The Large Synoptic Survey Telescope Preliminary Design Overview

V. L. Krabbendam[1], D. Sweeney[2] and the LSST Collaboration
[1]NOAO/LSST, 950 N Cherry Tucson, AZ 85719
LLNL/LSST, 7000 East Avenue, Livermore, CA 94550

Abstract

The Large Synoptic Survey Telescope (LSST) Project is a public-private partnership that is well into the design and development of the complete observatory system to conduct a wide fast deep survey and to process and serve the data. The telescope has a 3-mirror wide field optical system with an 8.4 meter primary, 3.4 meter secondary, and 5 meter tertiary mirror. The reflective optics feed three refractive elements and a 64 cm 3.2 gigapixel camera. The LSST data management system will reduce, transport, alert and archive the roughly 15 terabytes of data produced nightly, and will serve the raw and catalog data accumulating at an average of 7 petabytes per year to the community without any proprietary period. The project has completed several data challenges designed to prototype and test the data management system to significant pre-construction levels. The project continues to attract institutional partners and has acquired non-federal funding sufficient to construct the primary mirror, already in progress at the University of Arizona, build the secondary mirror substrate, completed by Corning, and fund detector prototype efforts, several that have been tested on the sky. A focus of the project is systems engineering, risk reduction through prototyping and major efforts in image simulation and operation simulations. The project has submitted a proposal for construction to the National Science Foundation Major Research Equipment and Facilities Construction (MREFC) program and has prepared project advocacy papers for the National Research Council's Astronomy 2010 Decadal Survey. The project is preparing for a 2012 construction funding authorization.

Keywords: LSST, Survey, Telescope, Project Overview, Ground Based

1. INTRODUCTION

The Large Synoptic Survey Telescope (LSST) is a comprehensive project to image the whole available sky in a 10 year survey, analyze the data to produce alerts and object catalogs, archive the raw and processed data, and serve the data without any proprietary period. LSST will be the next generation in survey capability that will enable another leap in our understanding of the cosmos. The short and repeated exposures taken during the survey will open a movie-like window into the universe that will satisfy the professional scientist and the public as well with unprecedented image and catalog data. LSST will uniquely bring the faint time domain to astronomy and astrophysics serving multitudes of research from its single database.

The scientific motivation of LSST is largely unchanged since described by Sweeney in 2006 [1] and Ivezic et. al. [2] but the broad reach has been detailed in the LSST Science Book [3] published and available to the public at *http://www.lsst.org/lsst/scibook*. This comprehensive document, developed by over 250 collaborators, describes an array of investigations supported by LSST that address some of today's most pressing questions in astronomy and high energy physics.

The project is currently in the preliminary design phase where the hardware and software designs continue to develop and construction plans continue to be refined. All technical, scientific, and survey requirements continue to be met by the planned observatory. The project recently completed the initial 4.5 year NSF design and development effort and has received funding for the next 2.5 year Final Design Phase to bridge the project to the expected fiscal year 2013 construction authorization. This new award was reviewed in

Ground-based and Airborne Telescopes III, edited by Larry M. Stepp, Roberto Gilmozzi, Helen J. Hall
Proc. of SPIE Vol. 7733, 77330D · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857942

December 2009 with good result and positive recommendation. Current activities focus on a Preliminary Design Review that will be scheduled pending results of the Astro2010 decadal survey.

The LSST project is a public-private partnership led by the LSST Corporation founded as a 501(c)3 not-for-profit corporation in the State of Arizona for the sole purpose of building and operating the LSST. The project is organized as a central project office leading separate groups to address the major subsystems. These are the Telescope and Site, the Camera, Data Management and Education and Public Outreach groups. There are over 30 Institutional Partners in the LSST Corporation that have joined to contribute to both the technical development and governance of the project. A complete description of the LSST management structure and evolution over the design and development period is described by Sweeney et. al. in "*Management Evolution in the LSST Project*" [4]. The public website at www.LSST.org is available to review the project news bulletins and supplemental scientific, technical and management materials.

The technical scope and design concepts have remained consistent since described by Krabbendam in the 2008 SPIE manuscript "*The Large Synoptic Telescope Concept Design Overview*" [5]. This current paper provides a design overview but focuses on the changes that have occurred since that description.

2. SYSTEM DESIGN AND ENGINEERING

LSST has a central systems engineering effort responsible for the development of system and subsystem requirements, for broad project-wide design, and for the final integration of the observatory. This effort is led by the LSST Project Systems Engineer and systems engineers from each of the major subsystems. This group works together to maintain technical unity of the distributed project. The following sections discuss the elements of LSST that have project-wide impact and are therefore controlled directly from the project office and systems engineering.

