



Vera C. Rubin Observatory  
Systems Engineering

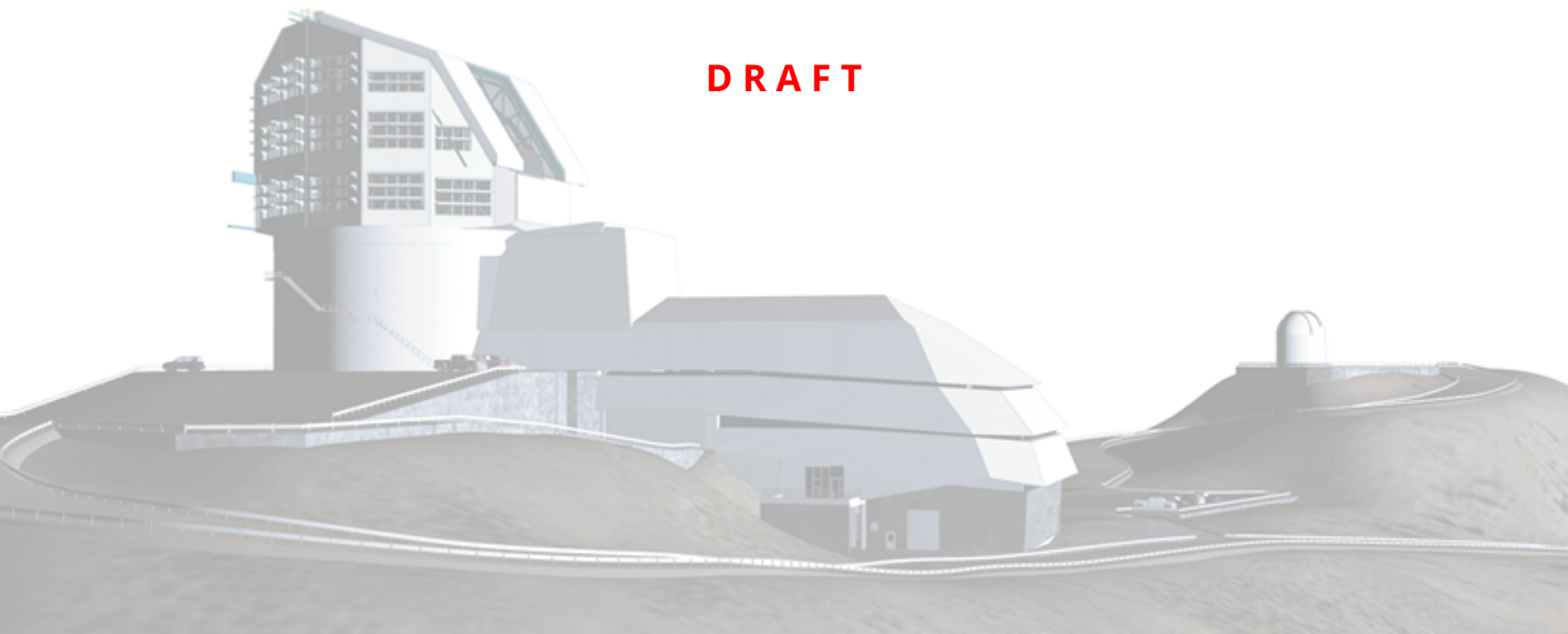
# An Interim Report on the On-Sky Commissioning Campaign with LSSTCam

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SITCOMTN-170

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**DRAFT**



## Abstract

From 15 April to 21 September 2025, the NSF-DOE Vera C. Rubin Observatory conducted an on-sky commissioning campaign using the LSST Camera (LSSTCam) to test the end-to-end functionality of hardware and software, as well as operational procedures. This interim report provides a preliminary technical overview of our understanding of the integrated system performance based tests and analyses conducted during the on-sky commissioning campaign with LSSTCam. The objectives are to synthesize what we have learned about the system in a timely way to inform Early Operations optimization, and to inform the Rubin science community on the progress of the LSSTCam on-sky campaign. The report is organized into sections that describe major activities during the campaign, as well as multiple aspects of the demonstrated system and science performance. All of the results presented here are to be understood as work in progress using engineering data and the initial versions of the data processing pipelines; the report is a living document that will be updated as analyses are refined.

## Change Record

Version	Date	Description	Owner name
1	YYYY-MM-DD	Unreleased.	Bechtol

*Document source location:* <https://github.com/lsst-sitcom/sitcomtn-170>

Draft

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# An Interim Report on the On-Sky Commissioning Campaign with LSSTCam

## 1 Introduction

The NSF-DOE Vera C. Rubin Observatory on-sky commissioning campaign using the LSST Camera (hereafter LSSTCam) began on 15 April 2025 and ended on 21 September 2025. This interim report provides a concise summary of our understanding of the integrated system performance based tests and analyses conducted during the LSSTCam on-sky campaign. We seek to distill, and to communicate in a timely way, what we have learned about the system to support the transition from Rubin Observatory Construction to Operations. The report is organized into sections that describe major activities during the campaign, as well as multiple aspects of the demonstrated system and science performance.

### Warning: Preliminary Results

All of the results presented here are to be understood as work in progress using engineering data and the initial versions of the data processing pipelines. It is expected at this stage, immediately following the completion of the on-sky commissioning campaign, that several analyses are still in progress, and that some of the discussion will concern open questions, issues, and anomalies that are actively being worked by the team to enhance the system reliability. Additional documentation will be provided as our understanding of the demonstrated performance of the as-built system progresses.

### 1.1 Charge

#### Charge Development Historical Note

The initial version of the charge developed in September 2025 is provided below for reference.

We identify the following high-level goals for this interim report:

- **Document our current understanding of the integrated system performance** to support systems engineering verification activities associated with demonstrating Construction Completeness [SITCOMTN-005].
- **Transfer knowledge to support the transition from Construction to Operations** to inform the Early Operations optimization period and to support the Early Science Program [RTN-011].
- **Inform the Rubin Science Community** on the progress of the on-sky commissioning campaign using LSSTCam.

Formal acceptance testing with respect to system-level requirement specifications (LSE-29 and LSE-30) will be recorded using the LSST Verification & Validation (LVV) system. By design, several of the analyses presented in this report correspond to system-level requirements, and therefore, this report is anticipated to serve as a verification artifact to support several of those systems engineering activities.

**The groups within the Rubin Observatory project working on each of the activities and performance analyses are charged with contributing to the relevant sections of the report.** The anticipated level of detail for the sections ranges from a paragraph up to a page or two of text, depending on the current state of understanding, with **quantitative performance** expressed as summary statistics, tables, and/or figures. The objective for this document is to **summarize the state of knowledge of the system**, rather than how we got there or “lessons learned”. The sections refer to additional supporting documentation, e.g., analysis notebooks, other technotes with further detail, as needed. Given the timelines for commissioning various aspects of the system, it is natural that some sections will have more detail than others.

The anticipated milestones for developing this interim report are as follows:

- 18 Sep 2025: Define charge
- 22 Sep 2025: On-sky commissioning campaign with LSSTCam completed; start of final construction downtime and its first operations engineering downtime
- 8 Oct 2025: Detailed outlines with initial versions of essential figures and performance statistics for report sections made available for internal review (content can be on un-

merged development branches); a goal is to help systems engineering with mapping of report content to requirements verification

- 15 Oct 2025: Revised drafts of report sections made available for internal review; development branches merged to main branch; editing for consistency and coherency throughout the report
- 22 Oct 2025: Start of Construction to Operations Transition Workshop; advanced draft ready for review by full Rubin Observatory team
- 31 Oct 2025: Initial version of report is released

## 2 Executive Summary

Executive summary here.

### Versioning Note

This interim report provides a preliminary technical overview of the LSSTCam on-sky campaign based on analyses through October 2025.

### 2.1 Accomplishments

- **Accomplishment.** Description.
- **Accomplishment.** Description.
- **Accomplishment.** Description.

### 2.2 Areas of Ongoing Investigation and Further Development

- **Issue.** Description.
- **Issue.** Description.
- **Issue.** Description.

### 3 Sensor Performance and Instrument Signature Removal

- Usable pixels, effective field of view, fill factor
- Read noise
- Crosstalk
- Dynamic range (brightest and faintest objects)
- Summary table of key Camera performance metrics
- Section needs at least one figure to visualize focal plane; maybe a flat?
- Standard visit (i.e., snaps) evaluation?

We performed comprehensive in-dome calibration to generate calibration products and validate LSSTCam. Calibration data not requiring external illumination included biases and darks. We operated the Flat Field Projector with single-LED flats and generated Photon Transfer Curves (PTCs). We exercised both calibration system sources: a white-light LED with a fiber spectrograph and photodiode plus electrometer, and a tunable laser with the same metrology chain. We used the Collimated Beam Projector (CBP) for filter scans (and no-filter scans) and to acquire crosstalk spot data. These activities validated the calibration pathways and established in-situ sensor performance baselines.

