Large Synoptic Survey Telescope (LSST)

System AI&T and Commissioning Plan

Chuck Claver
and
The LSST Commissioning Planning Team

LSE-79 (rel4.0)

Latest Revision: November 2, 2018

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<th>Date</th>
<th>Description</th>
<th>Owner name</th>
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<td>1.0</td>
<td>7/8/2011</td>
<td>Initial version</td>
<td>Chuck Claver</td>
</tr>
<tr>
<td>1.1</td>
<td>8/2/2011</td>
<td>Added activity sequences for DM pipeline testing and verification; added staffing tables by year-type at the commissioning activity centers.</td>
<td>C. Claver</td>
</tr>
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<td>1.2</td>
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<td>Updated schedule and resources to PMCS baseline</td>
<td>C. Claver</td>
</tr>
<tr>
<td>2.0</td>
<td>9/15/2012</td>
<td>Major revision to address changes in Camera delivery, addition of a Commissioning Camera and overall project schedule</td>
<td>C. Claver</td>
</tr>
<tr>
<td>2.1</td>
<td>9/15/2013</td>
<td>Reformat to comply with standard project document formatting.</td>
<td>C. Claver</td>
</tr>
<tr>
<td>2.2</td>
<td>9/20/2013</td>
<td>Additional edits by S. Wolff. Update staffing levels per PMCS-3</td>
<td>C. Claver</td>
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<td>2.3</td>
<td>10/5/2013</td>
<td>Updated requirements for Operation Readiness</td>
<td>C. Claver</td>
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<tr>
<td>10/8/2013</td>
<td></td>
<td>Implementation of 10/5 revision per LCR-158</td>
<td>Robert McKercher</td>
</tr>
<tr>
<td>1/7/2017</td>
<td></td>
<td>Large-scale updates (including title change to include system AI&amp;T) for January 2017 Commissioning Review.</td>
<td>C. Claver</td>
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<tr>
<td>7/25/2017</td>
<td></td>
<td>Updated with EPO information</td>
<td>B. Emmons / C. Claver</td>
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<tr>
<td>3.0</td>
<td>9/20/2017</td>
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<td>C. Claver</td>
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<tr>
<td>6/1/2018</td>
<td></td>
<td>Updates to schedule and refrigeration path finder description.</td>
<td>C. Claver</td>
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<tr>
<td>10/01/2018</td>
<td></td>
<td>Added reference to Commissioning Execution Plan – LSE-390 and reference to decouple budget and</td>
<td>C. Claver</td>
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The LSST System AI&T and Commissioning Plan

Acronyms and Definitions of Terms

Standard LSST Acronyms and Definitions

- Glossary of Abbreviations (Document-11921)
- Glossary of Definitions (Document-14412)

Acronyms and Definitions Specific to this Document

- AI&T: Assembly Integration and Test
- CCT: Core Commissioning Team
- LSSTCam: The Department of Energy (DOE) designation for the MIE-funded camper for LSST
- ORR: Operations Readiness Review
- SVT: Science Verification Team
- TCT: Technical Coordination Team

Reference Documents

- LSST Commissioning Execution Plan (LSE-390)
- Commissioning Camera Reference Design (LSE-199)
- Hazard Analysis Plan (LPM-49)
- LSST System Requirements (LSR) (LSE-29)
- Observatory System Specifications (OSS) (LSE-30)
- Project Execution Plan (LPM-54)
- Risk and Opportunity Management Plan (LPM-20)
- Safety Policy (LPM-18)
- Science Requirements Document (SRD) (LPM-17)
- Summit Site Safety, Health and Environmental Plan (LPM-114)
- Verification and Validation Process (LSE-160)

Document Scope and Purpose

This document describes the LSST Commissioning Plan that carries the National Science Foundation (NSF) LSST and Department of Energy (DOE) LSSTCam funded projects from the end of systems fabrication through to operations readiness. This plan includes a definition of four (4) distinct phases of commissioning, principal objectives for each phase, key activities and tasks, and the management
structure to carry out the work described. Lastly, we provide the criteria by which the project will be judged as “operation ready.”

This document:

1. Defines the overall management structure, lines of authority, oversight, and data distribution policies that will be in place for the two-year commissioning period;
2. Defines the boundary conditions that separate activities owned by subsystem assembly, integration and test (AI&T) and those that are part of this commissioning plan with appropriate schedule milestones for subsystem hand-off and acceptance;
3. Describes the necessary pre-conditions that each of the three subsystems – Camera, Telescope and Site (T&S), and Data Management (DM) along with the Observatory Control system (OCS) – must satisfy prior to the start of the two-year commissioning period;
4. Summarizes the expected remaining technical integration activities and tests that must be accomplished during the Early and Full System AI&T periods;
5. Outlines the verification methods that will be used to show compliance with the survey performance detailed in the LSST Science Requirements Document (SRD) (LPM-17) and the LSST System Requirements (LSR) (LSE-29);
6. Describes the specific tests, measurements, and analyses that will be performed to show compliance with the SRD/LSR;
7. Defines the criteria, methods, and review process that establish the readiness of LSST for operations; and
8. Outlines contingency plans in the event key preconditions are not met.

Note: The plan and schedule presented in this document is formally captured in the Projects Primavera P6 PMCS baseline including the sequencing and logical dependencies of described activities. Exact dates implied in this document are subject to change depending on the use of Project schedule contingency (see Figure 2 below) prior to the onset of activities described herein. When referring to this document the reader should consult with the most recent Project P6 PMCS baseline for accurate dates. Further, resource loading and budget implications are also captured in the Project P6 PMCS baseline and are summarized in the LSST Commissioning Execution Plan (LSE-390). Changes to budget and resource allocations will be reflected in the Project P6 PMCS baseline and LSE-390. The intent is to decouple changes in budget and resource allocation from changes in the Commissioning Plan logic presented in this document.
The LSST System AI&T and Commissioning Plan

Executive Summary

The Commissioning Phase of the LSST Project is the final stage in the combined NSF and DOE LSST construction project. Commissioning includes the full system assembly, integration and test (AI&T) efforts as well as the science verification activities. This System AI&T and Commissioning Plan is driven by a combination of engineering and scientifically-oriented activities to show compliance with technical requirements and readiness to conduct science operations (acquiring data, processing data, and serving data and derived data products to users). LSST System AI&T and Commissioning will be carried out over four phases of activity:

- **Phase-0** Pre-commissioning preparations (work breakdown structure [WBS] 06C.02.02);
- **Phase-1** Early System AI&T with a commissioning camera (ComCam) (WBS 06C.02.03);
- **Phase-2** Full System AI&T when the LSSTCam is shipped to Chile, integrated on the telescope and the data management system (DMS) is exercised with full scale data (WBS 06C.02.04); and
- **Phase-3** Science Verification where a series of mini-surveys are used to characterize the system with respect to the survey performance specifications in the SRD/LSR and functionality of the Science/Public User Interfaces, leading to operations readiness (WBS 06C.02.05). The Science Verification Phase concludes with an Operations Readiness Review (ORR).

It is also important to understand that the various commissioning phases represent a continuum of increasing system functionality and capability and that the plan presented here is meant to be flexible to take full advantage of opportunities as they occur.

![Figure 1: The timeline of the Commissioning WBS 06C.02 to Level 4.](image-url)
LSST System AI&T and Commissioning activities are supported by both DOE and NSF funding (See LSE-390 for a description of agency roles and responsibilities). On the NSF side the funding to support these activities is part of the Major Research Equipment and Facilities Construction (MREFC) award. On the DOE side, the fabrication of the LSSTCam is supported by Major Item of Equipment (MIE) funding to the point where the LSSTCam has been verified to meet its requirements at SLAC. Shipping of the LSSTCam to Chile and all subsequent integration and commissioning activities related to LSSTCam are supported by DOE Commissioning (DOE-COM) funds.

Each of the three principal subsystems – Data Management, Camera, and Telescope & Site, along with the Observatory Control System – must pass their respective acceptance tests demonstrating they have met their respective pre-conditions to enter System AI&T and Commissioning (see Section 3). Education and Public Outreach (EPO) must pass their private beta user acceptance testing of interfaces and tools using simulated and legacy survey data to enter Commissioning. The transition from the Project “construction/fabrication” phase to major integration and commissioning activities starts with the three-mirror telescope having demonstrated nominal on-axis image quality with a Shack-Hartmann camera followed by Early System AI&T with ComCam resulting in “Engineering First Light”. This “Engineering First Light” occurs approximately five (5) years after the start of MREFC construction (see Figure 1). The full science camera will be delivered to the observatory approximately nine (9) months later to begin the Full System AI&T phase. At the start of Early Integration and Test, the Data Center at the Base Facility in La Serena, Chile will be fully integrated and ready to accept and process ComCam data. The cloud-based EPO Data Center will be fully integrated and ready to store and use the public subset of ComCam data. The Data Management will have delivered functional pipelines for both Alert production and Data Release Production. These pipelines will have extensively tested using legacy survey data (e.g. CFHTLS, SDSS, Subaru HyperSurpime Camera, Zwicky Transient Factory among others) and detailed simulations. Additionally, the DM group will deliver progressively more capable services to support the transport, analysis and interaction with the data as integration and commissioning advance.

The LSST System Assembly, Integration and Test and Commissioning effort has been planned out over several phases (Figure 2Error! Reference source not found.). The first phase of commissioning under Early AI&T is designed to test and verify the system level interfaces using ComCam (see Sec. 5.1.1 and LSE-199 for description). During this period, the telescope active optics system will be brought into compliance with system requirements; the scheduler will be exercised and all safety checks verified for autonomous operation; and early DM algorithm testing will be performed with on-sky data from ComCam using the commissioning cluster at the Base Facility.

The second phase of activities under Full System AI&T is designed to complete the technical integration of the three principal subsystems and EPO, show full compliance with system level requirements as detailed in the Observatory System Specifications (OSS) (LSE-30) and system level interface control documents (ICDs), and provide full scale data for further DM/EPO software and algorithmic testing and development. System level requirements that flow directly to subsystems without any further derivation will be tested for compliance, at the subsystem level and below, under the supervision of Project Systems Engineering. This document includes the general approach and goals for these tests. It is expected that roughly four (4) months into the Full System AI&T phase the telescope and camera will be fully integrated and routinely producing science grade images over the full field of view (FOV), at which point “System First Light” will be declared.

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The third and final phase of activities under Science Verification is designed to fully characterize the system performance specifications detailed in LSST System Requirements Document (LSE-29) and the range of demonstrated performance per the LSST Science Requirements (LPM-17). These activities are based on the measured “On-Sky” performance and informed simulations of the LSST system. This document discusses the general philosophy and structure of the observational verification. The detailed description of the observational programs used for science verification will be covered in the Science Verification Matrix. An Operations Readiness Review (ORR) defines the end of the Science Verification phase, when the project will present results of the commissioning effort to the NSF and a panel of community representatives. The ORR will signify the end of construction and the conclusion of the MREFC project and DOE Commissioning (DOE-COM).

Figure 2: A high level view illustrating the various phases of the LSST Construction project and the transition into operations.

Both the Early and Full System AI&T phase start with a series of technical activities aimed at making the hardware interactions work. These technical periods are followed by periods of “sustained observing” where bulk data will be produced to exercise the data processing, software algorithms, and user interfaces. It is the Project’s intent to make this bulk data and science verification mini-surveys available to the LSST data rights community for further investigations on a best effort basis along with a public subset for EPO product verification purposes. At the time of this writing, a formal commissioning data policy is in development and will be released well in advance of the start of integration and commissioning activities.

The Commissioning Execution Plan (LSE-390) provides a summary of the explicit roles and responsibilities between the two funding agencies (NSF and DOE) support the commissioning scope of work.
1 Scope, Definitions and Planning Strategy

The LSST System AI&T and Commissioning Plan covers the final system level assembly, integration and testing (AI&T) of the three principal subsystems (Telescope, Camera and Data Management) as well as Education and Public Outreach (EPO).

1.1 Commissioning Plan Inputs

The scope of procedures, activities and schedule contained within the System AI&T and Commissioning Plan are derived from the following inputs while adhering to the LSST Safety Policy (LPM-18), the Summit Site Safety, Health and Environmental (SHE) Plan (LPM-114) and other applicable safety procedures:

- Requirements for Operations Readiness (section 1.1.1);
- System level Verification Plan per LSE-160 including systems modeling language (SysML) based verification event sequences and logic (section 1.1.2);
- Subsystem assembly, integration and test plans (T&S: LTS-104; Camera: LCA-40; DM: LDM-502; EPO: LEP-41) defining what will be completed (see section 4 on subsystem prerequisites) and what AI&T activities will remain into the Commissioning Phase;
- Scientifically motivated system performance characterization (section 6);
- Technical optimization of system operations (section 1.1.4);
- Emergent technical issues (section 3.6); and
- Roles and Responsibilities between the funding agencies (NSF and DOE) as described in LSE-390 – The LSST Commissioning Execution Plan.

1.1.1 Requirements for Operations Readiness

The primary high-level strategic input to developing this System AI&T and Commissioning Plan are the requirements for the Operations Readiness Review (ORR). At the conclusion of the Commissioning Phase of the LSST construction project an ORR will be undertaken by an external panel, jointly appointed by the DOE and NSF, in consultation with the LSST Project Team. The ORR also signifies the end of the NSF MREFC funded construction project and DOE Commissioning. In order for the LSST project to declare that the construction project is complete and is ready to enter its Operations Phase, the Project shall demonstrate that following requirements have been met:

1. The project team shall demonstrate that the integrated LSST system (Camera, Telescope & Site and Data Management subsystems) as well as the Education and Public Outreach (EPO) system have met the technical specifications enumerated in the LSST Observatory System Specifications (LSE-30);
2. The project team shall characterize and document the performance of the integrated LSST system with respect to the survey performance requirements and specifications enumerated in
the LSST System Requirements and Science Requirements Document (LSE-29 & LPM-17 section 3 respectively);

3. The project team shall conduct at least one Science Verification mini-survey that will be autonomously driven by the scheduler and will last at least 30 days;

4. The project team shall process the data from the one (or more) of the Science Verification mini-surveys to produce a Level 2 Data Release and make it available to the Commissioning Team through the DM Science User Interface as well as a subset for the EPO Public User Interface;

5. The project team shall demonstrate that the integrated LSST system can collect and process time-domain Level 1 data products, including the generation and distribution of alerts;

6. The project team shall demonstrate that the integrated LSST system can monitor and assess the quality of the data as it is being collected;

7. The project team shall demonstrate that the LSST community services and user interfaces can deliver data and data products;

8. The project team shall demonstrate that relevant metadata are being collected and archived;

9. The project team shall deliver a complete set of documented operational procedures and supporting technical documents needed to operate the LSST as a scientific facility for the purpose of conducting a 10-year survey; and

10. The project team shall deliver all reports documenting the as-built hardware and software including: drawings, source code, modifications, compliance exceptions, and recommendations for improvement.

Non-compliance exceptions to the above requirements will be considered following internal and external reviews of the assessed performance and operational impacts.

1.1.2 System Verification Planning & Analysis

The primary technical input to the System AI&T and Commissioning Plan is the System Verification Plan. The LSST System Verification process is described in LSE-160. Shown in Figure 3, the process traverses the entire span of the LSST Design, Development, and Construction projects, beginning with the identification of all the requirements and ending with the Operations Readiness Review (ORR).

This section focuses on the planning and analysis process steps directly related to the development of Verification Events and Scheduling, identified as steps 3 through 5 in Figure 3. These steps, while sometimes overlooked or skipped by projects, ensure that all requirements are mapped to Verification Events. Additionally, these planning and scheduling steps attempt to make efficient use of Verification Activities, with the goal of combining the verification of requirements into a concise number of Verification Events. This explicit review and analysis of the verification plans before scheduling events allows for like Verification Activities to be grouped, eliminating redundant activities, which ultimately saves the project cost and schedule.
An overview of Steps 3 through 5 is provided below in order to give context to the objects and stereotypes utilized during the SysML implementation.

1.1.2.1 Step 3: Verification Planning

Analysis conducted as part of the Verification Planning process ensures the following: requirements are verifiable early in the project’s lifecycle, thereby reducing the number of iterations required to refine the requirements to an acceptable level of fidelity; better estimates of the resources and effort needed to verify a given requirement, thereby improving the over cost and schedule estimates; and optimization of the verification effort by grouping similar verification activities into a smaller number of verification events.

The verification plan for each requirement consists of:

- **Verification Owner**: This is the functional team that has responsibility for conducting the verification activities.
- **Responsible Technical Authority**: This is the name of the individual (or role name of an individual) that has responsibility for developing and executing the verification plan. This person serves as the Point of Contact for all questions, concerns, and comments related to the particular verification plan.
- **Verification Method**: This identifies one of the four accepted methods for verification where the options are Test, Demonstration, Analysis, and Inspection.
- **Verification Level**: Options are Same as Requirement, where verification activities take place at the same hierarchical level as the requirement in question, Higher Level Assembly, where verification takes place at a higher level assembly, and Lower Level Assembly, where verification takes place at a lower level assembly.
• **Verification Requirement**: This is a statement that defines precisely what will be done to verify the requirement. If a test or demonstration is to be conducted, it should state what type of test or demonstration will take place (for example, a vibration test), where it will take place (if known), and if any special test equipment is required (special test equipment is defined as any equipment that is not typically available at the facility at which the test or demonstration will be conducted). It should also specify what project hardware and/or software is needed. If an analysis is to be conducted, the analysis tool should be specified as well as any boundary conditions and limiting assumptions that are relevant to the analysis.

• **Success Criteria**: This is a statement that defines the explicit pass/fail criteria. This statement should be clear enough that an independent third party observer should be able to determine if the verification event was successful or not. For performance and other quantitative requirements, the success criteria should include the specific value (or range), units, and any statistical information necessary. For inspections and demonstrations, the Success Criteria should state who the Designated Witness is that is approved to view the verification activity and provide an assessment of its results.

More than one Verification Method may be defined for a requirement if deemed necessary. In such a case, each method should be discussed in terms of the subsequent parameters. Each specific instance of a Verification Method is referred to as a Verification Activity.

1.1.2.2 **Step 4: Identify Task Interdependency**

The next step in the verification analysis process is to identify the interdependencies of the Verification Activities. Typically, after defining all of the Verification Activities during Verification Planning, one will notice that some Verification Activities can be naturally grouped and conducted at the same time. For instance, a group of Verification Activities may all require the same test hardware. In these cases, it may make sense to compile multiple Verification Activities into a Verification Event, which can result in cost and schedule savings for the program, as redundant or nearly redundant activities can be eliminated.

The mapping of Verification Activities into Verification Events must be well documented to ensure that no Verification Activities are forgotten and get overlooked. Verification Activities can then be sequenced to show predecessor/successor relationships, which then become key inputs to Verification Scheduling.

1.1.2.3 **Step 5: Schedule Verification Events**

Once Verification Activities are reviewed and grouped into Verification Events where appropriate, the Verification Events must be scheduled. Predecessor/Successor relationships are analyzed along with any additional constraints specified (such as availability of hardware or software needed) to create an integrated verification schedule. A reasonable amount of time for contingency should be factored into the overall schedule to account for Verification Activities that may not meet their Success Criteria on the first attempt, require rework, or are delayed due to hardware or software unavailability, etc.

1.1.3 **Implementation of the Verification Process**

LSST uses a model based systems engineering (MBSE) environment (utilizing the Systems Modeling Language – SysML) to capture requirements verification plans, grouping of verification activities into
events, and the sequencing of those verification events. The verification event sequences can then be exported and compared to the top-down plan developed in the project management controls system (PMCS) to ensure consistency. The follow sections describe this process.

All LSST project-controlled requirements relationships can now be made from Requirements to Verification Planning to Verification Events (see Figure 4).

![Figure 4: An example of using SysML and Model based Systems Engineering to map elements representing System Requirements (yellow) to Verification Requirements (teal) and subsequently on to Test Cases (purple).](image)

Each requirement has an associated Verification Plan element. Subsequently, like Verification Activities are mapped to Verification Events. The Test Case SysML element is used to model Verification Events. This SysML implementation step corresponds to step 3 in the LSST Verification and Validation Process (V&V) (LSE-160).

Associated Verification Events (Test Cases) are then sequenced on Activity Diagrams to show predecessor/ successor relationships, events that are conducted in parallel/ series, and any outside constraints that must be realized before a Verification Event can be executed (see Figure 5). The results of these Activity Diagrams are then used to validate or update the LSST’s Integrated Master Schedule for
the Commissioning period.

Figure 5: As part of the LSST verification process, derived test cases are sequenced using a SysML Activity Diagram. The left panel shows the sequencing of the image quality test cases from Figure 4 corresponding to step 4 in the analysis process. Further refinement of test cases (right panel) leads to procedures used to plan integration and commissioning activities.

As the verification plan matures, individual Verification Events can be further detailed to specify the individual steps and actions that must occur to execute a particular Verification Event. The resultant activity diagrams (Figure 5, right panel) are used as direct inputs by the Commissioning team for writing and planning detailed test and analysis procedures.

An important aspect of LSST’s V&V planning process is ensuring that it is capable of being integrated with LSST’s PMCS, which is utilized by the Project Management Office (PMO) to control and manage the Integrated Master Schedule (IMS) as well as to conduct Earned Value Management (EVM). The V&V Planning implementation methodology ties into the IMS (which utilizes Primavera P6) as shown in Figure 6.
The V&V Process ensures mapping of Verification Event Activities & Actions to P6 Primavera activity steps. Each of the individual Actions on the Activity Diagram can be mapped as steps within the IMS activity. This allows the project to take earned value credit on an action-by-action basis for this activity. Additionally, this explicit mapping ensures that each requirement will be formally verified by a scheduled, costed, and resource loaded PMCS activity.

This step is where the bottom-up Verification Planning and top-down IMS commissioning schedule development approaches merge. The SysML-based Verification Event sequent integration acts as an independent assessment of the schedule’s completeness. The schedule will be refined and updated if additional verification events, constraints, or predecessor/successor relationships are uncovered through the course of developing detailed V&V plans. This SysML implementation step corresponds to step 5 in the LSST V&V Process.

1.1.4 Scientifically Motivated System Characterization

The science-driven requirements for the data products to be delivered by LSST are defined in the Science Requirements Document (SRD) (LPM-17). They are derived from four main science themes (Constraining Dark Energy and Dark Matter, Taking an Inventory of the Solar System, Exploring the Transient Optical Sky, Mapping the Milky Way), which are believed to fully exercise the technical capabilities of the system (such as photometric and astrometric accuracy and image quality). The SRD lists a minimal set of the most challenging requirements for the LSST system; separate documents deal with more extended and detailed requirements (the two high-level documents directly derived from the SRD are the LSST System Requirements Document (LSR) (LSE-29) and the Observatory System Specifications Document (OSS) (LSE-30) as illustrated in Figure 7.
The SRD specifications come in two flavors: the required properties of individual field observations (visits) and constraints for observing cadence that generate ensemble properties of the survey. The former are specified in detail, and they directly constrain the capabilities of the hardware and software systems. Meeting these detailed specifications is one of main commissioning goals. The SRD does not specify error budget distribution between the hardware and software systems – as a general principle, the SRD specifies that the measurement errors for fundamental quantities, such as astrometry, photometry and image size, should not be dominated by algorithmic performance.

The fundamental image properties, specified in the SRD, that need to be characterized during the commissioning phase are:

- Image depth (attained magnitude/flux limit at some fiducial signal-to-noise ratio)
- Image quality (size and ellipticity)
- Astrometric accuracy
- Photometric accuracy

The characterization of these quantities needs to account for the fact that in all cases they are not single numerical values but rather distributions. The range of observing conditions over which these quantities will be characterized must reflect the anticipated conditions for the entire LSST survey.

After verifying that the SRD requirements are met, and providing a quantitative characterization of the fundamental image properties, a number of additional “beyond-the-SRD” tests and quantitative analyses will be performed during commissioning (as well as during the operations phase). They must demonstrate that survey data of sufficient quality can be taken with adequate efficiency and sampling of observing conditions, processed with adequate fidelity, and served to users. In particular, these tests
and analysis will need to demonstrate that various systematic effects, both in raw image data as taken, and potentially introduced during the data processing step, are sufficiently small as to not jeopardize the main LSST science goals described in the SRD (for example, the quality of star/galaxy separation, subtle systematic errors in astrometry, photometry and galaxy shape measurements, detection and processing of transient sources). Many, if not all, of these tests will have been developed and exercised on precursor data by the Data Management team as part of their algorithm and pipeline development efforts.