2.1 Requirements definition design configuration

The configuration controlled LSST Science Requirements Document (SRD) has been updated in 2010 with only minor changes to further describe and define existing parameters and to remove redundancies in the requirements. The scientific reach, technical capabilities and survey requirements are substantially unchanged. The document is publically available at http://www.lsst.org/lsst/science/survey_requirements .

The LSST requirement control and flow down effort was previously described [5] to be handled through modeling in the Systems Modeling Language (SysML). In the two years of preliminary design the challenges of requirements analysis, system functional requirements, detailing interface definitions and coordinating the overall design have led to an increased role of SysML. The systems engineering effort has developed a system architecture model in SysML to support several key purposes: 1) Capture and document the functional and performance requirements along with their flowdown and traceability from the highest level system requirements down to the requirements defining the LSST subsystems; 2) Analyze and validate the system architecture to ensure that all system level (subsystem to subsystem) interfaces are identified and adequately specified; 3) Analyze and validate that the system architecture and the set of requirements are sufficient to support the required system behavior necessary to carry out the survey specified in the LSST Science Requirements Document.

The LSST system architecture model provides an efficient approach to managing the requirements and design and provides a single point for top level configuration control. The SysML database is the control point for the system requirements and configuration. Through the application's built-in capabilities, version control is provided and documents can be generated from the data including system and interface requirements at any level of the system architecture. The model is now developed to include two additional levels of system requirements below the Science Requirements Document: 1) the LSST System Requirements (LSR) provides the set of requirements for what the LSST must be and do to achieve the survey defined in the SRD and 2) the Observatory System Specifications (OSS) that captures the set of requirements defining how the LSST will meet the requirements in the LSR and SRD.

The SysML architecture model is the core of the systems engineering effort. Error budgets for parameters like throughput, image quality, and image elipticity are still used to evaluate certain parameters but the final record of the requirements and design are held in the model. A full description of the model and how it is used in LSST is provide by Claver et. al. in "*Using SysML for MBSE Analysis of the LSST System*" [6].

Table 1 lists the summary requirements that define the major system aspects of the LSST.

Table 1: LSST system requirements summary

Sky coverage	20,000 degrees^2 (General Survey)
Standard cadence (per visit)	15+1 s expose/shutter + 2 s read + 15+1 s expose/shutter + 5 s slew/read = 39 s total
Etendue	319 meter^{2}degrees^2
Field of View	3.5 degrees (9.6 square degrees)
Effective clear aperture (On-Axis)	6.68 m (adjusted for obscuration)
Wavelength coverage (Full response)	320nm to 1080nm
Number of active filters in camera	Five
Initial filter set *(FWHM points - nm)* and Residual design aberrations *(mean 80% encircled energy diameter for each filter band)*	u: 330 - 403 nm 0.26 arcsec g: 403 - 552 nm 0.26 arcsec r: 552 - 691 nm 0.18 arcsec i: 691 - 818 nm 0.18 arcsec z: 818 - 922 nm 0.19 arcsec y3: 970 - 1015 nm 0.20 arcsec
Final f-ratio	f/1.234 (r-band)
Plate scale	50.0 microns/arcsec
Image diameter at focal plane	64 cm

2.2 Optical Design

The optical design for LSST is a 3-mirror Mersene-Schmidt wide field of view system with an 8.4 meter diameter primary aperture, a 3.4 meter diameter secondary, a 5 meter diameter tertiary, three refractive lenses and a filter before reaching the 64 cm diameter focal plane. This design has remained stable with only minor adjustments since the referenced 2008 overview paper. Version 3.3 of the optical design has increased the spacing of the filter and third refractive lens (dewar window) to allow more room for the filter exchange mechanism. The optical design is under configuration controlled and described in LSST document LSE-11. The performance of the optical system is inherently good across the full field of view and the image quality error budget allocated to the system components is within specifications.

