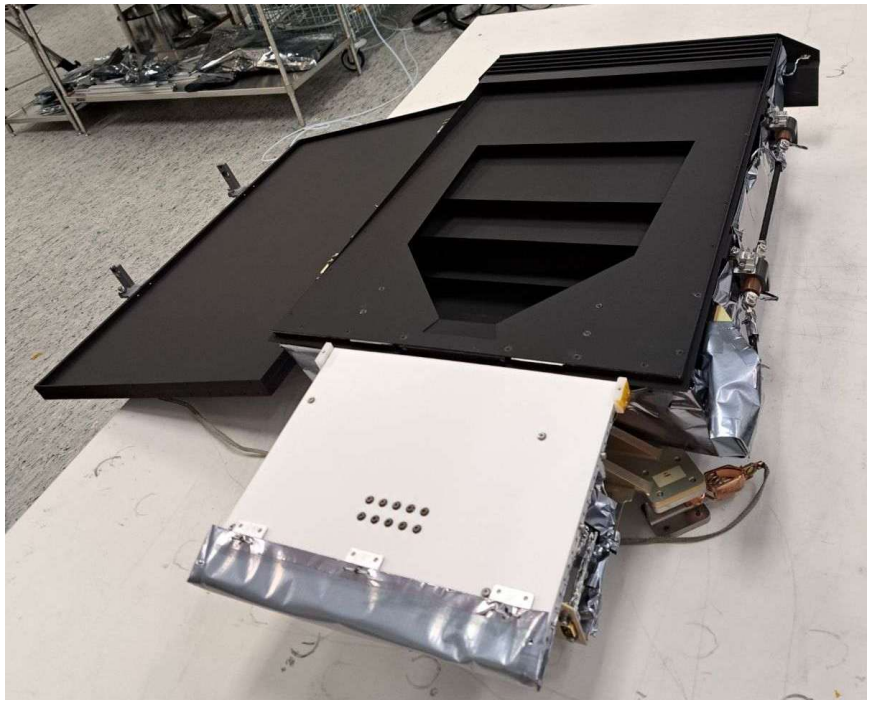

| Resource | CBE | Cont. | Total |
|---|---|---|---|
| Mass (kg) | 16.88 | 7.05% | 18.07 |
| Power (W) | 15.49 | 12.00% | 17.35 |
| Length (mm) | 889 | - | 889 |
| Width (mm) | 438 | - | 438 |
| Height (mm) | 149 | - | 149 |
| Data Rate (GB/day) | 1.41 | 34.20% | |

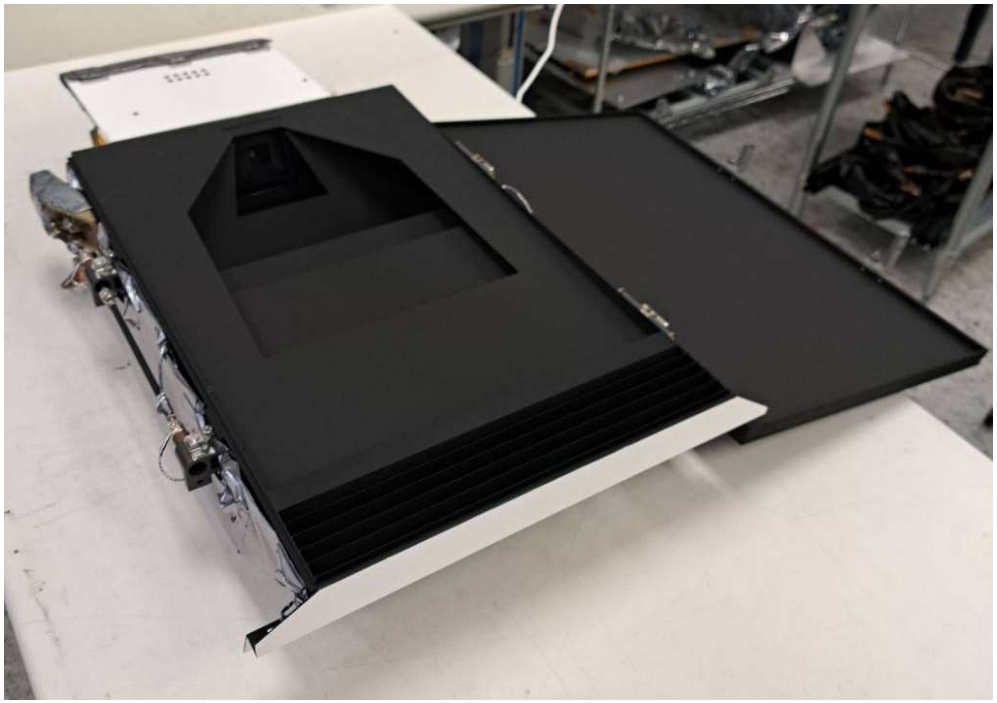
* LV update provides additional margin

# WFI Instrument

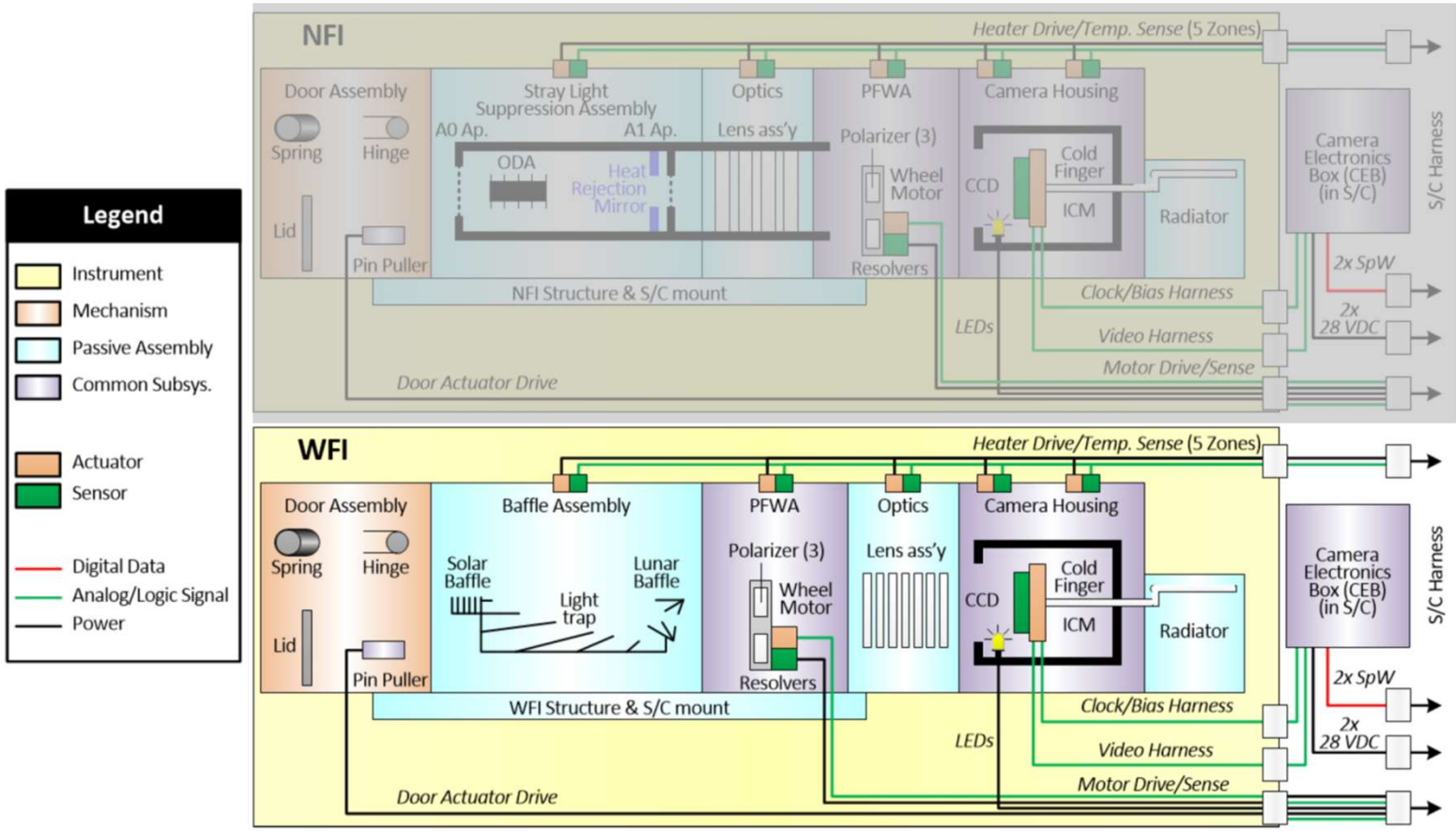


# Integrated Instrument (WFI-3)





# WFI Block Diagram



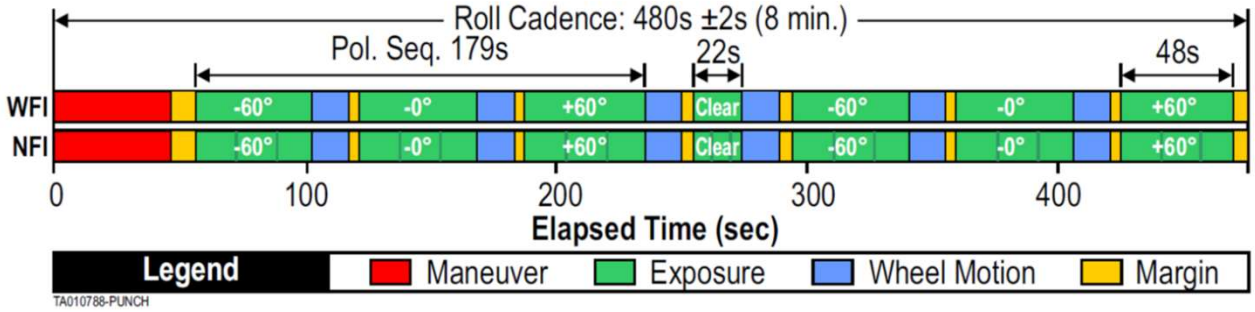
# WFI Level 2 Driving Requirements

- All Requirements validated

| ID | Requirement | Value | Performance | Status |
|---|---|---|---|---|
| 1057 | Passband | Width: 300+/-100nm<br>Center: 550+/-75nm | 450-750nm | PASS |
| 1063 | Field of View (FOV) | 20 $R_\odot$ – 160 $R_\odot$ | 17.4 $R_\odot$ – 180$R_\odot$ | PASS |
| 1064 | Instantaneous FOV | 40 deg$^o$ square truncated by 50 deg$^o$ circle | 40.2$^o$ FOV Baffle, >50$^o$ OLA FOV | PASS |
| 1068 | Angular Resolution | 4 arcmin | 2.4 arcmin | PASS |
| 1071 | Norm. Sensitivity | 7E-17 $B_\odot$ | 3.7E-17 $B_\odot$ | PASS |
| 1076 | Polarization | 3 angles | -60$^o$, 0$^o$, +60$^o$ | PASS |

