Vera C. Rubin Observatory
Systems Engineering

An Interim Report on the ComCam On-Sky Campaign

Many authors

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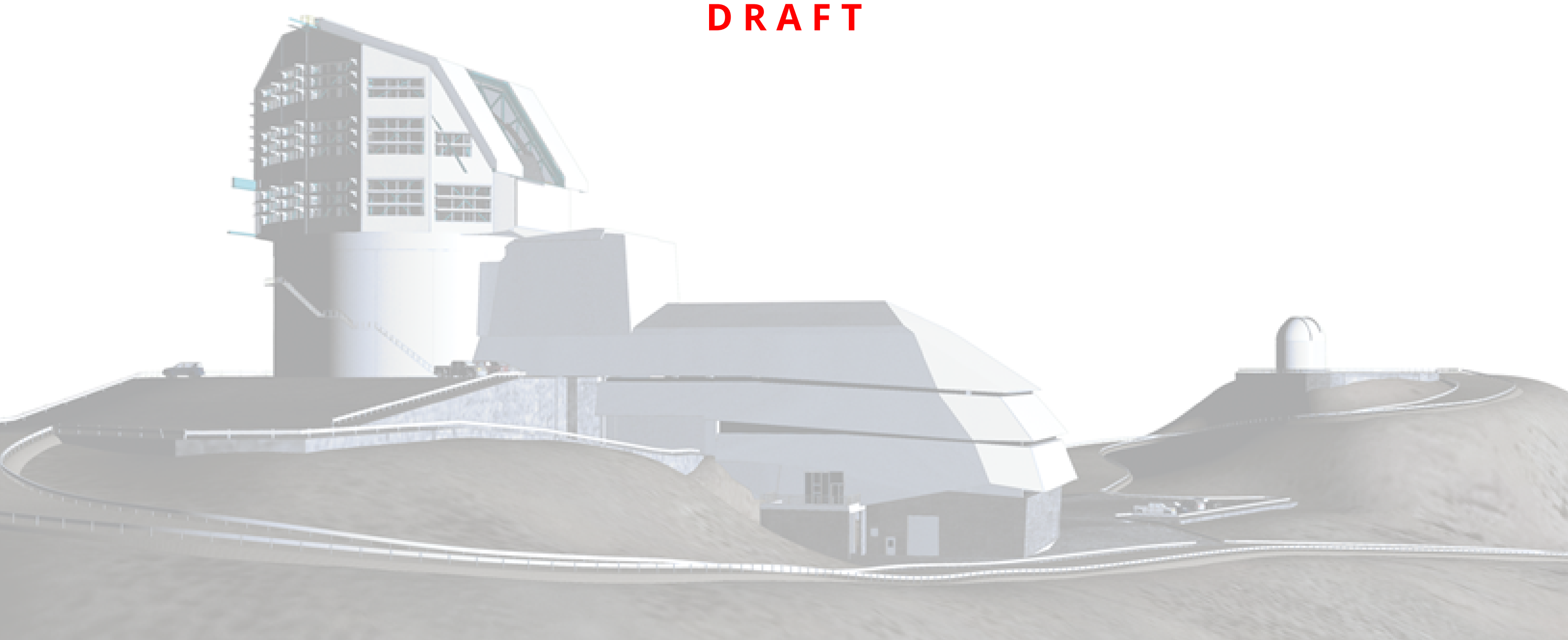

Abstract

A summary of what we have learned from the initial period of ComCam observing

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An Interim Report on the ComCam On-Sky Campaign

1 Introduction

The Vera C. Rubin Observatory on-sky commissioning campaign using the Commissioning Camera (ComCam) began on 24 October 2024 and is forecasted to continue through mid-December 2024. This interim report provides a concise summary of our understanding of the integrated system performance based tests and analyses conducted during the first weeks of the ComCam on-sky campaign. The emphasis is distilling and communicating what we have learned about the system. The report is organized into sections to describe major activities during the campaign, as well as multiple aspects of the demonstrated system and science performance.

1.1 Charge

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

- **Rehearse workflows for collaboratively developing documentation** to describe our current understanding of the integrated system performance, e.g., to support the development of planned Construction Papers and release documentation to support the Early Science Program [RTN-011]. This report represents an opportunity to collectively exercise the practical aspects of developing documentation in compliance with the policies and guidelines for information sharing during commissioning [SITCOMTN-076].
- **Synthesize the new knowledge** gained from the ComCam on-sky commissioning campaign to inform the optimization of activities between the conclusion of the ComCam campaign and the start of the on-sky campaign with the LSST Camera (LSSTCam).
- **Inform the Rubin Science Community** on the progress of the on-sky commissioning campaign using ComCam.