2.3 System Simulations

The LSST project has continued to pursue a robust system simulation effort to support engineering and design analysis and science level performance analysis [7]. The LSST will generate tens of terabytes of images and detect hundreds of millions of sources every night. The need to analyze these data in real-time in order to identify moving sources (e.g. potentially hazardous asteroids) or transient objects (e.g. supernovae), requires new approaches for analyzing astronomical data streams. To enable the development of these techniques the LSST has undertaken a program to generate high fidelity simulations of the LSST data flow (comprising images and catalogs) and the LSST observing sequence. The results of this work will be used in designing and testing algorithms for use by the data management groups, evaluating the capabilities and scalability of the reduction and analysis pipelines, testing and optimizing the scientific returns of the LSST survey and providing realistic LSST data to the science collaborations and engineering teams alike. The effort is segregated into three portions: 1) operations simulation (or cadence simulation), 2) catalog development, and 3) image simulation. The latter two are integrated into a single extensible framework tightly coupled to allow simulations of catalogs and images that reflect the expected properties of the LSST survey.

2.3.1 Operations Simulation

The operation simulator addresses the survey performance by simulating observations over N years using realistic hardware performance, site cloud and seeing statistics, and multiple scientific programs. The latter are sets of observing requirements developed to support different types of science (weak lensing, near earth objects, supernovae, etc.) with unique or specific observation cadence requirements, for example, filter, airmass limits and visit timing parameters. The scheduler/simulator arbitrates between the various programs to determine an efficient observing sequence. The simulator is driven with hundreds of system performance parameters and observational priorities. The full output includes the detailed pedigree of all observations made to understand the telescope and observing conditions during each exposure allowing scientific analysis of the survey performance. Over the ten years, LSST will make roughly 5.4 million observations that are each identified in the Ops history table output. A description of the simulator and the baseline survey data sets are available at: http://www.noao.edu/lsst/opsim/ . Results showing how the single LSST survey achieves its requirements are described by Cook et. al in "*Implementation of the LSST Operations Simulator for Testing Observatory Design, Observing Cadences and Delivery of LSST Science*" [8].

2.3.2 Catalogs Development

The LSST simulation framework incorporates catalog inputs to provide a parameterized realization of the sky above the atmosphere. These catalogs include galaxies derived from an N-body simulation of a Λ-CDM cosmology, stars that match the observed stellar distributions within our Galaxy, asteroids generated from simulations of our Solar System, and a 3-D model for Galactic extinction. Parameters to populate the catalogs are gathered from many sources of observations, simulations, published models and randomly to provide a realistic input to validate engineering and scientific investigations. This includes thin-disk, thick-disk and halo star components for stellar sources, distribution and colors of the stars, template spectral energy distributions, proper motions and some randomly assigned light curves for variability as described by Connelly et. al. in reference [7].

2.3.3 Image Simulation

To generate the simulated images, photons are drawn from the spectral energy distribution of each source in the input catalog and ray-traced through the atmosphere, telescope and camera to generate a CCD image. The atmosphere is modeled using a Taylor frozen screen approximation with the atmosphere described by six layers in motion. The density fluctuations within these screens are described by a Kolmogorov spectrum with a defined outer scale. The photons are reflected and refracted by the optical surfaces within the telescope and camera using geometric optics techniques in a fast ray-tracing algorithm and all optical surfaces include a spectrum of perturbations based on design tolerances. Photons continue into the silicon of the detector where conversion probability, refraction as a function of wavelength and temperature, and charge diffusion within the silicon are modeled for all photons. Photons are pixilated and the readout process simulated including blooming, charge saturation, charge transfer inefficiency, gain and offsets, hot pixels and columns, and QE variations. The flexibility of the simulation tool and affect of the various ray trace elements is shown in Figure 1 and an example of a full focal plane and single amplifier are shown in Figure 2.

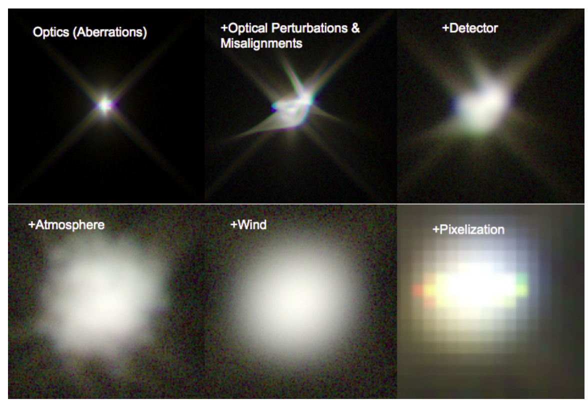

Figure 1: The image simulation framework is flexible enough to switch off and on different optical components. From left to right and top to bottom we show the resulting PSF as we progressively add more components to the optical path (including perturbations in the optical surfaces and a six-layer atmosphere).