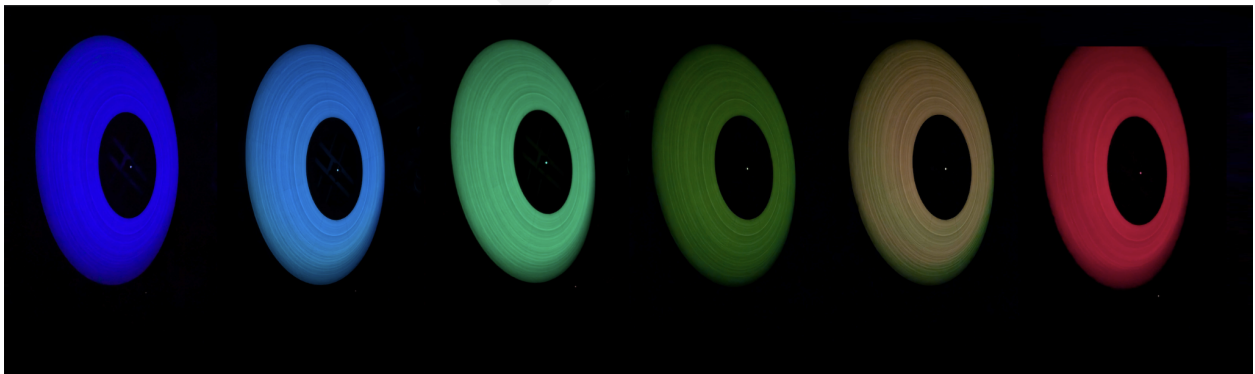


FIGURE 1: Our flat field screen illuminated by our single LEDs and pairs of single LEDs. The LEDs from left to right are named Royal Blue, both Royal Blue and Green, Green, Lime, both Lime and Deep Red, Deep Red)

A total of 188/189 sensors are operational, with only R30/S12 currently non-operational. The median amplifier loses  $\sim 0.45\%$  of its area to defects, while the mean across amplifiers is closer

to  $\sim 0.7\%$ . Elevated defect counts appear where effective QE is lower at detector edges, especially for Cy0 and Cy7 amplifiers. No new static defect classes have been identified on e2v devices (hot/cold pixels and columns remain as expected), while a subset of ITL detectors exhibits “vampire” pixels and locally higher noise. Dynamic masking still requires work, including treatment of e2v edge bleeds and occasional flare-type artifacts when bright stars fall on extreme detector edges. Overall,  $\gtrsim 99\%$  of the focal plane is active and usable within the calibrated field.

defectsPixels

u/ferte/DM-42200/defects\_verify/20250912a/20250912T203728Z

PhotoCalib: None, Astrometry: None

Table: verifyDefectsResults, Bands: u, g, r, i, z, y

Median: 4172.00

 $\sigma_{MAD}$ : 481.10

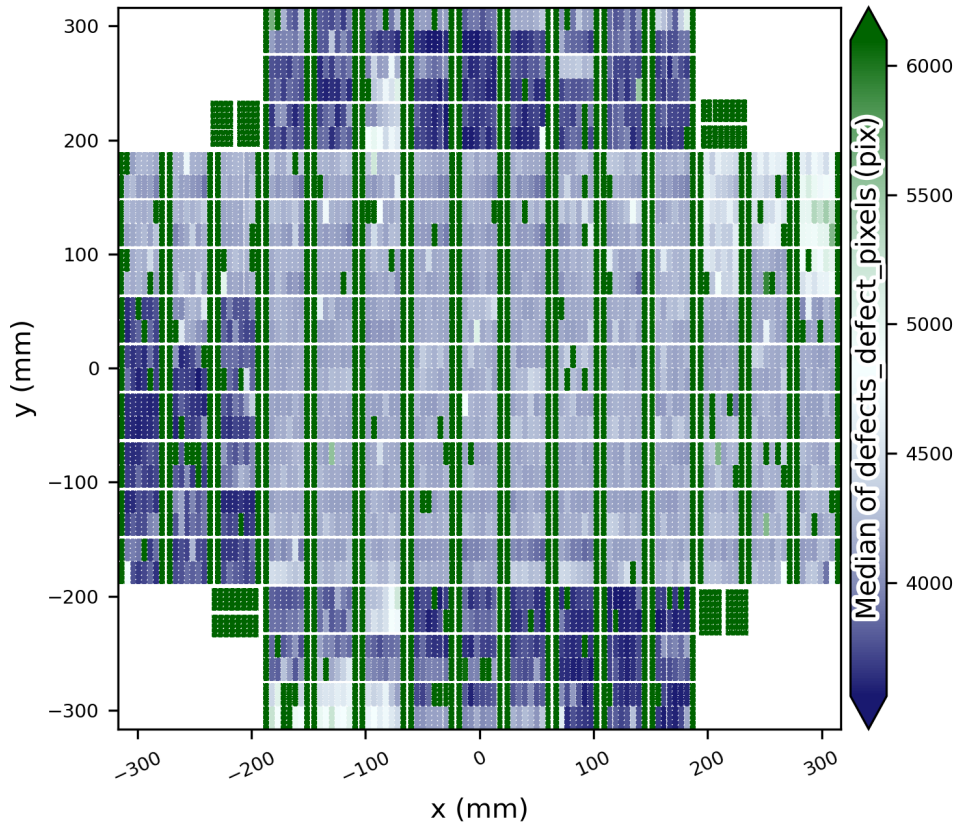
 $n_{points}$ : 3088


FIGURE 2: Usable pixels summary: 188/189 sensors operational (R30/S12 offline), median amplifier defect area  $\sim 0.45\%$  (mean  $\sim 0.7\%$ ), with edge-related QE behavior raising counts in Cy0/Cy7 amplifiers; no new static defect types on e2v, “vampire” pixels seen on some ITL detectors.

Optical vignetting limits the fully calibrate-able radius to the camera requirement of 317 mm (black circle). We introduced a PARTLY\_VIGNETTED mask plane for 317–350 mm radius (red circle), where calibration is expected to be feasible but at reduced fidelity relative to the inner zone. If calibration to 350 mm is achieved, the residual loss of area relative to the geometric

maximum radius of 365 mm (blue circle) is minimal, affecting only the extreme corners of the focal plane. Regions outside 350 mm are treated as fully vignettted and excluded from science products.

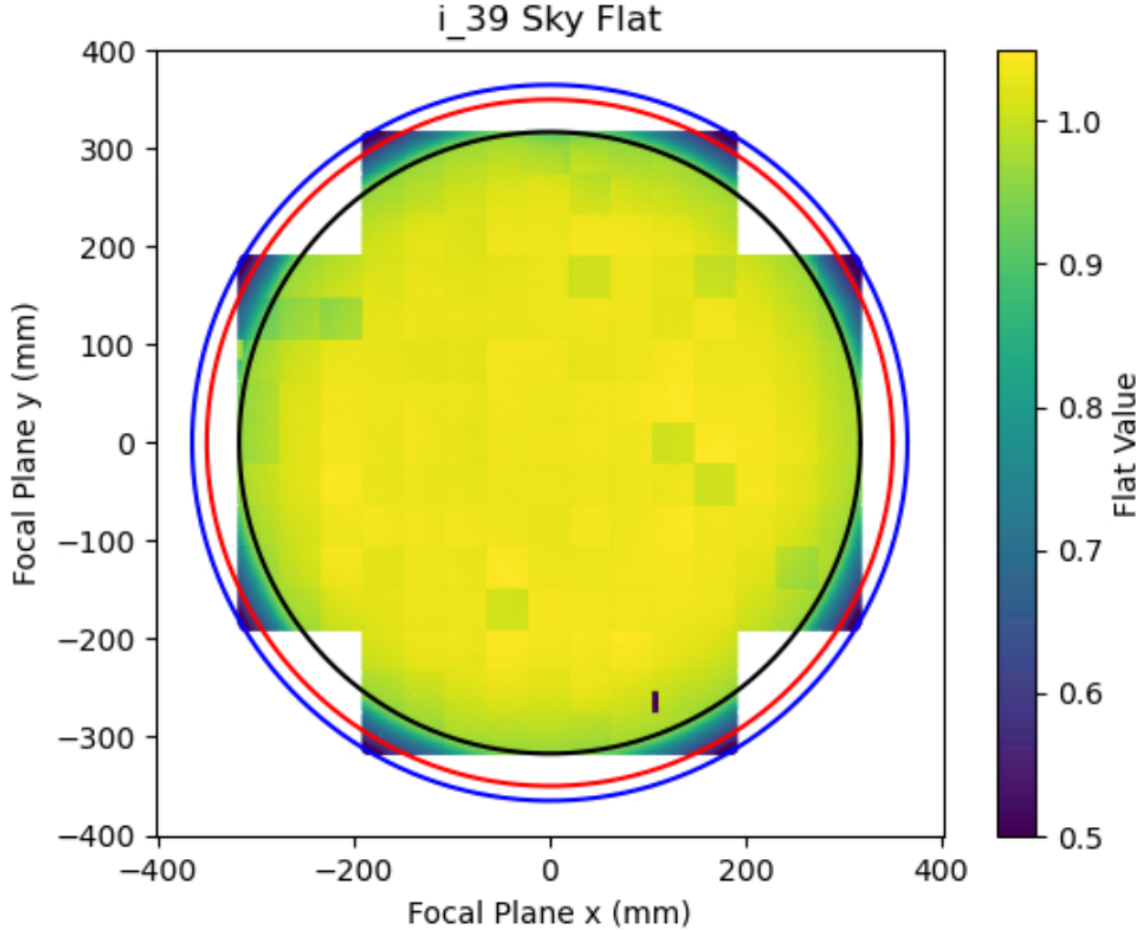


FIGURE 3: Optical vignetting and calibrate-able field of view: requirement radius 317 mm (black), target extension to 350 mm (red) for partial vignetting, and geometric maximum 365 mm (blue).

