THE LARGE SYNOPTIC SURVEY TELESCOPE
DESIGN AND DEVELOPMENT

PROPOSAL SUBMITTED TO THE NATIONAL SCIENCE FOUNDATION

BY THE LSST CORPORATION

DECEMBER, 2003

TABLE OF CONTENTS

A. PROJECT SUMMARY

The Large Synoptic Survey Telescope (LSST) is a wide-field telescope facility that will add a qualitatively new capability in astronomy. For the first time, the LSST will provide time-lapse digital imaging of faint astronomical objects across the entire sky, with a resolution that would require over two thousand High Definition TV screens to view each 10-second exposure. The LSST has been identified as a national scientific priority by diverse national panels, including multiple National Academy of Sciences committees. This judgment is based upon the LSST's ability to address some of the most pressing open questions in astronomy and fundamental physics, while driving advances in data-intensive science and computing. For example, the LSST will provide unprecedented 3-dimensional maps of the mass distribution in the Universe, in addition to the traditional images of luminous stars and galaxies. These mass maps can be used to better understand the nature of the newly discovered and utterly mysterious Dark Energy that is driving the accelerating expansion of the Universe. The LSST will also provide a comprehensive census of our solar system, including potentially hazardous asteroids as small as 100 meters in size. These are but two examples of the wide-ranging science that we know can be carried out with the LSST data set. By looking at the entire accessible sky every few nights, the LSST will provide large samples of events which we now only rarely observe, and will create substantial potential for new discoveries. The LSST will produce the largest non-proprietary data set in the world. This "open-data" approach is a precedent-setting aspect of the LSST project.

This proposal requests funding to carry out the next stage of LSST project development; we will produce a comprehensive design and operations model, with cost estimates, for both the LSST hardware and software. We shall lay the scientific, technical and managerial groundwork for the construction phase of the LSST. We have identified the main high-risk aspects of the project, and have placed a priority on their management and amelioration. Our experienced team of scientists, engineers and project managers will effect the program outlined here. We pay particular attention to early reduction of risk in 3 areas: the camera's detectors (2.3 Gigapixels are needed to fill the 7 square degree field), the large optical elements (the telescope's primary mirror will be 8.4 meters in diameter), and the project software (we need to contend with 18 Terabytes per night, in real time).

The broader impacts of the LSST will be profound, as scientists, the public, and schoolchildren around the world will have ready access to the data. Broader impacts of the initial design and development activity proposed here include 1) the training and education of personnel at all levels, integrating state-of-the-art computational science with astrophysics, 2) using existing LSST "precursor" projects to advance the state-of-the-art in real-time database schema and access tools, and 3) developing and refining an LSST education/outreach program via LSST precursor survey data that will pay near-term dividends in K-adult education. Finally, we note the significant technical overlap between the LSST and other imaging systems and software under development in the national security arena.

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TABLE OF CONTENTS

C.1 INTRODUCTION

> "The Committee supports the Large Synoptic Survey Telescope project, which has significant promise for shedding light on the dark energy."
>
> *Connecting Quarks with the Cosmos*

> "The SSE [Solar System Exploration] Survey recommends [the construction of] a survey facility, such as the Large-Aperture Synoptic Survey Telescope (LSST)…to determine the contents and nature of the Kuiper Belt to provide scientific context for the targeting of spacecraft missions to explore this new region of the solar system…"
>
> *New Frontiers in the Solar System*

> "The Large-aperture Synoptic Survey Telescope (LSST) 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 10,0000 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 thorough gravitational lensing."
>
> *Astronomy and Astrophysics in the New Millennium*

These studies, conducted by the National Research Council to recommend research priorities for the coming decade, have all endorsed the construction of a wide-field telescope, the LSST, that will survey the entire visible sky every few days to extremely faint limiting magnitudes. Advances in microelectronics, large optics fabrication, and computer hardware and software now make it possible to build a system that will address a broad range of problems in astrophysics and solar system exploration in qualitatively and quantitatively new ways.

The LSST system will obtain sequential images of the entire observable sky every few nights. These images can be co-added to provide unprecedented depth and area coverage. The same images can also be subtracted from each other to highlight celestial sources that change in brightness, position, or both. Repeat imaging on a variety of timescales from 10 seconds to years will open a new "time window" on the universe. A distinguishing feature of the experimental design is that multiple science programs can be carried out in parallel; a common set of images will address a wide diversity of science goals. The LSST facility will enable programs that would take over a century on current facilities. The data will be reduced in real time and the resulting images, database, search tools, and software will be made publicly available.

Because of its unprecedented capabilities and its promise for discovery at the frontiers of astronomy and physics, the LSST has brought together scientists and engineers from many universities, the Department of Energy, the national observatory, and the private sector. Together, this group has devised a system concept that will meet the requirements of the three decadal surveys: an 8m class telescope, a camera system with a 7 square-degree field of view, and a suite of image-processing pipelines that will produce and provide access to images in real time. There are engineering challenges in fields ranging from device physics to data mining. The 2.3 billion pixel camera will be the world's largest imager. The acquisition, real-time processing, cataloging, and accessing of data at the extraordinary rates that will be realized by the LSST (anticipated to be 18 Terabytes per night) will catalyze significant developments in computational science and engineering.

This proposal requests funding for the design and development phase of the LSST project. During the performance period of this grant, the LSST Corporation, whose members currently include the Research Corporation, the Universities of Arizona and Washington, and NOAO will assume overall management responsibility for the LSST collaboration, which will produce a system design that is mature enough to allow the project to proceed to pre-construction review with a fully costed project plan. While many of technical challenges are not yet solved, we expect to establish that they can be solved with confidence and that, provided funding is available in a timely manner, that first light can be achieved by 2011.

The following sections of the proposal provide the scientific motivation for the project; the requirements placed on the telescope, instrument, and software by the scientific goals; preliminary designs for hardware and software systems developed to date; the proposed activities during the design and development phase, including key design and trade studies; and the plan for project management. The Appendices contain additional detailed information and background material. The unprecedented sky coverage, cadence and depth of the 8 meter class LSST observations will make it possible to attack high priority scientific questions that are quite simply beyond the reach of any existing facilities. Many fundamental problems in astronomy ranging from planetary science to cosmology can be addressed through a common data set—multiple exposures in a small number of broad passbands to very faint magnitudes over a large area of the sky. The 18 terabytes of data that will be obtained each night will open a new time-window on the universe, enabling the study of variability in both time and position. Rare and unpredicted events will be discovered. The combination of LSST with contemporaneous space-based missions will provide powerful synergies. The LSST science drivers are briefly discussed in the sub-sections that follow. This builds on the work done by the LSST Science Working Group. The flow-down to observational requirements and instrument specifications is discussed in section C3.

C.2 SCIENCE WITH THE LSST

OPENING THE OPTICAL TIME WINDOW

Characterization of the variable optical sky is one of the true observational frontiers in astrophysics. No optical telescope has yet searched for transient phenomena at faint levels, over enough of the sky, to significantly constrain the population of optical transient phenomena. Vast regions of parameter space remain unprobed: no existing facilities have the apertures and fields of view required to survey faint, fast, and wide simultaneously. At the faint flux levels that will be reached by LSST, current surveys are only able to probe down to timescales of hours. LSST will survey the sky on a variety of timescales down to 20 seconds. This factor of a thousand increase in discovery space holds the promise of the detection and characterization of rare violent events and new astrophysics.

The simultaneous requirements for short, sky-limited exposures and fast pace on the sky in order to ensure frequent revisits, implies a telescope etendue (defined as the product of collecting area in meters squared times solid angle in square degrees) in a single exposure that exceeds 200. With a smaller etendue (i.e. smaller aperture or smaller field of view), either longer or more exposures are required, and the diminished pace means that the visible sky cannot be covered frequently. In one possible scenario, every night LSST surveys 3800 square degrees, with 500 square degrees revisited on 1-15 minute timescales and 200 square degrees on a 25 second timescale. The detection of transient emission provides a window on diverse astrophysical objects, from variable stars to stellar explosions to the mergers of compact stellar remnants. Perhaps even more exciting is the potential for discovering new, unanticipated phenomena (Paczynski 2001). A few optical bursts without precursor objects have already been seen in SN surveys (Schmidt *et al.* 1998) and by an optical burst survey (Becker, et al 2002; see Figure 1).

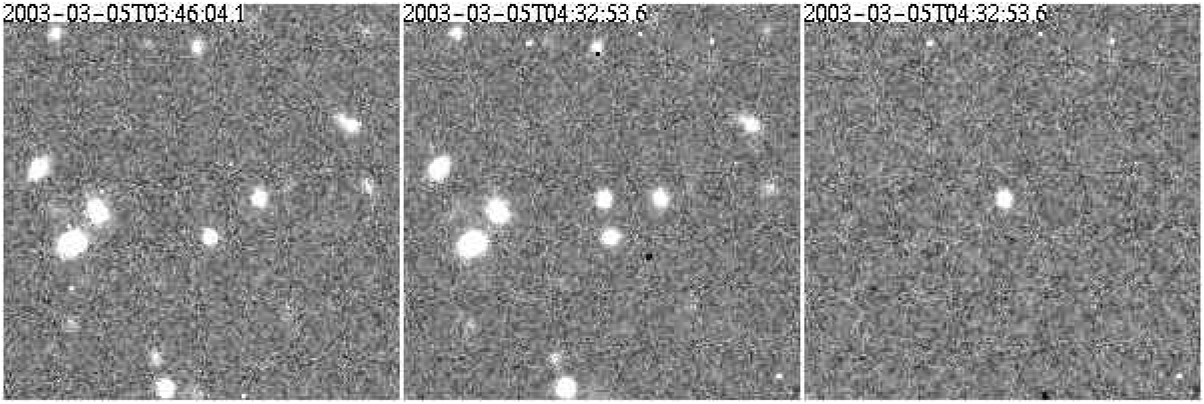


Figure 1. Optical burst detected by difference imaging (right hand frame) in the Deep Lens Survey.

Explosive Events

Known types of catastrophic stellar explosions, such as supernovae and gamma-ray bursts, produce optical transients decaying with timescales ranging from hours to months. Some classes of GRBs result from the explosion of massive stars. These hypernovae are known to produce bright optical flashes decaying with hour timescales due to emission from a reverse shock plowing into ejecta from the explosion. In addition, GRBs produce optical afterglows decaying on day to week timescales, which result from emission from a jet-like relativistic shock expanding into the circumstellar medium. As the outward-going collimated shock evolves, the spectral peak of the afterglow evolves from the X-ray to the optical and then radio. Repeatedly surveying 3800 square degrees of the sky each night, LSST is ideal for the discovery of these events. While events such as GRBs and X-ray flashes (XRFs) have been seen before, LSST will open up large regions of phase space for systematic exploration.

It is expected that the number of observable optical afterglows exceeds the number of observable GRB events. A combination of relativistic beaming and lateral expansion of the ejecta make the jet-like radiating region visible from off-axis angles that increase as the shock evolves. Thus, constraints on the rate of "orphan" optical afterglows (those seen from far enough off-axis that the initial GRB event was not visible) provide constraints on jet collimation and evolution, as well as on the overall rate of these energetic explosions. LSST, with its combination of sensitivity and sky coverage is expected to detect thousands of orphan afterglows (Totani and Panaitescu 2002), many at low redshift (Price *et al*. 2003). Perhaps even more interesting are explosive events yet to be discovered, such as mergers among neutron stars and black holes. These may have little or no high-energy emission, and hence may be discoverable only at longer wavelengths (Paczynski & Li1998). Note that LOFAR is expected to come on-line contemporaneously with LSST.

The detection of variability with LSST will provide another important way to test the basic nature of gravity. LSST will obtain light curves from the multiple images of lensed fluctuating quasars. With the basic cosmological parameters determined from other experiments, and lens masses obtained from either weak lensing or velocity dispersion data, time delay data for these systems can be considered as tests of gravity on kiloparsec length scales, a range not easily tested by other means.

Extreme Physics

The planned space experiment EXIST (hard X-ray) will observe the high-energy sky with unprecedented sensitivity and with very large (several steradian) fields of view. LSST provides the ideal complement in the optical. By ~2012 EXIST will survey most of the sky in a single 90-minute orbit, obtaining X-ray light curves for thousands of black holes ranging from the stellar to the supermassive on timescales of minutes to weeks. By monitoring large regions of the sky, LSST will provide the crucial optical light curves sampled on day and shorter timescales, with baselines extending over years for hundreds of these same objects. Such multi-wavelength studies of variability are the best hope for understanding the structure of the powerful jets that emanate from many black holes, the acceleration processes of high-energy particles, and the evolution of the particle energy distribution.

Stellar Eruptions

Continuous observations will provide the opportunity of flagging rare stellar variability events in real time, allowing detailed follow-up with other telescopes. Examples of such events are LBV outbursts, the shedding of giant dust clouds or naked thermal pulses during late AGB evolution, disk instabilities during inflow (CVs), outflow (Be stars), planet formation, and mode switching or onset/cessation of pulsation in periodic variables. With the LSST data on transients available in near real-time, it will be possible to schedule, in advance, spectroscopic studies of relatively rare phenomena, secure in the knowledge that samples will be available when time is granted.

SMALL BODIES IN THE SOLAR SYSTEM

Trans-Neptunian Objects

The Kuiper Belt and other distant, small-body populations are remnants of the early assembly of the solar system. Runaway growth of solid bodies in the inner solar system produced the giant planets; these subsequently ejected most of the remaining planetesimals with perihelia interior to Neptune. Further out, for some reason runaway growth never occurred, and the Kuiper Belt region still contains a portion of the early planetesimal population. The KBOs are our only chance to study directly this phase of planetary system formation.

The history of accretion, collisional grinding, and perturbation by existing and vanished giant planets is preserved in the orbital elements and size distributions of the KBOs. There is a drop in the space density of ~200 km objects beyond 50 AU that is unexplained, just one hint that the Kuiper Belt contains clues to major events in the history of the outer solar system. LSST has the power to discover tens to hundreds of thousands of new KBOs, map their orbital distribution, and determine their colors and light curves. Examining the joint distribution of these quantities will allow disentangling the history of the outer solar system but can only be effected with very large sample sizes.

More complete sky coverage will ensure the discovery of important but rare objects. With ~800 KBOs currently known, we are still discovering objects that force us to revise our basic scenarios. For example, 2000 CR105 has a highly elliptical orbit with a perihelion beyond Neptune. A handful of similar objects are known. It is difficult to explain these orbits as the result of gravitational scattering off of any of the giant planets in their current orbits (Gladman *et al.* 2002). Are these objects hints of new populations that contain valuable clues to solar system history? Such questions can only be decided with the far more exhaustive sampling LSST will provide.

LSST and The Impact Hazard

We are immersed in a swarm of Near Earth Asteroids (NEAs) whose orbits approach that of Earth. About 20% these, the Potentially Hazardous Asteroids (PHAs), are in orbits that pass close enough to Earth's orbit (<0.05 AU) that perturbations with time scales of a century can lead to intersections and the possibility of collision. Beginning in 1998, NASA set as a goal the discovery within 10 years of 90% of the estimated 1000 NEAs with diameters > 1 km. It is expected ongoing surveys will in fact discover about 80% of these large NEAs by 2008.

Significant damage can be produced by much smaller impactors. In the size range between 50 and perhaps 200 m, asteroids striking Earth would explode low enough in the atmosphere to have the effect of a large nuclear explosion of tens to many hundreds of megatons. With a size between 200 m and 1 km in diameter, an asteroid striking Earth would pass through the Earth's atmosphere to strike the surface at cosmic velocity. Over land, such a cratering impact would devastate up to tens of thousands of square kilometers; potentially even more devastating would be the tsunamis raised if such an object struck the sea. Because the frequency of impacts increases more rapidly with diminishing size while the area damaged decreases more slowly, the greatest damage over a long period of time is associated with the smaller asteroids.

A recent NASA report, *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters* (August 2003), concludes that there are about a million NEAs larger than ~50 m in diameter capable of causing ground damage. There are ~50,000 NEAs (~10,000 PHAs) larger than 200 m. The NASA report concludes that a reasonable next goal should be to reduce the residual hazard by an additional order of magnitude, which would require discovering about 90% of PHAs down to about 140 m diameter. Because the risk distribution from sub-km diameter impacts peaks toward the lower end of the size spectrum, a categorically more ambitious survey is called for, not just continuation of the present surveys for another decade or two.

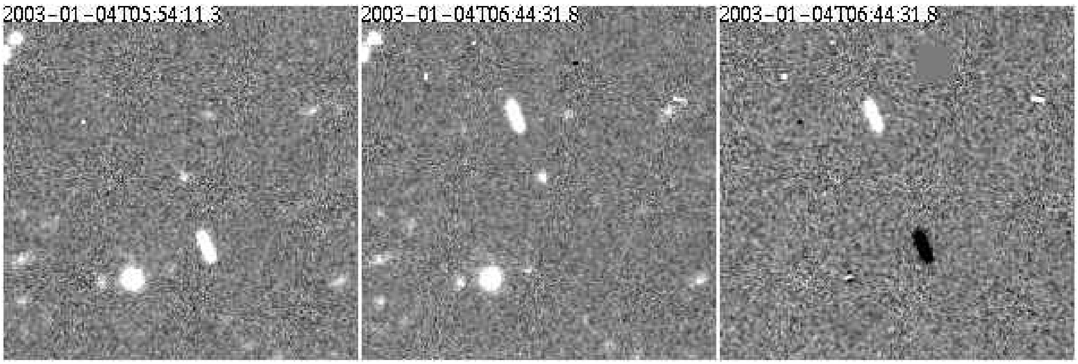


Figure 2. Asteroid detected in difference imaging from the Deep Lens Survey.

Modeling indicates that an LSST survey covering 9,000 square degrees of sky along the ecliptic, three or four times a month, to a limiting V magnitude of 24.0 should achieve a ten-year completion of about 90% of PHAs larger than 250 m, and about 80% completion down to 140 m as called for by the NASA report (see also Jedicke etal 2003).

Main-Belt Asteroids, Centaurs, and Comets

Since NEAs and even PHAs will be detected at distances of 1 AU or more, their motions will be nearly indistinguishable from main belt asteroids (MBAs); in fact, a substantial fraction of them will be indistinguishable from MBAs until preliminary orbit solutions are obtained. Thus it will be necessary to catalog and track MBAs if for no other reason than to be able to separate PHAs from this background "noise." An ecliptic survey to V = 24.0 should accumulate a catalog of more than a million MBAs within a few years. Such a dense catalog of orbits will provide an extraordinarily detailed dynamical picture of the asteroid belt, revealing a wealth of detail about asteroid collisional evolution, perhaps including very recently formed families from recent collisions among asteroids, and detecting additional signatures of the radiation pressure evolution of orbits.

Centaurs and distant comets will be readily separated from MBAs and NEAs by their slower motions but with the same observational cadence. A key question in cometary research is the size-frequency relation of cometary nuclei. Currently detected comets are generally seen only after they come close enough to the sun for their brightness to be significantly increased by coma. Detection of comets farther from the Sun may make it possible to observe their bare nuclei and thereby obtain more accurate statistics on the size-frequency distribution. Centaurs are closely related to TNOs, having evolved inward from the Kuiper Belt analogously to the way NEAs evolved in from the main belt. Cataloging Centaurs is thus essential to a complete study of KBOs.