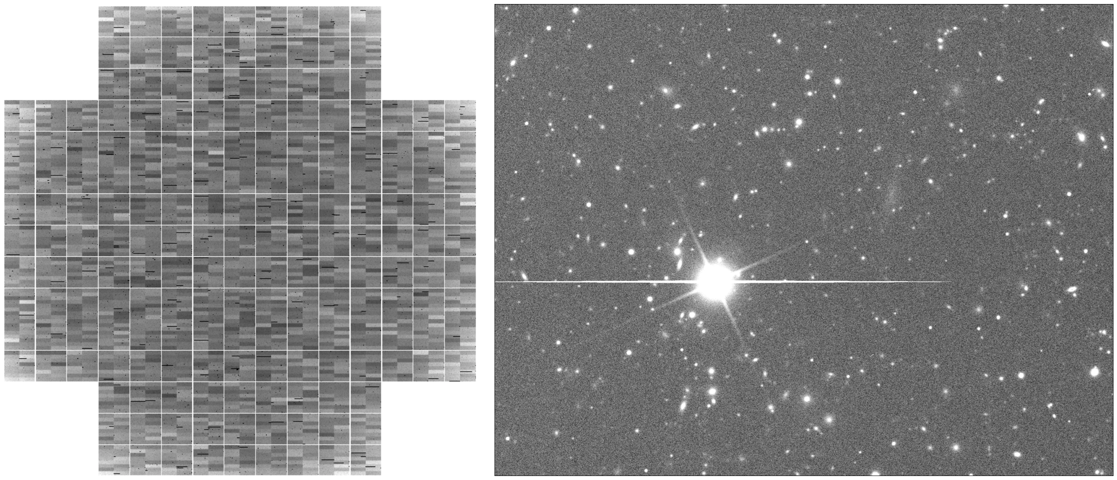

Figure 2: The left panel shows a full focal plane simulated for the LSST. The patchwork structure reflects the variation in the gain of the individual amplifiers. The right panel shows an image from part of a single amplifier. The distribution of galaxies, and the diffraction spikes and bleed trails of bright stars are visible within the image.

3. TELESCOPE AND SITE

The telescope and site subsystem for LSST is designed to meet challenging image quality, slew and settle, and reliability requirements. The design has engineering challenges but meets its requirements with proven methods from previous experience, and is well within current development capabilities. This includes all subsystems from the facility and site, the telescope structure, the optical elements, the measurement and control of the wavefront and the software to control the system [5].

In December 2008, a key development occurred when the Chilean authorities granted AURA, the host organization in Chile, all the permits necessary to build and operate the LSST summit facility on Cerro Pachón. This finalized the formal part of the process that started in July 2008 with the submittal of a Declaration of Environmental Impact (*Declaración de Impacto Ambiental [DIA]*) to the *Comisión Nacional del Medio Ambiente (CONAMA)*, a federal-level Chilean agency comparable to the U.S. Environmental Protection Agency. Since then, the civil design work for initial excavation of the summit has been completed and in early 2010 LSST contracted with ARCADIS Geotecnica Consultores, a Santiago based engineering firm, to lead the formal architectural design effort for the summit facility. Figure 3 shows an early rendering of their work on the facility.

Figure 3: Rendering of LSST summit facility shows focus on site topography and aerodynamics

There has been significant progress with the fabrication of the three optical reflective surfaces. Generous private donations to LSST have allowed the casting and optical fabrication of the primary monolithic mirror to begin at the University of Arizona and the fabrication of the secondary mirror at Corning Incorporated. The single monolithic borosilicate mirror with both the primary and tertiary surfaces has been fabricated through completion of front surface generation. Figure 4 shows the mirror and the dramatic difference in shape between the two surfaces [9]. The 3.4 meter diameter secondary mirror is a thin meniscus-type construction using ULE[tm] low expansion glass. The mirror was delivered in November 2009 with the concave surface to near net shape within 40 microns and the remainder of surfaces acid etched. Figure 5 shows the secondary mirror substrate at final inspection in Canton NY.

