VERA C. RUBIN OBSERVATORY

U.S. National Science Foundation

U.S. DEPARTMENT of ENERGY | Office of Science

LSST: From First Light to Mapping the Cosmos

Guillem Megias Homar
KIPAC, Stanford University

Vera C. Rubin Observatory

Credit: O. Bonin

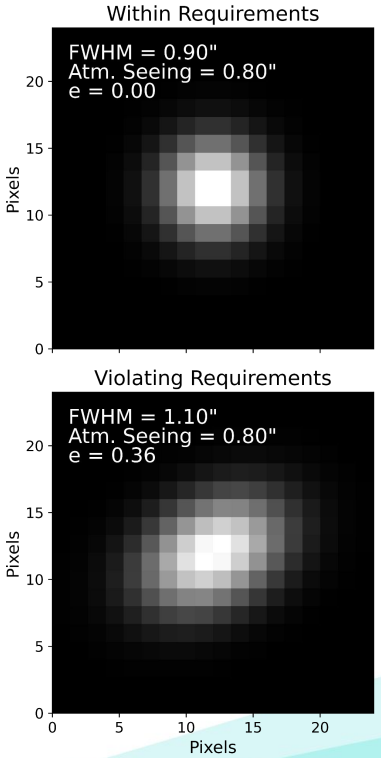
Vera C. Rubin Observatory

Cosmology with LSST

- **Weak Gravitational Lensing:** LSST's deep, high-resolution images of billions of galaxies across half the sky will enable precise mapping of dark matter and the growth of structure.
- **Galaxy Clustering:** LSST's unprecedented galaxy sample size and photometric redshift reach will allow detailed studies of large-scale structure evolution.
- **Baryon Acoustic Oscillations (BAO):** LSST's wide-area, deep galaxy survey will measure the BAO feature over a broad redshift range to trace the expansion history.
- **Type Ia Supernovae:** LSST's rapid, multi-band cadence will produce well-sampled light curves for millions of supernovae to constrain dark energy.
- **Strong Gravitational Lensing:** LSST's image depth and resolution will reveal thousands of new lenses, enabling precise time-delay cosmography.
- **High-Redshift Quasars:** LSST's sensitivity to faint sources over large areas will identify rare, distant quasars probing the early Universe.

We need sharp images!!!

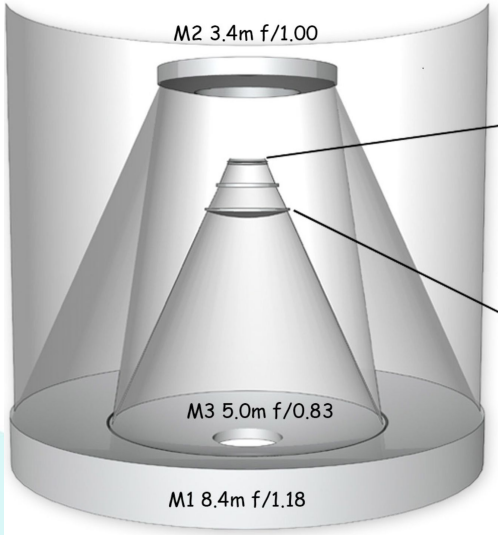
- **Astrometry**: Accurate star positions depend on precise centroiding
- **Faint Source Detection**: A narrow PSF makes it easier to detect weak and distant sources.
- **Weak Lensing**: Small distortions in galaxy shapes can only be measured with a stable and well-characterized PSF across FOV.
- **Image Subtraction**: Clean subtraction between exposures relies on consistent PSF shapes
- **Photometry**: Smooth PSFs allow reliable aperture corrections and flux calibration.
- **Crowded Fields**: In dense star fields, sharp PSFs reduce blending, allowing separation of overlapping sources.
- …



Unprecedented Science Demands Unprecedented Engineering

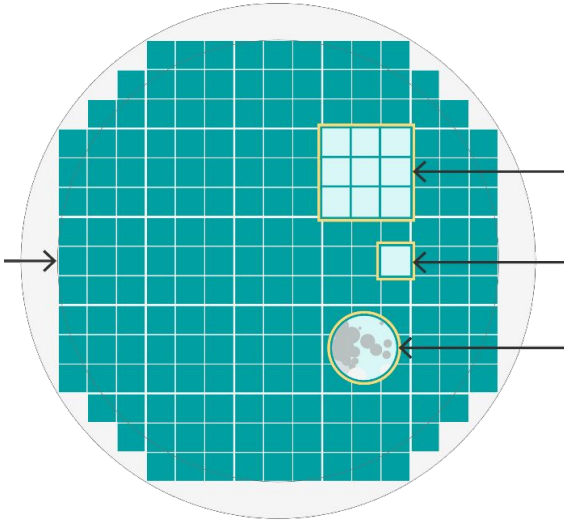
Three-mirror anastigmat (Modified Paul-Baker):

- Aperture: 8.4 meters
- 50 degrees of freedom
- Etendue: 319 m^2deg^2



Largest Digital Camera Ever Built

- 3.5 deg FOV
- 3.2 Gigapixels
- 0.2 arcsec / pixel



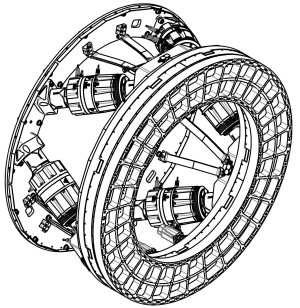
Data Management

- Handles 20TB of data every night during 10 years
- Calibrates images and generates alerts

Hexapods

- Active control of rigid body motions for M2 and the Camera
- Goal: Align the optical components with respect to M1M3

Component	Resolution	Range
M2 Hexapod X/Y axis	5 μm	±6.7 mm
M2 Hexapod Z axis	1 μm	±5.9 mm
M2 Hexapod Tip / Tilt	$3.3 \cdot 10^{-5}$ deg	±0.12 deg
M2 Hexapod Rotation in Z	$30 \cdot 10^{-5}$ deg	±0.05 deg
Camera Hexapod X/Y axis	5 μm	±7.6 mm
Camera Hexapod Z axis	1 μm	±8.7 mm
Camera Hexapod Tip / Tilt	$8.19 \cdot 10^{-5}$ deg	±0.24 deg
Camera Hexapod Rotation in Z	$60 \cdot 10^{-5}$ deg	±0.1 deg

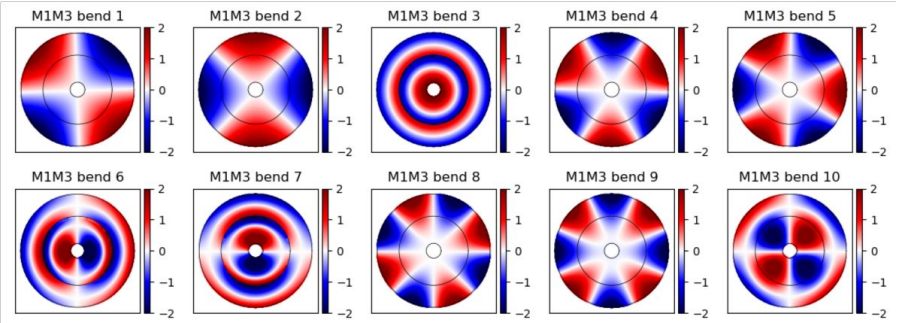


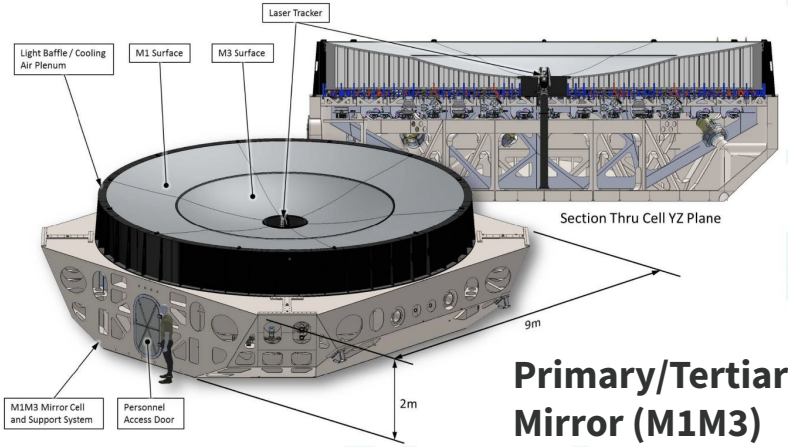
M2 Hexapod

Camera Hexapod

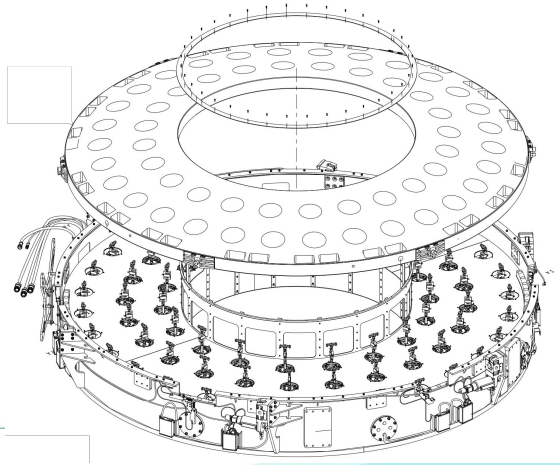
Mirrors

- Controlling mirror surfaces with nanometer precision
- Active control of over 20 bending modes per mirror
- 156 actuators on the primary-tertiary mirror (M1M3) and 76 on the secondary mirror (M2)



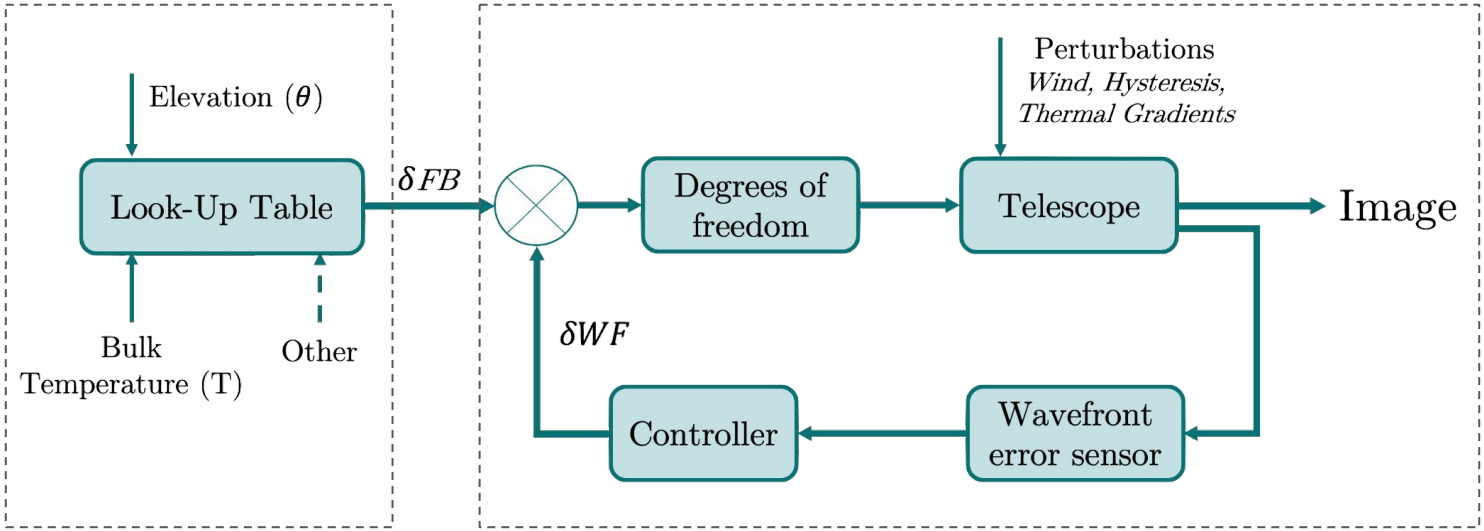


Primary/Tertiary Mirror (M1M3)



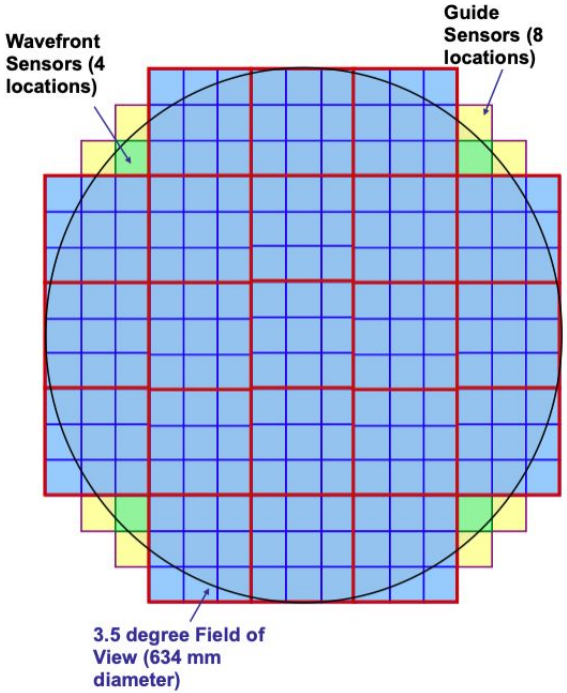
Secondary Mirror (M2)

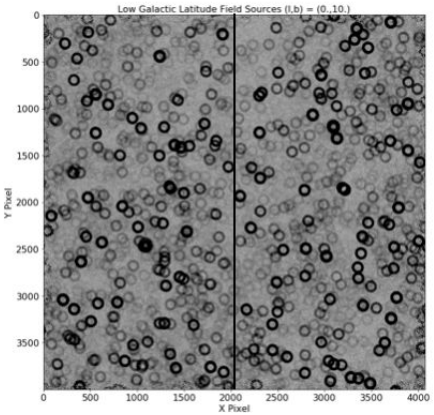
Active Optics System

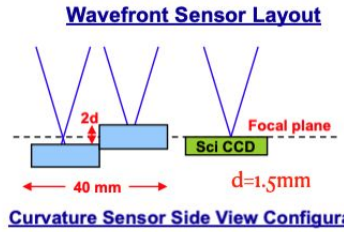


Wavefront sensing

- We use curvature wavefront sensing.
- The intensity difference in two out-of-focus images is proportional to the gradient of the wavefront
- Use the wavefront estimation to derive the telescope correction







Commissioning Timeline

- **October 24th, 2024**: Commissioning Camera (ComCam) goes on-sky

Team selfie through the pinhole of the Commissioning Camera

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Credit: RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/A. Pizarro D.