GALACTIC STRUCTURE & ASTROMETRIC STUDIES

Astrometry and the Solar Neighborhood

LSST will mark the dawn of a new age in our study of nearby stars. It will be able to measure the parallax of every object in its field. The power of such measurements was illustrated by Hipparcos (Perryman *et al*., 1997) for bright stars. LSST will produce measurements and uncertainties for the position, parallax, and proper motion of an estimated 10^{10} stars. It will provide the first distance-limited catalog of parallaxes of all stars above a given (faint) apparent magnitude limit in the observed sky. This will eliminate the selection biases inherent in all previous surveys and provide a complete measurement of the local luminosity function. A complete census of stars within 10 pc should be available after only a few years of observation. The recent discoveries of L- and T-dwarfs and other low-luminosity objects are just previews of the types of objects waiting to be discovered.

Binary stars offer one of the few opportunities to measure stellar masses, but searches for binaries are difficult and rarely undertaken. LSST will provide an almost complete, volume-limited inventory of stellar systems, and within each system, common proper motion data can be used to identify major components. The residuals from fits for position, proper motion, and parallax of all stars in the LSST archive will be searched for the signatures of Keplerian motion using Fourier techniques. Since astrometry will be carried out in each of the survey passbands, the amplitude of the astrometric perturbation can be measured as a function of color. This will allow a statistical identification of the binary components involved, in turn allowing selection of interesting classes of binaries to be made from the database. Combining the parallax and binarity data will greatly advance understanding of star formation.

The Structure of the Galactic Halo

Halo stars contain a fossil record of the history of our Galaxy. LSST will probe the Galactic halo both locally, by selecting nearby halo stars from their kinematics, and at great distances, using RR Lyrae, horizontal branch, and main sequence turnoff stars. The halo and its inhomogeneities have been traced using SDSS data (Ivezic et al. 2000). Measurements of relatively local stars suggest that the Galaxy has a stellar halo with a steeply falling density and perhaps a cutoff beyond 50 kpc. LSST will reach fainter than the main sequence turnoff at this distance, making these turnoff stars an excellent tracer of the halo out to perhaps 100 kpc. Current attempts to use giants to probe the halo require accurate characterization of the properties of each star. In contrast, distant turnoff stars will vastly outnumber other stars that are that blue; proper motion can be used to eliminate further contaminants, such as foreground white dwarfs (which will be 100 times closer). This will enable a statistical approach to probing the halo, matching models of specific halo properties to observed number counts and proper motion distributions.

LSST will play a role in the study of galactic dark matter by providing dynamical information to map the inner halo through proper motions. Measuring the full 3-D velocities of stars in the local neighborhood will provide a sample of fast-moving stars from which orbits can be constructed. A self-consistent model for the mass distribution of the Galaxy would not only need to explain the velocity distribution function but would also have to match the number density of objects at larger radii. For example, if one finds that many local stars have apogalacticons of 100 kpc, there must be a corresponding population of stars at 100 kpc revealed by turnoff star probes. Tracing a whole population in this manner is far more constraining than simply using a satellite galaxy or two at large radii. Dynamical tracers, such as RR Lyrae stars at large radii, are important because they provide independent measures of the total enclosed mass. Requiring consistency between these distant velocity measurements and the local velocity distribution function will provide much tighter constraints than currently possible. Ongoing work using Schmidt plates (Clewley et al. 2002) has found ~100 halo objects at a galactocentric distance > 30 kpc; LSST will dwarf these studies.

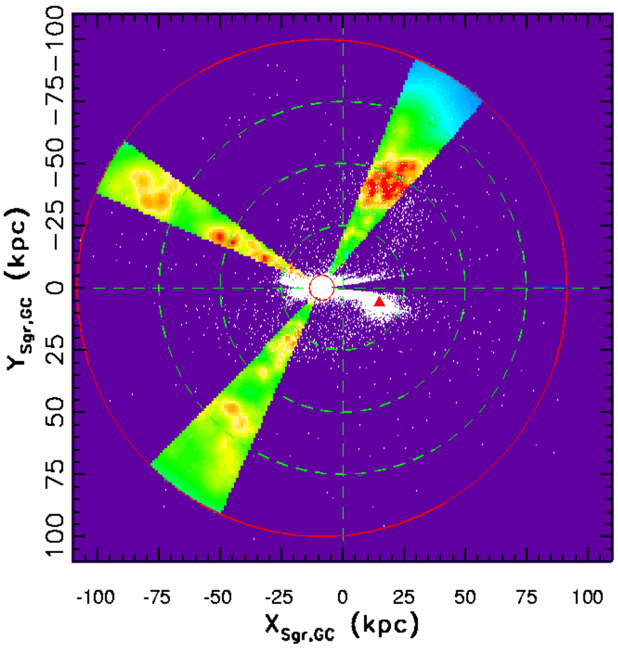


Figure 3. Stellar density.

Tracing the Assembly of the Galaxy

Because of the long dynamical relaxation timescale at large radii, the structure of the halo is linked to the accretion history of the Galaxy. Two populous stellar streams have been discovered in the last ten years, but we expect tens or hundreds of smaller streams. To trace these streams, one needs both distances and velocities to halo stars. LSST provides the best avenue for obtaining each of these over large areas of the sky. RR Lyrae, horizontal branch, and main sequence turnoff stars can be used to provide distances to any over-densities identified as potential streamers. Proper motion measurements over a decade of observations will provide information on the kinematic coherence of an overdensity. Figure 3 (Ivezic et al 2003) shows stellar density times the cube of the galactocentric radius of SDSS candidate RR Ly stars within 10 degrees of the Sgr dwarf tidal stream plane (triangle is the position of the Sgr dwarf core). LSST will extend such mapping to a volume 50 times larger. While radial velocities have traditionally been much easier to obtain than tangential velocities, the opposite will hold true using LSST for the large number of stars involved.

The kinematics of the local halo sample will also enable a measurement of the halo velocity ellipsoid, which reflects the angular momentum distribution of the accreted material. Measuring the distribution of distant stars using standard candles such as RR Lyrae or horizontal branch stars and local kinematics using proper motions will provide a detailed history of the growth of our Galaxy.

THE PHYSICS OF DARK ENERGY

Observations with the LSST will result in advances in fundamental physics. In the last decade, astrophysicists have converged on a standard model of cosmology. While this model is remarkably successful in explaining current data on the nature of the universe on the large scale, it invokes two mysterious new components not yet detected in any laboratory: dark matter and dark energy. LSST can characterize this unseen portion of the universe with great precision using the subtle distortions of distant galaxies produced by weak gravitational lensing. When extended to a large fraction of the full sky, the lensing techniques already being used on small patches of the sky can produce the 3-D mass maps over large volumes that are required for high-precision cosmology.

What is the physical origin of the recent acceleration of the expansion of the universe: "dark energy" or new gravitational physics? LSST's greatest leverage on dark energy hinges on the fact that dark energy evolves strongly in redshift across the prime LSST range. The multiple analysis methods described below rely on maximal area coverage of the sky in order to characterize resolved sources in large volumes of space and to reach low angular modes. The multiple methods are sensitive to different forms of systematic errors, meaning that multiple analyses within the LSST data set can provide cross-checks on cosmological inferences. Photometric redshifts allow us to determine the redshift of the cluster lenses as well as the differential shear of sources at different redshifts. The dark energy equation of state w is the ratio of pressure to energy density of the universe.

Cluster Counting via Weak Lens Tomography

The runaway collapses initiated by gravitational instability offer another way to probe cosmological perturbations, this time on smaller scales. The number of massive galaxy clusters depends very sensitively on the amplitude of density fluctuations and on the cosmic distance scale. Both depend on the details of dark energy. The counting of clusters vs. redshift thus provides a superb way to constrain the equation of state of dark energy. LSST is expected to find about 200,000 clusters in its mass maps; combined with photometric redshifts, a cluster sample of this size offers 2-3% precision on the equation of state (Tyson et al. 2003). Using shear data for source galaxies at different redshifts, the detected cluster redshift can be estimated in a baryon independent way, in addition to mapping the cluster mass on the plane of the sky. This 3-D technique has been developed recently (Wittman etal 2003), and LSST can apply it to the whole visible sky. A large area is needed to reach the required statistical precision.

The shape of the observed distribution dN/dz with mass and redshift will be compared with N-body simulations. Cluster counting achieves its best accuracy at $z<1$, where the dark energy is thought to be most active and is thus distinguished from, and complementary to, higher redshift probes such as $z>1$ supernovae or high-z redshift surveys for acoustic peaks. The systematic shear error for massive clusters is small compared with the signal. Because of the exponential sensitivity to mass it is important to avoid mass proxies. Other techniques for surveying for clusters are baryon biased. This bias is complex and scale dependent. This distinguishes the method from higher redshift probes such as $z>1$ supernovae or high-z redshift surveys for acoustic peaks. Here, the degeneracy line is $4w-\Omega_M = const$, the same as the powerful technique of shear-shear tomography discussed below, but the systematics are different.

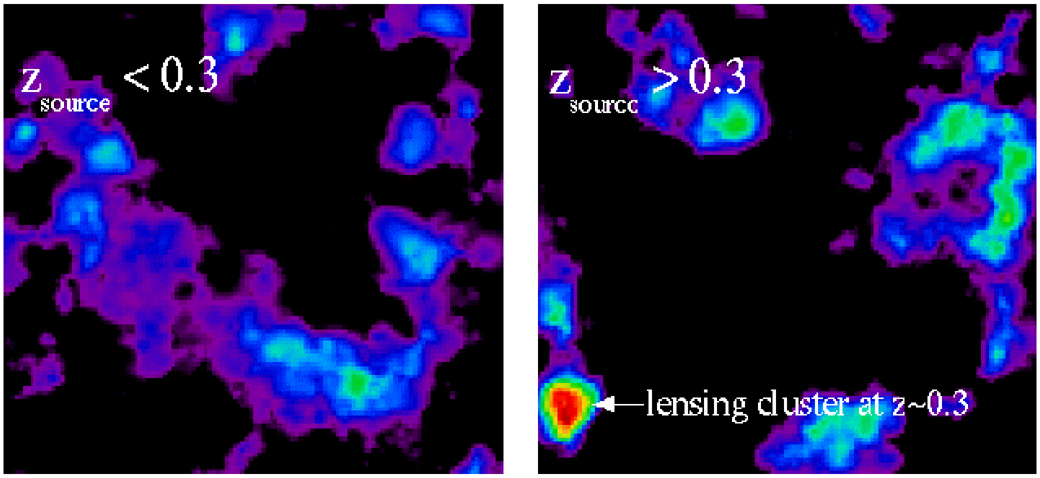


Figure 4. 3-D mass tomography from the Deep Lens Survey. These mass maps of a 40' field show two slices in redshift. Similar 3-D mass tomography has found clusters up to z=1.

Shear Tomography

Using the same data, an independent probe of dark energy comes from weak lens shear tomography, in which shear of sources in various redshift bins is correlated over wide angles. LSST can measure the cosmic shear power spectrum with precision, addressing the physics of dark energy. Using photometric redshifts to characterize the lensing signal as a function of source galaxy redshift will improve the results over 2-D power spectra (Hu & Keeton 2002). A large area is needed to reach the required statistical precision.

The universe may have additional surprises for us regarding the evolution of cosmic perturbations. For example, non-zero neutrino masses or other small admixtures of hot dark matter would cause the LSST-measured shear power spectrum to be tilted in scale relative to the CMB prediction. Only by probing the dark matter directly with full-sky weak lensing will we be able to push to one percent level precision on the dark energy equation of state *w* and its evolution with redshift. For fixed growth at some redshift the degeneracy line is $4w\text{-}\Omega_M = const.$ The left panel in Figure 2 shows an estimate of the precision achieved in the cosmic shear survey of 15,000 square degrees to sources at z=3. A density of 70 sources per square arcminute and a shear floor of 0.0001, and WMAP CMB Ω_M prior were used. The effect of including 2-point galaxy correlations is also shown (Hu & Jain 2003).

The shear signal from gravitational lensing depends on the relative separations of the source, lens, and observer. By comparing the differential signal between sources at multiple redshifts (shear cosmography), one can achieve precise measurements of the distance-redshift relation (Bernstein & Jain 2003). This method differs from the shear power spectrum in that it does not attempt to characterize the statistics of the mass distribution of lenses, but focuses on measuring relative cosmological distances. The systematic effects in cosmography are challenging and different from those of other weak lensing analyses.

Cross-Correlating LSST Shear with CMB

Combining CMB anisotropy with weak lens cosmic shear and mass tomography of lenses over the redshift range $0.1 < z < 1$ will enable precision measures of the equation of state of dark energy *w* and its derivative, s well as the spectrum of the primeval density fluctuations. Dark energy influences mass structure formation (via changes in the expansion rate) mostly around $z=0.4$. While the CMB anisotropy is not sensitive to the dark energy, it is helpful for probing dark energy when combined with LSST because of the degeneracies it breaks. With, e.g., the dark matter density determined well from CMB data, departures of LSST data from the CMB prediction can be ascribed to dark energy.

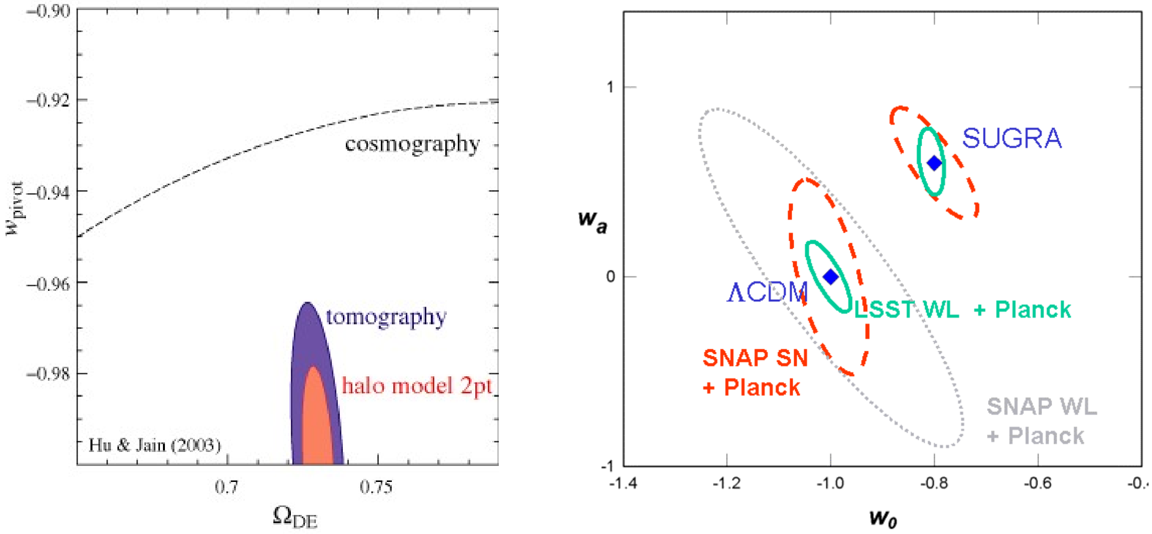


Figure 5. Weak lensing shear tomography. Error ellipsoids (1σ) in the planes of the relevant dark energy (DE) parameters for the 8.4-m LSST 15,000 sq.deg tomographic survey and for SNAP. *Left*: DE equation of state *w* for three LSST shear tomography techniques. *Right*: This LSST survey and SNAP SN & 300 sq.deg WL surveys in the w-w_a plane, for two cosmological models. $w_a = 2\,dw'$, where $w'=dw/d\ln(1+z)$.

Combining the two measurements will pin down *w* to the 2% level as well as tightly constrain the initial power spectrum. Weak lens shear data over 15,000 deg^2 is required. This LSST survey will also constrain the time derivative of *w* to better than 6% (Knox 2003; Knox & Song 2003). Limits on the relevant parameters are shown in the right panel of Figure 5, excluding the cosmography technique. Two models which are indistinguishable with CMB are shown: ΛCDM and a supergravity model. Weak lens shear data provides a precision measure of cosmology complementary to SNe.

Moderate Redshift Supernovae

LSST will discover 100,000 SN per year in the range $0.1 < z < 0.7$. It will follow up on these supernovae with lightcurves that are much denser and cover more colors than in any current or planned survey. Statistics of color and detailed light curves, as well as sample spectra, will enable studies of "third parameter" dependencies, shedding light on any systematic errors in the type Ia SN technique. More interestingly, with these SN spread all over the sky, anisotropies may be detected: flows and any spatial and temporal dependence of *w* would be revealed. A variation in *w* with direction would have serious implications for fundamental physics. Hubble flows derived from SN Ia luminosity distances could be cross-correlated with the CMB, yielding a separate constraint on dark energy with much higher S/N than the Integrated Sachs-Wolfe observations, ideally complementing constraints from lensing. The degeneracy line of the weak lens techniques in w - Ω_M space is nearly orthogonal to that of SN-based measurements of luminosity distance vs. z.

Integrated Sachs-Wolfe Effect

CMB photons passing through clusters of mass are blue-shifted if the expansion is accelerating. Scranton et al. (2003) have cross-correlated WMAP against 3400 sq degrees of SDSS multi-color imaging and have detected an achromatic positive correlation between the two datasets at >95% confidence, providing independent evidence for dark energy. The error on the ISW is primarily dominated by sample variance, as the effect is only seen on large angular scales. To improve significantly upon the SDSS-WMAP detection of the ISW effect will require more sky coverage (the effect depends linearly with area). Deeper optical photometry would provide better estimates of the photo-z's as well as higher redshift galaxies (out to z~1). This would then allow finer resolution in the redshift direction and could provide a measure of the ISW effect in many independent redshift shells, yielding an estimate of the equation of state. The only surveys that will provide these improvements are the LSST + WMAP. Current models of dark energy parameterize our ignorance. Will the separate probes of dark energy show consistency? All these lensing probes, as well as SN, SZ, and ISW, test the foundations of our cosmological model and have the potential of revealing physics beyond our current models.

The New and Unanticipated

The projects listed above have been chosen because of their scientific significance and the fact that they drive the LSST design in key areas: image quality, cadence, astrometric precision, and photometric accuracy. The implications for telescope design are discussed in the next section. We note here that a design that meets the requirements of the science drivers discussed above will also support a wide variety of other projects, and examples already proposed include: the detailed distribution and nature of dark matter via exploitation of rare strong lens clusters, analysis of supernovae to study the peculiar motions of galaxies and to provide data on the evolution of stellar populations in galaxies with a wide range of ages; the detection of astrometric wobbles due to the reflex motion caused by planets around nearby stars; the assessment of the importance of galactic encounters through the search for intergalactic novae as indicative of stripped stellar populations; determination of the white dwarf luminosity function; and a complete census of L and T dwarfs within 10 pc.

Whenever humans have looked at the sky in a new way, nature has responded by revealing a wealth of new and unimagined phenomena. LSST will open up to discovery the most fleeting of occurrences and will enable us to study long-lived families of objects in unprecedented detail. We will catch the most violent events in the act and be able to trace the fossil records of these events long after they occur. We will move from the study of individual objects to populations *en masse*, and from the observation of the luminous objects that constitute only a tiny fraction of the universe to characterization of its underlying dark matter and energy. LSST is the next fundamentally new way to look on the universe; nature is surely ready for us to begin. In the following section we discuss the flow-down from these LSST science requirements to instrument specifications.

Scientific Planning

It is obvious from this brief overview that the LSST will enable a host of very diverse science programs. A Science Working Group chaired by Michael Strauss and reporting directly to the NSF is currently evaluating the scientific potential of LSST and preparing a report that will discuss scientific priorities and requirements. The D&D proposal is broadly consistent with the discussions of the SWG to date, and their final report will guide the science planning for LSST.

