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Contents

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New frontiers with LSST: leveraging world facilities

Abstract

Comprehensive understanding of new astrophysical phenomena requires multi-wavelength and/or temporal investigations using a variety of instruments on multiple facilities. Because of cost these large facilities or instruments tend to be unique. Astronomy thus must evolve to a coordinated collaboration of world facilities. GTC is perfect for co-observing with LSST to leverage discovery. The shared sky overlap and the joint science discovery space is more than sufficient. Such world collaborations, while effective scientifically, need to be planned in advance.

1. Introduction

Driven by the availability of new instrumentation, there has been an evolution in astronomical science towards comprehensive investigations of new phenomena, encompassing complementary observations using a range of special facilities. Science and specialized instrumentation know no borders. Thus, our field is driven towards coordinated use of world facilities - world collaboration. This is particularly true of discoveries emerging from a new generation of sky surveys. Imaging data from a large ground-based active optics telescope with sufficient étendue ($\geq$300m^{2}deg^2) can address many scientific missions simultaneously. By providing unprecedented sky coverage, cadence, and depth, the Large Synoptic Survey Telescope (LSST) will make it possible to attack high-priority scientific questions that are far beyond the reach of any existing or planned facility. LSST will produce a 6-band (0.3-1.1 micron) wide-field deep astronomical survey of over 30,000 square degrees of the sky to 34 deg north latitude using an 8.4 m (6.7 m effective) telescope and 3.2 Gpixel camera. Each patch of sky will be visited 1000 times (2 x 15 sec exposures each time) in ten years. With 20 trillion photometric and temporal measurements covering 20 billion detected objects, this will produce the world's largest database.

The 30 terabytes of pipeline processed data obtained each night will open the time domain window on the deep optical universe for variability and motion. Rarely observed events will become commonplace, new and unanticipated phenomena will be discovered. The combination of LSST with contemporary facilities such as Gran Telescopio Canarias (GTC), E-ELT, TMT, and JWST will provide powerful synergies. The deep coverage of ten billion galaxies provides unique capabilities for cosmology. Astrometry, 6-band photometry, and time domain data on 10 billion stars will enable studies of galactic structure. This chapter describes the evolving astronomy survey frontier, the LSST survey, and the science synergies with the full range of complementary facilities.

2. Evolving Research Frontiers

Over the past decade, large scale sky surveys, such as SDSS, 2MASS, GALEX and many others have proven the power of large data sets for answering fundamental astrophysical questions. This observational progress, based on a synergy of advances in telescope construction, detectors, and information technology, has had a dramatic impact on nearly all fields of astronomy, and areas of fundamental physics. The LSST builds on the experience of these surveys and addresses the broad scientific goals of the coming decade.

Survey science tends to fall into several broad categories: (1) Statistical astronomy, where large datasets of uniformly selected objects are used to determine distributions of various physical or observational characteristics; (2) Searches for rare and unanticipated objects - every major survey that has broken new ground in sensitivity, sky coverage or wavelength has made important serendipitous discoveries, and surveys should be designed to optimize the chances of finding the unexpected; and (3) Surveys of the sky become a legacy archive for future generations, allowing astronomers interested in a given area of sky to ask what is already known about the objects there, to photometrically or astrometrically calibrate a field, or to select a sample of objects with some specific properties. All three of these survey science modalities reach their full scientific potential often through use of complementary facilities.

3. Astro Sociology

The exponential increase in survey data and the resulting science opportunities has resulted in the development of a new breed of scientist, the “survey astronomer”. These include both the people who develop the infrastructure of these surveys and those who analyze these data. The hardware and computational technical challenges and the exciting science opportunities are attracting scientists from high-energy physics, statistics, and computer science.

The way astronomers pursue their science is also evolving. Breakthroughs in observational astronomy in the last fifty years have been driven by two types of facilities (often working in synergy):

- Survey facilities are often dedicated telescopes with a wide field of view, which gather data on large numbers of objects, for use in a wide variety of scientific investigations.
- Observatories are designed to allow detailed studies of individual objects or relatively small fields in a given waveband. Much of the push towards telescopes of ever larger aperture is motivated by studies of individual objects.

The history of astronomy has taught us repeatedly that there are unanticipated surprises whenever we view the sky in a new way. Complete, unbiased surveys are the best technique we have both for discovering new and unexpected phenomena, and for deriving the intrinsic properties of source classes so that their underlying physics can be deduced. Both types of facilities, wide-field and narrow-field, are driven by new technological developments.

