Large Synoptic Survey Telescope

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Contributor: HandWiki Huang

The Large Synoptic Survey Telescope (LSST) is a wide-field survey reflecting telescope with an 8.4-meter primary mirror, currently under construction, that will photograph the entire available sky every few nights. The word synoptic is derived from the Greek words σύν (syn "together") and ὄψις (opsis "view"), and describes observations that give a broad view of a subject at a particular time. The telescope uses a novel 3-mirror design, a variant of three-mirror anastigmat, which allows a compact telescope to deliver sharp images over a very wide 3.5-degree diameter field of view. Images will be recorded by a 3.2-gigapixel CCD imaging camera, the largest digital camera ever constructed. The telescope is located on the El Peñón peak of Cerro Pachón, a 2,682-meter-high mountain in Coquimbo Region, in northern Chile , alongside the existing Gemini South and Southern Astrophysical Research Telescopes. The LSST Base Facility is located about 100 kilometres (62 mi) away by road, in the town of La Serena. The LSST was proposed in 2001, and construction of the mirror began (with private funds) in 2007. LSST then became the top-ranked large ground-based project in the 2010 Astrophysics Decadal Survey, and the project officially began construction 1 August 2014 when the National Science Foundation (NSF) authorized the FY2014 portion ($27.5 million) of its construction budget. The ceremonial laying of the first stone was performed on 14 April 2015. Site construction began on April 14, 2015, with engineering first light anticipated in 2019, science first light in 2021, and full operations for a ten-year survey commencing in January 2022. LSST, unlike almost all previous large astronomical observatories, has committed to making all data public as soon as it is taken. In their words "By providing immediate public access to all the data it obtains, it will provide everyone, the professional and the “just curious” alike, a deep and frequent window on the entire sky."

Keywords: decadal ; astrophysics ; 3.2-gigapixel

1. History

LSST is the successor to a long tradition of sky surveys.[1] These started as visually compiled catalogs in the mid 1700s, such as the Messier catalog. This was replaced in the late 1800s by photographic surveys, starting with the Harvard Plate Collection, the National Geographic Society – Palomar Observatory Sky Survey, and others. By about 2000 the first digital surveys, such as the Sloan Digital Sky Survey (SDSS), began to replace the photographic plates of the earlier surveys.

LSST evolved from the earlier concept of the *Dark Matter Telescope*,[2] mentioned as early as 1996.[3] The fifth decadal report, *Astronomy and Astrophysics in the New Millennium*, was released in 2001,[4] and recommended the "Large-Aperture Synoptic Survey Telescope" as a major initiative. Even at this early stage the basic design and objectives were set:

> The **Large-aperture Synoptic Survey Telescope (LSST)** is a 6.5-m-class optical telescope designed to survey the visible sky every week down to a much fainter level than that reached by existing surveys. It will catalog 90 percent of the near-Earth objects larger than 300 m and assess the threat they pose to life on Earth. It will find some 10,000 primitive objects in the Kuiper Belt, which contains a fossil record of the formation of the solar system. It will also contribute to the study of the structure of the universe by observing thousands of supernovae, both nearby and at large redshift, and by measuring the distribution of dark matter through gravitational lensing. All the data will be available through the National Virtual Observatory (see below under “Small Initiatives”), providing access for astronomers and the public to very deep images of the changing night sky.

Early development was funded by a number of small grants, with major contributions in January 2008 by software billionaires Charles Simonyi and Bill Gates of $20 and $10 million respectively.[5] $7.5 million was included in the U.S. President's FY2013 NSF budget request.[6] The Department of Energy is funding construction of the digital camera component by the SLAC National Accelerator Laboratory, as part of its mission to understand dark energy.[7]

In the 2010 decadal survey, LSST was ranked as the highest-priority ground-based instrument.[8]

NSF funding for the rest of construction was authorized as of 1 August 2014.[9] The camera is separately funded by the Department of Energy. The lead organizations are:[7]

- The SLAC National Accelerator Laboratory will design and construct the LSST camera
- The National Optical Astronomy Observatory will provide the telescope and site team
- The National Center for Supercomputing Applications will construct and test the archive and data access center

- The Association of Universities for Research in Astronomy is responsible for overseeing the LSST construction.

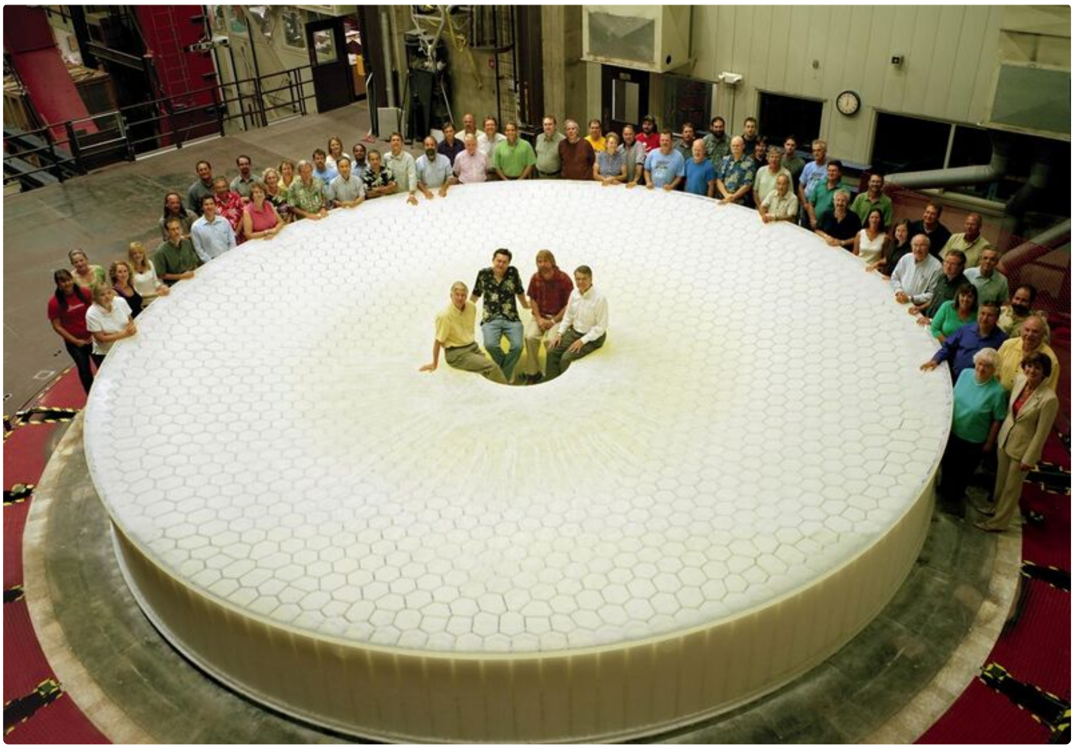
(As of November 2016) the project critical path was the camera construction, integration and testing.[10]