With the SWG report as a starting point, a key task for the D&D phase will be to translate these priorities into quantitative requirements for the telescope, camera, site, and data system. During the D&D phase, we will establish a Scientific Advisory Committee that will develop a detailed plan for converting the flow of data from LSST into specific scientific results. The community will be given an opportunity to apply for membership. Based on these applications and on the scientific interests of the partners we will select three or four science themes--possibly dark energy and weak lensing; asteroid detection and characterization; astrometry; and time domain studies--and develop detailed scientific plans for the LSST. We will also conduct simulations to determine to what extent the selected programs can be served with the same data set, and hence what fraction of the observations can be conducted in parallel and which ones are best conducted in special campaigns.

The science planning process will ensure that the design specifications of LSST will meet the requirements of diverse scientific programs but will also help to guard against uncontrolled growth in requirements and hence costs. A key element of cost control is defining where the work carried out within the project stops and what kind of interface is made available to support community exploitation of the very rich data set.

C.3 TELESCOPE AND INSTRUMENT REQUIREMENTS

While detailed science planning will be one of the major tasks of the D&D phase, independent scientific advisory panels and the project team have already have already held a series of meetings and have concluded that a large number of key scientific investigations that require rapid coverage of very large areas of the sky can be carried out through a similar set of standard filters. The similarity of basic requirements leads in principle to a simplified operational model. Ideally, LSST would support a single, continuous observing program, which would fill a data base with multi-color data that could be used by all of the science programs described in the previous secton and by any science program that requires optical photometry and astrometry. A few of the proposed programs, however, appear to require special cadences, long exposure times, emphasis on special parts of the sky, or near-real-time multi-color data. Reconciliation of these requirements, optimization of the scheduling algorithm, and detailed specification of the science requirements for the LSST facility and data management system are principal goals of the D&D phase. In the section that follows, we summarize the requirements as they have been determined so far along with some of the key issues that remain to be addressed.

Independent scientific advisory panels and the project team have identified a large number of key scientific investigations that require rapid coverage of very large areas of the sky through standard filters. The similarity of basic requirements leads in principle to a simplified operational model. Ideally, LSST would support a single, continuous observing program, which would fill a database with multi-color time-tagged data that could be used by all of the above science programs and by any science program that requires optical photometry and astrometry. Reconciliation of these requirements and optimization of the scheduling algorithm is one of the goals of this proposal. Here we summarize the flow-down to instrument requirements by science driver.

Weak Lens Tomography

The errors in measurement of cosmological parameters are statistical in nature, and benefit from measurements of the largest possible volume. Characterization of large-scale anisotropies, which are the easiest to compare with experiments such as WMAP, requires covering much of the sky. The primary leverage for addressing dark energy is in the redshift dependence of the shear field. Reducing errors in measurements of the shear field at each point on the sky as a function of redshift argues for a survey that includes the largest possible number of galaxies. Weak lensing thus requires both a deep survey and one covering as much of the sky as possible. A decade-length survey of 15,000-20,000 square degrees with a system with etendue $A\Omega > 200$ m^2 deg^2 can measure over 200,000 massive clusters. Accomplishing this goal requires an effective PSF FWHM of less than 0.7 arcsec in an R-band stacked image with a 10-σ detection limit of 26.5 AB magnitude. The PSF low order moments must be stable at the 1% level during an individual exposure. Weak lensing thus makes the highest demands on image quality of any proposed study.

Distance information for tomography comes primarily from photometric redshifts of the source galaxies. This requires multi-color imaging in at least five bands stretching over as wide a wavelength range as possible. Going as red as the 1 micron Y band would be useful as it would extend the reach of diagnostics such as the 4000Å and Balmer breaks out to z~1.3. For maximum volume, it is better to go wide than deep; this ensures resolved source galaxies at $z < 2$, trading number density of sources for brighter galaxies ($V < 26$) and depth for area. Photometric redshifts require an accuracy for galaxies brighter than $R = 26$ of 0.1 in $(1+z)$ and requires deep photometry in 4 or 5 other bands, though not necessarily with as high image quality, with photometric calibration accurate to 2%. Weak lensing makes no demands on the cadence of observations; observations at all epochs can be added together. Indeed, addition of observations made at different times of the year and different camera rotations helps to reduce systematic errors in determining galaxy shapes. Multiple short exposures optimize reconstruction of the high-resolution image stack.

Supernova Cosmology

LSST's wide field makes it an ideal "supernova factory." Supernovae are relatively frequent events, and because LSST surveys such a large volume of space per field, only a few fields spaced around the sky would suffice to measure cosmological parameters as a function of redshift and direction. A survey to $z = 1$ is possible and makes several demands on system design: red sensitivity and relatively long dwell times with frequent repeat visits to the chosen fields. Because the required number of fields is small, the overall impact on scheduling is not expected to be severe. Each field will require observations in four, preferably five, filter bandpasses every five days although the full filter complement need not be obtained during the same night. The depth required for each field on a given night is $V=26$ and $Z = 24$ (600 – 1200 seconds), which can come from multiple visits. Individual fields would be followed for three months to allow the most complete time coverage of detected supernovae. Again, photometric calibration at the 2% level will be important.

Solar System Census

The Near Earth Object search and the Time Window place the greatest constraints on the operating cadence. We therefore plan to use the NEO cadence for the majority of LSST observations. This cadence, with its roughly logarithmically spaced intervals, is also well-suited to discovering a wide variety of optical transients. A preliminary study of survey strategies indicates that the most effective survey pattern is to cover the ecliptic region of the sky to as small solar elongation as practical, preferably down to within 60º of the solar direction and within 20 degrees of the ecliptic. The smallest NEOs will be detected only in close proximity to Earth, when their apparent motion on the sky will be at its maximum, at more than a degree per day. At a rate of one degree per day, it takes 17 seconds for an image to trail across a seeing disk of 0.7 arc seconds; two successive ten-second exposures will thus have minimal trailing loss. Two images 15 minutes apart suffice to discriminate moving targets (even TNOs) from stationary transients, and at the same time allow unambiguous linkage between objects in the two epochs by a potential orbit. The rates of motion obtained are, in turn, sufficient to link images of the same objects at least several days later; a repeat time of three days is thus quite acceptable for linking objects and determining orbits. A functional survey strategy is thus to cover the sky area three times per lunation. With 50 mas astrometry, an arc of only six days (three observing nights separated by three days each) is sufficient to obtain satisfactory orbits for the majority of objects.

A ten-year survey of 15,000 square degrees of sky within 20 degrees of the ecliptic to V=24.0 will detect about 90% of asteroids larger than about 250 meters in diameter, with about 80% completion down to the 140-m diameter called for by the NASA report mentioned in the previous section (Jedicke, etal 2003). Exposures that reach the sky limit before significant trailing occurs, i.e. within 15-20 seconds, are required. This places several stringent requirements on LSST. To enable cosmic ray detection, one can use two successive ten-second exposures. The readout time of the 2.3 Gpixel array must then be less than 2 seconds, and the telescope must be able to move to a new field several degrees away and settle in less than 7 seconds, if the efficiency of the system is not to be degraded. The limiting magnitude, exposure times, area coverage, and revisit frequencies of this project require a single telescope/camera system etendue of more than 200. Non-standard wide filters which would be required to maintain this cadence for small aperture telescope/cameras are not needed for LSST. Multi-color photometry will help in the NEO science. It remains to be determined whether filters outside the g, r, and i bands have high enough etendue to be useful for the NEO search.

A survey for Trans-Neptunian Objects and other faint contents of the solar system requires net exposure of one hour to reach R=27, resulting in a 60-fold increase in the density of observable KBOs and a 50-fold decrease in their observable mass. Fields should be uniformly spaced along the ecliptic, and revisit times of several months are necessary to determine orbits. The need to spend so much time exposing near the ecliptic also imposes modest geographical requirements on the LSST site.

Opening the Optical Time Window

LSST surveys faint, fast, and wide simultaneously. Exploiting this window for discovery requires optimizing the design across all of these measures, regularly obtaining as much information as possible so as to catch even rare events “in the act.” The NEO survey requirements, augmented by the need for color information, are conducive to discovering rare, transient events on a wide range of timescales to R = 24. A etendue of over 200, as provided by the LSST, would be enable detection of a type of transient that occurs on average once per night in 20% of the sky at R = 24. A search for fainter transients (such as distant supernovae and GRB afterglows) will require longer dwell times, but such searches can be accommodated with less than complete coverage of the sky. In order to ascertain whether an object of a given brightness is new, a fairly complete knowledge of the sky is required to at least that magnitude. Thus an operational constraint imposed by all transient-finding activities, including the search for NEOs, is that a deep, multi-color survey of the sky be completed first.

Contents and History of the Galaxy

Mapping the assembly of our Galaxy via stellar streams requires photometry to R = 26 in co-added stacks, with 0.02 magnitude accuracy, easily in accord with requirements from many other programs. The most stringent requirements arising from galactic observations are astrometric. During an initial survey, fields must be visited twice per lunation in the same color. This allows separation of parallax from proper motion. After this, one visit per year is sufficient to measure parallax, proper motion, and wiggles from unseen companions.

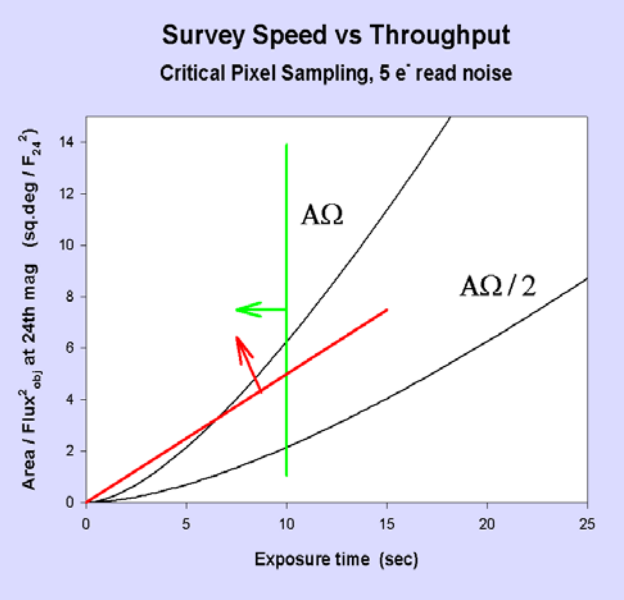
The LSST goal is to achieve an astrometric accuracy of one-hundredth of a pixel per observation and one-thousandth of a pixel for the mean of many observations. Experience with other ground-based surveys, including the SDSS, suggests that this goal is achievable. After the LSST sensors have been selected, a detailed laboratory and observing campaign will be needed to understand the technology and to verify centroiding algorithms at the milli-pixel level. Telescope and PSF stability requirements are similar to those required for weak lensing. The system of J2000 is based on Hipparcos stars (V < 10), and astrometry levies a requirement that some method must exist to map the coordinate system from these bright stars to LSST's much deeper exposures. Optimal sensor technology would allow for magnitude compensation by fast readout of subarrays.

Putting it Together

These requirements are summarized in Table 1 and fall into four broad classes:

- the fraction of the sky that must be covered;
- the frequency and cadence of revisits to the same field;
- the number of photometric bands required for temporal sampling and/or for accumulated data;
- the depth, image quality, and photometric and astrometric calibrations that are required, both per visit and as accumulated, from all images taken over the project duration in each passband.

Taken together, the requirements mean that the LSST system must be able to obtain sufficiently rapid and deep observations with small enough overheads that adequate sky area can be covered in a specified amount of time to satisfy the cadence requirements. These requirements have optical etendue implications for the telescope/camera. Figure 6 charts the relative speeds of a survey to V = 24 for two values of the telescope/camera etendue: LSST's 270 m^2 deg^2 and half of that. For efficient surveying to faint limiting magnitudes, the square root of the sky background counts in each exposure (the shot noise) must greatly exceed the noise of the detector and must fill traps. For the lower etendue system, the sky noise limit is not reached for exposure times less than 20 seconds. This limits the area of the sky that may be surveyed per unit time. Smaller etendue (AΩ). systems thus cannot cover the visible sky multiple times per month through standard filters.



Surveys constrained to short exposures get a double boost from high AΩ: once from the area covered to a limiting flux and once again from the shorter exposure times (and thus faster survey pace) required to overcome device noise. An LSST exposure time calculator has been developed: http://www.ctio.noao.edu/lsst/etc/. The 8.4-m LSST with standard filters and current detector performance at –40 C reaches 24th V mag in 10 seconds over its entire 7 square degree FOV. Short exposure times (the area to the left of 10 seconds) are optimal for detecting short timescale optical bursts and minimize trailing for NEOs. Once observations are sky-noise limited, longer exposures reach deeper (the steep part of the curve). The area to the upper left of the tilted red line is the operating region that meets the pace requirements: covering the visible sky three times per lunation. A conclusion from this plot is that splitting the 8.4-m LSST into two 6.5-m telescopes and two cameras covering 3 degrees (each with half of the original etendue) would result in a system that could not meet the science requirements for rapid pace and short exposures.

The images must also meet quality benchmarks, and the S/N characteristics of individual images should improve maximally as individual exposures are co-added. An early concept model for a system that addresses all of these requirements is given in the next section. A key advantage of this concept is that its high etendue makes it possible to cover the entire visible sky several times per month, thus enabling multiple parallel science programs. The interplay between the detailed design and requirements will be evaluated carefully and iteratively throughout the design and development phase, but it is already clear that a buildable concept, which is described in the next section, can meet the requirements summarized in Table 1.

Operational Strategy

Observation planning is a key element in the design of the overall project. The central issue in observation planning is to find the "least common super-set" of observations that satisfy the requirements of all projects. An informed and balanced trade-off must take into account not only the science requirements but also:

- the constraints imposed by availability of a given field (ephemerides);
- the overhead accrued in pointing and reconfiguring (e.g., filter changes) the telescope;
- weather and image quality permitted by the atmosphere;
- total project duration.

In broad terms, the observing plan calls for an initial `static survey' to create a reference map of the sky, one to which subsequent observations can be compared to identify variable sources. This in turn will enable prompt tagging and posting of objects for follow up observations. Near-real-time identification is particularly important for short term transients, both for reprogramming the LSST target list and for enabling observations that must be made by other facilities. The static survey is expected to take place in the first one to two years, with the length of time devoted to it strongly dependent on the filters chosen. Because this survey does not require observations at specific times, it can be interleaved with other commissioning activities on the telescope.

Developing the best observing plan for the subsequent repeated scans of the sky will be challenging and will involve balancing the priorities and resource demands of many projects. In addition to their impact on telescope design and site selection, the science requirements drive the details of *how* the data acquisition must be done in the face of observing constraints, weather, and seeing patterns. In achieving a compromise schedule, it is important not merely to adjudicate between the demands of various scientific programs, but also to assess quantitatively how rapidly various scientific results degrade with changes in system design. To do this well, a set of tools will be developed to evaluate the detailed effects of a given observing schedule. These tools will be based upon a complete simulation of operating the LSST given a design, site, and all known constraints. Synthetic datasets resulting from such simulations will be analyzed as real data, and the results of these analyses will be used to refine the observing program. Here we report on the results of a first simulation of the capabilities of our LSST system reference design to survey large areas of the sky to faint limits in many filters.

Simulations of Survey Volume: the need for High Etendue

The need for a system etendue as large as 270 m^2 deg^2 becomes obvious when simulating realistic LSST operations, constrained by the science requirements. This is a two-step process beginning with an estimate of the 10σ limiting magnitudes in all the science filters. For this estimate we use a uBVRIzY system. While this covers the full wavelength range, the detailed filters have not yet been chosen. Using the 8.4m LSST exposure time calculator for the estimated optical etendue, including all losses and detector QE curves, an exposure of ten seconds gives 10σ photometric accuracy of 21.8 u, 24.0 B, 23.9 V, 23.5 R, 22.8 I, 22.0 z, and 21.1 Y Vega magnitude. While a pre-survey in all science filters is planned for up to two years, we focus here on the main part of a decade long survey using the reduced set of BVRIz. [A survey covering over 14,000 deg^2 going to 26.5 V equivalent mag in all the seven filters with the 8.4m LSST is easily shown to be infeasible in a decade of 70% workable weather.]

One of the priority missions of this proposed D&D phase is the optimization of the observing algorithm, given the science requirements. Here, we summarize a first attempt at this using the 8.4m LSST ETC and a Monte Carlo simulation program by Abi Saha. The next-field next-filter selection algorithm is that devised by Zeljko Ivezic primarily to satisfy the NEA and transient object detection requirements: Each visit to a field consists of two 10 sec exposures; a pair of visits must each contain an R exposure. For this simulation visits are 30 sec long, giving time for readout and move/settle. This results in over 40 R exposures per field per year. Clearly this could be tuned to optimize the other science as well. We used the following additional parameters in the simulation: latitude 27 deg south, 70% workable weather (simple randomized model), avoid 20 deg of the Galactic plane, airmass < 2, avoid fields with declination different from –27 deg by >50 deg, 3 nights of down time at full moon. Observations are in I and z when a >0.25 moon is up.

The algorithm can be adjusted to trade area for depth or depth uniformity. An idea of the limits can be obtained from two simulation runs which did this. In one decade-long simulation, depth uniformity was not strictly enforced: 14,600 deg^2 were covered to mean 10σ limits of 27 AB mag in BVR, 26 AB mag in I, and 25.3 AB mag in z. In this case, which goes fainter than the science requirements in most filters, one would want to trade depth for both increased areal coverage and uniformity. In another Monte Carlo, depth uniformity was imposed via clipping those fields with exposures less than 2000s in B or V, 3600s in R, and 1000s in each of I and z (an optimal algorithm would adjust field priority to avoid such post-facto clipping of data). The result for this “intersection” data was: 14,100 deg^2 covered to 10σ limiting AB magnitudes of 26.8B, 26.8V, 26.9R, 25.8I, and 25.0z. Through optimizing it thus should be possible to cover nearly 15,000 deg^2 to an equivalent AB mag of 26.5V in five passbands at 10σ in co-added stacks. But it is already clear that a 10 year survey of such a volume requires the 8.4m LSST etendue, even if limited to five filters.

Table 1. Science Objectives and Flow Down to System Requirements

Science Goals	Observational Requirements	Telescope/Camera/Site Requirements
Nature of Dark Energy ☐ *w* to 2% ☐ d*w*/dt to 5% ☐ *w*(φ) over 2π ☐ correlate with CMB All sky weak lensing (WL). Rapid revisit SN (2nd param studies)	☐ WL shear > 0.001 vs z ☐ 15,000-20,000 sq deg to V=26.5 mag (WL) ☐ σ color-z to 0.1(1+z) ☐ ~200 exposures per sky patch per filter ☐ Photom calib: 0.02 mag ☐ 900 sec/filter/field/night, repeat every 5 nights on small # of fields (SN)	☐ Image quality: < 0.7" FWHM in V,R,or I bands, PSF quad moment stable < 1% per 10 sec. Shear systematics < 0.0002 in 300 image av. ☐ 5 bands, for photometric redshifts (WL) & 2nd parameter studies (SN): 350 nm to 1 μm ☐ Southern site to match Antarctic SZ surveys? ☐ $A\Omega > 250$, noise/read < 5e
Optical Transients ☐ Extreme physics ☐ Rare new objects ☐ Orphan GRB statistics ☐ SNe in arcs + μlensing	☐ Broad coverage in cadence, 15 sec to year timescale ☐ Evolution of spectral energy distribution ☐ Requires deep initial multiband template ☐ Frequent revisits, max sky coverage	☐ Requires multi-colors ☐ Target latency of <1 min for alerts, high throughput pipeline ☐ $A\Omega > 200$ in a single camera to see events as rare as 1/night over 1/5 of the sky: fast pace. Noise/read < 5e.
Solar System ☐ PHAs down to 100m ☐ Small KBOs + colors ☐ MBA statistics, colors	☐ Max coverage in ecliptic. Magic elongation ☐ 6 visits, 15 min sep, per sky patch per lunation ☐ Area coverage > 11000 square degrees ☐ Sufficient AΩ product to get 90% completeness for PHAs in 10 years.	☐ Maximum exposure of 15 sec to avoid trailing losses ☐ Image quality < 1" FWHM $A\Omega > 200$ per camera, noise/read < 5 e. ☐ Multiple 500-800nm filters
Galactic Structure, Astrometry ☐ Extreme halo dwarfs ☐ History of formation: stellar streams, Galaxy & local group ☐ Dense astrometry grid ☐ Planets around stars	☐ Maximize temporal baseline ☐ Early multiband all-sky survey ☐ Parallax Survey ☐ Photometric calibration: 0.02 mag ☐ Astrometry cadence: 2 visits per month ☐ Area coverage: > 15,000 square degrees	☐ Multi color, large area, r<26: $A\Omega > 200$ ☐ Time base hours to years ☐ Image quality < 0.8 arcsec ☐ All categories need astrometry & photometry of >10 mag stars: fast sub-array read or auxiliary facility and transfer

C.4 THE LSST SYSTEM REFERENCE DESIGN

The 8-m class telescopes that have come into operation over the past decade have all had relatively narrow fields of view. The D&D phase of the LSST effort will establish the feasibility of breaking this paradigm, maximizing the telescope etendue (the AΩ product) and operational efficiency for the single purpose of conducting the deep synoptic surveys discussed in the previous two sections of this proposal. The section that follows describes the overall system architecture of a facility that would meet the science requirements. Some of the critical requirements for each subsystem are described briefly. The subsequent section describes the work to be completed during the D&D phase.