Although astronomers often make use of multiple specialized facilities, the cost of these instruments has been rising. One can question whether the traditional model of a suite of the same type of instruments duplicated on many telescopes is an optimal in the future. In the E-ELT era observing time on 8-10 m telescopes will likely evolve in complementary roles, either in instrumentation or observing strategy. For example, it will be possible for collaborations to pursue highly effective joint observations with other facilities (survey and/or different wavelength). 8 10m class telescopes will be able to serve a unique enabling scientific role which would be difficult if observing time was assigned in traditional small blocks of nights reserved for the largest facilities. Telescope allocation committees and observatory directors have recognized that taking such strategic planning risks has scientific payoffs (the HDF is an example.)

Another kind of risk-taking which is crucial to preserve in all areas of science is access to experimental observing modes and novel instrumentation experiments. While some of this can take place on small telescopes, much of it must happen on 8 10m class telescopes simply because of the usual photon-starved nature of the experiment. This is the engine for technical innovation and resulting discovery. Astronomers must be empowered to take these risks. It also makes possible the needed career paths for instrumentalists, already an endangered species.

For these reasons, in an ELT era the 8 10m telescopes will play a critical new enabling role for scientific discovery. The sociology (web collaborations of scientists self organized around problems, or multi facility co-observing) may be novel, but so too will the scientific discoveries.

4. Planning for Science Leverage

Many of the most important astronomical problems we face require multiple probes via interlocking surveys. Cross-correlation between surveys allows science that would be impossible with any one survey alone. This comparison can be temporal (comparing the proper motion of an object between the POSS and the SDSS, for example) or across wavelength regimes (looking for long-term optical counterparts to gamma-ray bursts).

The discoveries made in surveys are often exploited by detailed study with other telescopes. Unusual objects from an imaging survey will require follow-up spectroscopy to determine their physical nature; one can imagine, for example, a great deal of synergy of this sort between the LSST and the E-ELT and between LSST and GTC. Similarly, transient objects such as the gamma-ray bursts which synoptic surveys will find, require multi-wavelength follow-up over an extended period of time, to allow these discoveries to be placed in astrophysical context. We cannot guess what currently unknown types of objects or phenomena will be discovered. But we can rest assured that collaborations of world facilities will be required for the full exploration of the resulting science.

5. Surveys, Moore's Law, and World Facilities

Surveys have been an engine for discoveries throughout the modern history of astronomy, and have been among the most highly cited and scientifically productive observing facilities in recent years. This observational progress has been based on advances in telescope construction, detectors, and above all, information technology.

Aided by rapid progress in microelectronics, current sky surveys are again changing the way we view and study the Universe. The next-generation instruments, and the surveys that will be made with them, will maintain this revolutionary progress. Figure 1 charts the trend in optical sky surveys over 50 years. The effect of technology is clear. While the available collecting area of telescopes has remained roughly constant, the information content of sky surveys (using the number of galaxies measured per year to a given signal-to-noise ratio as a proxy) has risen exponentially. This is in large part due to high efficiency imaging arrays growing to fill the available focal plane, and to the increase in processing power to handle the data flood. The corresponding increase in science output is a result of the development of software to analyze these digital data in new ways.

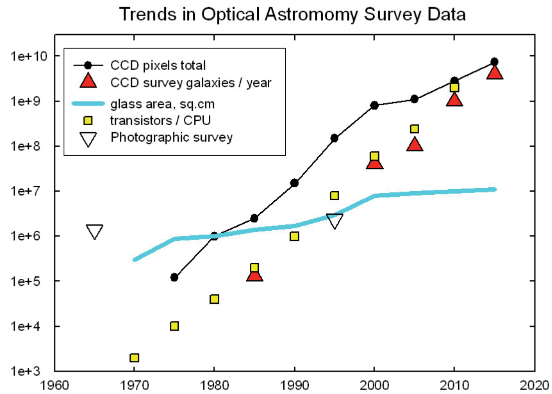


***Figure 1.** Data trends in optical surveys of the sky. While photographic surveys covered large area, the data were not as usable as digital data and did not go as faint. Information content (in galaxies surveyed per unit time to a given S/N ratio) in CCD digital surveys roughly follows Moore's law. Processing capability has kept up with pixel count. Next generation wide-fast-deep surveys will open the time window on the universe.*

Shown in Figure 1, photographic surveys had the large focal plane area advantage early on, but have been eclipsed by CCD surveys, driven by the exponential rise in pixel count and computer processing capability – both enabled by the microelectronics "Moore's Law". Plotted vs time is the sum of all CCD pixels on the sky, as well as the number of transistors on a typical CPU. Processing capability keeps up with the data rate. Also plotted is the result of CCD surveys – the number of galaxies photometered per unit time – ranging from a survey using a single 0.16 Mpixel CCD on a 4 m telescope to the 3.2 Gpixel 8.4 m LSST.