Read-noise maps show all channels in specification, with ITL devices having slightly higher medians than e2v and some top-bottom amplifier shifts visible on subsets of ITL sensors. Gain maps show nominal values consistent with design and optimal ADC usage. PTC turn-off levels indicate amplifier dynamic ranges typically near  $\sim 10^5$  DN, with subsets lower; pixels above the turn-off are saturated in processing. CBP spot data confirm that the updated sequencer reduces noise and correlations, but crosstalk coefficients require re-derivation post-change; first-order terms are largely removed while higher orders remain to be tuned for DP2 processing. No new major anomalies were uncovered during these campaigns, and calibration

improvements are being integrated iteratively into ISR and downstream processing.

### 3.1 Summary

All calibration systems were exercised end-to-end, and their products validated in dome. Operational yield is 188/189 sensors with  $\geq 99\%$  active focal-plane area within the calibrate-able region. A PARTLY\_VIGNETTED mask enables use out to 350 mm radius with controlled fidelity, minimizing area loss to extreme corners while avoiding over-fitting in fully vignettted zones. Read noise, gain, and dynamic range meet expectations, and post-sequencer crosstalk calibration is in progress for DP2.

### 3.2 Bright Stars and Moon

On-sky validation that the Camera can survey the night sky in the presence of bright sources

### 3.3 Sensor Anomalies

Any sensor anomalies that are worth noting

### 3.4 LSSTCam Performance during the LSSTCam On-sky Campaign

Brief summary of LSSTCam performance during the campaign, any open questions, outstanding issues

This could include any discussion on Camera subsystems, e.g., focal plane optimization, filter exchange system, cryo, camera shutter, that should be highlighted

## 4 System Optical Throughput for Focused Light

- Standard bandpass; includes the sensors, filters, lenses, mirrors, and (a standard) atmosphere. Measured with CBP? Monochromatic flats with flat field screen?
- Imaging depth in multiple bands (LSR-REQ-0090); also express as zeropoint to separate



out the effects of image quality; could be comparison to refcats and/or spectrophotometric standards

- Figure to show throughput variation of throughput across field of view (LSR-REQ-0109); potentially separating out vignetting and CCD response
- Discussion on Sensitivity Factor (fS) in the System Performance Diagram

## 4.1 Standard Bandpass

## 4.2 Measured Zeropoints

# 5 Measured Sky Backgrounds

During the LSSTCam on-sky campaign, dedicated tests were performed to characterize the background, evaluate the performance of the SkyCorrectionTask, and verify compliance with project-level requirements.

## 5.1 Sky Brightness Determination

Sky brightness measurements were performed using forced photometry on randomly placed “sky sources” across the focal plane. For each position, the local sky flux was compared to the model prediction. Across the sample of real LSSTCam data, the precision of the sky brightness determination was better than 1% in approximately 99% of all measurements, meeting the system requirement (Fig. 4).

These tests used data from weekly DRP processing runs (e.g., week 18) that employed the full-focal-plane background modeling introduced with the SkyCorrectionTask. This task, initially developed for HSC, was commissioned for LSSTCam and now fits large-scale gradients across the entire focal plane. Comparisons between per-detector and full-focal-plane background solutions show that the latter reduces over-subtraction near bright, extended sources and improves uniformity across the field.

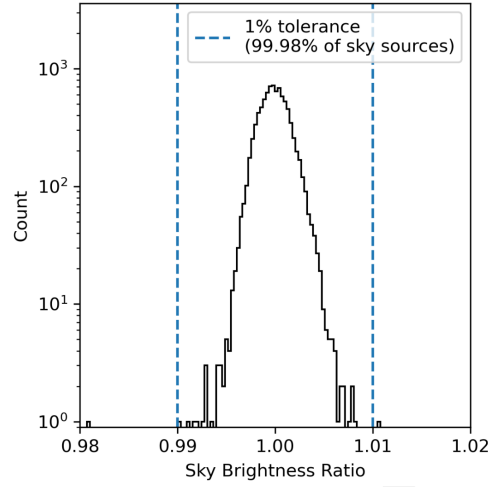


FIGURE 4: Performance of sky brightness determination using forced photometry of randomly placed sky sources. Nearly all measurements ( $\sim 99\%$ ) achieve better than 1% precision, satisfying the system requirement.

## 5.2 Limiting Surface Brightness Sensitivity

Random sampling of sky regions from ten representative  $g$ -band LSSTCam visits yields a limiting surface brightness of  $\sim 28 \text{ mag arcsec}^{-2}$ . This limit is defined as three times the standard deviation of the background flux distribution within 10 arcsecond boxes. Further validation using radial photometry of the brightest cluster galaxy (BCG) in Abell 360 confirms that surface brightness features are detected to similar levels in multiple bands. These measurements demonstrate that the system is achieving the expected depth for extended, low surface brightness structures (Fig. 5).

## 5.3 Optical Ghost Area Impact

The contribution of optical ghosts to the effective background and usable imaging area was evaluated using ray-tracing simulations with the Batoid optical model. Simulated stars of varying brightness were placed at different field positions, and the fractional area of the focal plane impacted by ghost reflections was measured as a function of bandpass. The mean ghost-affected area across all filters is  $\sim 0.6\%$ , with the largest values in  $u$  and the smallest in  $r$  and  $i$ . This satisfies the system requirement that the fractional area impacted by ghosts remain below 1%. On-sky verifications confirm that the simulated ghost patterns correspond well to observed behavior (Fig. 6).

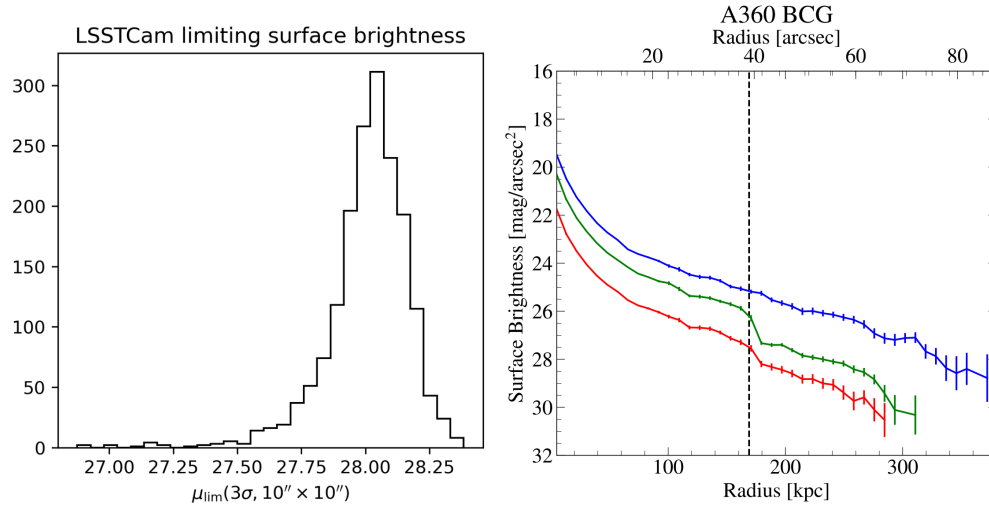


FIGURE 5: Low surface brightness performance. *Left*: Random sampling of  $g$ -band LSSTCam visits yields a limiting surface brightness of  $\sim 28$  mag arcsec<sup>-2</sup>. *Right*: Radial photometry around the BCG in Abell 360 confirms consistent surface brightness sensitivity across filters.

## 5.4 Summary

The commissioning campaign demonstrated that LSSTCam background modeling meets or exceeds requirements. Sky brightness precision is better than 1%, limiting surface brightness sensitivity reaches  $\sim 28$  mag arcsec<sup>-2</sup>, and the fractional area affected by optical ghosts remains below 1%. These results validate both the photometric and low surface brightness performance of the system and establish a foundation for continued optimization of background modeling in future data releases.