# WFI Conops

- Conops common to WFI & NFI
- Two sets of polarization sequences per 8 min roll cadence
- 20 seconds PFW rotation time




| PUNCH Observing Sequence Schedule | | | |
|---|---|---|---|
| **Time (s)** | **Length + margin** | **NFI Action** | **WFI Action** |
| 0 | 47+4 | Roll & set PFW to -60° | Roll & set PFW to -60° |
| 51 | 48+1(*) | Expose 3x13s at -60° | Expose 45s at -60° |
| 98 | 15+5 | Set PFW to 0° & settle | Set PFW to 0° & settle |
| 118 | 48+1(*) | Expose 3x13s at 0° | Expose 45s at 0° |
| 165 | 15+5 | Set PFW to 60° & settle | Set PFW to 60° & settle |
| 185 | 48+1(*) | Expose 3x13s at 60° | Expose 45s at 60° |
| 232 | 15+5 | Set PFW to CL & settle | Set PFW to CL & settle |
| 252 | 22+1(*) | Expose 3x5s at CL | Expose 19s at CL |
| 273 | 15+5 | Set PFW to -60° & settle | Set PFW to -60° & settle |
| 293 | 48+1(*) | Expose 3x13s at -60° | Expose 45s at -60° |
| 340 | 15+5 | Sep PFW to 0° & settle | Sep PFW to 0° & settle |
| 360 | 48+1(*) | Expose 3x13s at 0° | Expose 45s at 0° |
| 407 | 15+5 | Set PFW to 60° & settle | Set PFW to 60° & settle |
| 427 | 48+1(*) | Expose 3x13s at 60° | Expose 45s at 60° |
| 474 | 1 to 11 | Sync for next roll | Sync for next roll |
| (*) 2-second overlap with following event | | | |

# WFI Instrument Status

| Milestone | WFI-1 | WFI-2 | WFI-3 |
|---|---|---|---|
| Camera Focus | PASS | PASS | PASS |
| Vibe | PASS | PASS | PASS |
| TVAC / TBAL | PASS | PASS | PASS |
| SCOTCH | PASS | N/A (Descoped) | N/A (Descoped) |
| Optical Performance | PASS | PASS | PASS |
| PSR / EIDP | Complete (10/24/2023) | Complete (3/8/2024) | Complete (4/12/2024) |
| Delivery | Complete (1/22/2023) | Complete (3/22/2024) | Complete 5/14/2024 |

# WFI Requirements Verification

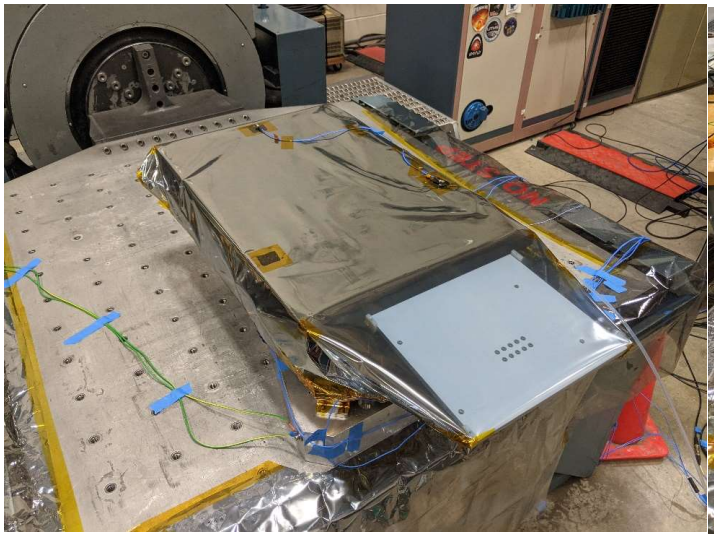
## WFI Requirements Verification Summary Table

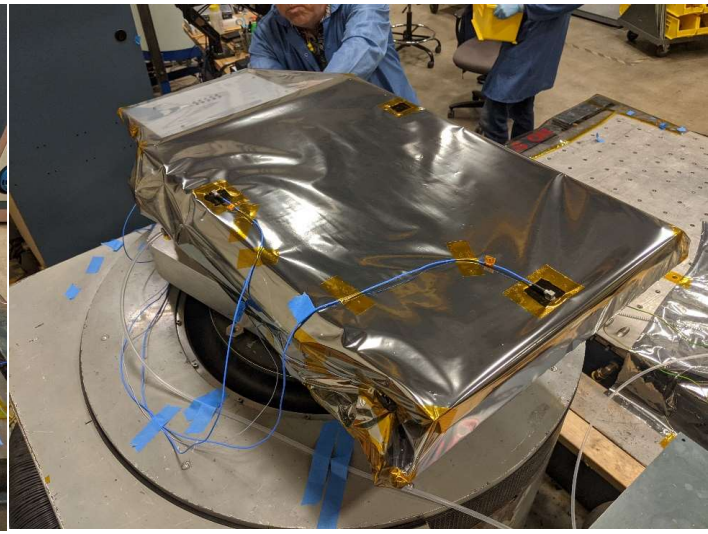
| Level | Total Requirements | Passed | Deferred | Waiver | Open | Percent Verified Items |
|---|---|---|---|---|---|---|
| WFI Level 3 / 4 | 113 | 110 | 1 | 2 | 0 | 100% |
| WFI Level 5 | 20 | 20 | 0 | 0 | 0 | 100% |
| Total | 133 | 130 | 1 | 2 | 0 | |

- Two Waivers (Metering Bracket Reflectivity, Solar Shield Position) approved -- Negligible performance impact

- No Outstanding MIUL Open Items
- No MUAs

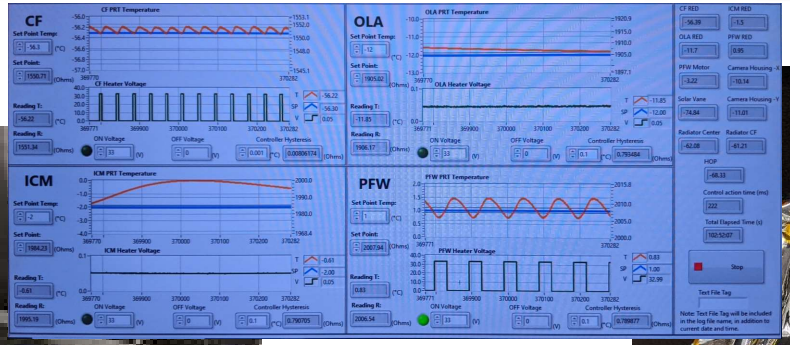
# WFI Structural Verification (Vibration Testing)

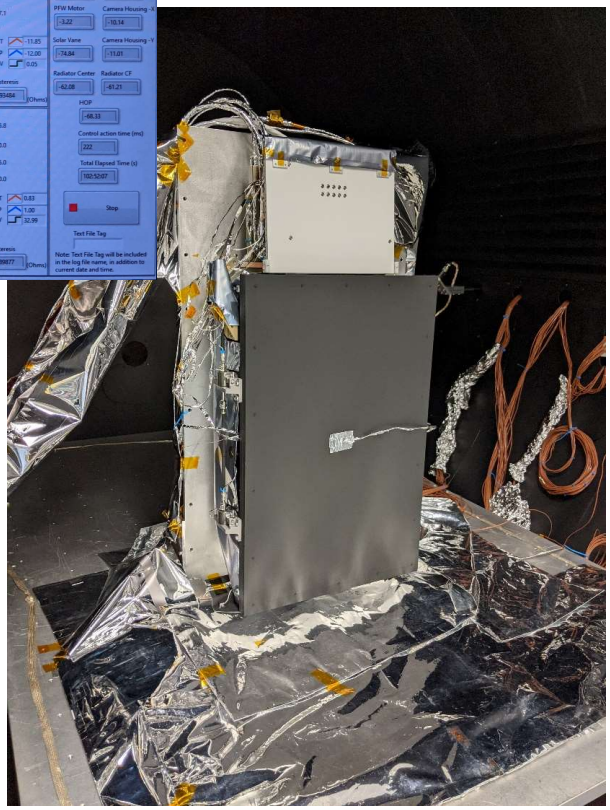




WFI-3 Vibration Testing Completed

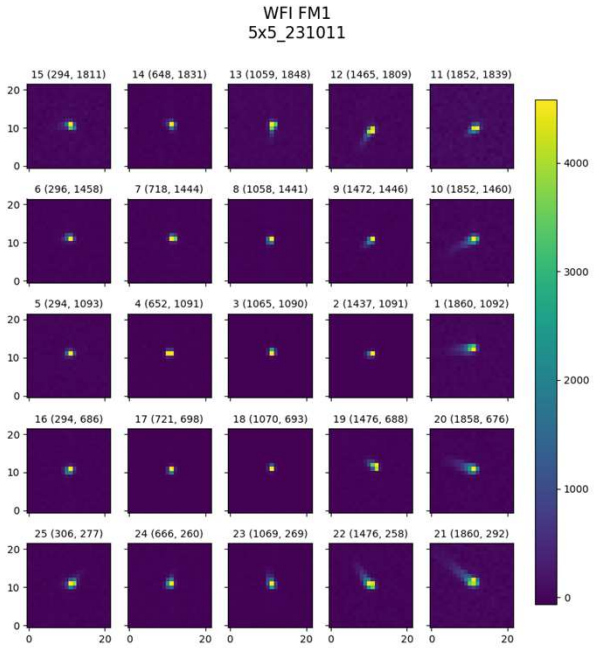
# WFI Thermal Verification (TVAC / TBAL)

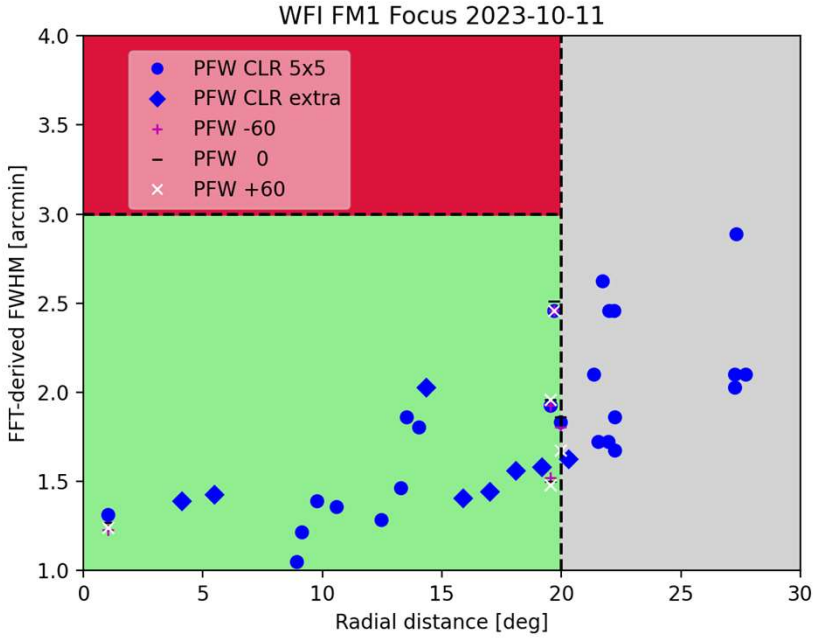


WFI-FM003 TVAC / TBAL Complete
(meeting ERD requirements)