From the start, CCD detectors had more than an order of magnitude higher sensitivity than photographic plates (and far better dynamic range). The population of faint blue galaxies was discovered immediately in the first small CCD survey in the early 1980s. This high efficiency coupled now with many square degree focal plane arrays on large aperture wide-field telescopes means that for the first time we can tile the sky quickly with deep exposures - opening up a new window on the universe.

6. Time Domain: A New dimension

Exploration of the variable optical sky is one of the new observational frontiers in astrophysics. No optical telescope to date has had the capability to search for transient phenomena at faint levels over enough of the sky to fully characterize phenomena. Variable and transient phenomena have historically led to fundamental insights into subjects ranging from the structure of stars to the most energetic explosions in the universe to cosmology. Existing surveys leave large volumes of discovery parameter space (in wavelength, depth, and cadence) unexplored.

Because of its wide coverage and broad time sampling, some of the transient object science will be accomplished largely from the LSST database, combined where appropriate with multi-wavelength databases from other facilities, space and ground. For fast or repeating transients, the LSST Deep Drilling sub-survey of ~50 selected ten square degree fields will yield the highest quality data with excellent sampling. However, much of the transient science enabled by LSST will rely on additional observations of selected transient objects based on their classification using the LSST data. The LSST science collaborations and the world astrophysics community are developing a roadmap for multi-observatory collaboration. Some of the additional observations will be in the follow-up mode and some will (optimally) be in a "co-observing" mode where complementary facilities monitor the same sky during LSST operations. For example, it is known that there are non-repeating bursts on tens of seconds timescales over a wide spectral range; progress in opening this new window can be made in a co-observing mode with both space and ground facilities. Both GTC and E-ELT spectroscopy co-observing in the optical and near IR would capitalize on the new discoveries.

Spectroscopic follow-up will be a world effort. Some observatories are already beginning the process of evaluating optimal modes and spectroscopic instruments for maximal use of LSST transient data. A well-designed follow-up strategy must include end-to-end planning and must be in place before first light. In terms of the required photometric and spectroscopic follow-up, generally there are two distinct cases of transients.

7. Rare bright transients detected by LSST on their way up:

In this case the transients will be sparse on square degree scales. Efficient follow-up would then focus on one transient at a time. Requirements include multi-band simultaneous photometry and IFU spectroscopy on rapidly deployed telescopes around the world that can continuously follow transients brighter than ~22 nd mag. An example is the Las Cumbres Observatory Global Telescope Network of 2 m telescopes and photometric + IFU instruments dedicated to follow-up. It will be important that 1-4m class facilities be capable of following the brief transient to its peak brightness, which could be 10th mag or even brighter.

8. Many faint (22-24th mag) transients:

Every night LSST is expected to deliver data on variability for ~100,000 objects and information on tens of thousands of astrophysical transients. The majority of these will be moving objects or variable stars. Accurate event classification can be achieved by real-time access to the required context information: multi-color time-resolved photometry and host galaxy information from the survey itself, combined with broad-band spectral properties from external catalogs and alert feeds from other instruments.

For photometry, LSST itself provides sparsely time-sampled follow-up on hours-days timescales. Because we expect many transients per LSST field of view, efficient spectroscopic follow-up would best be carried out with multi-slit or multi-IFU systems. Wide field follow-up would be possible with AAT/AAOmega and Magellan/IMACS. If built, BigBOSS may eventually be at the Blanco at CTIO. Some northern facilities will partially overlap with the LSST survey: GTC (with first and second generation instruments), BigBOSS at the Mayall, Keck MOSFIRE and DEIMOS, MMT/Hectospec, and LAMOST. Smaller field of view spectroscopic follow-up in the south can be done with Gemini/GMOS, the VLTs, and SALT/RSS. It is possible that new instruments will be built for these and other spectroscopic facilities by 2015. As described below, there will be considerable overlap with GTC, and therefore this a science opportunity for GTC IFU spectroscopy and AO imaging and near IR spectroscopy. Multi-object spectroscopy in the optical and near IR and multi-dIFU over 8 arcminute or larger fields of view will be particularly effective in leveraging LSST data.