In May 2018, Congress surprisingly appropriated much more funding than the telescope had asked for, in hopes of speeding up construction and operation. Telescope management was thankful but unsure this would help, since at the late stage of construction they were not cash-limited.[11]

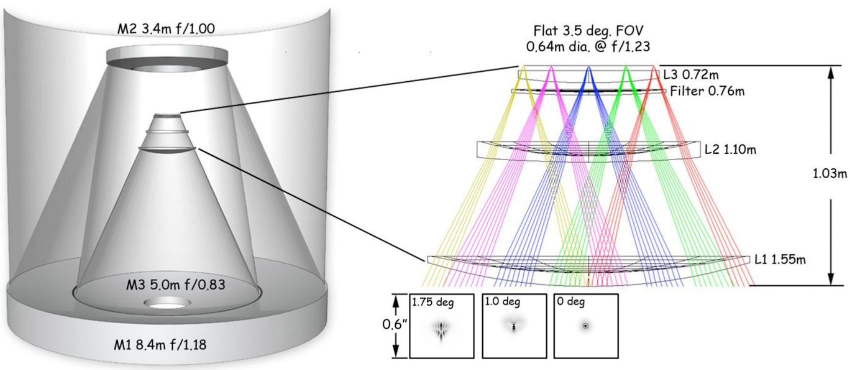
2. Overview

The LSST design is unique among large telescopes (8 m-class primary mirrors) in having a very wide field of view: 3.5 degrees in diameter, or 9.6 square degrees. For comparison, both the Sun and the Moon, as seen from Earth, are 0.5 degrees across, or 0.2 square degrees. Combined with its large aperture (and thus light-collecting ability), this will give it a spectacularly large etendue of 319 $m^2 \cdot degree^2$.[12] This is more than three times the entendue of best existing telescopes, the Subaru Telescope with its Hyper Suprime Camera,[13] and Pan-STARRS, and more than an order of magnitude better than most large telescopes.[14]

2.1. Optics



The LSST primary/tertiary mirror successfully cast, August 2008. https://handwiki.org/wiki/index.php?curid=1451058



Optics of the LSST Telescope. https://handwiki.org/wiki/index.php?curid=1666386

The LSST is the latest in a long line of improvements giving telescopes larger fields of view. The earliest reflecting telescopes used spherical mirrors, which although easy to fabricate and test, suffer from spherical aberration; a very long focal length was needed to reduce spherical aberration to a tolerable level. Making the primary mirror parabolic removes spherical aberration on-axis, but the field of view is then limited by off-axis coma. Such a parabolic primary, with either a prime or Cassegrain focus, was the most common optical design up through the Hale telescope in 1949. After that, telescopes used mostly the Ritchey–Chrétien design, which uses two hyperbolic mirrors to remove both spherical aberration and coma, leaving only astigmatism, giving a wider useful field of view. Most large telescopes since the Hale use this design—the Hubble and Keck telescopes are Ritchey–Chrétien, for example. LSST will use a three-mirror anastigmat to cancel astigmatism: three non-spherical mirrors. The result is sharp images over a very wide field of view, but at the expense of light-gathering power as the large second mirror blocks much of the aperture of the telescope.

The LSST primary mirror (M1) is 8.4 meters (28 ft) in diameter, the secondary mirror (M2) is 3.4 meters (11.2 ft) in diameter, and the tertiary mirror (M3), inside the ring-like primary, is 5.0 meters (16 ft) in diameter. The secondary mirror is expected to be the largest convex mirror in any operating telescope, until surpassed by the ELT's 4.2 m secondary c. (circa) 2024. The second and third mirrors reduce the primary mirror's light-collecting area to 35 square meters (376.7 sq ft), equivalent to a 6.68-meter-diameter (21.9 ft) telescope.[12] Multiplying this by the field of view produces an etendue of 336 $m^2 \cdot degree^2$; the actual figure is reduced by vignetting.

The primary and tertiary mirrors (M1 and M3) are designed as a single piece of glass, the "M1M3 monolith". Placing the two mirrors in the same location minimizes the overall length of the telescope, making it easier to reorient quickly. Making them out of the same piece of glass results in a stiffer structure than two separate mirrors, contributing to rapid settling after motion.

The optics includes three corrector lenses to reduce aberrations. These lenses, and the telescope's filters, are built into the camera assembly. The first lens at 1.55 m diameter is the largest lens ever built, and the third lens forms the vacuum window in front of the focal plane.

2.2. Camera

A LSST focal plane array model, actual size. The array's diameter is 64 cm. This mosaic will provide over 3 gigapixels per image. The image of the moon (30 arcminutes) is present to show the scale of the field of view. https://handwiki.org/wiki/index.php?curid=1175159

A 3.2-gigapixel prime focus[15] digital camera will take a 15-second exposure every 20 seconds.[12] Repointing such a large telescope (including settling time) within 5 seconds requires an exceptionally short and stiff structure. This in turn implies a very small f-number, which requires very precise focusing of the camera.

The 15 second exposures are a compromise to allow spotting both faint and moving sources. Longer exposures would reduce the overhead of camera readout and telescope re-positioning. allowing deeper imaging, but then fast moving objects such as near-Earth objects would move significantly during an exposure.[16] Each spot on the sky is imaged with two consecutive 15 second exposures, to efficiently reject cosmic ray hits on the CCDs.[17]

The camera focal plane is flat, 64 cm in diameter. The main imaging is performed by a mosaic of 189 CCD detectors each of 16 megapixels.[18] They are grouped into a 5×5 grid of "rafts", where the central 21 rafts contain 3×3 imaging sensors, while the four corner rafts contain only three CCDs each, for guiding and focus control. The CCDs provide better than 0.2 arcsecond sampling, and will be cooled to approx −100 °C.[19] to help reduce noise.

The camera includes a filter located between the second and third lenses, and an automatic filter-changing mechanism. Although the camera has six filters (UGRIZY) covering 330 to 1080 nm wavelengths, the camera's position in front of the mirror limits the size of its filter changer. It can only hold five of them at a time, and one of the six must therefore be chosen to be omitted each night.