# 6 Delivered Image Quality

## 6.1 Delivered Image Quality Distribution

- Examples of some of our best images to demonstrate system capability
- Figure: distribution of PSF FWHM for an ensemble of visits
- Figure: PSF size and ellipticity distribution across field of view for an ensemble of visits

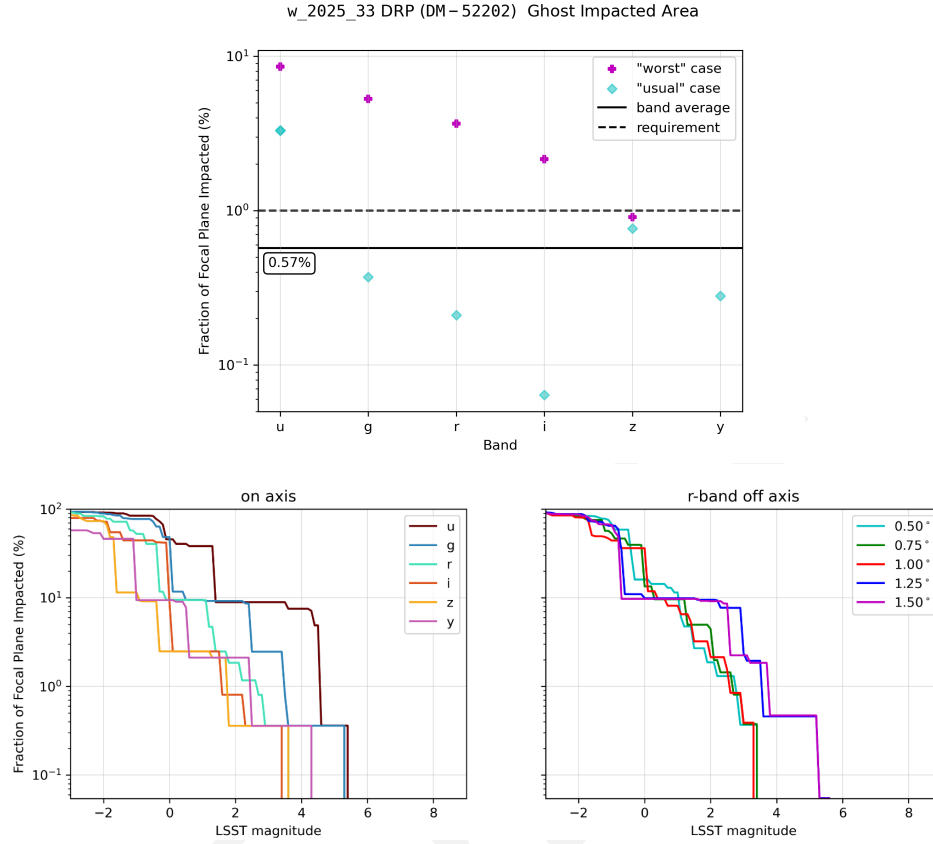


FIGURE 6: Fraction of the focal plane impacted by optical ghosts simulated with Batoid. The mean loss is  $\sim 0.6\%$  across all filters, with worst performance in  $u$  and best in  $r$  and  $i$ , satisfying the requirement that ghost area loss remain below 1%.

## 6.2 Image Quality Budget

Discussion on current assessment of the various contributions to the delivered image quality, accomplishments, open questions, outstanding issues

Discussion on current state of characterizing the atmosphere contribution

## 6.3 PSF Characterization

The characterization of the point spread function (PSF) provides a key measure of the image quality and calibration performance achieved during LSSTCam commissioning.

### 6.3.1 Focal Plane Residuals

Average PSF size residuals across the focal plane are at or below the 0.5% level, indicating sub-percent accuracy in the PSF modeling (Fig. 7). When the residuals are stacked across ensemble visits, distinct spatial structures become visible. A ring-like pattern at the edge of the field corresponds to vignetting effects. Small amplifier-level offsets are observed on e2v sensors. Most notably, a “blob” pattern appears on ITL sensors, consisting of circular features within each device.

These ITL features are highly correlated with the height map of each sensor measured during laboratory testing at SLAC. (Fig. 8). Blink comparisons between the PSF residual maps and the measured height maps show an excellent correspondence. This confirms that local defocus from sensor height variations produces the observed PSF structure. The PSF thus serves as a secondary map of focal-plane topography, which can be incorporated into future models to further reduce residuals.

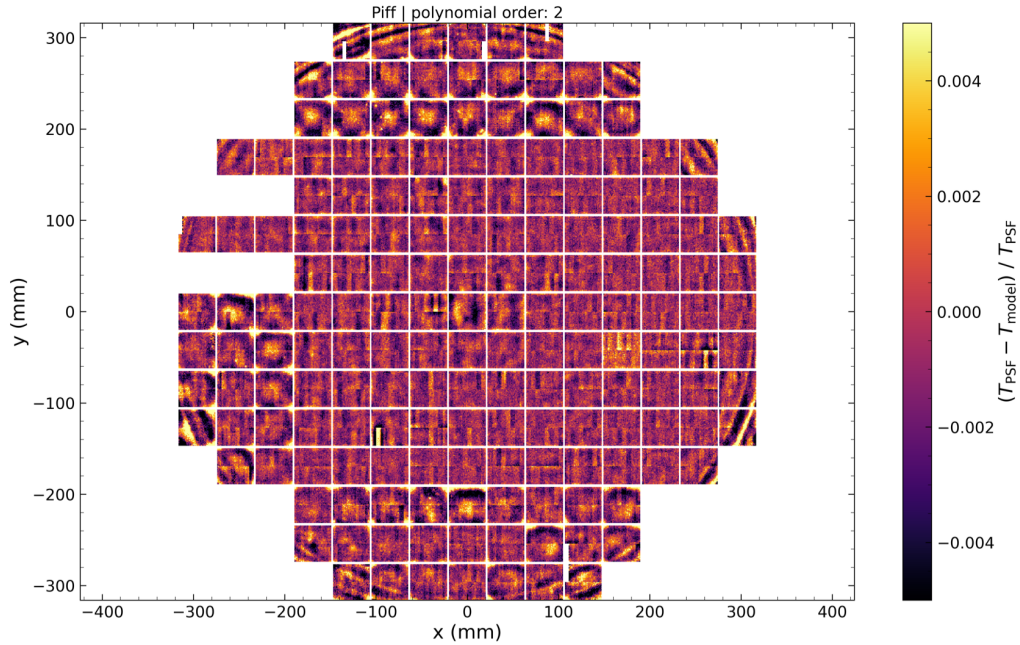


FIGURE 7: Average PSF size residuals across the LSSTCam focal plane. Residuals are at the  $\leq 0.5\%$  level. The ring at the edge corresponds to vignetting, small offsets appear on e2v sensors, and the blob pattern on ITL sensors matches the laboratory-measured sensor height map from SLAC.

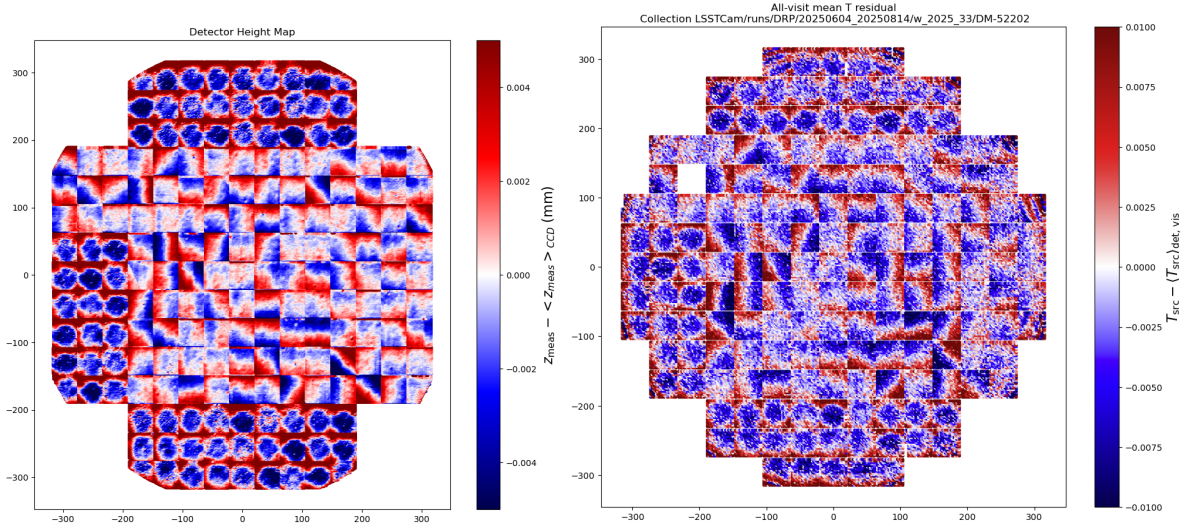


FIGURE 8: Size residuals are highly correlated with the laboratory-measured sensor height map from SLAC.

### 6.3.2 Brighter-Fatter Correction

The dependence of PSF size on source flux—the brighter-fatter effect—has been modeled and corrected using an electrostatic approach. This new model achieves accuracy better than 0.5%, satisfying and exceeding both Rubin internal requirements and external dark-energy science goals. Comparisons of residual PSF size as a function of flux show that the electrostatic model removes the previous over-correction observed in the default pipeline. Implementation of this improved correction in standard processing is in progress.

### 6.3.3 Ongoing and Future Work

Several enhancements to PSF modeling are under active development. A chromatic PSF model has been demonstrated and implemented in the pipeline but is not yet enabled by default. Work is underway to transition from per-CCD to full focal plane PSF modeling. Efforts are also in progress to shift from pixel coordinates to sky coordinates for PSF interpolation and to incorporate laboratory-measured sensor height information directly into the model. Each of these improvements is expected to further reduce PSF residuals and improve astrometric and shear accuracy.