1.1.5 Technical Optimization of System Operations

Technical operations optimization entails activities aimed at improving the overall system performance beyond technical requirements. An example of such an optimization would be how to best operate the dome vents under varying external conditions to optimize the delivered image quality—balancing thermal flushing with wind induced buffeting on the Camera-Telescope system. These activities will be explored while ComCam and/or LSSTCam is engaged in their respective “sustained observing” periods.

1.2 Boundary Definitions between Subsystems and System AI&T and Commissioning

To facilitate planning for System AI&T and Commissioning, it is useful to have working definitions for the boundaries between the activities covered by subsystem AI&T and those at system level AI&T covered by this plan. This plan was developed the following guiding principle:

An activity is considered part of commissioning when it involves a delivered component from one subsystem “touching” that of another subsystem.

Using this principle, the definitions for activities involving the subsystems that are within the scope of the commissioning plan are:

Data Management: Commissioning activities involving DM start when components receive “real” image data from one of the principal sources including the Auxiliary telescope/instrument, ComCam and/or the full Science Camera. The onset of these activities begins when the Auxiliary Telescope starts producing calibration spectra from the sky, currently planned for August 2018. It is recognized DM will still be doing subsystem development and testing throughout the commissioning period with a gradual decline in this effort as the Project enters the Science Verification Phase. The key data production milestone dates on the current schedule are:

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-Mar-19</td>
<td>Start Aux. Tel. On Sky Data</td>
</tr>
<tr>
<td>16-Dec-19</td>
<td>Start of Operational On-Sky Data from Auxiliary Telescope</td>
</tr>
<tr>
<td>13-Feb-20</td>
<td>Start of ComCam re-Verification</td>
</tr>
<tr>
<td>16-Jul-20</td>
<td>Start of On-Sky &amp; Calibration Data with ComCam</td>
</tr>
<tr>
<td>28-Sep-20</td>
<td>Start of LSSTCam re-Verification</td>
</tr>
<tr>
<td>26-Oct-20</td>
<td>Sustained Observing with ComCam</td>
</tr>
<tr>
<td>10-May-21</td>
<td>Start of On-Sky &amp; Calibration Data with LSSTCam</td>
</tr>
<tr>
<td>20-Jul-21</td>
<td>Sustained Observing with LSSTCam</td>
</tr>
<tr>
<td>08-Sep-21</td>
<td>Start of Science Verification mini-Surveys</td>
</tr>
</tbody>
</table>

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Telescope and Site: The telescope and other associated deliverables will be integrated on site at the Summit Facility. In this sense there is not a single moment of delivery for the telescope to the LSST Observatory System. Commissioning activities involving the Telescope & Site WBS starts when the Summit Facility becomes available for outfitting of LSSTCam provided hardware/software needed to support the Camera maintenance areas (e.g. white room and clean room facilities). This is followed with the arrival of ComCam in Chile for final assembly and re-verification leading to the beginning of Phase 1, Early System AI&T. Hand-off milestones are used to track when various deliverables from T&S (WBS 04C) can accept commissioning activities (see section 3.1).

Calibration Systems: The systems used for generating inputs to the Calibration Products Pipeline (CPP) are part the Telescope & Site WBS 04C. These include the auxiliary telescope and a spectrometer, a collimated beam projector and a calibration screen with broadband and tunable narrowband illumination. Commissioning activities related to calibration testing and verification begin when data from one of the hardware systems is sent to the DMS for processing in the CPP. The timeframe when data from these systems are available is indicated in the Data Management milestones above.

Camera: LSSTCam commissioning activities begin with shipping of the camera and integration tooling from SLAC to Chile and the re-verification on the Cerro Pachón summit. Re-verification activities of the Camera will be led by DOE personnel, but coordinated through the Commissioning team and plan. These activities are currently scheduled to start February 14, 2020 with a Camera Pre-Ship Acceptance review at SLAC. Commissioning covers all shipping costs with the exception of the camera shipping container(s). Additionally, there are some pre-LSSTCam activities related to commissioning preparation, ComCam, and summit preparation that run in parallel with the LSSTCam MIE project.

Education and Public Outreach: Commissioning activities involving EPO start when ComCam mini-surveys and alert stream data are made available from DM. Pre-commissioning private beta testing will occur with simulated and legacy survey data.

1.3 Planning Strategy

The LSST System AI&T and Commissioning has been planned around four phases of activity:

- **Phase-0** a period of pre-commissioning preparation developing the hardware/software tools and test procedures that will be carried out in subsequent phases,
- **Phase-1** a period of Early System AI&T with the telescope, a commissioning camera (ComCam) and subscale data services and processing;
- **Phase-2** a period of Full System AI&T with the integration of the Camera, Telescope, EPO Data Center, and full scale data services and processing; and
- **Phase-3** a final Science Verification period that is focused on characterizing the system with respect to the survey performance specifications in the SRD/LSR and demonstrating operations readiness by conducting 2 mini-surveys and Science plus EPO user interface testing.

Because LSST will be a single use facility, the scheduling of commissioning activities is unconstrained by external demands. Each of the system level AI&T phases have an early technical component where the focus is on making the hardware and software control systems working with each other. Following an internal review to check performance and progress, these technical integration efforts are followed by
sustained observing periods meant to generate significant data for testing of algorithms and pipelines. Once either ComCam (Early System AI&T) or LSSTCam (Full System AI&T) are physically integrated with the telescope, commissioning activities will have both day and night time components to them. Once activities with significant night time components have started, we have built in dedicated “engineering punch list resolution” blocks approximately once every month. This allows the commissioning team to take stock on unresolved issues and “catch its breath” and resolve significant prioritized issues without typical workday constraints.

In addition, when developing and evolving the LSST System AI&T and Commissioning Plan, we also have factored historical averages for weather by estimating the number of nights needed, time of year when the activity is scheduled and the mean cloud cover fraction (see Figure 8). For example, when estimating the required number of visits (2 x 15-second exposures) for a given procedure over a span of time we multiply the hours available in a night by the expected mean cloud cover fraction for the time of year under consideration and then estimate the number of nights needed.

![Figure 8: Mean cloud cover fraction (red) with 1-sigma variation (green) for the Cerro Pachón region from 1975-2005. The length of the night between the beginning and end of nautical twilight is indicated (purple).](image-url)
1.4 Working Assumptions in Commissioning

The plan in this document was developed with the following assumptions:

- Resources needed for routine operation and maintenance of the Facilities in Chile are a given and part of the continued scope of the Project Office or the Telescope & Site WBS; and
- Resources needed to support operations at the National Center for Supercomputing Applications (NCSA) to maintain and provide computing hardware and service infrastructure needed for processing the System AI&T and Commissioning data is captured in the Data Management WBS; and
- Resources needed to support operations of the EPO Data Center (EDC) and provide computing infrastructure needed for processing the Commissioning data is captured in the Education and Public Outreach WBS.
2 Commissioning Management Plan

2.1 Project Organization in System AI&T and Commissioning

During System AI&T and Commissioning, the overall Project organizational structure remains unchanged. The Project Director, Deputy Director and Project Manager retain overall responsibility and authority as described in the Project Execution Plan (PEP) (LPM-54). The System AI&T and Commissioning effort is part of the Project Systems Engineering scope of work. The specific responsibility for the planning and execution of the System AI&T and Commissioning work is assigned to the Systems Scientist. The Systems Scientist has the responsibility to complete the work on schedule and within the allocated budget and has the authority to direct resources as required to meet the functional objectives described in this plan. The Systems Scientist and Systems Engineering Manager jointly will oversee broader systems engineering effort. During the Systems AI&T and Commissioning period, the “commissioning” and “verification” efforts will be distributed to the Systems Scientist and the Systems Engineering Manager respectively. Figure 9 below, provides the organizational structure of the Project Commissioning Team.

![Organizational Structure Diagram]

Science Verification/Validation
- Science Validation Lead: Keith Bechtol - UWisc
  - Data Release Processing: Lead - Keith Bechtol - UWisc
  - Alert Production Processing: Lead - Andy Connolly - UW
  - Calibration Products Processing: Lead - Merlin Fischer-Levine - Princeton

System Integration
- System Integration Lead: Bo Xin - AURA-Lsst
  - Calibration AI&T: Lead - Patrick Ingraham - AURA-Lsst
  - ComCam AI&T: Lead - Brian Staider - AURA-Lsst
  - LSSTCam AI&T: Lead - Margaux Lopez - SLAC

Technical Coordination
- Technical Coordination Lead: Jacques Sebag - AURA-Lsst

Interface to Technical Development Teams

Science Validation is Distributed  System Integration is in Chile

Figure 9: The Project organization at the time System AI&T and Commissioning commence indicating the Project Commissioning Team (orange boxes) having responsibility and authority over the System AI&T and Commissioning effort.

The subsystem technical teams will remain administratively under their respective subsystem managers. These subsystems will be responsible for executing the scope of work that continues in parallel with the system wide integration and commissioning (e.g. maintenance and routine operations activities). Each subsystem will assign staff to be directly involved in the System AI&T and Commissioning effort. The
assigned staff will take their priorities from, and functionally report to, the Systems Scientist through the Technical Coordination Team (TCT). The TCT (see section 3.2) provides a direct connection to the subsystems, maintaining a technical and administrative connection between the commissioning and development, operational and maintenance efforts.

During this time period, each subsystem will have continued responsibilities, but the Project priority will be the System AI&T and Commissioning effort. The DM part of the Project still will be undergoing planned development during the System AI&T and Commissioning phases. Interactions between the Project Commissioning team and the ongoing DM development effort are described in section 3.3. The LSSTCam team will be highly focused on the integration and commissioning support as well as any remaining MIE closeout actions. The management team for LSSTCam will remain at SLAC to organize these DOE supported efforts. The T&S team will focus on supporting the commissioning effort, in particular the early AI&T efforts and system integration as described in the Telescope Integration and Test Plan (LTS-104). The T&S team will maintain responsibility for the safe operation and maintenance of the LSST Summit Facility and Base Facility, providing the care and control to support the priority activities of the commissioning effort.

2.2 Commissioning Team Organization, Roles & Responsibilities

As the commissioning phase draws near, beginning in calendar 2017, the Project Commissioning Team led by the Systems Scientist will form. This Project Commissioning team will be responsible for developing, evolving and maintaining the System AI&T and Commissioning Plan (this document and associated P6 schedule), coordinating the pre-commissioning preparations and the safe execution of integration and commissioning activities once these start.

The Project Commissioning team consists of three subgroups, a Technical Coordination Team, (TCT), the System Integration Team (SIT) and the Science Validation Team (SVT) each with their own lead(s) reporting to the Systems Scientist as Commissioning Lead. SVT in commissioning will be a distributed group, while many of the SIT will spend most, if not all, of their time in Chile. Members of any team may migrate from one to the other over the course of commissioning as their roles, assignments and location map to specific activities.

The TCT is made up from representatives out of each subsystem. This team is responsible for assisting in the tactical planning of daily activities needed to support system integration and commissioning, issue and problem resolution, maintenance, and routine operations. While this team will be focused mainly on activities in Chile, it will also address the coordination of activities at the other primary LSST sites, namely NCSA and Tucson Headquarters. The representation from the subsystems at a minimum will include subsystem AI&T managers, chief engineers, the Summit Manager, Summit Safety Coordinator and IT Coordinator.

The TCT along with their managers are responsible coordinating their resource to carry out the technical activities derived from the strategic monthly planning and the more detailed weekly and daily schedules.

The SIT, a scientific and technical team responsible for meeting the overall objectives of the System AI&T and Commissioning effort, reports directly to the Systems Scientist. It is expected that this team will spend the majority of their time in Chile carrying out the on-site integration and commissioning activities. The SIT is meant to be the primary on-site scientific and technical analytics and planning
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pipelines also need deployment-time "smoke testing" to ensure correct operation in the service infrastructure. The methodology to be used is

- Development occurs on a ticket branch;
- Code is tested in the continuous integration system (building and unit tests for stack code; integration tests for both);
- Code commits are cherry-picked to a commissioning release branch, tagged, built, deployed, and smoke-tested by L1 service staff under control of the commissioning release manager; and
- The code is merged to the “master” branch if found to be useful.

New releases of stack code and pipeline configurations incorporating changes by both DM and the Commissioning team are "cut" as commissioning releases under control of the commissioning release manager, including freezing of the desired feature set via tagging and branching.

Issues passed from the Commissioning team to the DM construction team are expected to have high priority. Significant resources have been allocated in the DM construction plan to support investigation and fixing of these issues. If this allocation is exceeded, management will reprioritize construction and commissioning tasks via an LSST Change Request (LCR).

### 2.4 Work Management and Authorization

Specific work activities carried out during the System AI&T and Commissioning period will be derived from several needs. First and of highest priority are those needed to support the System AI&T and Commissioning Plan. Next in the order of priority is the work needed to correct issues that have been discovered and are blocking further progress with System AI&T and Commissioning. This is followed by work needed to maintain the operational systems and their routine operations. Because of its nature the work that is needed on any given day/week can become fluid during System AI&T and Commissioning. Recognizing this potential for fluidity, we have developed a strategy and toolset to help us manage the work detail as they develop during execution of the System AI&T and Commissioning plan. The work planning and management will be done on three timescales:

- **Monthly Project-wide Planning Meeting**
  
  On a monthly basis, the Systems Scientist will convene the representatives from each the three Project Commissioning Team subgroups along with the Systems Engineering manager, subsystem managers, Project manager, Director and Deputy Director for a one day review of current status and a two-month look ahead of the current P6 based PMCS baseline plan. This meeting is essential to understand the planned activity schedule, work that may interfere or prohibit other work and any significant deviations arising from previous activities. Additionally, this meeting will be essential in assigning and notifying shared resources to the highest priority activities. The current safety record will also be reviewed along with any specific safety concerns stemming from planned activity and appropriate mitigation plans put in place.

- **Weekly site-specific “tailgate” meetings**
  
  At each LSST site where System AI&T and Commissioning activities are occurring there will be a weekly site-specific “tailgate” meeting. This meeting will be led by the local “on-duty scientist” and review the detailed work plan with a two-week look ahead according to the objectives and
priorities set at the Monthly Project-wide Planning Meeting. These weekly “tailgate” meetings are specifically aimed to setting the week’s work assignments to personnel and anticipate the needs for the following week. Specific safety issues related the week’s work are addressed with procedure reviews and adjustments as necessary.

- **Daily site-specific work authorization and safety review**

  Daily site-specific work authorization meetings (particularly at the Summit facility) are focused on safety with reviews of anticipated hazards, safe work procedures, coordination of work location conflicts, and reminders of work safety. These “plan of the day” meetings are co-led by the local “on-duty Scientist” and the local work authorization manager. For example, the Systems Scientist (or designee) and the Summit Manager will lead the daily work authorization meeting at the Summit Facility. Work is authorized through pre-vetted procedures and released to occur that day by the assigned individuals. Any variations from the authorized procedures at the Summit Facility will require approval from the Summit Manager and Summit Safety Coordinator.

To aid in the management of this work, LSST has developed a toolset that allows for the integration of both long term plans along with the capabilities to dynamically re-evaluate priorities and tasks on weekly and daily timeframes, as well the capabilities to execute the work and record the results, associated artifacts and issues uncovered. The main tool LSST will use is JIRA, which is a work management software tool that allows for generation of tickets assigned to individuals to do the work that move through defined workflows. LSST has developed a customized JIRA project called “LSST Operations” (LOPS) that includes an additional add-in called Kanoah Tests. Kanoah Tests is a test management tool that provides additional capabilities to generate Test Cases, Test Runs, Test Plans, Test Results, Test Reports, and Issues all in a common platform with traceability. The LOPS JIRA project has been designed with various kinds of work in mind: verification tasks, integration tasks, maintenance tasks, etc.

In the case of system verification tests, LSST will use a combination of 1) MagicDraw, an MBSE tool where all of the project’s requirements are contained along with the verification test plans for each requirement and 2) JIRA. A third tool called Syndeia, which integrates MBSE tools with many other software platforms, is used to deeply link elements in the two platforms and provide synchronization capabilities. Figure 10 shows a schematic of how MagicDraw and JIRA are integrated to execute the full verification lifecycle.
Figure 10: The LSST Work Management System Environment workflow for Verification Activities

After the Verification Test Plans are developed for each requirement, a ticket representing that plan is auto-generated in JIRA using Syndeia. These Verification tickets are associated with a workflow (Figure 11). The tickets start in the “Backlog” state, which means they have been unassigned to Test Case(s). The Test Case (i.e. Verification Event) development is performed using the Kanoah Tests add-in. Individual steps for each Test Case can be generated (called “Test Scripts”). Test Cases can then be sequenced into Test Runs (equivalent to Activities in P6). These Activities can then be grouped into Test Plans (equivalent to Commissioning Phases). After the planning is complete and verification activities are to be executed, the Verification ticket is moved to the “In Progress” state. Kanoah Tests allows for each test run to be executed multiple times and keeps track of the results of each instance. Results (pass, fail, blocked, etc.) are captured for each run of a Test Case. Items that are “Failed” or “Blocked” generate issues tickets for the problem to assigned and resolved. Test artefacts can be attached to the results of the Test Run. Test reports can be generated. The results are recorded against each Verification ticket through deep linking.
Figure 11: The JIRA based workflow developed for processing tickets for each Verification Test Plan.

After all test runs for a verification ticket have been successfully executed, the Verification ticket is moved to the “In Analysis” state where the Responsible Technical Authority (RTA) reviews the results. If the RTA agrees that the results are sufficient to verify the requirement, the RTA moves the ticket to the “In Review” state. If the RTA believes additional verification work is needed, the verification ticket can be returned to either the “Backlog” or “To Do” state depending upon the conditions. Once the ticket is in the “In Review” state, ownership of the ticket is transitioned from the RTA to a member of the LSST Verification Team under the direction of the Systems Engineering Manager. The Verification Engineer/Scientist reviews the results and makes a final decision on compliance. Once the Verification Engineer agrees that the requirement has been satisfied, the ticket is moved to the “Passed” state.

After the Verification ticket has been closed out as “Passed,” that result is fed back to MagicDraw to set a Verification Compliance field in the Verification Plan as “Yes,” which is the end of the chain.

Final verification matrices to support the ORR can then be generated from MagicDraw and detailed test reports can be generated from Kanoah Tests.

2.5 Environment, Health & Safety

The LSST Safety Policy (LPM-18) will continue to be the guiding document that defines LSST’s safety culture, expected safety behaviors, and details broad responsibilities for all those who work for LSST. The LSST Project is centrally managed but executed by several teams in distributed locations and with different funding sponsors. This LSST Safety Policy covers all LSST Project efforts while recognizing and relying on existing Safety, Health and Environmental policies in place at participating institutions.

Given that environmental conditions on the summit can be uncomfortable and activities can be
complex, the Summit Site Safety, Health, and Environmental Plan (LPM-114) details required communications, minimum safety processes and procedures. Due to the varied activities that will be occurring on the summit, the following processes will be enforced: 1) Work Stop Authority, 2) the morning Plan of the Day, and 3) the overarching authority to direct work of the Site Manager. In addition, many other safety control processes will be in place, including but not limited to

- Known hazards are recognized in the LSST Hazard Analysis process and are mitigated or minimized;
- All employees working in Chile will have an ODI (obligation to inform) to understand the hazards of their job;
- All employees working in Chile are required to attend general safety training specific to working at the site and trained for specific hazards related to their work such as lock out-tag out; and
- All procedures will include hazard recognition, safety equipment needed and mitigation strategies.

2.6 Risks and Hazards in Commissioning

2.6.1 Risks

LSST Commissioning will maintain a shared risk registry developed using the template of the DOE MIE project risk registry (LCA-30). The risk analysis follows key concepts presented in both the Camera Risk Management Plan (LCA-29) and the LSST Risk and Opportunity Management Plan (LPM-20). Risks and contingent events can affect the commissioning schedule and budget; managing risks is essential and helps determine sufficiency of contingency funding.

The bottom up estimates for scheduled work are, as required, success oriented. LSST Commissioning has intentionally budgeted in small periods of time to resolve expected minor issues. We cannot foresee which risks will be realized. Rather, the risk registry allows us to evaluate the impacts of each risk if realized and to fund risk reduction activities.

2.6.2 Hazards

The safety of people and property is paramount in all LSST efforts. The design for safety has included assembly and construction processes and the resulting commissioning and operational concepts. As procedures are developed for the observatory, job hazard analysis will be included to protect people, equipment, and processes from known hazards.
3 Sub-System AI&T and Commissioning Prerequisites

Each of the LSST subsystems will have gone through substantial testing and are expected to be in an advanced state of readiness prior to their entry into the System AI&T and Commissioning Phase. The acceptance criteria and expected state for each of the subsystems required to enter the Commissioning Phase are described in the subsections that follow.

3.1 Telescope & Site (WBS 04C)

The Telescope & Site group (T&S) is responsible for the primary telescope components such as the mirrors, coating chamber, dome, mount, summit and base facility buildings (Figure 12), as well as the summit network infrastructure, telescope and observatory control software, and the survey scheduler. The transition of activities between T&S and Commissioning occurs over a period of several months. Because several T&S and Commissioning activities will be happening in parallel, the Commissioning schedule tracks several milestones that are pertinent to the commissioning effort including events indicating the handoff of equipment, software and floor space. Figure 13, shows the created milestones currently integrated into the Commissioning IMS. This section discusses the acceptance criteria and expected state of the system at the milestones where handoffs occur.

Figure 12: The main deliverable elements from the Telescope & Site work package include the Summit and Base Facilities, the telescope mount assembly, mirrors systems, dome system, mirror coating plant, control room and auxiliary telescope.

The contents of this document are subject to configuration control and may not be changed, altered, or their provisions waived without prior approval.
The first significant milestone to the Commissioning team is the completion of the Summit network, this transition marks when communication between devices can occur. This is specifically relevant for monitoring equipment and for when testing of this remotely operated equipment can begin. Shortly thereafter, the completion of the summit computer room marks when the Camera Control System (CCS) and Data Acquisition (DAQ) computers can be installed, the first in a string of Commissioning activities discussed in section 5.2. The last significant summit networking related milestone is the installation of the Engineering Facility Database (EFD) and Data Distribution Service (DDS). This marks when the monitoring services can be recorded and archived, an essential service for tracking environmental conditions, and how building properties such as vibration will evolve as components are integrated. The next milestone signals the “Substantial Completion of the Dome.” At this time, the enclosure becomes protected from the external environment, signalling when dome environment monitoring can be implemented. Performing heating/cooling measurements as well as measuring the dome seeing prior to installation of the telescope mount assembly (TMA) as performance baselines that will be used for comparison during commissioning activities involving technical performance operation activities (discussed in section 5.2). The general monitoring component of the Observatory Control System (OCS) provides the tools to analyze and visualize the telemetry and events to allow operators to see the current state of the observatory and trends emerging from the data. A functional version (Monitor v1.0) will be available in May 2019, and the final stable version (Monitor v2.0) will be ready at the T&S completion milestone.
The completion and verification of functional performance for the Auxiliary Telescope (AT) System, a 1.2 meter telescope and imaging spectrograph dedicated to characterizing the transmission function of the atmosphere during LSST observations, marks the handoff of the AT hardware and control software to the commissioning team. The AT system is composed of several major components, the AT building, telescope mount, mirrors, dome, spectrograph, imager, and associated calibration equipment. The verification of the AT related requirements in the Telescope and Site Subsystem Requirements (LSE-60) are to be performed prior to entering the Commissioning phase in August 2018. At this time, the AT and AT dome will be fully operational and integrated with the Telescope Control System (TCS) and OCS control software. The spectrograph will be tested with its detector and readout electronics system; the data will be stored and analyzed locally and not ingested into the LSST data stream. Ingestion of the data by DMS acts as the defining boundary or hand-off of the Auxiliary Telescope System to Commissioning as defined in section 1.2. The spectral analysis software being written by the DM group then will be used to measure the temporal and spatial variation of the atmospheric parameters, notably the effects water and aerosol, then use this information to optimize the AT scheduler algorithm. For this reason, the AT scheduling algorithm will undergo functional testing based on simulated LSST positioning, events, and weather in the T&S Assembly Integration and Verification (AIV) phase, but not be used directly with the hardware until the Commissioning phase. The planned Commissioning activities involving the AT are discussed further in the Commissioning Plan section of this document.