2.3. Image Data Processing

Allowing for maintenance, bad weather and other contingencies, the camera is expected to take over 200,000 pictures (1.28 petabytes uncompressed) per year, far more than can be reviewed by humans. Managing and effectively data mining the enormous output of the telescope is expected to be the most technically difficult part of the project.[20][21] In

2010, the initial computer requirements were estimated at 100 teraflops of computing power and 15 petabytes of storage, rising as the project collects data.[22] By 2018, estimates had risen to 250 teraflops and 100 petabytes of storage.[23]

Once images are taken, they are processed according to three different timescales, *prompt* (within 60 seconds), *daily*, and *annually*.[24]

The *prompt* products are alerts, issued within 60 seconds of observation, about objects that have changed brightness or position relative to archived images of that sky position. Transferring, processing, and differencing such large images within 60 seconds (previous methods took hours, on smaller images) is a significant software engineering problem by itself.[25] Approximately 10 million alerts will be generated per night.[26] Each alert will include the following:[27]:22

- Alert and database ID: IDs uniquely identifying this alert
- The photometric, astrometric, and shape characterization of the detected source
- 30×30 pixel (on average) cut-outs of the template and difference images (in FITS format)
- The time series (up to a year) of all previous detections of this source
- Various summary statistics ("features") computed of the time series

There is no proprietary period associated with alerts—they are available to the public immediately, since the goal is to quickly transmit nearly everything LSST knows about any given event, enabling downstream classification and decision making. LSST will generate an unprecedented rate of alerts, hundreds per second when the telescope is operating.[28] Most observers will be interested in only a tiny fraction of these events, so the alerts will be fed to "event brokers" which forward subsets to interested parties. LSST will provide a simple broker,[27]:48 and provide the full alert stream to external event brokers.[29] The Zwicky Transient Facility will serve as a prototype of LSST system, generating 1 million alerts per night.[30]

Daily products, released within 24 hours of observation, comprise the images from that night, and the source catalogs derived from difference images. This includes orbital parameters for solar system objects. Images will be available in two forms: *Raw Snaps*, or data straight from the camera, and *Single Visit Images*, which have been processed and include instrumental signature removal (ISR), background estimation, source detection, deblending and measurements, point spread function estimation, and astrometric and photometric calibration.[31]

Annual release data products will be made available once a year, by re-processing the entire science data set to date. These include:

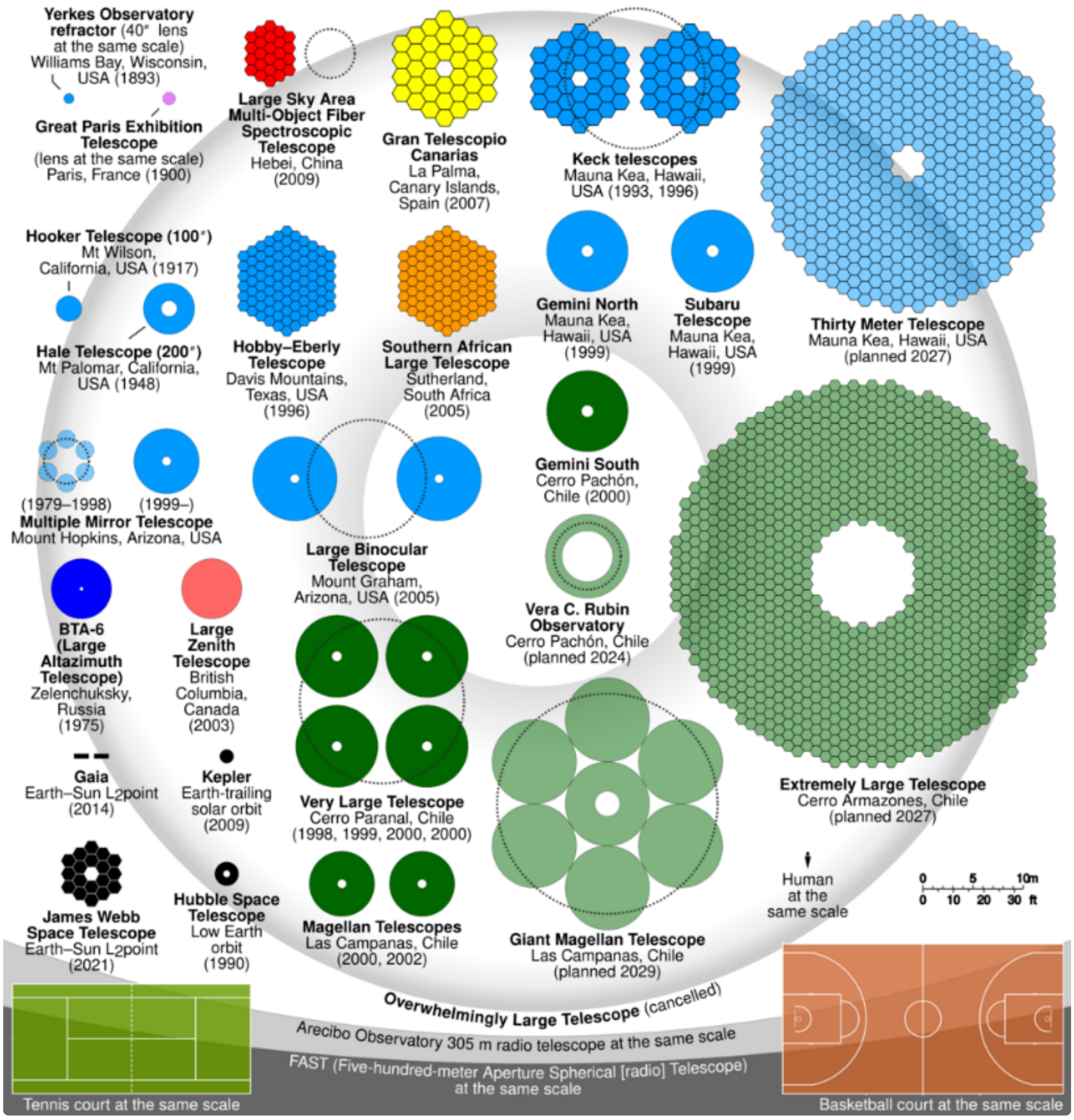
- Calibrated images
- Measurements of positions, fluxes, and shapes
- Variability information
- A compact description of light curves
- A uniform reprocessing of the difference-imaging-based prompt data products
- A catalog of roughly 6 million solar systems objects, with their orbits
- A catalog of approximately 37 billion sky objects (20 billion galaxies and 17 billion stars), each with more than 200 attributes[23]

The annual release will be computed partially by NCSA, and partially by IN2P3 in France.[32]

LSST is reserving 10% of its computing power and disk space for *user generated* data products. These will be produced by running custom algorithms over the LSST data set for specialized purposes, using Application Program Interfaces (APIs) to access the data and store the results. This avoids the need to download, then upload, huge quantities of data by allowing users to use the LSST storage and computation capacity directly. It also allows academic groups to have different release policies than LSST as a whole.

