LARGE SYNOPTIC SURVEY TELESCOPE (LSST) $48,820,000

The FY 2019 Budget Request for the Large Synoptic Survey Telescope is $48.82 million. This is the sixth year of support for a nine-year project that began in August 2014. The National Science Board approved not-to-exceed total project cost is $473.0 million for NSF's contribution to the project's scope.

Appropriated and Requested MREFC Funds for the Large Synoptic Survey Telescope
(Dollars in Millions)

FY 2014 Actual	FY 2015 Actual	FY 2016 Actual	FY 2017 Actual	FY 2018 Request	FY 2019 Request	FY 2020 Estimate	FY 2021 Estimate	FY 2022 Estimate	Total Project Cost
$27.50	$79.64	$99.67	$67.12	$57.80	$48.82	$46.34	$40.75	$5.36	$473.00

LSST is located in Chile and, when completed, will be an 8-meter-class wide-field optical telescope designed to carry out surveys of nearly half of the sky. The initial 10-year survey has a cadence enabling repeat observation of each survey field approximately twice weekly. The requirements for LSST were set by considering four key science areas:

- the physics of dark energy and dark matter
- a census of small bodies in the solar system, including potentially hazardous Near Earth Objects
- the structure and contents of the Milky Way galaxy
- the nature of transient astronomical objects on time scales ranging from seconds to years.

By satisfying the requirements defined by these key investigations, the LSST survey will result in a comprehensive data set that will enable hundreds of fundamental astrophysical studies by the entire research community on these and other topics. Thus, LSST has the potential to advance every field of astronomical study, from the inner Solar System to the large-scale structure of the Universe.

Baseline History
LSST is a joint NSF/Department of Energy (DOE) project to build an instrument that was ranked the top large ground-based astronomy project by the National Research Council 2010 Decadal Survey.[4]

Prior to NSF's construction award, NSF, DOE, and private (non-federal) partners invested over $130.0 million in LSST-related work. About 70 percent supported design and development and about 30 percent, from the non-federal funding, supported casting and polishing of the innovative combined primary-tertiary mirror (M1M3), initial site preparation, and prototype detector creation and evaluation, all of which significantly reduced construction risk.

NSF and DOE conducted a series of reviews in 2011 and 2012 to determine the project baseline, including the NSF Preliminary Design Review (PDR) and a subsequent cost estimation review. Plans were kept up-to-date to synchronize the DOE and NSF funding profiles as reviews continued, leading to NSF's Final Design Review (FDR) in December 2013. NSF then carried out a detailed cost analysis prior to following through on its approval process and making an award in the last quarter of FY 2014.

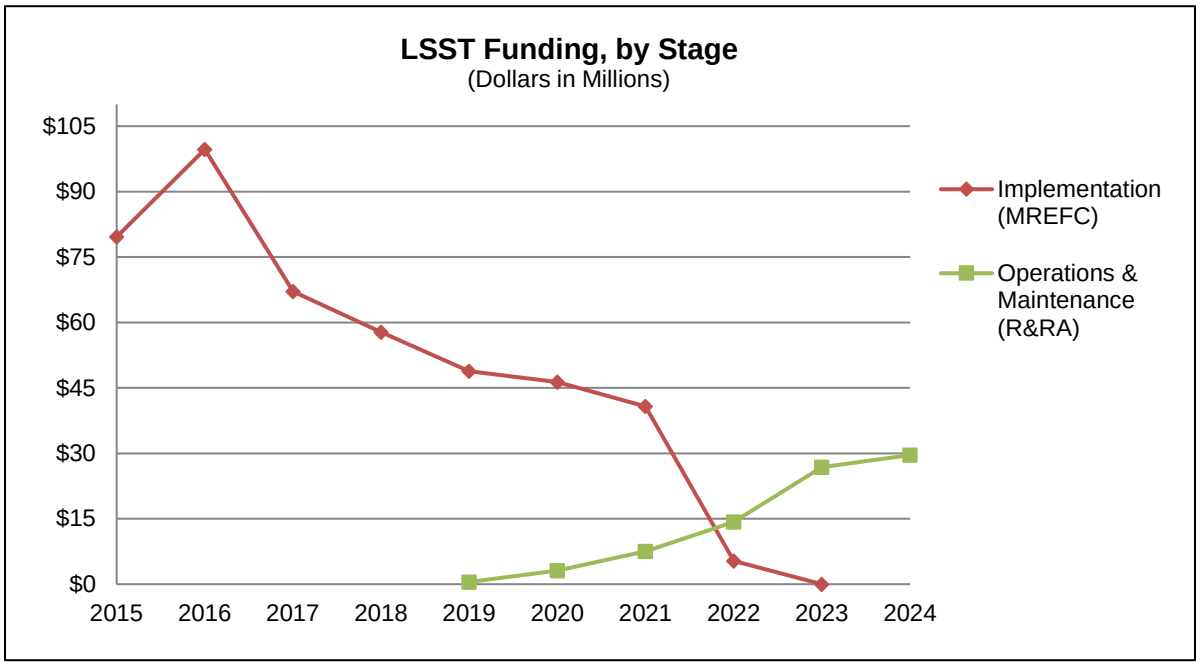
[4] http://sites.nationalacademies.org/bpa/BPA_049810