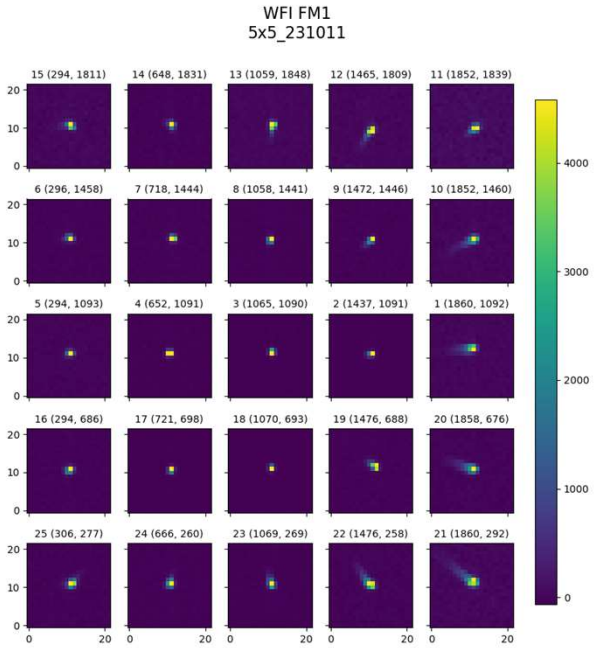
# WFI Optical Focus Testing

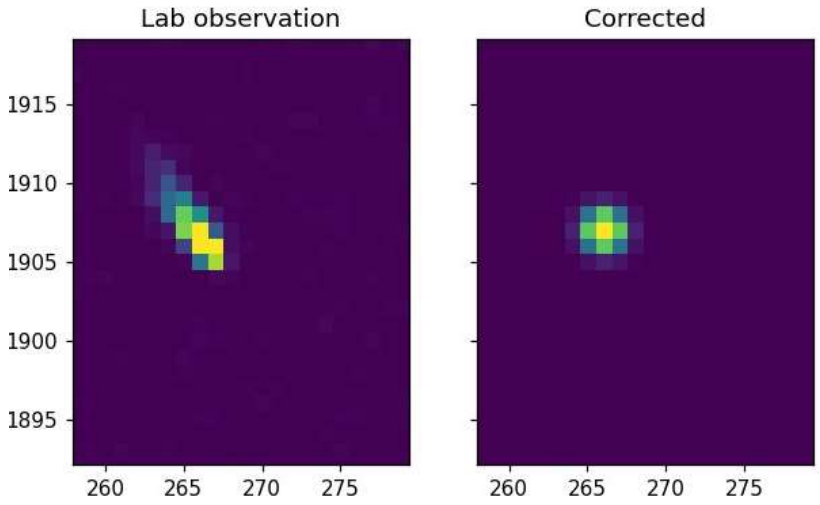



WFI-1 Optical Performance testing (all filters)
Meets requirements

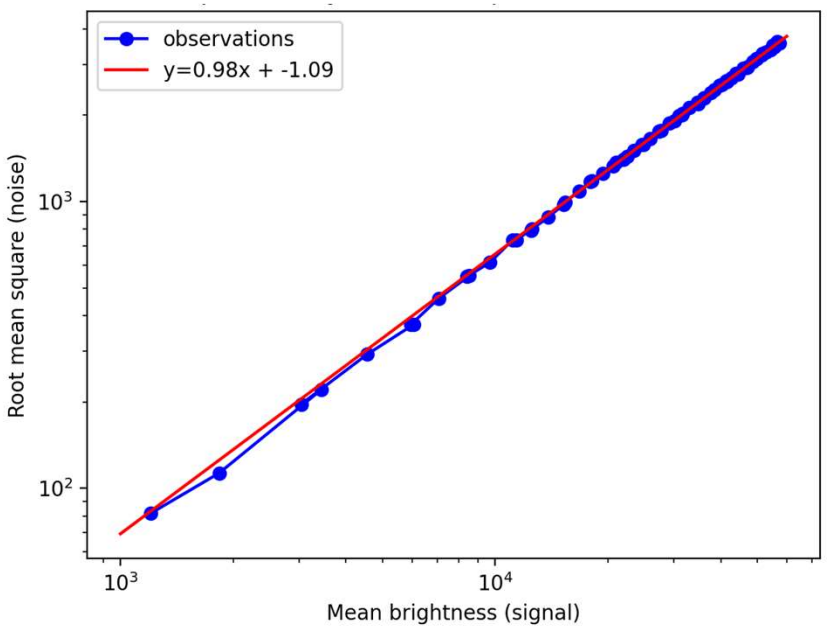
# Point Source Regularization



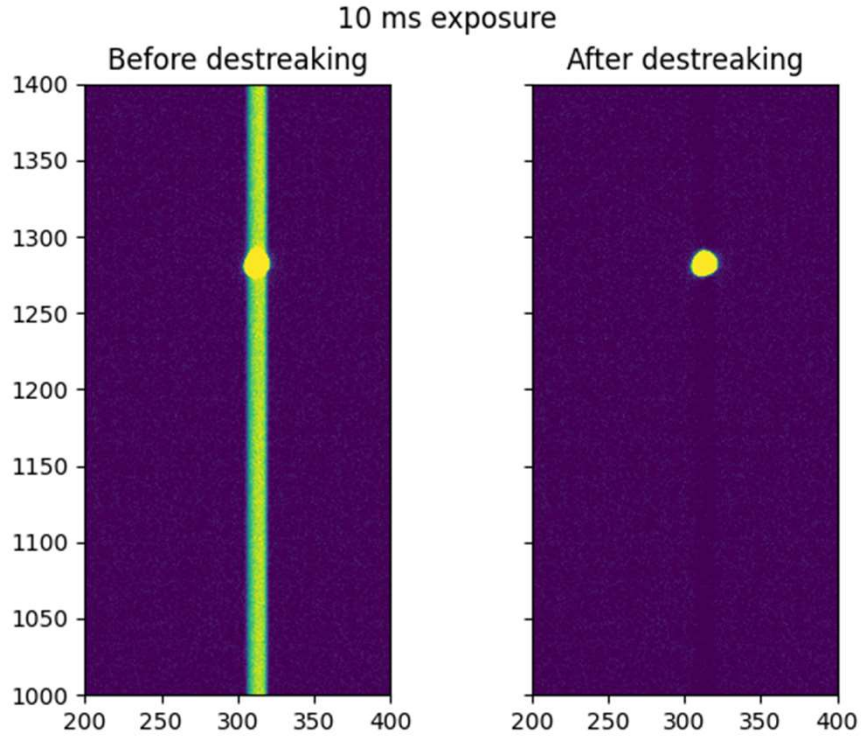




PSF is well understood and Software Pipeline is ready to create Mosaics

# TVAC / SOC Calibration -- WFI



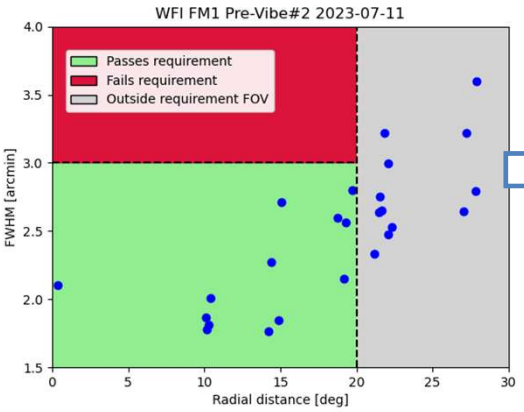

Photon Transfer Curve



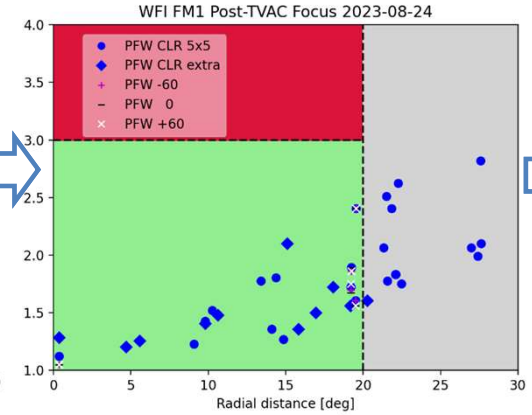

SOC De-streaking Analysis Validated on Cold Operational Data

# WFI Instrument/Observatory Focus Repeatability

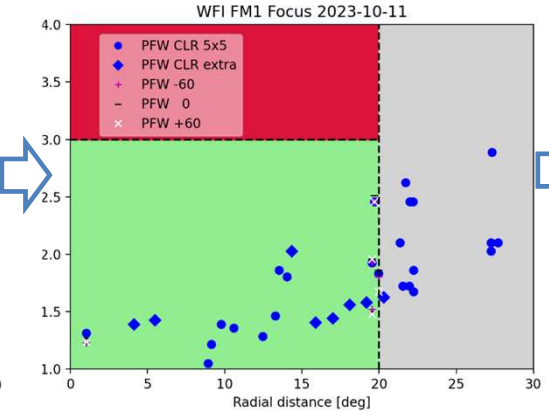
**Pre-Environmentals**



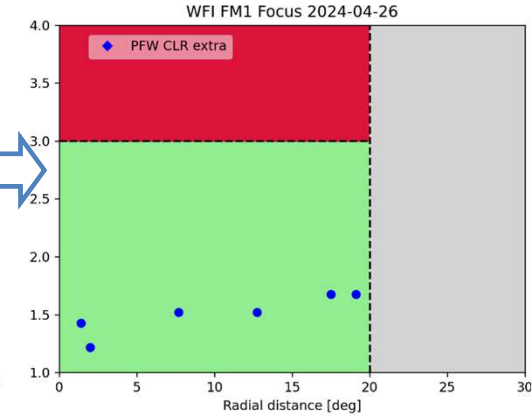

**Post-Environmentals**

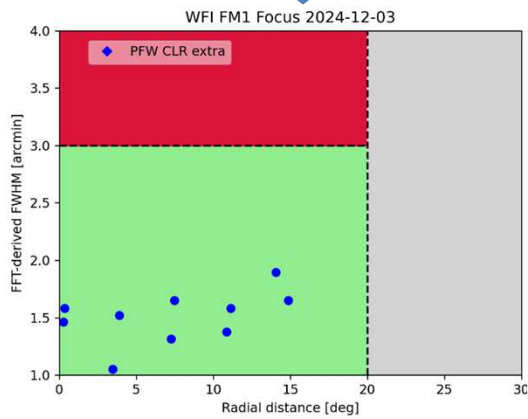



**Post-SCOTCH**




**Post-Obs Integration**

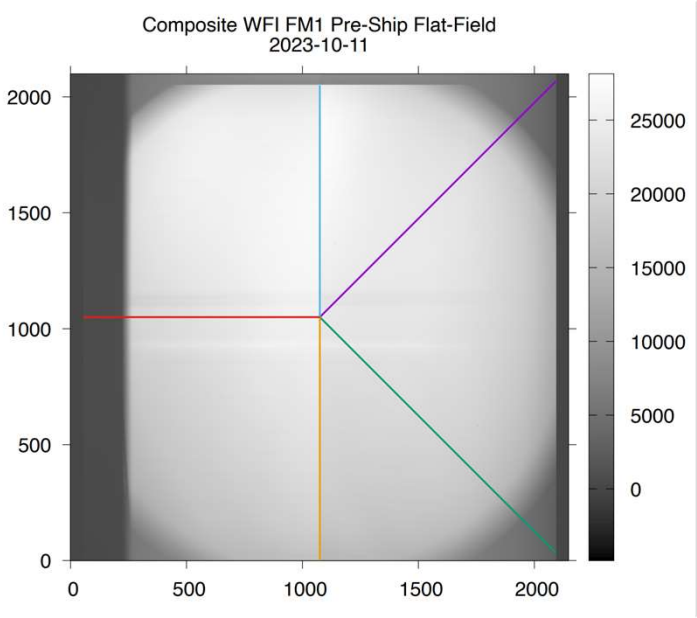


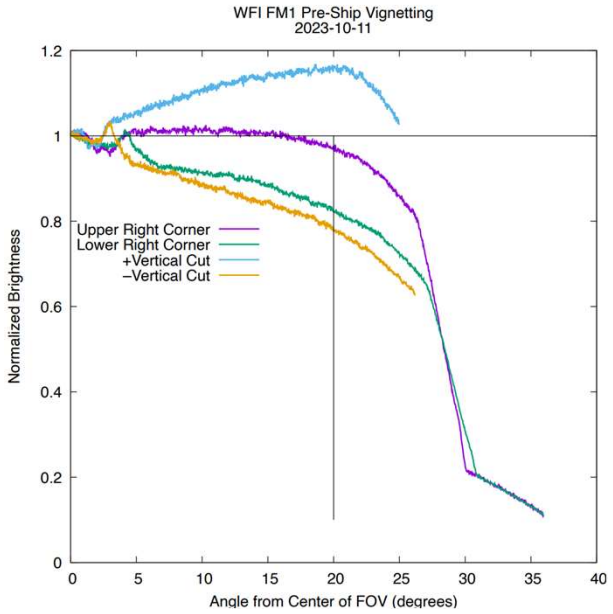