Other planned systems engineering activities will specifically address system-level verification ([LSE-29] and [LSE-30]) using tests and analysis from the ComCam campaign. While the analyses in this report will likely overlap with the generation of verification artifacts for systems engineering, and system-level requirement specifications will serve as key performance benchmarks for interpreting the progress to date, formal acceptance testing is not an explicit goal of this report.

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 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 Nov 2024: Define charge
- 4 Dec 2024: First drafts of report sections made available for internal review
- 11 Dec 2024: Revised drafts of report sections made available for internal review; editing for consistency and coherency throughout the report
- 18 Dec 2024: Initial version of report is released

Warning: On-sky Pixel Image Embargo

All pixel images and representations of pixel images of any size field of view, including individual visit images, coadd images, and difference images based on ComCam commissioning on-sky observations must be kept internal to the Rubin Observatory Project team, and in particular, cannot be included in this report. Embargoed pixel images can only be referenced as authenticated links. See [SITCOMTN-076] for details.

2 System Performance Analysis

3 Active Optics System Commissioning

The goals for commissioning of the Active Optics System (AOS) with ComCam are to demonstrate that we can align the telescope optics, determine and correct for optical aberrations using the hexapods and bending modes for M2 and M1M3, and apply these corrections as a closed loop system. A stretch goal is to demonstrate that, for the limited field-of-view of ComCam, we can meet the image quality requirements of the LSST system (i.e., with the optical system delivering less than 0.4 arcseconds to the image quality budget) and do so consistently as a function of elevation and temperature. We have achieved many of these goals, but there are still significant challenges in delivering seeing limited images consistently as a function of variable observing conditions.

AOS commissioning started on 2024-10-24 with the first ComCam images delivering a 1.7 arcsecond full-width half-maximum (FWHM) image quality. This is a testament to the exceptional metrology work of the engineering and optical teams during assembly and to the optimization of the Look-Up Table (LUT) for all the active optics components using the laser tracker data as well as mirror force balance data throughout 2024.

Sub-arcsecond image quality was achieved on the night of 2024-11-06, with a best image quality of 0.65 arcsecond FWHM on the night of 2024-11-15. Corrections for the optical aberrations have been achieved using two independent approaches; the TIE wavefront estimation algorithm, which is an inversion method, and the Danish wavefront estimation algorithm, which is a forward modeling method. The AOS system was able to achieve closed-loop corrections across varying elevations and stellar densities, with most optical modes utilized (excluding the three highest-order modes on M2). Closed-loop operations have been run autonomously by the observing specialists to show that the scripts and procedures are mature. Preparations are underway to prototype a fully autonomous survey-mode triplet-taking block before the conclusion of ComCam's on-sky operations.

While we have demonstrated that Rubin can achieve the optical performance requirements for the AOS system there are significant challenges in meeting the optical performance requirements consistently as a function of temperature and elevation. It is not currently clear which aspects of the optical system are limiting its performance but the AOS team is working to understand the source of high levels of defocus and some amount of astigmatism that are present in the Zernike measurements. The team is also working to improve the computational efficiency of the system, which currently takes 5 minutes to complete a closed-loop iteration.

After significant development, the AOS algorithms appear robust for a range of source densities and image qualities. A number of failure modes of the AOS software are present and being investigated. These include failures in processing images through Rapid Analysis when donuts cannot be detected on all sensors, and difficulty in measuring the wavefront when the images are significantly defocused (e.g., when the intra or extra focal images appear in focus). The AOS team is working to improve the robustness of the system to monitor these and other failure modes.

Figure 1 shows the FWHM delivered by the optical system (black line) as we correct the alignment and bending modes of the mirrors and camera over the nights 2024-11-25 to 2024-12-01. The FWHM is estimated from the Zernike amplitudes measured from out-of-focus donuts. The grey and blue lines are the 500nm and zenith corrected image qualities measured by SOAR and from the Rubin images respectively. The dashed green line is the 0.25 arcseconds image quality requirement for the telescope optics. From these measurements the AOS system is shown capable of meeting the image quality requirements. Delivering this consistently and without significant fine tuning is the current focus for the AOS team.