Completion of the Camera Maintenance Area, with the refrigeration lines installed, is being tracked since it is required to begin the installation of the camera refrigeration system. Camera refrigeration pathfinder exercises, described in section 5 of this document, also require the White Room and TMA to be completed. Completion of the Clean Room milestone marks when the Camera can be moved into the area for assembly. At the time of these milestones, the areas will be fully compliant with the specifications defined in the Summit Facility Interface between the Camera and Telescope (LSE-65).

Arrival of ComCam on site marks the handoff of the Camera and T&S construction team’s completion of ComCam with delivery to the Commissioning team. ComCam reassembly and reverification tests mark the onset of first major commissioning activities inside the Summit Facility, and more specifically the white room. At this time, ComCam has had its hardware functionality verified in Tucson using a local instance of the CCS and DAQ but requires integration with the operational control software instances (CCS, DAQ, DMS, and OCS) at the Summit Facility. These Commissioning activities are described in section 5.

At the time ComCam is on the telescope, the TCS Supervisor application is functioning with all TCS components and with real hardware for all TCS functionalities, except those requiring the science camera. The OCS verification has been completed with all the OCS components functioning, commanding, sequencing, and supervising the observatory subsystems. The OCS Middleware (v4) is transporting all the messages (commands, events and telemetry) between the OCS, TCS, CCS (the ComCam version) and DM, then storing them in the EFD. The OCS Scheduler v2.0 implements the science for the baseline survey and configurable proposals for commissioning activities, at this time the Scheduler has been verified using simulation, but has not been used in conjunction with the telescope. This is left as a Commissioning activity.

The Global Interlock System (GIS) is the safety system whose function is to manage the interlocks identified in the hazard register not already included in the interlocks delivered with the subsystems.
The GIS is required for safe operation and testing of all observatory related hardware and software. The preliminary design of the GIS is captured in the LSST Summit Safety Interlock System (LTS-99), and the documentation will be updated to detail the final design of this system. This milestone marks completion of the system, which indicates when more integrated testing can safely begin. Prior to this system being fully installed and integrated, tests and interim procedures must be direct and localized to ensure safety to the equipment and personnel before the GIS is fully operational.

The LSSTCam has its own safety system as described in LCA-139 and LCA-140. LCA-139 describes the design of the camera protection system. LCA-140 describes a list of protection scenarios and how the camera would respond to various events. Also included in the camera safety system is the ability to provide access control for maintenance. The camera will accept only two signals from the GIS: an earthquake warning, if available, and master abort. The camera protection system would then take appropriate actions.

The milestone indicating completion of the Base Facility Data Center Building marks when T&S have installed the necessary utilities and the building is in a state of readiness for DM to start assembling and installing the computing hardware. This also identifies when the Commissioning Cluster can be installed at the Base Facility. Upon installation of this cluster, activities requiring large computational analyses, not available on the summit, can begin. An example of this is the Active Optics System (AOS) calibration files (a deliverable of the DM group) that are required during the early phases of ComCam testing, as discussed in section 5.

The last milestone being tracked is the completion of the T&S construction contract. At this point, all T&S subsystems, including the summit and base facilities, have undergone acceptance testing to a level agreed upon by both T&S and the System Engineering group; contracts with the hardware vendors are completed; and their associated AI&V activities are finished. The construction team then hands off all systems to the Commissioning team for testing. Although the components have been accepted, there are activities, specifically related to optimization of the hardware usage, that are scheduled for Commissioning. Details of the states of each subsystem at the end of the AIV phase are found in the Telescope Assembly and Integration Plan (LTS-104), and documents referenced therein. The following paragraphs summarizes the systems where Commissioning activities are planned for to optimize their performance.

The telescope enclosure (dome) will be fully completed and would have been tested during the AIV phase. However, activities such as optimization of the dome vents during operations to maximize cooling, and to minimize dome seeing will continue through Commissioning. The TMA also will be fully functional, but the optimal combinations of telescope, dome vent gate positioning, and wind gate position to minimize windshake will be left as a commissioning activity. A similar approach is adopted for the telescope image quality, where during the T&S AIV on-axis image quality assessments are performed but are limited to a very small field of view.

Approximately two months prior to the start of Early System Ai&T, the telescope integration plan specifies that the three-mirror optical system will begin optical testing with Project Systems Engineering oversight. These tests include interferometry of the primary-tertiary mirror (M1M3) assembly at the M3 radius of curvature to verify the M1M3 pre-shipping support matrices as well as to build and refine the initial look-up tables for the elevation dependencies of the M1M3 mirror support. After these tests, the secondary mirror (M2) is tested with an on-axis Shack-Hartmann wavefront sensor and/or a high speed
camera and surrogate mass to simulate the science camera on the rotator-hexapod assembly. There will be roughly four months of on-sky time with the telescope in this configuration to allow analysis of the on-axis optical aberrations and refinement of the alignment and mirror support look-up tables, as well as optimization of the thermal control system. Given the tests summarized above, it is expected that at the end of the T&S AI&V phase, the telescope will be delivering SRD-like image quality to ComCam over a limited field-of-view around the optical axis and can point and track to its open loop specifications (OSS-REQ-0303). However, testing and optimization of the M1M3 mirror thermal control system is limited to the environmental conditions experienced during that period and to a limited field of view. Further testing and optimization is planned during the Commissioning phase.

The active optics system performance will not be fully and tested at the end of the T&S integration since it requires the full field of view of the LSSTCam and the wavefront sensor processing pipeline in order to fully test against the complete set of AOS requirements. The strategy agreed upon by T&S and the System Engineering team was to verify the AOS via test of the on-axis correction at several zenith angles, then perform an analysis to determine the performance over a larger field. Several Commissioning activities, discussed in section 5, are dedicated to AOS and image quality verification and optimization.

Without the wide-field LSSTCam being installed at the telescope focal plane during the AI&V stage, the In-Dome calibration hardware verification uses primarily testing intermediate step activities rather than full end-to-end system demonstration. The In-Dome Calibration Systems refer to all calibration related components that are primarily used to calibrate the relative transmission function of the 8.4 meter telescope. The complement of hardware consists of the calibration screen, calibration screen characterization hardware, laser transport and tuneable narrow-band and a broad-band screen illumination system, and the Collimated Beam Projector (CBP).

The calibration screen is a 10.3 meter diameter annulus that is suspended on the LSST dome and used for flat-field calibration activities. The screen is illuminated using both a tunable narrow-band source and a broad-band (white light) source, non-simultaneously. The existent light from the screen is then characterized using a two NIST-calibrated photodiodes and a fiber-fed spectrometer, all of which are located on the top end of the TMA. Performing flat field calibrations requires careful synchronization between these pieces of hardware and the LSST camera. At the end of the telescope AIV phase, the screen illumination hardware and characterization hardware will be fully functional and their ability to perform and respond upon a complicated sequence will be demonstrated. The full optimization and end-to-end tests utilizing a camera at the LSST focal plane will be performed during the commissioning phase, as discussed in section 5.

The CBP is a small aperture, wide field telescope used in reverse, projecting patterns such as point-like sources through LSST and onto the camera. The CBP will be fully integrated and its requirements will be verified prior to the installation of ComCam. The performance level verification will be based solely upon optical and opto-mechanical testing performed by the CBP vendor prior to acceptance, and functional tests performed on-site with the TCS and OCS. Integration of the CBP control software with the DM developed coordinate transformation relationship tool and analysis of the data taken using the CBP is a commissioning activity. It is anticipated that the CBP will be tested using DECam and the Blanco telescope prior to commissioning. This exercise will be performed to better integrate the system and develop the necessary tools, as well as producing a dataset that the DM team can use to test and optimize their reduction software. This early testing will enable a more efficient and streamlined
commissioning process, which is further discussed in section 5.

3.2 Camera (WBS 03C)

The LSST Camera (LSSTCam) is a DOE funded Major Item of Equipment (MIE) project led by SLAC National Accelerator Laboratory. The end of the MIE construction project is defined as the “Camera Pre-Ship Review Complete” milestone. At this stage, the LSSTCam has been verified that it has met all performance and functional requirements and is ready to ship. The LSSTCam, shipping container(s), functional spares and all integration and test hardware used during for integration, test and verification are included in the MIE scope. Details of these MIE deliverables can be found in Camera project work breakdown structure (LCA-125). Shipping costs, non-camera shipping containers and all summit work will need to be covered by DOE Commissioning. Additionally, early operations will need to maintain level of effort support for DOE project management for Early Ops, systems engineering and software support of the CCS and DAQ. Where possible, subject matter expertise will be preserved at SLAC through commissioning and into operations with funding for contingent event support.

3.2.1 LSSTCam

The LSSTCam (Figure 14) will be integrated and tested at the SLAC per the LSSTCam Integration and Test Plan (LCA-40). During this phase of the LSSTCam construction, all of its subsystem requirements (LSE-59) and interfaces will be verified to the extent possible without integration onto the telescope. Demonstration of compliance with its requirements through a review process signifies the LSSTCam has met its shipping readiness milestone.

The Camera, its support hardware, and test apparatus will then be shipped to Chile from SLAC. The Camera is scheduled to arrive in Chile via airfreight and will be brought to the Summit Facility by truck roughly three months prior to the start of Full System AI&T. During this time, the camera will be reassembled (if need be) in the camera service space at the Summit Facility, and a subset of verification tests run at SLAC will be rerun to show shipping readiness will be re-run to verify that no functional or performance damage occurred during shipping.

As part of the post-shipping re-verification, the camera will be connected to the Summit Facility network. With the camera on the network, the data path between the Camera and the DM processing pipelines at the Base Facility and Archive Center will be established and verified with live pixel data from the science focal plane array (FPA). During this initial testing the command and control of all Camera functions with the OCS will also be verified. Successful completion of these tests will signify that the camera has met its acceptance criteria and is ready to enter the commissioning phase and start Full System Integration and Test.

3.2.2 Summit Camera Maintenance Facilities

The Summit Facility has three locations provided for camera maintenance. A clean room (Class-10,000) facility, a white room (Class-100,000) and the camera servicing area near the mirror coating facility. This area will be constructed by the MREFC project and turned over to System AI&T and Commissioning. The clean room and white room will be certified as meeting their class standards by the Telescope & Site team prior to handover. LSST System AI&T and Commissioning effort outfits and commissions these areas with test stands, tools, consumables, etc. as described in section 4.1.2.
3.2.3 Spares

The LSSTCam project will provide the following spares described in this section to ensure its functionality over its 15-year operational lifetime including AI&T, commissioning and the planned 10-year LSST survey. The camera provides spares for the two main camera mechanisms with lifetimes that are expected to be shorter than the camera lifetime: the shutter and the filter auto-changer and the associated support fixtures: the filter loader (x2) and the filter storage clean box.

The LSSTCam shutter has been specified to reliably operate over 1 million actuations or about a year’s worth of operation. The shutter will be swapped annually and refurbished while the spare is in use for the following year. The filter auto-changer mechanism will similarly be exchanged and refurbished on an annual basis to maintain reliable operation.

The LSSTCam can hold on-board five out of the six ugrizy optical filters. To install the sixth filter, the filter loader removes one of the filters from the camera and transports it to a clean filter storage box that can hold all six filters. The filter loader then is used to install the new filter. Two filter loaders are provided by the LSSTCam project along with a single filter clean storage container.

Figure 14: A cross sectional view of the LSSTCam fully assembled. Full functionality and performance of LSSTCam will be verified at SLAC prior to shipment to the Summit Facility in Chile.
3.2.4 Fixtures and Test Stands

To go along with the spares of camera hardware, there are also fixtures and test stands that will require storage in locations other than in the camera maintenance area, and with various levels of access. Below is a list of the hardware and ease-of-access grouping.

**Used During Telescope Operations**

- Filter Loader with cart, 2x (1.2m x .75m)
- Filter Storage Clean Box (1.7m x 1.2m)
- Filter Bench Top Stand
- Spare Auto Changer (in clean box)
- Auto Changer Clean Box Cart, 2x (1.7m x 1.7m)
- Auto Changer Lift Fixture
- Filter Shipping Container, 6x
- Filter Covers, 12x
- Spare Shutter (in clean storage box)
- Shutter Installation Rails
- Shutter Stand-alone HCU
- Shutter Lift Fixture

The LSSTCam project also provides the complete set of integration and test fixturing used during the camera integration and test (I&T) period. These fixtures are provided so that if any camera maintenance is required the LSST has the ability to perform required work on summit.

**Used Only During Camera Maintenance**

- UT Support Stand (2m x 2m)
- Camera Lift Fixture
- Cryo Lift Fixture
- Cryo Spreader Bar
- Test stands 5, 7 and 8.
  - RAFT level metrology, cryostat and optical test
- Bench for Optical Testing (BOT)
  - Cryostat level metrology and optical testing
- Camera Calibration Optical Bench (CCOB)
  - Camera level calibrated spot projector
- Raft Integration System
  - Device for installing/removing an RTM from the cryostat

LSST expects that once the LSSTCam arrives on summit, it will remain there throughout the lifetime of the project. However, the camera shipping container(s) will be preserved and will need to be stored...
locally.

Seldom Used (Only for Shipping and Receiving the LSST Camera)

- L1-L2 Shipping Container (3.2m x 3.2m)
- L1-L2 Support Stand (2.75m x 2.2m)
- L1-L2 Lift Fixture (on support stand)
- Camera Shipping Container (6m x 2.5m)

3.3 Data Management (WBS 02C)

At the start of the commissioning with ComCam, the Data Management System (DMS) will have production versions of the Calibration Products Production (CPP), Alert Production (AP - Level 1), Data Release Production (DRP - Level 2), and Data Access Center services operational and tested with precursor (Figure 15) and/or simulated data at ComCam scale (i.e. single raft - 144 megapixel). Testing will have verified that the production systems are operating in the same way as prototype-level systems that already will have been integrated and operational for up to two years prior. It should be noted that these are initially stable versions of the final Alert Production and Data Release Production systems, adequate to test the system through batch processing. Their full capabilities will be emerging and tested throughout the commissioning period as part of the planned continuation of the MREFC DM development effort (see section 5.3). The start of DM Commissioning will be the connection of the production AP system to either the real OCS or to the Camera DAQ for ComCam, whichever comes first, with the latter expected to occur soon after ComCam arrives at the Summit during its re-verification and before it is integrated with the telescope. Note that connections of DM systems to other subsystems already will have occurred, including EFD-to-DM and early integration pathfinder exercises connecting DM Prototype Level 1 service systems with the Camera DAQ Test Stand and simulators for the OCS, CCS, and TCS.

![Figure 15: An example of photometry derived from exiting LSST algorithms and pipelines using precursor/legacy data from Hyper-SuprimeCam on the Subaru telescope (left) and SDSS Stripe-82 (middle, right).](image)

Deployment of production systems involves deployment of hardware components (computing and storage), with the purchasing process beginning at least one year prior to the need date, followed by
configuration definition, vendor selection, purchase, delivery, integration/installation, and burn-in. Compute hardware for the Chilean Data Access Center at the Base Facility will be purchased for delivery directly to La Serena; the hardware does not pass through the Archive Center at NCSA. Software configurations are defined through management tools (e.g. Puppet, Docker, Kubernetes) so that reproducible deployments are automated. Deployment also includes staffing and training of personnel to manage, maintain, support, and upgrade the systems and services to provide an agreed service level. Note that all services deployed during Commissioning will continue into Operations (although software, hardware, and process components may be modified and upgraded).

3.3.1 DMS Services

An archiving service for capturing and archiving images and metadata from Auxiliary Telescope systems, including the equivalents of the Camera DAQ, CCS, TCS, and OCS, will have been operational for at least several months. This includes networking components at the Summit, compute and network hardware components at the Base, and Data Backbone storage services at the Base and Archive. It also includes extraction and transformation of the Engineering and Facility Database contents, including the Large File Annex, as well as loading the transformation results into the “Transformed EFD” at the Base and Archive. Operational procedures and responses will have been developed.

Prototype L1 services, including both archiving and prompt processing services, will have been integrated and tested at the Archive, beginning with images delivered by the Camera DAQ Test Stand to be installed in early 2017. The services will include capture and archiving of raw images and associated metadata to the Data Backbone, capture and transfer of crosstalk-corrected images and associated metadata to the Archive and delivery to Alert Production science pipelines, preloading templates and catalogs based on "nextVisit" events, alert generation, and alert distribution to an LSST mini-broker as well as alert publishers for external brokers. The services will be tested from the Camera DAQ with simulated LSST images and from the prompt processing forwarders with precursor data from ZTF at all expected cadences and source densities, in areas with complete and incomplete templates, and with various lengths of simulated DIAObject/DIASource history from zero to 10 years. The services will have been shown to meet DM-level requirements, and early integration pathfinder exercises will have demonstrated system-level integration up to the level of simulating a full 24-hour cycle, including various faults. Quality control (QC) systems will be in place to capture metrics from the pipeline execution and archive, monitor, and display them.

The production L1 system hardware, sized to handle ComCam data loads, will have been installed at the Summit, the Base, and the Archive and tested using the same methods as the Prototype L1 system to ensure it performs to requirements, with additional tested against the provisioned wide area network connecting the Base and NCSA.

A Prototype Batch production service will have been integrated and tested at the Archive, beginning with raw calibration and science images in the Data Backbone and telemetry in the Transformed EFD. The periodic and annual Calibration Products Productions and the science pipelines through coaddition will have been exercised on simulated LSST data and precursor data, where available and shown to meet DM-level requirements. QC systems will be in place to capture metrics from the pipeline execution and archive, monitor, and display them. The Quality Assurance (QA) environment (see below) will have been instantiated at the Archive and used to analyze the results of a Level 2 (L2) production.
The production L2 system hardware, sized to handle ComCam data loads, will have been installed at the Archive and tested using the same methods as the Prototype L2 system to ensure it performs to requirements.

A preliminary Data Access Center (pDAC) will have been integrated and tested at the Archive, including authentication/authorization and resource management systems; access to the Data Backbone for file-based data products; the Qserv distributed database and other data product databases; data access (DAX) web services; and Science User Interface and Tools (SUIT) services, including both portal and notebook capabilities. The system will have been tested using SDSS, WISE, HSC, ZTF, and simulated LSST data, including actual science usage on the precursor datasets.

The production hardware, sized to handle ComCam data loads, will have been installed at the Chilean and US DACs. An instance of the Data Access Center environment will have been installed and tested on each, and data transfers to the Chilean DAC will have been tested. Bulk export services to data rights partners will have been tested using precursor and simulated data.

The Commissioning Cluster hardware, sized to handle ComCam data loads, will have been installed at the Base. An instance of the QA environment will have been installed and tested using precursor and simulated LSST data in the Data Backbone.

### 3.3.2 Pipelines

The pipelines will produce results necessary for the rest of Commissioning, particularly initial technical operations with ComCam. Instrument signature removal, including linear feature (satellite) removal and optical ghost masking; cosmic ray detection; point spread function (PSF) estimation; and astrometric and photometric fitting on full visits will all be delivered prior to ComCam operations. Full-visit background estimation, single-frame deblending, master calibration image generation, and atmospheric characterization will be available.

The pipelines will meet Key Performance Metric (KPM) criteria at the beginning of sustained scheduler-driven operation of ComCam as tested with precursor survey and simulated data. Those tests will have been performed at least annually prior to the ComCam integration milestone to demonstrate progress towards the KPM criteria. They will be re-verified once sufficient ComCam data is available during the first scheduler-driven, science-oriented data taking block.

We also will have analyzed data from Brookhaven’s Test Stand 8 and the Camera test equipment (Bench for Optical Testing, Camera Calibration Optical Bench) at SLAC in an offline mode using DM software.

### 3.3.3 The LSST Science Platform

The LSST Science Platform is a set of user services (Figure 16) to provide access and resources for the scientific user community. These services will be the primary means for how scientist with LSST data rights to connect to the US and Chilean Data Access Centers and interact with the survey data. The LSST Commissioning team will be the first “customer” for these services when the System AI&T and Commissioning phase start. The services comprising the LSST Science Platform are; the Science User Interface Portal; a Jupyter like computing and analysis Notebook; LSST computing resources; file system & storage; the LSST QServ database; and the LSST Image Processing and Analysis software stack.
Figure 16: The environment provided to the Commissioning Team on the Commissioning Cluster to access, analyze and visualize data. The same services are provided to QA staff in the production environment and to science users in the Data Access Centers.

There are two modes for users to access these services: 1) users can use the portal to do queries, visualizations and create web-based dashboards, or 2) they can connect through JupyterHub to a single-user notebook to do ad hoc analysis and visualization. These two modes of operation are built out of various components as listed below. The underlying databases and files in the Data Backbone are shared between them; in particular, this provides a way to transfer data from the more experimental notebook mode to the portal dashboard mode.

Access in Portal mode:

A web-based science user interface query/visualization portal will be provided using Firefly widgets. It will have access to all data products, including files managed by the Data Backbone and catalogs in the Qserv distributed database and other non-distributed databases.

The Data Backbone will arrange for access to files, replicating them where required including retrieving them from tape archives.

A Global Metadata Service will be created to allow identification of product files in the Data Backbone. The Global Metadata Service also stores information about available databases. These other databases include the SQuaSH quality control database and provenance databases.

Data will be retrieved via DAX web services, which communicate with the Global Metadata Service. The DAX services include a low-level “dbserv” service providing a raw SQL/ADQL interface to Qserv and other databases as well as translation of the query output into various formats including VOTable. At a higher level, DAX includes the “metaserv” service that provides metadata about images and other data products, often by querying underlying databases. It can also be used to generate lists of identifiers that can be passed to other DAX services or to the Data Butler. DAX also includes an “imgserv” service that retrieves image data products of all types (including raw, processed visit, difference, coadded), regenerating them based on provenance if necessary, and provides operations on them including mosaic/cutout and format translation.

Per-user storage for files and databases (both distributed and non-distributed) will be provided for storing the results of and inputs to the portal.
Authentication and authorization will be provided to implement controls on access to data-rights-only, group-wide, or personal data and other resources (such as compute, storage, and bandwidth).

Initial delivery of this mode is occurring in early 2017 as part of the Prototype Data Access Center deployment.

**Access with in Notebook mode:**

A JupyterHub service will be provided that allows users to create notebooks in which they can perform ad hoc data analysis and visualization.

Retrieval of data for use in the notebook will primarily be via the Data Butler client library, which returns loaded, in-memory Python objects. The Butler is responsible for presenting files from the Data Backbone and can also query databases. In addition, python_mysqlclient and SQLAlchemy database interfaces will be available to connect to Qserv and non-distributed databases, including per-user databases.

The LSST Science Pipelines toolkit will be available in the notebook environment to perform analysis, and Firefly widgets will be available to visualize results.

One or more batch clusters will be provided for batch computing. Transport of computations from the notebook world to the batch world, controlled by the notebook, will be defined. A workload management service will direct jobs to an appropriate compute resource given data availability, resource quotas, current load, etc.

Initial delivery of the “notebook” mode is being targeted for the end of 2017 as part of the internal development environment for Science Pipelines QA deployment.

**QA Environment**

There is a separate production instances of the LSST Science Platform environment for QA on Alert Production (L1) and Data Release Production (L2) data products, with a different list of authorized users, a different update cadence, and potentially different upgrade procedures. The other main differences are that this QA instance has access to unreleased intermediates and the internal, being-loaded Qserv instance containing the DRP catalog data products.

**DMS Computing Resources for Commissioning**

A Commissioning computing cluster provided by the Data Management team with architecture as close as possible to the Data Management System’s (DMS) computing clusters will be installed at the Base facility in La Serena. Commodity Linux boxes will provide these computing resources; a shared file system will be provided by a GPFS-based high-bandwidth distributed storage cluster. The Commissioning cluster will have the capacity of four trillion floating point operations per second of computing power and one petabyte of storage. The commissioning compute cluster would consist of 25 nodes plus a spare, providing 1,000 cores (five cores per camera CCD). Each compute box would have 160 gigabytes of memory (four gigabytes per core), for a total across the system of four terabytes. The storage would consist of 96 drives (plus three spares) of about 11 terabyte capacity, with an aggregate available bandwidth of 14 gigabytes per second. Four disk controllers would be used to host the drives, and two GPFS Network Storage Device nodes would be needed to control and provide access to the storage system. The overall capacity of such a cluster is approximately 10% of the compute power needed for
the Data Management Alert Production (39 TFLOPS).