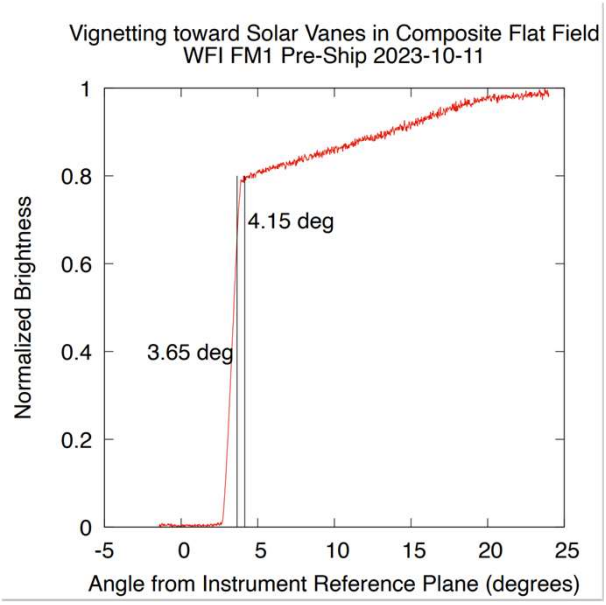

WFI-1 Delivery Focus Consistent with Pre-Environmental Focus

**Post-Obs Environmentals**

# WFI Optical Vignetting Testing

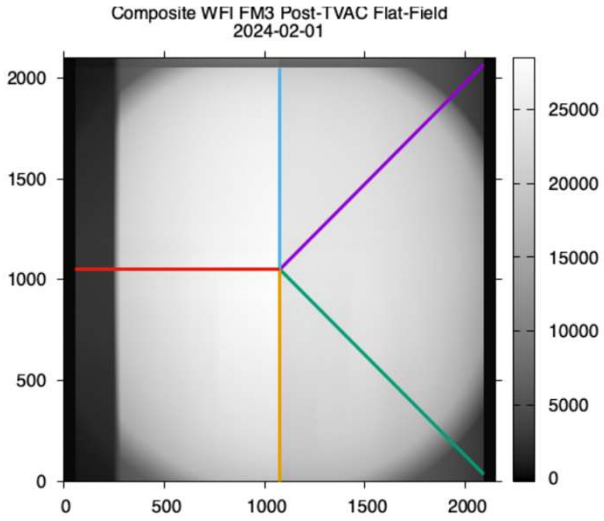


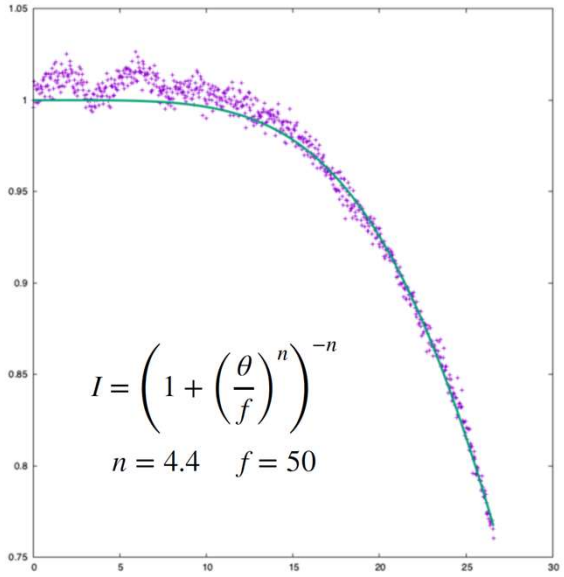



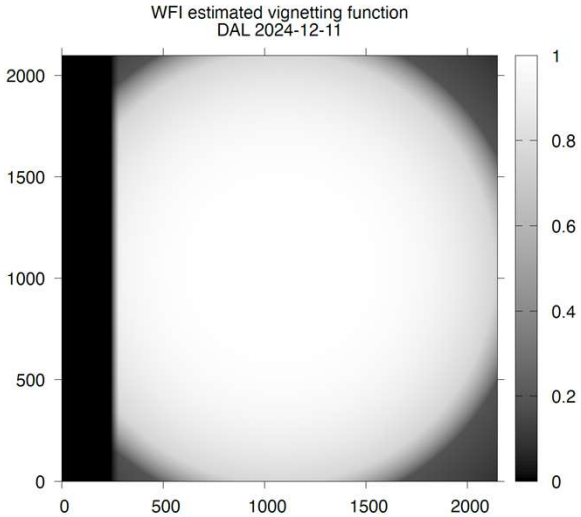




WFI-1 Flat Fields meet Vignetting Requirements

# WFI Observatory Vignetting Model

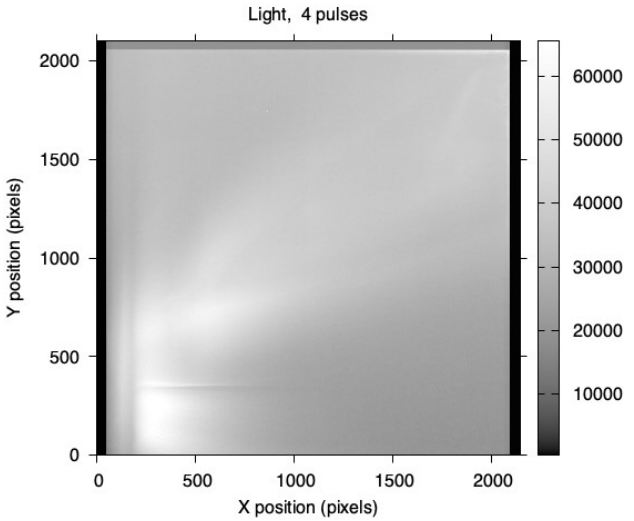


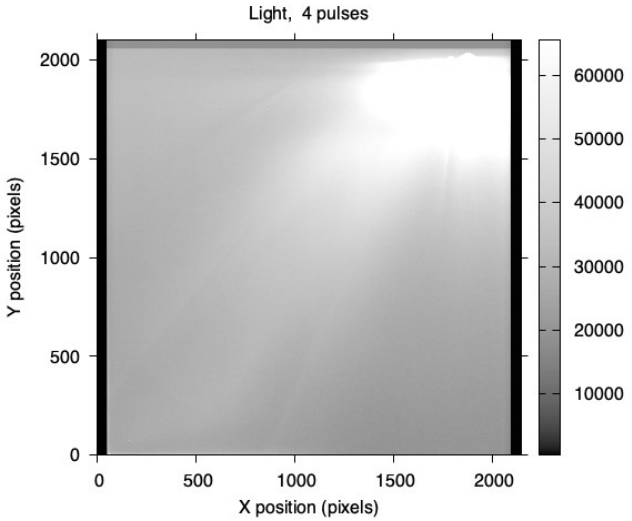



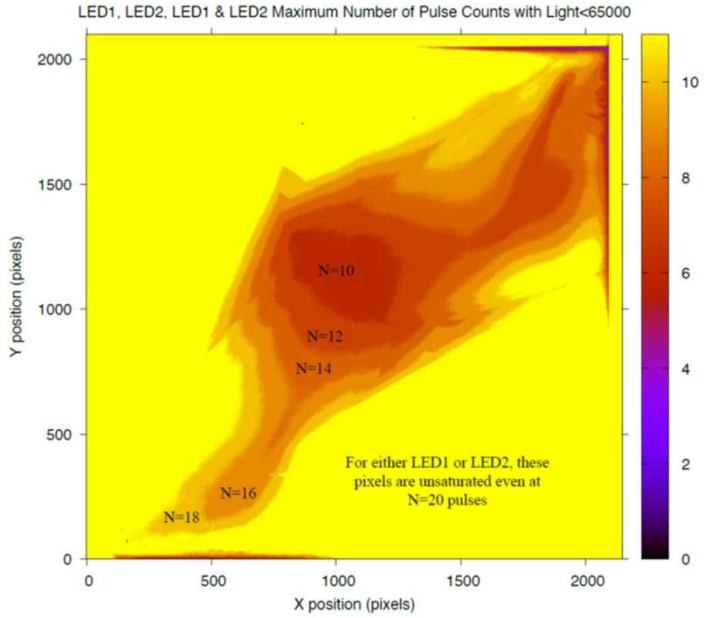




WFI Vignetting Model Ready for PUNCH Software Pipleline

# WFI Post-Vibe LED Testing

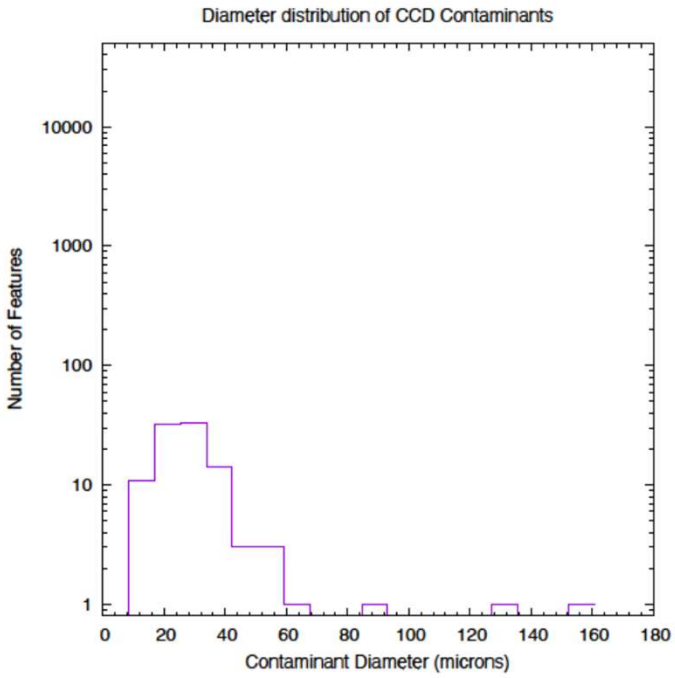


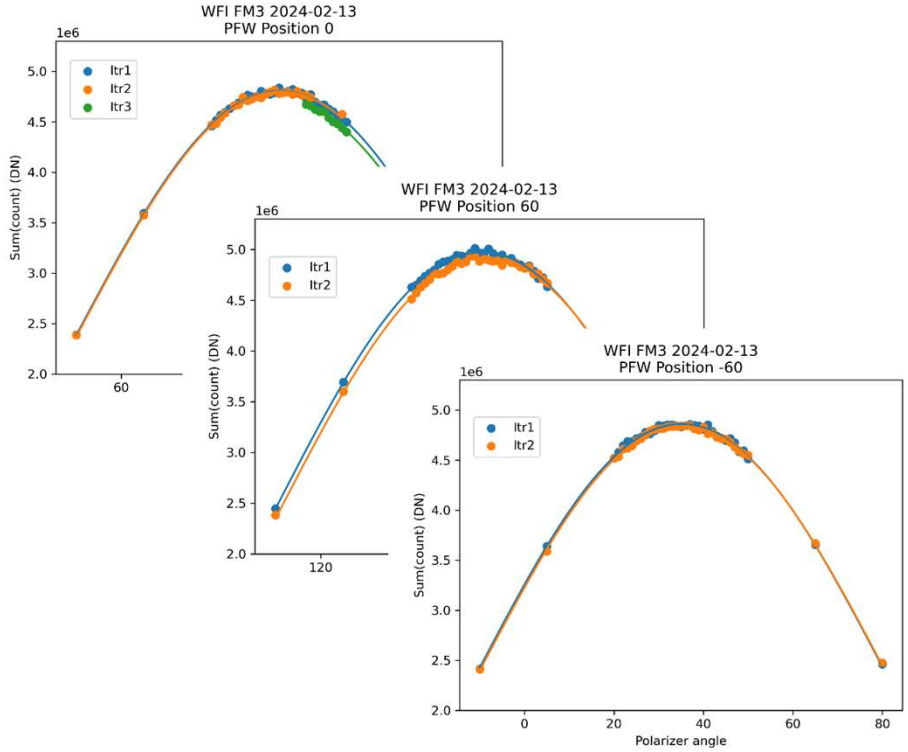




WFI-3 LED Testing completed
(Meets science requirements)

# WFI Post-Vibe LED/PFW Testing




WFI-3 LED Testing completed
(Verifies minimal CCD Obscured pixels)



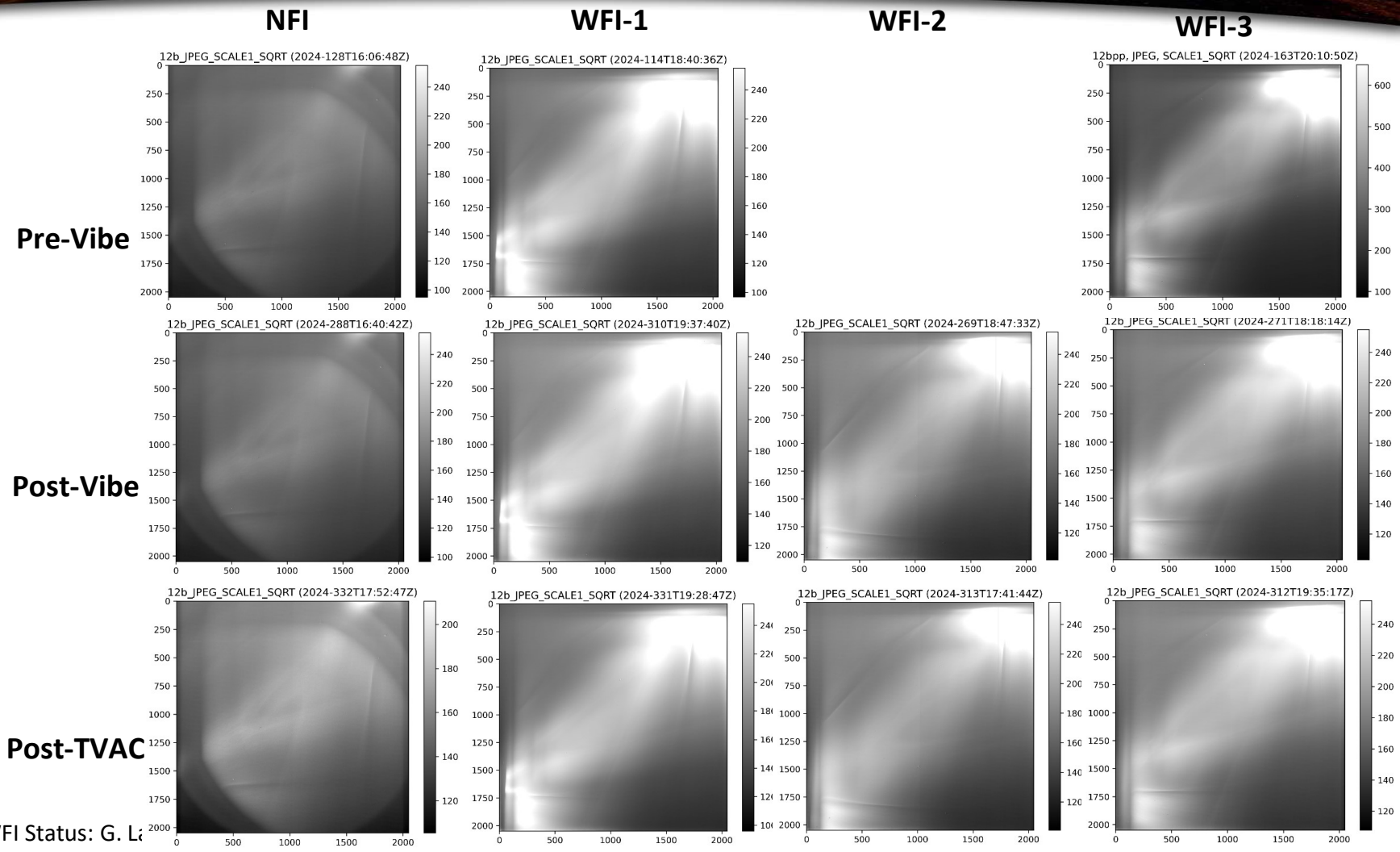

WFI-3 Polarizer Testing completed
(Verifies Polarizer Angles)