Efficient follow-up will depend on focusing limited resources on the interesting transients. After the first year of operation LSST will be able to produce enough archival and current transient information to enable useful event classification. Combining the optical transient data with survey or archival data at other wavelengths will be routine through the VO. We expect that the community will make significant progress on classification of transients before LSST operations begin, given lessons learned from Palomar Transient Factory and PS1 in the optical and MAXI in the X-ray. There is 11,000 – 18,000 deg^2 overlap in the GTC-LSST shared sky, so that the most important factor in joint science is the accuracy of classifications in order to minimize errors in sample spectroscopic selection. Classification accuracy is driven by the precision deep LSST photometry and many repeat measurements.

About 90% of the observing time will be devoted to a uniform deep-wide-fast (main) survey mode. All scientific investigations will utilize a common database constructed from an optimized observing program. The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The survey area (shown in Figure 3) will cover 30,000 deg^2 with $\delta < +34.5$ deg, and will be imaged many times in six bands, ugrizy, spanning the wavelength range 320 -1050 nm. The main deep-wide-fast survey mode will observe a 20,000 deg^2 region to +15 deg dec about 1000 times (summed over all six bands) with pairs of 15 second exposures during the anticipated 10 years of operations, resulting in a co-added map with 5σ point source limiting magnitude of 27.7. This map will enable photometric and other measurements of 10 billion stars and a similar number of galaxies.

Figure 2. Two views of the sky to the same signal-to-noise level. On the left is shown a 7.5x7.5 arcminute part of an SDSS field. On the right, to LSST one-year depth and a factor of two worse angular resolution than LSST, 2800 galaxies are seen in this same 0.016 deg^2 field which covers the field of view in a single pointing of the GTC.

The remaining 10% of the observing time will be allocated to special programs such as a Very Deep + Fast time domain survey (so-called "Deep Drilling" fields). The north ecliptic survey from dec 15-34 deg is planned in griz bands, at higher airmass. For transient and variable phenomena LSST extends time-volume discovery space a thousand times over current surveys.

9. LSST Science Drivers and Surveying Strategy

A wide-fast-deep survey of a large fraction of the sky in multiple optical bands is required in order to explore many of the exciting science opportunities of the next decade. The most important characteristic that determines the speed at which a system can survey the sky to a given depth is its étendue (or grasp): the product of its primary mirror area and the field-of-view area. The effective étendue for LSST will be more than an order of magnitude larger than that of any existing facility. As was the case with SDSS, we expect the scientific community will produce a rich harvest of discoveries.

The LSST surveys will overlap 11,500 deg^2 with the GTC AO observable sky, and up to 18,000 deg^2 in non-AO modes. In that 11,500 deg^2 overlap area there are 2.3 billion galaxies brighter than 25th i AB mag which will have photometric redshifts in the LSST data, and an estimated 5000 to 50,000 variable or transient alerts per night from LSST. In other words, the overlap area is not a constraint on GTC-LSST science.

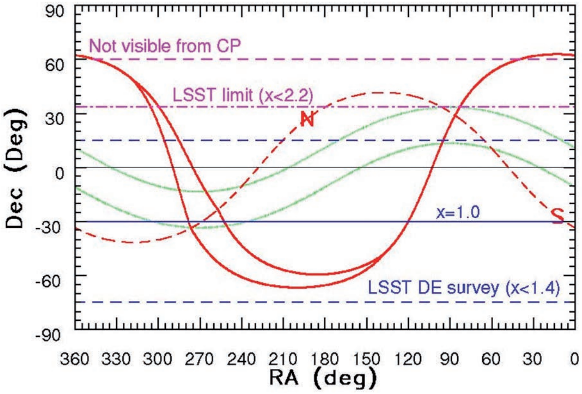


***Figure 3.** A plot of LSST survey sky coverage in equatorial coordinates. The sky above 60^o dec is not observable. The Galactic poles are marked by N and S, and connected with the galactic center by a great circle, shown by the red dashed line. The horizontal solid blue line (dec = -30^o) passes through the LSST zenith and the two dashed blue lines (dec = -75^o and dec = 15^o) outline the region for which the minimum airmass reaches values below 1.4. The area bounded by $-75^o < \text{dec} < 15^o$ is 24,000 deg^2. The galactic plane regions with the highest stellar density are enclosed by solid red lines. The ecliptic band is shown in green. The overlap between the planned LSST main survey of 20 billion objects and the GTC AO sky coverage is 11,500 deg^2. LSST will also survey the north ecliptic region to $+34^o$ dec at higher airmass, and the south pole region.*

Below we briefly describe four science themes. LSST will meet the requirements for these plus a very broad range of other scientific programs [Ivezic, et al. 2008arXiv0805.2366I]