An early version of the LSST image data processing software is being used by the Subaru telescope's Hyper Suprime-Cam instrument,[33] a wide-field survey instrument with a sensitivity similar to LSST but one fifth the field of view: 1.8 square degrees versus the 9.6 square degrees of LSST.

3. Scientific Goals



Comparison of primary mirrors of several optical telescopes. (The LSST, with its very large central hole, is near the center of the diagram). https://handwiki.org/wiki/index.php?curid=2043084

LSST will cover about 18,000 deg^2 of the southern sky with 6 filters in its main survey, with about 825 visits to each spot. The magnitude limits are expected to be r<24.5 in single images, and r<27.8 in the full stacked data.[34]

The main survey will use about 90% of the observing time. The remaining 10% will be used to obtain improved coverage for specific goals and regions. This includes very deep (r ~ 26) observations, very short revisit times (roughly one minute), observations of “special” regions such as the Ecliptic, Galactic plane, and the Large and Small Magellanic Clouds, and areas covered in detail by multi-wavelength surveys such as COSMOS and the Chandra Deep Field South.[17] Combined, these special programs will increase the total area to about 25,000 deg^2.[12]

Particular scientific goals of the LSST include:[35]

- Studying dark energy and dark matter by measuring weak gravitational lensing, baryon acoustic oscillations, and photometry of type Ia supernovae, all as a function of redshift.[17]
- Mapping small objects in the Solar System, particularly near-Earth asteroids and Kuiper belt objects. LSST is expected to increase the number of cataloged objects by a factor of 10-100.[36]
- Detecting transient optical events including novae, supernovae, gamma-ray bursts, quasar variability, and gravitational lensing, and providing prompt event notifications to facilitate follow-up.
- Mapping the Milky Way.

It is also hoped that the vast volume of data produced will lead to additional serendipitous discoveries.

NASA has been tasked by the US Congress with detecting and cataloging 90% of the NEO population of size 140 meters or greater.[37] LSST, by itself, is estimated to detect 62% of such objects,[38] and according to the National Academy of Sciences, extending its survey from ten years to twelve would be the most cost-effective way of finishing the task.[39]

LSST has a program of Education and Public Outreach (EPO). LSST EPO will serve four main categories of users: the general public, formal educators, citizen science principal investigators, and content developers at informal science education facilities.[40][41] LSST will partner with Zooniverse for a number of their citizen science projects.[42]

Some of the data from the LSST (up to 15 terabytes per night) will be made available by Google as an up-to-date interactive night-sky map.[43]

4. Comparison with Other Sky Surveys

There have been many other optical sky surveys, some still on-going. For comparison, here are some of the main currently used optical surveys, with differences noted:

- Photographic sky surveys, such as the National Geographic Society – Palomar Observatory Sky Survey and its digitized version, the Digitized Sky Survey. This technology is obsolete, with much less depth, and in general taken from sites of worse seeing. However, these archives are still used since they span a much larger time interval—more than 100 years in some cases.
- The Sloan Digital Sky Survey (2000–2009) surveyed 14,555 square degree of the northern hemisphere sky, with a 2.5 meter telescope. It continues to the present day as a spectrographic survey.
- Pan-STARRS (2010–present) is an ongoing sky survey using two wide-field 1.8 m Ritchey–Chrétien telescopes located at Haleakala in Hawaii. Until LSST begins operation, it will remain the best detector of near-Earth objects. Its coverage, 30,000 square degrees, is comparable to what LSST will cover.
- The Dark Energy Survey (2013–present) looks at 5,000 square degrees of the southern sky with the 4-meter Victor M. Blanco Telescope. The area is entirely contained within the anticipated survey area of LSST. DES avoided the Milky Way since it was primarily concerned with distant galaxies.[44]
- Gaia (2014–present) is an ongoing space based survey of the entire sky, whose primary goal is extremely precise astrometry of a billion stars and galaxies. Its limited collecting area (0.7 m^2) means it cannot see objects as faint as other surveys, but its locations are far more precise.

5. Construction Progress

The Cerro Pachón site was selected in 2006. The main factors were the number of clear nights per year, seasonal weather patterns, and the quality of images as seen through the local atmosphere (seeing). The site also needed to have an existing observatory infrastructure, to minimize costs of construction, and access to fiber optic links, to accommodate the 30 terabytes of data LSST will produce each night.[45]

As of February 2018, construction is well underway. The shell of the summit building is complete, and 2018 will see the installation of major equipment, including HVAC, the dome, mirror coating chamber, and the telescope mount assembly. It will also see the expansion of the AURA base facility in La Serena and the summit dormitory shared with other telescopes on the mountain.[26]

By February 2018, the camera and telescope shared the critical path. The main risk was deemed to be whether sufficient time was allotted for system integration.[46]

The project remains within budget, although the budget contingency is tight.[26]

5.1. Mirrors

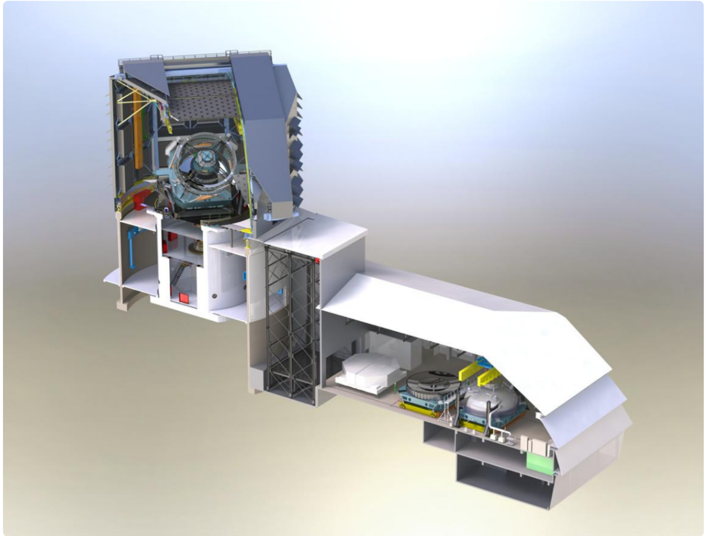
The primary mirror, the most critical and time-consuming part of a large telescope's construction, was made over a 7-year period by the University of Arizona's Steward Observatory Mirror Lab.[47] Construction of the mold began in November 2007,[48] mirror casting was begun in March 2008,[49] and the mirror blank was declared "perfect" at the beginning of September 2008.[50] In January 2011, both M1 and M3 figures had completed generation and fine grinding, and polishing had begun on M3.