The trade-offs between storage and CPU capacity necessary for the ComCam cluster may differ from those necessary for the DM computing clusters designed primarily for Operations. For example, it seems likely that the Commissioning cadence will produce fewer total images per year than the operational one. Therefore, it may be appropriate to purchase less storage and more compute as a result. These trade-offs will be evaluated and finalized as the Commissioning Plan is completed. The final layout of the Commission Cluster will be determined just before hardware purchase and the detailed testing plans are complete.

The commissioning cluster will have another instance of the environment will be instantiated on the Commissioning Cluster, with its own list of authorized users, update cadence, and upgrade procedures. This environment does not have specialized access to unreleased intermediates. This will be the primary environment for the Core Commissioning Team to perform ad hoc data reduction and analysis. This will give the Core Commissioning Team access to all DM software, including the science pipelines, data access middleware, process execution middleware, and even the science user interface. However, it is not anticipated that the DM distributed database (QServ) would run on the commissioning cluster, but would be accessible from NCSA. Custom processing pipelines can be executed and with sufficient coding even integrated with custom observatory control scripts.

### 3.4 System Networking

The LSST Observatory is distributed over four primary sites: the Summit Site, the Base Site, the Archive Site, and the Project Headquarters. While the sites are geographically distributed, they are all functionally integrated. Dedicated high-bandwidth fiber optic lines connect the summit and base, with the others connected through secure shared networks. Control functions are distributed for operational efficiency and to provide robust, reliable, safe operation.

LSST is investing in infrastructure that will guarantee adequate network links from Cerro Pachon to La Serena to North America during Commissioning and Operations. Each of the main links is further described below (more details can be found in the LSST Observatory Network Design (LSE-78)).

#### 3.4.1 Summit to Base Link

The key driving requirements for the Summit to Base communications are the bandwidth and reliability required to transfer the crosstalk-corrected image data and associated EFD meta-data for alert processing, transfer the raw image data to the Base Center, and handle OCS command and control traffic. LSST will install a fiber pair utilizing dense wavelength division multiplexing (DWDM) technology to provision three high bandwidth Lambdas with end nodes that will be owned and operated by LSST. This capacity is nominally divided into flows for image data transfer and a separate flow for OCS command and control data, but these allocations many change based on further design.

#### 3.4.2 Base to Archive Link

The minimum requirement for peak bandwidth, packet loss and network jitter, from the Base Center in La Serena to the Archive Center in Illinois is established by the need to transfer the crosstalk-corrected images for transient alert processing. The peak requirement for raw image data is much less, because the raw image data only need to arrive at the destination before the next night of observing starts. The
peak requirement for annual data release transfer from the Archive to the Base is even less, as this can occur over the period of a month or more.

The primary network infrastructure is path diverse from Santiago flowing either side of South America. LSST-available bandwidth on each coast of South America will be more than adequate for LSST requirements. Provisions for “bursting” will be available utilizing the two diverse links from Santiago to NCSA. The requirement calls for an isolated channel to service the image data stream link during observing hours.

3.4.3 Networking Integration

LSST will provide DACs in Chile and the US co-located with the Base and Archive Centers so data transfers between each site will be via local internal networks with 100 Gb/s or higher bandwidth. User access to the DACs will be via public and Research and Education Network (REN) connections (e.g. Internet and Internet2, XSEDE, ESNet), and the aggregate bandwidth will be limited only by the connectivity of the hosting and using institutions. In cases of stand-alone DACs or science centers funded outside the project, the entity developing and operating the center will be responsible for providing network connectivity to LSST Archive Center to enable data transfer.

The key networking integration milestones are the following (see Table 1):

- From Cerro Pachón Summit Facility to the existing AURA data center in La Serena and on to NCSA (via 100G managed ring) – September 2017
- From Cerro Pachón Summit Facility to the new Base Facility in La Serena and on to NCSA (via 100G managed ring) – September 2018
- From Cerro Pachón Summit Facility to the new Base Facility in La Serena and on to NCSA (via 100G spectrum link) - September 2019
Table 1: Networking integration milestones during both construction and commissioning.

<table>
<thead>
<tr>
<th>FISCAL YEAR</th>
<th>Construction</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summit</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
</tr>
<tr>
<td>Mountain - Base</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Base (LAN)</td>
<td>0</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
<td>Full</td>
</tr>
<tr>
<td>Base - Santiago</td>
<td>4 + 100</td>
<td>4 + 100</td>
<td>40 + 100</td>
<td>2 x 100 best case</td>
<td>100 + 40 worst case</td>
<td>2 x 100 best case</td>
</tr>
<tr>
<td>Santiago-Boca Raton</td>
<td>100g lit on (lambda)</td>
<td>100g lit on (lambda)</td>
<td>100g lit on (lambda)</td>
<td>100g lit on (lambda)</td>
<td>100g lit on (lambda)</td>
<td></td>
</tr>
<tr>
<td>Boca Raton - Chicago</td>
<td>0</td>
<td>100g lit on (lambda to Esset in Atlanta)</td>
<td>100g lit on (lambda to Esset in Atlanta)</td>
<td>100g lit on (lambda to Esset in Atlanta)</td>
<td>100g lit on (lambda to Esset in Atlanta)</td>
<td></td>
</tr>
<tr>
<td>Chicago - Archive</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>100 best case</td>
<td>40 likely case</td>
<td>40 likely case</td>
</tr>
<tr>
<td>Santiago-Miami</td>
<td>10x10G available for burst, 20% reserved</td>
<td>10x10G available for burst, 20% reserved</td>
<td>10x10G available for burst, 20% reserved</td>
<td>2x100G available for burst, 20% reserved</td>
<td>2x100G available for burst, 20% reserved</td>
<td></td>
</tr>
<tr>
<td>Miami - Chicago</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>100 best case</td>
<td>40 likely case</td>
<td>40 likely case</td>
</tr>
<tr>
<td>Chicago - Lyon</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>100 best case</td>
<td>20 likely case</td>
<td>20 likely case</td>
</tr>
<tr>
<td>Chicago - Tucson</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>100 best case</td>
<td>20 likely case</td>
<td>20 likely case</td>
</tr>
<tr>
<td>END TO END MIN CONNECTIVITY Gbps</td>
<td>10</td>
<td>100</td>
<td>100</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
</tbody>
</table>

3.5 Education and Public Outreach (WBS 05C)

Among large astronomy projects, LSST is unique in dedicating substantial effort during construction to produce an Education and Public Outreach (EPO) program that can be deployed near the beginning of Science Operations. EPO is also one of the most ‘downstream’ aspects of the overall project, benefiting from (and reliant upon) the Commissioning preparation and efforts of the three principal subsystems, most notably Data Management’s mini-survey and generation of alerts.

The purpose of EPO is to provide non-specialists access to LSST data through tools and interfaces that engage diverse communities with authentic research experiences and activities. EPO will achieve this through four main initiatives: 1) the EPO Portal, 2) formal education activities using science notebooks, 3) a streamlined workflow/toolset for developing citizen science projects with LSST data, and 4) multimedia for informal science centers. All of these initiatives depend on making data available in a way that is responsive to requests and easy for non-specialists to use. Therefore, a foundational component of the EPO program is a scalable data center tuned to unique EPO audience needs.

LSST has allocated a subset of LSST data for public use (as described in LSE-131). This data (or data derived therefrom) is categorized as follows:

- Alert stream: real-time flow of text and image data
- Animated images: image data organized into time-series groupings with movie-like playback
- Color images: ugrizy co-added images combined to output RGB-like color images
- Single-filter images: co-added images from a single filter
- Database: tabular relational data
Public data is transferred from the U.S. Data Access Center (DAC) at NCSA to the cloud-based EPO Data Center (EDC) on a nightly and annual basis:

<table>
<thead>
<tr>
<th>Data</th>
<th>Frequency</th>
<th>Derivative Source</th>
<th>Est. Quantity</th>
<th>Est. Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>alert stream</td>
<td>nightly</td>
<td>Community broker</td>
<td>10 million</td>
<td>400 GB</td>
</tr>
<tr>
<td>animated images</td>
<td>nightly</td>
<td>Compressed Processed Visit Image (PVI)-based images (for animation)</td>
<td>1,000</td>
<td>2.8 TB</td>
</tr>
<tr>
<td>color images</td>
<td>annual</td>
<td>Annual Data Release co-add images</td>
<td>sky coverage</td>
<td>243 TB</td>
</tr>
<tr>
<td>single-filter images</td>
<td>annual</td>
<td>Annual Data Release co-add images</td>
<td>sample set</td>
<td>1 TB</td>
</tr>
<tr>
<td>database subset</td>
<td>annual</td>
<td>Annual Data Release catalog</td>
<td>231 billion rows</td>
<td>7 TB</td>
</tr>
</tbody>
</table>

These data are then used by the following EPO products:

<table>
<thead>
<tr>
<th>Data</th>
<th>EPO Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>alert stream</td>
<td>• EPO Portal (Sky Viewer overlay and Object Pages)</td>
</tr>
<tr>
<td></td>
<td>• Data2Dome-compliant feed (for planetarium fulldome display)</td>
</tr>
<tr>
<td>animated images</td>
<td>• EPO Portal (Object Pages)</td>
</tr>
<tr>
<td>color images</td>
<td>• EPO Portal (Sky Viewer tiles and Object Pages postage stamp)</td>
</tr>
<tr>
<td></td>
<td>• Formal Education activities</td>
</tr>
<tr>
<td></td>
<td>• Citizen Science</td>
</tr>
<tr>
<td>single-filter images</td>
<td>• EPO Portal (Object Pages postage stamps)</td>
</tr>
<tr>
<td></td>
<td>• Formal Education activities</td>
</tr>
<tr>
<td></td>
<td>• Citizen Science</td>
</tr>
<tr>
<td>database subset</td>
<td>• EPO Portal (Sky Viewer and Object Pages metadata)</td>
</tr>
<tr>
<td></td>
<td>• Formal Education activities</td>
</tr>
</tbody>
</table>

The following sections define high-level integration Commissioning activities for EPO:

3.5.1 EPO Data Center

Similar to the LSST Science Platform, the EPO Data Center (EDC) provides infrastructure for an online portal, science notebooks, computing, storage, database, and software. This allows us to collaborate...
during development and share best practices. However, significant differences exist.

The EPO data center is tuned to the unique requirements of the general public. For example, “nearly half of web users expect a site to load in 2 seconds or less, and they tend to abandon a site that isn’t loaded within 3 seconds.”¹ In addition, the average attention span of the general public is 8 seconds.² Contrast that user experience with a typical astronomy researcher who is accustomed to batch processes, serialized data loading, and visualization processing that can take minutes, hours, or even days.

Equally important, field research and evaluation performed by LSST EPO during construction has confirmed that target audiences will interact with LSST EPO programming through mobile devices, which will be accounted for in EPO interfaces.

Another consideration for LSST EPO is that the user load and usage is unpredictable. Unlike astronomy research, which has a relatively small and predictable user base with known access patterns, use of EPO products can grow quickly with word-of-mouth recommendations, social media sharing, and general popularity. Accordingly, the EDC will follow agility best practices popularized by cloud computing by leveraging on-demand computing, object storage, and auto-scalable architecture.

V&V activities for the EDC and integration with the DAC include:

- Network load test
- Object Storage load test
- Database load test
- Web Server/CDN load test
- Compute scalability
- Science Notebook scalability
- Cybersecurity

### 3.5.2 Citizen Science

Considering the size of the LSST dataset, some research projects might be impractical or even impossible for individual researchers and their teams to accomplish. Citizen science offers a platform to enable public volunteers to come together to contribute to real science and help LSST Researchers achieve their results. LSST EPO has partnered with Zooniverse³, a popular citizen science framework and hosting service, to leverage and improve the potential for citizen science with LSST data.

The Zooniverse Project Builder⁴ allows LSST Researchers to design citizen science projects with tools that will be specifically designed by LSST EPO to function with LSST data. Both the annual data release catalogs and images (Level 2) and time domain alert stream (Level 1) data products can be used for LSST

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¹ [https://blog.kissmetrics.com/speed-is-a-killer/](https://blog.kissmetrics.com/speed-is-a-killer/)
³ [https://www.zooniverse.org/](https://www.zooniverse.org/)
⁴ [https://www.zooniverse.org/lab](https://www.zooniverse.org/lab)
Citizen Science. LSST Researchers will define their projects, build a workflow within the Zooniverse Project Builder, and pull in a small sample of LSST data to test functionality before fully launching to the public.

By focusing on streamlining the integration of LSST data with the Zooniverse framework and supporting self-service tools, LSST EPO will enable far more citizen science projects, and therefore science results that citizen scientists contribute to, than could be supported solely by LSST EPO.

V&V activities for Zooniverse and integration with the DAC include:

- Implementation of the *Unified LSST Authentication and Authorization Service* (see LSE-279)
- Metadata scrubbing and generation of postage stamp images
- Network load test
- File storage load test

### 3.5.3 Alert Stream

To make the LSST alert stream meaningful and useful for the public, EPO will require some form of classification. EPO will leverage a community broker (like ANTARES⁵) for this capability. During Construction, a precursor dataset (like ZTF) will be leveraged for prototyping EPO products that rely on alert stream data.

V&V activities for the community broker and integration with the EDC include:

- Network load test
- Extract, Transform, Load (ETL) test

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⁵ [https://www2.cs.arizona.edu/projects/antares/](https://www2.cs.arizona.edu/projects/antares/)
The Commissioning Plan: Pre-Commissioning Preparations

In preparation for System AI&T and Commissioning, the project will have a “preliminary design” equivalent review – Commissioning Preliminary Design Review (ComPDR) – with enough lead time to make corrections to the plan, complete remaining simulations, analysis and tool development needed for all key activities, tasks and procedures. Holding a Commissioning PDR circa early 2017 leaves two plus years to fully develop and complete analytic and data visualization tools based on the LSST Software Stack, develop and run simulations of critical commissioning activities and procedures, and synchronize the final implementation plan with a fully developed set of verification requirements. A January 2017 Commissioning PDR also gives two plus years (from this writing) to develop increased fidelity of the Commissioning Plan activity details, procedures, prototypes of the analysis and data visualization tools and initial simulations of key procedures of commissioning activities.

Approximately nine (9) months prior to the scheduled onset of the Commissioning Phase, circa January 2019, the project will hold a “final design” level Commissioning Readiness Review. This allows for approximately 15 months after the ComPDR to ramp up the staffing and needed expertise for the core Commissioning Team; complete the full suite of analysis and data visualization tools; and complete the validation of task procedures analysis tools through simulations. The Commissioning Readiness Review serves as a final check that the activities, tasks and procedures are complete and ready for implementation.

In addition to reviews, Pre-Commissioning Preparations include scope to support

- Oversight of the development, assembly and testing of ComCam at the NOAO facilities in Tucson, AZ;
- Development and validation of test procedures and their analysis scripts through simulations, design; and
- Development, procurement and delivery of hardware specifically needed by the commissioning effort that is not covered by other MREFC WBS packages nor the DOE-MIE LSSTCam project.

These are described in the following sections.

4.1 Commissioning Camera: ComCam

A commissioning camera (ComCam as described in LSE-199) consisting of a single science raft populated with nine engineering grade sensors (144 megapixels) is being developed as part of the construction effort to produce a 40x40-arcmin field-of-view at the three-mirror telescope focus. A three-element corrector will produce <0.3 arcsec FWHM images in the LSST’s u-g-r-i-z-y filter bands. ComCam will utilize the same CCS+DAQ as the full LSSTCam to facilitate system level interface testing during the Early System I&T phase, including interfaces for the DAQ-DM (LSE-68) for science sensor readout and transfer, DAQ-TCS (LSE-67) for wavefront sensor readout and transfer, CCS-TCS (LSE-66) guider sensor readout and the OCS-Camera Control System (LSE-71) for supervisory control.

ComCam will be integrated onto the telescope using the rotator/hexapod interface of the Top-End Integrating Structure (TEIS) with a surrogate mass assembly to mimic the full camera mass and center of gravity (Figure 17). This will allow early mapping of the telescope flexure and its subsequent correction...
with the Active Optics System (AOS). The sensor readout electronics control three (3) sensors each. These electronics can be configured such that two of the three sensors can be operated as guiders, while the third is unused. This will allow ComCam to be configured where outer corner sensors are operated as guiders and the inner sensors are operated in a standard integrating mode. In this configuration ComCam will be used to fully test the Camera-Telescope guider interface.

The full LSSTCam has four (4) wavefront sensors arranged in a square pattern around the periphery of the LSST’s 3.5-degree field-of-view. These wavefront sensors consists of two adjacent 2kx4k sensors with their focal position split by +/-1.5mm to provide intra and extra focal images used to solve Transport of Intensity Equation for the aberrated wavefront. While ComCam will not have any dedicated wavefront sensors installed, it can be operated in a way to approximate the acquisition wavefront data used to close optical loop of the AOS. Using the hexapod to piston ComCam +/-1.5mm on either side of focus allows either intra or extra focal images to be acquired. This will allow ComCam to be used to develop the active optics look up tables and verify the Camera-Telescope wavefront sensing interface.

ComCam is being developed jointly by both the MREFC Telescope & Site and DOE LSSTCam efforts. The DOE funded LSSTCam project is responsible for delivery of a single Raft Tower Module (RTM) in a cryostat along with the necessary additional hardware and software to support its operation as an imaging system. The Telescope and Site team within the NSF-funded LSST project is responsible for delivery of the frontend components necessary for operating the cryostat as a camera mounted at the LSST telescope focus. ComCam is built up from the following system elements with responsibilities for each indicated:

- One RTM (DOE MIE) consisting of
  - Nine 4K x 4K LSST science CCDs (engineering or “near” science grade, DOE MIE);
0 Three Raft Electronics Boards (REBs, DOE MIE);
- A data acquisition system that conforms to the Data Acquisition Interface between Data Management and the Camera (LSE-68, DOE MIE);
- An optical corrector (NSF MREFC) that produces images across a 20 arcmin FOV, with FWHM < 0.5 arcsec with same plate scale as LSST (50 microns/arcsec);
- A high quality “photometric” shutter (NSF MREFC);
- A filter-changing mechanism that allows for one of three filters selected from the six LSST filters (ugrizy) to be placed in the beam (NSF MREFC);
- A set of six filters that match the LSST passbands (NSF MREFC);
- A dual thermal control system that regulates the focal plane and circuit board temperatures (DOE MIE);
- A cryostat that encloses the single raft tower module with associated feed-through ports and vacuum pumping system (DOE MIE);
- An instance of the Camera Control Software (CCS, DOE MIE) that allows for scripted operation of the commissioning camera with appropriate interfaces to the Telescope Control Systems (TCS, NSF MREFC) and Observatory Control System (OCS, NSF MREFC);
- An instance of the data acquisition system (DOE MIE) scaled to ComCam data sizes;
- The software for centroid determination when sensors are run in guider mode (NSF MREFC); and
- The software for wavefront curvature analysis when the system is run in wavefront sensor mode (NSF MREFC).

4.1.1 Camera Summit Facilities Preparation

The Summit Facility service building contains facilities for camera maintenance, repair and testing. These facilities are broken down into three distinct regions, with each room outfitted to meet the requirements for certain camera assembly, maintenance and test activities: 1) a staging and test area; 2) a class 100,000 “white” room and 3) a class 10,000 “clean” room. Both the “white” and “clean” rooms will have gone through standard start-up procedures and have been certified to meet their cleanliness standards. At this point all three of the camera maintenance regions will need to be outfitted with LSSTCam specific fixtures, test stands and other support equipment necessary to re-verify LSSTCam upon arrival and provide maintenance capabilities during routine operations. For each of the three areas, we will first describe the work that is performed in the area followed by a description of the preparation required in the area prior to camera hardware arriving.

4.1.1.1 Staging and Test Area

Area utility: The staging and test area exists as a region within the third floor high bay of the Summit Facility. It has access to 10T and 60T cranes, though some of the area overhead is shadowed by a walkway above. This area will be used to receive the camera, perform re-verification measurements of the FPA metrology and reverify camera throughput. This area has no control on the cleanliness so operations requiring a clean environment will need temporary clean tents.

The following equipment will permanently exist in the staging and test area:
• Camera Integration Stand

**Required preparation:** The staging and test area must be clear of other equipment and have bolt patterns installed in the floor at the camera integration stand location(s). Requisite tools will be assembled and organized in tool chests. The overhead crane must be certified for use with the camera and fit tests with camera list fixtures performed.

![Diagram of camera integration stand](image)

Figure 18: The LSSTCam staging area mechanical layout showing the placement of the integration stands used for re-verification and maintenance. The dashed lines indicate the limits of crane access in the high bay area.

### 4.1.1.2 White room

**Area utility:** The white room is an 8.6 meter x 7.3 meter room with better than class 100,000 cleanliness. The room is equipped with a 10T crane with a 3.7 meter hook height. This room is used for camera assembly and maintenance that requires opening the camera body. Types of operations that will be performed include:

- Installing the lens 1-lens 2 (L1-L2) assembly upon receiving the camera
- Installing filters into the filter storage box
- Servicing the shutter and auto changer assemblies
- Removing the cryostat from the camera body housing

The following equipment will permanently exist in the white room:

- Saddle Support Stand
- Cryostat Support Stand
- Shutter Service Stand
- Auto Changer Service Stand
Required preparation: The white room must undergo an initial cleaning. Bolt patterns will need to be installed in the floor at the various permanent and temporary fixture location(s). Requisite tools will be cleaned and assembled and organized in tool chests. Storage for various pieces of camera maintenance hardware will also be installed. Gowning equipment and supplies must be installed. Utilities including power, cooling liquids, compressed gases and networking need to be verified. Once all equipment and tooling is installed in the room a final cleaning to meet required cleanliness follows.

Figure 19: The “white” room layout showing the positions for test stands used for L1L2 alignment (upper left); shutter servicing (upper right); filter auto-changer maintenance (lower right) and cryostat testing (lower left).

4.1.1.3 Clean room

Area utility: The clean room is a 4.3 meter x 12 meter room with better than class 10,000 cleanliness. This room is used for camera maintenance and assembly that requires opening the cryostat. Types of operations that will be performed include:

- Removing and replacing an RTM
- Servicing the cryostat internal components
- Replacing any failed components inside the cryostat

The following equipment will permanently exist in the clean room:

- Bench for Optical Testing (BOT)
- Raft Integration System
- Single Raft Electro-Optical Test Stand (TS8)
- A-frame Crane

**Required preparation:** The clean room must undergo an initial cleaning. Bolt patterns will need to be installed in the floor at the various permanent and temporary fixture location(s). Requisite tools will be cleaned and assembled and organized in tool chests. Storage for clean camera replacement hardware (raft tower spare[s]) is installed. Electrostatic discharge control (ESD) certification and compliance work must be performed. Utilities including power, cooling liquids, compressed gases and networking need to be verified. Once all equipment and tooling is installed in the room a final “horizontal and vertical” cleaning follows and the clean room is placed into operation.

![Clean Room, Electronics Annex, Ante Room](image)

**Figure 20:** The “clean” room layout showing test stands.

### 4.1.2 Simulations, Procedure Development & Validation

Simulations have long been an important part of the LSST project. In particular, in the past a few years, the project has developed the LSST integrated model, which is a high-fidelity model of the to-be-built Camera-Telescope optomechanical and electro-optical system. As systems are delivered the integrated model will ultimately represent the as-built Camera-Telescope. The model is integrated because it is a joint simulation of optics, structure, sensors electronics and control. It links engineering, environmental and operational parameters to key LSST performance metrics including: single visit image quality, ellipticity, limiting depth etc. The LSST integrated model also has the capability of simulating full focal...
plane images and time sequenced observational data.

To date, the integrated model has been used by the Project to perform various trade and acceptance studies, evaluate system performance against requirements, and predict the observatory’s overall scientific performance. As part of the System AI&T and Commissioning Plan, the integrated model will be a tool that will primarily be used in two ways: 1) during the pre-commissioning preparation phase we will use the model to simulate planned observational procedures and use the simulated images to validate the procedure, accompanying analysis script(s) and expected results, and 2) while carrying out commissioning activities, the model will serve as a diagnostic tool for troubleshooting software or hardware problems.