# Observatory LED Trending (NFI & WFI)

Updated

- Observatory testing pre- and post-environmentals
- LED imaging performed on NFI/WFI-1/2/3

**LED Imaging Stable through end-to-end Observatory Testing (Verifies CCD / LED Performance)**



# NFI/WFI Observatory TVAC Bias/Read Noise Trending

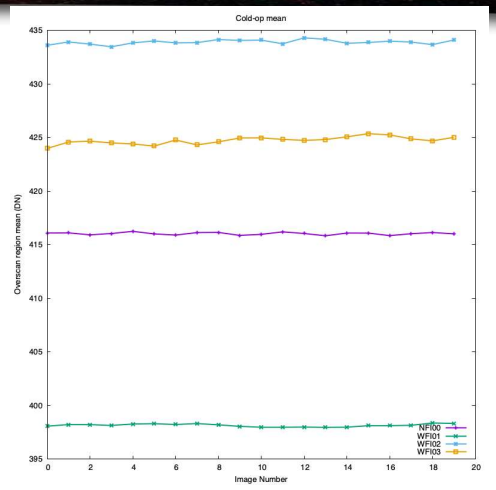
- Observatory TVAC testing examined Bias & Read Noise
- Cold CCD, S/C Systems Operating (Radio link, reaction wheel, torque rod active)
- Bias values are consistent with nominal CCD temperature fluctuations (< +/- 0.5 DN)
- Read Noise trends are small (< +/- 0.02 DN)
- Both HotOp & ColdOp show similar trends

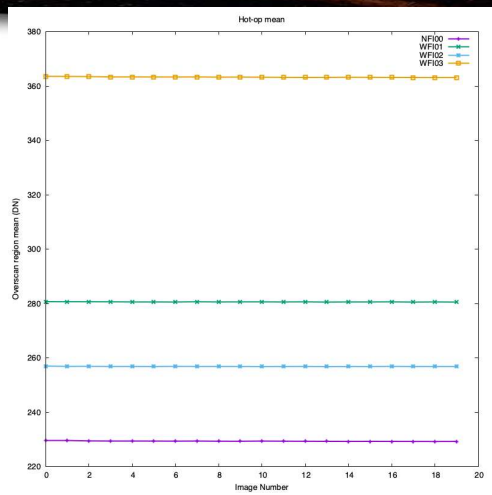
**NFI**

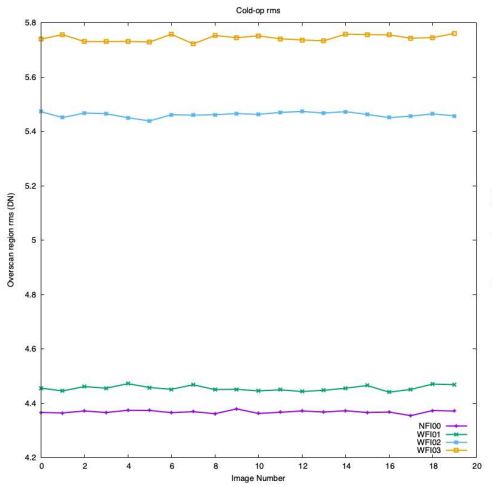
**WFI-1**

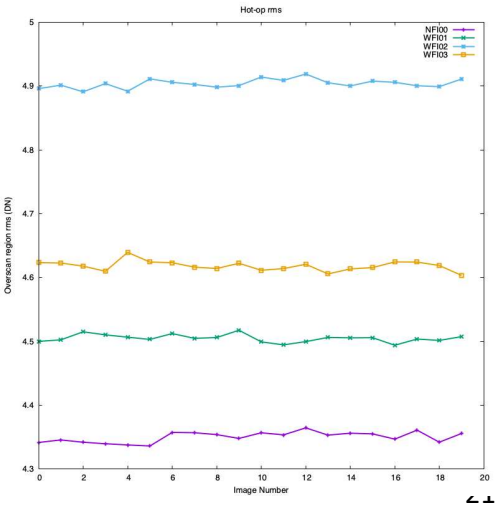
**WFI-2**

**WFI-3**



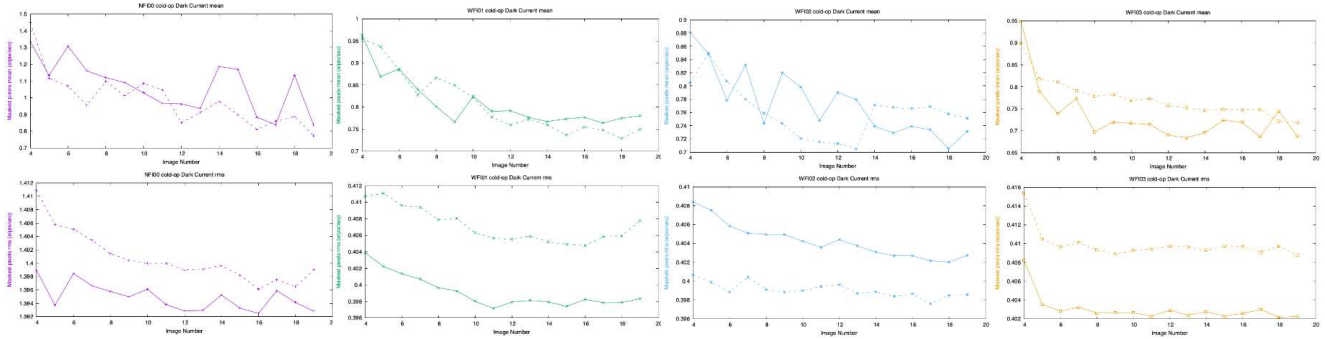

Bias & Read Noise Stable through end-to-end Observatory Testing
(Verifies CCD EMI/EMC Performance)