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Credit: RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/ B. Quint & A. Pizarro D.

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Credit: RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/T. Lange.

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Credit: RubinObs/NOIRLab/SLAC/NSF/DOE/AURA/Y. Utsumi

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Credit: RubinObs/NOIRLab/SLAC/DOE/NSF/AURA

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Virgo Cluster

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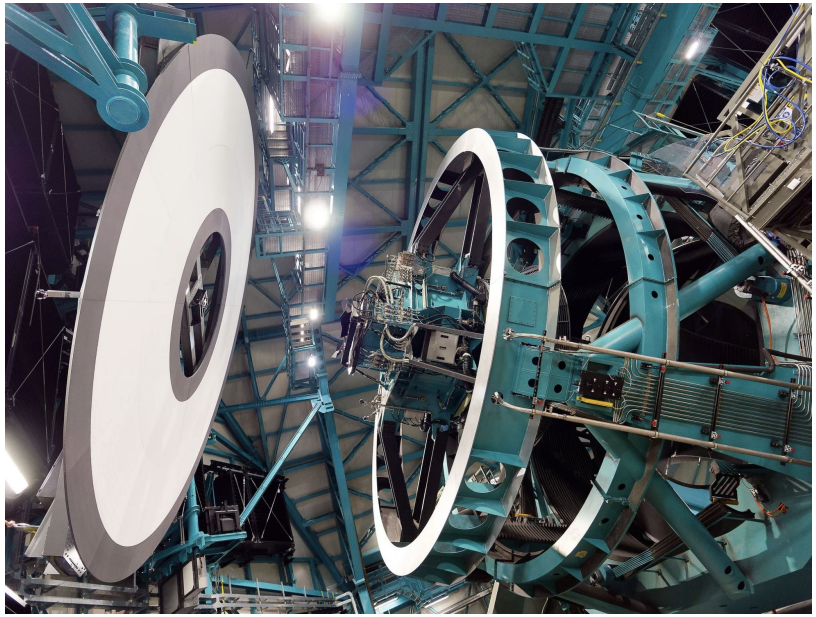
- **June - August 2025**: Commissioning work



Credit: RubinObs/NOIRLab/SLAC/DOE/NSF/AURA/W. O'Mullane

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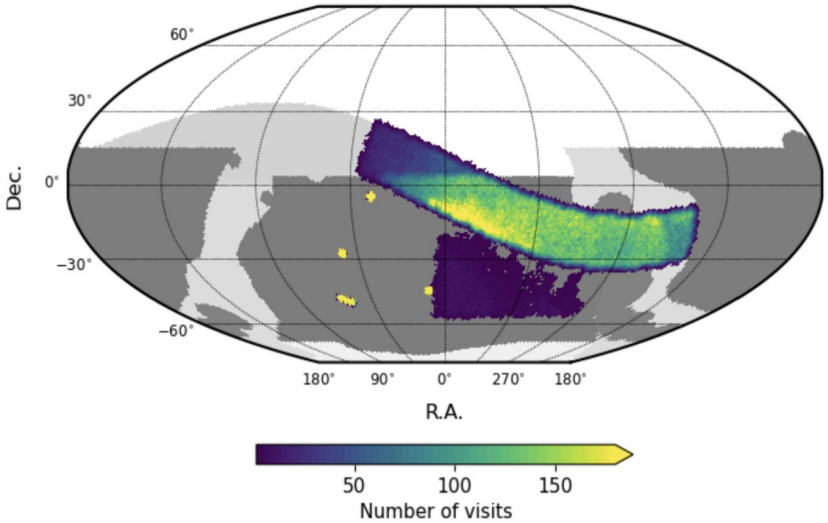
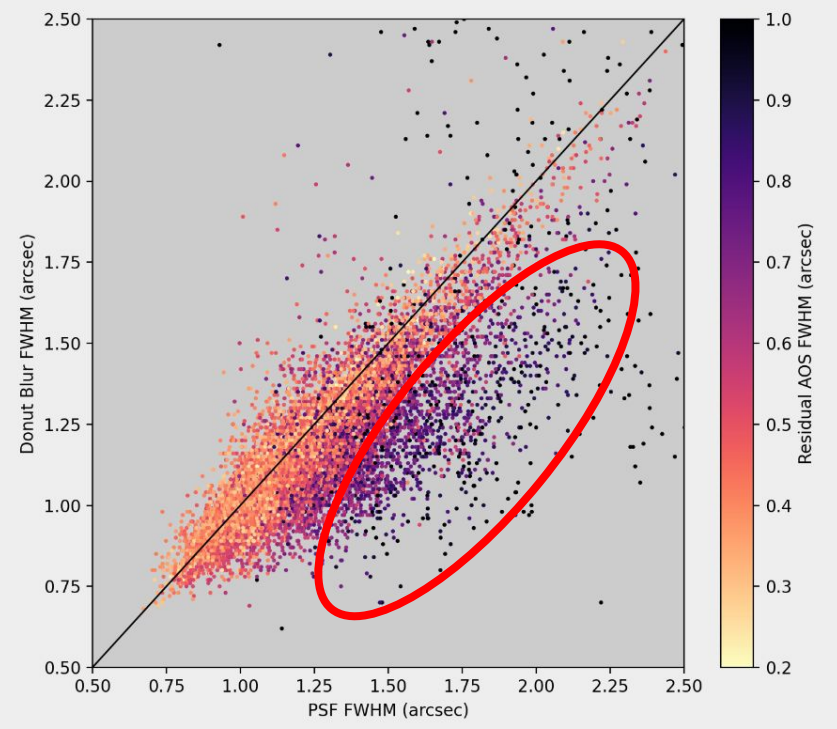
- **July - August 2025**: Science Validation Surveys



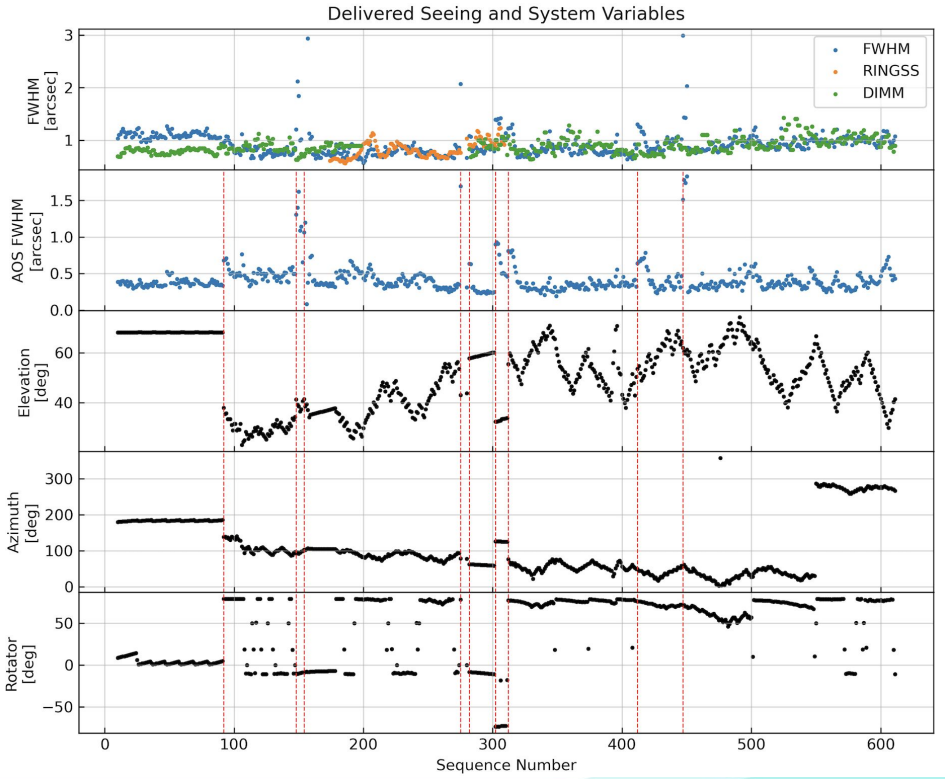
Overall Performance

- Goal: Seeing-limited image quality
- Many probes for measuring the atmospheric seeing
- Differential Image Motion Monitoring (DIMM)
- Estimate through out-of-focus image blur.
- Current work: tackle this region!



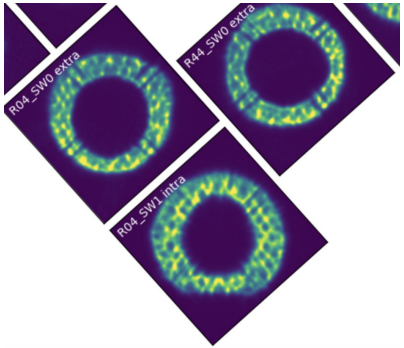
Nightly Performance

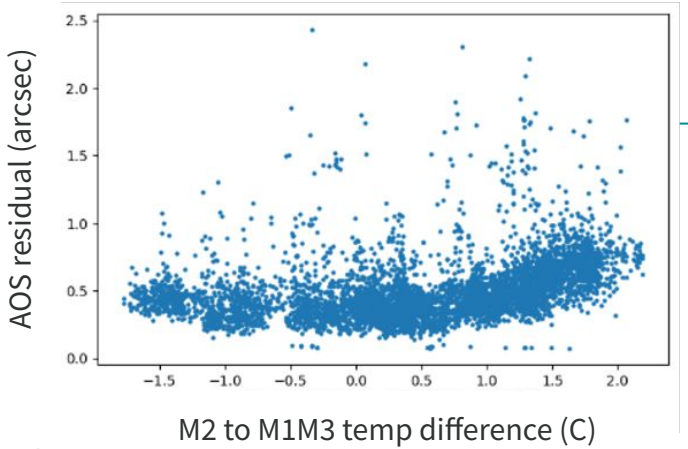
- Need to maintain uniform and consistent PSF throughout the telescope parameter-space
- A good example of a night during which we match the atmospheric seeing measurements
- Some issues still correcting for certain jumps in the parameter space

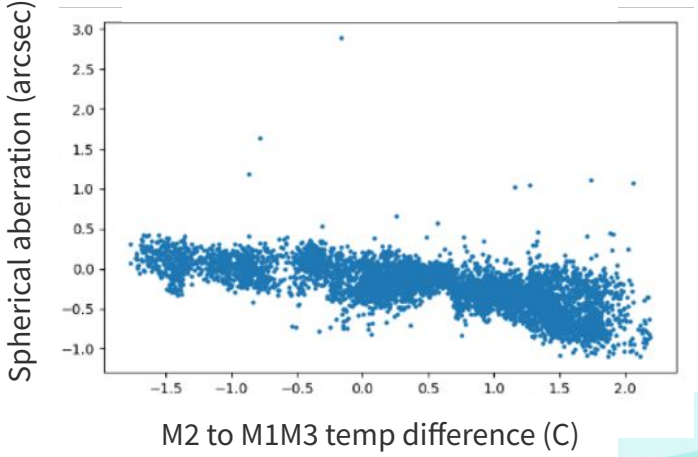


Thermal effects

- The thermal control system of M1M3 and the top end are still being commissioned
- We see a strong correlation of our performance and some of our measured aberrations on temperature differentials
- And the out-of-focus images look like dalmatians sometimes!



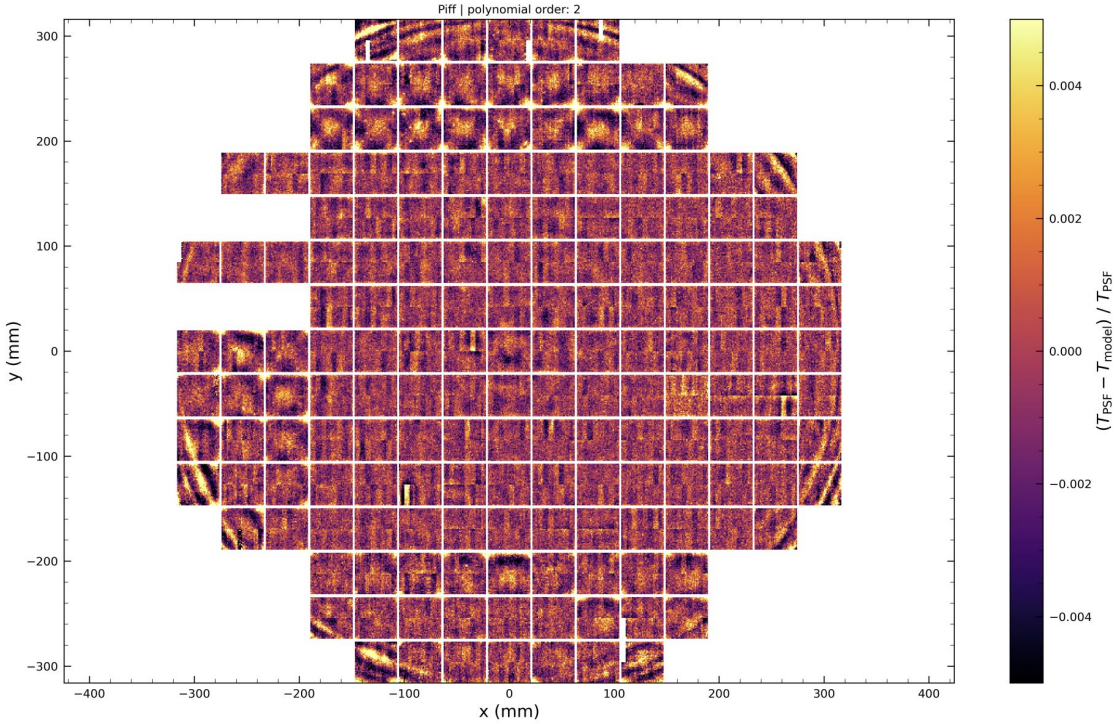




PSF Modeling

- Ring pattern on the edge of focal plane, due to vignetting
- Amplifier to amplifier variation on e2v detectors
- A blob on ITL detectors correlated with height variation within CCD
-

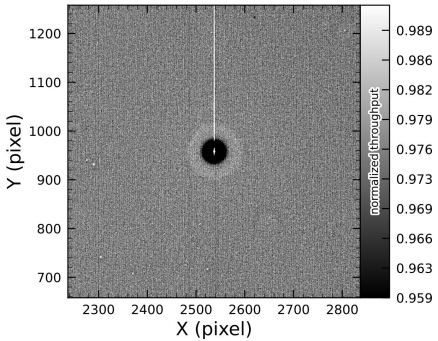
Credit: Pierre-François Leget



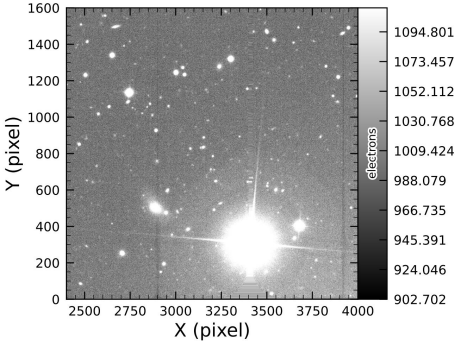
Sensor effects!