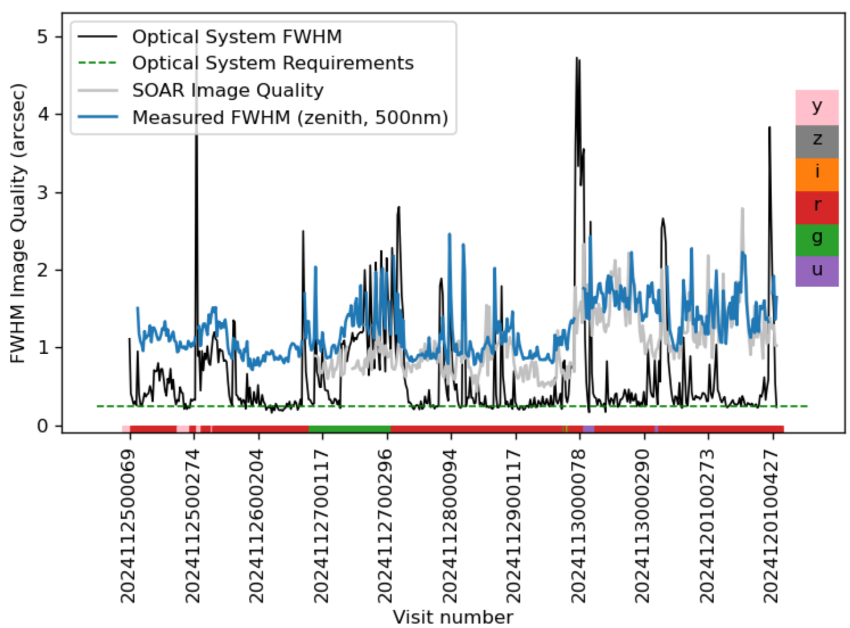

FIGURE 1: The FWHM delivered by Rubin (blue), the image quality from Rubin's optical system estimated from the AOS (black), and the image quality measured by SOAR (gray). The Rubin and SOAR measured FWHMs are corrected to 500nm and zenith.

3.1 Initial Alignment

Initial alignment of the AOS utilizes an updated laser tracker nominal frame based on a Final Element Analysis Model. This ensures that the system is brought into focus prior to the start of observations. Combined with a measurement of the impact of gravity on the telescope, these refinements simplified the alignment process, demonstrating the value of accurate laser tracker data. Once we were able to get on-sky images using curvature wavefront sensing, we finalized the initial state of the hexapods position to ensure a well aligned system at the start of the night. Work is ongoing to understand the stability of the initial hexapod and bending mode positions across nights to determine how well we can predict the configuration of the AOS system at the start of each night.

3.2 Coordinate Systems

During the first few weeks, significant effort was devoted to understanding and refining coordinate systems at different steps of the active optics closed-loop process (wavefront sensor estimation and correction calculation). We conducted the test by introducing one degree of freedom at a time and correcting for it. We identified a rotation discrepancy in ComCam's installation compared to the expected design, requiring adjustments in our alignment procedures. The coordinate discrepancies were resolved empirically in the early AOS tests. Based on these data the expected as-delivered coordinate system(s) for the mirrors, hexapods, and sensors will need to be derived from first principles and validated prior to AOS observations with LSSTCam.

3.3 Wavefront estimation

The wavefront estimator proved robust across diverse observing conditions of seeing, mount elevation and a few filters (r,i and y band) On dense fields such as 47 Tuc or NGC 253, the estimator provided accurate results for all sensors except the central one. Comparison of observed PSFs with simulations confirmed the accuracy of Rubin's ray-tracing software, `Batoid`.

Wavefront estimation and closed-loop convergence has been demonstrated using `TIE` and `Danish`. Other advancements include the implementation of sparse Zernikes, allowing selective inclusion of Zernike polynomial terms while minimizing cross-contamination of modes with identical azimuthal dependencies.

Despite delivering good optical quality, Zernike measurements indicate persistently high levels of defocus and some amount of astigmatism. We are continuing to investigate the source and impact of these measurements.

3.4 Closed Loop

Following resolution of initial issues with the AOS pipelines, closed-loop operations were achieved across varying elevations and filters (u, g, r, i, z, and y). Most optical modes were utilized, excluding the three highest-order modes on M2. Consistency in results across nights confirmed the need for further refinement of the LUT. In favorable seeing conditions, the system achieved sub-arcsecond image quality, with FWHM as low as 0.65 arcseconds. Autonomous closed-loop operations were run by observers, demonstrating the maturity of the system.

The closed loop process still takes 5min often requiring 5 or more iterations. The best performance for the closed loop achieved convergence in two iterations but delivering this consistently has not been achieved and tuning the closed-loop gain and making further adjustments to improve computational efficiency remains a priority for the team.