10. Dark Energy and Dark Matter

LSST is unique in that its deep, very wide-field, multi-color imaging survey can undertake four cosmic probes of dark matter and dark energy physics with a single data set and with much greater precision than previously: (1) Weak lensing cosmic shear of galaxies as a function of redshift, (2) Baryon acoustic oscillations (BAO), (3) Redshift distribution of shear peaks (i.e. clusters), and (4) Type Ia supernovae. Dark energy affects the cosmic history of the Hubble expansion H(z) as well as the cosmic history of mass clustering (which is suppressed at epochs when dark energy dominates). If combined, different types of probes of the expansion history (via distance measures) and structure history can lead to percent level precision in dark energy parameters. Using the cosmic microwave background as normalization, the combination of these LSST deep probes over wide area will yield the needed precision to distinguish between models of dark energy, with cross checks to control systematic error.

11. Inventory of the Solar System

The small bodies of the Solar System offer a unique insight into its early stages. LSST, with its unprecedented power for discovering moving objects, will make a giant leap forward in the Solar System studies. The baseline LSST cadence will result in orbital parameters for several million moving objects; these will be dominated by main-belt asteroids, with light curves and colorimetry for a sub-

System

Étendue	319 m^2 deg^2
Sky coverage	20,000 deg^2 (Main Survey)
Field of view (diameter, area)	3.5 deg (9.6 deg^2)
Effective clear aperture (on-axis)	6.7 m (accounting for obscuration)
Wavelength coverage (full response)	350-1080 nm
Number of concurrent filters in camera	5
Filter set	u, g, r, i, z, y

Telescope

Configuration	3-mirror, Alt-azimuth
Final f/ratio; plate scale	f/1.23; 50 microns/arcsec
Diameter of optics (physical)	M1: 8.4 m; M2: 3.4 m; M3: 5.02 m
First camera lens; focal plane diameter	Lens: 1.55 m; field of view: 63 cm
Residual Aberrations (arcsec) 80% encircled energy	u: 0.26 g: 0.26 r: 0.18 i: 0.18 z: 0.19 y: 0.2

Camera

Pixel size; pixel count	10 microns (0.2 arcsec); 3.2 Gpixels
Readout time	2 sec
Dynamic ranage	16 bits
Camera rotation range	± 90 deg
Focal plane device configuration	4-side buttable, >90% fill factor
Filter change time	120 seconds

Data Management

Real-time alert latency	60 seconds
Raw pixel data/night	15 TB
Yearly archive rate (compressed)	Images; 5.6 PB; Catalogs: 0.6 PB
Computational requirements	Telescope: < 1 Tflop; LaSerena: 30 Tflop; Archive Center: 250 Tflop by year 10
Bandwidth	Telescope to LaSerena: 40 Gbits/sec; LaSerena to archive: 2.5 Gbits/sec avg.

System Capability

Single-visit depths (point source; 5σ)	u: >24 g:25.0 r:24.7 i:24.0 z:23.3 y:22.1 AB mag
Baseline number of visits over 10 yr	70, 100, 230, 230, 200, 200
Main survey depths (point source; 5σ) zenith	u: >26.3 g:27.5 r:27.7 i:27.0 z: 26.2 y:24.9 AB mag
Photometry accuracy (rms mag)	repeatability: 0.005; zeropoints: 0.01
Astrometric accuracy at r=24 (rms)	parallax: 3mas; proper motion: 1mas/yr

Table 1. LSST System Parameters.

stantial fraction of detected objects. This represents an increase of factors of 10 to 100 over the numbers of objects with documented orbits, colors, and variability information.

12. The Transient Optical Universe

Characterization of the variable optical sky is one of the true observational frontiers in astrophysics. To date, no optical telescope has had the capability to search for transient phenomena at faint levels over enough of the sky to fully characterize the phenomena. LSST will survey the sky on a variety of time scales from years down to 15 seconds. Because LSST extends time-volume space a thousand times over current surveys, the most interesting science may well be the discovery of new phenomena.

The LSST, with its repeated, wide-area coverage to deep limiting magnitudes, will enable the discovery and analysis of rare and exotic objects, such as neutron star and black hole binaries, and high-energy transients, such as optical counterparts to gamma-ray bursts and X-ray flashes (at least some of which apparently mark the deaths of massive stars). LSST will also characterize in detail AGN variability and new classes of transients, such as binary mergers and stellar disruptions by black holes. LSST will also monitor an unprecedented number of periodic variables, such as RR Lyrae stars (pulsating stars used as standard candles), which will be used to map the Galactic halo and intergalactic space to distances exceeding 400 kpc. GTC optical and near-IR spectroscopy would be a powerful probe of new transient phenomena.