- **Vampire pixels** are visible on the images as a bright defect surrounded by a region of depressed flux. They conserve charge.
- Bright defects on Comcam: some detectors a layer of photoresist wax was incompletely removed from the detector surface during production.
- **Crosstalk correction** works mostly as expected but tends to oversubtract
- Saturated sources can create a second type of bleed, where the central bleed drops below the background level. Only happens on ITL detectors

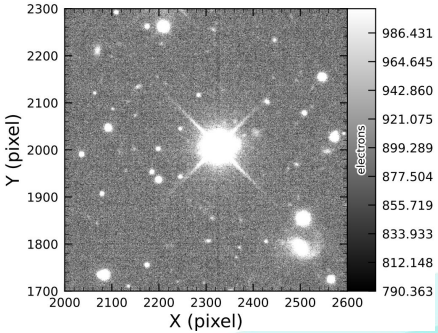
Vampire pixels



Oversubtracted crosstalk



ITL Dip

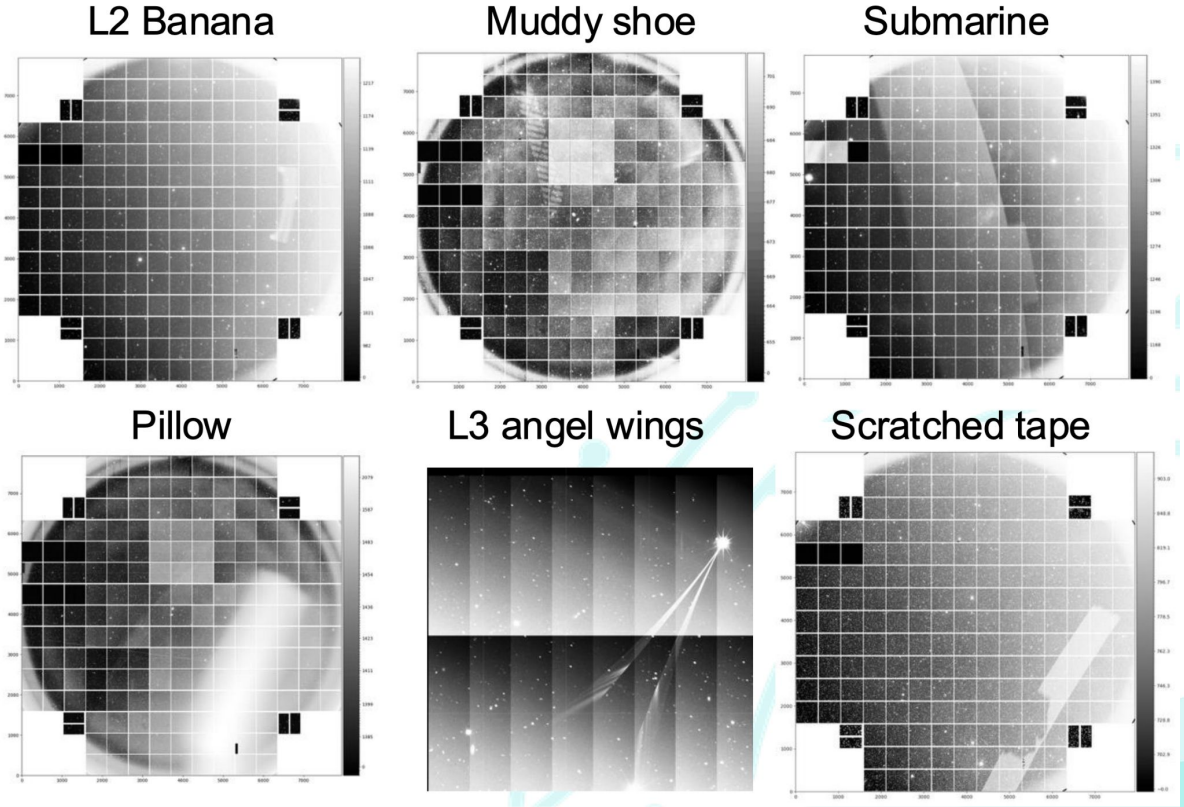


Credit: DP1 Paper

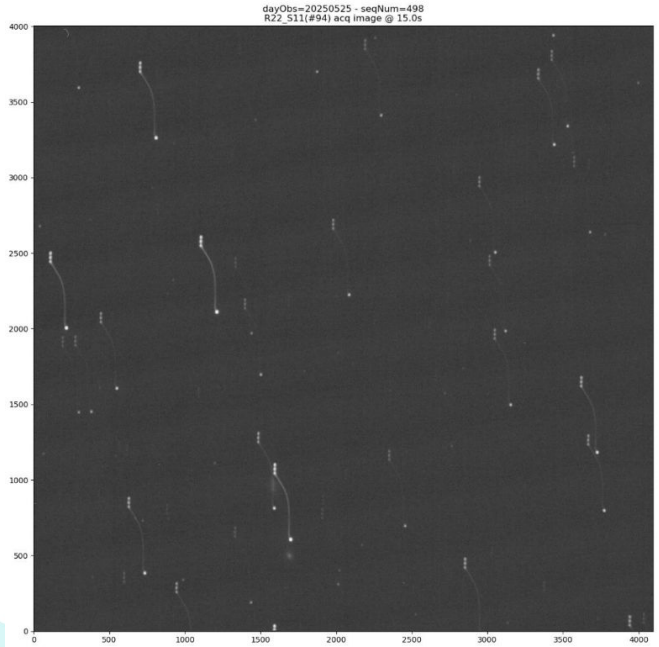
Straylight

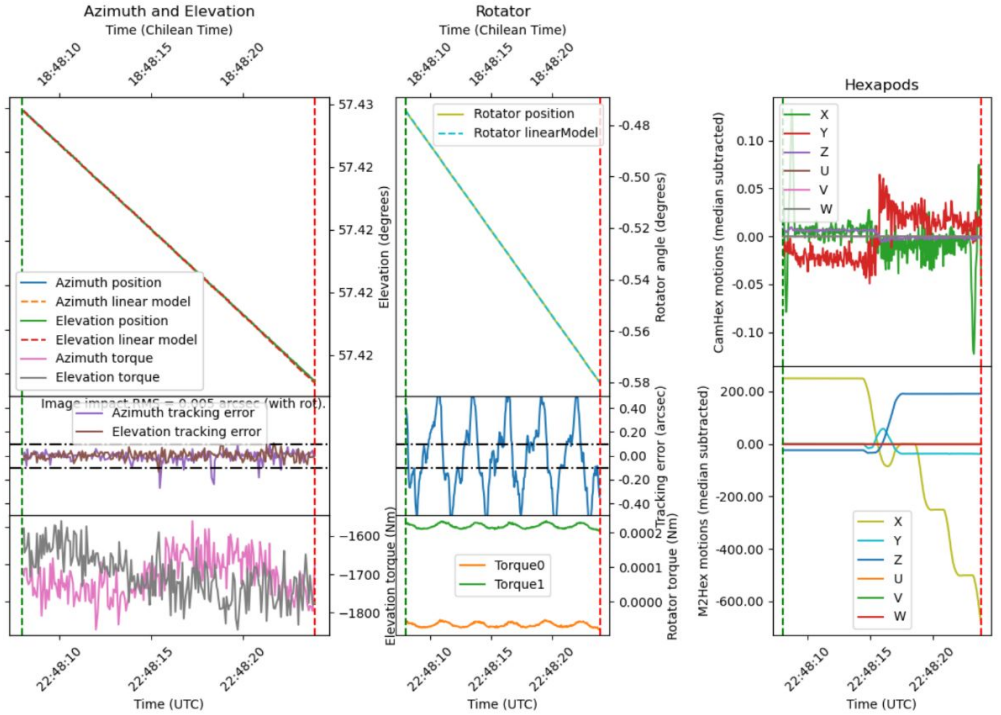
Credit: Gabriele Rodeghiero

- A wide range of different stray light features has been discovered during
- We understand the opto-mechanical origin
- Many of the features will self-resolve upon the installation of the Light Windscreen