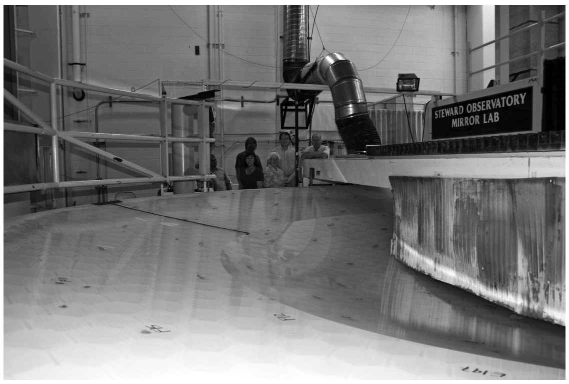

Figure 4: Several LSST staff members behind the M1M3 primary mirror after initial grinding of the two surfaces was completed

Figure 5: The 3.4 meter diameter secondary mirror substrate at delivery by Corning in Canton, NY

The telescope structure is a compact, stiff and very agile pointing system. The configuration and performance is unchanged but the preliminary design efforts have focused on further analysis, system details and interfaces, particularly to the mirrors, camera, and facility [10]. Engineering efforts have also focused on several elements of the primary mirror support system. Papers on the thermal control system design, the hardpoint actuators and the axial support actuators for the primary mirror system are presented at this conference [11, 12, 13].

A key element in establishing routine, robust, and efficient operation of the LSST is the control system. LSST has chosen a tiered architecture centered on a middleware layer that uses an open source Data Distribution Standard (DDS). The middleware layer is utilized in the Observatory, Telescope and Camera Control systems and offers common services and a standard interface for all applications, thus removing the messaging overhead from individual applications [14]. The recent upgrade of the Blanco telescope control system is a direct demonstration of this technology successfully implemented [15].

4. CAMERA

LSST's single scientific instrument shown in Figure 6 is a very large optical camera with 3.2 Gigapixels covering the flat 64 cm diameter focal plane, the readout electronics, shutter, filters, and three refractive optical elements [16]. The design focuses on well-sampled and quality imaging, as well as efficiency. It has

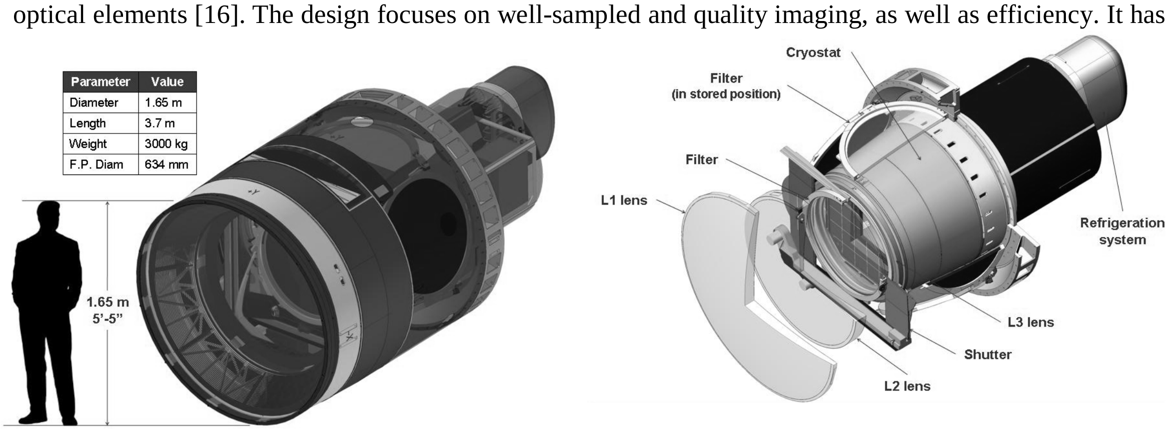

Figure 6: The LSST camera shown complete, left, and with the outer housing removed, right

good quantum efficiency across the LSST wavelengths and high pixel fill factor. It is also time efficient with very short readout time, on board filters, and short filter change-out times. Design development of the camera has progressed in the preliminary design with robust designs vetted with analysis, prototyping and testing.

Figure 7: Detector Lab for LSST CCDs

The camera focal plane is tiled with 189 4k x 4k CCDs that are each highly parallelized 16-channel devices to support the 2 second readout requirement. The devices are back illuminated, 100 micron thick, fully depleted silicon sensors that offer excellent quantum efficiency in the challenging red end of the 0.3 to 1.0 micron wavelength range. Development contracts are in place at e2v and STA/ITL to design and prototype these devices. Several CCD units have been delivered by each vendor and LSST has been focused on evaluation of their performance. Figure 7 shows some of the lab testing that has been set up at Brookhaven National Labs and French National Institute of Nuclear Physics and Particle Physics, (IN2P3) in Paris to evaluate these thick CCDs [17]. Devices from each supplier have also been assembled into instruments and deployed on sky for on sky tests as well. The early prototypes have performed well and are leading to full prototype devices expected later this year. These will address all aspects of the current design, including the +/- 5 micron flatness specification for the packaged 4 side butable sensor. Efforts to date indicate that the challenging LSST devices can be fabricated to meet requirements and process yield, and capacity exists to produce the full compliment of sensors necessary to meet the development schedule.