The mirror was completed in December 2014.[51] The M3 portion especially suffered from tiny air bubbles which, when they broke the surface, caused "crow's feet" defects in the surface.[52] The bubbles trapped grinding abrasive, which produced scratches a few mm long radiating out from the bubble. Left as-is, these would enlarge the telescope's point spread function, reducing the sensitivity by 3% (to 97% of nominal) and increase the portion of the sky obscured by bright stars from 4% to 4.8% of the survey area. (As of January 2015), the project was exploring ways to fill the holes and scratches and concluded no further polishing was necessary as the mirror surfaces exceeded the structure function requirements.

The mirror was formally accepted on 13 February 2015.[53][54] It was then placed in the mirror transport box and stored in an airplane hangar[55] until it is shipped to Chile.[56]

The secondary mirror was manufactured by Corning of ultra low expansion glass and coarse-ground to within 40 μm of the desired shape.[57] In November 2009, the blank was shipped to Harvard University for storage[58] until funding to complete it was available. On October 21, 2014, the secondary mirror blank was delivered from Harvard to Exelis (now a subsidiary of Harris Corporation) for fine grinding.[59] As of June 2018, the mirror is nearing completion and scheduled for delivery in October 2018.[60]

5.2. Building



Cutaway render of the telescope, dome, and support building. The full resolution version is large and highly detailed. https://handwiki.org/wiki/index.php?curid=1311195

Site excavation began in earnest March 8, 2011,[61] and the site had been leveled by the end of 2011.[62] Also during that time, the design continued to evolve, with significant improvements to the mirror support system, stray-light baffles, wind screen, and calibration screen.

In 2015, a large amount of broken rock and clay was found under the site of the support building adjacent to the telescope. This caused a 6-week construction delay while it was dug out and the space filled with concrete. This did not affect the telescope proper or its dome, whose much more important foundations were examined more thoroughly during site planning.[63][64]

The building was declared substantially complete in March 2018,[65] and (as of November 2017), the dome is expected to be complete in August 2018.[26]

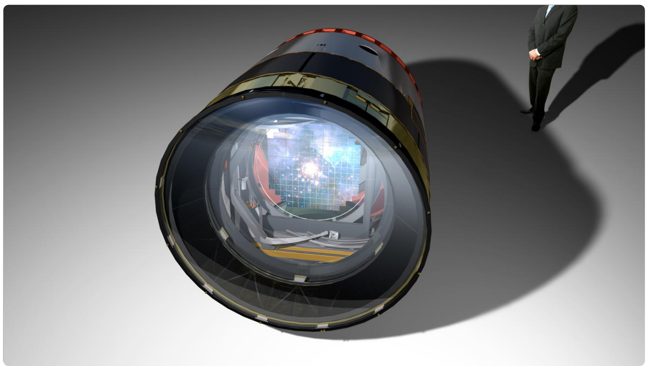
5.3. Telescope Mount Assembly

The telescope mount, and the pier on which it sits, are substantial engineering projects in their own right. The main technical problem is that the telescope must slew 3.5 degrees to the adjacent field and settle within four seconds.[66][67]:10 This requires a very stiff pier and telescope mount, with very high speed slew and acceleration (10^{o}/sec and 10^{o}/sec^{2}, respectively[60]). The basic design is conventional: an altitude over azimuth mount made of steel, with hydrostatic bearings on both axes, mounted on a pier which is isolated from the dome foundations. However, the LSST pier is unusually large (16 m diameter) and robust (1.25 m thick walls), and mounted directly to virgin bedrock,[67] where care was taken during site excavation to avoid using explosives that would crack it.[64]:11–12 Other unusual design features are linear motors on the main axes and a recessed floor on the mount. This allows the telescope to extend slightly below the azimuth bearings, giving it a very low center of gravity.

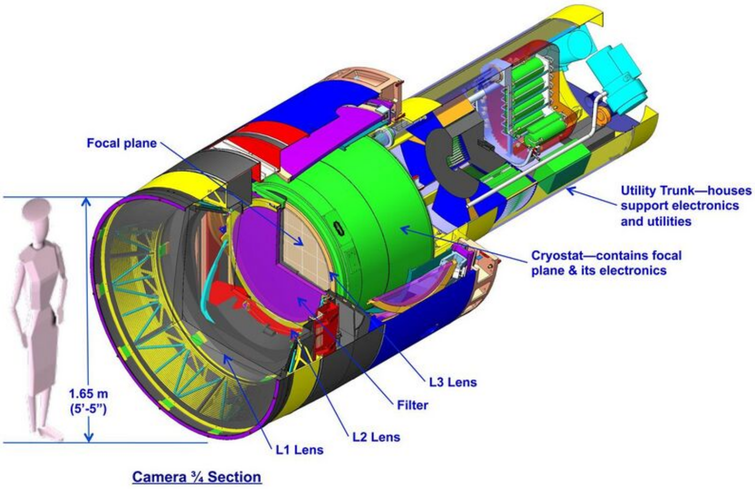
The contract for the Telescope Mount Assembly was signed in August 2014.[68] The nearly-completed TMA was inspected in April 2018, and is scheduled to ship from its construction site in Spain to Chile in November.[69]

5.4. Camera

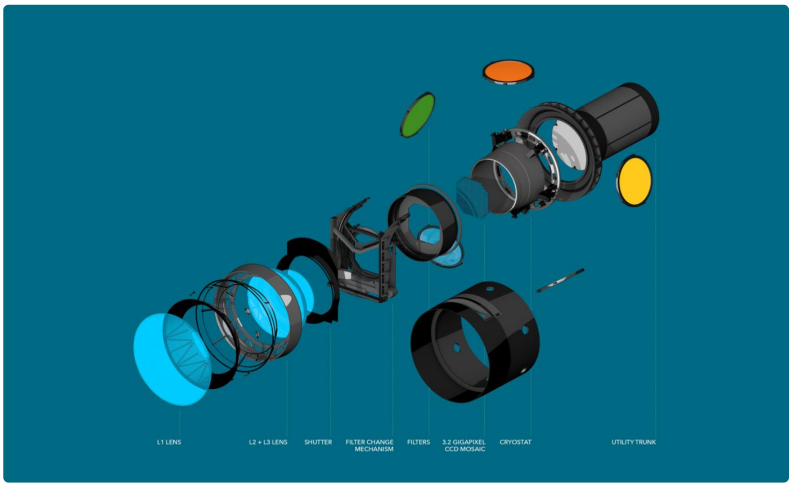
In August 2015, the LSST camera project, which is separately funded by the U.S. Department of Energy, passed its "critical decision 3" design review, with the review committee recommending DoE formally approve start of construction.[70] On August 31, the approval was given, and construction is beginning at SLAC.[71] As of September 2017, construction of the camera was 72% complete, with sufficient funding in place (including contingencies) to finish the project.[26]