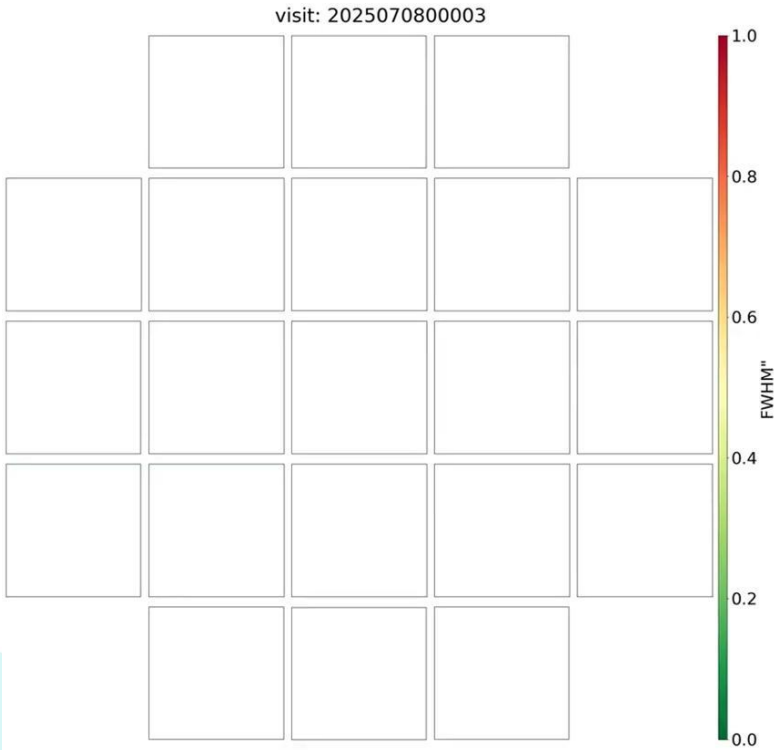


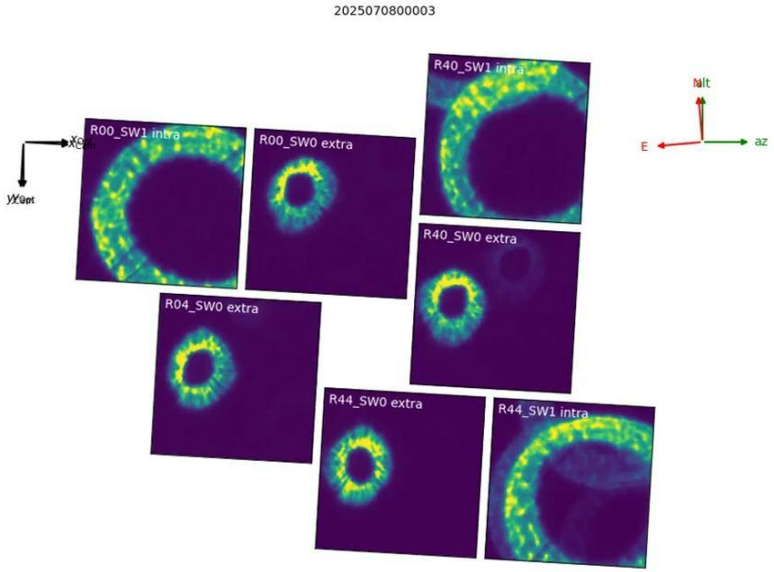
Mount and Hexapods Errors





AOS in Action



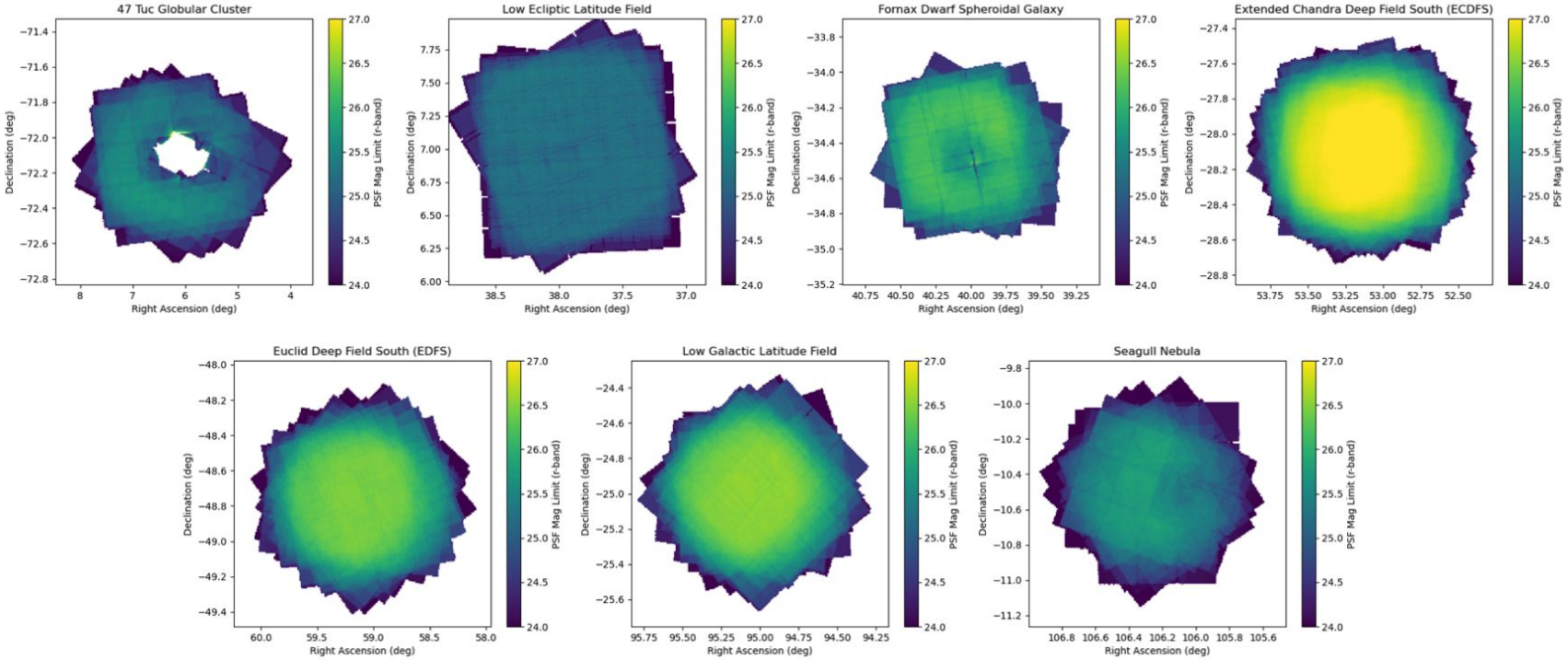


Data Releases Plan

Rubin Early Science – Data Release Scenario

Data Product	Jun 2021	Jun 2022	Jun 2023	Jun 2025 – Jul 2025	Mar 2026 – May 2026	Sep 2026 – Jan 2027	Sep 2027 – Jan 2028	Sep 2028 – Nov 2028
	DP0.1	**DP0.2**	**DP0.3**	**DP1**	**DP2**	**DR1**	**DR2**	**DR3**
	DC2 Simulated Sky Survey	**Reprocessed DC2 Survey**	**Solar System PPDB Simulation**	**ComCam Data**	**LSSTCam Science Validation Data**	**LSST First 6 Months Data**	**LSST Year 1 Data**	**LSST Year 2 Data**
Raw Images	●	●	–	●	●	●	●	●
DRP Processed Visit Images and Source Catalogs	●	●	–	●	●	●	●	●
DRP Coadded Images and Object Catalogs	●	●	–	●	●	●	●	●
DRP Cell-based Coadded Images and ShearObject Catalog	–	–	–	–	●	●	●	●
DRP ForcedSource Catalogs	●	●	–	●	●	●	●	●
DRP Difference Images and DIA Catalogs	–	●	–	●	●	●	●	●
DRP SSP Catalogs	–	–	●	●	●	●	●	●

Data Preview 1 (DP1)

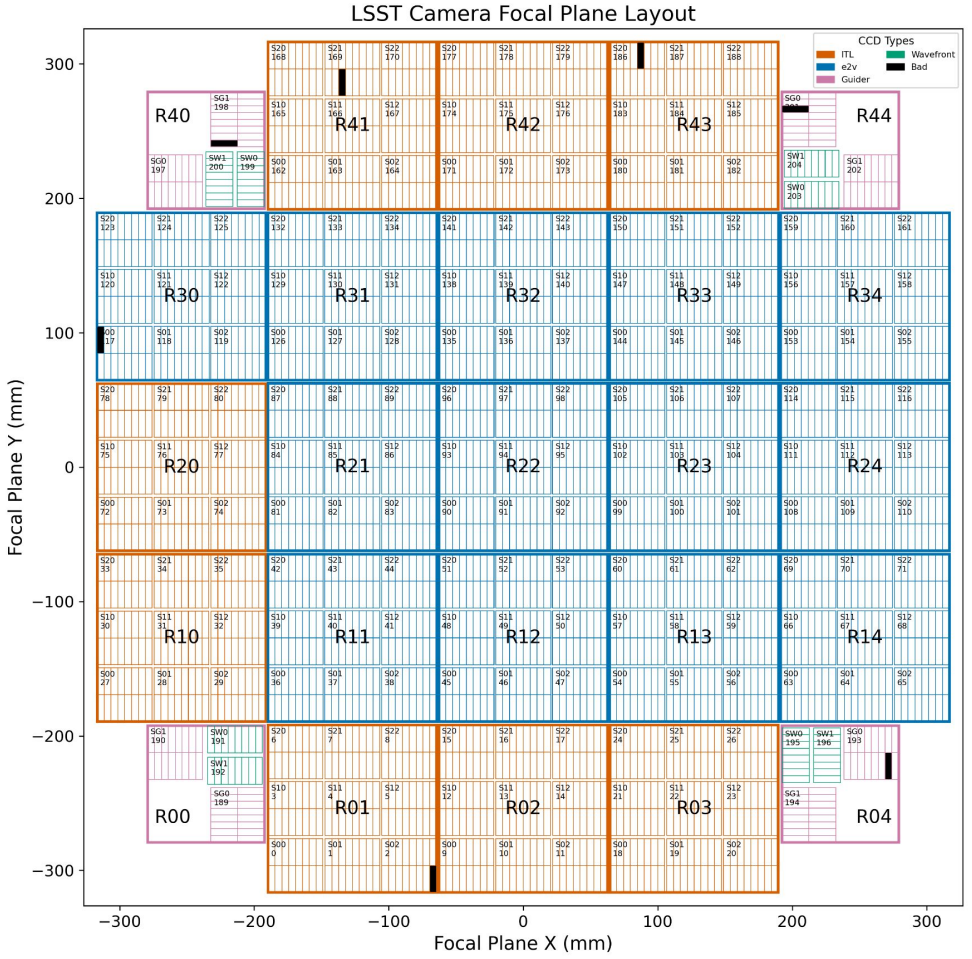


A true collective effort

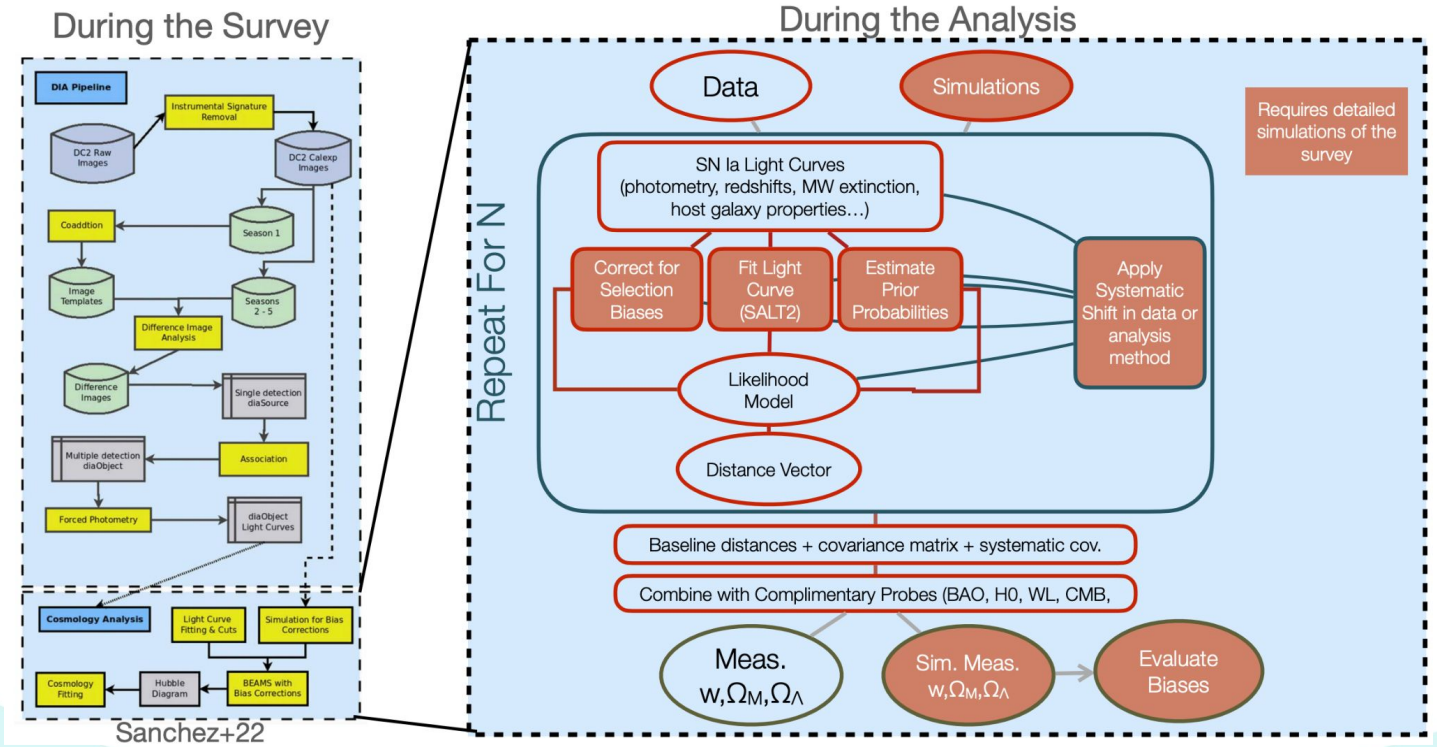
450+ scientists, engineers, technicians, software developers, project managers, administrators, and support staff make Rubin

Backup slides

Focal Plane

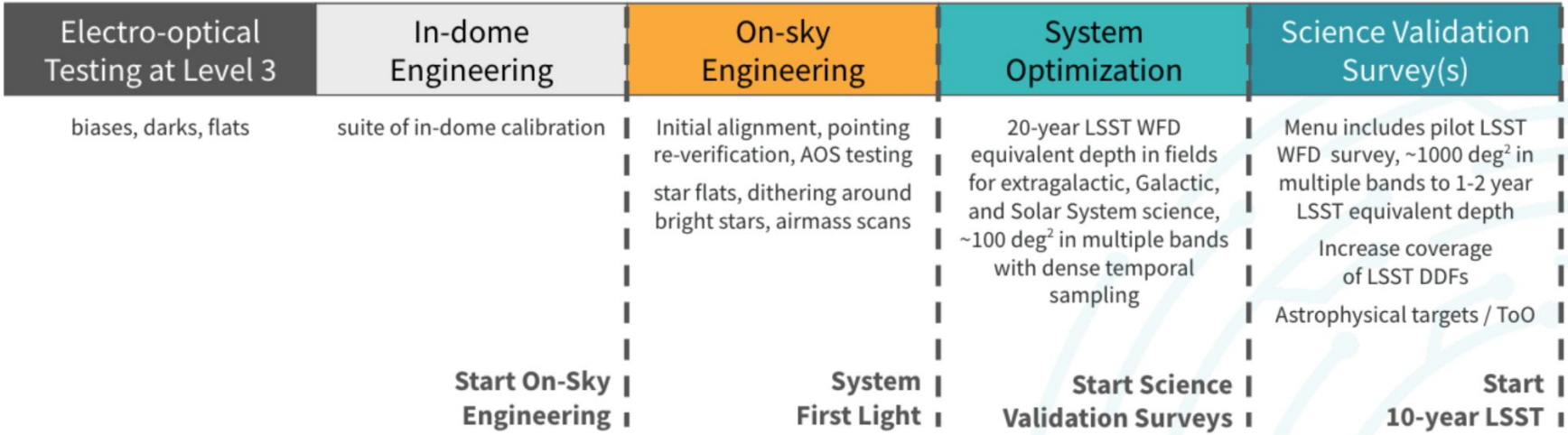

LSST Camera Focal Plane Layout
CCD Types
ITL
e2v
Guider
Wavefront
Bad
R00
R01
R02
R03
R04
R10
R11
R12
R13
R14
R20
R21
R22
R23
R24
R30
R31
R32
R33
R34
R40
R41
R42
R43
R44
Focal Plane X (mm)
Focal Plane Y (mm)
300
200
100
0
−100
−200
−300