As we develop further details of the System AI&T and Commissioning Plan, we will use the model to validate the procedures for verification tests and their subsequent analyses. We will simulate the time sequenced observations needed by those tests, develop the analysis scripts using the LSST software stack and validate by means of simulations that both the procedure and analysis will yield the results needed by a given test. We will start this work in fiscal year 2017 so that when commissioning commences we will have dozens of these “pre-canned” tests and scripts ready to go. This way we can minimize having to make up analysis and new scripts on the fly.

Once Commissioning is underway, we will use the model as an exploratory tool to diagnose problems as we go. For example, suppose we see some strange image artifacts. Using on-sky time to explore the source of the artifact is expensive. In such situations, we can use our simulation tools to first explore the parameter space for the source and determine the most probable cause. Multiple people can do this exploration in parallel on multiple machines on the Commissioning Cluster. It should be possible to turn targeted simulations and analysis with a week, thus allowing the results to assist with the weekly planning and 2-week look ahead work plan. Then we can use on-sky time to try the highest-probability cases first.

**Integrated Model Overview**

The LSST integrated model is made of three primary elements: 1) the outside environment is shown in yellow; 2) a representation of the physical hardware is in blue; and 3) the system feedback signals and controls (Figure 21). We describe the structural system by finite element models (FEM) of the steel, glass, and actuators. The control block of the integrated model includes the Look-up Table (LUT) feed-forward, the wavefront sensor feedback, guiding, force balance, and thermal control of the various components of the system.
The central optical engine of the integrated model is Photon Simulation (PhoSim), an ultra-fast custom photon Monte Carlo ray-tracing tool that is described in detail in Peterson et. al, AJS 218, 14 (2015). PhoSim has been developed and designed as part of the LSST project to be a high-fidelity physics-based image simulation tool. It is capable of simulating time sequenced full focal plane images. During its development, the Project and Phosim teams have conducted numerous and detailed validation tests of all aspects of PhoSim, including optical path difference with respect to ZEMAX, surface deformation relative measurements and finite element analysis (FEA) models and atmospheric turbulence relative to measured performance from the LSST site.

This integrated model has been used in many compliance analyses and trade studies. To showcase the high fidelity of the integrated model, we give an example of how it has been used in capturing the as-built M1M3 mirror surfaces and evaluating the optical performance. Figure 22 (left) shows a high resolution map of M3 surface containing high spatial frequency residuals, “crow’s feet”, from optical figuring. The high-resolution M1 and M3 surfaces have been put into our optical model, the resultant Point-Spread-Function (PSF) radial profiles with and without crows’ feet are found in Figure 22 (right). The simulations showed that the 5-sigma image depth loss due to “crows’ feet” is about 0.012 magnitudes. Meanwhile there is ~0.8% of area loss around bright stars due to increased background brightness. No noticeable effect was found on PSF ellipticity. The integrated model will be continually updated with as-built measurements, like those from M1M3, as components are finalized and delivered to the system.
The synthesized surface map (left) of M3 with high spatial frequency features left over from fabrication included. The simulated PSF radial profile (right) showing the increased contribution to the PSF width from the residual “crows’ feet” on both M1 and M3 surfaces.

When Commissioning starts, the integrated model will be the best representation of the system we have except for the system itself. Such a high fidelity model will allow parallel exploration to determine likely cause when anomalies are discovered without using up valuable on sky time. Once the most like cause of an anomaly is determined it can be confirmed with minimal on-sky making more efficient use of available time.

ComCam Alignment Evaluation

As a first step in applying the integrated model to the needs of the Commissioning effort, we have used the integrated model to analyze the capabilities of ComCam to determine the telescope alignment and surface figures of the M1M3 and M2 mirror systems. The optical design for ComCam has been implemented in the integrated modeling framework (Figure 23). In our current simulations, we have included the gravitational and thermal deformations of the mirrors as predicted by their FEM. Uncertainties in the rigid-body positions of the M2 and Camera hexapods are introduced based on the vendor-provided laser tracker accuracy.
Figure 23: The optical implementation within the PhoSim optical ray-trace engine for ComCam (left) and for the LSST Camera (right) in the LSST Integrated Modeling framework.

The integrated model allows us to analyze the sensitivity matrix, the matrix of optical aberrations versus specific system perturbations, with ComCam to evaluate the efficacy in reconstruction (through matrix inversion) of the optical state of the system. Similar to the LSST Camera, the optical sensitivity matrix for ComCam is full rank in the absence of noise. However, the near-degeneracy of the sensitivity matrix is clearly visible in Figure 24. The smallest singular values are more than six orders of magnitude smaller than the largest ones. The near-degeneracy is even more significant than the LSST Camera, due to the smaller field of view of the ComCam. When noise is present, some of the degrees of freedom of the system are practically degenerate. To avoid the amplification of the noise during the matrix inversion, we set the five smallest singular values to infinity. As pointed out by Schechter and Levinson (PASP, 123, 812 2011), this creates a “benign misalignment” which does not harm the system performance.

We have simulated wavefront sensing using ComCam, where we piston the detectors by ±1.5mm, with 17\textsuperscript{th} mag stars located at the nine chip centers of ComCam and the telescope in its r-band configuration. These images were processed through the LSST wavefront sensing software (Xin et al, 2015, Appl. Opt. 54, 9045) to estimate the wavefront. The wavefront measurements obtained from the donut images were then used to estimate the system optical state.

Figure 24: Singular values of the ComCam sensitivity matrix (red circles), compared to the singular values of sensitivity
These simulation results show that the same control strategy we developed for the LSST Camera can successfully bring the system with ComCam into convergence, with superb image quality and ellipticity within their budgeted values. Figure 25 shows results from one of the simulation runs. Both the image size and the ellipticity have been averaged over the field and the broad wavelength band using the Gaussian Quadrature method. The black horizontal line on the figure’s left side shows the budgeted error on the image size corresponding to the error sources that have been included in the simulation. For this simulation run, the budgeted error is 140 mili-arcsec (mas), including the optical design error (80 mas), the AOS (79 mas), the gravitational and thermal distortions to the mirrors (83 mas). The SRD requirement on the single-visit ellipticity is that the mean ellipticity be below 4%, which is well above what we have in the figure’s right side.

For both the state estimator and the AOS controller, we have implemented and tested a set of alternative strategies that could be useful for troubleshooting during commissioning. For example, in additional to the baseline optimal controller, we have also implemented and tested the interface where we simply truncate the sensitivity matrix, i.e., to freeze a subset of control motions and only let the others be actively controlled by the AOS. Our tests of this alternative control strategy show that while the resultant image quality is generally less optimal than the baseline strategy, it has the advantage of being conceptually simpler, hence making troubleshooting problems easier, and usually results in more stable system states.

4.1.3 Miscellaneous Hardware Tools

The System AI&T and Commissioning effort will require additional hardware that is not specifically required by any of the LSST subsystems, but are needed to facilitate various planned commissioning tests. These currently include

- An aluminum pin-hole filter mass simulator. This is essentially an aluminum replica of one of the LSST filters where a grid of configurable pin-holes centered in front of each of the 21 science rafts. This will allow pin-hole images to be obtained showing the interior structure of the LSSTCam and telescope to probe for stray and scattered light;
- Pin-hole assembly for the L1 lens cover to allow basic imaging tests during re-verification of the LSSTCam when it arrives in Chile;
- A Camera maintenance area “flat” field light source for functional re-verification tests of LSSTCam in Chile;
- Refrigeration pathfinder hardware (except lines, compressors and compressor racks) including test cryostat(s), mounting hardware and controllers;
- A portable differential image motion monitor (DIMM) for seeing measurements in the dome and around the summit facility to calibration the facility DIMM with on-site performance;
- Laser tracker for camera alignment after shipping to Chile;
- A portable thermal infrared IR camera to look for heat plumes and heat sources affecting dome seeing; and
- Miscellaneous monitoring equipment to track the performance provenance as the Summit Facility is built up and out fitted, for example vibration transducers for the dome pier and lower enclosure, ground current monitors, RFI spectrum analyzer, etc...

In addition to the above test equipment, there are miscellaneous storage and shipping containers that will be provided by DOE-COM funds. Note: The DOE MIE project only supports the shipping container for the LSSTCam.
5 **The Commissioning Plan: System Assembly, Integration & Test**

5.1 **Early System AI&T with ComCam: WBS06C02.02**

The first phase of system integration is with ComCam, a preliminary instrument that replicates much of the functionality of the LSSTCam, allowing the test and partial verification of critical interfaces that are common to both cameras. This section outlines the planned activities that utilize ComCam. It is envisioned that basic functionality and a first layer of optimization of the camera, its interfaces, and the coordination with other subsystems is achievable with ComCam. This period of testing will enable a more efficient verification of the full LSSTCam, where the large majority of these activities will be repeated to complete the verification of the full system. The scope of Early I & T includes the following general objectives:

- Tests of network connectivity and bandwidth using live data between the Summit and Base Facilities and between the Base and Archive facilities;
- Tests of command and telemetry interfaces between Camera Control System and OCS;
- Build/refinement of telescope pointing model;
- Test Camera-Telescope Guider interface and telescope guiding functionality;
- Verification and characterization of active optics performance using ComCam as a wavefront sensor;
- Build/refinement of active optics look-up tables;
- Demonstration of safe autonomous scheduler driven observing operations;
- Verification of time-dependent survey cadence with as built scheduler – observatory interactions;
- Test/refinement of instrumental signature removal pipeline and algorithms on live data;
- Test/refinement of Data Management photometric calibration performance on live data;
- Test/refinement of Level-1 data products with Data Management alert production algorithms; and
- Initial tests of Level-2 data release production.

5.1.1 **ComCam Shipping and re-Verification: WBS 06C02.02.01**

ComCam will be assembled and fully functionally verified in Tucson, after which it will be shipped to the Summit Facility in Chile. Upon ComCam’s arrival on the summit, a series of reassembly and testing activities, shown in Figure 26, are planned to re-verify ComCam performance and functionality prior to its installation on the telescope.
After shipping ComCam to the summit, it will be unpacked and inspected on site. The camera White Room will be used for the inspection. The data acquisition system (DAQ) for ComCam will be installed on site in the computer room and tested with the previously installed Camera Control System (CCS). The optical corrector will be inspected to ensure no damage occurred during shipping. The ComCam cryostat will be re-assembled with the optical corrector including the shutter and the filter changer using a dedicated test stand in the “white” room. A laser tracker will be available to verify alignment. All the utilities and networking will be connected to ComCam while in the White Room. This will allow full functional tests to be conducted through the OCS command-control interface. All the mechanisms will be tested independently using local controllers. The ComCam cryostat will be pumped and the detectors will be cooled. ComCam will be delivered with its own cooling system, as it is not using the same refrigeration system as the LSST camera. The ComCam cooling system and utilities are expected to use the telescope Dynalene system for heat removal.

Prior to the delivery of ComCam to the summit, the CCS and DAQ computing systems and network interfaces will be installed on the summit in order to facilitate early network communication verification activities. The integration activities prior to the receipt and assembly of ComCam will be focused on telemetry and high-level interactions between subsystems. The first opportunity for system-wide software integration including the CCS, DAQ, OCS, and DMS will be when ComCam is in the white room on the summit. Integration with the TCS is primarily communications based as much of the TCS will be in a simulation mode while ComCam is not on the telescope. Even while operating in a controlled environment, a large portion of the software integration can be completed. This includes coordination of sequencing with the OCS and the opportunity to supply data to the DMS and ensure that the appropriate meta-data from all of the appropriate systems are associated with the image. The ability to read out the detectors in only designated regions-of-interest will also be exercised, as well as the ability to designate the four corner detectors as guiders that read out at a faster rate. This is an important prerequisite to guiding activities that will be performed once on the telescope. Upon completion of the functional tests and software integration to the level possible without telescope interaction, ComCam will be ready to be installed into the Camera Assembly.

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5.1.2 Calibration Systems AI&T: WBS 06C02.02.02

The commissioning of the calibration systems, including the In-Dome systems and Auxiliary Telescope, are coordinated such that they can be used as tools for diagnosis, support, verification, and characterization throughout System AI&T and Commissioning. The first of these calibration systems to come online is the Auxiliary Telescope (AT) and its spectrometer.

The purpose of the AT and its spectrometer is to obtain data that characterizes the spatial, temporal and wavelength dependent atmospheric transmission. This will primarily be performed over the current observed area of the LSST, but occasionally used in a mode where full sky characterization is prioritized, irrespective of the current LSST pointing. To accomplish these objectives, the Auxiliary Telescope has three primary modes operation: 1) scheduler driven basing its observations on previous LSST survey visits and a forward map where the LSST telescope is predicted to go in the following ~5-10 minutes; 2) scheduler driven all-sky coverage; and 3) manual script driven whose use-cases are based upon special programs for testing purposes. Each of these modes will be tested and verified as part of the AT commissioning activities.

Commissioning activities with the Auxiliary Telescope, shown in Figure 27, starts with the verification of image data transport from the spectrometer through the DAQ interface (LSE-68) to the Data Management System (DMS) at NCSA. This is a prerequisite to testing and verifying the part of the Calibration Products Pipeline (CPP) used for processing the AT data. In parallel with verifying the instrumental signature removal (ISR) processing, interactions between the Auxiliary Telescope, OCS and AT Scheduler are tested. Robotic operation of the telescope is also optimized to ensure high reliability over all seasons, weather, and environmental conditions. Once the spectrometer ISR is verified, then the processing, observing procedures and algorithm for generating the atmospheric transmission function is verified. The revised observing procedures are fed back to the AT Scheduler algorithm at which time the system is ready for operations to support further activities with ComCam and LSSTCam for the remainder of the System AI&T and Commissioning effort.
The In-Dome calibration systems, including the calibration screen and the Collimated Beam Projector, will undergo commissioning activities of their own with both ComCam and LSSTCam. Although both calibration systems will be fully operational and verified before handing off to the Commissioning team, neither system will be optimized for operation. The optimization of these instruments can be largely completed with ComCam, with only re-verification and small parameter updates required with the LSSTCam.

The suite of activities planned for commissioning of the calibration screen system involve creating an algorithm that controls the timing of the ComCam/LSSTCam shutter with the illumination system and characterization systems. For example, when performing a flat field observation, the photodiodes must first be activated to acquire data, then camera shutter is opened, the laser illumination system, already acting in closed-loop operation to compensate for vibration, opens the shutter for a designated amount of time. At this time, the spectrograph(s) are measuring the output of the light source. After the designated time expires, or the photodiode reaches a given count level, the laser shutter closes, the camera shutter then closes, and the photodiode stops measuring the incident light. The procedure must be developed, automated, and optimized for every flat sequence, including the 300-1125 nm bandpass measured with 1 nm resolution. Moreover, the effects of scattered light on the flat fields must be quantified, examined and fed back into the parts of the Calibration Products pipeline (CPP) that used to process these data. If necessary, un-illuminated frames may be interlaced with the flat fields to measure and correct for scattered light. Much of this testing, including the algorithm development and the hardware sequencing will be performed with ComCam. It is anticipated that the amount of open-shutter time, or number of required exposures per wavelength will have to be adjusted for the LSSTCam.

Commissioning activities involving the CBP are of similar nature. Determination of proper exposure times for each wavelength and CBP beam position on the telescope pupil are required. Furthermore, the coordination of the CBP pointing and mask rotation, combined with the LSST position must be mapped to the LSST focal plane. This relationship is being captured by a coordinate transform and mapping tool being developed by DM. This tool must be incorporated into the CBP control system. Once completed, the CBP will be used to perform numerous characterizations and verifications of the LSST camera. One of the early tests will be to replicate the measurement of the filter transmission curves measured using the Filter Metrology System developed by the Camera Team. Scripts and algorithms will then be developed to monitor the evolution of the filter response curves for a set number of physical positions on the filter. Other CBP related tests include: measurement of the detector gains as a function of...
temperature, characterization of amplifier crosstalk, linearity characterization and correction.

5.1.3 Camera Refrigeration Pathfinder: WBS 06C02.02.03

The purpose of the Refrigeration Pathfinder is to verify the full LSSTCam refrigeration system, since ComCam will be using a different cooling system. It will share some of ComCam’s utility trunk volume when installed on the TMA, and allows for verification of the compressors and refrigeration lines as well as the initial conditioning of the systems. Critical activities include oil additions, refrigerant mix adjustments, and load curve testing. This can be accomplished without affecting ComCam performance.

The LSSTCam refrigeration pathfinder will be used both in the camera maintenance facility (White Room or Staging Area) and on the TMA. In both cases, decontamination of the lines is the primary goal. The lines on the TMA provide the additional challenge of the significant elevation change between the compressors and the refrigeration system. However, similar configurations will have been tested at SLAC well in advance of commissioning.

The pathfinder will first be installed in the camera maintenance area White Room, with the first set of compressor cabinets installed in the machine room. This activity is scheduled to start March 2019 and be completed by mid July 2019. It involves connecting, purging, evacuating, and charging all of the six cryo and two cold lines running to the White Room from the compressors in the machine room. Once testing is completed, the lines will be disconnected and sealed. At this time, the compressor cabinets in the machine room will be moved up to the TMA and installed.

Concurrently with pathfinder maintenance area activities, the lines on the TMA must be pre-cleaned. During the purge, evacuate and charging activity of the line pairs, the TMA is partially restricted. Pumps will be mounted to the TMA such that the purging process can be running concurrently with TMA testing. However, some cleaning activities will restrict the TMA to the horizontal service position due to personnel access, therefore this work must be coordinated with other planned activities involving the TMA.

Once maintenance area testing is complete, TMA lines are cleaned, and the compressor cabinets are moved up to the TMA, scheduled to occur July 2019, the system will be ready for the refrigeration pathfinder to be mounted on the telescope. Pathfinder activities on the TMA are scheduled to start January 2020 and run concurrently with ComCam integration activities on the telescope, since the pieces of hardware are interconnected. There are six sets of cryo lines and only two can be tested with the pathfinder at one time, so once the first set of lines is performance tested then time will be needed to switch over to the second set of lines before testing can continue. This requires restricting the TMA to the horizontal position for a short period of time (no more than 8 days), so this work must be coordinated with ComCam observing activities. Refrigeration pathfinder testing is expected to complete in October 2019.

Testing thermal performance of the refrigeration system with the pathfinder provides additional knowledge to the refrigeration team about aspects of the system including pressure drops due to elevation changes and performance changes from tweaks to refrigerant mix. This knowledge is directly applicable to the final camera since the heat exchange systems are almost identical. However, the performance test portion of the refrigeration pathfinder sequence may be de-scoped if it interferes with higher priority commissioning needs.
Figure 28: There are two refrigeration systems for the LSSTCam that will need commissioning. The first sequence is the commissioning activities for the “white room” system used for re-verifying LSSTCam after it ships to Chile. The commissioning the system on the TMA in preparation for integrating LSSTCam on the telescope is shown by the second activity sequence.

5.1.4 ComCam - Telescope AI&T: WBS06C02.02.04

The process of commissioning ComCam with the telescope begins with readying the telescope top-end for ComCam. This process begins with the removal of the Camera Support assembly from the Telescope Top End, then loading it onto the camera cart for transportation to the lower Summit Facility service area via the Platform Lift. This item is the first in the waterfall of ComCam and Telescope Commissioning activities shown in Figure 29. The Shack-Hartmann, CMOS Camera and their mounting structures are removed from the camera surrogate mass that is mounted on the camera rotator interface. ComCam is then integrated within the camera surrogate mass and connected to the camera cable wrap utilities.

The corrector front lens will be protected with a lens cap that will be removed only after installation on the telescope. It is currently foreseen that the cryostat will have to be disconnected from its closed-loop cooling system for integration within the camera surrogate mass. The cooling system will be installed on the telescope separately and re-connected to Comcam after installation on the telescope. The camera
cart is then transported to the platform lift for transfer to the telescope. See section 5.3.2 for more details on how the camera support assembly is installed on the telescope.

![Figure 29: The sequence of activity planning packages to install, integrate and test ComCam and perform system level test and verification once ComCam is installed on the telescope.](image)

After installation on the telescope, all the utilities will be connected to ComCam and the testing sequence performed in the White Room will be repeated. In addition, all the systems located within the camera support assembly will also need to be reconnected and re-tested, such as the camera rotator and camera hexapod systems. A standard procedure will be followed each time the camera support assembly is removed or installed in the telescope. ComCam is directly accessible from the deployable platforms designed on the telescope to access the LSST camera. For example, they will be used to change which filters are installed, to access the cryostat and to remove the cap on the front lens.

Upon installation on the telescope, re-verification of the communication interfaces between the control systems is performed. At this time, the majority of the TCS functionality is not in simulation mode and can be exercised. Dark or bias frames are taken with ComCam and ingested into the Data Management system. Verification of hardware components, such as the shutter and filter mechanisms, are also performed at multiple telescope and rotator positions and compared to their nominal performance as well as the value that is used by the Scheduler. At this time, the Calibration screen and illumination system will not have been optimized for operation. However, the system will be sufficiently operational to perform non-optimal flat fields that can be used to determine an approximate gain. This preliminary gain measurement can then be used as a test case in changing configuration files and ensuring the change is properly incorporated by the data management system.

In parallel, and following, the control system interface commissioning is a series of Electro-Optical tests that are being performed to both characterize and optimize the camera, calibration, and observatory related hardware. The IMS utilizes three instances of “Electro-Optical” testing periods. The generalized
term is used rather than identifying the numerous individual activities going on in that time period. A subset of such tests is shown in Table 2, with the system readiness level shown in the column labelled, “System Readiness.” During each allocated time period, functional and characterization testing across multiple systems is ongoing, which are appropriate for that level of system readiness. Also, this time will be used to take early datasets to validate the needs and readiness levels required for future tests. In the first period of testing, the overall system readiness level is low; therefore the testing is largely focused on closed dome activities. However, early on-sky testing will occur, such as the optical alignment and on-axis image quality tests of ComCam.

![Figure 30: ComCam is installed mounted to the Top End Integrating Structure. Steel plates (black blocks) are added to simulate the LSSTCam’s mass, CG and moments. The front disc has the same diameter as L1 on the LSSTCam that will allow LSSTCam installation procedure to be tested and verified.](image)

At this time, the on-axis image quality will be assessed and compared to the result obtained previously during T&S Ai&T using only the three-mirror system with the Shack-Hartmann and high-speed CMOS cameras. The off-axis image quality at this point will be a good validation of our FEA models of the mirrors. Short unguided images will be taken at a series of elevations to test the level of fidelity of the FEA models, as image quality should decrease uniformly over the field. During this testing period, the in-dome calibration screen and illumination system operation will be optimized, for all filter bandpasses. Furthermore, daily calibrations (bias, flats, darks etc.) will be obtained creating a baseline for understanding the relationship between detector performance such as gain and crosstalk and the environment or telescope orientation. These measurements will also help constrain the rate of change of dust accumulation or movement and how it will affect the frequency for which flat-fields will need to be obtained. Naturally, as all these different types of images are acquired, the performance of the data ingestion system will be monitored and improved where required (e.g. associating the appropriate meta-data with each image).

During this period of Electro-Optical testing, the commissioning of the Collimated Beam Projector is occurring, this activity is called out explicitly as bringing this instrument to a high-level of operability is
critical for performing many characterization tasks, several of which are shown in Table 2. The CBP testing will include optimization of exposure times as a function of wavelength, and image quality analysis. The more sophisticated integration will include incorporation of the CBP Coordinate Transformation Tool that is being developed by the DM team but will also be used by the TCS to determine the desired pointings of the telescope relative to the CBP, functions properly and therefore ensures the incident light is on the user-designated areas of the pupil and focal plane. Once this tool is fully commissioned, then the scripting of sequences to both calibrate the light originating from the CBP, and perform complex characterization tasks, such as relative throughput testing of the filters, can commence. It is possible to perform certain tests without this Coordinate Transformation tool, such as the linearity and crosstalk measurements, but the efficiency would be degraded. One critical cross-check that will be performed in this phase is ensuring the filter transmission measurements using the CBP are consistent with the filter characterization performed by the vendor at acceptance.