Rendering of the LSST camera. https://handwiki.org/wiki/index.php?curid=1254753



Color-coded cutaway drawing of the LSST camera. https://handwiki.org/wiki/index.php?curid=1582147



Exploded view of the optical components of the LSST camera. https://handwiki.org/wiki/index.php?curid=1568787

5.5. Data Transport

The data must be transported from the camera, to facilities at the summit, to the base facilities, and then to the LSST Data Facility at the National Center for Supercomputing Applications in the United States.[72] This transfer must be very fast (100 Gbit/s or better) and reliable since NCSA is where the data will be processed into scientific data products, including real-time alerts of transient events. This transfer uses multiple fiber optic cables from the base facility in La Serena to Santiago, then via two redundant routes to Miami, where it connects to existing high speed infrastructure. These two redundant links were activated in March 2018 by the AmLight consortium.[73]

Since the data transfer crosses international borders, many different groups are involved. These include the Association of Universities for Research in Astronomy (AURA, Chile and the USA), REUNA[74] (Chile), Florida International University (USA), AmLightExP[73] (USA), RNP[75] (Brazil), and University of Illinois at Urbana–Champaign NCSA (USA), all of which participate in the LSST Network Engineering Team (NET). This collaboration designs and delivers end-to-end network performance across multiple network domains and providers.

References

1. Djorgovski, S. George, Ashish Mahabal, Andrew Drake, Matthew Graham, and Ciro Donalek (2013). "Sky surveys". Planets, Stars and Stellar Systems. Springer Netherlands. pp. 223–281. https://arxiv.org/ftp/arxiv/papers/1203/1203.5111.pdf.
2. Tyson, A. & Angel, R.. "The Large-aperture Synoptic Survey Telescope". The New Era of Wide Field Astronomy, ASP Conference Series. 232. San Francisco: Astronomical Society of the Pacific. pp. 347. ISBN 1-58381-065-X. http://adsbit.harvard.edu//full/2001ASPC..232..347T/0000347.000.html.
3. Press, W. H. (9-14 July 1995). "Prognosticating The Future Of Gravitational Lenses". in C. S. Kochanek and Jacqueline N. Hewitt. Astrophysical applications of gravitational lensing: proceedings of the 173rd Symposium of the International Astronomical Union. 173. International Astronomical Union. Melbourne; Australia: Kluwer Academic Publishers; Dordrecht. pp. 407. http://adsbit.harvard.edu//full/1996IAUS..173..407P/0000407.000.html.
4. Astronomy and astrophysics in the new millennium. Washington, D.C: National Academy Press. 2001. ISBN 0-309-07312-X.
5. Dennis Overbye (January 3, 2008). "Donors Bring Big Telescope a Step Closer". The New York Times. https://www.nytimes.com/2008/01/05/science/space/05scope.html?ex=1357189200&en=b96008fcade4d4f0&ei=5088&partner=rssnyt&emc=rss. Retrieved 2008-01-03.
6. "LSST Project Office Update". March 2012. http://www.lsst.org/News/enews/pon-201203.html. Retrieved 2012-04-07.
7. "World’s largest digital camera gets green light". 2011-11-08. http://www.rdmag.com/News/2011/11/Information-Tech-Electronics-Imaging-Astronomy-World-s-largest-digital-camera-gets-green-light. Retrieved 2012-04-07. /
8. "Large Synoptic Survey Telescope gets Top Ranking, "a Treasure Trove of Discovery"" (PDF) (Press release). LSST Corporation. 2010-08-16. Retrieved 2015-08-05. http://www.lsst.org/sites/default/files/docs/LSST_PR09.pdf
9. Kahn, Steven; Krabbendam, Victor (August 2014). "LSST Construction Authorization" (Press release). Lsst Corp. http://www.lsst.org/News/enews/directors-corner-201408.html
10. Construction Project Status. Nov 2016 https://www.lsst.org/about/project-status
11. Jeffrey Mervis (21 May 2018). "Surprise! House spending panel gives NSF far more money for telescope than it requested". AAAS. http://www.sciencemag.org/news/2018/05/surprise-house-spending-panel-gives-nsf-far-more-money-telescope-it-requested.
12. LSST System & Survey Key Numbers, LSST Corporation, http://www.lsst.org/scientists/keynumbers, retrieved 2015-08-05
13. Hiroaki Aihara et al. (2018). "The Hyper Suprime-Cam SSP Survey: Overview and survey design". Publications of the Astronomical Society of Japan 70 (SP1): S4. doi:10.1093/pasj/psx066. Bibcode: 2018PASJ...70S...4A. https://dx.doi.org/10.1093/pasj/psx066.
14. "Community Science Input and Participation". LSST. https://www.lsst.org/content/community-science-input-and-participation.
15. The camera is actually at the tertiary focus, not the prime focus, but being located at a "trapped focus" in front of the primary mirror, the associated technical problems are similar to those of a conventional prime-focus survey camera.
16. "LSST Tour". LSST. https://www.lsst.org/tour.
17. Ž. Ivezić (2014-08-29), LSST: From Science Drivers to Reference Design and Anticipated Data Products (v1.0), 0805, pp. 2366, Bibcode: 2008arXiv0805.2366I, http://www.lsst.org/content/lsst-science-drivers-reference-design-and-anticipated-data-products, retrieved 2015-08-05 , this is a comprehensive overview of the LSST.
18. "Technical Details". Large Synoptic Survey Telescope. http://www.lsst.org/about/camera/features. Retrieved 3 March 2016.
19. LSST Focal Plane https://www.lsst.org/about/camera/focalplane
20. Matt Stephens (2008-10-03). "Mapping the universe at 30 Terabytes a night: Jeff Kantor, on building and managing a 150 Petabyte database". The Register. https://www.theregister.co.uk/2008/10/03/lsst_jeff_kantor/print.html. Retrieved 2008-10-03.
21. Matt Stephens (2010-11-26). "Petabyte-chomping big sky telescope sucks down baby code". The Register. https://www.theregister.co.uk/2010/11/26/lsst_big_data_and_agile/print.html. Retrieved 2011-01-16.
22. Boon, Miriam (2010-10-18). "Astronomical Computing". Symmetry Breaking. http://www.symmetrymagazine.org/breaking/2010/10/18/astronomical-computing/. Retrieved 2010-10-26.
23. "Data Management Technology Innovation". LSST. https://www.lsst.org/about/dm/technology.
24. "Data Products". LSST. https://www.lsst.org/about/dm/data-products.
25. Morganson, Eric (22 May 2017). "From DES to LSST: Transient Processing Goes from Hours to Seconds". Building the Infrastructure for Time-Domain Alert Science in the LSST Era. Tucson. https://www.noao.edu/meetings/lsst-tds/presentations/Morganson_DEStoLSST.pdf.