PSF characterization during LSSTCam commissioning demonstrates that the system achieves sub-percent modeling accuracy across the focal plane. Residual patterns correlate strongly

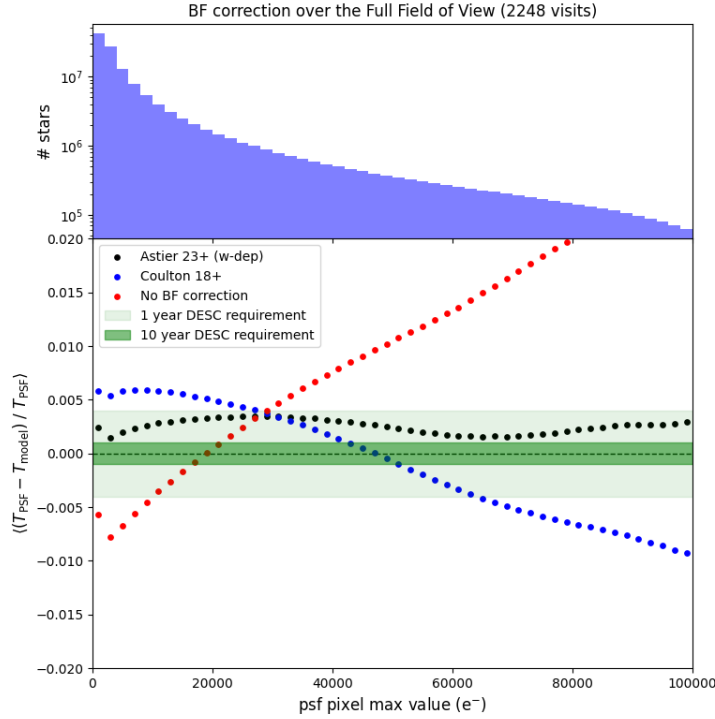


FIGURE 9: Brighter-fatter correction performance. The blue curve shows the uncorrected flux-dependent PSF size residuals, the red curve the current pipeline correction, and the black curve the new electrostatic model. The latter achieves sub-0.5% accuracy and removes the over-correction seen previously.

with known sensor characteristics, validating both the physical understanding and calibration fidelity of the system. With the inclusion of chromatic and full-focal-plane models in upcoming releases, PSF performance is expected to reach the design specifications required for precision cosmology.

## 7 Stray and Scattered Light

During the LSSTCam on-sky commissioning campaign, a diverse set of stray and scattered light artifacts were identified on the focal plane. In contrast to optical ghosts, features predicted from nominal reflections within the optical system, these artifacts arise from unwanted light paths that do not follow the designed optical train. They represent parasitic illumination reaching the focal plane through reflections, scattering, or incomplete baffling of external light sources.



To date, approximately fourteen distinct stray-light features have been cataloged. The team has determined the optical or opto-mechanical origin for the majority of these, while a few remain under investigation. Most of the remaining unidentified features are expected to be mitigated by the *Light Wind Screen* (LWS), which was recently installed and is expected to become fully operational in the coming months. Additional mitigations have included selective blackening of reflective surfaces inside the dome and telescope structure.

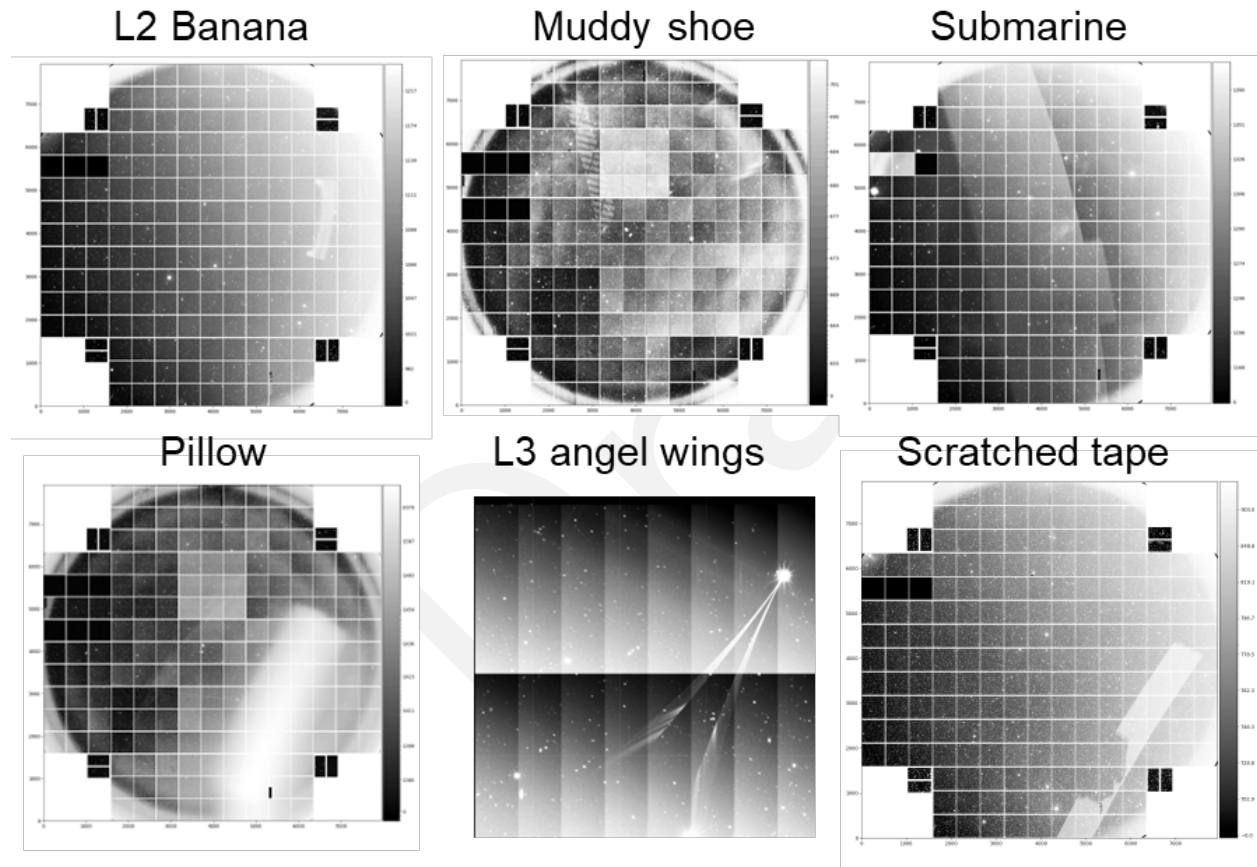


FIGURE 10: Representative examples of stray and scattered light features observed during LSSTCam commissioning. Approximately fourteen distinct artifacts have been cataloged, with the majority now traced to specific opto-mechanical origins. The remaining unidentified cases are expected to be mitigated by the Light Wind Screen and additional baffling improvements.

## 7.1 Detection and Characterization Workflow

Each newly identified feature follows a structured diagnostic workflow:

1. **Classification and Documentation:** Compare with the existing catalog to determine



whether the artifact represents a previously known type or a novel feature.

2. **Modeling and Reproduction:** Perform ray-tracing simulations using both Batoid and Zemax to reproduce the observed geometry and intensity distribution.
3. **On-Sky and In-Dome Testing:** Conduct dedicated observations—both on sky and using the Collimated Beam Projector (CBP)—to confirm the proposed optical paths.
4. **Source Identification:** Carry out astrometric searches to locate the bright star or planet responsible for generating the feature, typically at off-axis angles of 15–25 degrees.
5. **Mitigation Assessment:** Evaluate hardware and operational mitigations, including additional baffling, surface treatment, and observing constraints.
6. **Impact Evaluation:** Estimate the potential scientific impact on photometric and background measurements.

A total of nine hours of on-sky testing (twelve test cases) and fifteen hours of in-dome testing (eight test cases) were dedicated to this effort. Weekly coordination meetings between the stray-light task force and LSSTCam Science Unit have been maintained to ensure progress in both diagnosis and mitigation.

## 7.2 Example: The “Scratch Tape” Artifact

The most prominent and frequent stray-light feature identified during commissioning is colloquially referred to as *Scratch Tape*. It manifests as a series of bright, elongated streaks or “tape-like” bands across the focal plane (see Fig. 11). These features can reach surface brightness levels up to ~20% of the dark-sky background and appear in roughly 5% of all exposures. Their structured pattern and relatively high contrast make them among the most visually and scientifically significant artifacts observed.

Through a combination of pinhole imaging, twilight flats, and optical modeling, the origin of the Scratch Tape feature was traced to an unobstructed light path between the mid-level and center-section light baffles on the Telescope Mount Assembly (TMA). Light entering through this gap reflects off M1 and is scattered directly into the camera. Under normal operation, this path should be blocked by the LWS; however, the system was not yet deployed during early commissioning observations.