THE TELESCOPE

Optical Design

The baseline optical design for the 8.4-m LSST is based on a concept by R. P. Angel *et al* (2000), which modifies the Paul-Baker 3-mirror telescope to work at large apertures. Subsequently, Seppala (2002) further developed the Angel design to lessen the aspheric surfaces and produce a flat focal plane. The mature baseline design uses three aspheric mirrors (8.4-m diameter primary, 3.5-m secondary and 5-m tertiary), which feed a 3-element correcting camera resulting in a 3˚ (~7 sq. deg.) circular field of view (FOV) covering a 55-cm diameter flat focal plane.

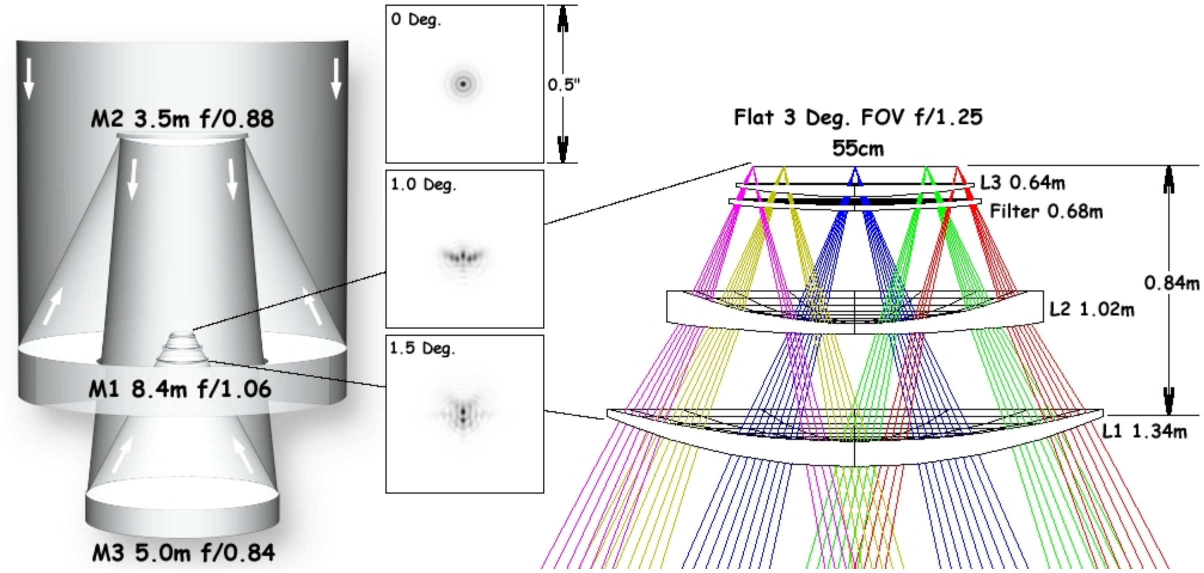


Figure 7. The overall optical path for the LSST baseline design (left) along with a more detailed view through the corrective camera optics (right). Insets show the diffraction PSFs at 650nm for three field radii.

The primary and tertiary mirrors for the LSST are both concave, and the baseline design incorporates the spun cast borosilicate mirror technology developed by the University of Arizona's Mirror lab. The support system for these two mirrors will be based on cell designs used in the 8-m LBT and 6.5-m Magellan telescopes. The large convex secondary will be a structured light weighted mirror made from a low expansion glass (*e.g.* Zerodur). The secondary support system will be based on working designs from other large secondary mirrors like those on the MMT and Magellan telescopes. The plan is to coat each of these mirrors with a high performance multi-layer coating in order to maximize system throughput, hence etendue (AΩ). We have a collaboration with LLNL to transfer this technology. The three refractive elements will be made from optical-grade fused silica. The convex surfaces of the first two lenses, L1 and L2, are 8th order aspheric, where all other surfaces are spherical. The filter is designed to be a zero power meniscus in order to keep the chief ray normal to the surface everywhere across the field of view. This is to ensure uniform band pass performance of multi-layer dielectric filters.

Table 2. Optical Design Summary

Optical Configuration:	3-mirror modified Paul-Baker
Aperture:	8.4 m
FOV:	7.1 square degrees
etendue (AΩ)	266 m^2deg^2
Wavelength Coverage:	300 – 1100 nm
Image Quality (80%EE dia.):	<0.25″ (BVRI), <0.35″ (U) FWHM
Effective Clear Aperture:	7.078 m (6.9 m inc. obscuration)
Final F-Ratio:	1.25
Plate Scale:	50.9 microns/arcsec

Telescope Design

The mount of the LSST telescope, with its fast f/1.25 3-mirror design and internal trapped focus, offers unique design challenges. The requirements for fast "slew and settle" time, tracking accuracy, and tight alignment tolerances drive the design. It must be possible to point the telescope quickly (<5 seconds) and repeatedly to adjacent field locations. Because of its compactness and its design maturity, we have chosen an Alt-Az mount configuration. Two of the conceptual designs being considered are shown in Figure 8.

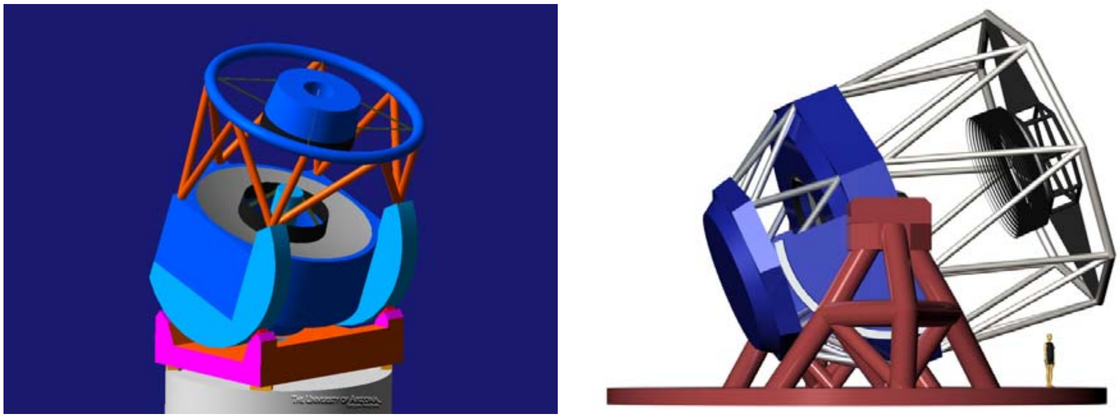


Figure 8. LSST Alt-Az Telescope concepts. At left is the dual "C" ring concept by W. Davison (UA, Steward Observatory). The right panel shows a concept by Claver and Muller (NOAO) based on a Gemini-like fork configuration.

Enclosure Design

The LSST dome performance must be high to follow the agile telescope. Furthermore, the dome will be required to provide the first line of defense against wind buffeting on the large secondary while simultaneously allowing sufficient air flow to minimize internal dome seeing. The wide slit required by the 3° FOV is a departure from current dome designs and must be made compatible with control of wind buffeting. The dome must also have sufficient space to for handling the large mirrors. These design goals while unusual are not perceived as particularly challenging.

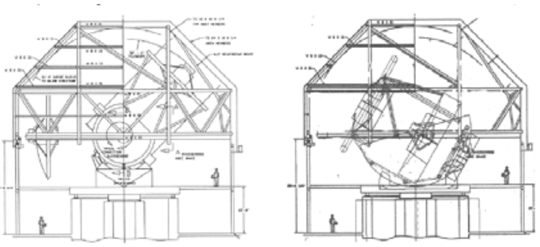


Figure 9. A dome concept showing a comparison between the 8.4-m LSST (right) and one of the 6.5-m Magellan telescopes utilizing a Magellan style dome.

THE CAMERA AND FOCAL PLANE ASSEMBLY

Camera Design

The LSST camera is a wide-field optical (0.35-1 μm) imager designed to provide a 3° FOV with better than 0.2 arcsecond sampling. The image surface is flat and has a diameter of approximately 55-cm. The detector format will be a circular mosaic providing approximately 2.3 Gigapixels per image. The LSST camera will also include a filter mechanism and, if necessary, shuttering capability. The camera is positioned in the middle of the telescope where physical volume is constrained to limit optical vignetting, and heat dissipation must be controlled in order to limit thermal gradients in the optical beam. The camera will be required to produce data of extremely high optical quality with minimal downtime and maintenance.

The camera concept currently under development is shown in Figure 10. The design shows a dewar within a dewar structure. Both dewars are back-filled to near atmospheric pressure with suitable gases. The inner dewar contains the detector array, held at a temperature of –40 C in order to achieve desired detector performance. The refractive element L3 (Figure 7) serves as the window of the inner dewar, while L1 serves as the window for the outer dewar. The outer dewar houses L2, the filters, and filter exchange mechanism, which can accommodate four 60-cm filters. This mechanism uses a novel approach to adapt to the extremely tight space constraints. The filter mechanism can be described as a "flower petal" arrangement, which supports compound translation of the filter as it is moved in and out of the beam.

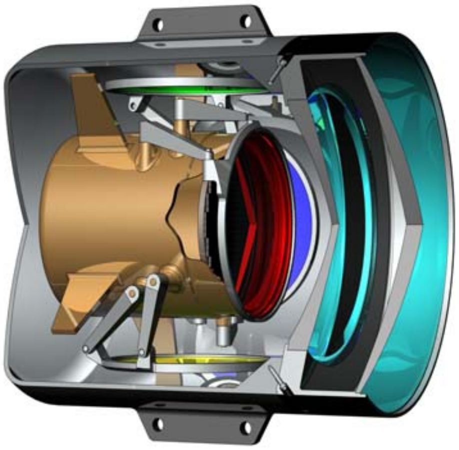


Figure 10. A sectional view of the camera dewar-in-dewar concept. The outer dewar houses the refractive elements for the wide field correction as well as the filter mechanism. The inner dewar holds the focal surface with detectors and interface electronics.

The camera mechanical mount will provide proper support and registration to the telescope and incorporate provisions to actively adjust the camera position and orientation to compensate for alignment variations with telescope elevation. In addition, the camera axial position must be adjustable to optimize focus at different filter wavelengths (the axial position of L2 must be similarly adjustable). Additional camera interfaces include electrical power, thermal cooling, fiber optic and Ethernet connections for control and data interfaces.

Detector Array Concept

Recent advances in CMOS and CCD plus ASIC hybrid imagers can now be applied to this 2.3 Gpixel camera. An array built from a mosaic of 1K or 2K modules is preferred. Parallel multiplexing many discrete modules allows for fast readout, which will be critical for efficiency, as exposure times must be short. The clocking electronics will be integrated with the individual detectors, and there are several attractive options for analog and digital ULSI packaging that minimize the interconnections. Each module will consist of a thick silicon detector for high QE over the full wavelength range from 350 nm to 1050 nm. The LSST's large focal plane and the required short exposure times make the traditional approach of CCD plus mechanical shutter difficult to implement. LLNL has developed a shutter concept for the LSST that would be capable of at least 10^6 exposures, or more than 1 year of LSST operations. However, hybrid CMOS detector arrays with integrated ASIC electronics, originally developed for IR arrays, are now being produced for visible-wavelength applications and would eliminate the need for a mechanical shutter. Work is in progress on both monolithic and hybrid CCD array + readout electronics solutions to our module requirements. Our concept for the focal plane array is shown in Figure 11 and is discussed further in Appendix II.

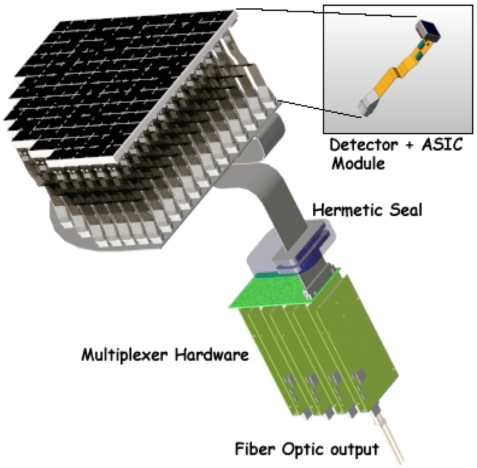


Figure 11. A quarter section of the detector array concept.

LSST DATA SYSTEM

Software is arguably one of the most challenging aspects of LSST. The data management system must process and store more than 6 Tera pixels per night, roughly the same as the whole 2MASS survey. This data rate and volume is unprecedented in astronomy, but we can find several "existence proofs" in the high-energy physics (HEP) community that argue that the LSST data can be handled in an affordable manner. Like LSST, HEP projects acquire massive amounts of data that must be processed (at least partially) in near real time, archived, and made available for offline exploration by the HEP community. The BaBar collaboration database at SLAC is over 800 TB and growing rapidly. Each of the four Large Hadron Collider (LHC) experiments will record over 1 PB of p-p collision data each year: roughly the same data rate as LSST. Even with current computing and storage technology, it is possible to handle LSST data volumes and rates, though not yet with the full real time response we will require. There is every reason to expect that we can learn from the HEP experience and select carefully from the technologies available at LSST first light in order to solve the data volume and rate issues.

In complexity as well, LSST exceeds previous astronomical surveys but by a manageable factor. Over the last decade the astronomy community has developed considerable experience with structuring and managing complex data arising from large surveys. SDSS, 2MASS, DLS, SuperMACHO and others have faced many of the same data complexity issues that LSST will present. LSST's new complexity derives from the extraordinarily broad range of science that will be possible. For the first time, astronomers determining NEO orbits will be sharing data structures with those determining weak lensing parameters and with those classifying variable stars. This will inevitably multiply the complexity of data structures. In what follows, we sketch a possible LSST data system architecture, not as a design proposal, but as a basis for discussing the software issues that we face. We then explore several of the issues that most critically affect the D&D phase of LSST.

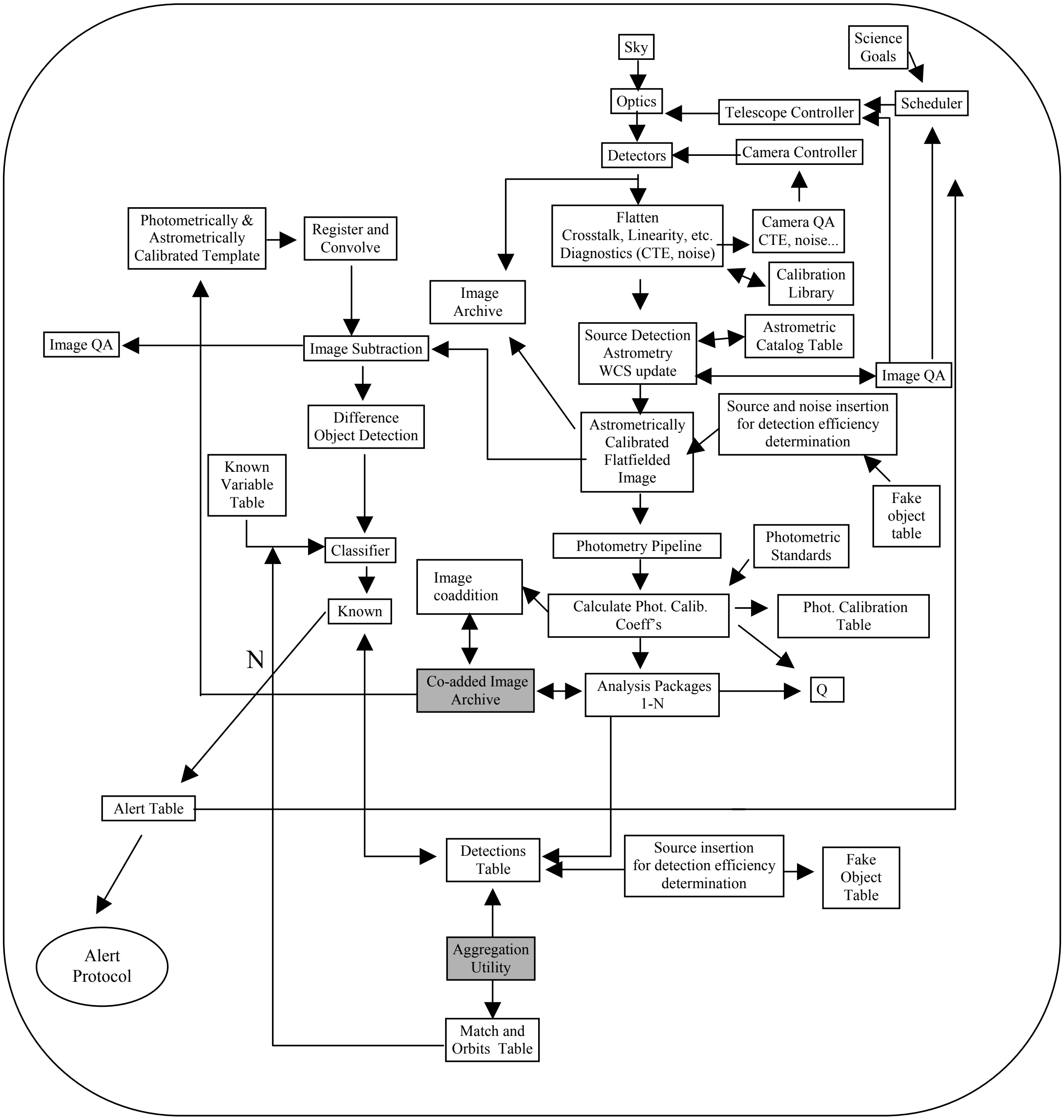


Figure 12. Data flow diagram for the LSST science data.

LSST Data Flow

Based on the preliminary science requirements and the experience gained from recent large surveys, we have generated a baseline data flow diagram (Figure 12). The data management system must move more than 2 Gigapixels of data from the camera into the data analysis system in 1-2 seconds at a rate of up to 5 gigabytes per second. These data must then move through pipelines that remove instrumental signatures, then through analysis pipelines, and into long term storage in about 2 seconds, with a hard upper limit of 10 seconds. The system will also put the analysis products into various databases, make quality assurance data available to the telescope control system in real time, generate prioritized lists of transient astrophysical phenomena by comparison with previous data including the initial multi-color survey, and make this information available to the telescope scheduler and the public in near real time with a latency of less than 30 seconds.