13. Mapping the Milky Way

The LSST is ideally suited to answering two basic questions about the Milky Way Galaxy: What is the structure and accretion history of the Milky Way? What are the fundamental properties of all the stars within 300 pc of the Sun? LSST will enable studies of the distribution of numerous main-sequence stars beyond the presumed edge of the Galaxy's halo, their metallicity distribution throughout most of the halo, and their kinematics beyond the thick disk/halo boundary, and will obtain direct distance measurements below the hydrogen-burning limit for a representative thin-disk sample.

LSST will produce a massive and exquisitely accurate photometric and astrometric data set. LSST will detect of the order 10^{10} stars, with sufficient signal-to-noise ratio to enable accurate light curves, geometric parallax and proper motion measurements for about a billion stars. Accurate multi-color photometry can be used for source classification and measurement of detailed stellar properties such as effective temperature and metallicity with an impressive accuracy (rms of about 100 K for temperature and 0.3 dex for metallicity).

14. LSST System

LSST has been designed to accomplish the science outlined above and much more with a single coherent dataset over a ten-year survey. An international site selection committee evaluated many sites in both hemispheres worldwide. The telescope will be located on Cerro Pachón in northern Chile and will survey the sky to +34 deg declination. Near real-time alerts for transients will be provided. The project scope accordingly includes construction of the facilities, acquisition of data, calibration of the observations, archiving both the raw and processed data, and serving data products and analysis tools to the user community.

The realization of the LSST involves engineering and technological challenges: the fabrication of large, high-precision optics; construction of a huge, highly-integrated array of sensitive, wide-band imaging sensors; and the operation of a data management facility handling tens of terabytes of data each day. A significant part of the cost of the facility and its operation is in data management: pipeline processing the data, serving the data and processing CPU intensive user queries and uploaded specialized data analysis scripts. The design and development effort, has been underway since 2000. Over 100 technical personnel at a range of institutions are currently engaged in this program. A selection of the high-level system specifications is presented in Table 1.

We have run full simulations of the LSST survey and system design, for a matrix of depth, data flow, and observing cadence so that we can optimize the system hardware design, develop the appropriate algorithms, and understand the limitations and trade offs for LSST science operations.

The LSST operations simulator (http://opsimcvs.tuc.noao.edu/) has established the étendue required to meet survey specifications in terms of the number of visits/per filter in 10 years, time sampling, and image quality. The simulator includes models for the weather and local seeing based on actual site measurements, the lunar cycle, telescope dynamics, etc. The LSST exposure-time calculator (http://lsst.org/etc) enabled derivation of requirements for system sensitivity parameters including effective aperture, mirror and lens coatings, sensor quantum efficiency, observing conditions, and usable sky brightness. The LSST image simulator (http://lsst.org/imsim) produces 'end-to-end" image simulations to verify the scientific performance of the complete LSST system design.

The LSST facilities include: (1) the telescope and associated support buildings on Cerro Pachón, Chile, (2) a Data Access and operations center in La Serena, Chile, (3) the Archive Center located at the National Center for Supercomputing Applications, Univ. of Illinois, Urbana-Champaign. All the sites are interconnected via dedicated high-bandwidth fiber optic links.

15. Telescope

An international committee evaluated potential sites and selected Cerro Pachón, Chile as the most advantageous for LSST. The LSST optical system consists of three reflective optical surfaces (primary, secondary, and tertiary) and three refractive lenses to flatten the focal plane and correct chromatic aberrations introduced by the filters. The annular primary mirror has an outer diameter of 8.4 m and an inner diameter of 5.0 m for an effective diameter of 6.7 m. Combined with the 3.5-degree field of view, the étendue of the LSST is 319 m^2 deg^2. Wavefront quality is maintained across the field of view for all bands via an active optics system so that intrinsic design aberrations are insignificant compared to atmospheric effects.

The LSST optical design combined with unique fabrication facilities at the University of Arizona allowed the co-planar 8.4 m diameter primary surface with the nested 5-m diameter tertiary surface to be cast into a monolithic mirror blank. The compound mirror provides a stiff primary mirror and simplifies control of the mirror system during operations. The casting has been completed successfully, and the mirror is now being prepared for polishing.

The 3.4 m diameter secondary mirror is a thin meniscus made of low expansion glass. The fusing of the glass boules has been completed at Corning. The 300 ton telescope structure is an alt-az configuration with an 8.2 Hz first frequency. Specifications require 5 second average step-and-settle times to subsequent pointings.

16. Camera

LSST's single scientific instrument is the large optical camera with 3.2 Gigapixels covering the flat 64 cm diameter focal plane. The camera system includes the readout electronics, shutter, 75 cm filters, and three refractive optical elements, the largest being 1.5 meters in diameter. The camera is 1.6 m diameter by 3.5 m long and weighs 3,000 kilograms.