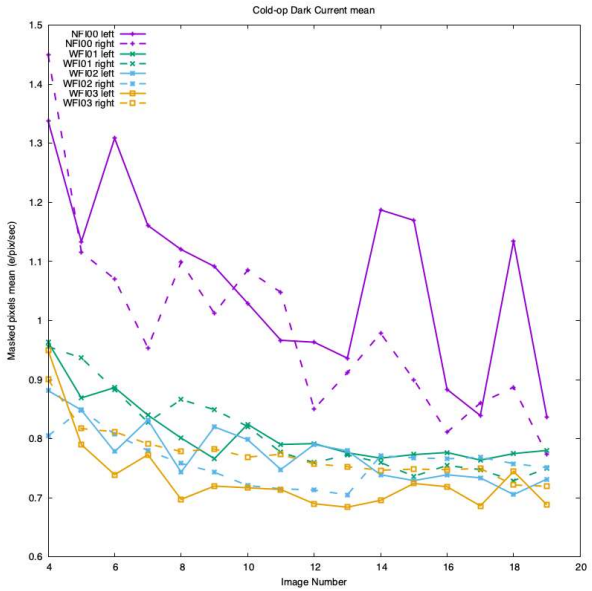
# NFI/WFI Observatory TVAC Dark Trending

- Observatory TVAC testing examined Dark current / Noise
- Cold CCD, S/C Systems Operating (Radio link, reaction wheel, torque rod active)
- Dark Current of ~0.7-1.3 e-/pix/s meets requirement of <5 e-/pix/s.
- Dark Current fluctuations are consistent with nominal CEB temperature fluctuations (~ +/- 0.1 e-/pix/s)
- Dark Current rms trends are small (< +/- 0.01 e-/pix/s)

Dark Current Stable through end-to-end Observatory Testing
(Verifies CCD EMI/EMC Performance)

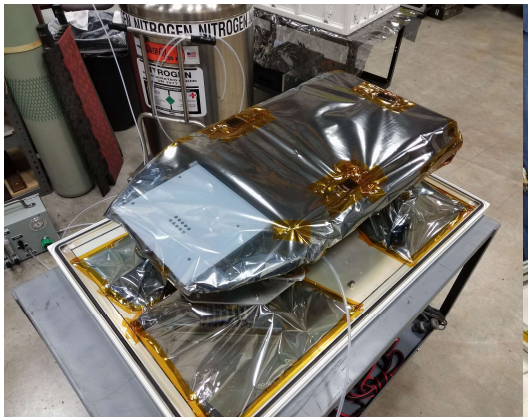
**NFI** **WFI-1** **WFI-2** **WFI-3**

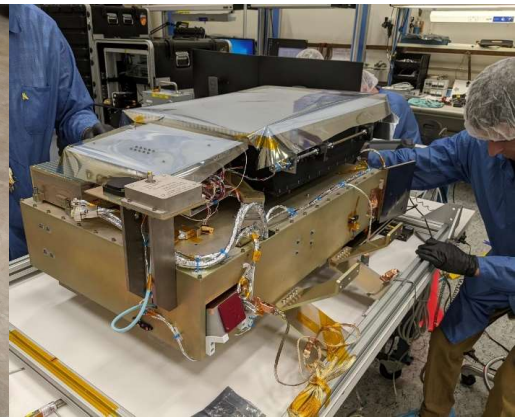


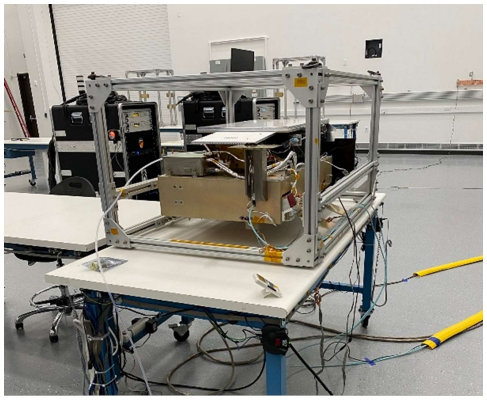


# WFI Delivery to Observatory

- All WFIs Successfully Delivered to Observatory I&T
  - WFI-1 (1/22/2023)
  - WFI-2 (3/22/2023)
  - WFI-3 (5/14/2023)
- Functional Testing
- Comprehensive Performance Testing (CPT)
  - Bias/Read/Dark Noise
  - LED / Flat Field
  - PFW
  - Door Testing
  - Optical Focus Testing