LSST Software Architecture

The LSST data flow requirements suggest a four-tier software architecture:

- A Telescope Control System, which manages the telescope and the camera system.
- A Core Data System (CDS), which processes and stores the camera pixel data stream, provides the infrastructure required by algorithms that access images, and implements the databases that store object data.
- An Image Analysis System (IAS), which further processes basic camera images, derives object information from those images, and detects transient events.
- A Science User System (SUS) that enables scientists and the public to use the archives and catalogs generated by the IAS and (under strictly controlled circumstances) allows access to the facilities of the CDS for further pixel-level processing.

The TCS presents few special challenges compared with previous large telescope and instrumentation projects. Perhaps the most interesting will be learning to control two or more actively-supported mirrors instead of the usual one; the LBT project is faced with the same issues, however, and will have a significant body of experience from which to draw. LSST's cadence puts severe requirements on operational reliability. It will be important to have a software system that monitors all aspects of the LSST operation and can predict, not simply report, failures. Significant progress in this regard has been made with the VLT system, for example.

The CDS accepts the stream of raw pixel data from the camera, archives it along with information about the conditions under which it was collected, and performs the necessary low-level processing to produce images suitable for science: flat fielding, cross-talk elimination, geometry correction, sky subtraction, stitching together images from individual detectors, etc. These steps have all been performed by other large astronomical imaging surveys. Still, LSST will present some special aspects, due to the wide field, optical design, and possible use of CMOS image sensors. These aspects are discussed in Appendix III. The computational requirements are within reach today, although certain potential CMOS implementations could increase the data rate from the camera by a factor of more than 100. At 1000 floating point operations per pixel and 2 Gigapixels (4 bytes) in 2 seconds, the low-level processing requires four teraflops; this can be obtained today using a computer system costing several million dollars. The CDS also provides the data storage infrastructure upon which the IAS and SUS depend. This infrastructure must support archiving of images, storage of catalogs, and tracking of data provenance.

The IAS will encompass the basic LSST science algorithms. It will also generate quality assurance information for the camera and the telescope. The IAS will perform image subtraction, object detection and classification, identification of transient events, detection efficiency determination, and artifact sensitivity determination. It will generate alerts in near real time. Table 3a lists algorithmic developments that will be required during the design and delivery phase. These algorithms are discussed further in Appendix III.

The SUS will be the public interface of LSST and will be used to formulate and process complex queries over the LSST data. The SUS will also support education and public outreach access, which will probably not entail the complexity of science queries but may be demanding in volume.

C.5 DESIGN CHALLENGES, TRADES AND TASKS

The LSST telescope facility, data management, and camera pose several significant technical design challenges. It is our philosophy to focus on the areas of highest risk with early design and development efforts, some of which have already been started. Where possible, we will investigate and build on existing technologies to further mitigate risk. Table 3a summarizes the key trades and design studies that will be undertaken during the D&D phases for data management. Table 3b gives this summary for the telescope, supporting facilities, and camera. In the following sections, we describe the issues and how we plan to address them.

THE TELESCOPE

Optical Design

The LSST baseline optical design is mature. During the D&D phase of the LSST project we will examine this optical design in the context of the scientific requirements. We will evaluate trades to understand the “derivatives” in cost, complexity, and feasibility for critical performance requirements (*e.g.* field of view, image quality, tolerance sensitivity, etc.).

We will re-evaluate the current baseline design’s field of view (FOV). While we expect to maintain a FOV of at least 3° (~7 sq. deg.), we wish to examine the trades involved achieving slightly larger coverage in each exposure. It is critical that we settle on the FOV quickly because it significantly impacts most other aspects of the LSST system.

We will also conduct a detailed perturbation analysis of the baseline optical design. The design and development of the LSST will require us to determine the optimum set of variables for initial alignment and its maintenance. We plan to conduct a rigorous analysis of all the degrees of freedom in the LSST optical system using singular-valued decomposition on the matrix of influence functions in the wavefront from each of the degrees of freedom. Through this analysis we will determine the optimal set of controlled variables to be used as alignment and surface compensators, their maximum range, and the precision of control required. This analysis will also determine the tolerances on the non-compensated degrees of freedom that will fold back into the system design and performance estimates.

Once the optimum set of compensators is determined, we will conduct a full simulation. This simulation will include effects from noise from the wavefront and laser metrology systems, actuators, and wind buffeting. It will also include interaction from the telescope mount servo systems.

Physical Optics

The most challenging optic in the LSST telescope design is the 3.5-m convex secondary mirror. The two key issues are: 1) fabricating the mirror substrate and 2) polishing and testing the aspheric surface. We will explore and study various technologies for fabricating the secondary mirror substrate including machined light-weight, fused light-weight, meniscus, and thin phase sheet. Once a technology for the secondary is chosen we will develop and test where necessary an integrated design for the secondary mirror and support structure.

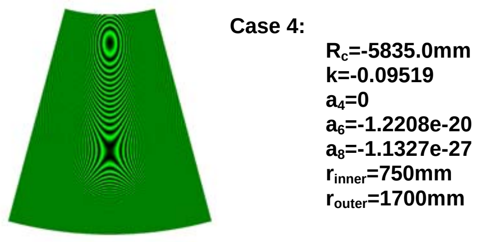


Figure 13. A simulated PSDI interferogram of a 1/12 sector of the LSST secondary

We are considering two methods of aspheric metrology for testing the secondary. One approach is mechanically based swing-arm profilometry; a probe touches the surface (optically or physically) to determine mirror surface coordinates at a collection of points. The second approach is optical interferometry using a technique developed by LLNL called PSDI (Figure 13). We will explore these methods or a combination of the two as a means to test the convex secondary during its polishing stages. Figuring of the secondary mirror will be done using the stressed lap techniques developed at the University of Arizona's Mirror Lab.

In our current design the LSST will use spun cast borosilicate mirrors for both the primary and tertiary. Telescopes that use borosilicate mirrors make no distinction between mechanical surface deformation and those caused by CTE effects generated by thermal imbalances. In particular the thermal sensitivity of borosilicate makes these mirrors particularly sensitive to changes in radius. We will evaluate the feasibility of controlling the wavefront errors, in particular focus shifts, caused by mechanical and thermal instabilities. If it proves that there is a control problem, we will develop an alternate implementation of the tertiary using low expansion glass. Thermal management is an important activity.

The effective throughput of the LSST depends on the cube of the coating efficiency on the three mirrors. Because of this it is desirable to use a multi-layer enhanced coating for these optics. We will explore the feasibility of applying multi-layer enhanced coatings (*e.g.* LLNL's Wideband Durable Silver Coating) to large optics and the issues for long-term use in the LSST.

All of the mirrors in the LSST will be supported by active systems to compensate for mechanical flexure and thermal irregularities in the glass substrate and in the telescope structure. We will develop the optimum actuator spacing and substrate thickness on both of the upward looking primary and tertiary mirrors. The primary mirror support system will require some additional engineering study with regard to support issues because its large 4.4-m central hole makes it more susceptible to lateral deformation than previous 8-m mirrors. We will conduct studies using detailed finite element and modal analysis on structural models of each mirror to determine the optimum actuator locations, substrate thickness, and light-weighting geometry.

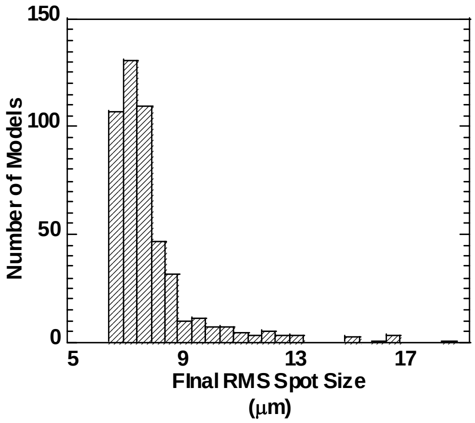


Figure 14. The distribution of image quality after 5 successive solutions based on wavefront analysis of the LSST optical system as it has been perturbed in 48 degrees of freedom are shown

The large lenses in the camera will require careful design of their mounting systems as well. Finite element analysis of these lenses shows that the self-induced bending from gravity is negligible and has essentially no impact on the LSST optical performance. Thus the chief source of deformation in the camera lenses will be from their cells and any coupling of these to the camera body deflections. We will develop and test designs for lens cells that keep mechanical flexure in the camera isolated from the lenses and maintain proper spacing and alignment of the camera optics.

Active Optics and Alignment System

The fast optical system of the LSST places stringent requirements on alignment and surface tolerances and raises two questions: First, can the optical system be assembled to the level of precision needed to deliver the required image quality? Second, can the assembled optical system be maintained in such a way as to meet the image quality requirements?

The alignment and surface control information will be derived from two sources of metrology: commercially available laser distance-measuring interferometery and in-situ wavefront sensing from the camera focal plane. The two systems provide both complementary and redundant information. The laser metrology system will be used during initial and post-maintenance assembly to place the optical system within the capture range of the wavefront least-squares solutions. During routine operation the laser system will provide a redundant check on the wavefront solutions for the rigid body positions of the camera and the three large mirrors. The D&D effort will focus on demonstrating the feasibility of this concept through detailed numerical modeling.

The fine alignment and surface solutions will be determined from a number of wavefront measurements made in multiple locations through out the focal plane. The exact number that is required will be determined during the D&D effort. We are currently exploring placing adjacent pairs of small detectors, one in front of, and the other behind, focus in the focal plane array to obtain wavefront curvature solutions. With 10-30 such detector pairs, occupying less than 1% of the total imaging area, a sufficient subset will have valid solutions at any telescope pointing. The valid wavefront information is then fed to a "reconstructor" that disentangles surface errors from alignment errors and passes the information on to the control system for implementation.

Telescope and Mount Configuration

The most demanding requirement for the LSST telescope and mount is the rapid cadence of observations. The requirement to repoint the telescope to a new position 1 FOV away (3˚), settle, and track in 5 seconds or less will drive the design of the telescope, mount, and servo systems. The other demanding requirement for the telescope is maintaining the critical alignment of the fast reflecting optics to several tens of microns over 10-m length scales.

For a variety of reasons we believe that the equatorial mount configuration is neither feasible under this requirement nor cost effective. During the D&D phase we will consider two basic alt-az mount configurations: 1) a dual "C" ring concept and 2) a fork style configuration. Second-generation design and FEA models will be developed in order to determine how well the designs meet the LSST requirements. Trade-offs and alternatives will be evaluated in terms of meeting the mount requirements, cost, complexity, and ease of maintenance. The principal issues for each of the telescope mount concepts, given the rapid cadence, are the drive and mirror support servos. These will be addressed separately for each mount concept. First, we will study existing servo systems on functioning telescopes and use these to establish an analytic scaling to what would be required for the LSST. This information will next be imported into a theoretical model of the LSST servo system and be optimized to meet the design requirements. Second, we will study the influence of the fast cadence on the settling and stability of the mirror support systems.

Sensitivity analysis of the baseline design shows that uncompensated alignment errors of the 3-mirror system must be kept within several tens of microns, where the defocus tolerance of the camera-telescope system is ±15 microns at f/1.25. The critical issue here is whether the OSS can be made sufficiently stiff while controlling the mirror and camera loads in order not to place excessive demands on the mount servos. We will also determine if alignment can be accommodated within the mirror cells or whether a smart active structure is necessary. We will develop and evaluate truss designs to determine the feasibility of maintaining the tight optical alignment tolerances while meeting the LSST cadence requirement.

Enclosure Design

The dome must be as agile as the telescope while at the same time it must provide some protection against wind loading on the large secondary. Agility leads towards smaller more compact design like that used for the Magellan telescopes or a co-rotating design similar to the MMT. However, the desire to shield the telescope and also to provide room for handling the optics leads to larger dome sizes. During the D&D phase we will investigate the three enclosure styles. Ultimately the enclosure performance will be incorporated into the full system model to determine its impact on observing efficiency and hence on the LSST science. The enclosure design will also have to accommodate site-specific issues.

Site Selection

The first site selection task is to flow the science requirements down to a set of requirements for the site. From these requirements we will generate a list of potential sites. LSST plans to make use of an existing site in order to hold down costs and because we believe that we can identify a developed site that meets the science requirements for this project. Factors to be considered in evaluating candidate sites include: 1) the fraction of clear nights and the weather patterns over time scales from a week to the El Nino cycle--weather patterns will be convolved with cadence requirements in order to evaluate the science throughput; 2) the seeing and the effect of ground layer turbulence on image quality--it is likely that in order to achieve high resonant frequencies, LSST will be built close to the ground; 3) sky brightness during the likely operational lifetime of a decade; 4) surface winds and wind directions relative to likely observing patterns--it will be necessary to minimize the effects of wind on the secondary; and 5) soil conditions, again with the goal of maximizing the resonant frequency. Since LSST is not being designed for the thermal IR and cannot make use of adaptive optics, precipitable water vapor, IR emissivity, and tropospheric winds will not be relevant. Additional considerations will include environmental regulations and the time scale for obtaining permits to initiate construction; the fee for access to the site, if any; the cost of construction and operation; and the available mechanisms for moving large quantities of data from the mountain to a data center that can be accessed by the community.

Potential sites include Chile, the southwestern US, northern Baja Mexico, the Canaries, and Hawaii. The strategy for evaluating sites will be to: 1) establish the science requirements with appropriate weighting factors; 2) compile existing data bases, both from remote sensing measurements by satellites and from existing observatory records; and 3) model airflow over sites that make the initial cut. Potential sites already have a body of site data for us to use. Those sites that meet a significant fraction of the requirements will be further evaluated with additional data as needed. The second phase of the site selection process will be aimed at reducing the remaining potential sites to a single recommended site with ranked alternatives. The LSST project is forming a site selection committee from its community of users. This committee is being supplied with the data and charged to make a final recommendation and ranked order of alternates. The site selection process will proceed rapidly, and is involving the science working group and the External Review Board (see management section). The results from this committee will be submitted to the LSST Board for approval and incorporated into preparations for the overall CoDR. Following the CoDR we will contract with an A/E firm for preliminary design of the site and facilities.

Systems Performance Modeling

Since the design of the previous generation of large telescopes (*e.g.* Gemini, Keck), there have been significant improvements in the capabilities of proven analysis tools and the development of newer, more flexible tools. Effective use of modern computer modeling techniques significantly increases confidence in designs and lowers risk during construction. The LSST team will undertake the development of a comprehensive set of performance models including an integrated end-to-end optical/mechanical/thermal model, as well as suitably detailed engineering models of the major elements of the system. All aspects of the design that could affect the quality of science results will be incorporated into these models. The models will serve as tools for gauging the adequacy of the system design as it develops, providing guidance for optimizing design choices, and informing the trade studies. The models will provide a quantitative basis for evaluating the preliminary design, as well as a means for judging the impact of changes during construction.

THE CAMERA AND FOCAL PLANE ASSEMBLY

Detector Technology

The 2.3 Gpixel imager, a mosaic of over 500 modules, is on the critical path. The LSST camera is one of the largest challenges of the project. The full requirements for the LSST detector are shown in Appendix II. There are currently no detectors available from a single vendor that meet all these specifications. An ongoing NSF supported effort will evaluate state-of-the-art technologies including thick high-resistivity silicon back-illuminated CCDs and hybrid silicon photodiode-CMOS array detectors to develop a suitable candidate detector for the FPA. The Independent Test Lab (IDTL) will test the CMOS modules and the U. of Arizona test lab will test the CCDs During the D&D phase, we propose to design the focal plane and complete the tests of a cost-effective imager module, whether based on CCD or CMOS technology. We will undertake the engineering for the focal plane assembly, including module parallelism and flatness tests. We will also design the necessary testing and quality assurance programs that will be crucial during the imager module delivery and acceptance phase.About 100 microns of silicon is required to meet the target specification of 40% quantum efficiency at 1000 nm wavelength. Even with high resistivity material, cooling to -40 °C will be required to suppress dark current noise.

CCDs: Large-format, back-illuminated CCDs on high resistivity silicon can be made thick enough to achieve the high NIR QE (S. Holland, 2003). However, this requires special processing. CCD development will require careful study to extend the low read noise characteristic of these detectors up to high readout rates, typically an order of magnitude faster than detectors in use today in scientific applications. Along with fast read rates the CCD power dissipation will increase. Thermal management will be critical. Each CCD module would consist of an array of small CCDs, separately addressable, with antiblooming. Use of CCDs will require mechanical shutter in the camera. CCD development will require careful study to extend the low read noise characteristic of these detectors up to high readout rates, typically an order of magnitude faster than detectors in use today in scientific applications.

CMOS: The other candidate detector type is a hybrid detector consisting of a thick, high-resistivity silicon photodiode array bump-bonded to a CMOS readout IC (ROIC). Monolithic CMOS active pixel sensors are unsuited to the LSST because they have low fill factor (typically < 40%), cannot be made on thick high resistivity material, and their performance based on standard state-of-the art CMOS technology is not at the level required for scientific applications. For hybrid CMOS detectors a shutter is not required. Also readout speed and antiblooming requirements are more easily met. All three aspects, the photodiode array, the CMOS readout, and the bump bonding, pose potential challenges if the required performance is to be achieved. Sensors with small tiling gap and low dark current require special guard ring structures. Read-noise of 5 electrons at high readout rate will require a fully noise-optimized ROIC design. In addition, the ROIC should perform as many control and interface operations as possible to minimize the signal interconnects flowing off the focal plane.

The D&D effort will focus on how to make the most effective use of commercially available technology while utilizing the expertise available in collaborating research institutions. The principal goals will be to arrive at: 1) a prototype device, which could be produced by a commercial vendor in the required quantity to cover the very large focal plane at a reasonable cost; and 2) an FPA design that could be maintained with minimal telescope down time when the replacement of nonfunctioning sensors becomes necessary. We will undertake a detailed evaluation of device response, e.g., quantum efficiency profile over the pixel area and point spread function *vs* wavelength, noise performance, the functioning of the data readout, photometric performance, and the mechanical parameters relevant to the assembly of the focal plane.

We emphasize that the activities covered here are a follow-on and in addition to an existing NSF ATI grant to study existing technologies for both hybrid CMOS and CCD leading to a down-select to single CMOS and CCD vendors. That team is already working on technology evaluation and testing. Some of the activities described here will be supplied in-kind from participating DOE labs, specifically ASIC design, some critical functionality tests, FPA mechanics and thermal design, and prototype module metrology. Brookhaven National Labs, along with the evaluation/test team, will play a lead role in the LSST focal plane array development. We will evove to a focus on one technology.

Camera Electronic Design

Once a vendor has been selected to produce the imager hybrids, the remaining interface electronics will be designed. This requires extensive engineering that goes beyond the initial testing and selection under the current NSF grant. These interface components include the readout IC (unless supplied by the vendor), backplane, and fiber-optic interface to the data acquisition and control system. The critical issue for the electronics development is to retain the fast readout speed of the imager without degrading the image quality and with minimum power dissipation inside the dewar. A test stand will be constructed to perform detailed evaluation of vendor modules. The test stand will provide an environmental enclosure to maintain imager hybrid modules at the appropriate temperature, supply all optical and electrical inputs, and receive and process (via a combination of software and hardware) all output signals.

The CMOS ROIC design task will include technology selection, characterization of the transistor performance at low temperature, simulation of the analog and digital blocks, power and clock trees, bias and interface circuits, ESD protection, and layout and verification. It is expected that between three and six iterations of the ROIC will be necessary to achieve the required performance. Backplane design will consist of the electrical design of power conditioning, control signal distribution, and data multiplexing blocks, including hardware and firmware; mechanical interface to the camera and alignment system; and development of assembly, test, and repair procedures. For the interface to the data acquisition system, a study of high speed data transmission formats will be required to optimize throughput while maintaining signal integrity.