Table 2: A subset of the electro-optical tests that will be performed with both ComCam and LSSTCam. Large amounts of the early testing will be performed while the dome is closed using the Calibration equipment.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Method</th>
<th>ComCam time estimate</th>
<th>Full Camera time estimate</th>
<th>System Readiness</th>
<th>Commissioning data reduction required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative system throughput measurement with an</td>
<td>Illumination from Calibration Screen and CBP, compare measure LSST</td>
<td>360 hours, or two</td>
<td>360 hours, or two</td>
<td>Calibration</td>
<td>combined analysis of light on focal plane and calibration</td>
</tr>
<tr>
<td>without filters</td>
<td>detector photoelectrons vs. calibration photodiodes</td>
<td>weeks</td>
<td>weeks</td>
<td>Screen and CBP</td>
<td>light sources.</td>
</tr>
<tr>
<td>Gain determination under nominal conditions</td>
<td>Photon transfer curve (Poisson statistics) using pairs of flat fields</td>
<td>30 hours</td>
<td>30 hours</td>
<td>Calibration Screen</td>
<td>Photon transfer curve analysis</td>
</tr>
<tr>
<td>Gain determination temperature dependence</td>
<td>pairs of flats, using Poisson statistics,</td>
<td>120 hours</td>
<td>120 hours</td>
<td>Calibration Screen</td>
<td>photon transfer curve analysis</td>
</tr>
<tr>
<td>Crosstalk matrix determination under nominal</td>
<td>Spots on the array from CBP, on one amp per CCD at a time</td>
<td>1.5 hours</td>
<td>1.5 hours</td>
<td>CBP using one-spot-per-CCD mask</td>
<td>centroiding on spots and appropriate aperture photometry on all amps</td>
</tr>
<tr>
<td>conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crosstalk matrix temperature dependence</td>
<td>Spots on the array from CBP, on one amp per CCD at a time</td>
<td>15 hours</td>
<td>15 hours</td>
<td>CBP using one-spot-per-CCD mask</td>
<td>centroiding on spots and appropriate aperture photometry on all amps</td>
</tr>
<tr>
<td>Linearity correction determination</td>
<td>Images with staggered exposure times</td>
<td>4 hours</td>
<td>4 hours</td>
<td>Stable CBP flux</td>
<td>analysis of sequential spots, at different durations.</td>
</tr>
<tr>
<td>Astrometric positioning of each CCD</td>
<td>on-sky rastered imaging in i band</td>
<td>0.5 hours</td>
<td>3 hours</td>
<td>On-Sky Capability</td>
<td>astrometric reduction of images</td>
</tr>
<tr>
<td>Photometric stability across focal plane</td>
<td>on-sky rastered imaging in i band</td>
<td>0.5 hours</td>
<td>3 hours</td>
<td>On-Sky Capability</td>
<td>photometric reduction of images</td>
</tr>
<tr>
<td>CBP multi-pinhole mask exitance calibration</td>
<td>Slew CBP to overlay adjacent pinhole images on co-boresighted reference</td>
<td>10 hours</td>
<td>30 hours</td>
<td>CBP using one-spot-per-CCD mask</td>
<td>CBP data analysis code, coordinate transformation tool</td>
</tr>
<tr>
<td>Validation of wavefront sensor performance</td>
<td>on-sky operation of wavefront sensors</td>
<td>5 hours</td>
<td>no additional time</td>
<td>On-Sky Capability</td>
<td>Put ComCam data through AOS pipeline</td>
</tr>
</tbody>
</table>

The next set of activities is the refinement of the telescope and ComCam pointing model. During this time, thorough pointing testing will be performed to update the pointing model for the telescope mount
to incorporate the effects of adding ComCam and to explore dependencies on the local environment. Re-verification of the slew and settle requirements for the telescope will also occur during these tests. This period will also allow a thorough verification and further calibration of the FEA model being used to compensate for gravitational and thermal effects of the primary mirror. These refinements of the FEA model will be used as part of the updating the initial look-up tables used for the active optics control.

At this point, the system readiness level will have sufficiently advanced to include adequate communication between the systems, coordination of events, and characterization of the detectors to begin commissioning of the Guiding system. The Raft Electronics Boards (REBs) each control three sensors. A REB can be configured such that two out of its three sensors can be operated as if they were guiders found in the LSSTCam corner rafts. For these tests ComCam will be configured such that the outer most four of the nine sensors in the raft will be run as guiders and the central three sensors as normal imaging devices. This will allow a preliminary verification of the Guider Interface between the Camera and Telescope (LS-E-66) to ensuring the specified regions of interests around each guide star is correctly computed and communicated to the CCS. In this configuration a number of tests will include fields of all varieties, from high to low stellar densities, over large guide star magnitude ranges, and under various sampling rates up to the required 9hz.

Upon completion of the Guider Commissioning, initial testing of the TCS and DAQ interfaces for wavefront sensing applications will begin. Because there is no intrinsic wavefront sensing capability built into ComCam, wavefront data will be obtained by offsetting the z-position of the camera in order to obtain intra- and extra-focal images. These data will then be used to test the AOS pipeline and algorithm, a critical component of the system. Due to the differences between this method and the system employed for the LSSTCam, only a partial verification of the Wavefront Sensor Interface between the Camera and Telescope (LS-E-67) can be obtained.

Upon completion of this event, a weeklong period is designated for general engineering activities. The “Engineering Punchlist Resolution” activities are weeklong planning packages aligned to bright time each month. Due to the increased sky brightness, this time is optimal for i) performing closed-dome engineering activities, ii) using the time to repeat tests that may not have been fully successful on the first attempt, iii) completing and/or updating documentation such as test reports, procedures, and iv) updating the document containing the lessons learned during commissioning. Performing on-sky night time testing is not precluded during this time, but we anticipate that it will be significantly reduced and focused on engineering related issue resolution.

Upon completion, another period of Electro-Optical tests occurs in conjunction with the creation of the measured AOS lookup table. Updating the initial AOS Look-up Table (LUT) to real data will be done by measuring and optimizing the image quality over a wide range of telescope positions, but mainly focusing on calibrating the elevation dependence. This will be the first time field dependent optical aberrations will be measured to reconstruct the many potential perturbations in the LSST opto-mechanical system. Because ComCam is designed to act as a spare LSSTCam raft, there are no on-board dedicated wavefront sensors. In order produce wavefront sensor-like data, ComCam will be positioned by the hexapod to create intra- and extra-focal images, the AOS pipeline will then be used to calculate the required distribution of bending modes to apply to the mirror in order to achieve the best possible image quality over the entire ComCam field of view (see section 4.1.3). Upon determining the best actuator positions for a known series of telescope positions, interpolation is used to determine the best
configuration for any telescope pointing.

This series of testing requires on-sky data, specifically with good seeing conditions. Furthermore, the dependence of the thermal environment will be characterized and accounted for. During non-ideal observing conditions, guider testing and characterization will continue measuring the effects of telescope position and particularly the effect of wind shake and optimum dome venting. The time will also be used to perform ghosting and stray light measurements. This can be done using a combination of bright stars, which illuminate the entire pupil, and the CBP which illuminates only a small portion. A pinhole mask will also be placed in the filter mechanism to create an image of the telescope interior on the ComCam detector as illuminated by the calibration screen or bright star. This method is useful for identifying surfaces of the telescope structure are contributing to stray light and can be subsequently treated to minimize their effects. Lastly, a detailed understanding of the telescope throughput as a function of position in the focal plane is a prerequisite for next following series of planned testing. The position dependent throughput map will be derived from a combination CBP and the Calibration screen data that will be obtained by this time.

The last series of planned commissioning activities prior to the ComCam being ready for Bulk Data Production is focused on verification of the AOS. At this time, integrated testing of the guiders and AOS system will be performed. This includes the verification of the de-blending algorithms. With the focal plane image quality being stable, the distortion will be characterized and the astrometric performance measured. Analogous testing of the photometric performance will also be obtained. These observations will be performed in coordination with the Auxiliary Telescope, analogous to how the LSST survey will be performed. Combination of the CBP and Calibration screen data, combined with the atmospheric transmission data from the Auxiliary Telescope, will provide the first full system test of the photometric performance of the LSST system.

Once ComCam is ready for Bulk Data Production, which is shown as the first milestone in Figure 29, the first of three “Technical Operations Optimization” periods begin, each having a three-week duration. These periods run in parallel with sustained scheduler driven observing aimed at software testing as described in section 6. Fully integrated system commissioning is planned during these tests with the objective aimed at deriving the optimal usage and characterization of the LSST’s hardware-software systems. For example, this implies but is not limited to: deriving optimal wind gate configurations depending upon the wind direction and telescope orientation, examining and quantifying dome seeing, measuring image quality as a function of environmental conditions, implementing coordinated observing with the Auxiliary Telescope, testing the required frequency of calibrations, and monitoring ComCam detector performance. The system performance aspects required for use in the Scheduler will be updated in during this phase of commissioning.

During this time period, large amounts of data will be produced and processed through the data management system (see section 6 for detailed discussion) science pipelines. It is expected that designated areas of the sky will be re-visited multiple times and the relative astrometric and photometric performance evaluated and monitored. Although these tests will aim to use scientifically interesting fields, the goals of these activities are strongly geared towards engineering activities. Upon completion, a series of mini-survey’s will be completed that will be used to verify system capability and performance, while providing a dataset motivated by scientific goals.
5.1.5 Science Pipeline Testing with ComCam

During the opto-mechanical and electro-optical integration and test activities with ComCam all imaging data will be processed with the LSST’s software stack. Even though the software updating will be a continuous process, we have scheduled planned software/middleware updates once a month to coincide with the engineering punch-list resolution blocks. This will allow the DM software team to consolidate updates made during previous commissioning activities and to release new features as part of the ongoing development effort.

During early ComCam-Telescope hardware integration, the software focus is on using the results from the electro-optical testing to update and verify the Instrument Signature Removal (ISR) pipeline code. Getting good and accurate ISR is necessary in order for the subsequent science algorithms to be tested. Once Bulk Data Production with ComCam is approved and initiated software testing will focus on the science algorithms for Alert Processing (AP) and Data Release Processing (DRP) using data from the “scheduler driven observing” periods.

5.1.6 Early System Verification Tests with ComCam

LSST’s verification strategy is to verify requirements as early as possible. Formal system verification begins as soon as all prerequisites for a given verification activity are met. Figure 32 provides an overview of the major AI&V Phases and the general categories of system-level verification activities.
There are several general groups of system-level requirements that can be verified very early even before the start of Pre-commissioning Preparations with ComCam. Requirements that specify general system characteristics (for example: facility types, facility locations, facility characteristics and capabilities, mirror configurations, instrument type, design standards, and process requirements) as well as some system-level verifications that rely upon subsystem-generated artifacts can be verified very early while the subsystems are still conducting their own subsystem AI&V. Requirements will be verified as early as possible so that the number of open requirements needing verification in Commissioning is minimized.

Most of the prerequisites for system-level interface requirements are satisfied by ComCam, given that the utility connections between ComCam and the Telescope; command, telemetry and event interfaces between ComCam and OCS, and image readout and delivery interfaces between ComCam and DM are the same as those for the Full Camera. After requirements are verified, their verification status is continually monitored throughout the rest of the Commissioning phase. With software in particular, as new versions are released and implemented into the baseline, incremental verification activities are undertaken to ensure that the new code base’s execution does not violate previously approved verification activities. With each incremental release of software, incremental unit, integration, and regression tests will be performed and mapped to previously approved verification activities. Any results that show deviations from previously verified requirements will result in those requirements’ verification status being reopened, and plans to re-verify those requirements will be implemented into the overall commissioning plan.

The follow sections show summary matrices of interfaces, functionality, and performance that can be verified by ComCam using the following categories of verification:

- **Full (F)** - the requirement (or group of requirements) can be fully verified
- **Partial (P)** - the requirement (or group of requirements) can be partially verified. This means either some of the requirements in the group can be fully verified and others not or that portions of the scope of an individual requirement can be verified but other portions not. Requirements (or groups of requirements) that are partially verified are also mapped to
subsequent verification activities during Systems AI&T and/or Science Verification and Full System Characterization.

- **Incremental (I)** - the requirement has been previously fully verified but a new version of the hardware or software has been introduced and is incrementally verified to ensure previous results are not invalidated. The incremental verification activities are narrow and limited in scope, focusing primarily on the features of the unit or component that have changed from the previous version.

- **Monitor (M)** - the requirement has been previously fully verified but the key aspects of the requirement are executed again in subsequent verification activities. These requirements are noted as Monitored in the subsequent verification activities so that any results that may invalidate previous successful verifications will be noted and traced to the impacted requirements.

**System Interfaces**: Many of the system-level interfaces will be verified with ComCam. Table 3 shows a matrix of system-level Interface Control Documents that can be partially or fully verified with ComCam activities.

**System Functionality and Performance**: Many of the functional and performance requirements specified in both the LSST Systems Requirements (LSR; LSE-29) and Observatory System Specifications (OSS; LSE-30) can be partially verified with ComCam. Table 4 shows the matrix of system-level performance and functional requirement groups that can be partially verified with ComCam activities.

Table 3: A matrix mapping of when system interfaces can be partially verified with ComCam during each group of activities in Early System AI&T.
Table 4: A matrix mapping of when groups of LSR and OSS requirements can be partially verified with ComCam during each group of activities in Early System AI&T.

<table>
<thead>
<tr>
<th>Activity Area</th>
<th>Activity Group</th>
<th>Activity Name</th>
<th>Calibration &amp; Verification</th>
<th>Commissioning &amp; Planning</th>
<th>Pre-Commissioning Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>21-1-1 Power for Performance</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>21-1-2 Engineering Model</td>
<td></td>
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<td>21-1-3 Engineering Functions</td>
<td></td>
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<td></td>
<td></td>
<td>21-2-1 Early System AI&amp;T</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>21-2-2 System-Wide</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>21-2-3 System-Wide AI&amp;T</td>
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<td></td>
<td></td>
<td>21-3-1 System-Compliance and Efficiency</td>
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<td></td>
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<td>21-3-2 System-Compliance</td>
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<td>21-4-1 System Security</td>
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<td></td>
<td>21-6-2 System Final</td>
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</table>

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5.2 Full System AI&T with LSSTCam: WBS 06C02.03

Full System AI&T covers all commissioning activities involving the full science camera (LSSTCam) beginning with the shipping and re-Verification at the Summit Facility and ending with a pair of sustained observing campaigns for science pipeline testing.

5.2.1 LSSTCam Shipping and re-Verification

The LSST Camera shipping plan is detailed in LCA-14953. This document covers the time period from the camera pre-ship review at SLAC until the camera arrives at the summit. Also included in this document are the shipping plans for camera test and support equipment.

The MIE project includes the design and construction of the camera shipping container(s). Shipping containers for all other camera-related hardware are provided through DOE-COM support of System AI&T and Commissioning as are all shipping costs. Recent projects indicate approximately two weeks for hardware shipped from the United States by air to reach the summit and six weeks if shipped by sea. The current plan for shipping the camera is to reuse the L1/L2 shipping container provided by the camera optics subsystem and ship the remainder of the camera as a unit in a separate shipping container via air freight.

The LSST Camera re-verification plan is detailed in LCA-14954. The document covers the time period from camera arrival at the summit until the camera is ready to be integrated with the top end integrating structure provided by the telescope and site subsystem (see the planning sequence shown in Figure 33).

Upon arrival all camera hardware is unpacked and visually inspected, and telemetry from the shipping containers is examined. The cryostat+utility trunk (UT) is then removed from the camera body and installed into the bench for optical testing (BOT), where a final metrology scan of the focal plane is made to re-verify flatness. No variation from the pre-shipping state is expected, but at this point the overhead to perform this check is minimal.

The cryostat/UT assembly is then reinstalled in the camera body while mounted to the saddle support stand. The L1/L2 lens assembly is reinstalled and the camera alignment procedures from LSSTCam AI&T are repeated. After the camera is fully assembled, it is moved to the camera integration stand (Figure 34) where alignment is verified, utilities are connected and aliveness tests are performed with the CCS prior to pumping down and cooling the camera.

The camera calibration optical bench (CCOB) is installed underneath LSSTCam where tests are conducted to re-verify electro-optical performance. Once the focal plane is at operating temperature,
LSSTCam throughput testing is repeated with data flowing through the full data path. After review, the camera will be made available for telescope integration. A warm up of the camera and disconnection of maintenance area utilities will be required prior to moving the camera from the integration stand and into the camera rotator on the camera cart.

![Image of LSSTCam on Integration Stand](image.png)

**Figure 34:** LSSTCam on Integration Stand used for re-verification tests after shipping to Chile. The figure also shows the lines of sight for the laser tracker to verify alignment of L1-L2, the Camera Body and Cryostat. This same configuration is used with the CCOB to vary the LSSTCam throughput in each of the six filters.

The table below is taken from LCA-283 (Table 37) and lists the camera requirements that will be re-verified with the CCOB. In addition to measuring optical throughput most of the camera functionality is tested including power up, thermal and vacuum control, shutter open/close, filter changes, and data taking. By examining ghost reflections in the CCOB camera alignment is also rechecked (see LCA-283).

**Table 5:** The primary re-verification tests that will be done on LSSTCam after re-assembly at the Summit Facility in Chile.

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The contents of this document are subject to configuration control and may not be changed, altered, or their provisions waived without prior approval.
5.2.2 LSSTCam-Telescope Integration and Test

Many of the procedures that were used and validated to install and test ComCam will be repeated for the installation and test of the LSSTCam. This section describes main planning activities for the installation of LSSTCam and the subsequent final system performance and interface verification tests that will be conducted.

At the start of this period LSSTCam will have been re-verified on its Integration Stand (Figure 35) in the Summit Facility maintenance staging area. The Top End Integrating Structure (TEIS) with ComCam is removed from the TMA and brought down to the maintenance staging area. ComCam is removed from the hexapod/rotator and the TEIS is readied for accepting the LSSTCam. The procedure for transferring LSSTCam from the Integration Stand to the hexapod/rotator on the TEIS will be reviewed, rigging checked and test runs conducted. In parallel with these activities are “Pre-LSSTCam Install Engineering” activities to prepare the telescope top end to accept the TEIS with LSSTCam integrated. This engineering effort includes pre-verification preparation of the LSSTCam refrigeration lines, fiber optic data and networking connections, etc.

Once these initial activities are completed, procedures updated and status documented an Integration Readiness Review will be held. This review will focus on ensuring both the LSSTCam and Telescope are
properly prepared for integration; critical lift plans, procedures are in place, understood and have received their own safety reviews, including all critical lift plans (e.g. any movement of glass requires a critical lift plan). Only following this review will the LSSTCam begin the transfer from its Integration Stand to the hexapod/rotator on the TEIS and ultimately to the telescope itself.

Figure 35: The planned activity sequence for install and testing LSSTCam on the telescope assembly beginning with the removal of ComCam and ending two periods of sustained observing for software testing and operations optimization.

The LSSTCam transport cart is designed to support the TEIS + LSSTCam assembly consisting of the rotator, the hexapod, the cable wrap and the integrating structure with the offset. The camera cart will be located in the maintenance staging and test area next to the “white” room (Figure 36). The rotator and hexapod will be already mounted on the LSSTCam transport cart as well as the Camera cable wrap. The overhead gantry crane will be used to transfer LSSTCam from its integrating stand to the hexapod/rotator mounting interface. This is considered a critical lift and the plan will be part of the internal review review. Once the LSSTCam is physically integrated with the TEIS + hexapod/rotator (Figure 37) the LSSTCam utilities will be connected thought the top-end cable wrap. At this point the LSSTCam, hexapod/rotator, TEIS and cable wrap assembly will be connected to the Summit Facility network where full command-control functional tests with the CCS and OCS will be conducted. LSSTCam will not be re-tested with FPA at cryogenic temperatures at this stage.
Figure 36: The Summit Facility side view with Camera ready to be transferred from its Integration Stand to the hexapod/rotator +TEIS on the LSSTCam transfer cart.

Figure 37: The configuration of the integrated LSSTCam on the hexapod/rotator and Top-End Integrating Structure. The final axial dimension of the offset structure serves as a compensator for the as-built telescope mount dimensions to place the LSSTCam at its required position within mid-travel of the hexapod actuators.

After completion of the functional testing, the LSSTCam transportation cart will be moved onto the platform lift and the platform lift will be elevated to the dome entrance (Figure 38). The cart will be
moved into the dome and placed in front of the telescope top end. The telescope will be pointing at horizon and the camera installation guide rods will be attached to the telescope. The laser tracker will be operational to guide the camera assembly during installation and the camera lifter will be suspended on the dome crane.

Figure 38: Facility top view with Camera installed on Camera Cart showing transfer to Platform Lift

The LSSTCam + TEIS assembly is integrated into the telescope mount assembly using a dedicated lifting fixture (Figure 39). The dome crane is used to lift this assembly where it will be inserted thru the secondary mirror center hole. Alignment of the LSSTCam assembly is maintained using previously installed guide rods and movable trim weights within the lifting fixture. The in-situ laser tracker will be used to provide high precision real-time positional feedback. This is a critical lift that will be part of the internal review review. Once the LSSTCam assembly is physically installed on the telescope, the lift fixture and guide rods will be removed.

At this point the LSSTCam utilities are connected including clean power, networking, dedicated fiber optics for the DAQ, coolant supply for the utility trunk, and the LSSTCam refrigeration lines. Before the coolant and refrigeration lines are connected functional “aliveness” tests will be conducted through the CCS and OCS. These tests will verify the communication and command interfaces are correctly functioning between the CCS, TCS and OCS. Functional tests involving operation of the shutter and filter changer will be done at various rotator angles. The in-situ laser tracker will be used to measure the rotational dependence of the LSSTCam deflection on the hexapod/rotator and fed back into the active optics look-up tables.

After verifying basic functionality on the telescope LSSTCam will be connected to its refrigeration system. The refrigeration lines will have been previously cleaned, purged and tested during Early AI&T. The cleaning and purging process will be repeated with LSSTCam, but is expected to be shorter in duration than the initial start-up. While the refrigeration system is being brought on line, the LSSTCam
cryostat is undergoing final vacuum pumping. Only when the prerequisite vacuum is achieved will the refrigeration system be turned on to beginning cooling the FPA. While the FPA in LSSTCam is cooling to operational temperature (~100C) the telescope can be operated without constraints. This will allowed the elevation dependence of the LSSTCam deflection to be measured using the in-situ laser tracker. These measurements will be used to further refine the active optics look-up tables and verify the control of the hexapod positioning of LSSTCam. Early images taken with LSSTCam will be sent to NCSA and used to verify the DMS data acquisition interface and networking performance. At the later stages of cool down limited on-sky activity will be used to re-verify the telescope pointing model.

Figure 39: Camera assembly suspended from the Dome crane using the camera lifting fixture (left); Camera Assembly installed on telescope with scissor lift for personnel access (right).

Once the FPA is at operating temperature full electro-optical and on-sky testing can begin. The suite of electro-optical tests first done with ComCam (see Table 2) will be repeated with LSSTCam. These tests will provide final verification of FPA performance in the true operating environment including read noise, linearity and crosstalk. Final system throughput and filter responses are measured and verified at this time as well. The data from these tests will be sent to NCSA for processing as part of the final verification of the instrument signature removal algorithms in the Calibration Products Pipeline.

The electro-optical tests are primarily scheduled as daytime activity. The main emphasis for night time operation is building and verifying the active optics look up tables and optical feedback from the wavefront sensors. Early observations will be used to characterize the general system performance, verify interfaces and provide a baseline from which to build from. Characterization will include:

- Establish and verify feedback to the TCS from the corner raft guide sensors; complete final verification the camera-telescope guider interface including region of interest selection and image transport to the TCS;
- Map the position of best focus using “focus-sequences” over the full focal-plane-array as a function of elevation, azimuth and rotator angle, adjust hexapod control to best fit focal surface, and update hexapod control look-up tables as needed;
- Map the PSF size and shape over the full FPA as a function of elevation and azimuth;
- Map the optical aberrations over the full FPA using the camera FPA as a wavefront sensor;
- Process all images through the DMS instrumental signature removal pipeline;
- Update calibration data products for the instrument signature removal including:
  - Bias & dark master images
  - Narrowband flat images from the dome screen in each filter
  - Wideband flat images from the dome screen
  - Shutter timing corrections
  - Illumination corrections from “star flats”
- Characterize stray and scattered light versus lunar angle and azimuth to verify that the FRED point source transmittance function matches the as-built system; and
- Obtain early data for DM pipeline debugging.

Once the basic camera-telescope integration and characterization is completed, the focus of the Camera-Telescope integration activities turns to testing and verification of the active optics system. The tasks used to calibrate the wavefront sensors and those needed to verify the optical reconstruction will be interleaved. It is expected that these two activities will have to iterate with each other to achieve desired performance.