26. Victor Krabbendam (28 November 2017). LSST status update. LSST Project/NSF/AURA. Figures shown at 33:00. https://gallery.lsst.org/bp/#/folder/3308857/63601294

27. Bellm, Eric (26 Feb 2018). "Alert Streams in the LSST Era: Challenges and Opportunities". Real-Time Decision Making: Applications in the Natural Sciences and Physical Systems. Berkeley. https://simons.berkeley.edu/talks/eric-bellm-2-26-18.

28. 10 million events per 10 hour night is 278 events per second.

29. Saha, Abhijit; Matheson, Thomas; Snodgrass, Richard; Kececioglu, John; Narayan, Gautham; Seaman, Robert; Jenness, Tim; Axelrod, Tim (25–27 June 2014). "ANTARES: a prototype transient broker system". Observatory Operations: Strategies, Processes, and Systems V. 9149. Montreal: SPIE. pp. 914908. doi:10.1117/12.2056988. https://sandmark.cs.arizona.edu/~rts/pubs/spie14.pdf.

30. Bellm, Eric (22 May 2017). "Time Domain Alerts from LSST & ZTF". Building the Infrastructure for Time-Domain Alert Science in the LSST Era. Tucson. https://www.noao.edu/meetings/lsst-tds/presentations/Bellm_ZTF_LSST.pdf.

31. M. Jurić, T. Axelrod, A.C. Becker, J. Becla, E. Bellm, J.F. Bosch, et al. (9 Feb 2018). "Data Products Definition Document". LSST Corporation. https://docushare.lsstcorp.org/docushare/dsweb/Get/LSE-163/LSE-163_DataProductsDefinitionDocumentDPDD.pdf. p. 53.

32. "LSST-French Connection". April 2015. https://www.lsst.org/news/enews/lsst-french-connection.

33. Bosch J, Armstrong R, Bickerton S, Furusawa H, Ikeda H, Koike M, Lupton R, Mineo S, Price P, Takata T, Tanaka M. (8 May 2017). "The Hyper Suprime-Cam software pipeline". Publications of the Astronomical Society of Japan. https://arxiv.org/pdf/1705.06766.pdf.

34. Steven M. Kahn, Justin R. Bankert, Srinivasan Chandrasekharan, Charles F. Claver, A. J. Connolly, et al.. "Chapter 3: LSST System Performance". LSST. https://www.lsst.org/sites/default/files/docs/sciencebook/SB_3.pdf. p. 72.

35. "LSST Science Goals" (in en). The Large Synoptic Survey Telescope. https://www.lsst.org/science. Retrieved 3 April 2018.

36. R. Lynne Jones, Mario Juric, Zeljko Ivezic (10 Nov 2015). "Asteroid Discovery and Characterization with the Large Synoptic Survey Telescope (LSST)". IAU-318 - Asteroids: New Observations, New Models. http://lanl.arxiv.org/abs/1511.03199.

37. "Planetary Defense Frequently Asked Questions". NASA. 29 Aug 2017. https://www.nasa.gov/planetarydefense/faq.

38. Grav, Tommy; Mainzer, A. K.; Spahr, Tim (June 2016). "Modeling the performance of the LSST in surveying the near-Earth object population". The Astronomical Journal 151 (6): 172. doi:10.3847/0004-6256/151/6/172. Bibcode: 2016AJ....151..172G. http://iopscience.iop.org/article/10.3847/0004-6256/151/6/172/pdf.

39. Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies. National Academies Press. 2010. doi:10.17226/12842. ISBN 978-0-309-14968-6. https://www.nap.edu/catalog/12842/defending-planet-earth-near-earth-object-surveys-and-hazard-mitigation. , page 49.

40. "Education & Public Outreach". LSST. https://www.lsst.org/about/epo.

41. "Large Synoptic Survey Telescope (LSST) EPO Design". LSST Corporation. 29 Nov 2017. https://docushare.lsstcorp.org/docushare/dsweb/Get/LEP-31.

42. "PROJECT & SCIENCE NEWS for Tuesday, May 8, 2018". LSST. https://www.lsst.org/news/digest/08ma20018.

43. "Google Joins Large Synoptic Survey Telescope (LSST) Project". uanews.org. January 10, 2007. Retrieved 29 April 2013. http://uanews.org/node/12956

44. Željko Ivezić (24 Mar 2014). "Similarities and differences between DES and LSST". Joint DES-LSST workshop. Fermilab. http://faculty.washington.edu/ivezic/talks/DES-LSST.pdf.

45. "Site in Northern Chile Selected for Large Synoptic Survey Telescope" (PDF) (Press release). LSST. 17 May 2006. https://www.lsst.org/sites/default/files/docs/Site%20Selection%20506%201%20FINAL%20w.pics.pdf

46. Steven M. Kahn (21 February 2018). "Project Status". LSST Science Advisory Committee Meeting. Princeton. https://project.lsst.org/groups/sac/sites/lsst.org.groups.sac/files/Kahn_projectstatus.pdf.

47. Steward Observatory Mirror Lab Awarded Contract for Large Synoptic Survey Telescope Mirror http://uanews.org/story/steward-observatory-mirror-lab-awarded-contract-large-synoptic-survey-telescope-mirror

48. Inage Gallery: Mirror Fabrication http://www.lsst.org/gallery/mirror-fabrication

49. LSST High Fire Event http://www.lsst.org/News/highfire_event.shtml

50. Giant Furnace Opens to Reveal 'Perfect' LSST Mirror Blank, LSST Corporation, 2009-09-02, http://www.lsst.org/sites/default/files/docs/LSSTC08-outoftheoven-1.pdf, retrieved 2011-01-16

51. LSST.org (December 2014). "LSST E-News - Volume 7 Number 4". http://www.lsst.org/News/enews/201412.html. Retrieved 2014-12-06.