Camera Opto-Mechanical Design

The baseline opto-mechanical design for the camera will be refined and developed during the D&D phase. Specific issues for investigation include gravitational distortions as a function of alt orientation, the thermal response and control of the focal plane, accessibility concerns for potential replacement of individual sensors and electronic components, optimal cabling assemblies, requirements for the telescope/camera interface, and fabrication and testing of the lenses and filters.

A complete finite element model of the camera design will be developed early in the program with its output coupled to an optical ray trace code. This will enable us to perform end-to-end simulations of the image quality across the field as a function of various environmental effects. Initially, this will be used to establish an engineering tolerance matrix for the various subcomponents of the system. The alignment and assembly of the focal plane will require special consideration. Absolute positional tolerances will be at the <5 µm level over the 55-cm diameter of the field. Achieving such positional alignment is likely to require a custom fixturing facility with interferometric feedback. A design for such facility will be developed and prototyped early in the program. Appropriate designs for the camera mechanisms will be developed and tested. Issues include lifetime requirements, responses to thermal and mechanical stresses, and requirements on control system software. The fabrication of the three refractive lenses in the camera will be studied with candidate vendors, along with the requirements for verification and testing.

Extremely Large Filters

The silica-substrate, dichroic filters in the LSST camera are 68 cm in diameter. All the filters are meniscus with equal radii of curvature of 3.3 m. As part of the optical balancing in the LSST optical design the filter thickness is a function of spectral band. Dichroic filters consist of thin-film metallic oxides and nitrides with absorbing layers possible to eliminate harmonics of the pass band. Typically, 20 or more layers are required. Coating methods include magnetron or ion sputter deposition, thermal evaporation, and electron beam deposition. Numerous commercial suppliers provide dichroic filters using all of these approaches. The challenge for the LSST filters will be to *uniformly* coat the multilayer stack onto the large, curved substrate so the spectral band response is uniform across the entire FOV. A sensitivity analysis will be performed on the specific coating structure to determine the uniformity specifications for the LSST filters.

OBSERVATORY OPERATIONS

Observatory operations must be optimized to produce the suite of scientific results proposed in a defined and limited period of performance. Operations planning requires definition of a staffing model adequate to assure effective on-sky time, very low down-time, and high data pipeline throughput with negligible losses. It also requires the development of an efficient observation scheduler, based on extensive simulations aimed at maximizing the broad range of science, and a workable model for data access for a broad range of users. Completion of commissioning should find an observatory ready to acquire data at full operational efficiency. To accomplish that ambitious goal in a brief commissioning period requires an extremely thorough plan for testing each subsystem and optimizing overall performance. The task for the D&D phase is to develop a prototype scheduler and estimate the scope of commissioning activities with enough precision to assure that adequate staffing and time are requested in the final proposal.

Just as the image quality error budget flows down to requirements on individual subsystems, so will a limit on time lost to inefficiency or failure drive performance reliability limits on system components. One D&D task is therefore to determine the best approach to life cycle estimation for each critical component and devise a strategy for sparing. A maintenance model must also be developed for those components for which slightly degraded performance can be restored routinely to near their peak. The maintenance and upgrade schedule is a significant input into the observation planning, and the size and skill mix of the operations staff set cost levels for commissioning and science operations. The combination of staffing model and systems maintenance model will provide a first cut at the annual operating expenses, an essential component for system-level trades and costing of the full construction proposal. See Table 3b for a summary of the telescope, camera, and other hardware tasks.

LSST SOFTWARE AND DATA MANAGEMENT ISSUES

Taking the data processing architecture sketched in the preceding section as a point of reference, we now present the main software issues, suggest some possible solutions, and present our plan for the D&D phase of the project. The discussion centers on the following questions: what are the challenges; what tools and experience can we bring to bear on them; what are the major uncertainties, and what should be the development plan.

Challenges

In addressing data management, the project must address a fundamental issue: how much is enough? What derived quantities will the project determine and publish and what will it leave to others to determine? While the project must provide flexible, easily-used and easily-understood software to enable community use of the data, how much computer power should it provide and to what extent can it rely on individual groups and other projects such as NVO? We will engage both the astronomical and education/outreach communities in a dialog to determine how to optimize the use of LSST data. LSST faces the challenge of providing real time alerts of transient phenomena, deep image stacks, a database containing the time history of the characteristics of billions of astronomical objects, and stunning pictures. The LSST database will eventually comprise one of the largest data sets of the international Virtual Observatory (VO), particularly in the context of data fusion with x-ray, gamma ray, radio, and gravity wave data sets. The National Center for Supercomputer Applications (NCSA) is partnering with us in this database and data server area. Our team includes some of the major participants in the US National Virtual Observatory (NVO) initiative, and we will work with the NVO to ensure that LSST data and meta-data conform to VO standards and to optimize VO access to LSST data. We will specify functional subunits of the database and data and develop plans to distribute the full LSST data and the database and subunits to multiple sites.

Object Catalog Characteristics

Because of the complexity of providing services to so many different user communities, we feel that the nature of the object catalogs deserves special attention.

LSST science algorithms will work mostly with catalogs of objects rather than directly with image data. Based on past trends, public demand may also be mostly for object catalogs; for every request for image data from Macho or SDSS, there were more than 100 for catalog data. However, the LSST@Home project discussed in the EPO section could change that.

There are several difficulties associated with defining these catalogs and producing them from the image data. Some arise from knowing what, and how much, to catalog. There are many possible parameters for describing an individual object. At a minimum, we need the spatial coordinates, the epoch, the passband, shape parameters, flux measure(s), and information about the observation that produced the data. But some parameters have meaning only in the context of the particular method used to detect the object. For example a PSF-fitting algorithm will associate PSF parameters with each object. An image-subtraction algorithm, while also detecting objects, will produce different information and may be more or less useful than PSF fitting for a particular purpose. For extended objects, different shape parameters must be included in the catalog. The variety of shape description techniques is large, including principal component analysis, wavelets, etc. Experience has shown that inclusion of these parameters in the object catalogs is crucial for further stages of analysis.

Most science goals will require the association of all the multiple catalog entries that refer to a single object. For example, an object color can be assigned only by using multiple exposures taken with different filters. Science that relates to time variability requires association of detections taken over a span of times. Moving objects such as NEOs must be associated over both space and time. In general, association algorithms can produce only probabilistic results. Limited spatial resolution and changing image quality will result in significant uncertainty in association at the faint end of the object luminosity distribution. It will be at the database level where this disambiguation of detections occurs, and it will rely critically on the cataloged characteristics.

This multiplicity of analysis methods and diversity of characterization parameters will require more than a single LSST catalog. Largely due to the probabilistic nature of object associations and the related issue of deblending under different conditions, the logical structure of LSST catalogs is likely to be complex.

The dependence of catalog contents on the details of the object detection algorithms, especially in light of the clearly evolving nature of the existing algorithms, indicates that catalog definitions will change during the life of LSST. This is especially true for algorithms that utilize multiple images simultaneously for object detection.

Since catalog production consumes large amounts of CPU, catalog data will lag image data by variable amounts. Further, recently defined catalog types may not yet have been produced for older image data. Management of catalog production and communicating catalog state to science algorithms are both significant tasks. These tasks include, for example: 1) data provenance--what algorithms have been used, on exactly what data, to produce a particular item in the database? and 2) re-creation of identified datasets (e.g. those used to produce published papers), and associated processing algorithms. Since these object catalogs will also be very large, there is clearly a challenge in efficiently connecting a science algorithm to the catalog data it needs and in integrating new catalogs into the system.

Relevant Tools and Experience

The LSST community has four broad areas of experience from which it can draw in planning the LSST data system: large area time-domain surveys such as Macho, Super Macho, and DLS; large area imaging surveys such as SDSS and 2MASS; NCSA massive computation missions, and HEP experiments such as BaBar and those using the LHC. Astronomy and high energy physics have experience that bears on LSST in different, largely complementary, ways. The astronomy community brings to the table a deep understanding of the nature of the data we will be collecting and of the science that we wish to do with it. It has extensive experience with the algorithms that will be required to produce various types of science data from raw imager data and at least educated guesses as to how these algorithms will evolve in the future. It also has nontrivial experience with managing large astronomical datasets, despite the largest being only about 0.1% of LSST in size. A particularly important tool for LSST data system development will be the execution of precursor experiments such as SuperMacho, Essence, and the Deep Lens Survey. By collaborating closely with the development of the data systems for these projects, we will be actively prototyping the LSST system. Finally, astronomy has a culture that values, and succeeds at, accomplishing projects cost effectively.

The High Energy Physics community has already produced successful data systems that handle data rates and volumes comparable to LSST, with database designs that allow flexible reprocessing of data in multiple catalogs. The members of this community have extensive experience with careful, automated monitoring of data system performance and integrity. With a longer association with truly large datasets, they have experience using high performance computing technologies such as the GRID in data exploration and archiving. HEP has developed a successful planning process for software development and employed a variety of tools such as flexible software frameworks to ease development and the use of data challenges to assess the state of the data path and to drive its development. We must bear in mind, however, that HEP applications access their data with a very different pattern than we expect for LSST. While HEP applications are characterized by large granularity of data access, LSST will have the majority of accesses at individual object level. And where HEP applications tend to make a few major passes over their data, LSST will have a much broader distribution, with many small scale passes as well as fewer large ones.

Major Uncertainties

LSST planning must take account of the state of technology that will exist when data acquisition begins in approximately 2011. Some aspects, such as CPU speed and disk capacities, may be estimated with confidence. One area of concern is disk I/O bandwidth. Other aspects are more uncertain. It is not clear what network bandwidth will be available from the telescope to the outside world. We cannot confidently predict how developed or useful GRID computing capabilities will be. Most importantly, we are uncertain as to the capabilities of database systems that will be available at first light. The *achievability* of LSST does not depend on how these characteristics evolve. Many aspects of LSST's implementation, and the nature of the capabilities offered to users, however, will be dependent upon them. To a significant degree NCSA's role in the LSST collaboration will center on these problems. We focus here on database issues.

Database Systems

The sheer volume of LSST data requires a sophisticated data management system. We will need to access the data with object granularity, so simple file tracking and persistent store is not adequate. Data access must be performed very efficiently, using indices and in parallel. For acceptable IO speeds the system will need to run several hundreds if not thousands of disks in parallel and maintain good load balancing. Since we want to deploy inexpensive storage, we need fault tolerant algorithms for the data storage. Similar systems are in use today at the file system level (e.g. Google), but databases also offer many of these features.

We will investigate whether to adopt a commercial database, a parallel file system, or a combination of both (parts of the data are stored in files, but tracked by a database). At present the choice is not obvious: given the vagaries of database optimizers it can be faster to sweep through a dataset stored as a set of files than to process the corresponding query. The ease of use argument is also not compelling – despite the availability of fourth-generation computer languages, many scientists still prefer to use C or FORTRAN, and do not find their lower level of abstraction a significant handicap. We also need to investigate the costs and benefits of open source vs. commercial databases. In recent years, the momentum in database research has increasingly shifted to the few large commercial vendors (Stonebreaker 2002). At the same time open source databases like MySQL have built a customer base in the millions but offer little in terms of support or robustness. There are a variety of database features that need to be evaluated for the management of Petabyte size data. These range from support for astronomical datatypes to software and hardware price and performance and are discussed in detail in Appendix III. If we choose not to buy a database, then we have to provide alternative implementations of data loading, organization, indexing, data query, security and data management (reorganization, recovery). We will assess these alternatives in the D&D phase.

Data Management Development Plan

We propose a series of design and development activities for the three year funding period:

- Begin the staffing of a DP team for the LSST project, inheriting knowledge from precursor surveys.
- Determine the overall scope of the LSST project along the "sky-to-publication continuum." This question is primarily a DP one: where does LSST end and VO begin? LSST QA and DA teams will certainly supply at least one key science result.
- Determine use cases for the system. Who are our customers? What are their requirements and what are their capabilities? This will involve considerable interaction with the SAC, which will already be organized by the time this proposal is funded.
- Develop a software architecture in support of LSST Investigate architectures successfully used in similar projects such as GAUDI developed at CERN or the Alma Common Software developed at ESO and compare with lighter systems such as a dependency driven scheduler, e.g. DAGMan scheduling Condor. Investigate database engine technology. The software architecture mediates between the database and the science user – what requirements are there on the database engine itself? Identify and prototype critical aspects of architecture to determine scalability, ease of use, etc. Prototype a pipeline; for example, reanalyze DLS and MACHO using the software framework. Develop metacatalog (the "catalog catalog" or registry) infrastructure concept for managing a multi-catalog, and multi-generation multi-catalog, environment.
- Assess the state of critical algorithms such as image subtraction, galaxy classification, moving object linkage, and start R&D projects to solve identified problems.
- Start open source project. Enlist developers from the community (attracting industry and some HEP experience) Get prototype architectures into use in current surveys for in-use user feedback
- Establish a series of successively more complex and realistic "data challenges" as a part of the design and development process, using previous survey data and simulated data. Use data challenges (first-level in terms of quantity) as part of the design process. Data Challenges will take the forms of initial processing of raw pixels to images, initial processing of images to various forms of catalog, and re-computation of catalog data to test metacatalog infrastructure

Finally, at the conclusion of the design and development phase:

- Develop Conceptual Design for data system and review
- Develop a management plan and schedule for the construction phase
- Develop and cost an implementation plan for the construction phase

Table 3a. Key data management tasks to be performed in D&D phase.

Topic	Tasks	Key Issues	R
SCIENTIFIC ANALYSIS			
Difference Image Reconstruction	Algorithms for minimizing errors	Fraction of bad subtractions; handling image defects; photometric accuracy	1
Object Aggregation / Moving object linkage / Data model	Catalog based massive correlation vs optimal orbit eigenvector	Efficiency of linkage under different seeing; false link rate reduction; optimal data structure	1
Automated Quality Assessment	Photometric consistency and continuous synthetic injection	Automated instrumental monitoring & feedback; pipeline interactions; response of analysis to unexpected features; separation of weather and system problems, data integrity	1
Automated Object Classification	Accurate classify algorithms	False classification rate; pollution of DB; GENIE (trainable auto SW) and/or Bayesian, choice of sufficient statistics	1
Optimal image co-addition	Various algorithms; regular & WL stacks	Optimal reconstruction; PSF rounding; photometry preservation; error minimization	2
Astrometric Calibration	Algorithms generating new dense grid	Optimal data strategy; SW for sewing overlap fields; magnitude range of existing standards	2
Photometric Calibration	Existing standard systems vs. self-defined system	Filter transformations; limited # of standards; magnitude range; sky distribution & observing cadence	2
PSF determination	Various algorithms	Robust automatic characterization of PSF(x,y) even in moderately crowded fields	2
Object Measurement	Optimal algorithms for shape, photometry, & classification	systematic errors; distribution of errors (population of tails); variable blending; measured object parameters; shear error	2
INFRASTRUCTURE			
Data Product Definition and integration with NVO	Key sci & standard (static) products & user defined tasks	Data types; data products; metadata standards, supported queries; user tools; science user interfaces, public access	1
Architecture / Framework	Evaluate alternatives (from high energy physics, astronomy…)	Latency; resource contention; science module immunity; scalability; support of science-level debugging; custom design?	1
Database	Generate requirements and survey current DB	Scalability; relational and object strengths; index pyramid	1
Data transport (mountain to data center)	Network infrastructure and mountain pipeline	Latency; data security; redundancy; bandwidth; QA; QoS; shipping media	2
Data storage, Data Center	LSST specific and/or supercomputer center (e.g., SDSC/SRB)	Range of uses; usage tree; raw data access models; maturity of GRID and related infrastructure	3

Key Trades and Design Studies

Table 3b. Key telescope & camera design and trade studies to be performed in D&D phase.

Topic	Tasks/Trades	Key Issues	R
Optical Design	Field of View – 3-4 degrees	Sky coverage rate, image quality, filter size focal plane area.	1
Detector Technology	Hybrid CMOS vs. CCD	Availability cost, necessity for a shutter with CCDs, readout mode flexibility.	1
Secondary mirror metrology	Methods	Enable testing of convex secondary, mix of profilometry and interferometry.	1
Active Optics / Alignment	Degrees of freedom	Optimum compensators for misalignment and surface errors, metrology and error sensing	1
Mount Configuration	C-ring vs. Fork alt-az	Slew speed, settle time, cost, complexity serviceability.	1
Array electronics	On chip vs off chip ASIC	Availability, cost, complexity, power and heat management, connectivity, signal integrity	2
Secondary mirror technology	Structured light weight vs. thin phase sheet	Total weight of assembly, coupling to slew & settle performance, surface figure resistance to wind buffeting.	2
Mirror coatings	Aluminum vs multi-layer	System optical throughput, durability, maintenance, feasibility, facilities.	2
Optical support structure	Intrinsically stiff – “dumb” vs. active – “smart”	Optical alignment, wind response, cost, complexity, total weight.	2
Guiding/Tracking	Open vs. Closed loop	Pointing accuracy, available sky, mount requirements, cost, complexity, observing overhead.	2
Filter exchange mechanism	Internal vs. External	Number of filters, time to exchange, failure risks.	2
Site selection	Northern vs. Southern hemisphere	Natural seeing, weather patterns, infrastructure, science drivers.	2
Tertiary mirror technology	Borosilicate vs. Low expansion	Control over system optical performance with two borosilicate mirror, total weight, slew-settle performance.	3
Laser metrology	Commercial vs. Custom	Precision and accuracy in telescope environment, integration with alignment plan	3
Enclosure	Dome vs. Co-rotating	Dynamic agility, coupling to telescope mount, wind protection, air flushing, maintenance support	3

C.6 EDUCATION AND PUBLIC OUTREACH PROGRAM

LSST will create the first true celestial cinematography – a revolution in public access to the changing universe. To prepare for this opportunity for exploration, tools and displays will be developed using current deep sky multi-color imaging. The Education and Public Outreach plan for the D&D phase of the LSST project builds on the strengths of precursor LSST data, the project's planned science investigations and public access, and previous efforts to use astronomical data sets for inquiry-driven outreach. LSST precursor data will be used in teacher-scientist partnerships, student investigations, and projects emphasizing the public use, appreciation, and analysis of the data.

Partners: Our major partners in the proposed LSST outreach effort bring proven educational strengths to the project. **Steward Observatory:** enormously successful *Astronomy Camps*; cognitive science-based Conceptual Astronomy and Physics Education Research (CAPER) Group; and new java-based libraries of astronomy education tools, course management systems, and information delivery. **American Museum of Natural History's Hayden Planetarium:** expertise in using data-driven media in its planetarium to reach very large numbers of the general public, as well as a team of outreach astronomers investigating data tools for public access. **University of Washington:** Project Astro, and their distribution of Sloan Digital Sky Survey data sets in accessible formats. **NOAO:** research-based science education (national Teacher Leaders in Research Based Science Education program for secondary teachers), the *Astronomy Village* projects), and the *Astronomy Education Review*.