Total Funding Requirements for LSST

(Dollars in Millions)

	Prior Years[1]	FY 2017 Actual	FY 2018 Request	FY 2019 Request	ESTIMATES FY 2020	FY 2021	FY 2022	FY 2023	FY 2024
R&RA:									
Concept & Development	$57.13	-	-	-	-	-	-	-	-
Operations & Maintenance	-	-	-	0.50	3.10	7.50	14.30	26.80	29.60
Subtotal, R&RA	$57.13	-	-	$0.50	$3.10	$7.50	$14.30	$26.80	$29.60
MREFC:									
Implementation	206.81	67.12	57.80	48.82	46.34	40.75	5.36	-	-
Subtotal, MREFC	$206.81	$67.12	$57.80	$48.82	$46.34	$40.75	$5.36	-	-
TOTAL REQUIREMENTS	**$263.94**	**$67.12**	**$57.80**	**$49.32**	**$49.44**	**$48.25**	**$19.66**	**$26.80**	**$29.60**

[1] Concept & Development funding and Implementation funding are cumulative of all prior years; Operations & Maintenance funding reflects prior year actual obligations only.



LSST Science Plan

The site at Cerro Pachón, Chile was selected for LSST because of the excellent sky transparency and image quality (known as seeing), dark skies, small fraction of cloudy nights, and the geological characteristics that enable the rapid telescope motions required to carry out the LSST survey. LSST will collect nearly 40 terabytes of multi-color imaging data every night for 10 years, producing a long-lived dataset of considerable utility. It will produce the deepest, widest-field sky image ever, and issue alerts for changing and transient objects within 60 seconds of their discovery. Repeated deep imaging of every part of the accessible sky will turn up explosive events such as cataclysmic variable stars, supernovae, and the optical counterparts of X-ray flashes, as well as finding moving objects and better characterizing those already known. Estimates of LSST's ability to locate Near Earth Objects (NEOs) and Potentially Hazardous Asteroids (PHAs) have been refined by LSST Project members, as well as by external studies, including an independent Jet Propulsion Laboratory study supported by NASA's Planetary Defense Coordination Office. Assuming other existing NEO efforts continue, at the end of LSST's 10-year prime mission, the catalog for objects larger than about 140 meters across should be about 75 percent complete for NEOs (about 80 percent

for PHAs), approximately 15 percent more complete than without LSST.

LSST data will be widely accessible, and discovery opportunities will be available to K-12 students as easily as to professional astronomers. An innovative citizen science program will involve people of all ages in LSST discoveries. More than half of the cost during operations is for data management, including user-friendly interfaces tailored for the different anticipated communities. The survey strategy makes the same dataset usable for almost all of the astronomy community as well as for educators and the general public. The primary data archive is planned to be located at the National Center for Supercomputing Applications in Illinois.

Management and Oversight

- NSF Structure: NSF oversight is handled by a program officer in the MPS Division of Astronomical Sciences (AST) working cooperatively with NSF staff from MPS, BFA, OGC, OLPA, and OISE. The NSF program officer works closely with counterparts in the DOE Office of High Energy Physics, who have oversight responsibility for the LSST camera sub-project. Inter-agency coordination is accomplished through weekly meetings of a joint oversight group and was formalized through a Memorandum of Understanding signed in July 2012.
- External Structure: The responsible awardee for LSST construction is the Association of Universities for Research in Astronomy, Inc. (AURA), a non-profit science management corporation consisting of 44 U.S. institutional members and four international affiliates. AURA works closely with the LSST Corporation (LSSTC), which initiated LSST development and remains responsible for privately raised funding. AURA and LSSTC established the LSST Project Office as an AURA-managed center for construction; this office is overseen by the AURA Management Council for LSST. The LSST Project Director and the LSST Project Manager are experienced in large facility construction and operation and are appointed by AURA, with the approval of NSF and DOE.

Reviews

- Technical Reviews: Reviews were conducted throughout the design and development phase, culminating in NSF's FDR in December 2013, with DOE involvement. All major sub-systems undergo regular system-level design reviews organized by the LSST Project Office with external participants.
- Management, Cost, and Schedule Reviews: Cost, schedule, and risk are also scrutinized by the technical reviews. During construction, NSF and DOE are holding regular joint progress reviews. These include:
  - Major reviews held by both NSF and DOE prior to the MREFC award found the Basis of Estimate documentation to be quite adequate, with small improvements requested.
  - On May 7, 2014, the National Science Board (NSB) issued Resolution NSB-14-24, authorizing NSF management to proceed with the construction award, subject to the resolution of any substantive cost issues identified in the NSF review process. All cost issues were subsequently resolved, allowing the MREFC award to be issued in August 2014
  - The first annual construction review was originally scheduled for August-September 2015 but was deferred until February 2016. The review panel made several recommendations to improve project execution. To get back on schedule, the second progress review happened in August 2016 and was also successful, except that the Data Management (DM) systems were undergoing a major replan and could not be fully evaluated. A follow-up and successful DM-focused review took place in July 2017, providing support for significant use of cost contingency. The latest joint agency progress review occurred in September 2017.
  - In conjunction with the first progress review, NSF organized an Earned Value Management (EVM) validation review to consider both the adequacy of the system used for EVM, and the LSST Project staff's ability to use EVM tools and methods. The review made some minor recommendations, which were adopted. NSF formally accepted the LSST EVM system in January 2017. A follow-up EVM surveillance review coincided with the 2017 annual progress review.