52. Gressler, William (15 January 2015). "Telescope and Site Status". AURA Management Council for LSST. pp. 8–13. http://www.lsst.org/sites/default/files/documents/AMCL_Jan_2015_Gressler.pdf. Retrieved 2015-08-11.

53. LSST.org (April 2015). "M1M3 Milestone Achieved". http://www.lsst.org/News/enews/m1m3-milestone-201504.html. Retrieved 2015-05-04.
54. Sebag, Jacques, William Gressler, Ming Liang, Douglas Neill, C. Araujo-Hauck, John Andrew, G. Angeli et al. (2016). "LSST primary/tertiary monolithic mirror". Ground-based and Airborne Telescopes VI. 9906. International Society for Optics and Photonics. pp. 99063E.. https://arizona.openrepository.com/bitstream/handle/10150/622513/99063E.pdf;jsessionid=147C317CDAD3AE8580666A81964FDA0B?sequence=1.
55. Beal, Tom (28 February 2015). "Big mirror about to move from UA lab". Arizona Daily Star. http://tucson.com/news/blogs/scientific-bent/big-mirror-about-to-move-from-ua-lab/article_992c2619-6037-5409-9756-da29c695e64b.html. Retrieved 2015-05-04.
56. Jepsen, Kathryn (January 12, 2015). "Mirror, mirror: After more than six years of grinding and polishing, the first-ever dual-surface mirror for a major telescope is complete". Symmetry. http://www.symmetrymagazine.org/article/january-2015/mirror-mirror. Retrieved 2015-02-01.
57. Victor Krabbendam (2011-01-11). "LSST Telescope and Optics Status". American Astronomical Society 217th Meeting. Seattle, Washington. http://www.lsst.org/sites/default/files/docs/aas/2011/217-RC-931-AAS_Krabbendam.ppt.pdf. Retrieved 2015-08-05. This updated plan shows the revised telescope centre at 6653188.0 N, 331859.1 E (PSAD56 datum). This is the same WGS84 location to the resolution shown.
58. "LSST M2 Substrate Complete and Shipped", LSST E-News 2 (4), January 2010, http://www.lsst.org/News/enews/m2-1001.html
59. "LSST M2 Substrate Received by Exelis", LSST E-News 7 (4), December 2014, http://www.lsst.org/News/enews/m2-relocation-201412.html
60. Victor L Krabbendam (June 12, 2018). "The Large Synoptic Survey Telescope (LSST) Construction Status – 2018". LSST. https://docushare.lsst.org/docushare/dsweb/Get/Document-28703.
61. Kaboom! Life's a Blast on Cerro Pachón, LSST Corporation, April 2011, http://www.lsst.org/sites/default/files/enews/first-blast-201104.html, retrieved 2015-08-05
62. Krabbendam, Victor (2012-01-09). "Developments in Telescope and Site". American Astronomical Society 219th Meeting. Austin, Texas. http://lsst.org/sites/default/files/docs/aas_219/med/219-RC-1705-AAS_Krabbendam.pdf. Retrieved 2012-01-16.
63. "Excavation Activities on Cerro Pachón", LSST E-News 8 (2), August 2015, http://lsst.org/news/enews/excavation-activities-cerro-pachón
64. Barr, Jeffrey D.; Gressler, William; Sebag, Jacques; Seriche, Jaime; Serrano, Eduardo (27 July 2016). "LSST Summit Facility – Construction Progress Report: Reacting to Design Refinements and Field Conditions". SPIE Proceedings 9906: 99060P. doi:10.1117/12.2233383. ISBN 978-1-5106-0191-8. Bibcode: 2016SPIE.9906E..0PB. https://docushare.lsstcorp.org/docushare/dsweb/Get/Document-21494/. , p. 12
65. "A Key Event". 23 March 2018. https://www.lsst.org/news/key-event.
66. Five seconds are allowed between exposures, but one second is reserved for the mirrors and instrument to be aligned, leaving four seconds for the structure.
67. Neill, Douglas R.; Krabbendam., Victor L. (2010). "LSST Telescope mount and pier design overview". Ground-based and Airborne Telescopes III. 7733. International Society for Optics and Photonics. pp. 77330F. doi:10.1117/12.857414. Bibcode: 2010SPIE.7733E..0FN. https://www.researchgate.net/profile/Douglas_Neill/publication/241525403_LSST_Telescope_mount_and_pier_design_overview/links/56f9 Telescope-mount-and-pier-design-overview.pdf.
68. "LSST: TMA Contract Officially Signed", LSST E-News 7 (4), December 2014, https://www.lsst.org/News/enews/201412.html
69. "TMA Safety Review". LSST Corp.. 4 May 2018. https://www.lsst.org/news/tma-safety-review.
70. "LSST Camera Team Passes DOE CD-3 Review". 10 August 2015. http://www.lsst.org/news/lsst-camera-team-passes-doe-cd-3-review. Retrieved 2015-08-11.
71. "World's Most Powerful Digital Camera Sees Construction Green Light" (Press release). SLAC. 31 August 2015. https://www6.slac.stanford.edu/news/2015-08-31-world%E2%80%99s-most-powerful-digital-camera-sees-construction-green-light.aspx
72. "Lighting up the LSST Fiber Optic Network: From Summit to Base to Archive". LSST Project Office. 10 April 2018. https://project.lsst.org/lighting-lsst-fiber-optic-network-summit-base-archive.
73. "Amlight-Exp Activates two new 100 Gbps Points-of-Presence Enhancing Infrastructure for Research and Education" (Press release). Florida International University. 29 March 2018. https://www.amlight.net/?p=3055
74. "Chile inaugura primer tramo de Red Óptica de alta velocidad" [Chile inaugurates first stretch of High Speed Optical Network] (Press release) (in español). Red Universitaria Nacional. 16 April 2018. http://www.reuna.cl/index.php/2018/04/16/primer-tramo-de-red-optica-de-alta-velocidad-desde-el-big-data-astronomico/

75. "Brazilian scientists to partake in International Astronomy project" (Press release). Rede Nacional de Ensino e Pesquisa. https://www.rnp.br/en/destaques/brazilian-scientists-to-partake-in-international-astronomy-project