Plan: Our plan is centered on two areas: 1) Rapid distribution of data for informal education learning environments; and 2) Mentored student-research. The use of LSST precursor data in an informal museum or science center setting represents an ideal opportunity to expose large numbers of people to the magnificence of the vast LSST data set. However, the large amount of data will require new approaches to scientific visualization and display, a specialty of the Hayden Planetarium. Hayden's team of astronomers, scientific visualization experts, and programmers will adapt the key features of the Deep Lens Survey and eventually LSST data sets for presentation in planetarium theaters, display walls and large screen environments including their AstroBulletin exhibit and web. NOAO will work to adapt these programs and images into other smaller science centers such as the Kitt Peak Visitor Center and will develop techniques for creating images and posters suitable for widespread distribution. Hayden and NOAO will also explore the use of electronic paper ("e-paper" or "e-ink") for producing large-scale, changeable displays of LSST data and for highlighting changes in the sky detected by LSST. A parallel effort to involve the public in LSST data will be the development of a distributed computational program modeled on the SETI@home program, which would parcel out LSST data to individual users for automated analysis. One project is the use of massive parallel processing by the public to search for faint trans-Neptunian objects, which will be the focus of a design study.

LSST precursor data can become a key part of projects emphasizing student-centered research in the classroom, similar to the nationally recognized TLRBSE at NOAO and the Hands On Universe (HOU) Project at Lawrence Hall of Science. However, these people-intensive program designs are not scalable for the LSST EPO program; we will build on the TLRBSE experience to create new strategies to deliver data and background training on using it for student-driven research projects to a large and geographically distributed set of mentor teachers in a highly leveraged and cost-efficient manner. The LSST education program will design and develop a student research program for a large audience in conjunction with a teacher professional development program centered on student-based research projects The effective use of LSST data by students, teachers, and the public without the extensive personal 'scaffolding' and support present in the HOU and TLRBSE projects is certainly doable. It requires an educational approach that relies on using Internet-based approaches developed by the project partners. The team will focus on evaluating data processing tools suitable for use by teachers and students and moving these into formal education settings. Training will be developed so that the tools can be used almost immediately after limited initial training.

Steward Observatory's *Astronomy Camp* programs provide an ideal venue for pilot-testing LSST tools with a diverse national audience consisting of students, adults, and educational leaders. By expanding the summer camps with LSST support and incorporating large data sets into the camp observing and research experience, the program will be able to create LSST "ambassadors" charged with distributing and supporting LSST images and data across the country. The astronomy camps are ongoing, and provide direct services to students, our ultimate audience in the formal education arena. LSST support, through scholarships, can also broaden the camps efforts to enroll underserved groups aid in the broader recruitment of teachers and leaders serving underserved groups.

Year one: an LSST outreach workshop will be held in Tucson, to bring together the project partners with existing groups (e.g., NVO, SDSS, HOU) using astronomical data sets in educational settings and discuss how to best use precursor data. It will also serve as a venue for aligning "best practices" and lessons-learned from our project partners. In this year, informal science education visualization and display efforts at the Hayden will ramp up. Steward and NOAO will define the types of data and tools most applicable for student research and develop the Internet-based mini-course for teachers and students on using the data. All partners will explore the requirements for the LSST@home development effort. Exploration of LSST-type tools and data will begin at Astronomy Camp, and will be incorporated as part of the camp program.

Year two: prototype testing of the Internet-delivered instructional materials and analysis tools will be done with a distributed audience of teachers and students. Visualization efforts at Hayden will continue with the Deep Lens Survey data. A prototype display will be set up at Kitt Peak Visitor Center and audience interviews will explore best ways to display and understand large data displays. Prototype e-paper displays will be explored. A test group of teachers and students will pursue research activities using prototype data tools, after taking the Internet-based training. Additional astronomy camp members will be trained as LSST ambassadors and camp members will use large data sets in their camp activities.

Year three: each of the preceding activities will continue to develop and will extend beyond the project partners to a national audience. National-scale planning will begin for education efforts related to the next phase of LSST. The visualization display at Hayden will be completed and results from the KPNO/Hayden study of public perception of large-scale images will be studied for its educational implications. In addition to these activities, each year NOAO will continue to lead an active public information campaign with brochures, posters, color handouts, etc., based around major community meetings and workshops (AAS, ASP, AAVSO, etc.) and project development milestones. The purpose of this publicity campaign will be to communicate the growing progress in the development of LSST to the media, naturally attentive audiences such as amateur astronomers, and subsequently, the general public.

Cost for educational outreach efforts over the three years is $424K, with 55% of the support for development of the student research program and 45% divided among informal science education efforts at the Hayden Planetarium and the Kitt Peak Visitor's Center, prototyping of LSST@Home, and the Steward Observatory *Astronomy Camp*. The American Museum of Natural History will provide 70% of the funding for its LSST related programs such as the *MegaDisplay* and *AstroBulletin* exhibits and Web-based programs.

C.7 MANAGEMENT PLAN

In March 2003, four organizations formed the LSST Corporation (LSSTC), a non-profit 501C3 Arizona corporation. Members are the University of Washington, the University of Arizona,, the Research Corporation, and NOAO. Two representatives from each of the member institutions serve on the Board of Directors. In addition, there are several at-large board members with expertise in key science and/or technology areas. Dr. John Schaefer, the President and CEO of the Research Corporation, is the first President of the LSST Board. Under the By-Laws of LSSTC, the Board manages all business and affairs of the corporation. The Board has final authority over all project activities, budgets, and key personnel assignments. The LSST Corporation plans to expand its institutional membership; qualifications for membership include a shared vision for the nature of the LSST endeavor and a commitment to advancing the project through technical, scientific, and/or financial contributions. The Board will consider all applications for membership from national or international institutions.

The US Department of Energy will be a major partner along with the National Science Foundation in the construction and operation of the LSST. DOE participation is based on their fundamental interest in the LSST probe of dark matter and dark energy. The DOE will conduct reviews, audits, and technical briefings analogous to the NSF. While full DOE funding is not yet approved, initial funding and the business and management plan are in place. Management at SLAC, BNL, and LLNL have committed internal funds of about $10M during the D&D term. In briefings at the DOE Office of Science, it has been proposed that DOE construction funding begin in October, 2005. Reviews of this project by the various advisory committees of the DOE are being planned now.

The DOE laboratories have assumed ownership of the LSST camera system. The camera is defined as the outer dewar and its contents; this represents about a third of the project hardware costs and one fifth of the total project (see Section C4 for a description.) SLAC will take the lead and act as the interface with the DOE Office of Science. While the plan is for DOE to fund the camera project, there will be participation from non-DOE organizations. Beyond the camera, the involvement of the DOE laboratories brings to the LSST project fundamental, enabling technical capabilities, honed from extensive experience with numerous previous and ongoing large experiments.

While LSST is a distributed project there is a single management plan. All participating organizations including the DOE labs will be coordinated and accountable to the LSST Director and Project Manager.

Management Structure

Management of the entire LSST project, including the Design and Development (D&D) phase proposed here, is based on proven project management practices. The guiding principles of the management plan include:

- An LSST Director and Project Manager, each reporting directly to the LSST Board and supervising scientific and engineering teams, respectively
- A Change Control Board (CCB) and a Science Advisory Board (SAB) with well-defined roles and responsibilities

- A management structure and tracking system based on the appended Work Breakdown Structure (WBS)
- A formal Risk Management Procedure (RMP) to characterize budget, technical, and/or schedule risks, assign risk numbers to each WBS element, and track changes in risk as progress is made during the D&D phase
- Rigorous, formal program reports and reviews, including whatever reviews and reports are required by the NSF
- An Executive Advisory Committee with members chosen on the basis of their familiarity with construction or operation of similar facilities, interactions with federal agencies, or commercial R&D projects of similar nature and scope to review and provide advice to the LSST Board annually

Figure 15 shows the overall management structure. As described above, the Board is the primary governing body. The Director and Project Manager work in collaboration to manage the project. The Board sets policies and approves a limited set of high level requirements. The Science Advisory Board and Change Control Board maintain oversight and endorse major changes in technical scope and direction of the project. Both the Director and Project Manager are members of both committees. Disagreements, if any, between the Director, Project Manager, and/or either the Advisory or Change Control Boards will be resolved by the Board of Directors. The white boxes in Figure 15 denote scientific components led by the LSST Director. Shaded boxes show engineering components led by the Project Manager. Names in italics are sub-system scientists reporting to the Director and working closely with sub-system project managers. The Project Manager reports to the LSST Director on scientific issues but reports directly to the LSST Board on issues related to execution of the WBS elements. The goal is a collaborative management team of the LSST Director and the Project Manager.

As shown in Figure 15, three sub-system teams labeled Data Management, Camera, and Telescope/Site will execute the primary WBS tasks. Each sub-system team is led by a scientist and a project engineer. The sub-system scientists report to the Director. Each sub-system project engineer will:

- Have responsibility for performance of specific WBS components
- Manage appropriate staff, budget, and deliverables
- Coordinate with their sub-system scientist
- Develop and own the Risk Management Score Card for their respective WBS tasks
- Represent their project to the Project Manager and to the Change Control Board.

The composition of the sub-system teams is intended to unite the scientific and engineering interests of the program. During the D&D phase, each team needs to negotiate an optimum reconciliation of ambitious scientific requirements, technical specifications, budget, and schedule. Each sub-system team has at least one Risk Management Coordinator who is responsible for the risk scorecards for that group.

The key risk areas of Array Technology and Software Architecture will each have senior advisory committees that will assess the proposed technologies and system architecture and provide direct technical assistance where appropriate. In recognition of the very large challenges posed by Data Management, two nationally recognized scientists will head the advisory committee on software architecture, which will be charged with coordinating the pipeline and database architecture, ensuring that LSST benefits from lessons learned by other projects, and keeping the project informed about the latest innovations in both hardware and software design. These two experts will work in close coordination with the Data Management team leaders. Beginning with a national LSST data workshop, the goal will be to build an operating prototype for the data system.

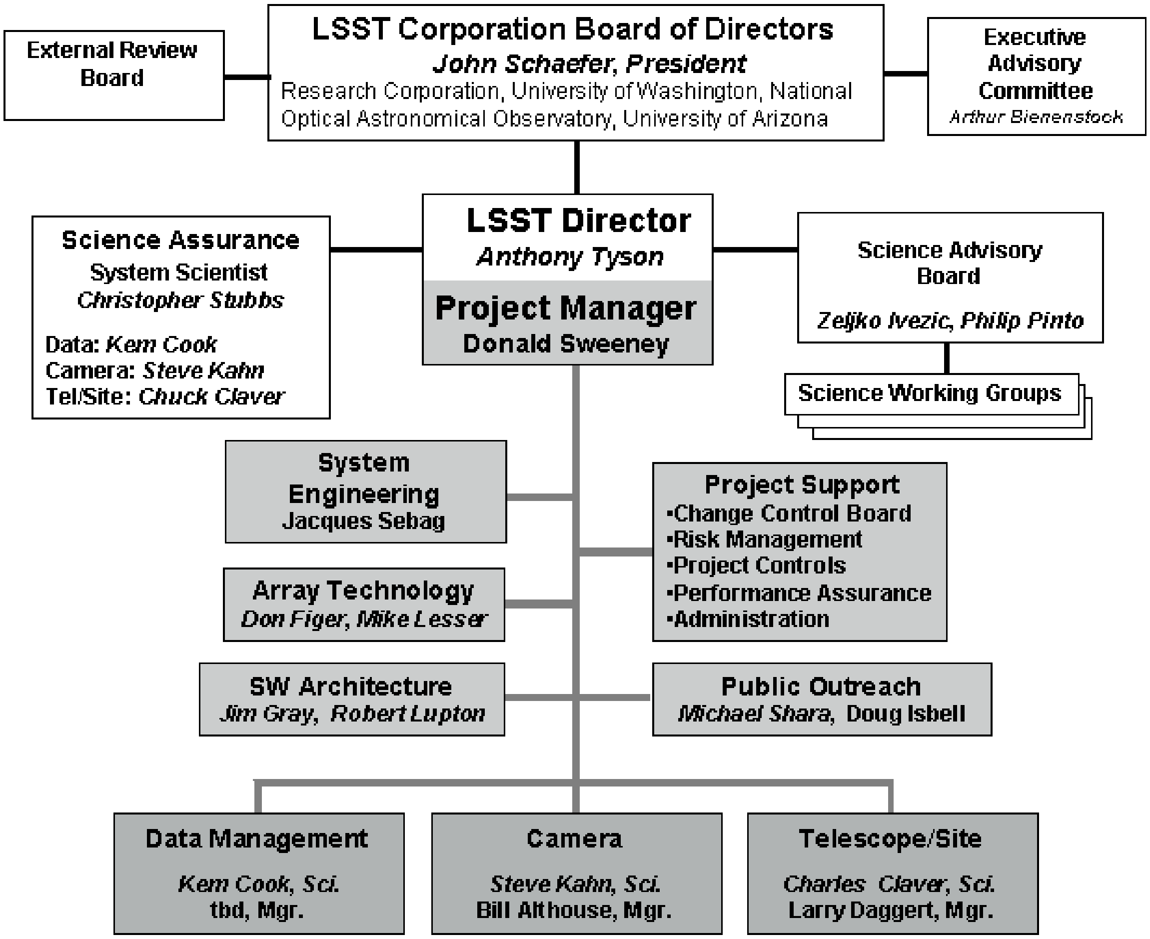


Figure 15. LSST D&D Management Structure

The LSST project has the good fortune that its management team is largely in place. The Project Director is Prof. Anthony Tyson (University of California, Davis and Lucent Technologies, Bell Labs) and the Project Manager is Dr. Donald Sweeney (LSSTC). The System Scientist is Prof. Christopher Stubbs (Harvard University). All three major LSST sub-systems have identified science leaders, as shown in Figure 15. **Appendix X** contains brief biographical sketches of these personnel. Two have engineering managers, and recruitment for the data systems manager has been initiated.

Work Breakdown Structure

The detailed Work Breakdown Structure (WBS) is presented in Appendix 4. The top-level of the WBS is divided into six parts and is directly related to the management structure presented in Figure 15. Table 4 shows the relationship between the WBS and the management structure. The technical challenges and approaches associated with each WBS element are discussed elsewhere in this proposal.

The project schedule is based on the WBS and includes all activities for the D&D phase regardless of the source of funds. Project expenses will be tracked according to cost accounts based on the WBS. For each task the funding source will be identified and the account number will designate that costs are to be assigned and tracked against either private funds or funds from the NSF.

Table 4. The LSST top-level WBS with designated management.

WBS	Title	Management Owner
1.0	Data Management	Kem Cook, LLNL Manager, TBD
2.0	Camera	Steve Kahn, SLAC Bill Althouse, SLAC
3.0	Telescope	Chuck Claver, NOAO Larry Daggert, NOAO
4.0	Site	
5.0	Public Outreach	Doug Isbell, NOAO Michael Shara, AMNH
6.0	Management	Tony Tyson, UC-Davis/Lucent Don Sweeney, LSSTC/LLNL

Program Reviews and Reports

Each sub-system leader is expected to convene weekly meetings and post minutes to the documents archive. The Project Manager will convene weekly meetings of the sub-system leaders. Outside peer reviewers will be invited to critique the program at appropriate intervals. All presentation materials will be archived. Reports will be prepared according to the terms of the finding agency grants. All refereed publications will acknowledge support and be placed in the document archive.

Management of Distributed Projects

Like many large, scientific projects, work will be performed by a number of member participants and contractors at geographically distributed sites. The five current members of the LSSTC will each participate along with currently non-member organizations such as Stanford Linear Accelerator Center, Lawrence Livermore National Laboratory, Brookhaven National Laboratory, Harvard University and Princeton University. Most of these participants will contribute substantial effort on an in-kind basis. These efforts are reflected in the Budget.

All aspects of the project will be accountable to the LSST Project Manager to assure performance on the integrated WBS. All participants performing work in-kind must execute a Memorandum of Understanding (MOU) to adhere to these governance principles. The basic principles of the MOU include:

- Written agreements of the Statement of Work with well-defined deliverables and schedule
- Careful application of formal management tools including budget control, schedule tracking, and risk analysis
- Frequent reviews and site visits to promote collaboration, the free exchange of information, and monitor progress
- Acknowledgement of the authority of the central system of governance
- Signatures on the MOU by institutional officials and the individual contributors to assure that the projects have both an institutional and individual commitment.

Fortunately, several senior members of the LSST management team have extensive experience successfully managing distributed projects. Donald Sweeney, the Project Manager, managed the Extreme Ultraviolet Lithography Program, which was conducted at three national laboratories and sponsored by a consortium of six international IC manufacturers. LSST Director Anthony Tyson has wide interactions with the science and engineering community and managed the international collaboration Deep Lens Survey, an LSST precursor, and several R&D projects. William Althouse, the Camera Project Manager, was the Project Manager for GLAST, an international project sponsored by DOE and NASA with in-kind contributions from organizations in Europe and Asia. All subsystem managers have extensive management experience in their specialties.

Timeline and Deliverables

The LSST project follows a timeline with LSST first light in December, 2011. The timeline and deliverables for the D&D phase of the project follow from the master plan. Table 5 shows the key Deliverables and due dates for a number of milestone events during and adjoining the D&D funding period.

The first six deliverables in Table 5 are due prior to the beginning of the D&D funding. Our ability to accomplish these deliverables is testament to the commitment of our partners cost-sharing obligations. Critical items such as freezing the optical design, final site selection, and ordering glass for the primary are precursors to NSF funding.

Deliverables during the D&D phase include the Conceptual Design Review, submission of the NSF construction proposal, and the Preliminary Design Review. The critical path calls for the NSF construction proposal to be submitted by October, 2005 with construction funding beginning in October, 2007.

A complete list of Deliverables during the D&D phase classified by WBS element with due dates is tabulated in Appendix IV. The Appendix tabulation also includes the person-effort associated with each deliverable classified by funding source.

Table 5. Timeline and Key Deliverables

Activity / Milestone	FY05	FY06	FY07	
Optical Design Frozen	▲			
Science Requirements Document Complete(SRD)	▲			
Site Selection	▲			
Functional Performance Requirements Doc (FPRD)	▲			
Interface requirement documents complete (IRD)	▲			
D & D Funding Begins	▲			
Conceptual Design Reiew	▲			
Order Primary Mirror Glass		▲		
Submit Construction Proposal		▲		
Mount Design RFQ		▲		
Order Primary Mirror casting			▲	
Place Mount Design contract			▲	
Dome Design RFQ			▲	
Preliminary Design Review			▲	
Construction Funding Approved				▲
Site construcion begins				▲
Place Dome Design / Fab contract				▲
First light Dec. 2011				

Budget Planning and Risk Management

The Project Manager will have the authority to associate funding with elements of the WBS. With appropriate oversight, each sub-system leader will be authorized to manage funding within his or her own project. The Project Manager will maintain and distribute the contingency fund. The LSST project has the services of financial coordinator David Brooks. Project expenses will be tracked according to cost accounts. Accounting for all funds will be in accordance with Generally Accepted Accounting Principles (GAAP), and all applicable federal circulars and regulations will be followed in accounting for NSF funds. Institutions making in-kind technical contributions using internal resources will be expected to document their ability to perform tasks and to acquire equipment and facilities necessary to perform their Statement of Work, including milestone reviews.

Risk management is an important part of the management plan. Everyone in the LSST project will be educated in the precepts and procedures of risk management. All sub-system leaders will be required to rank their WBS elements. The risks associated with technology, schedule, and budget will be rated on a risk scale. Interdependence risks will also be assessed and tracked. A risk scorecard will be maintained as part of the design process. Risk assessment will be part of every quarterly and design review. In collaboration with the Director, risk mitigation action plans will be developed for areas of high risk. The process will be overseen by the Risk Management Manager.