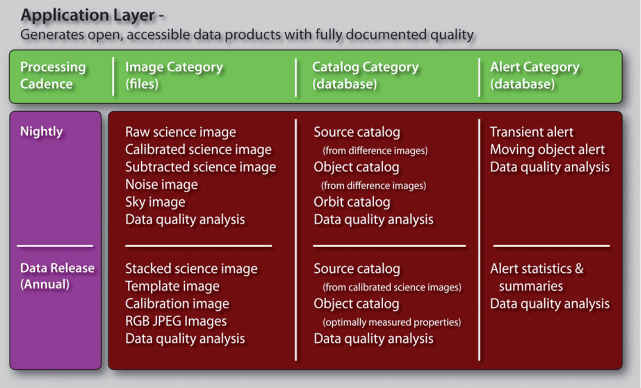
The camera focal plane is tiled with 189 4k x 4k innovative CCDs with 10 micron pixels. Each CCD has 16 readout channels to support the 2 second readout of the entire sensor and focal plane. The devices are back illuminated, 100 micron thick, fully depleted silicon sensors that offer excellent quantum efficiency in the challenging red end of the 0.3 to 1.1 micron wavelength range. Delivery of the commercial prototype sensors is scheduled for mid-2010.

17. Data Management

The LSST software and hardware system must automatically ingest ~15 terabytes (TB) of raw 16-bit/pixel images taken each night, apply proper system corrections, verify data quality, process the data to identify and publicly broadcast categorized alerts, archive the data, create catalog products, and serve the data to the community. The alerts of discovered transient, moving, and variable objects are to be issued within one minute. The system is sized to keep up with data generation on a daily pace and for catalog releases and full re-computation on yearly intervals.

The LSST data products are organized into two groups distinguished by cadence (see Figure 4). Nightly data products are generated by pipeline-processing the image data stream during observing and issuing alerts. A highly automated process generates and archives raw science images, creates a catalog of variable sources, and issues transient alerts within 60 seconds of detection. Archive center data products include calibration images, co-added images, and the resulting catalogs. Archive center data products also classify objects based on both their static and time-dependent features. These data products are generated on a slower cadence at the Archive Center at NCSA; their release will be validated with data quality assessments.

Over the 10-year survey, the LSST project will accumulate 250 TFLOPS of dedicated computational power and 165 petabytes of digital storage. In order to ensure that both the LSST data products and the data reduction algorithms are completely open and usable by the community, the LSST Data Management System is being developed as an open source system. All software used in the DMS will be available in source form to anyone in the community under an open source license. This ensures that the data quality and data provenance for all data products are completely transparent, provides a means for rapid development of analytical codes, and enables researchers to document the complete derivation of all scientific results.



Application Layer -
Generates open, accessible data products with fully documented quality

Processing Cadence	Image Category (files)	Catalog Category (database)	Alert Category (database)
Nightly	Raw science image Calibrated science image Subtracted science image Noise image Sky image Data quality analysis	Source catalog (from difference images) Object catalog (from difference images) Orbit catalog Data quality analysis	Transient alert Moving object alert Data quality analysis
Data Release (Annual)	Stacked science image Template image Calibration image RGB JPEG Images Data quality analysis	Source catalog (from calibrated science images) Object catalog (optimally measured properties) Data quality analysis	Alert statistics & summaries Data quality analysis

Figure 4. A summary of LSST data products. Transient alerts will be issued to the world within 60 seconds (likely less than 30 seconds after detection). JPG color images will also be world public. All other data and meta-data products will be available to collaborating observatories. With 20 trillion photometric and temporal measurements covering 20 billion detected objects, this will produce the world's largest non-commercial database.

18. Partnerships and Current Status

The LSST project is being managed by LSSTC, which is a non-profit organization. As of July 2009, 28 institutions (universities, DOE laboratories, corporations) have joined LSSTC. This is described at http://www.lsst.org/lsst/about/team.

Over 250 scientists have joined the ten autonomous LSST science collaborations. These scientists are actively refining the science cases, defining the required data products, developing optimal algorithms and calibration strategies for photometry, astrometry, photometric redshifts, and image analysis, etc. Membership in the science collaborations is open to staff at the member institutions, and through periodic open calls for applications for membership to the US and Chilean communities (information is available at http://www.noao.edu/lsst/collab_prop/Scicollab.htm). Foreign organizations joining LSST will also be able to join the science collaborations.