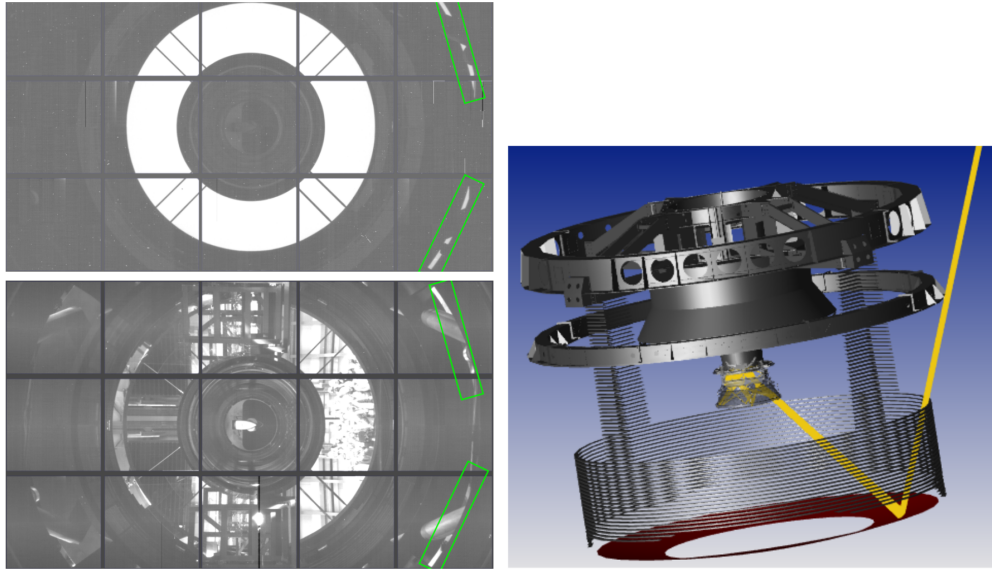


FIGURE 11: Identification of the light path responsible for the “Scratch Tape” artifact. *Left:* pinhole and twilight flat analyses demonstrating light entering between the mid-level and center-section baffles on the TMA. *Right:* ray-tracing and CBP results confirming that light reflects off M1 and enters the camera directly through this gap.

The feature was successfully reproduced through targeted on-sky tests by placing bright stars  $\sim 20$ – $22$  degrees off-axis in the identified azimuthal sector. Both Zemax and Batoid simulations confirmed that the observed path is consistent with reflections between the two baffles and M1. Independent CBP experiments verified the same geometry under controlled dome conditions.

### 7.3 Mitigation Plan

A short-term mitigation has been designed by extending the mid-level baffle by approximately 22 cm to block the problematic light path. This hardware extension, developed collaboratively by J. Andrew, D. Neal, and colleagues, is scheduled for installation in late November. Although the LWS will ultimately provide a more comprehensive solution, the baffle extension offers a robust and immediate reduction of the Scratch Tape feature with no expected optical or mechanical drawbacks.

Following installation, additional on-sky and in-dome tests will be performed to verify that the light path is fully blocked. Further mitigations under study include refinements to the M2 baffle coating, additional blackening of reflective surfaces near the auto-changer, and evaluation

of direct paths from M3 to the camera. In parallel, algorithmic approaches for detecting and removing residual stray-light features at the data-processing stage are being explored.

## 7.4 Summary

The investigation of stray and scattered light during LSSTCam commissioning has demonstrated a systematic framework for discovery, modeling, and mitigation of parasitic optical features. The majority of identified artifacts now have confirmed optical origins and practical mitigation paths. Continued refinement of the opto-mechanical model, expanded baffling, and the activation of the Light Wind Screen are expected to significantly reduce stray light in future operations.

## 8 System Timing and Dynamics

- Standard Visit Duration (OSS-REQ-0288)
- Readout time – discussed with the Camera?
- Time Interval Between Visits (OSS-REQ-0289)
- Maximum time for operational filter change (OSS-REQ-0293)
- Telescope Azimuth Slewing Rate (TLS-REQ-0029)
- Telescope Elevation Slewing Rate (TLS-REQ-0159)
- Summative assessment on rate of acquiring observations

### 8.1 Standard Visit Definition

Discussion on decision to use 30-second exposures

### 8.2 Visit Timing and Interval between Visits

Camera readout time, filter change times

Telescope motion settings, slew and settle, distribution of time between visits

### 8.3 Effective Survey Speed

Observing efficiency factor ( $f_O$ ) for System Performance diagram

Survey simulations combined with telescope motion capabilities; compare with actual rate of acquiring visits during SV surveys

## 9 Data Management

The primary purpose of this section is to describe that data management has been able to support the operational aspects of running Rubin Observatory during commissioning

- Calibration products and ISR during commissioning
- Brief description (paragraph or two; maybe a table) of data processing campaigns during on-sky commissioning, mainly reporting on the functional capabilities; algorithms and data products are discussed elsewhere; pointers to other references
- Figure with representative pixel-level color coadd images?

## 10 Calibration

### 10.1 Astrometry

Astrometric calibration establishes the geometric fidelity of the LSSTCam imaging system and ensures that object positions are consistent across visits and with external reference catalogs. The analysis presented here summarizes the current performance achieved during the Science Validation campaign and identifies the dominant sources of residual error.

#### 10.1.1 Global Calibration

The global astrometric calibration is performed using the `gbdesAstrometricFit` model, which fits for source proper motions and parallaxes across all visits. Differential chromatic refraction (DCR) fitting will be enabled in upcoming processing runs. Recent improvements include the

introduction of multiprocessing and the switch from small tract-level runs to larger HEALPix regions. These changes significantly reduced total processing time and improved overall convergence stability.

The resulting astrometric repeatability meets design expectations in most regions of the sky observed with full focal-plane dithers. Figure 12 shows the AM1 metric, defined as the standard deviation of the separation between pairs of objects approximately five arcminutes apart. Typical values are at the  $\sim 10$  milliarcsecond (mas) level, with localized regions showing higher scatter that are under investigation.

### 10.1.2 Residual Patterns and Atmospheric Contribution

Mean astrometric residuals binned by position in the focal plane are shown in Figure 13. The residuals in both X and Y directions reveal effects at the chip level. For example the features on the ITL detectors are consistent with the laboratory measured sensor height maps. These higher order distortions remain at the individual chip level and will be modeled out in future iterations.

Because LSSTCam uses relatively short 30-second exposures, atmospheric turbulence introduces correlated position shifts across the field. A Gaussian-process model has been developed to represent this atmospheric component and is being tested for inclusion in the standard pipeline. This model reproduces the observed E-mode correlation structure seen in the residuals and reduces the single-visit scatter by roughly 50% when applied.

After subtraction of the modeled atmospheric term, stacked residual maps reveal additional fine-scale structure, including chip-dependent distortions and faint tree-ring patterns on ITL sensors. These effects are below the atmospheric level but are now detectable due to reduced noise and will be incorporated into refined models.

### 10.1.3 Refined Camera Distortion Model

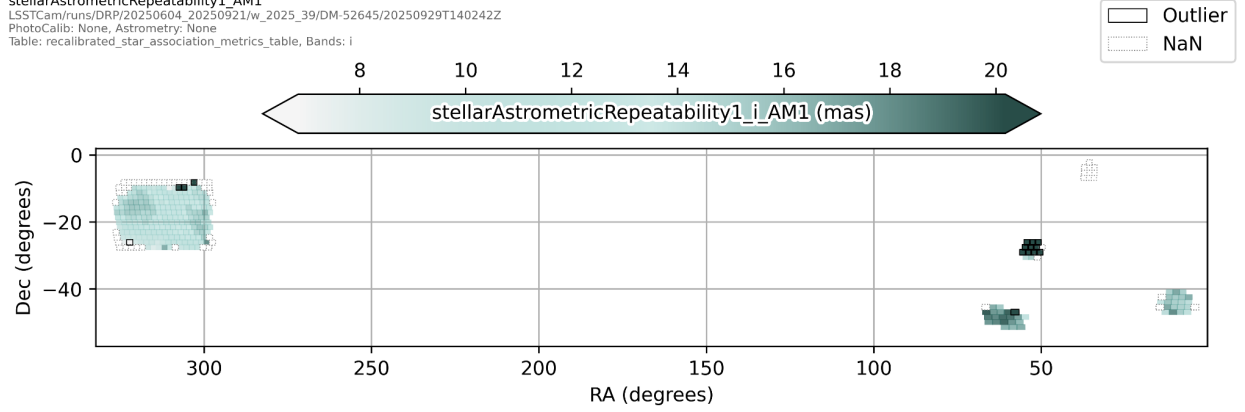
Astrometric solutions have been used to derive an updated camera distortion model, replacing the pre-commissioning geometric model from `obs_1sst`. This new model reflects the as-built optical system and the measured alignment of detectors in situ. The difference between the two models is shown in Figure 15. After removing a first-order affine transformation, small

stellarAstrometricRepeatability1\_AM1

LSSTCam/runs/DRP/20250604\_20250921/w\_2025\_39/DM-52645/20250929T140242Z

PhotoCalib: None, Astrometry: None

Table: recalibrated\_star\_association\_metrics\_table, Bands: i



Num tracts: 326

Num nans: 56

Median: 13.508;  $\sigma_{MAD}$ : 2.223

Tracts with  $|value| > 3.0\sigma_{MAD}$ : 5064, 24.8; 5281, 24.3; 8221, 23.8; 5063, 23.7; 5280, 23.7

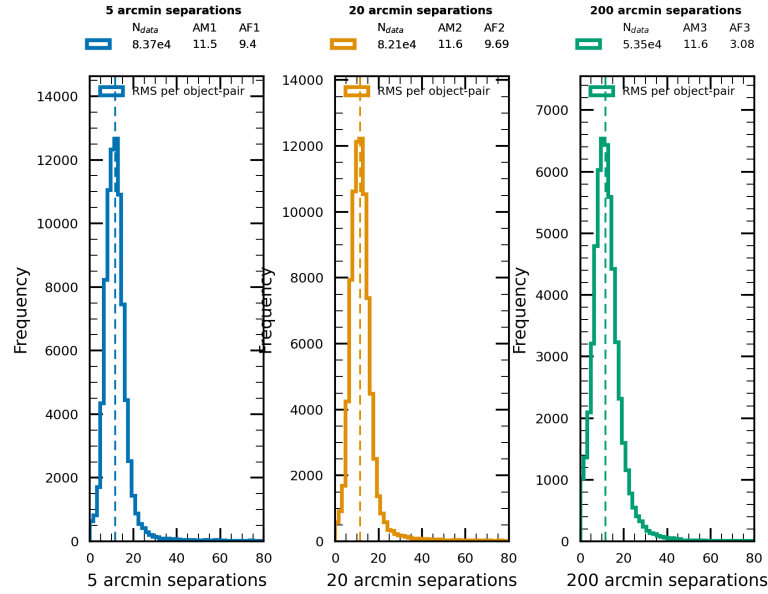


FIGURE 12: Map of the AM1 astrometric repeatability metric across the Science Validation survey region. The majority of the field achieves 10 mas RMS repeatability, consistent with design specifications.

chip-to-chip residuals and systematic trends between ITL and e2v sensors become visible.