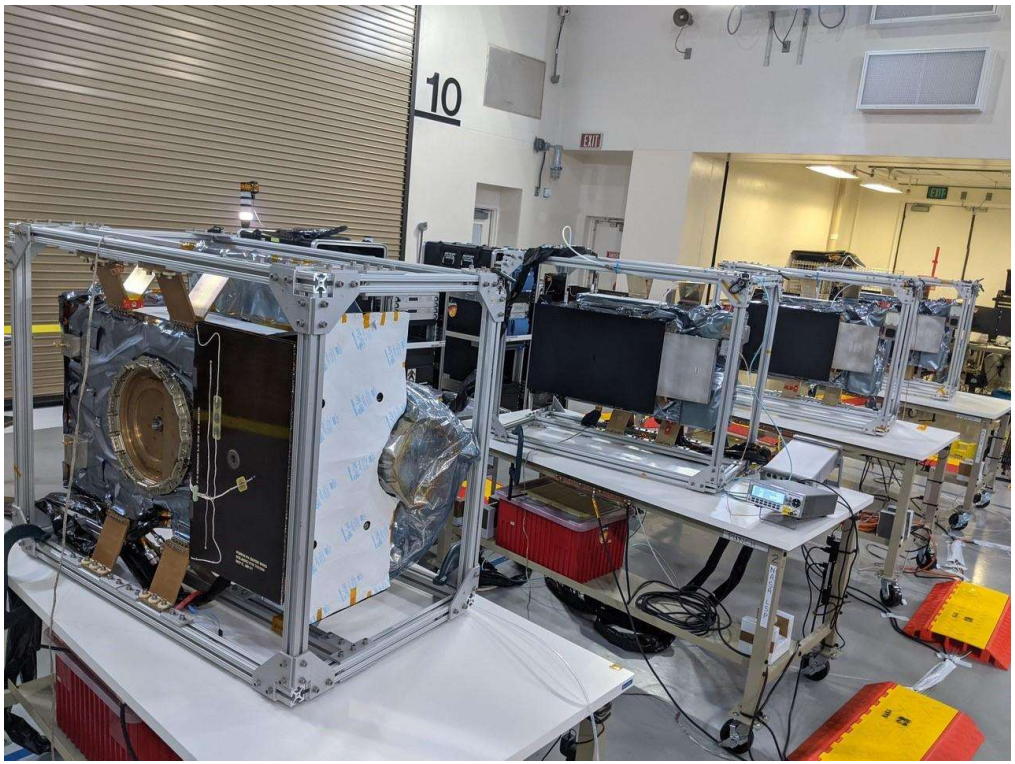






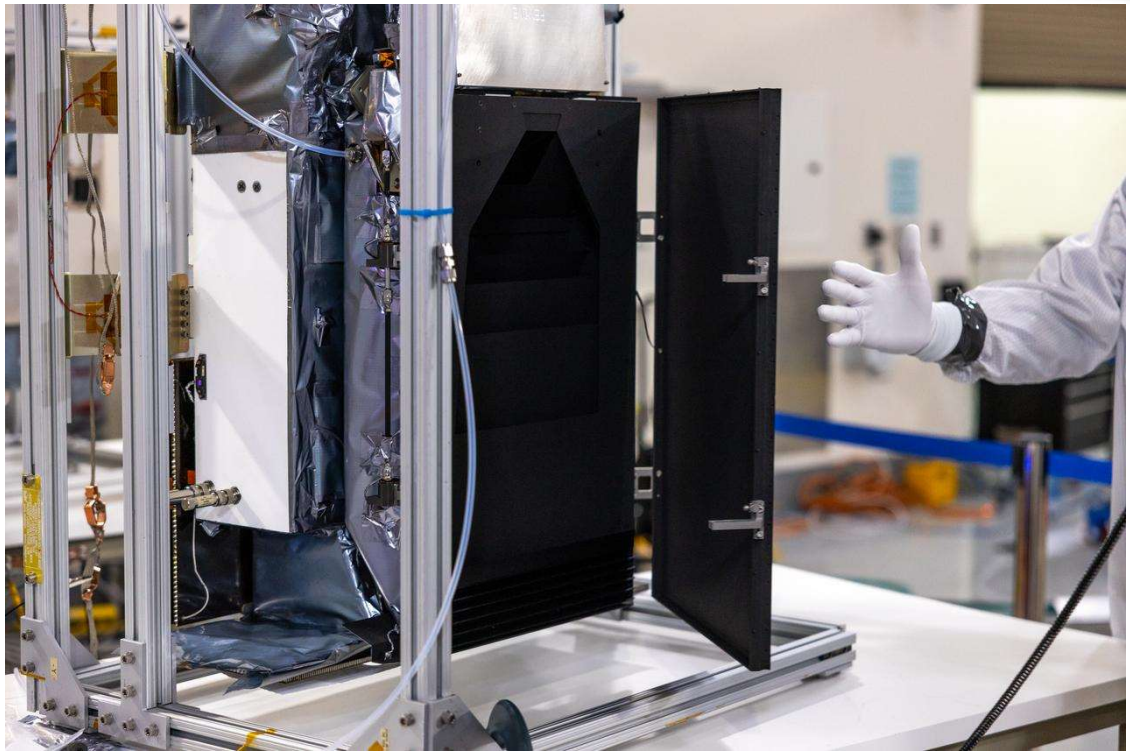
# PUNCH I&T @ VSFB

- Vandenberg SFB I&T
  - Delivery & Inspection



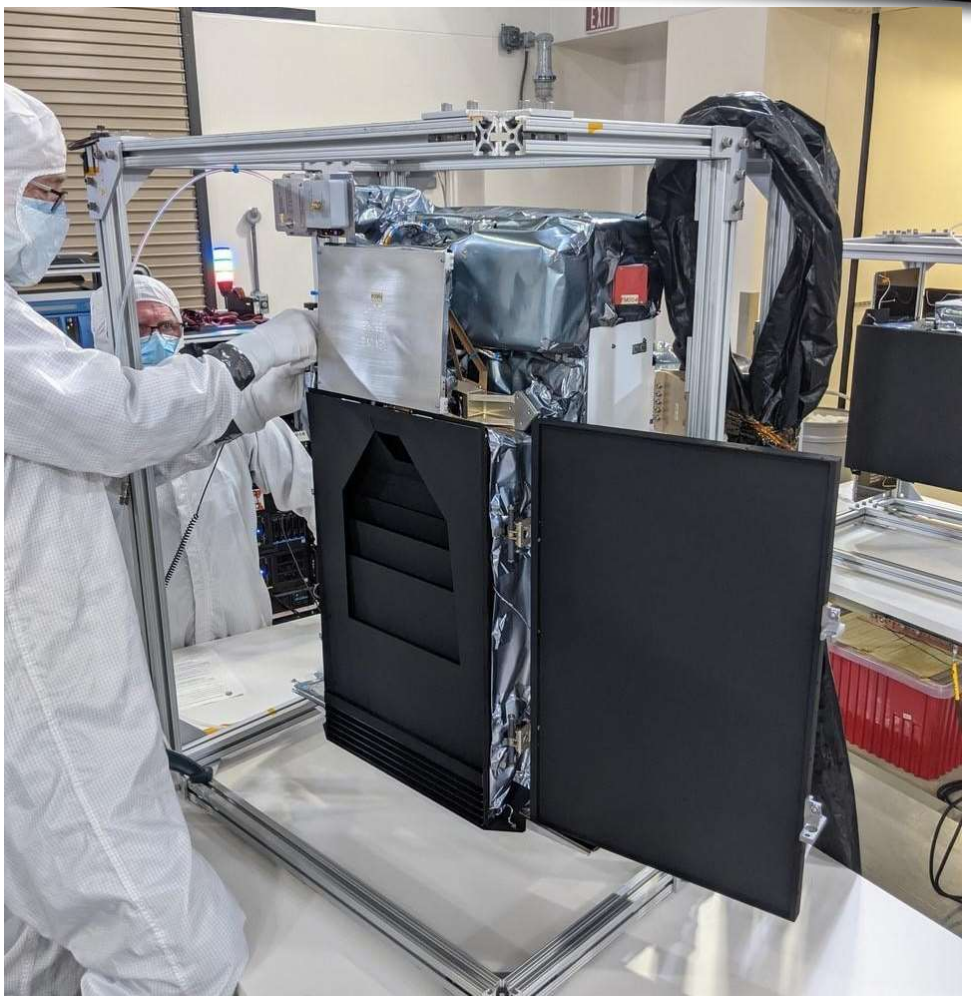

# PUNCH I&T @ VSFB

- Vandenberg SFB I&T
- Functional Testing
- Comprehensive Performance Testing (CPT)
  - Bias/Read Noise
  - LED / Flat Field
  - PFW
  - Door Testing

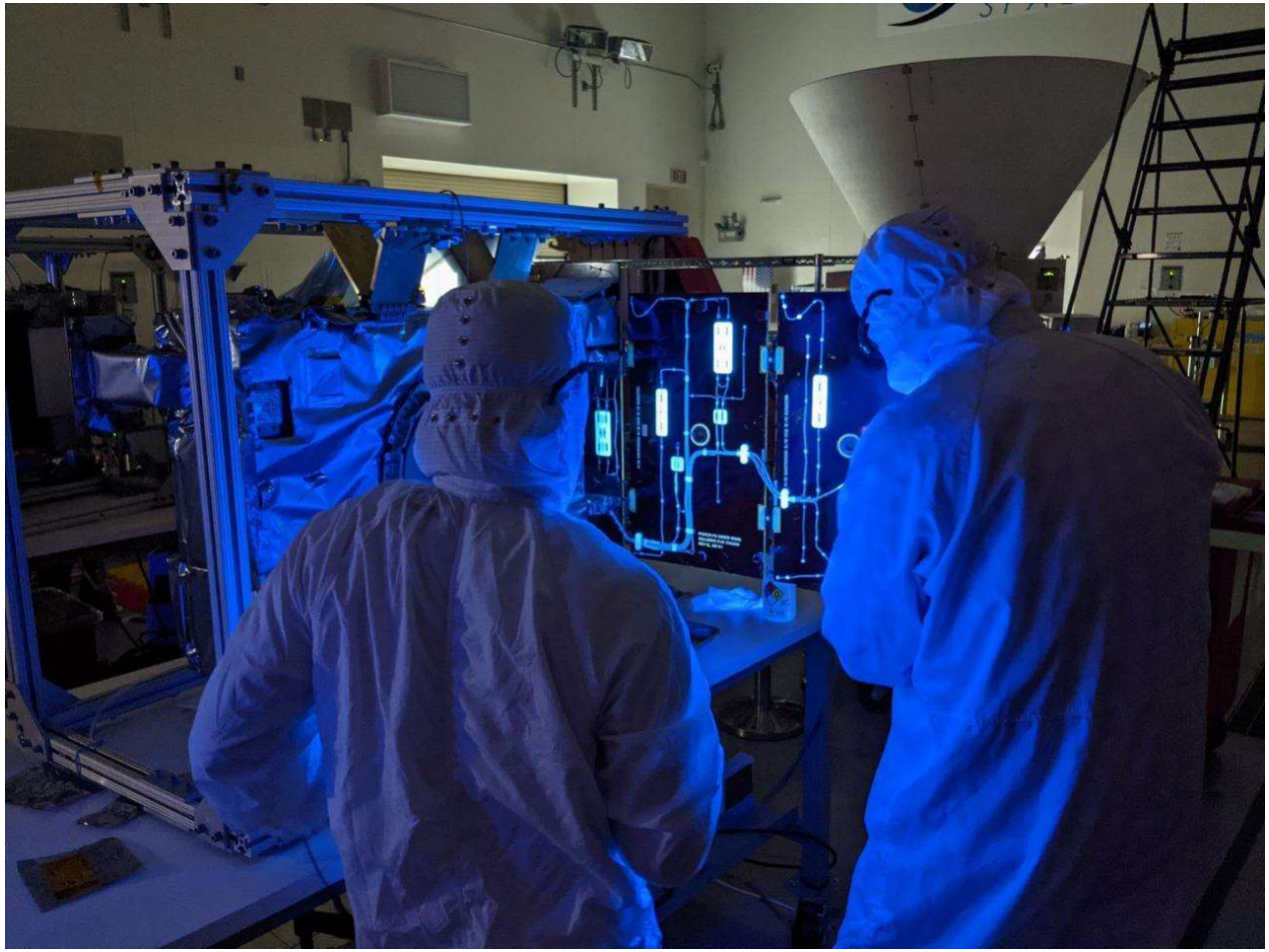


# PUNCH I&T @ VSFB

- Vandenberg SFB I&T
- Functional Testing
- Comprehensive Performance Testing (CPT)
  - Bias/Read Noise
  - LED / Flat Field
  - PFW
  - Door Testing

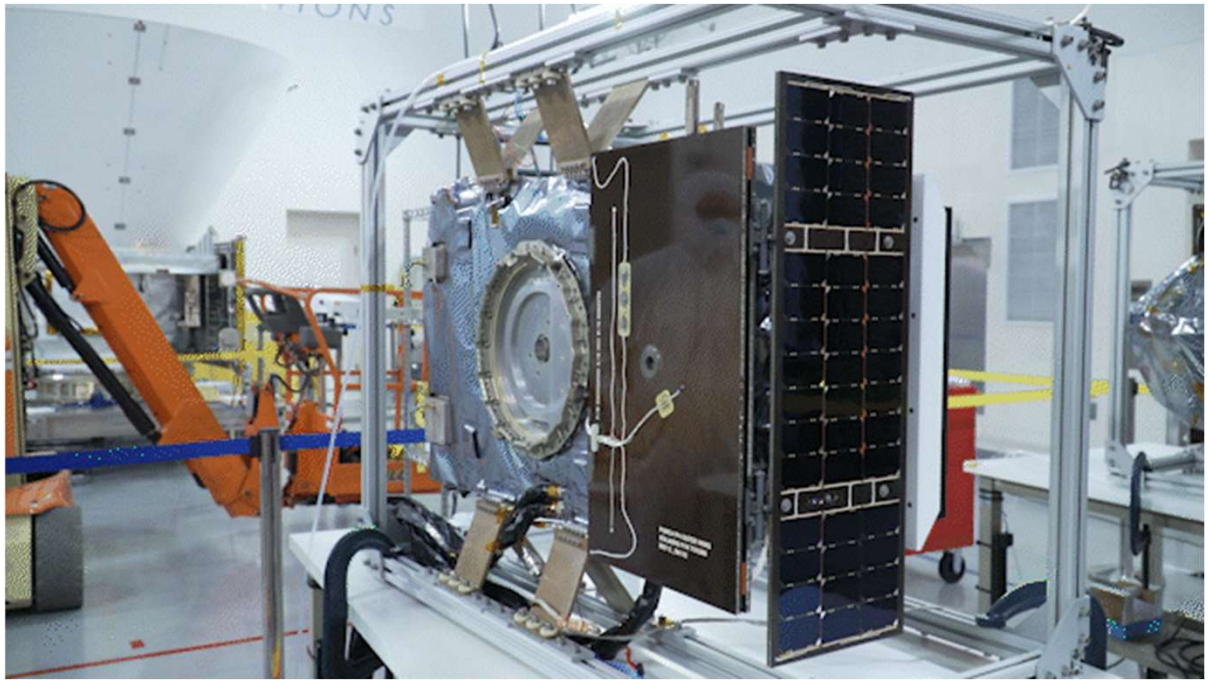


# PUNCH I&T @ VSFB



# PUNCH I&T @ VSFB

- WFI-2 Solar Array Deployment



# Commissioning / Calibration

- On-orbit calibration of WFI & NFI Instruments individually
- On-orbit commissioning/validation of the “single virtual observatory” – cross-instrument calibration and SOC testing

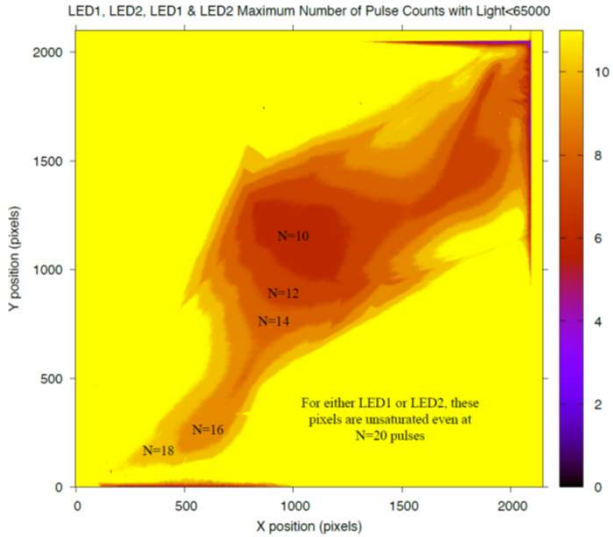
- Commissioning phases:

| | | |
|---|---|---|
| Spacecraft Commissioning: | L to L+30days | (includes WFI/NFI functional checks) |
| Instrument Commissioning: | L+30days to L+60days | (instrument calibration) |
| Constellation Commissioning: | L+60days to L+90days | (validate “virtual” instrument) |

- Instrument commissioning plan well defined
  - Identifies ADCS/Camera/PFW Commanding, Imaging types, Required Polarizers

# Closed-Door Activities

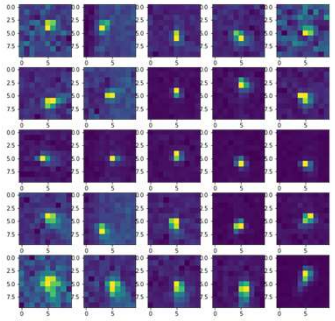
- Thermal Verification (PRTs, Heaters, Heater Control)
- Camera Verification (Bias, Darks, LED imaging, Linearity)
  - Continue against trending of noise from TVAC
- PFW Verification (motion, resolver function)

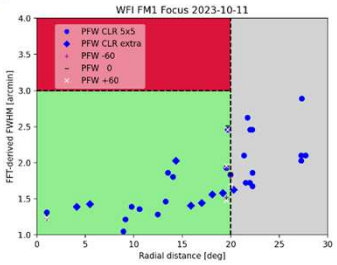


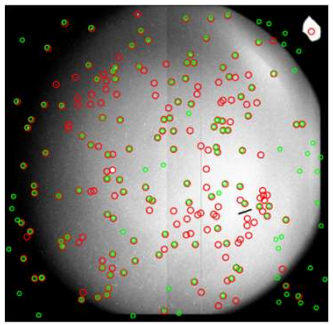

LED Composite Flat Field: similar for both NFI and WFI since the LEDS are integrated into the camera housing

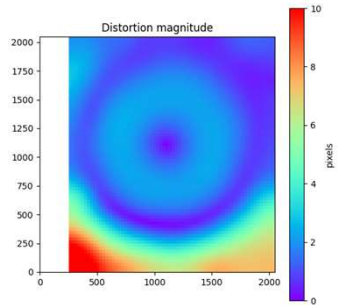
# Open Door Activities

- Starfield Imaging validates several instrument parameters
  - WFI Baffle alignment to S/C
    - Offset measured between predicted & measured pointing
    - Update boresight pointing in ADCS
  - PSF performance
    - Analyze stars in field of view, compare to predictions from test data and update PSF mapping for each instrument
  - Platescale, FOV, Distortion
    - Perform astrometry fit to determine optical parameters
      - Done previously on EM WFI night sky observations
  - Photometric performance
    - From starfield, determine CCD response / vignetting function as function of position.
    - Repeat imaging over a minimum of two weeks to ensure stars have drifted over the field of view.