Our goal is to make as many of the LSST data products as possible world-public. We have an open collaboration and funding model for LSST, based on contributions from organizations around the world, US funding agencies, and private grants. In this model, there is no proprietary time and the data is as open as world-wide contributions permit. LSST is committed to providing open access to the data with no proprietary period. However, access is not without cost. Rather than duplicate the data processing and reduction facility, the most cost effective approach for foreign organizations would be to build a data access center and then support their share of the US data processing.

The current budget covers US and Chilean access only. For US and Chilean scientists there is no proprietary period for any of the data products. The policy governing access by non-US scientists will be determined by the US funding agencies and the LSST Board of Directors. There are a number of ways a foreign partner can become involved in the LSST project and likely a number of routes to operations support. From a science perspective any organization wishing to explore new and difficult frontiers with LSST (and thus have the in-depth understanding of the properties of the data that is required) should join the LSST collaboration now during the final design stage rather than later when the survey parameters have been fixed. For example, an agreement is already in place with the French high energy physics lab IN2P3, which is contributing to the camera development. Membership in the collaboration, on planning committees, and on steering committees for science and operations will be limited to those who are partners at this stage of the project.

With start of telescope (Figure 5) construction in 2011, engineering first light will occur in 2014. One year of integration and test follows engineering first light. The 3.2 Gpixel LSST camera will be installed and operational no later than 2015. Full survey operations will begin no later than 2016. At that time, calibrated images, pipeline results, nightly catalogs, and real-time alerts of transients will be available on a nightly basis. The archive and data access centers will be fully operational. The first LSST Data Release will occur after six months. Data Releases involve periodic major reprocessing of all data accumulated to date with full data quality validation and provenance metadata. After one year, the second Data Release will follow. Data Releases will follow on an annual basis until the end of the survey.

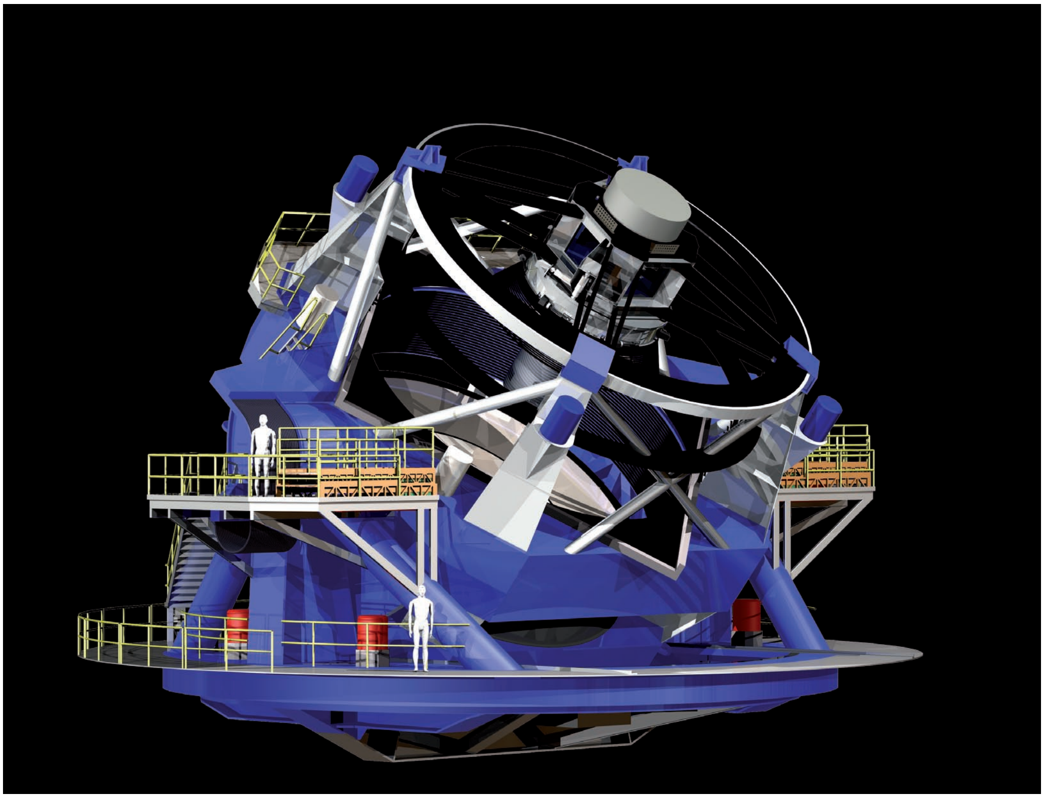


Figure 5. The 8.4 m LSST telescope.