The refined camera model is now incorporated into single-frame processing, improving the accuracy of instrumental calibration and the consistency of WCS solutions.

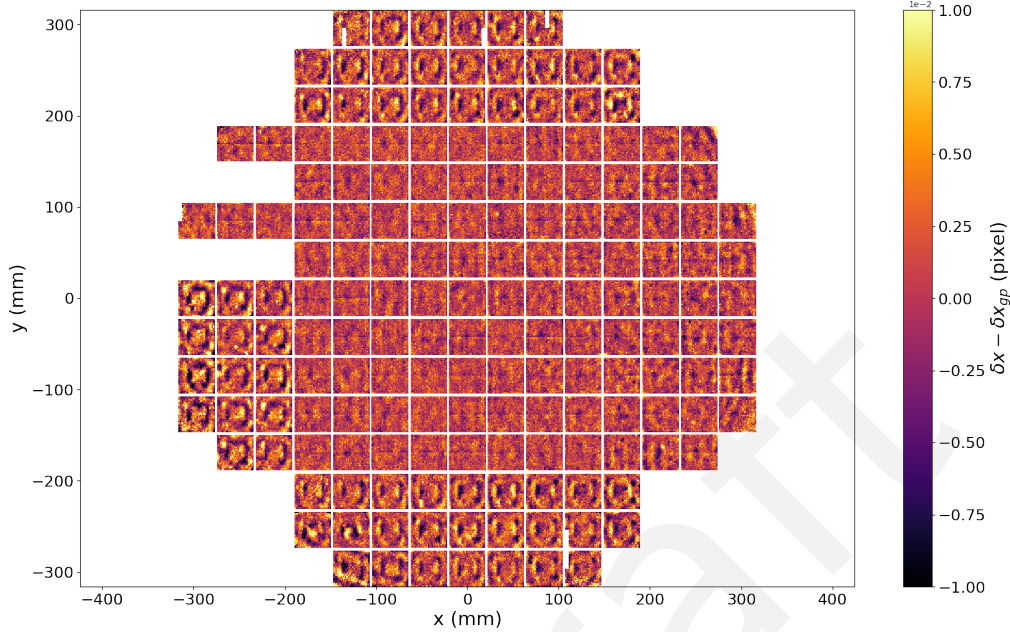


FIGURE 13: Mean astrometric residuals across the focal plane in X (left) and Y (right) directions. The spatial structure is consistent with atmospheric turbulence and small chip-level distortions.

#### 10.1.4 Summary

Astrometric repeatability with LSSTCam currently achieves approximately 10 mas precision, consistent with design specifications in regions with focal-plane-scale dithers. Residuals at the single-visit level are dominated by atmospheric turbulence and are well described by a Gaussian-process model that reduces scatter by about a factor of two. Fine-scale detector distortions are now measurable and are being folded into updated calibration models. A refined, on-sky camera distortion model has been adopted for single-frame processing and continues to improve the overall geometric calibration of the system. Future work will integrate DCR fitting, parallaxes, and the Gaussian-process atmospheric model directly into the global solution for DR1.



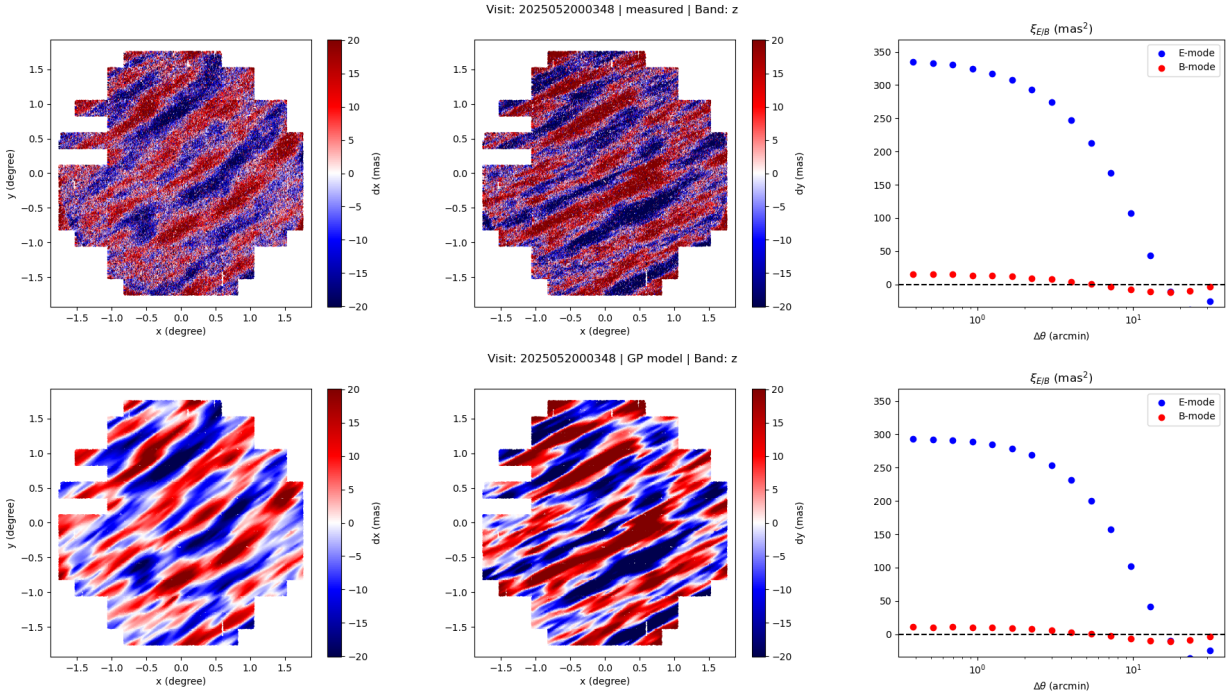


FIGURE 14: Gaussian-process modeling of atmospheric turbulence. The model captures large-scale correlated patterns in the residuals and reduces single-visit astrometric scatter by about 50%.

## 10.2 Photometry

- Figure: histogram of photometric repeatability for ensemble of visits; panel for each band?
- Figure: illumination correction
- Figure: average photometric residuals in focal plane coordinates for ensemble of visits; maybe a two-panel figure to show full focal plane and an individual detector
- Any other correlations of photometry that are worth exploring further (e.g., residuals w/ respect to stellar color, stellar flux, airmass)

Photometric calibration establishes the flux scale uniformity across the focal plane and over time, providing the foundation for all downstream science measurements. The LSSTCam system now achieves internal photometric repeatability at or below the 5 millimag (mmag) level, consistent with design requirements.



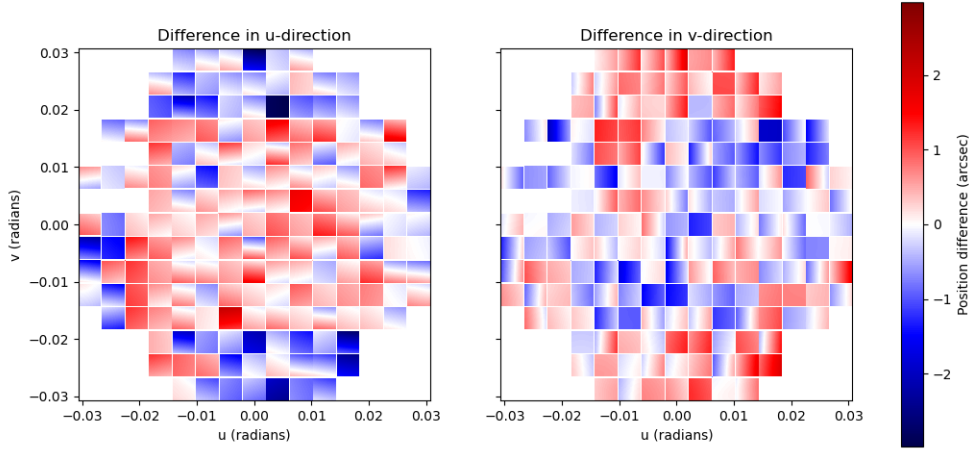


FIGURE 15: Comparison between the pre-commissioning camera model and the astrometry-derived distortion model. Residuals after removing a first-order affine term reveal fine-scale chip-to-chip differences and sensor-dependent trends.