Supernova Precision Cosmology with LSST

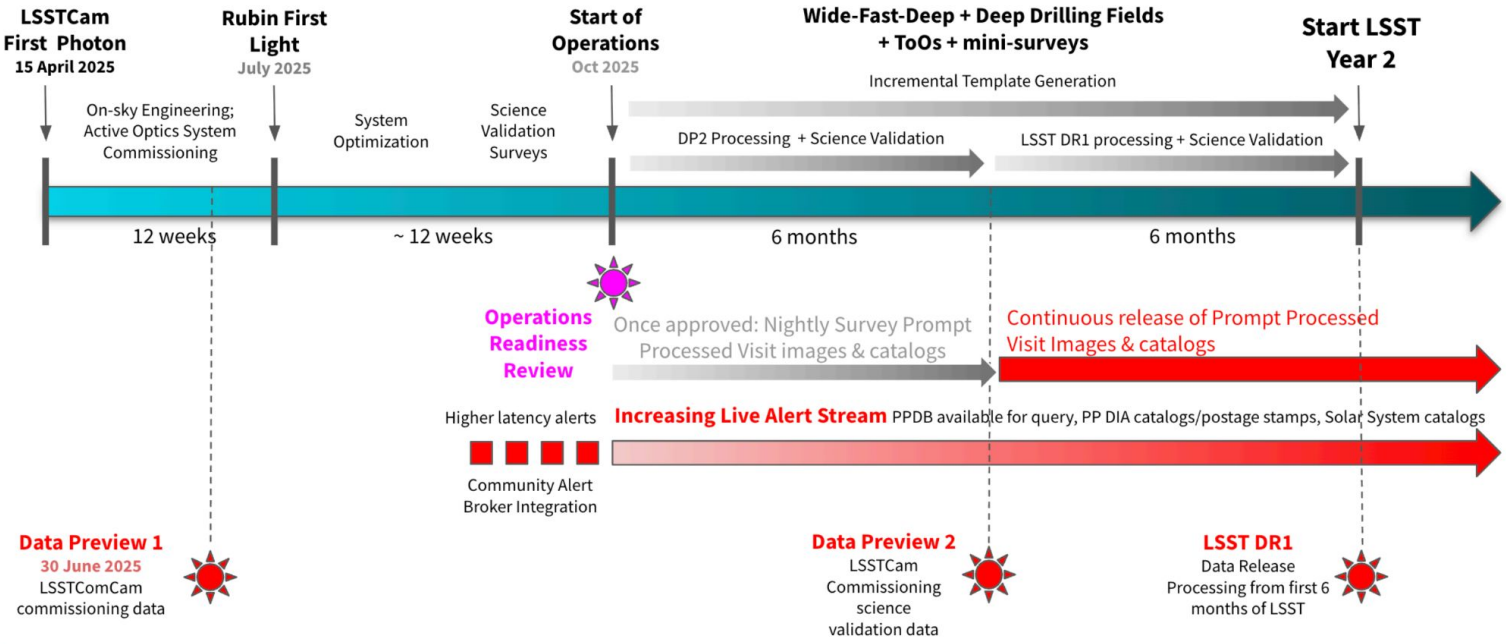


Credit: David Jones

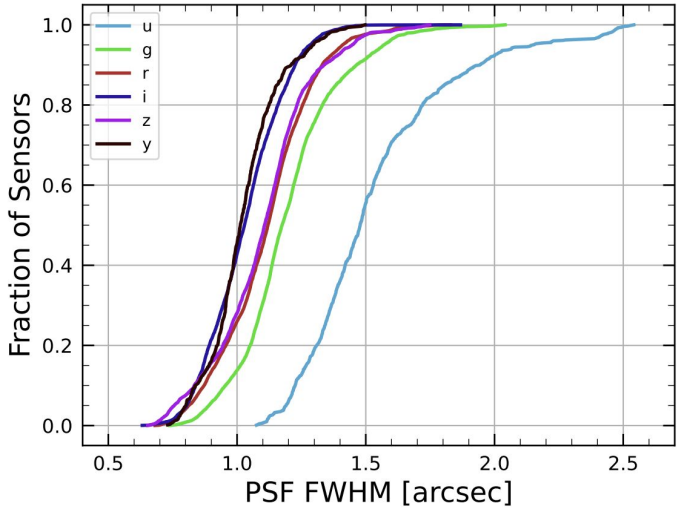
Outline Plan for Commissioning Data

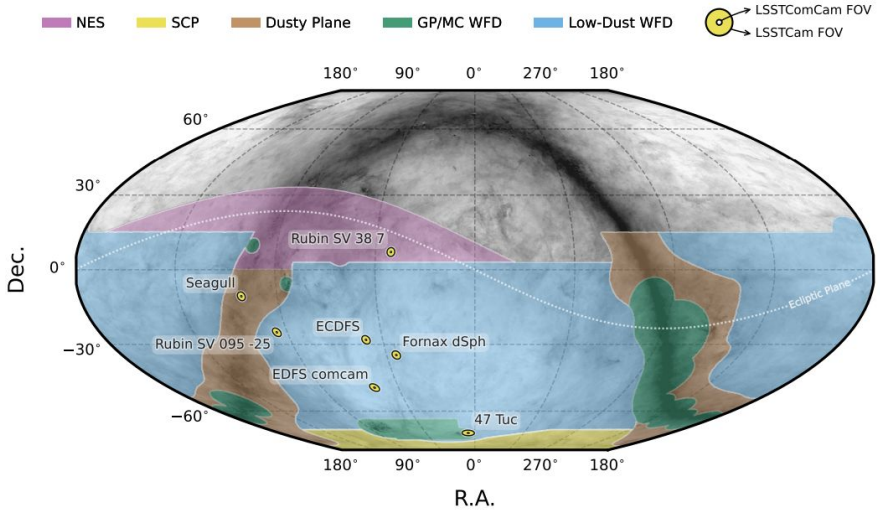


Detailed Commissioning Plan

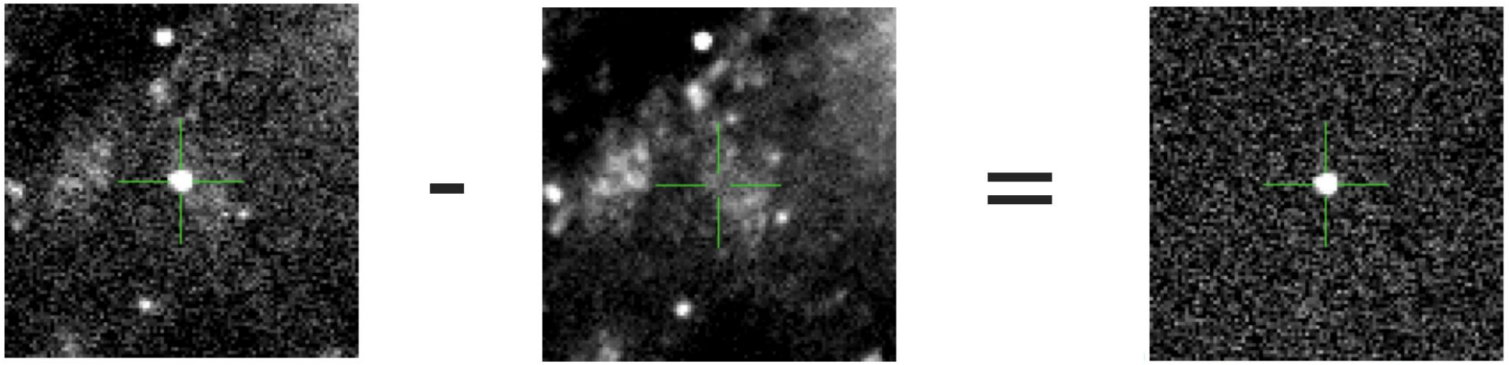


Data Preview 1 Fields





Difference Imaging

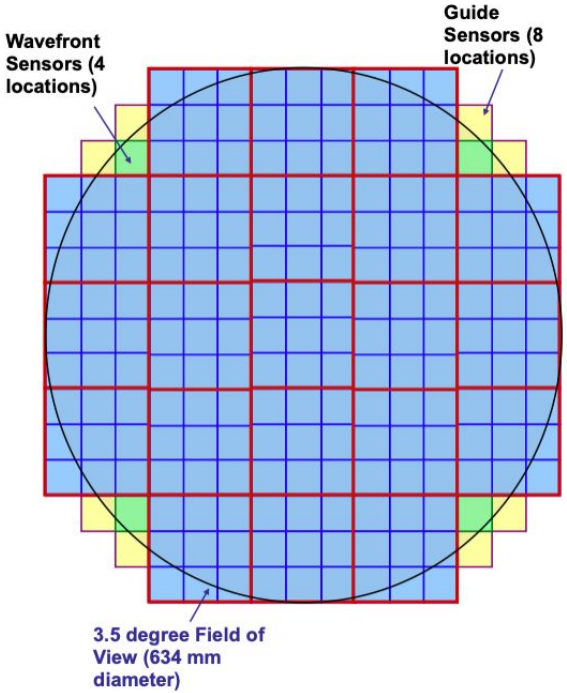


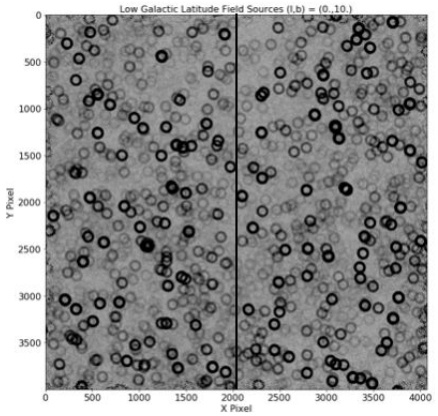
Credit:
Eric Bellm

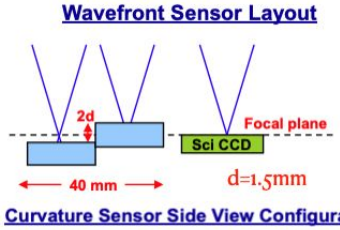
Our baseline algorithm is decorrelated Alard & Lupton image differencing, which is very similar to ZOGY

Moving from ComCam to LSSTCam

- During ComCam run we verified the alignment of the telescope and the behavior of the AOS closed loop in a specific pointing. Best PSF achieved was ~0.6”
- ComCam does not have defocused sensors. The AOS images were obtained by defocussing the entire focal plane intra- and extra-focally.
- Transitioned to **survey mode**: the loop is not closed on the same field but from one field to another. New background task that calculates and applies corrections between consecutive exposures.

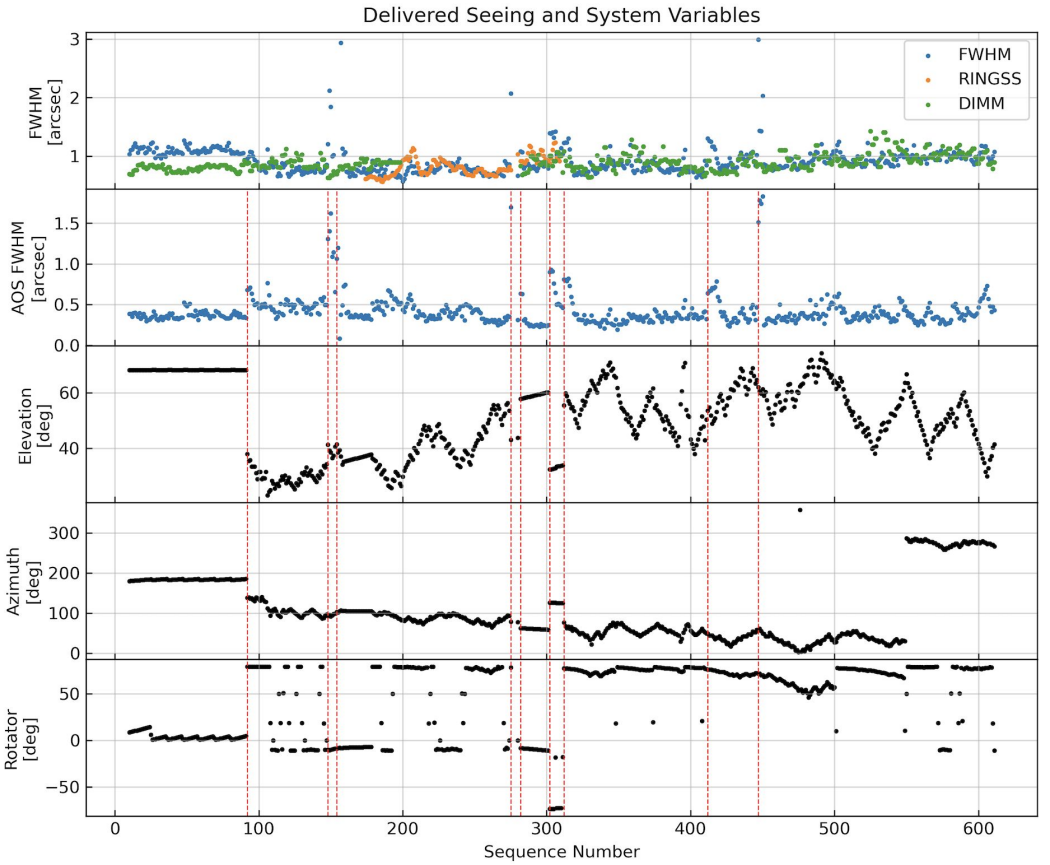






Performance

- A good night example
- AOS keeps the residuals consistent through the night except for large swings as the telescope moves
- AOS residuals are only illustrative - they don’t encapsulate the full picture

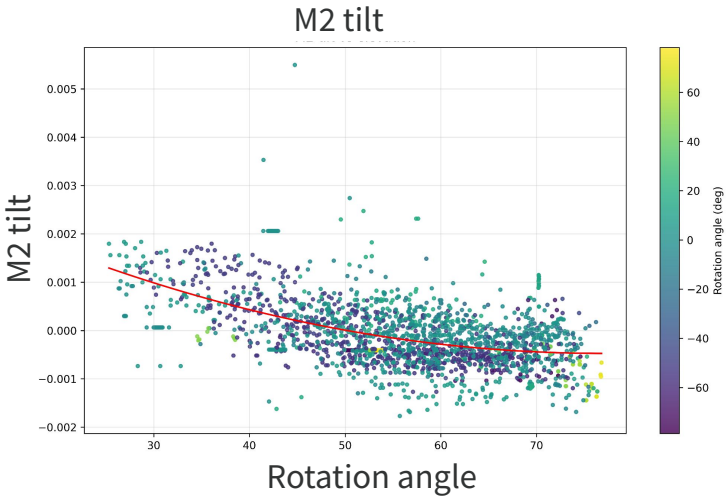


Issues and Works in Progress!

- The AOS system is able to autonomously derive corrections as we move through the sky, but the system contribution to the image quality is higher than required.
- In the next slides we will go over the main components of the AOS system, detailing our current status and the things we are working on.
- Many of these updates we are working on, require a variety of tests that we want to run to finish up the tuning and make sure it works better.
- So, let’s dive into them!

Open Loop model verification using on-sky data

- With ComCam, we developed and tested the LUT update procedure.
- With LSSTCam, we perform dedicated elevation and rotator angle sweeps to update the LUT.
- Using Science Verification (SV) data to validate and refine the LUT proves difficult because it entangles different dependencies.
- Currently, LUT corrections are limited to elevation and rotator angle.



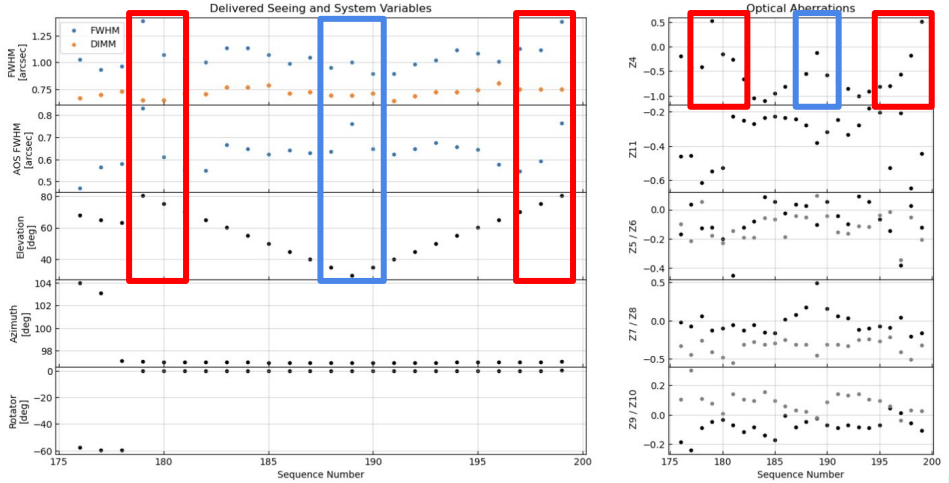
Recent LUT fit over the past two weeks

Elevation LUT

To probe the misalignments and mirror surface errors changes as we move in elevation, we are running elevation sweeps in multiple nights.