# Open Door Activities

- Multiple images of the star field provide
  - Baffle solar attenuation performance
    - Nominal pointing
    - Starfield photometry provides attenuation performance
    - Optimize WFI performance by adjusting WFI pitch angle
  - Polarizer efficiency
    - Image polarized source at each PFW filter position
    - Compare stellar photometry over an orbit, (including observatory rolls) to measure PFW polarizer efficiencies
- Performing full exposure sequence in preparation for Phase E
  - Optimize exposure times / summing

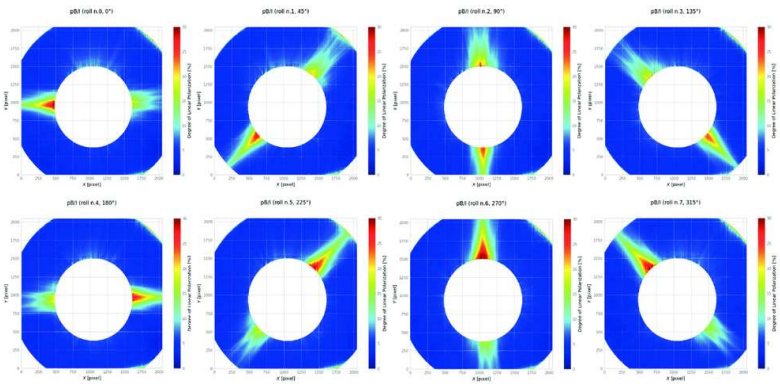
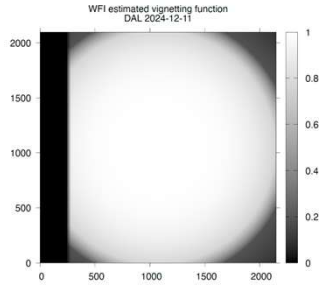


Figure shows Solar Orbiter Metis polarization calibration. PUNCH will preform a full roll during every orbit.




WFI Vignetting Functions

**Polarizer Axis Mapping (Degrees)**

| x,y in mm | -21 | -18 | -15 | -12 | -9 | -6 | -3 | 0 | 3 | 6 | 9 | 12 | 15 | 18 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | | | | | | | | 0.11 | | | | | | | |
| 18 | | | | | -0.01 | -0.01 | 0.21 | 0.09 | 0.03 | 0.06 | 0.03 | | | | |
| 15 | | | | 0.60 | -0.06 | 0.03 | 0.00 | 0.02 | -0.01 | 0.07 | -0.01 | 0.04 | | | |
| 12 | | | 0.01 | -0.02 | 0.00 | -0.01 | 0.06 | 0.09 | 0.05 | 0.05 | 0.01 | -0.01 | 0.03 | | |
| 9 | | 0.00 | 0.00 | 0.06 | -0.03 | 0.02 | 0.05 | 0.01 | -0.01 | -0.02 | -0.02 | 0.02 | -0.01 | 0.02 | |
| 6 | | 0.01 | -0.01 | -0.03 | 0.04 | 0.04 | 0.03 | 0.07 | 0.04 | 0.02 | 0.00 | -0.01 | -0.01 | 0.05 | |
| 3 | | -0.03 | 0.06 | 0.01 | -0.04 | 0.03 | 0.01 | 0.03 | 0.07 | -0.02 | 0.05 | -0.04 | -0.02 | 0.05 | |
| 0 | 0.00 | 0.09 | 0.00 | 0.02 | 0.03 | 0.01 | 0.13 | 0.00 | 0.00 | -0.02 | 0.01 | 0.00 | -0.08 | -0.01 | 0.05 |
| -3 | | -0.04 | 0.01 | 0.06 | -0.05 | 0.05 | 0.02 | -0.01 | 0.02 | 0.00 | -0.01 | 0.01 | -0.03 | 0.00 | |
| -6 | | 0.01 | -0.01 | -0.03 | 0.04 | 0.04 | 0.03 | 0.07 | 0.04 | 0.02 | 0.00 | -0.01 | -0.01 | 0.05 | |
| -9 | | 0.06 | 0.02 | 0.01 | 1.61 | -0.03 | 0.36 | 0.01 | 0.06 | -0.01 | -0.22 | 0.10 | 0.33 | -0.02 | |
| -12 | | | 0.03 | -0.26 | -0.40 | 0.25 | 0.02 | 0.09 | -0.05 | -0.05 | 0.04 | -0.01 | 0.04 | | |
| -15 | | | | 0.08 | 0.02 | -0.02 | -0.04 | 0.02 | -0.04 | -0.02 | 0.05 | -0.18 | | | |
| -18 | | | | | 0.00 | -0.01 | -0.01 | 0.05 | 0.00 | 0.03 | -0.02 | 0.21 | | | |
| -21 | | | | | | | | 0.21 | | | | | | | |

Polarizer uniformity

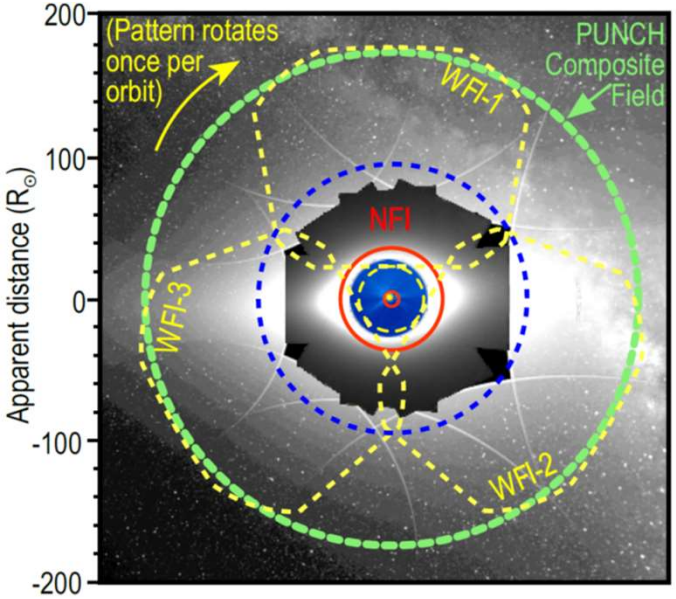
# Single Virtual Observatory Commissioning

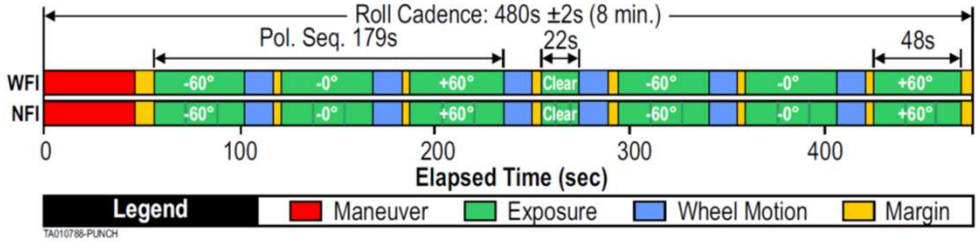
- Each instrument is *individually* calibrated for
  - PSF
  - FOV/plate scale/distortion
  - Photometric performance (Occulter performance / vignetting function)
  - Polarimetry

- Constellation calibration ensures *relative* calibration across the cameras, by directly comparing simultaneous measurements in overlapping fields of view.
- The four principal calibration quantities are refined to produce higher quality relative calibration to ensure the cameras function as a single "virtual instrument" after SOC processing.

# Single Virtual Observatory Commissioning

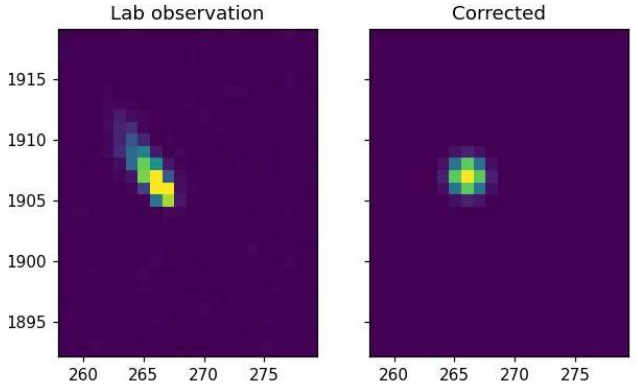
- All constellation calibrations are performed at the SOC level
- Uses same science data as used to calibrate the individual instruments

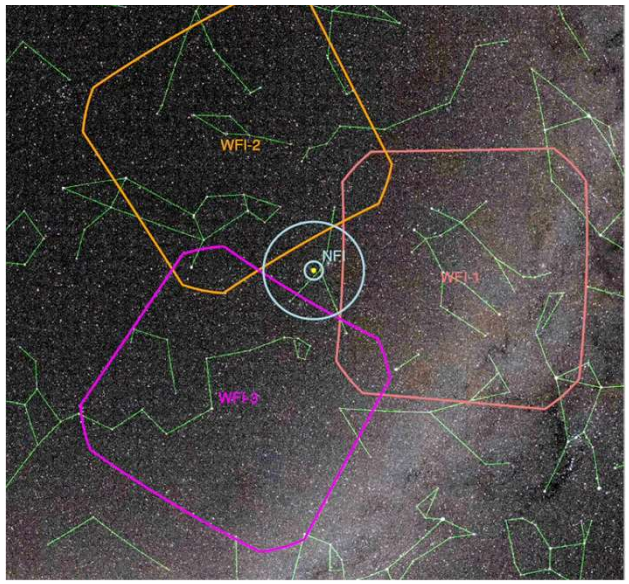


# Single Virtual Observatory Commissioning

- Cross check and verify:
  - PSF correction
    - Tune L1 PSF calibration to ensure instruments are matched.
  - Photometric performance (instrument photometry and vignetting)
    - Verify standalone calibration curves
    - Adjust calibration to improve relative precision
  - Distortion calibration
    - Adjust derived instrument calibration functions to achieve required co-alignment across each field
  - Polarimetric calibration
    - Verify that known catalog high-polarization stars and solar wind features are measured the same, independent of source camera
- All FOVs overlap, providing cross-calibration “patches” between instruments for each cross-check



# Go PUNCH!