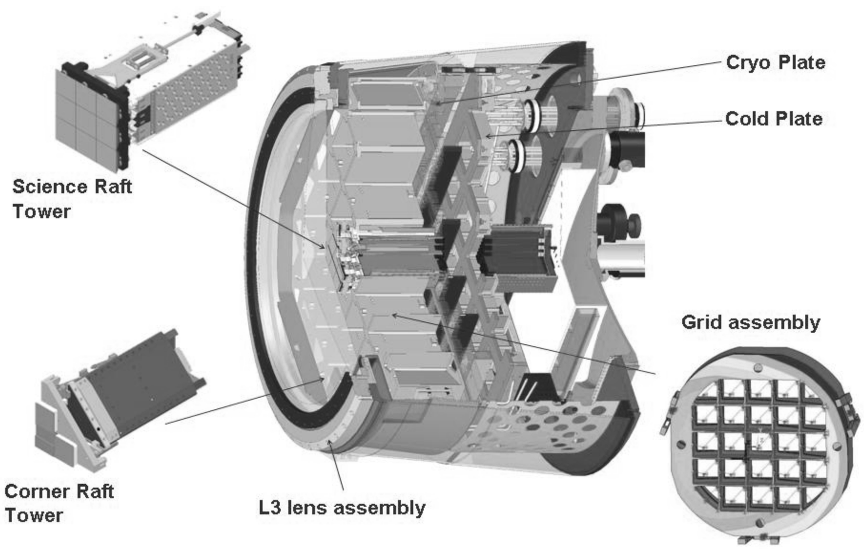

Figure 8: LSST dewar shown cut out with several of the key components identified

The camera system design has also progressed significantly in all other mechanical, electrical, and software subsystems with a focus on mitigating technical risks. Prototype and testing is underway for the filter change mechanism and shutter. The filters themselves are being prototyped by multiple vendors. The 3 x 3 array of detectors mounted to a single “science raft” and the special corner rafts [18] that hold the guide and wavefront sensors have been analyzed in detail to insure designs are optimized and meet requirements. Figure 8 shows the details incorporated into the dewar. This must hold the focal plane at -100 C and stay clean holding all 189 science sensors, 8 guide sensors, 4 split wavefront sensors and all the associated electronics. A robust contamination testing and control program is underway.

5. DATA MANAGEMENT

The handling, processing, storage, and delivery of the vast LSST data stream are key elements in the LSST system. This software and hardware system must automatically ingest ~15 TB (Terabytes) of raw images

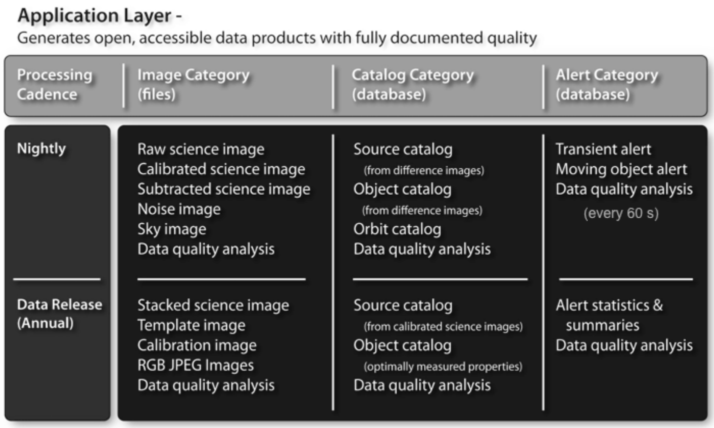

Figure 9: LSST data products generated continuously during operations and from periodic releases

taken each night, apply proper system corrections, verify data quality, process to broadcast categorized alerts, archive, process for catalog products, and serve the data to the community. This succession of activity is performed to produce the alerts on discovered transient, moving, and variable objects within one minute. It is further processed to keep up with data generation on a daily pace and for catalog releases and full re-computation on yearly intervals. This system can be implemented using existing fiber networks (except for a new 90km run from summit to base) and while the roughly 200 Tflop of computation facilities needed at the start of the survey, increasing to ~400 Tflops after 10 years, is substantial today, none of the sites are expected to rank within the top 500 supercomputer facilities when fully implemented in 2018 [19].