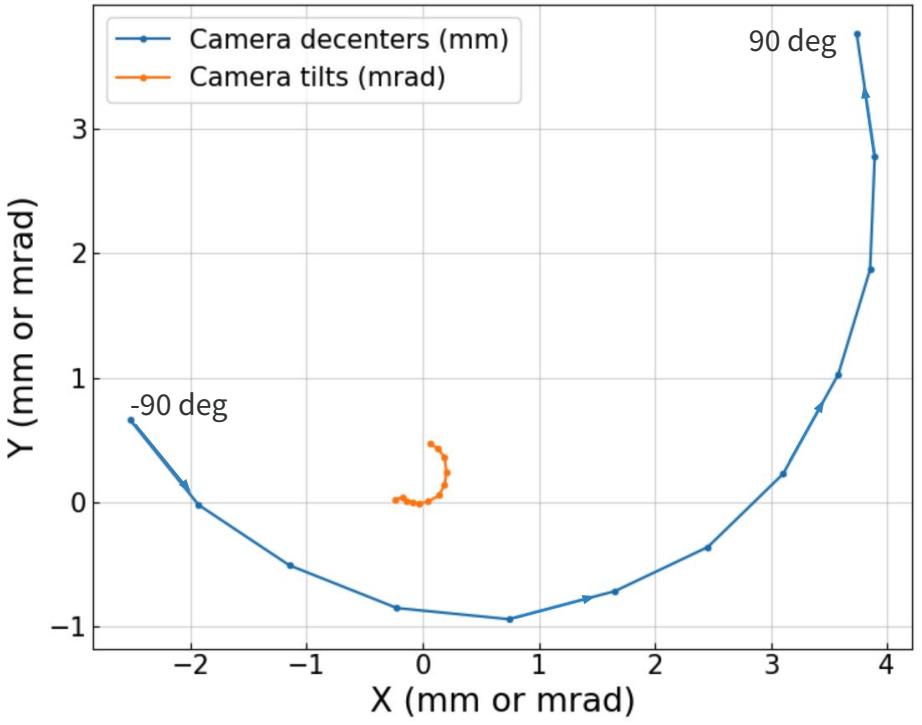
Currently performing worse at the extremes of range (low and very high elevations).

Some promising updates are on their way after all the data gathering we've done over the last week.



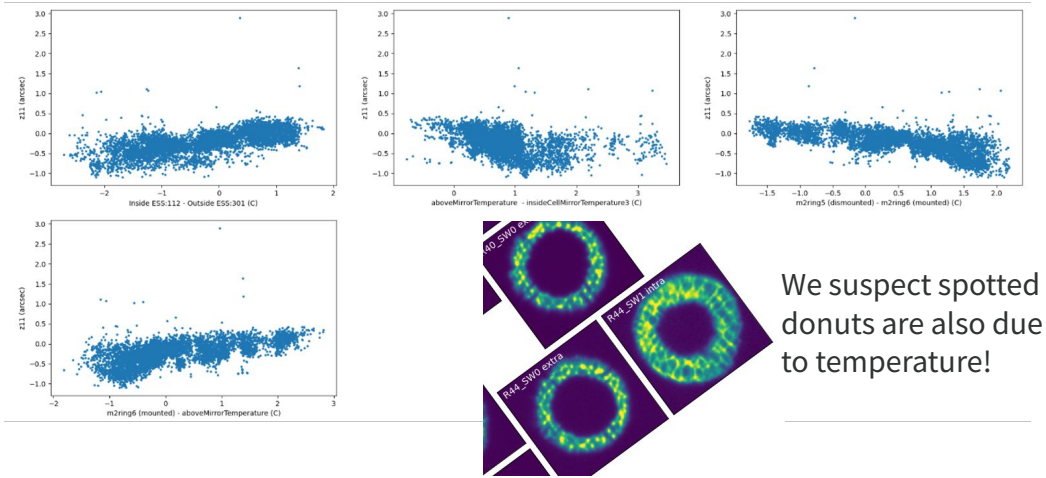
Rotator LUT

- The camera's rotation axis is **misaligned** with its optical axis.
- Lenses **L1/L2 are tilted** relative to L3.
- The **focal plane** is also tilted.
- As the camera rotates, these misalignments cause **image shifts and tilts**.
- The laser tracker measures these effects and provides data to update the **correction polynomials (LUT)**.



Temperature LUT

- We see strong dependencies of certain wavefront aberrations with temperatures
- We will perform on-sky tests that actively disentangle temperature and other dependencies to build a thermal LUT
- More thermal sensors are being installed to allow us to probe these dependencies better

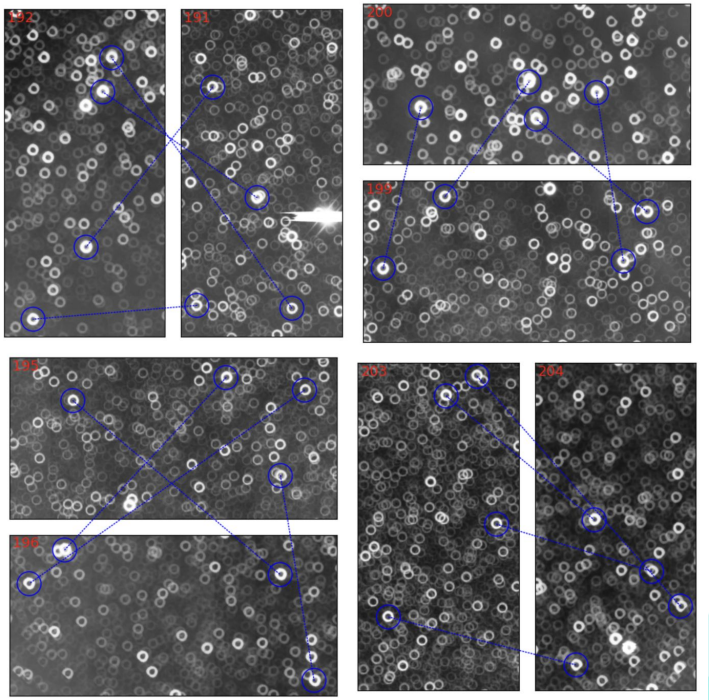


We suspect spotted donuts are also due to temperature!

Wavefront Estimation Pipeline Optimization & Robustness

- AOS closed-loop performance is mostly stable across a wide range of **atmospheric seeing, stellar densities, filters, and sky backgrounds.**
- The wavefront algorithm forward model is consistent with observed donut shapes
- Donut modelling is robust to blending in high density fields
- **Donut selection** algorithm has been refined to increase the number of available candidates
  - Some upgrades still **in progress** to rank donuts effectively and ensure availability even under very bright sky conditions (e.g., close to the moon)

Visualization showing the selected donuts for wavefront estimation



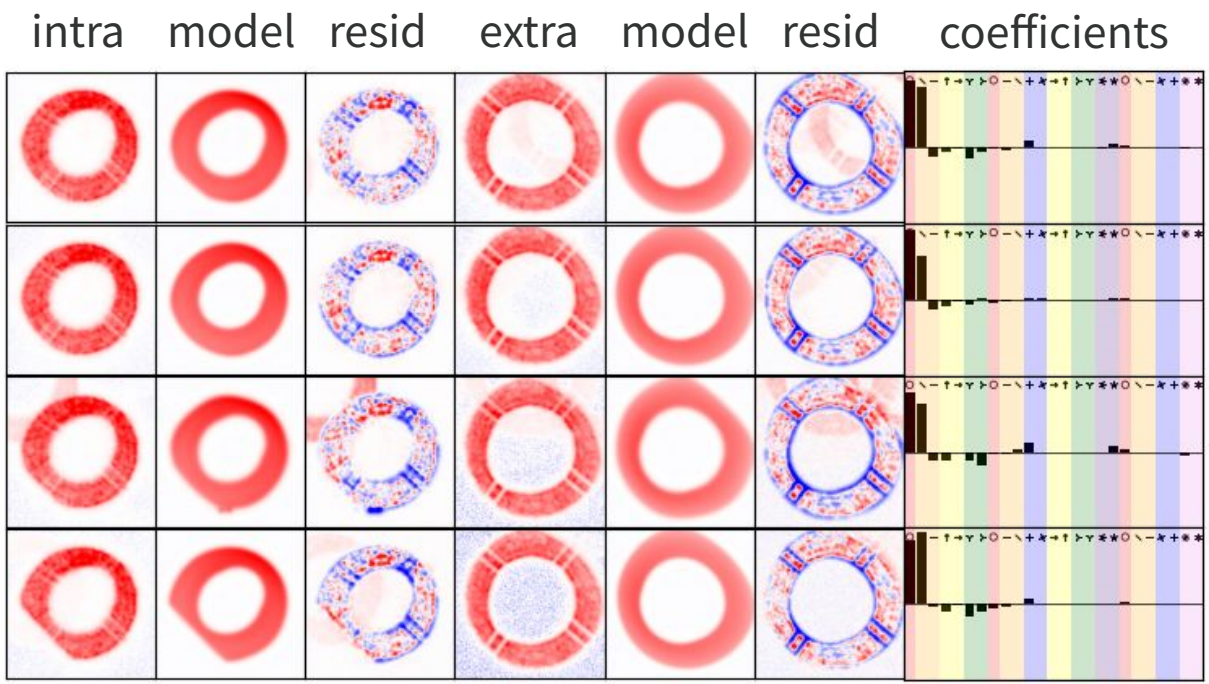
Wavefront estimation

Forward model including:

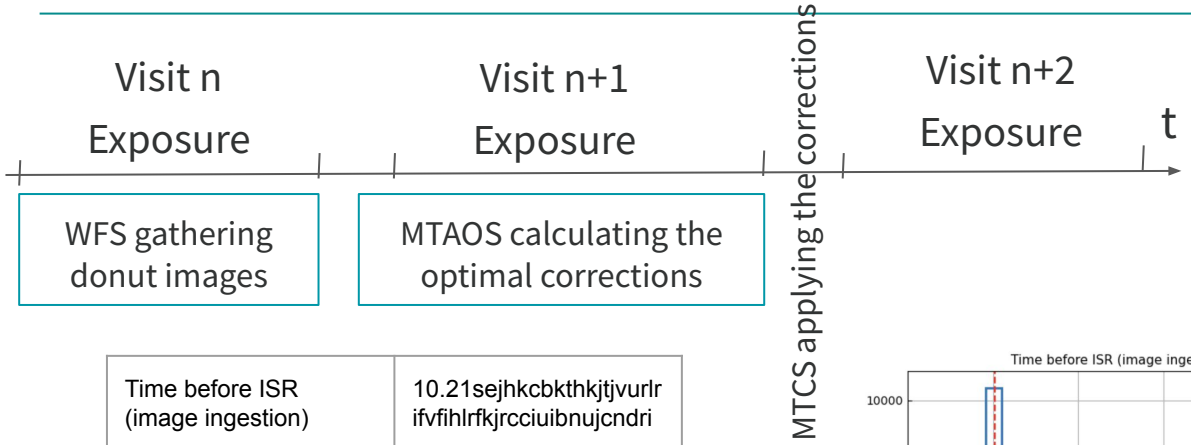
- Zernike wavefront aberrations
- centroid and “donut blur” terms
- vignetting
- pupil distortion
- spider shadow model is coming

About ~2 sec per donut

Also checked against alternative algorithm using the transport-of-intensity equation.

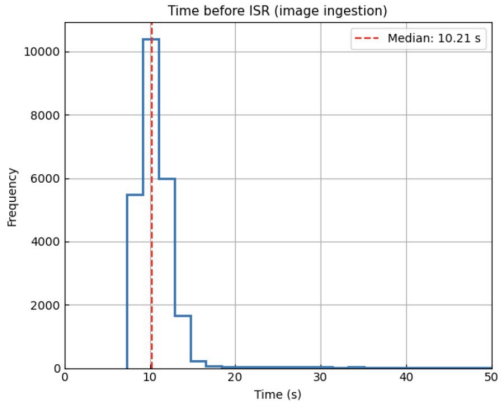


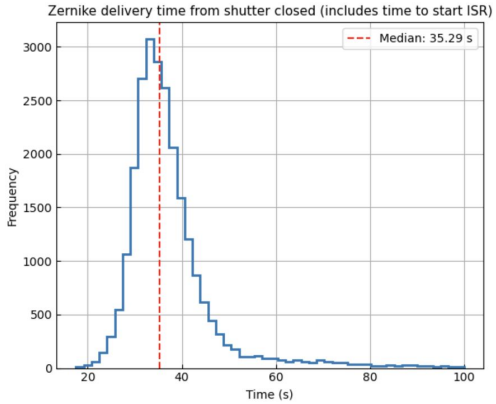
Pipeline Timing



Requirement is to calculate the correction in 31s

Time before ISR (image ingestion)	10.21sejhkcbkthkjtjvurlr ifvfihlrfkjrcciuibnujcndri
Corners ISR	2.74s
Wavefront Estimation Pipeline	9.64s
Overhead and IO	12.7s
Total	**35.29s**

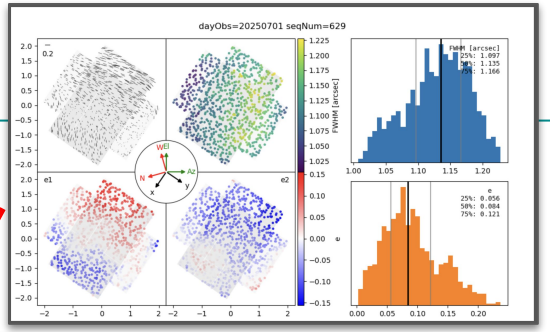


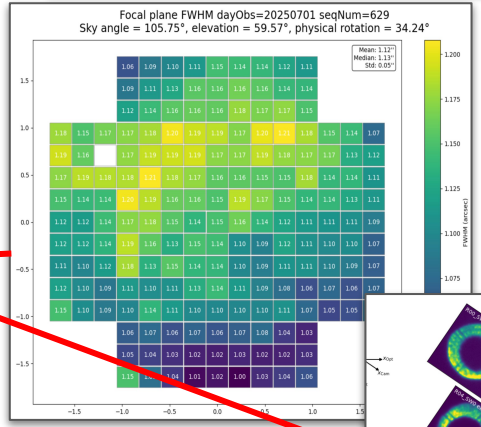


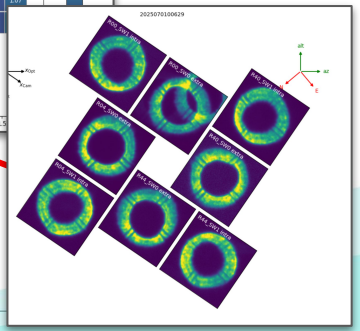
Real-time Monitoring of Delivered Data Quality