### 10.2.1 Reference Catalog and Initial Zeropoints

The first stage of the calibration uses the MONSTER reference catalog (Ferguson et al., DMTN-277, DMTN-277), a composite all-sky dataset cross-calibrated from SkyMapper, Pan-STARRS, Gaia XP, and other surveys. Each LSSTCam detector receives an individual zeropoint solution by matching instrumental fluxes to the reference catalog. This per-detector calibration already delivers sub-percent photometric repeatability in the *griz* bands, as shown in These initial zeropoints are used for prompt processing, which does not include a global calibration step.

### 10.2.2 Global Forward Calibration

The Forward Global Calibration Method (`fgcmca1`) combines all visits to produce a self-consistent photometric solution that includes illumination and chromatic corrections. This method jointly fits the atmosphere, instrumental throughput, and detector response across the focal plane. The resulting photometric repeatability is 4–5 mmag in all bands (*ugrizy*), meeting the LSST photometric uniformity requirement (Fig. 17).

At this precision, the observed scatter is approaching the limit set by Poisson noise in the stellar measurements themselves. The intrinsic calibration precision is therefore likely closer

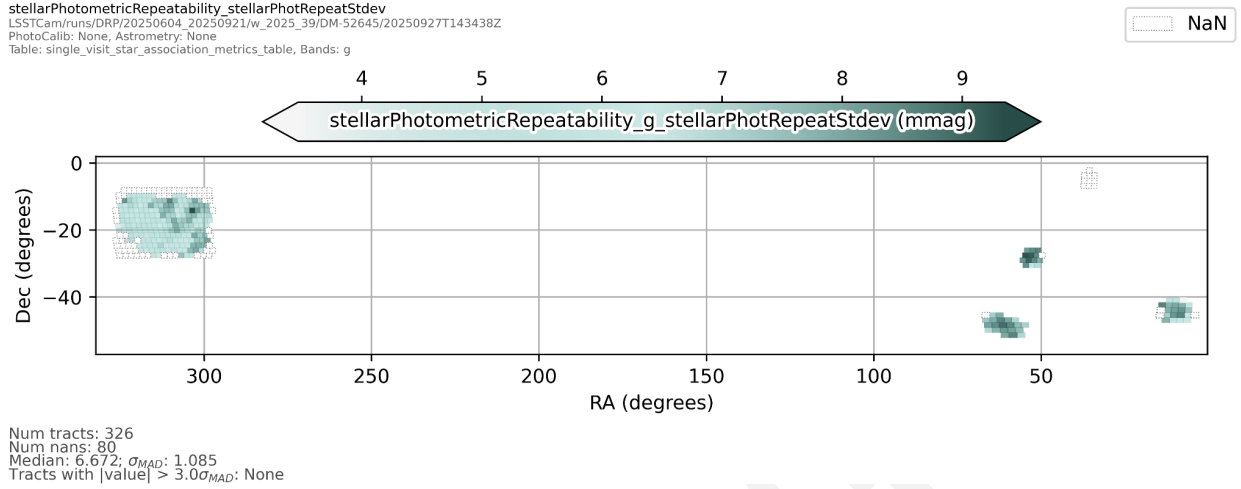


FIGURE 16: Per-detector zeropoint calibration using the MONSTER reference catalog. The preliminary calibration achieves better than 1% repeatability for bright, isolated sources in the *griz* bands.

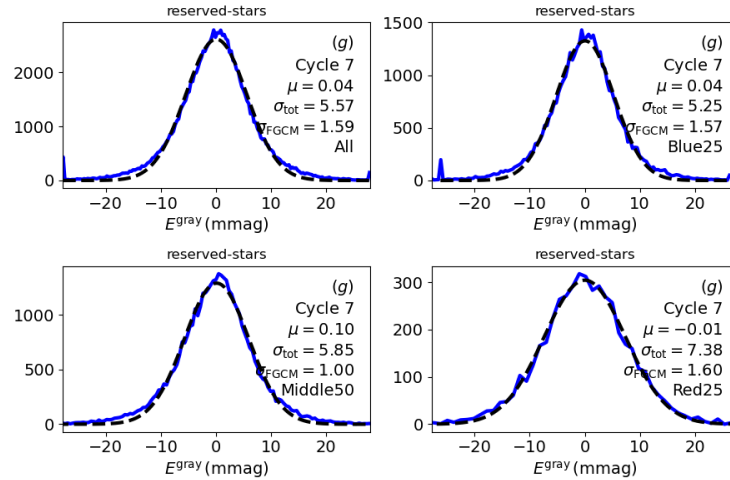


FIGURE 17: Photometric repeatability before and after application of the Forward Global Calibration Method (*fgcmcal*). The global solution achieves 4–5 mmag internal repeatability across all bands.

to the 2 mmag level.

### 10.3 Chromatic Response Across the Focal Plane

The chromatic response of the LSSTCam focal plane varies with both detector type and filter transmission. The effect is strongest in the *g* band, where the hybrid focal plane combines ITL and e2v sensors with slightly different quantum efficiency curves. Figure 18 com-

compares the predicted chromatic response—based on laboratory filter scans and detector QE measurements—to the measured on-sky response derived from stellar photometry.

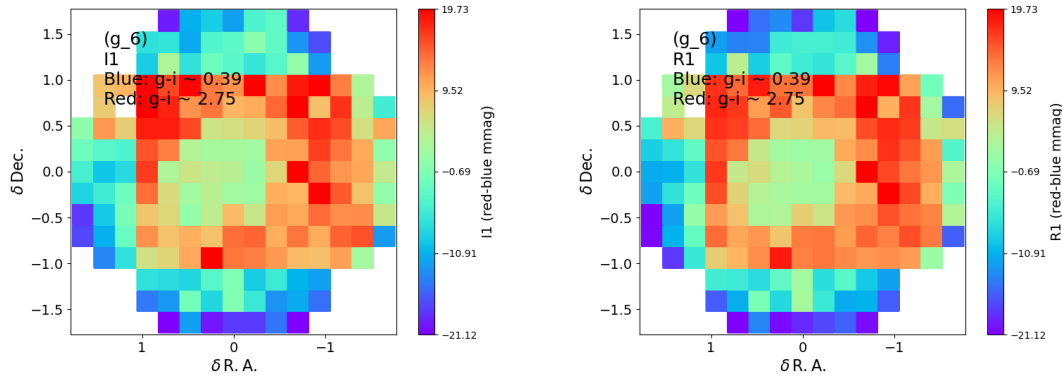


FIGURE 18: Predicted (left) and measured (right) chromatic response across the  $g$ -band focal plane. The measured variation is within  $\pm 20$  mmag, demonstrating excellent agreement with the predicted response. Accurate modeling of this chromatic structure is critical for maintaining uniformity at the sub-percent level.

The strong correspondence between the measured and predicted patterns indicates that the physical modeling of the detector and filter system is accurate at the level required for precision photometry. Incorporating these chromatic corrections into `fgcmcal` ensures that color-dependent throughput effects are accounted for in the final photometric solution.

### 10.3.1 Summary

LSSTCam photometric calibration now achieves internal repeatability at or below 5 mmag, comfortably meeting design requirements. Per-detector zeropoints using the MONSTER catalog already reach sub-percent precision, while the global `fgcmcal` solution provides 4–5 mmag repeatability across all bands. Measured chromatic response maps agree closely with predictions, validating the laboratory throughput models and confirming the accuracy of the chromatic correction applied in the pipeline. Future work will focus on refining illumination corrections and incorporating updated reference catalogs for the final DR1 global calibration.

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## C Acronyms

Acronym	Description
ADC	atmospheric dispersion corrector

AST	NSF Division of Astronomical Sciences
AURA	Association of Universities for Research in Astronomy
CBP	Collimated Beam Projector
CCD	Charge-Coupled Device
DCR	Differential Chromatic Refraction
DE-AC02	Department of Energy contract number prefix
DMTN	DM Technical Note
DOE	Department of Energy
DP2	Data Preview 2
DR1	Data Release 1
DRP	Data Release Processing
FWHM	Full Width at Half-Maximum
HEALPix	Hierarchical Equal-Area iso-Latitude Pixelisation
HSC	Hyper Suprime-Cam
ISR	Instrument Signal Removal
ITL	Imaging Technology Laboratory (UA)
LED	Light-Emitting Diode
LSR	LSST System Requirements; LSE-29
LSST	Legacy Survey of Space and Time (formerly Large Synoptic Survey Telescope)
LSST-DA	LSST Discovery Alliance
LSSTCam	LSST Science Camera
LVV	LSST Verification and Validation
LWS	Light-Wind Screen
M1	Primary Mirror
M2	Secondary Mirror
M3	Tertiary Mirror
NSF	National Science Foundation
OSS	Observatory System Specifications; LSE-30
PSF	Point Spread Function
PTC	Photon Transfer Curve
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
QE	quantum efficiency
RMS	Root-Mean-Square

RTN	Rubin Technical Note
SLAC	SLAC National Accelerator Laboratory
SV	Science Validation
TLS	Transport Layer Security
TMA	Telescope Mount Assembly
WCS	World Coordinate System
XP	B or R Photometry (Gaia)

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