3.5 LUT

The LUT underwent initial validation across elevations, azimuths, and rotator angles, leading to incremental improvements. While these updates enhanced performance, further refinements are needed to address second-order dependencies. Insights from ComCam data will inform these efforts, ensuring readiness for LSSTCam, which may present distinct challenges due to its larger focal plane and optical system.

3.6 Lessons Learned and Next Steps

Lessons Learned - Coordinate Systems: Precision and methodical testing of coordinate systems are essential. Starting with foundational tests and incrementally increasing complexity ensures reliability. - Observer Training: Comprehensive documentation, including a subsystem overview and closed-loop procedures, significantly enhances observer support capabilities. - Closed-Loop Performance: Iterative testing and tuning of the closed-loop system are essential for delivering a consistently high image quality as a function of temperature, elevation, and other observing conditions. Achieving this performance consistently and without significant fine tuning will be a significant challenge. - Engagement and Morale: Fun and engaging night summaries boost team morale, fostering a collaborative and motivated work environment. - Transferability: Some ComCam lessons learned, particularly LUT and coordinate system adjustments, will not fully transfer to LSSTCam, requiring repeated validation.

Next Steps - Conduct step-by-step closed-loop validations for LSSTCam, validating signs and rotations for intentional perturbations. - Collaborate with the Camera Team to anticipate and mitigate known camera tilts. - Implement and validate tests tailored to LSSTCam's larger focal plane dimensions. - Prepare RubinTV and donutViz for full-array LSSTCam mode and automate its execution for all triplet-taking sequences. - Adapt MTAOS to run as a continuous background task, supporting survey-mode operations. - Optimize the AOS pipeline for speed, including binning and ISR performance improvements.

4 Image Quality

5 Data Production

6 Calibration Data

7 Science Pipelines Commissioning Observations

8 Throughput for Focused Light

9 Delivered Image Quality and PSF

10 Istrument Signature Removal

11 Low Surface Brightness

12 Astrometric Calibration

13 Photometric Calibration

14 Survey Performance

15 Sample Production

16 Difference Image Analysis: Transience and Variable Objects

17 Difference Image Analysis: Solar System Objects

18 Galaxy Photometry

19 Weak Lensing Shear

20 Crowded Stellar Fields

21 Image Inspection

A References

[SITCOMTN-076], Bechtol, K., on behalf of the Rubin Observatory Project Science Team, S.R., 2024, Information Sharing during Commissioning, URL `https://sitcomtn-076.lsst.io/`, Vera C. Rubin Observatory Commissioning Technical Note SITCOMTN-076

[LSE-29], Claver, C.F., The LSST Systems Engineering Integrated Project Team, 2017, LSST System Requirements (LSR), URL `https://ls.st/LSE-29`, Vera C. Rubin Observatory LSE-29

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B Acronyms

Acronym	Description
2D	Two-dimensional
ADU	Analogue-to-Digital Unit
AOS	Active Optics System
CBP	Collimated Beam Projector
CNN	Convolutional Neural Network
COSMOS	Cosmic Evolution Survey
DC2	Data Challenge 2 (DESC)
DECaLS	The Dark Energy Camera Legacy Survey
DECam	Dark Energy Camera
DES	Dark Energy Survey
DIA	Difference Image Analysis
DIMM	Differential Image Motion Monitor
DM	Data Management
DR10	Data Release 10
DR2	Data Release 2
DRP	Data Release Production
EDFS	Euclid Deep Field South
FGCM	Forward Global Calibration Model
FWHM	Full Width at Half-Maximum
GBDES	Gary Bernstein Dark Energy Survey
HSC	Hyper Suprime-Cam
HST	Hubble Space Telescope
ISR	Instrument Signal Removal
ITL	Imaging Technology Laboratory (UA)
JPL	Jet Propulsion Laboratory (DE ephemerides)

LATISS	LSST Atmospheric Transmission Imager and Slitless Spectrograph
LSB	Low Surface Brightness
LSST	Legacy Survey of Space and Time (formerly Large Synoptic Survey Telescope)
LUT	Look-Up Table
M2	Secondary Mirror
ML	Machine Learning
MODTRAN	MODerate resolution TRANsmission model
NGC	New General Catalogue
PSF	Point Spread Function
QA	Quality Assurance
QE	quantum efficiency
RA	Risk Assessment
RMS	Root-Mean-Square
RTN	Rubin Technical Note
SDSS	Sloan Digital Sky Survey
SE	System Engineering
SED	Spectral Energy Distribution
SOAR	Southern Astrophysical Research Telescope
SSI	Synthetic Source Injection
SSP	Solar System Processing
TBC	To Be Confirmed
TMA	Telescope Mount Assembly
ZTF	Zwicky Transient Facility