Data for day: 2025-07-01 | Add/Remove Columns | Download Metadata | 20:12:57 UTC

Seq. No.	CCS Image Viewer	Witness Detector	Post-ISR mosaic	Calexp mosaic	PSF shape AzEl	FWHM Focal Plane	Mount torques	Image Analysis	Event timeline	Exposure time	Image type	PSF FWHM	Time since previous exposure	Reason	Filter	Program	DIMM Seeing	Residual AOS FWHM	Donut Blur
636										30.00	science	1.21	8.47	template_blob_r_33.0	r_57	BLOCK-365		0.43	1.16
635										30.00	science	1.16	8.57	template_blob_r_33.0	r_57	BLOCK-365		0.45	1.08
634										30.00	science	1.13	140.60	template_blob_r_33.0	r_57	BLOCK-365		0.41	1.09
633										30.00	science	1.16	12.82	template_blob_i_33.0	i_39	BLOCK-365		0.40	1.09
632										30.00	science	1.12	8.87	template_blob_i_33.0	i_39	BLOCK-365		0.38	1.06
631										30.00	science	1.12	8.09	template_blob_i_33.0	i_39	BLOCK-365		0.37	1.04
630										30.00	science	1.12	9.08	template_blob_i_33.0	i_39	BLOCK-365		0.35	1.03
629										30.00	science	1.12	9.89	template_blob_i_33.0	i_39	BLOCK-365		0.36	1.03
628										30.00	science	1.08	10.08	template_blob_i_33.0	i_39	BLOCK-365		0.37	1.02
627										30.00	science	1.08	164.64	template_blob_i_33.0	i_39	BLOCK-365		0.37	1.05
626										30.00	acq	1.06	3.37	infocus_correcting_sphericals	i_39	BLOCK-T539		0.41	1.03
625										30.00	acq	1.03	18.16	infocus_correcting_sphericals	i_39	BLOCK-T539		0.42	0.97
624										30.00	acq	1.08	3.37	infocus_correcting_sphericals	i_39	BLOCK-T539		0.50	1.01
623										30.00	acq	1.10	18.10	infocus_correcting_sphericals	i_39	BLOCK-T539		0.47	1.04
622										30.00	acq	1.22	3.35	infocus_correcting_sphericals	i_39	BLOCK-T539		0.57	1.09

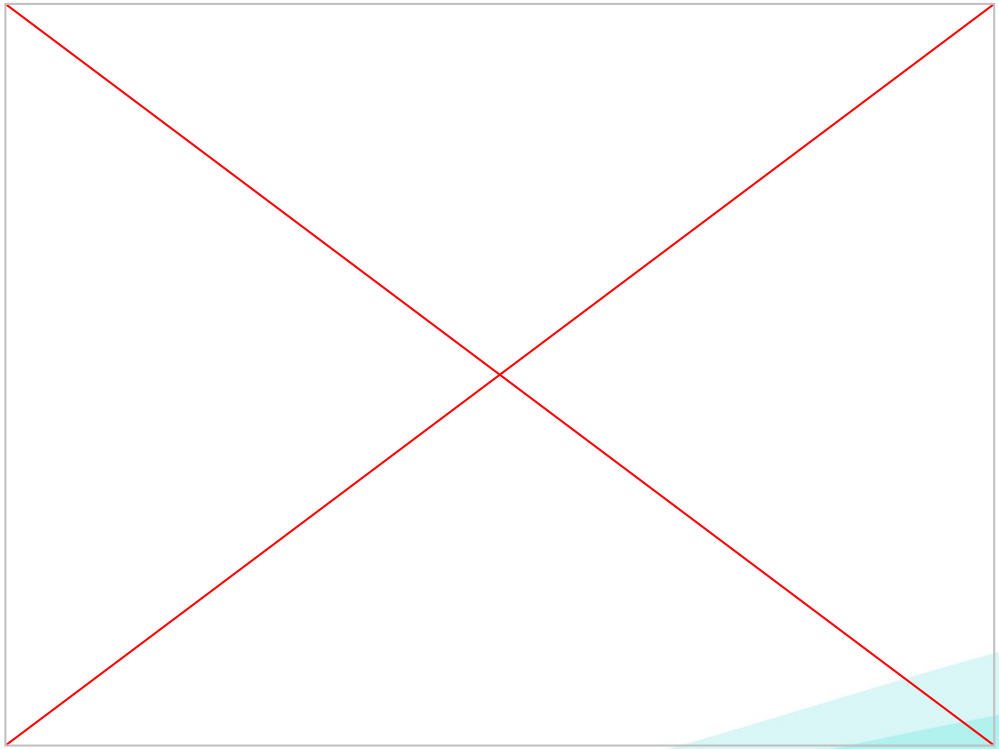






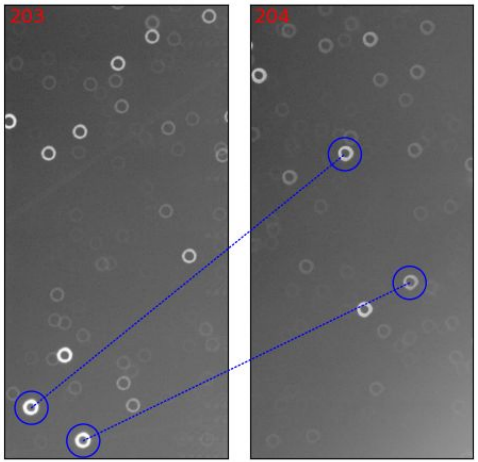
Wavefront Error Pipeline Optimization & Robustness

- Initial alignment and recovery from telescope faults requires WEP to work when the telescope is very out of focus
- WEP estimated donut radii from postage stamps when there was a large defocus in the system and regular wavefront estimation approach failed
- New, more robust donut correlator fits for radii using entire CCD

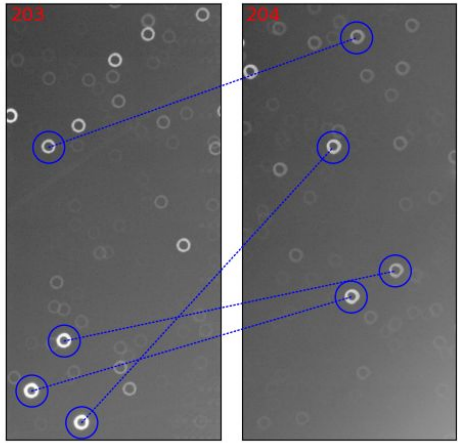


Donut detection failures

- We find that sometimes we won't detect donuts in all sensors, although they are clearly visible by eye
- Improvements have been tested offline and these updates are already live in Rapid Analysis
- Will eventually move to using the reference catalog and WCS for donut catalog generation



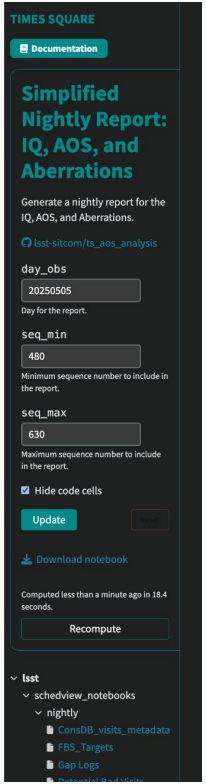
Before latest changes

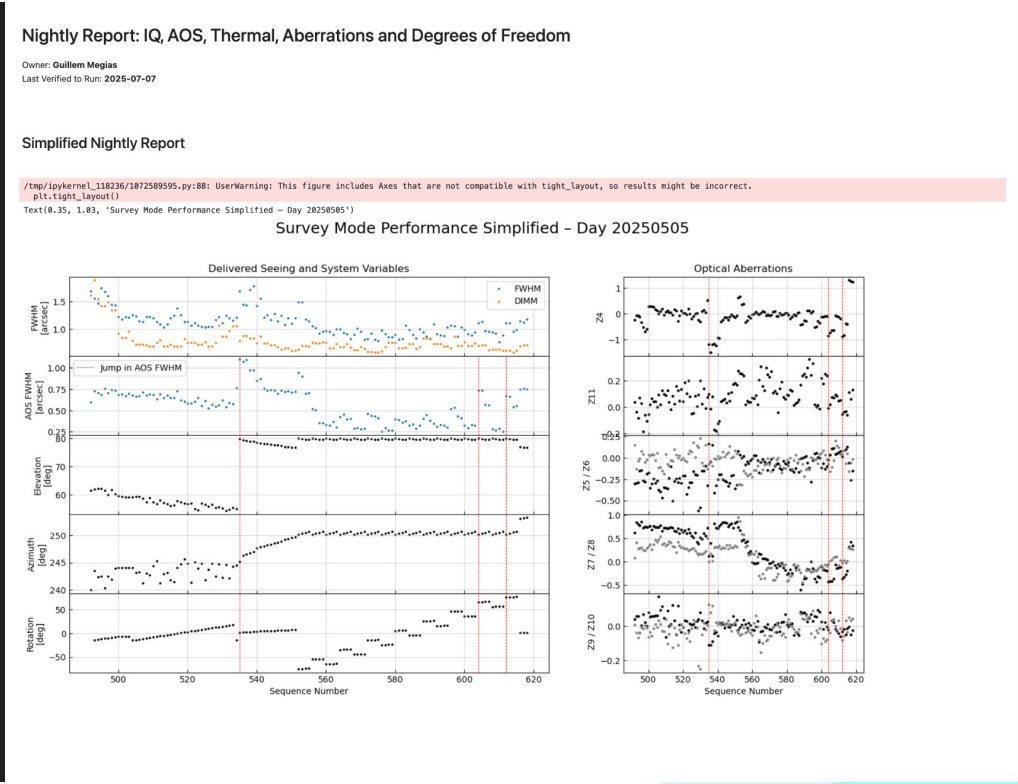


After

Times Square Notebooks

- Nightly reports available in Times Square
- Adding more information into cons_db that we can include in future versions of the nightly report



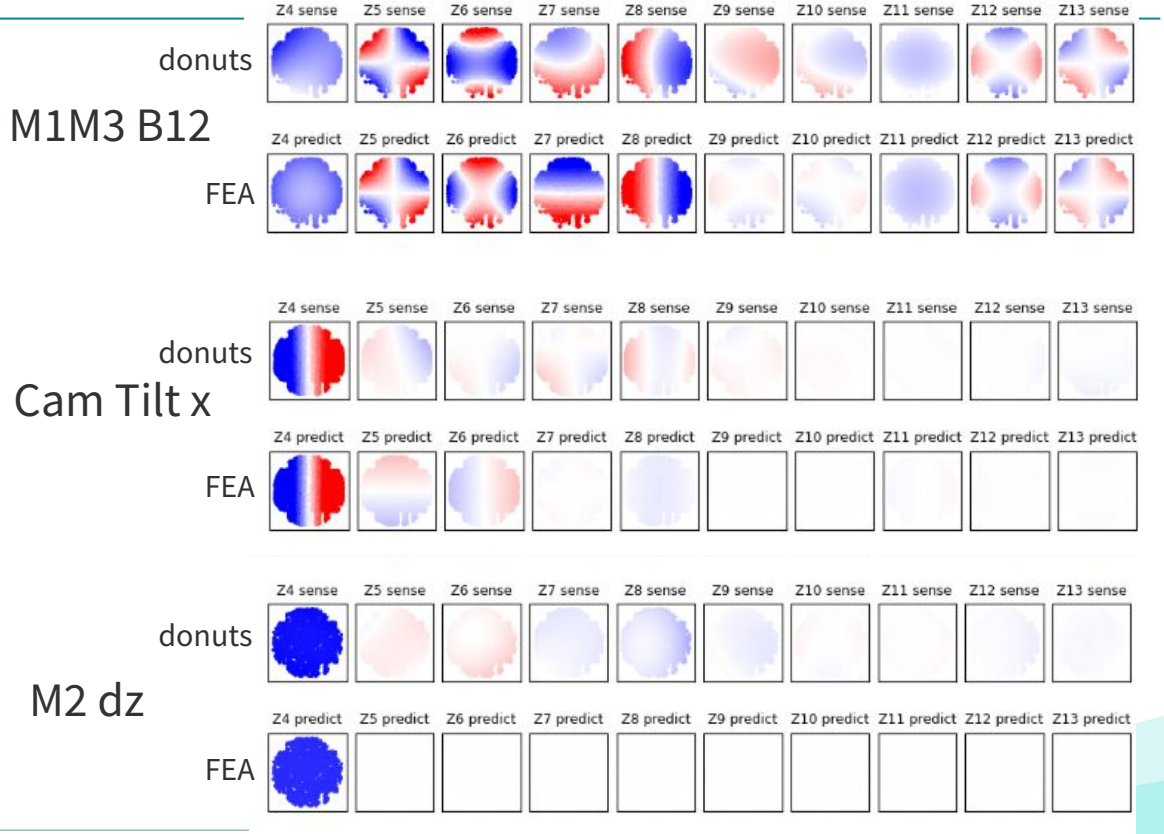


USDF Datasets

- Dataset Types
  - “aggregateAOSVisitTableRaw”, “aggregateAOSVisitTableAvg”
    - Overall visit summary tables with Zernikes along with metadata on the donuts
  - “aggregateDonutStamps”
    - All the donut stamps that go with the corresponding Zernikes
- Collections
  - In /repo/main
    - “u/brycek/aos_cwfs_danish”
      - Un-embargoed wavefront sensors from ACQ and Science visits run through the AOS pipeline
    - “u/brycek/aos_lsstcam_triplets_{algo}”
      - Full Array Mode visits run through the AOS pipeline
  - See more info at ls.st/campaigns

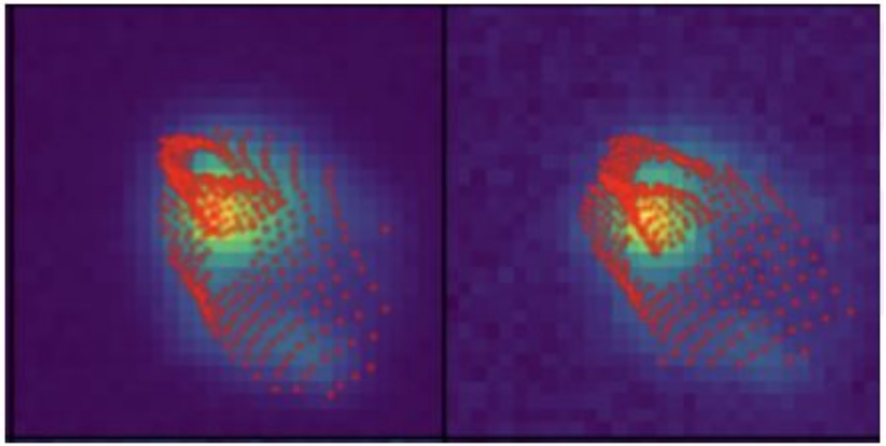
Sensitivity matrix

- d(wavefront)/d(dof)
- FEA sensitivities in good agreement with measurements (some small differences to follow up).
- Helps validate wavefront estimation. Algorithm choices.
- Probe repeatability. Understand wavefront estimate uncertainties.