The LSST produces data products at several cadences over the 10-year LSST survey. The data products requirements are driven by the overall science and survey requirements and the telescope and camera designs. The data products are organized into three groups, based largely on where and when they are produced. Level 1 data products are generated by highly automated processing pipelines of data during normal observing on a continuous and nightly basis. Level 2 data products are generated as part of a data release, which is performed at least yearly, and will be performed more frequently during the first year of the survey. These products will also be highly automated but significant human interaction will be required for quality assurance. Level 3 data products are derived from Level 1 and / or Level 2 data products to support particular science goals. These products will be created by externally developed software and only facilitated by the LSST data management system to allow broad and robust access to the entire survey. Level 1 and Level 2 data products that have passed quality control tests will be accessible to the public without restriction. Additionally, the source code used to generate them will be made available. Level 3 data products may be federated into the LSST database, the software may be included in the LSST pipelines, or they will remain separate and proprietary depending on the specific case. Figure 9 shows the list of data products supplied by the LSST.

The data management design has remained a three layer approach consisting of applications, middleware, and infrastructure. The software is built on an open source framework [20]. Figure 10 shows the block organization of the system including its pipelines. The development approach includes a nearly continual process of successive data challenges designed to test and demonstrate key features of the processing and data transport effort. Data challenge 3a has recently been completed by extending the development framework, extending the nightly pipeline prototype, first release

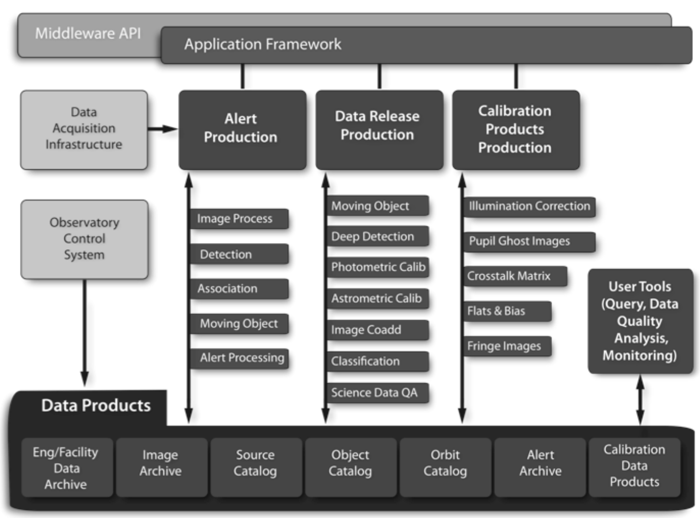

Figure 10: LSST data management software structure

of the data release pipeline, and science data quality analysis system. Data challenge 3b will continue scaled tests of data transfer, processing and data ingest of 15% of the final requirements.

The flow of data through the LSST Data Management System (DMS) starts with the interface to the camera data acquisition on the summit at Cerro Pachón, continues through Base and Archive Centers for data processing, and on to Data Access Centers (DAC) for distribution of data products to end user-accessible resources. This approach is unchanged from the concept design, however the locations of the two project funded DACs has been defined. For efficiency and to meet obligations to the host country of Chile, one DAC will be co-located with the Base Center in Chile and the other co-located with the Archive Center at the National Center for Supercomputing Applications in Illinois.

6. EDUCATION AND PUBLIC OUTREACH

Education and public outreach has always been a key element in the LSST Project. The current design and development phase includes an effort by a team of outreach and education professionals to develop the appropriate designs for programs and tools that bring the LSST data to the public in a usable manor. Making the LSST data available to the public without a proprietary period requires active development of tools to allow any world-wide citizen with computer access the ability to harvest the data for portions of interest. In addition to customized tools and learning programs, the EPO includes dedicated data access facilities equipped and configured to support the types of queries and data products necessary to support the general public.

System Area	Cost (FY2009 M$)
Telescope and Site	$151
Data Management	$78
Camera	$86
Commissioning	$12
Education and Outreach	$9
Project Management	$17
Contingency	$101
Total	$454
Annual Operations (M$/yr)	$37

Construction Funding Source	Total Request (FY2009 M$)
NSF	$297
DOE	$84
Private	$73
Total	$454

Table 2: LSST construction cost estimate with contingency and the proposed allocations of sponsoring agency

7. LSST CORPORATION AND MANAGEMENT

The LSST Corporation and Project Office continues to provide the central management of the LSST project from its offices in Tucson, Arizona. The project offices are located in space on the University of Arizona (UofA) campus to be in close proximity to the LSST teams at the UofA and the National Optical Astronomy Observatory. The corporate office provides the central support services for the corporation and serves to manage the entire project. The structure, tools, and processes implemented to manage the project continue to advance with the maturity of the project as described by Sweeney in reference 4.