  - In January 2017, DOE and NSF held a joint external agency review of the project's plans for commissioning and transition to early operations.
- After DOE Critical Decision (CD) reviews, DOE issued CD-3a approval for long-lead procurements in July 2014, and CD-2 approval, including setting the not-to-exceed Total Project Cost for the DOE sub-project, on January 7, 2015. CD-3 review in early August 2015 was followed by formal approval for full DOE construction funding on August 27, 2015.

Project Status
NSF's construction award was issued on August 1, 2014. Use of cost contingency and task-to-task float kept the project on the most optimistic schedule possible until recently, when delays with the main mirror cell have led to use of 10 weeks overall schedule contingency. Despite weather delays caused by an unprecedented El Niño event, the primary telescope building and dome installation will be completed in mid-FY 2018 and ready for the installation of necessary equipment and for the arrival of the telescope mount assembly. During the bid process, the estimated cost of the La Serena base facility was found to be in error, and some technical risk was realized. NSF has issued approval for the contract, and the approximately $4.0 million increase will be covered by available contingency. NSF- and DOE-supported activities remain tightly coordinated, both at the project level and between agency program officers.

Cost and Schedule
A complete re-estimate of the project occurred prior to the NSF FDR. The FDR panel found the NSF Total Project Cost (TPC) of $473.0 million to be reasonable and justifiable, but they nevertheless recommended that the project introduce possible additional de-scoping options. NSF carried out further cost review prior to making the award.

NSF policy changed from a probabilistic contingency estimation based on the Project Management Control System (PMCS) to requiring a joint cost and schedule Monte Carlo (MC) method. The LSST Project established the new MC method through their PMCS and showed that the computed TPC corresponds to a better than 90 percent chance that the final cost of the current construction scope will fall within the NSB-approved funding cap, and before the planned survey start date. This result was finalized in April 2015 and incorporated into the associated Cooperative Support Agreement.

In addition to NSF's contribution, DOE's baseline for the camera was fixed at $168.0 million by the CD-3 approval mentioned above. Construction also includes approximately $39.0 million from non-federal sources, all of which has been expended.

Risks
Technical: Much of the technical risk was retired during design and development. Since full construction began, no new major risks have appeared, and small, realized risks have been mitigated by use of cost and schedule contingency, including float internal to sub-projects. The Data Management construction effort has been identified as a risk and re-planning has been completed. Implementation of the recommendations of the July 2017 Data Management review, including the release of cost and schedule contingency, is currently underway.

Environmental and Cultural Compliance: Environmental and cultural impact mitigation continues as planned with no unforeseen issues.

Site: The possible site risk due to local geological anomalies, noted in previous requests, was realized during excavation. Since this risk was localized and anticipated, it was successfully handled. Site disruptions from geological events and extreme weather remain as possible risks with appropriate mitigation plans.

Environmental Health and Safety: The LSST project has a full-time head of safety with experience in AURA operations, which has a long positive safety record in Chile. Both the summit and base sites have on-site safety supervisors employed by LSST to monitor contractor and project activities. All safety plans are fully compliant with applicable standards from U.S., Chilean, and participating institutions, and are updated regularly. External reviews have given the project high marks for its safety culture.

Partnership Risk: Significant attention has been paid to partnership risk, and that risk has been mitigated by careful coordination and unified project structures. The LSST project director and deputy director oversee the entire project. A single project manager, agreed to by both NSF and DOE, manages the complete work breakdown structure elements. Budgetary management details are clearly set out between the project director, the project manager, the project's Change Control Board, the AURA Management Council for LSST, and the agency program officers, grants officers, and financial managers.

Operations Costs

Operation costs are funded within R&RA. The operations costs shown in the table immediately above are planning estimates based on the most recently available data. Although the FY 2019 Request is less than previous estimates, the overall 10-year operations cost estimate to NSF remains unchanged at $310.0 million (then-year US dollars). The final full operations costs and the amount required from non-federal partners will be determined through a review, approval, and award process that began with the project submission of a formal proposal for LSST operations in August 2017 and will include a review by the National Science Board in 2018 before the final award is issued.

In their joint Memorandum of Understanding, NSF and DOE agreed to fund operations, increasing agency support and revising the operations plans, as appropriate. MPS/AST is planning to provide approximately half of the original estimated steady-state amount, as well as pre-operations support, with the DOE Office of High Energy Physics providing one quarter, plus installation and commissioning support additional to the project construction cost. The project team has already established firm agreements to fund about half of the remaining one quarter with contributions from non-federal entities. Negotiations continue with potential partners to find the remaining balance.

Construction status on Cerro Pachón, November 2017. *Credit: LSST.*