AOS Resid FWHM

- Use measured wavefront coefficients to predict in-focus contribution of residual AOS errors.
- We track mean of four corners
  - Should project to science region and estimate FWHM there.
- Doesn't include wavefront terms we don't estimate. (biases low)
- Does include uncertainty in wavefront terms (biases high)
- Single number per exposure; ignores FOV variation.



Credit: SITCOM-149

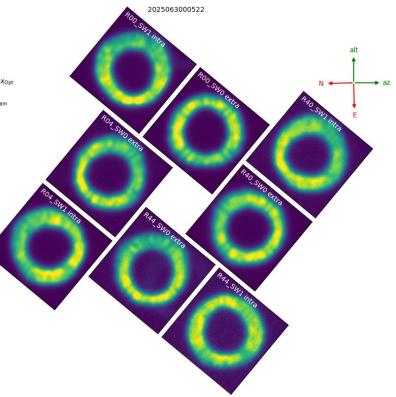
Background: (bad) commissioning PSF
Red: Optics prediction from wavefront.

Breaking down AOS / non-AOS contributions to Image Quality

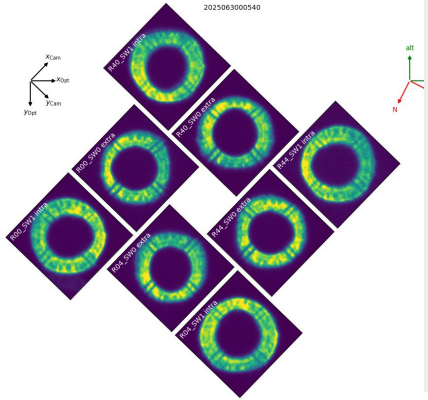
Donut blur ~ everything not AOS

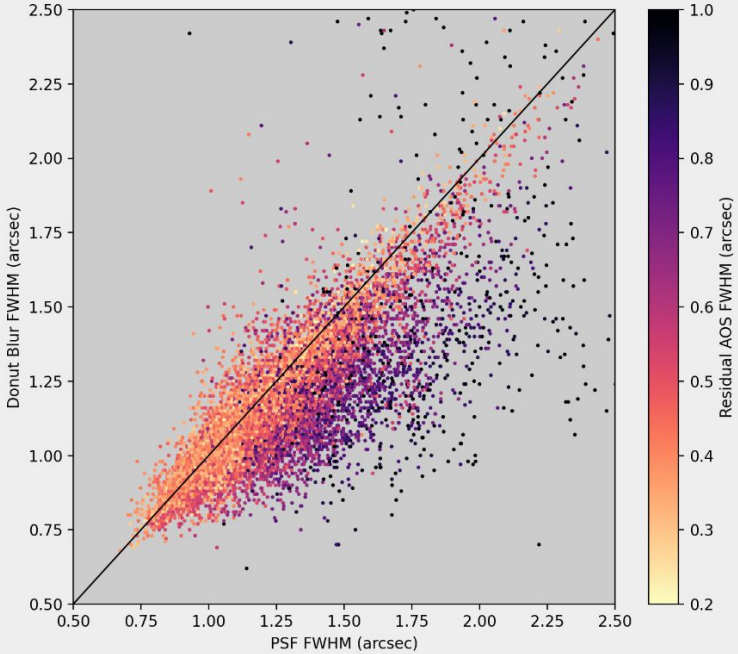
Delivered IQ is worse than donut blur when AOS Resid FWHM prediction is high: gradient on the right.

blur ~1.9 arcsec



blur ~1.0 arcsec



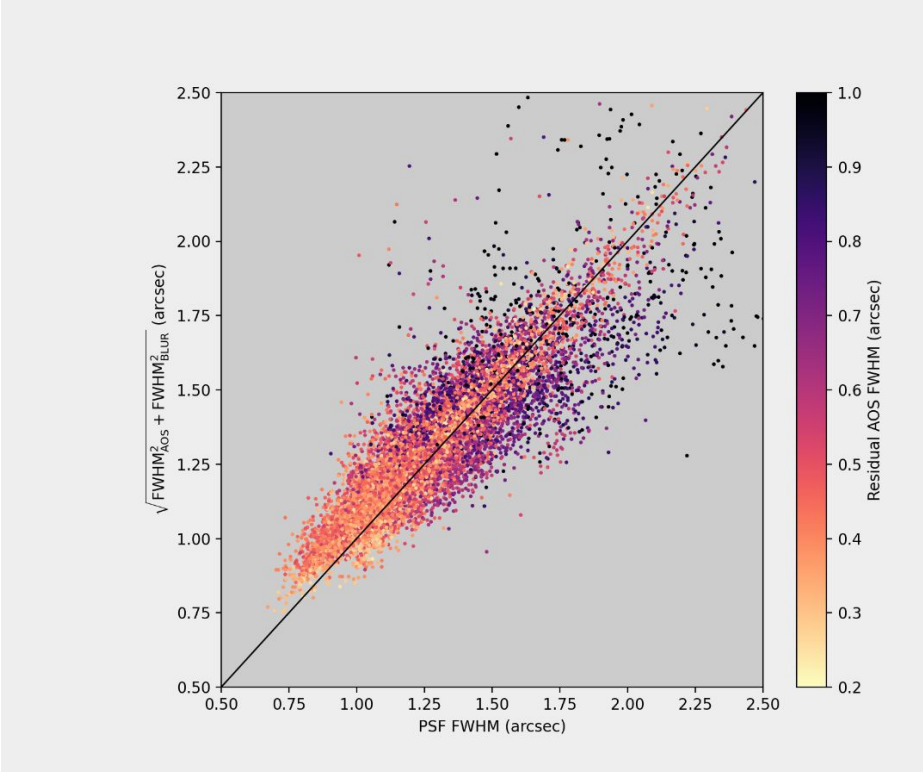


Breaking down AOS / non-AOS contributions to Image Quality

Donut blur ~ everything not AOS

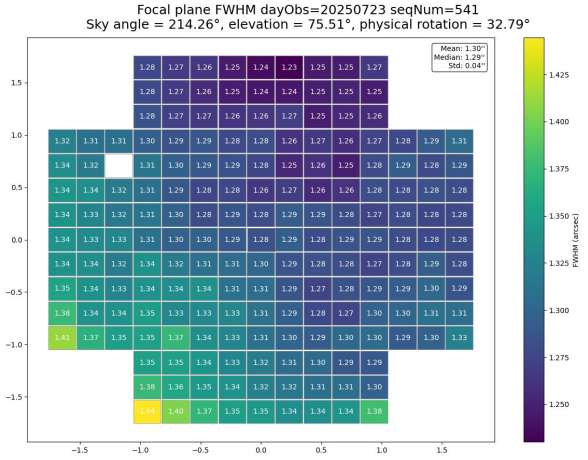
Delivered IQ is worse than donut blur when AOS Resid FWHM prediction is high: gradient on the right.

Delivered IQ is ~ quadrature sum of AOS Resid FWHM and donut blur.

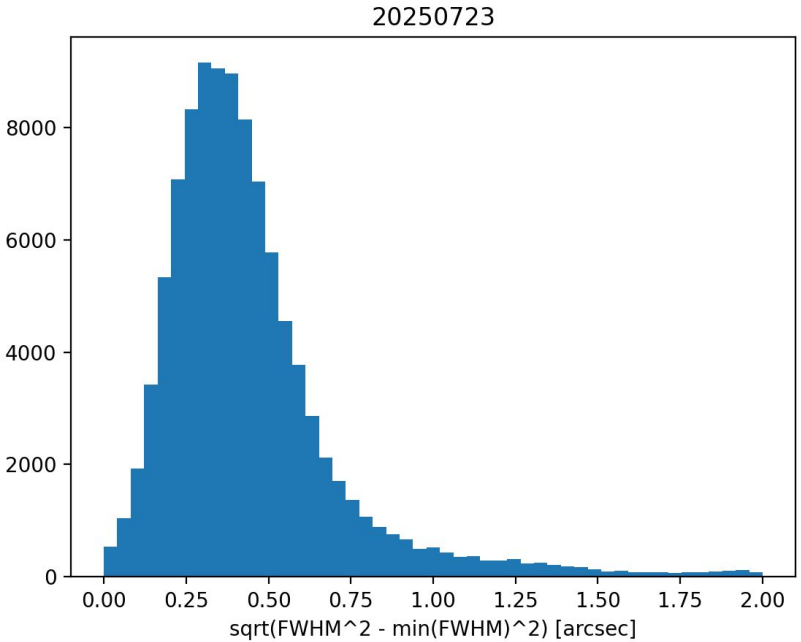


FWHM variation over FOV

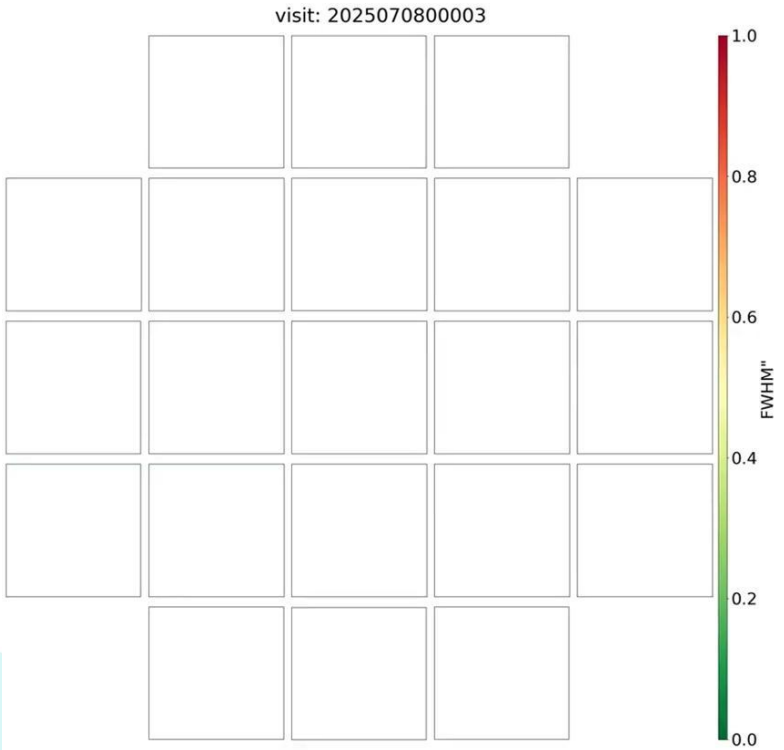
Posit minimum FWHM over field is non-AOS contribution. Look at quadrature difference to (lower) bound the AOS.

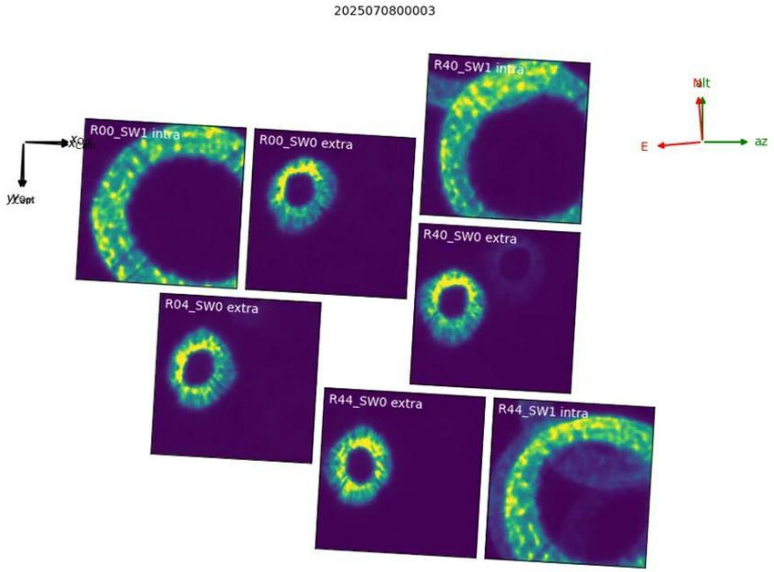


~lower bound for AOS performance



AOS in Action





Summary

- The AOS system is now running in survey-mode.
- The expanded operational range of SV is presenting a new challenge for AOS.
- We continue to look to improve
  - Donut selection robustness.
  - The performance of our wavefront estimation algorithms, understanding repeatability and uncertainties.
  - Characterization of AOS contribution to FWHM.
  - The open-loop component; will collect dedicated on-sky data - when running SV we entangle multiple dependencies that are difficult to disentangle.
  - Understanding of thermal effects; may include collecting dedicated on-sky data.

Thank you!

Some donuts from our very first on-sky image. They've become much harder to spot on the science sensors as the system has come together.