During the preliminary design phase the project management control system (PMCS) was migrated from the initial Primavera and Pro Pricer tools to a Primavera only system to capture a work breakdown structure based cost estimate and schedule. This new system is designed to provide all the same information from a single database and will be ready to incorporate earned value controls during the final design phase. The cost of the project embodied in the PMCS is developed from thousands of individual cost elements that are heavily attributed to vendor-provided cost estimates. The project costs have remained substantially unchanged since the concept design, adjusting slightly up and down with revised estimates, and adjusting

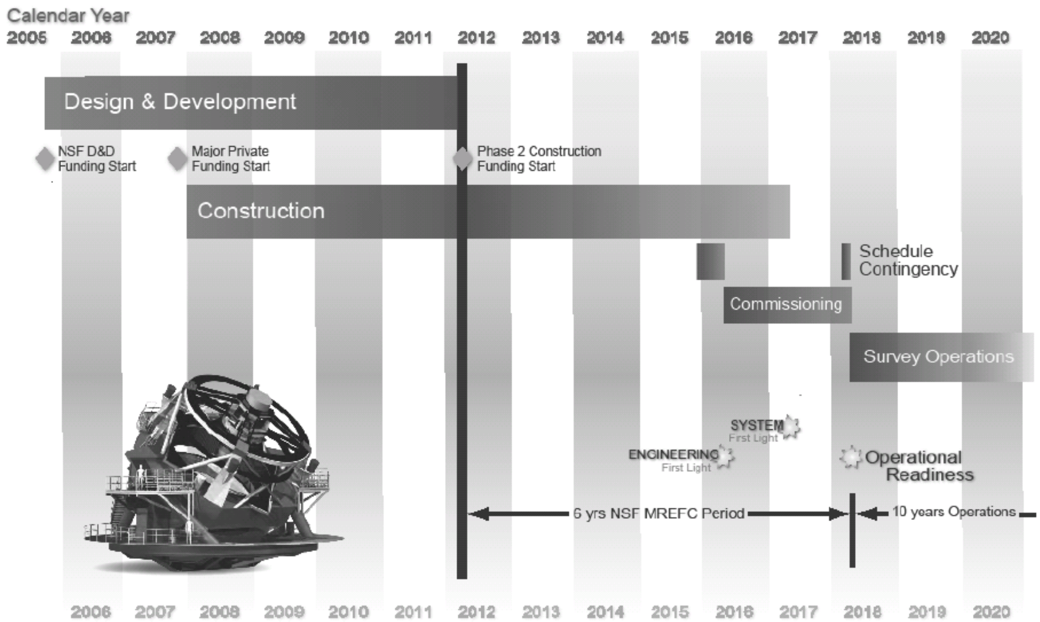

Figure 11: LSST Project Schedule for Design and Development, Construction and Commissioning with a 2012 Federal construction authorization

mainly with inflation as the project start date has adjusted. Table 2 shows the current $454 M cost of the project segregated by the major subsystems and cost elements and the distribution of the cost to the funding sources.

The project schedule for construction has also remained consistent. The 6 year schedule has each of the major subsystems completed in the first 4 years and the final system integration and science verification occurring in the last two year commissioning period. The project could be ready for the 2012 start as shown however a 2013 authorization is more realistic with the Decadal Survey providing its input later in FY2010. The project schedule is shown in Figure 11.

The LSST Corporation now has an institutional membership list of 34 institutions that consist of Universities, DOE Labs, NSF centers, and private institutions. The list is updated on www.LSST.org.

8. CONCLUSION

The LSST project has a well established cost and schedule as it moves through the Preliminary Design Phase. The project is well into the Design and Development effort and can be ready for a federal construction start in fiscal year 2012. The project enjoys significant non-federal financial support allowing the construction of long lead items like the mirrors and the pursuit of risk reduction efforts like the sensor prototyping.

9. ACKNOWLEDGEMENTS

The LSST development work is the result of efforts by the LSST collaboration of scientist, engineers, technicians, managers as well as the study work contracted to several outside entities. This team of dedicated and recognized experts in their field is what makes the LSST project a success. At the 2008 annual LSST all hands meeting there where 160 people that participated from the project team and Science Collaborations.

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