Calibrating the wavefront sensors consists of using the full LSSTCam science FPA as a wavefront sensor. At first, alternating intra-, extra-, and in-focus image sets will be used calibrate the focus position of the wavefront sensors with respect to the science FPA. The mean of the focus Zernike coefficient (Z4) is determined for each of the 189 science sensors from the intra- and extra-focal image pairs. A best-fit plane to the 189 mean Z4 coefficients is determined. The hexapod is adjusted iteratively until the mean focus error over the FPA is zero. The Z4 focus coefficient offsets for each of the corner wavefront sensors are recorded as a function of elevation, azimuth, and rotator angle. Updates are made to the active optics look-up tables as needed.

Using the method described above, the full science array will be used as a curvature wavefront sensor. The mean wavefront error at the center of the 189 science sensors will be evaluated using separate optical reconstructor to evaluate the optimal alignment and surface error corrections over the science field of view. These optimal corrections are compared to those estimated from the four wavefront sensors alone. Any systematic offsets from the state estimated by the four wavefront sensors and the optimal state will be used to optimize the AOS look-up tables and optical feedback algorithm.

5.2.3 System Verification Tests

System functionality, performance, maintainability, and availability requirements will be verified during the System Assembly, Integration and Test Phase and the Science Verification Phase. The following subsections describe these verification activities in additional detail.

System Interfaces: System interface testing will wrap up during System Assembly, Integration and Test with some interfaces re-verified with the LSSTCam. However, most interfaces are verified using ComCam, as ComCam was designed with common interfaces in mind. Interfaces verification will primarily be monitored (M) at this stage to ensure that ongoing activities do not invalidate previous
results. Table 6 shows the high level grouping of system level interfaces as they are mapped onto System SI&T activities using the same categorizations: Partial (P), Full (F), Incremental (I), and Monitor (M) as described in Section 5.1.6 Early Verification Tests.

**System Functionality and Performance:** Verification of system functionality and performance requirements will hit its peak during System Assembly, Integration and Test. Figure PDH shows high level groupings of requirements from the LSST System Requirements document (LSR, LSE-29) and the Observatory System Specifications (OSS, LSE-30) onto major activities scheduled for the System Assembly, Integration and Test phase as well as the Science Verification Phase. Single Image Performance, control capabilities, data collection capabilities, monitoring and diagnostics, as well as calibration capabilities will all be verified during the System AI&T Phase. Requirements that dictate functionality and performance over the life of the survey, such as data release processing, science priorities and survey monitoring, operational efficiency, system availability, and timing and dynamics will have their full verifications occur during Science Verification with the mini-Surveys were realistic subsets of time-domain data and telemetry can be obtained.

Table 6: A matrix mapping of when system interfaces can be verified with LSSTCam during each group of activities in Full System AI&T. System Interface Verifications will be monitored in the Science Verification Phase.
Table 7: A matrix mapping groups of system functional and performance requirements to key System AI&T and Science Verification activities where they will be verified or monitored.

5.3 DM Services during Commissioning

The first data management services that will come on-line are those that curate data for the Engineering Facilities Database (EFD). Early incarnations will be as simple as a systematic recording of site data with increasing richness as site systems are commissioned. EFD services begin to operate on the summit well before commissioning begins (September 2017). The completion of the Base Facility and occupancy begin in March 2018 and the Commissioning Cluster is expected to be available in January 2019.

With the start of On-Sky observations from the Auxiliary Telescope (August 2018) the DM systems the Data Backbone services will be capable of archiving all observations. ETL services (extract, transform, load) for the EFD also become operational at this time. Here also would begin the validation that mirroring of data across sites occurs properly. In addition early pipeline tests would begin through batch processing of selected data. When a stable pipeline is reached systematic nightly processing of Aux telescope data would begin followed by use of the batch system to systematically reprocess any archived data that is warranted.

Early commissioning of the telescope with ComCam begins in November 2019. Early work would revolve around technical elements (e.g. interfaces) with early data processing by DM occurring in a "sampling" mode. Once high-level validation of telescope/camera operations warrant this 'sampling' mode would grow in scope to process data for technical feedback to the commissioning team. Data Backbone services will be expanded and validated to include Archive to Base transfer.
Table 8: Data Management Services capabilities development schedule during the full commissioning phase of the project.

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<thead>
<tr>
<th>Service</th>
<th>Production-Ready Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aux Telescope Delivery (all services at Aux Telescope size):</td>
<td>Nov 2017</td>
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<tr>
<td>● EFD ETL Service</td>
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<tr>
<td>● Aux Telescope Archiving Service</td>
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<tr>
<td>● Data Backbone (Aux Telescope archiving)</td>
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<tr>
<td>ComCam Initial Delivery (all services at ComCam size):</td>
<td>Nov 2019</td>
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<tr>
<td>● Data Backbone Upgrade (Archive to Base transfers)</td>
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<tr>
<td>● Telemetry Gateway Service</td>
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<td>● OCS-Controlled Batch Processing Service</td>
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<td>● Offline (and Catch-Up) Processing Service</td>
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<td>● Batch Processing Service</td>
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<td>● Data Release Production Service</td>
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<td>ComCam Sustained Operations Delivery (all services at ComCam size):</td>
<td>Feb 2020</td>
</tr>
<tr>
<td>● Data Backbone Upgrade (product databases)</td>
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<tr>
<td>● Commissioning Cluster and QA Environment Upgrade (full capability)</td>
<td></td>
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<tr>
<td>● Prompt Processing Service</td>
<td></td>
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<tr>
<td>● Event Broker Hosting</td>
<td></td>
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<tr>
<td>Full Camera Delivery (all services upgraded from ComCam to Full Camera/DR2 size):</td>
<td>May 2020</td>
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<tr>
<td>● Main Camera Archiving Service Upgrade</td>
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<td>● Data Backbone Upgrade</td>
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<tr>
<td>● Prompt Processing Service Upgrade</td>
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<tr>
<td>● OCS-Controlled Batch Processing Service Upgrade</td>
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<tr>
<td>● Offline (and Catch-Up) Processing Service Upgrade</td>
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<tr>
<td>● Batch Processing Service Upgrade</td>
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<td>● Data Release Production Service Upgrade</td>
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<tr>
<td>● Commissioning Cluster and QA Environment Upgrade</td>
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<tr>
<td>● Data Access Center (US) Upgrade</td>
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<tr>
<td>● Event Broker Hosting Upgrade</td>
<td></td>
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<tr>
<td>Science Verification Delivery:</td>
<td>Nov 2020</td>
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<tr>
<td>● Data Access Center (Chile)</td>
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Sustained operations using ComCam are expected in February 2020. Here bulk data sets at a raft scale would be processed to start science pipeline validation and to assess observatory and scheduler performance. At this point Data Backbone Services for product databases will be validated. This period culminates with mini-surveys using ComCam where the data. Prior to the mini-surveys, work will concentrate to close the feedback loop between L1 processing and Observatory Operation, first in batch and then as prompt (live) processing. In addition, as templates become available, full L1 services (transient detection and alert generation) would be validated through batch processing. In addition with the arrival of mini-survey data, tests of the L2 batch processing system begin with the goal to obtain validation that Key Performance Metrics (KPMs) are being reached. Data products from the commissioning will be made available on a limited basis several months after a specific phase has been completed – e.g. Early System AI&T, Full System AI&T and Science validation. Images from a particular phase will be made 3 months after the completion of that phase, while the databases containing the source and object catalogs will be available an additional 3 months later. Thus prototype DAC services must be functioning by this time.

In October 2020, On-Sky and Calibration Data from the Science Camera begin. With full focal plane data, the processing and data transport now reach full capacity and technical validation of the L1 prompt and batch services are tested. Shortly thereafter (January 2021) sustained scheduler-driven observations with the Science Camera begin at scale and validation of all science pipelines begins.

The start of Science Verification Mini-Surveys begins to demonstrate and characterize the full system against all science and EPO requirements. Currently two mini-surveys are planned, the first (SV1) over 6 weeks covering 30 fields to 10 year survey depth. The second (SV2) would provide a final validation that operations with the scheduler produce the expected areal coverage and depth (see Sec. 6 for more detailed description). Here both Alert Production (L1) and Data Release Production (L2) pipelines would be exercised to further validate the science pipelines along with improvements that have been made based on the previous observations. During SV2, real-time alert production should occur with events forwarded to community brokers. Also, the scale of L2 production is such that it would be possible to validate the use of multiple computation sites (NCSA and IN2P3) are properly performance. Release of Full Camera images and static science catalogs are scheduled for July and October 2021, respectively. These set the earliest dates for an Operations Readiness Review. Reduced images, static catalogs, and moving object orbits would be provided through SUIT, EPO, and both US and Chilean DACs.
6 The Commissioning Plan: Science Validation & Full System Characterization

The final phase of the Commissioning Plan is a five-month period dedicated to Science Verification. The terms “Science Validation phase” and “Final Science Verification with mini-surveys” both refer specifically to this five-month period that comprises the observations, data reduction, and scientific analyses for two operational readiness mini-surveys. Most of the system requirements will be tested prior to the mini-surveys to provide early feedback during system integration. We use the term “Early Science Verification” to refer to data quality assessments made during the initial testing of both ComCam and LSSTCam, which are also described in this Section.

The science verification activities are structured around demonstrating that the system functional and survey performance comply with the specifications given in the Science Requirements Document (SRD, LPM-17) and LSST System Requirements (LSR, LSE-29). In addition, these activities mark the beginning of an extended effort to thoroughly characterize the capabilities of the “as-built” system, and to optimize system operation. The scope of science verification includes:

1. Determining whether the specifications defined in the LSR and SRD are being met;
2. Characterizing other system performance metrics in the context of the four primary science drivers;
3. Studying environmental dependencies and technical optimization that inform early operations;
4. Documenting system performance and verifying mechanisms to monitor system performance during operations; and
5. Validating data delivery, derived data products, and data access tools (e.g. LSST Science Platform) that will be used by the science community.

The overall goal during Science Verification is to quantify the range of demonstrated performance by using a combination of on-sky data, informed simulations of the LSST system, and external datasets. Observations taken during this period will enable higher-level data quality assessments that are not explicitly identified as requirements in the LSR or SRD, but nonetheless represent important benchmarks of scientific performance (e.g., source detection completeness, accuracy of star-galaxy separation, precision of photometric redshifts, and weak-lensing null tests). The two mini-surveys designed to demonstrate operational readiness with continuous scheduler-driven observations, and complete processing of associated data products through the Level-1 and Level-2 pipelines.

Another critical function of Science Verification is to provide feedback to the individual LSST subsystems and overall integration effort. Subtle and/or emergent problems may appear during the examination of high-level science data products that would not be evident during earlier and more technically oriented stages of testing. The Science Verification Team will be in close communication with the Core Commissioning Team, providing feedback through the work management process as described in section 2.

The science verification activities are structured into three sequential phases:
1. **Early Science Verification tests with ComCam.** The processing of science-quality images with ComCam represents a first opportunity to test DM pipeline algorithms and data quality assessment algorithms with on-sky data. Early Verification tests can be used to identify and diagnose problems, with multiple opportunities for iteration before final acceptance testing.

2. **Early Science Verification tests with LSSTCam.** Testing with the complete set of delivered system hardware begins with the integration of the Science Camera and acquisition of on-sky data.

3. **Final Science Verification with mini-surveys.** We have designed two six-week mini-surveys to validate the Level-1 alert production system and Level-2 10-year depth stacked imaged performance, respectively. This 5-month period corresponds to the dedicated Science Verification phase of the overall commissioning plan aimed at final acceptance testing.

The Science Verification period concludes with the Operational Readiness Review (ORR).

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**Figure 40:** Summary of the on-sky observations planned for the three periods of sustained observing during Commissioning.

The Early Science Verification and Final Science Verification periods include time for engineering related activities throughout, with more engineering time during the initial testing phases, and transitioning to near early operations levels during the mini-surveys. Early Science Verification testing with both ComCam and LSSTCam begin with 3-4 month periods focused on technical integration, followed by periods with sustained on-sky observations. During the sustained observing periods of Early Science Verification, ~25% of the total time will be set aside for engineering. After the conclusion of the mini-surveys, a two-month long pre-operation engineering period is scheduled leading up to the ORR.
The sequence of activity planning packages for the Science Verification phase, including the observations and analysis for two operational readiness mini-surveys, and the ORR. Corresponding activity sequences for Early Science Verification with ComCam and LSSTCam are shown in Figure 31 and Figure 40, respectively.

6.1 Early Science Verification Tests with ComCam

**Installation and Initial Checks:** The first four months of ComCam integration are focused on the engineering activities described in Section 5.4.1, such as testing of the pointing model, active optics system, calibration pipelines, and electro-optical testing. However, the first on-sky science quality images will be acquired during this period, and these will be processed to allow early checks of data quality and to quickly identify any problems. Validation of Instrument signature removal for on-sky data is one major activity for this period.

Example on-sky observations that may be taken during this period include:

- Raster a single field across each detector for determination of illumination corrections, initial color term determination, and verification of astrometric solutions.
- Dense rastering with 70-90% overlap of an area 3-5 times the field of view to determine illumination correction from the self-calibration algorithm.
- Repeated observations of fields across various airmasses, in multiple bands, to determine photometric repeatability.
- Repeated observations of celestial pole field, at different rotations, to understand fixed-airmass atmospheric systematics.
- Observations of celestial pole field though different amounts and kinds of clouds, to verify how well we suppress transparency variations with the calibration algorithms.
- Other engineering time for pointing model, wavefront correction tweaking, etc.

**Testing Key Performance Metrics:** Following the integration and technical testing of ComCam, we schedule a three-week block for basic data quality assessments motivated directly by the SRD and LSR requirements. We summarize below the requirements to be tested at this early verification stage and briefly describe how each will be quantified.

First, direct measurements of delivered image quality can be obtained from individual visits:
• **Delivered image quality.** Distribution of delivered seeing across the field of view. Note that requirement SXE requires observations at airmass = 2. Full characterization requires observations over a range of airmass.

• **Image Spatial Profile.** Measure the distribution of PSF profile characteristics over the field of view.

• **Image ellipticity distribution.** Similarly, the ellipticity distribution can be directly measured from the shapes (specifically, the second moments of best-fit elliptical double Gaussians) of unresolved sources across the field of view. The requirement is defined for a field with zenith distance less than 10 degrees.

Another set of requirements quantifies the system throughput and can be determined from single-visits taken under photometric conditions on dark nights with good seeing.

• **r-Band Reference Depth.** This requirement is defined in terms of signal to noise ratio (SNR) rather than source detection completeness and therefore does not strictly require deeper reference imaging. The requirement is defined for observations close to zenith.

• **Filter depths.** Analogous to r-band requirement for the single-visit depth in all six bandpasses.

• **Variation in depth over FOV.** Provided photometric calibration across the field of view, this requirement can be tested with individual visits. Dithered observations of the same field can provide an alternative direct measurement.

Aggregate statistics can then be assembled from the measured distribution of these properties accumulated over many visits.

The highest level requirements for the DM system come from the SRD and Observatory System Specifications (OSS, LSE-30) and have been flowed down to a set of DM Key Performance Metrics (KPMs), representing tests of the DM pipelines for calibration, astrometry, PSF determination, as well as completeness and purity for moving, variable, and transient sources.

• **Single-visit photometric repeatability.** This requirement tests calibration algorithms, errors and noise producing the necessary calibration data products, as well as errors and uncertainties in any reference catalogs used in the calibration process. This test requires multiple observations of the same fields in different epochs, spanning a range of conditions in terms of airmass and sky brightness. Photometric conditions are needed for testing this and the following photometry requirements.

• **Single-visit photometric spatial uniformity.** We anticipate that Gaia catalogs will exist with sufficient photometric accuracy and precision in the G-band at the time of LSST commissioning that these data will be used as the primary means of calibrating LSST images. In that case, independent references must be considered when selecting fields to verify the photometric spatial uniformity, such as standard star fields, *Hubble* CalSpec standards, and previous wide-field optical imaging surveys such as Pan-STARRS, DES, and HSC.

• **Band-to-band (color) photometric accuracy.** The verification of this requirement is to some extent limited by the availability of suitable spectral references. The intrinsic spectrum of a DA white dwarf star can be calculated from first principles given a measurement of the effective temperature and surface gravity, which can both be spectroscopically determined. Currently, a
network of faint DA white dwarf stars appropriate for LSST imaging depth (V~19), and covering a range of RA values, is being assembled as part of the Hubble CalSpec standards program.

- **Absolute photometric accuracy.** Similar to the color zero-point accuracy requirement, the absolute photometric accuracy can be tested by targeting faint Hubble CalSpec standards.

- **Relative astrometry.** Determine the distribution of measured angular separations between pairs of stars at multiple separations for many visits.

- **Absolute astrometry.** The absolute astrometric performance is measured relative to external reference catalogs, and therefore may be limited by the accuracy of those catalogs. We will select stable sources (e.g., bright quasars) and compare positions against a reference catalog. The Gaia DR1 provides an astrometric solution for 1.1 billion stars with a median Gaia G-band magnitude of 19 and median positional uncertainty of <2 mas. For comparison, the LSST design specification for absolute astrometric precision (AA1) is <50 mas.

- **Residual PSF ellipticity corrections.** This requirement is distinguished from other KPMs in that it is defined for the image stack, and thus requires a cumulative exposure equivalent to the 10-year survey depth to test, but only for the r and i bands.

The KPMs related to transient, variable, and moving objects will be primarily tested through the use of simulations since the requirements are defined in terms of detection and/or linkage completeness, and a statistically complete catalog of such objects at LSST depths is unavailable (this is a main science motivation for LSST). However, the system performance with respect to these requirements can also be evaluated using on-sky data through the identification of previously known or newly found Solar System objects in LSST images. Once orbits are determined, subsequent observations can be used to measure detection and linkage efficiency as a function observing cadence, environmental conditions, and source properties. Also, repeated observations of the same field on fast timescales (e.g., minutes) using small dithers can be used to estimate the rate of spurious Difference Image Analysis source detections since spurious detections are unlikely to be repeatable in terms of measured position, flux, etc. By contrast, genuine astrophysical sources should have repeatable measurements. In this way, on-sky data can be used to validate the simulations.

For the purpose of testing DM algorithms (as opposed to complete processing pipelines), it is not necessary to generate real-time alerts, and the searches can be performed offline using templates produced from the stack of observations.

- **Moving Object Linkage.** For complete testing, repeated observations of the same field are needed on a range of timescales up to three days. Individual subsets of visits can be used to validate the simulations on different timescales for objects moving at different rates.

- **Spuriousness metric efficiency - transients.** Repeated observations of the same field would allow the identification of previously known or newly found asteroids, variable stars, variable quasars, etc. Studies of known celestial objects could then be used to validate simulations based on the insertion and recovery efficiency of artificial sources. One distinction between detecting transients and Solar System objects is that transients are often correlated with the positions of stable sources (e.g., supernovae occurring in galaxies) and this tests the difference imaging analysis in a different regime.

- **Spuriousness metric efficiency - MOPS.** Testing is similar to that for transients.
Also, given that LSST does not use an atmospheric dispersion corrector, the relative astrometry between bands should be tested at an early stage of science verification.

- **Crossband Relative Astrometry.** Requires observations in multiple filters at a variety of airmasses.

The majority of tests described above can be accomplished using a common set of on-sky data if an appropriate set of reference fields are selected that contain absolute photometric references. Below we show a consolidated list of observations to be acquired during the three week KPM testing block. Importantly, this dataset includes multiple fields and multiple epochs in each field, and therefore represents several “instances” to not only check passing the requirement, but to begin exploring the distribution of performance and identification of various “edge cases”.

1. The first KPM testing dataset will consist of observations of ~20 fields distributed across the sky at a variety of source densities (i.e., Galactic latitudes). Several of these fields will contain sources in the faint extension of Hubble CalSpec standards. Each field will be observed in all 6 filters in five epochs that encompass a distribution of airmasses (as well as telescope azimuth angles). Each epoch will consist of five visits in each filter (ComCam can hold three filters at a time). The pointings in each field will be dithered to allow tests of delivered image quality, throughput, calibration, and astrometry across the full field of view. Photometric conditions are required. Estimated observing time = 34 seconds * 5 visits * 6 filters * 5 epochs * 20 fields = ~28 hours.

2. A second KPM testing dataset consists of repeated observations of a smaller number of fields reaching cumulative exposures equivalent to the 10-year stack in the wide-fast-deep survey, specifically, 200 visits in both the r and i bandpasses. These observations are designed to measure residual PSF ellipticities, and to test transient, variable, and moving object detection over a range of timescales. Three fields should be chosen along the ecliptic that together span a range of source densities. Each field should be observed in multiple epochs distributed over at least 3 consecutive nights and cover a range of airmasses. Dithered pointings will be used to approximate the coverage pattern expected in the wide-fast-deep survey. Estimated observing time = 34 seconds * 200 visits * 2 filters * 3 (dither pattern) * 3 fields = ~36 hrs.

In ideal conditions, the observations above would require roughly 64 hours of observation time. Photometric conditions are needed for the first set of observations, so accounting for 53% average photometric time fraction, and 85% usable time, ~95 hours are needed (at least 12 nights of observing). Given that weather patterns are often correlated, we budget a total of 4 weeks for these observations, including 1 week for engineering activities. If time is limited, or multiple iterations of the test are needed, the number of fields could be reduced.

As noted above, at least some of the observations should target moderately high stellar density fields to allow dense sampling of the PSF across the (instrumented portion of the) focal plane, but the stellar density should not be so large that source crowding becomes an issue.
Table 9: Science Verification matrix showing the methods and on-sky observations to be used to tests the SRD requirements for single image/single visit performance metrics.

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<td>*Crossband Relative Astrometry</td>
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Table 10: Science Verification matrix showing the methods and on-sky observations to be used to test the SRD requirements and Key Performance Metrics for full survey performance.

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<th>On-Sky Observations</th>
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<tr>
<td>On-Sky Statistical Simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-Sky Measurement Coupled with Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrapolation from On-Sky Observations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As a general note, the analysis of commissioning data will make use of DM data quality assessment tools, rather than ad hoc analysis codes to the largest practical extent. This practice allows vetting of data quality assessment algorithms and will validate a set of tools that can be used to monitor system performance over time. For instance, single-exposure and single-visit performance metrics that can be directly measured from LSST images will be implemented as QC tools developed by DM in advance of commissioning (section 6.4). The commissioning team will also take advantage the QA framework developed by DM in advance of commissioning (section 3.3.3). Where possible, these tools should map closely to the requirements defined in the SRD.

**20-year Depth Test:** After testing the KPMs, which mostly describe the delivered data quality at the level of individual visits, the second set of early Early Science Verification observations focus on stacked performance. Over a four-week period, we will observe ~10 fields to a depth equivalent to 20 years of the nominal wide-fast-deep survey in all six filters (~1700 total visits per field) in a limited area that includes a few reference fields with external datasets. The individual pointings for a given field will be dithered to approximate the coverage pattern for the wide-fast-deep survey. The goal for this test is to observe in a variety of conditions in terms of airmasses, sky brightness, and cloud cover to explore the range of conditions that might be encountered during operations. The observing time budgeted for this activity is 34 sec per visit * 1700 visits * 10 fields = 160 hours = 20 nights.

Whereas most KPMs focus on single-visit performance, these observations are designed to test the performance at full-survey depth. The 20-year depth will allow DM to slice the data in different ways to examine various potential systematics, e.g., best and worst seeing, highest and lowest airmass, highest and lowest sky-brightness. Note that this testing requires coordination with DM to select different
subsets of exposures for Level-2 processing.

The set of fields selected for observations will be distributed over the sky, roughly every two hours in RA, and should include a range of source densities. During this period, the selection of fields for observations will be driven by needs for testing DM algorithms, rather than optimizing the data quality for specific fields (which will be done during mini-survey 2). Where possible, the fields will overlap with established reference field containing deep imaging and/or spectroscopy from external data sets (see Figure 42 and Table 11).

Given the numerous repeated observations of the same fields with dense sampling in time, these observations will also produce a useful dataset for testing the Level 1 processing algorithms. Offline Difference Image Analysis will test alert generation algorithms as well as optimal template generation strategies.

Figure 42: Skymap in celestial coordinates showing locations of a set of candidate reference fields to be observed during commissioning. The background map (blue shaded) shows interstellar extinction, which is strongest along the Galactic plane. The dashed black curve indicates the ecliptic plane. Importantly, the reference fields are distributed over a broad range of RA values and therefore, suitable fields will be available throughout the commissioning period.
### Table 11: Key attributes of example reference fields from external datasets are compared with LSST.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Notes on band coverage and depth</th>
<th>Total Area (accessible to LSST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-Visit</td>
<td>{ugrizy} = {(23.9, 25.0, 24.7, 24.0, 23.3, 22.1) (5\sigma)}</td>
<td>-</td>
</tr>
<tr>
<td>10-yr Wide-Fast-Deep</td>
<td>{ugrizy} = {(26.1, 27.4, 27.5, 26.8, 26.1, 24.9) (5\sigma)}</td>
<td>18000 deg$^2$ (design)</td>
</tr>
<tr>
<td>HSC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wide</td>
<td>{grizy} = {(26.5, 26.1, 25.9, 25.1, 24.4) (5\sigma)}</td>
<td>1400 deg$^2$ (1350 deg$^2$)</td>
</tr>
<tr>
<td>Deep</td>
<td>{grizy} = {(27.5, 27.1, 26.8, 26.3, 25.3) (5\sigma) + 3 narrow bands}</td>
<td>27 deg$^2$ (13 deg$^2$)</td>
</tr>
<tr>
<td>Ultra-deep</td>
<td>{grizy} = {(28.1, 27.7, 27.4, 26.8, 26.3) (5\sigma) + 3 narrow bands}</td>
<td>3.5 deg$^2$</td>
</tr>
<tr>
<td>DES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wide</td>
<td>{grizY} = {(24.5, 24.3, 23.5, 22.9, 21.7) (10\sigma)}</td>
<td>5000 deg$^2$</td>
</tr>
<tr>
<td>SN-Shallow</td>
<td>{griz} = {(26.8, 25.6, 25.9, 25.7) (5\sigma)}</td>
<td>24 deg$^2$</td>
</tr>
<tr>
<td>SN-Deep</td>
<td>{griz} = {(27.1, 27.3, 27.0, 26.8) (5\sigma)}</td>
<td>6 deg$^2$</td>
</tr>
<tr>
<td>HST CLASH</td>
<td>-</td>
<td>(-0.03) deg$^2$ (17 of 25 fields)</td>
</tr>
<tr>
<td>HST COSMOS</td>
<td>-</td>
<td>1.7 deg$^2$</td>
</tr>
<tr>
<td>HST Ultra-Deep Field</td>
<td>{F814W} = {(27.2) (10\sigma)}</td>
<td>(-0.003) deg$^2$</td>
</tr>
<tr>
<td>HST Frontier Fields</td>
<td>{F435W, F606W, F775W, F850LP} ~ {(29) (10\sigma)}</td>
<td>(0.012) deg$^2$ (5 of 6 fields)</td>
</tr>
</tbody>
</table>

**Verification of automated survey scheduler:** On several nights interspersed over a four-week period, which collectively spans a range of environmental conditions (e.g., cloud cover, moon phase, seeing), the telescope will be run with the automated scheduler in the nominal survey cadence. This activity is meant to test the scheduler with feedback from real telemetry, to provide additional measurements of telescope slew and settle times, and to exercise the interfaces and procedures used by human operators of the observatory during sustained observing periods. The same tessellation pattern as planned for the LSST camera will be used, and the survey region will generally not be artificially constrained, in order to generate a realistic distribution of slew angles.

Auxiliary telescopes and instruments that provide system telemetry will have been tested as prerequisites for commissioning. During this period, the commissioning team will verify that such additional telemetry accurately predicts the features of the on-sky data taken with ComCam. When testing the scheduler response to cloud cover, for instance, we will demonstrate that the cloud/transparency camera produces appropriate output at the rate needed to inform the scheduler, validate that the predicted transparency matches that measured with ComCam, evaluate the visualization of the transparency maps, and validate the predictive cloud/transparency model.

Additional tasks associated with this activity include testing target of opportunity (ToO) interrupts,
intentionally degrading the performance of the system and determining how the scheduler responds, implementing simple survey scripts (e.g., dither pattern or fixed small area), and constraining the observations to a reduced survey area. By testing the scheduler in different configurations, we aim to generally verify that the scheduler performs in a predictable way with respect to the simulations.

6.2 Early Science Verification with LSSTCam

The early science verification plan for LSSTCam closely follows the verification activities with ComCam. The primary difference from the perspective of on-sky observations is that scheduler testing activities with ComCam will be superseded by the Science Verification Mini-Surveys (section 6.3).

Installation and Initial Checks: Section 5.2 describes the engineering activities associated with integration and early testing of LSSTCam. Similar to the ComCam integration, we will use science-quality images acquired during this four-month period as a first opportunity to characterize the delivered data quality and diagnose any problems.

Following this initial period, there are eight weeks of sustained observing with LSSTCam prior to the start of the Final Science Verification mini-surveys. The first period of four weeks will be focused on KPM testing with LSSTCam. The second period of four weeks is for 20-year depth testing. We anticipate that about 1 week per month will be used for engineering activities.

KPM Testing: During the first four weeks of sustained observations, we will repeat the set of observations for testing Key Performance Metrics with LSSTCam, as described in section 6.1 for ComCam. We will take advantage of the analysis tools and experience gained from ComCam for this early verification, with particular attention to performance over the larger field of view for the Science Camera. A different set of fields will likely be observed given the change in seasons, however, as shown in Figure 42, suitable reference fields with photometric standards cover the full range of RA values.

20-year Test: The second four-week block of sustained observations will observe roughly 10 fields to full survey depth, equivalent to ~1700 visits, mirroring the exercise with ComCam. Again, the emphasis during this test is exploring a range of environmental conditions. Reference fields will be selected to allow comparison to external datasets where feasible. The specific observing strategy is driven by needs to test DM algorithms. Similar to the test with ComCam, we budget 20 nights of observing time.

If template generation on these test fields can be completed early in the observing period, it will be possible to test real-time alert production during the remaining observations.

6.3 Final Science Verification with Mini-Surveys

The Commissioning plan concludes with a five-month period dedicated to “Science Verification” activities. The first 12 weeks of this period consist of continuous scheduler-driven observations for two mini-surveys followed by eight weeks of analysis and engineering activities leading up to the ORR. We anticipate that most of the requirements identified in the SRD and LSR will have been verified prior to this phase, and that the analysis of mini-survey data will emphasize a more comprehensive system characterization under nominal operational conditions, as well as identifying corner cases with the aid of a larger statistical sample of observations.

The data from this effort will be treated as though it were part of normal survey operations. The mini-
survey data could also be used to generate templates to be used during the first year of operations to generate real-time alerts, as described in section 6.6.

6.3.1 Mini-survey 1: Wide-area alert production

The first six-week mini-survey is designed to demonstrate autonomous scheduler-driven operation over a sustained period in a mode similar to the wide-fast-deep universal observing cadence, and to validate routine alert production with the Level 1 nightly processing pipeline. These observations will yield a useful dataset to examine metrics of survey progress over a wide area in a variety of conditions, and to monitor the interaction between scheduler logic and telemetry. The transient alert latency and transient alert throughput SRD requirements will be extensively tested during this period.

The observations for mini-survey 1 are designed to cover ~10% of the primary LSST survey footprint to fully exercise the Level-1 pipeline over a range of source densities, and to test performance in challenging analysis regions such as those with high interstellar extinction, near bright stars, and/or with prominent nearby galaxies. The observing strategy will balance the desire for uniform coverage over contiguous regions, with the need for measuring a range of source densities and Galactic latitudes. We plan to observe a long contiguous stripe at constant declination similar to (and perhaps even overlapping) Stripe 82 and/or the HSC equatorial fields.

Real-time alert production can only be tested in regions that have good-quality templates derived from prior observations with LSSTCam. Therefore, we will divide mini-survey 1 into two stages: (1) observations to derive templates, and (2) a period to re-observe same region and generate real-time alerts. The two stages will be separated by approximately six weeks to allow for template production as well as astrophysical evolution. This will be accomplished by conducting mini-survey 2 in between the two stages of mini-survey 1.

We intend to observe roughly 10% of the primary survey footprint in ~15 visits per each of six filters (equivalent to approximately 1 year of observations). Assuming 85% usable time, this corresponds to

\[
(170 \text{ fields} \times 15 \text{ visits/filter} \times 6 \text{ filters/field} \times 34 \text{ s/visit}) / (0.85 \text{ usability} \times 8 \text{ hrs/night} \times 3600 \text{ s/hr}) \approx 20 \text{ nights}
\]

The amount of time needed to acquire the images necessary for template generation will be determined by tests performed on the commissioning data itself as part of the Early Science Verification activities. For example, we may require separate templates at low and high airmass. For planning purposes, we conservatively assume that we need 10 photometric exposures per filter, assuming 53% photometric nights

\[
(170 \text{ fields} \times 10 \text{ visits/filter} \times 6 \text{ filters/field} \times 34 \text{ s/visit}) / (0.53 \text{ efficiency} \times 8 \text{ hr/night} \times 3600 \text{ s/hr}) \approx 22 \text{ nights}
\]

Accordingly, we plan for a three week template-building period followed by a three-week alert generation survey over ~1600 square degrees. If significant template building can be conducted with LSSTCam observations prior to the mini-survey, we can extend the period of alert generation and/or expand the sky area covered.
6.3.2 Mini-survey 2: 10-year depth survey

The second mini-survey is designed to demonstrate compliance with stacked image specifications through deep observations of a limited number reference fields covering a total of ~300 deg². During six weeks of continuous on-sky operations, ~30 fields will be imaged to the full 10-year survey depth in all six bands (equivalent to ~825 total visits per field). As with the 20-year depth tests conducted with ComCam and LSSTCam, specific pointings will be chosen to overlap with established reference fields containing deep multi-band imaging and spectroscopic datasets. Telescope pointings will be dithered to match the distribution expected in the wide-fast-deep (i.e., “universal cadence”) tiling scheme, and therefore, it may be advantageous to select adjoining fields to maximize the full-depth area. In contrast to the 20-year depth test, for which the objective is to explore a range of environmental conditions, the automated scheduler will be used in mini-survey 2 to maximize the delivered data quality, similar to nominal survey operations.

At this stage of Science Verification, emphasis will be placed on characterizing the high-level scientific performance of LSST beyond the SRD and LSR specifications. The Data Products Definition Document (DPDD) specifies that the Level-2 object catalogs will include columns for source shape measurements (adaptive second moments of source intensity, fitted disk+bulge model parameters), photometric redshift, a morphological “extendedness” parameter, and statistical variability metrics. Optimizing the algorithms that generate these quantities is beyond the scope of the Commissioning Team. However, baseline characterization of these quantities is a goal.

Comparison to external reference datasets as “truth” tables for LSST on-sky data will be essential for many of these investigations. As a concrete example, consider the basic task of source detection in full-depth images. Whereas signal-to-noise for individual sources can be measured directly from the LSST images, determining the source detection efficiency and purity requires additional simulations (injecting fake sources) and comparison to deeper imaging (e.g., from Hubble deep fields). Source detection efficiency is also function of individual source properties, such as color and surface brightness, as well as source environment. This latter aspect highlights the challenge of source deblending in crowded fields near the Milky Way disk and in the central regions of rich galaxy clusters. Furthermore, many science analyses will depend upon the robustness of star-galaxy separation. Deep space-based imaging is again vital for defining an appropriate test sample.

When evaluating the LSST 10-year stack performance, there are a limited number of external datasets of sufficient depth, area, and spectroscopic/multiwavelength coverage, to provide a statistically representative view of the galaxy population. This limitation poses a special challenge for testing the accuracy and precision of photometric redshifts derived from LSST data. Therefore, reference fields for mini-survey 1 will be selected to facilitate the testing of photometric redshifts. Even the deepest spectroscopic surveys at the time of commissioning are likely to be statistically incomplete at LSST full-survey depth, and systematically biased towards certain galaxy types, and therefore multi-band reference imaging may be the most effective way to validate photo-z performance (e.g., CANDELS, ALHAMBRA). In addition, it will be possible to evaluate photometric redshifts in a statistical sense by correlating the spatial positions of galaxies in different photo-z intervals: galaxies in the same photo-z bin should have correlated spatial positions, whereas cross-correlations between different photo-z bins should have substantially reduced signal. The photometric redshifts of galaxy clusters in particular can be constrained with excellent statistical precision due to the large number of bright member galaxies, as
well as the distinctive spectral features of those galaxies. Together, photometric redshift studies will enable powerful tests of galaxy photometry.

Some of the reference fields may also be chosen to include well-studied galaxy clusters that can be used to test gravitational weak lensing measurements (e.g., CLASH galaxy clusters). As the most massive gravitationally bound structures in the universe, galaxy clusters are an attractive first target for weak lensing studies given their large expected signal, and relatively well-constrained localization. With clusters, it will be possible to define signal and null tests by selecting galaxies in different photometric redshift intervals, examining tangential shear versus cross-component shear, and measuring the radial profile of the lensing signal. Lensing studies should begin with individual galaxy clusters that have prior mass estimates. Galaxy-galaxy lensing with certain well-studied galaxy samples for which the characteristic mass and redshift distributions are known may also be useful early tests of weak lensing.

Finally, the large number of images acquired in each reference field in mini-survey 2 will enable complementary tests of the Level-1 pipeline. The throughput of difference image analysis alerts will be different than for the nominal observing cadence, since a smaller area of the sky is imaged repeatedly. However, mini-survey 2 will allow detailed characterization of DIA sources since the sampling in time will be much higher than what would typically be achieved during normal operations. We will generate templates as soon as the requisite number of good-quality exposures can be obtained.

### 6.4 Science Verification Data Processing & SDQA

In addition to processing and distributing commissioning data (section 5.3), the DM team will provide tools to the commissioning team to help validate the SRD and LSR specifications, and to drill down into the data to diagnose any hardware and/or software issues. Prior to the start of commissioning, DM will verify that the KPMs meet their design values on precursor data, and ideally, the main task during final Science Verification will be confirming that system requirements are satisfied with on-sky LSST data. In practice, the DM, hardware, and commissioning teams are preparing to diagnose and resolve any subtle problems in the camera, telescope, and/or data processing pipelines that appear in the fully integrated system. This activity is similar to the testing performed during DM's algorithm development, and will establish procedures for data quality assessment that LSST will use during operations.

In addition to measuring the KPMs, the commissioning team will characterize other data products specified in the DPDD by repeating the analysis procedures that DM will have already defined and carried out precursor data.

During pipeline development (with precursor data), some KPMs may not be consistently met due to algorithmic and/or hardware issues, even during normal operations, some KPMs may fail on subsets of the data due to features of the data. In both cases, tools are needed to identify and understand the failure modes. There are also failure modes that are not revealed by KPMs. For example, a systematic offset between PSF and aperture fluxes at faint levels in 5% of exposures will not necessarily violate the KPMs defined for the photometric spatial uniformity or repeatability. DM is therefore developing a set of tools to interactively investigate features in the processed data.

#### Using the QA environment and QC pipelines during Science Verification

“QA pipelines” are identical in structure to other DM pipelines (e.g., instrumental signature removal, ISR) and are built from a set of python ‘tasks’ which may be reused in other contexts. The task of
ensuring that the KPMs are calculated, and tracking their values as the pipelines evolve and encounter new data is referred to as "Quality Control" (QC). The KPMs themselves are summary statistics built from measurements in many spatial regions (e.g., defined by either HEALPix or HTM).

In the following, we consider the data-related KPM for “Photometric Spatial Uniformity” (PA3) as a representative use case for the QA environment and QC pipelines to monitor system performance and diagnose anomalous features in the data. Note that PA3 applies to the properties of the ensemble of measurements of a region; the quality of processing of individual visits is more constrained by PA1 ("Photometric repeatability").

One possible way of measuring the photometric uniformity is to measure the position and width of the stellar locus in color-color space as a function of equatorial coordinates ($\alpha, \delta$). While comparison to Gaia photometry will likely become the primary calibration means for LSST objects, it is useful to have a second independent method to evaluate the measured colors of unresolved sources in Level-2 data products. Taking full advantage of the stellar locus approach requires some understanding of interstellar extinction and the metallicity dependence of stellar colors.

We will add a task to the “QA pipeline” to characterize the stellar locus in regions; this will result in a set of indexes $w, x, ...$ describing the shape of the stellar locus as defined by Ivezić et al. 2007 (AJ 134, 973); see Figure 43. These indices may be measured using any algorithm supported by the pipeline (e.g., PSF or aperture fluxes). Example plots from the HSC survey are shown in Figure 44. The system that DM is building will support interactive exploration of similar plots, with the ability to zoom and pan locked views of measured quantities (e.g., $w$ and seeing), as well as RGB true-color images of the sky. The tools will also allow us to display the color-color diagrams from which the measured indexes were measured (e.g., Figure 43). We will be able to control these display tools from a Jupyter iPython notebook, from which we will have access to the Tasks that generated the plots; we will be able to run these notebooks locally (e.g., on laptops) as well as remotely (e.g., on the commissioning cluster, displaying locally). This will enable us to rebuild the plots over a restricted part of the sky using a different set of quality cuts, photometric algorithm, or magnitude limit; if we need to recalculate on a large scale we will be able to submit the processing to a compute pool.

We will also be able to interactively choose areas of the sky to concentrate on; for example comparing the two panels in Figure 44 it is clear that something is going wrong around $\alpha \sim 137^\circ, \delta \sim 4^\circ$ which we need to investigate. A clue is provided by examination of Figure 45; in this example, the problem is related to exceptionally good seeing. The tools will then allow us to investigate the visits that went into the coadded data; this is an example where access to the processing tasks will be valuable, as we will probably not pre-compute all the 3-color diagrams for all visits for all parts of the sky with a range of cuts applied.
The contents of this document are subject to configuration control and may not be changed, altered, or their provisions waived without prior approval.
The example above used the stellar locus to explore the quality of stellar photometry. We will implement a number of other statistics defined in regions of the sky and, where appropriate, we will carry this analysis out in each photometric band. Where the analysis uses the `coadd' measurements, we will have the ability to repeat the analysis for individual visits.

Examples of additional statistics (including KPMs) are:

- Number density of QSOs selected by color; this probes the same data as the stellar locus analysis, but concentrates on outliers.
- The offset and scatter of photometry of stars using a variety of flux estimators relative to a reference catalog. This photometry is of the objects using all available epochs (as measured using multifit or by measurements on sufficiently principled coadds). The summary of this statistic corresponds to the requirement PA3.
- The variability of stars (after rejecting true variables) as a function of magnitude and measurement algorithm. The summary of the bright-aperture variability statistic is PA1. The tools will be able to provide summaries of these statistics, e.g., the variability in units of quoted photometric errors (i.e., $\chi$, which should be independent of magnitude) in a broad magnitude range.
- The scatter between PSF and other magnitudes for stars as a function of magnitude both in the `coadd' and single-visit (an input into star-galaxy classifiers); `other' will include aperture and

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Figure 45: The seeing distribution for the GAMA09H field in early HSC imaging. The pixel scale is 0.168". The region seen in Figure 44 characterized by offsets in PSF photometry coincides with a region observed with exceptionally good seeing. Credit: Takashi Hamana and the HSC Collaboration.

Other Statistics

The example above used the stellar locus to explore the quality of stellar photometry. We will implement a number of other statistics defined in regions of the sky and, where appropriate, we will carry this analysis out in each photometric band. Where the analysis uses the `coadd' measurements, we will have the ability to repeat the analysis for individual visits.

Examples of additional statistics (including KPMs) are:

- Number density of QSOs selected by color; this probes the same data as the stellar locus analysis, but concentrates on outliers.
- The offset and scatter of photometry of stars using a variety of flux estimators relative to a reference catalog. This photometry is of the objects using all available epochs (as measured using multifit or by measurements on sufficiently principled coadds). The summary of this statistic corresponds to the requirement PA3.
- The variability of stars (after rejecting true variables) as a function of magnitude and measurement algorithm. The summary of the bright-aperture variability statistic is PA1. The tools will be able to provide summaries of these statistics, e.g., the variability in units of quoted photometric errors (i.e., $\chi$, which should be independent of magnitude) in a broad magnitude range.
- The scatter between PSF and other magnitudes for stars as a function of magnitude both in the `coadd' and single-visit (an input into star-galaxy classifiers); `other' will include aperture and
model-fit fluxes. At the bright end we will use Gaia as a truth table; at fainter magnitudes sufficiently red stars are almost uncontaminated by galaxies.

- Astrometric accuracy (relative to Gaia) for bright stars (Gaia G < 20 mag)
- Repeatability of galaxy fluxes and colors (various algorithms, e.g., Petrosian and Model). Galaxy colors are better defined than total fluxes, although color gradients make the problem more complicated.
- Width and redshift-corrected position of the E-S0 ridgeline in known clusters of galaxies (as defined by running, e.g., RedMaPPer).

### 6.5 Data Delivery Services in support of Science Verification

As part of the commissioning effort, DM will serve data to the Commissioning and EPO Teams using the same data delivery services that will eventually be used by the LSST data rights community. The access and analysis of Science Verification data by the Commissioning Team will therefore serve a dual purpose to further test those services for representative use cases.

The data products from executing the Level 1 and Level 2 productions on mini-survey data will be published to the Data Access Centers as a reverification of the DM Data Release process. As described in Section 4.3.1, the Data Access Centers will have been integrated and tested using precursor and simulated data as part of DM delivery. The Data Release process involves the transfer of data products to Data Access Center systems, including EPO, the production of documents characterizing the release for science users and supporting documentation for the release for the Science Operations Department, internal review by the Data Release Board, authorization by the Data Release Board of publication of the data products, and enabling authorized access to the data products.

### 6.6 Preparing for Alert Production during Early Operations

Real-time alert production requires the availability of Data Release Production template imaging. As a by-product of the Science Verification effort, the planned set of on-sky observations would enable template generation over ~10% of the wide-fast-deep survey footprint prior to the start of full survey operations.

In the planning of Science Verification activities, we have prioritized the testing of the Level-1 and Level-2 data processing pipelines and associated data products, and have designed a set of on-sky observations to accomplish this goal. Generation of a complete set of templates over the primary footprint is not required for Observational Readiness and hence is not a core commissioning activity. However, the Commissioning Team recognizes that the selection of on-sky observations during Science Verification may have implications when planning alert production during early survey operations.

### 6.7 Operations Readiness Review

After the two mini-surveys, the observatory will enter an 8-week shutdown period during which on-sky observations will halt in order to prepare for the Operational Readiness Review (ORR).

The ORR defines the end of the Science Verification phase and marks the completion of the Commissioning Plan. The ORR will further signify the end of construction and the conclusion of the NSF MREFC fund project and DOE Commissioning (DOE-COM). The procedures and criteria for declaring
operational readiness, which will be evaluated at the time of the ORR, are described in Section 1.1.1.

6.7.1 Analysis of Commissioning Data

A major activity during this final period of Science Verification is the data processing and analysis for the two operational readiness mini-surveys. The Commissioning Team will compile results from Science Verification activities for final acceptance testing. The Commissioning Team will also continue the process of documenting the demonstrated capabilities and range of performance for the as-built system, including recommendations that inform early operations.

6.7.2 Pre-ORR Engineering

At this point in time, more than two years will have elapsed since the start of Early System Integration and Testing, which places the LSST Observatory on schedule for its 2-year major maintenance and servicing.

**M1M3 Mirror Recoating:** Remove, strip, clean, and re-coat the M1M3 mirror surfaces. Reinstall M1M3 mirror back into telescope. Associated activities include:

- Remove Top-End Integrating Structure with Camera and transfer to Summit Facility camera lab.
- Install camera dummy mass to allow the telescope to point to zenith for removal of the M1M3 mirror cell. Remove M1M3 mirror assembly and transfer to Summit Facility re-coating plant.
- Strip old coating, clean and re-coat mirror surfaces.
- Re-install M1M3 in telescope and prepare to receive the top-end integrating structure with the camera.

**Camera Maintenance and Servicing:** Clean, service, perform maintenance, and replace shutter. Associated activities include:

- Replace camera shutter with “fresh” operational unit;
- Inspect, service – repair filter mechanisms;
- Clean internal camera optics;
- Inspect, service, and repair utility trunk electronics