Technology Readiness and Key Personnel

A considerable effort from a broad community has led to a viable point design for the LSST system. This effort has been enhanced by lessons learned from some of the most ambitious survey projects undertaken to date, including the Sloan Digital Sky Survey, the MACHO microlensing survey, the DeepLens survey, and others in which the LSST participants have been engaged. These lessons range from management and costing issues to software algorithm development. Over sixty scientists and engineers from institutions across the nation have made in-kind contributions to the LSST System conceptual design. Technical and scientific working groups have been formed, and their deliberations have produced the design upon which the stakeholders have converged. While no potential 'show-stoppers' have been found, our proposed focus in the next three years is designed to buy down risk, minimize the cost, and maximize the early science of the LSST facility. Refer to the section entitled, “Senior Personnel,” for further details about staffing.

LSST Systems Engineering Framework

A strong systems engineering program will ensure success of this complex project. A detailed requirements flow down analysis coupled with a systems error budget plan will clearly define the desired capabilities and performance of the LSST facility. A distributed ICD tree will be developed to take advantage of the competence and skills of the partners. A systems control approach using end-to-end modeling will help identify critical areas and reduce technical risk. Systems engineering will also be strongly involved during the design phase in hardware and software tradeoffs of costs versus performance. A detailed integration and test plan combined with an operational and control plan will guarantee the final performance of the LSST telescope.

LSST is buildable today. While the LSST system is innovative, there are no technology research and development projects that are prerequisites. The timescale for LSST can be rather short provided funds are available on the optimum schedule: D&D engineering completed in the next three years, and “first light” for the telescope, camera, and data system achieved in 2011.

SENIOR PERSONNEL

The team that has been organized for the design and development of the LSST system includes over 60 scientists and engineers nationwide. Here we focus on the key senior personnel, arranged by task. Each of the following four paragraphs lists senior personnel in major task categories for the LSST Design and Development Engineering. Within each paragraph names in **bold** are designated senior personnel on this proposal, while other names are additional key personnel who are already working with these individuals. Some senior personnel listed here, particularly those associated with DOE labs, will not receive support under this proposal. The LSST Director and Project Manager report to the LSST Corp. Board; four representatives of the founding institutions are Co-PIs on this proposal: **John Schaefer** (LSST Corp and Research Corp), **Craig Hogan** (U. Washington), **Sidney Wolff** (NOAO), and **Philip Pinto** (U. Arizona).

Project Management: The organizational chart is shown in section C7. LSST Director **J. Anthony Tyson** (UC Davis & Bell Labs) works closely with Project Manager **Donald Sweeney** (LSST Corp and LLNL). The director and project manager are supported by System Scientist **Christopher Stubbs** (Harvard U.) and by Science Advisory Committee co-chairs **Zeljko Ivezic** (Princeton U. and U. Wash.) and **Pinto**. System Engineering is headed by **Jacques Sebag** (NOAO) and includes Jeff Morgan (U. Wash.) and Jim Thurston (SLAC). Public Outreach is co-chaired by Doug Isbell (NOAO) and Michael Shara (AMNH). Financial coordinator is David Brooks (University of Washington).

Data Management: This department covers data flow from the camera to the database, and includes astronomers and computer scientists involved in algorithm development for the several pipelines and data system design. **Kem Cook** (LLNL and NOAO) heads the Data Management team, supported by software architects **Jim Gray** (Microsoft) and **Robert Lupton** (Princeton). Other key senior personnel are **Tim Axelrod** (U. Arizona), Robert Brunner (NCSA), Andrew Connolly (U. Pitt), Steffen Luiz (SLAC), Chris Smith (NOAO), **Rob Pike** (Google), **Pinto, Stubbs**, **Alex Szalay** (JHU), **David Wittman** (UC Davis & Bell Labs), and Daniel Reed and **Richard Crutcher** (NCSA)

Camera: Coordination of the (mainly) DOE effort on the LSST camera is the responsibility of **Steve Kahn** (Stanford/SLAC), with camera project manager **Bill Althouse** (SLAC). The detector array D&D team is headed by **Tyson** and includes Mark Bautz (MIT), Bill Craig (LLNL, SLAC), **Don Figer** (STScI, JHU), Mike Lesser (U. Arizona), Paul O'Connor (BNL), and Veljko Radeka (BNL). Camera mechanical systems work includes Bill Craig (LLNL, SLAC), Todd Decker & Layton Hale (LLNL), and Gary Muller (NOAO). Camera optics includes Axel Brachman (SLAC) and Lynn Seppala (LLNL). Camera electronics includes Paul O'Connor (BNL), John Oliver (Harvard), and Jon Thaler (UIUC). Within the DOE "matrix", the key players will be SLAC, BNL, and LLNL, with contributions from other DOE-funded university groups.

Telescope, Site, Operations: The science effort for this department is led by **Charles Claver** (NOAO), supported by engineering manager **Larry Daggert** (NOAO). This WBS also includes instrument rotator, mirrors, structure, simulations, and dome. Optics personnel include Roger Angel and Jim Burge (U. Arizona), **Claver**, and Seppala. Mechanics and structure work packages include Larry Carey and Russ Owen (U. Washington), Warren Davison (U. Arizona), and Layton Hale (LLNL). Operations strategy includes **Cook**, Richard Green (NOAO), Alan Harris (JPL & U. Colorado), Fiona Harrison (Caltech), **Ivezic**, David Monet (USNO), Abhijit Saha (NOAO), **Stubbs**, and **Tyson**. Site evaluation includes Pinto, Nick Suntzeff, Abhijit Saha and Alistair Walker (NOAO).

ACRONYMS AND ABBREVIATIONS

AAS	American Astronomical Society
AAVSO	American Association of Variable Star Observers
AGB	Asymptotic Giant Branch
ASIC	Application-Specific Integrated Circuit
ASP	Astronomical Society of the Pacific
ATI	Advanced Technology and Instrumentation
AU	Astronomical Unit
CAPER	Conceptual Astronomy and Physics Education Research
CCB	Change Control Board
CDM	Cold Dark Matter
CMB	Cosmic Microwave Background
CMOS	Complementary Metal Oxide Semiconductor
CTE	Charge Transfer Efficiency
CV	Cataclysmic Variable
DE	Dark Energy
DLS	Deep Lens Survey
DOE	Department of Energy
ESD	Electrostatic Discharge
EXIST	Energetic X-ray Imaging Survey Telescope
FEA	Finite Element Analysis
FPA	Focal Plane Array
GRB	Gamma-Ray Burst
HOU	Hands on Universe
IC	Integrated Circuit
IDTL	Independent Detector Testing Laboratory
KBO	Kuiper Belt Object
kpc	Kiloparsec
LBT	Large Binocular Telescope
LBV	Luminous Blue Variable
LSSTC	Large Synoptic Survey Telescope Corporation
MBA	Main Belt Asteroid
MMT	Multi-Mirror Telescope
MOU	Memorandum of Understanding
NEA	Near Earth Asteroid
NIR	Near Infrared
NVO	National Virtual Observatory
PHA	Potentially Hazardous Asteroid
PSDI	Phase Shifting Diffraction Interferometer
QE	Quantum Efficiency
RMP	Risk Management Procedure
ROIC	Readout Integrated Circuit
SAB	Science Advisory Board
SN	Supernova
SNAP	Supernova/Acceleration Probe
SQL	Structured Query Language
SSE	Solar System Exploration
TLRBSE	Teacher-Leaders in Research-Based Education
TNO	Trans-Neptunian Object
VLT	Very Large Telescope
WBS	Work Breakdown Structure
XRF	X-ray Flash

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Design & Development Funding By Year - NSF request in bold

LLST WBS	FY05		FY06		FY06		Total		LSST **
	D & D NSF Prop.	Funded by Others *	**D & D NSF Prop.**	Funded by Others *	**D & D NSF Prop.**	Funded by Others *	**D & D NSF Prop.**	Funded by Others	Total D& D Funding
1.0 Science Data Processing	**$ 1,382,500**	$ 505,000	**$ 1,222,500**	$ 505,000	**$ 1,255,500**	$ 505,000	**$ 3,860,500**	$ 1,515,000	$ 5,375,500
2.0 Camera	**$ 233,333**	$ 1,625,000	**$ 233,333**	$ 1,865,000	**$ 233,334**	$ 2,165,000	**$ 700,000**	$ 5,655,000	$ 6,355,000
3.0 Telescope & Optics	**$ 1,852,000**	$ 730,000	**$ 1,680,000**	$ 710,000	**$ 1,204,000**	$ 730,000	**$ 4,736,000**	$ 2,170,000	$ 6,906,000
4.0 Site & Facilities	**$ 232,500**	$ 165,000	**$ 292,500**	$ 185,000	**$ 285,000**	$ 165,000	**$ 810,000**	$ 515,000	$ 1,325,000
5.0 Education & Public Outreach	**$ 123,000**	$ 75,000	**$ 153,000**	$ 75,000	**$ 148,000**	$ 75,000	**$ 424,000**	$ 225,000	$ 649,000
6.0 Project Management	**$ 405,000**	$ 850,000	**$ 781,000**	$ 700,000	**$ 680,000**	$ 700,000	**$ 1,866,000**	$ 2,250,000	$ 4,116,000
Contingency	**$ 500,000**	$ -	**$ 500,000**	$ -	**$ 600,000**	$ -	**$ 1,600,000**	$ -	$ 1,600,000
Yearly Totals	**$ 4,728,333**	$ 3,950,000	**$ 4,862,333**	$ 4,040,000	**$ 4,405,834**	$ 4,340,000	**$ 13,996,500**	$ 12,330,000	$ 26,326,500

* NOAO Funding is committed at $2,000,000 per year. See letter of commitment.

** Research Corporation has committed $30,000,000 to begin procurement of long lead time items not included in this table. See letter of commitment.

Summary of FTE by Project Group

LLST WBS	FY05		FY06		FY07		Total		LSST
	D & D NSF Prop.	Funded by Others	**D & D NSF Prop.**	Funded by Others	**D & D NSF Prop.**	Funded by Others	**D & D NSF Prop.**	Funded by Others	Total D& D Funding
1.0 Science Data Processing	**7.8**	2.5	**7.8**	2.5	**7.8**	2.5	**23.3**	7.5	30.8
2.0 Camera		10.8		12.4		14.4	**0.0**	37.6	37.6
3.0 Telescope & Optics	**10.1**	4.0	**8.5**	3.8	**6.4**	4.0	**25.0**	11.8	36.8
4.0 Site & Facilities	**1.1**	0.3	**1.1**	0.3	**1.0**	0.3	**3.1**	0.9	4.0
5.0 Education & Public Outreach		0.3		0.3		0.3	**0.0**	0.9	0.9
6.0 Project Management	**0.0**	5.0	**3.0**	4.0	**3.0**	4.0	**6.0**	13.0	19.0
Yearly Totals	**18.9**	22.9	**20.3**	23.3	**18.2**	25.5	**57.4**	71.7	129.0

FACILITIES EQUIPMENT AND RESOURCES

The Large Synoptic Survey Telescope project will have work performed at several, world-class facilities. Key facilities will be located at NOAO and Steward Observatory in Tucson, AZ; Lawrence Livermore National Laboratory, in Livermore, CA; Stanford Linear Accelerator Center in Palo Alto, CA; Brookhaven National Laboratory in Upton, NY; National Center for Supercomputer Applications in Urbana, IL; University of California-Davis; Harvard University in Cambridge MS, Space Telescope Science Institute in Baltimore, MA, Lucent Technologies in Murry Hill, NJ, and the University of Washington in Seattle, WA. The LSST Project Office will be located at 4703 East Camp Lowell Dr., Suite 201, Tucson, AZ 85712

LABORATORIES: The University of Arizona and the Space Telescope Science Institute in Baltimore have unique laboratories for characterization of scientific-grade focal plane arrays. SLAC has significant engineering capability (labs and personnel) which will be applied to the LSST Camera. Brookhaven National Labs has world class CMOS ASIC design and test capability. Lucent Technologies, Bell Labs, has a large group dedicated to solving complex interconnect problems of direct relevance to the LSST Camera. The University of California at Davis, has labs for assembling and operating a test camera dewar and test focal planes. Harvard University has a CMOS electronics design group and labs.

OFFICES: The LSST D&D phase has an average work force of approximately 40 full-time-equivalents (see Table A4-2). All necessary office space will be made available at each work location. NOAO has 2600 square feet of newly remodeled, dedicated office space with an adjacent conference room exclusively for LSST. The Kavli institute at SLAC has a suite of offices dedicated to LSST, as does UC Davis. Other organizations have comparable facilities. Office space for project management will be provided by the Research Corporation, Tucson, AZ.

COMPUTERS AND DATA: The National Center for Supercomputer Applications (NCSA) is collaborating on this project and views LSST data as their future mission. The extensive computer facilities at the DOE national laboratories are well known and will not be repeated here in detail. The national laboratories will make necessary equipment available as part of their in-kind contributions. SLAC and Brookhaven have extensive computation and data storage experience associated with high energy physics programs such as BaBar, RHIC, and Atlas. LLNL is part of the DOE advanced super computing initiative called ASCI. All the laboratories have advanced parallel computing initiatives, petabyte data stores, and develop 50Gb/sec class fiber optic data links. UC Davis has significant parallel computing capability needed for simulation of LSST data, and a visualization facility to be used in the data verification tests.

The LSST engineering program has most of the workstations required for design and system engineering; incidental personal workstations may be purchased. Servers, network support, and all peripheral equipment necessary to support LSST tasks are in place. High-speed data lines are available. Several terabytes of existing digital storage in the design center will be used for system modeling, design databases, and document archives. For data management software and architecture, the combination of NCSA, Google, and Microsoft is unmatched.

MAJOR EQUIPMENT: The Optical Sciences Center and the Mirror Laboratory both at the University of Arizona have the metrology and fabrication capability to manufacture all three of the LSST mirrors. While one or more of the mirrors may be fabricated by others, this is an option available to the project. Lawrence Livermore National Laboratory has major precision engineering laboratories and staff that will be used extensively in the camera fabrication.

OTHER RESOURCES

All participants in this distributed project have extensive machine shops, computer-aided design and computer-aided machining. They also have administrative support including procurement, personnel, accounting, budgeting, and clerical support as needed.

APPENDIX I – SCIENTIFIC COMPARISONS

COMPARING SNAP AND PAN-STARRS WITH LSST

How does LSST compare with the two other currently proposed major survey facilities, SNAP and Pan-STARRS? The three projects have different scientific goals and take quite different and complementary approaches to address different aspects of the general survey problem.

Three Facilities

SNAP is a proposed 2-m space telescope with a 0.7 square degree focal plane divided between infrared and optical arrays and a planned 4-year mission life. It is a specialized survey designed to study as many high-redshift type Ia supernovae as possible. Toward this end, SNAP includes significant photometric and spectroscopic capabilities in the infrared. The SNAP mission will cost in the vicinity of one billion dollars and may be launched in the middle of the next decade.

PanSTARRS is a novel design for an inexpensive, general-purpose survey engine. The current project will build an array of four 1.8-m telescopes, each with a CCD array covering 7 square degrees of sky. This prototype will test the idea that mass production of smaller telescopes and cameras may achieve economies of scale inaccessible to large, single telescopes. Since this approach is designed to be scaled to larger numbers of telescopes, we will compare both the current project and a potential larger version with 22 telescopes, which we will christen ManySTARRS.

LSST is designed to be as powerful and as versatile an all-sky survey system as possible from the ground using current technology. Due to its very high optical throughput, LSST will cover the entire visible sky deeply in a few nights. It is an 8.4-m single telescope with a detector array that also covers 7 square degrees of sky. It was designed to detect NEAs to as small a diameter as possible, to deliver high enough image quality to excel at weak lensing studies, and to be fast enough to allow multi-color observations of transient phenomena.

Three Figures of Merit

It is useful to have a figure of merit (FOM) to quantify relative capabilities. The figure of merit for a survey facility depends on its science mission in addition to its light grasp. Because each of these three facilities is so flexible that it can cover a wide range of possible science, we define three figures of merit, corresponding to three important survey missions: exploration of the faint time domain, a faint stellar photometric survey, and a faint, resolved, surface photometric survey of galaxies. The time-domain FOM characterizes the ability of a survey to detect sources that change brightness or position on short timescales: optical flashes and NEAs. The faint stellar FOM applies to surveys that look for change on slower timescales and are thus limited by how often the entire sky can be covered, not by the time for sources to change. The faint stellar FOM also applies to Galactic structure studies and science derived from a dense astrometric grid. The faint galaxies FOM applies to measurements of surface brightness of, e.g., resolved galaxies (galaxies larger than the blur from atmospheric seeing and/or resolved and well sampled by a space imager).

The basic figure of merit for all-sky surveys is the area on the sky that can be covered in a single exposure times the signal to noise ratio achieved in that exposure. This is then a measure of how fast the survey can accomplish a single pass over the sky to a given limiting magnitude.

Throughput

The signal in an image is proportional to the collecting area of the telescope times the efficiency of the optical system and the detector. Since the detector technologies and optical design quality are comparable for all of these systems, we have assumed equal efficiencies. The rate that signal can be covered on the sky is thus proportional to the étendue, or throughput, of the optical system: the collecting area of the telescope times the area on the sky covered by a single image ($A\Omega$). For a survey of transient or rapidly moving objects, the light-gathering capacity is also limited by the duration of a single exposure (τ); a system with small aperture may not collect sufficient signal to enable detecting a faint source in the available time.

Noise

The noise in an image is determined by the background brightness of the night sky and the intrinsic noise of the detector. If the system performance is limited by detector noise, only a larger aperture (hence more signal) can improve performance. To allow for optimizing on other design parameters, we therefore assume that all systems are operating in the sky-noise-dominated limit of exposure times; the FOM will have a factor of the square root of the night-sky brightness (β) in the denominator. For an equal signal/noise comparison, SNAP's figures of merit have been divided by $\beta = 1/3.5$ because of the decreased sky brightness in space at optical wavelengths (600nm).

As a consequence of detector noise, our figures of merit also reflect what science it is possible to accomplish, not just search efficiency. A system searching for brief transients with a small aperture per detector simply cannot detect faint events below some threshold. The duration of an event is either the burst timescale for stationary transients or the time for the image to trail across its PSF; for the fastest-moving NEAs, this time is about 10 seconds across 0.7 arc seconds. We have thus divided the faint time window FOM by the time taken to reach a sky-noise-dominated image in the V filter or 10 seconds, whichever is longer.

PSF

In surveys of unresolved (point) sources, the smaller the area over which the image is spread (Ω_{psf}), the less sky noise is acquired with the signal, and thus the figures of merit for unresolved sources have a factor of the point spread function (PSF) area in the denominator. This area is determined by the detector resolution and, for ground-based surveys, by atmospheric seeing.

Ground-based site seeing for both LSST and PanSTARRS is assumed to be equal to the median site seeing at the best sites, combined with the telescope PSF. A median delivered PSF FWHM of 0.7 arcsec is used (assuming critical sampling). PanSTARRS' 0.3 arcsec pixels do not critically sample this delivered PSF in a single exposure, degrading its effective FWHM to 0.8 arcsec.

The SNAP optics would deliver a 0.05 arcsec FWHM diffraction-limited PSF, leading to severe undersampling. To provide for accurate photometry, we thus use a minimum of 2 pixels (0.1 arcsec pixels) for Nyquist sampling. De-aliasing techniques (Lauer 1999, Bernstein 2002) developed for exactly dithered, undersampled Space Telescope images could work if each pixel had identical internal response and the dither was perfect. It is still unclear how well this can be accomplished in practice. If it can, from Fig. 3 of Bernstein (PASP 114, 98, 2002), including charge spreading, the effective PSF FWHM for SNAP stellar photometry in a series of 4 dithered exposures improves to 0.15 arcsec at 600 nm and to 0.28 arcsec at 1250 nm.

EFFICIENCY

Finally, the efficiency (ε) of a survey is determined by the fraction of time spent surveying. Ground-based surveys are limited by the available nighttime hours. We assume 8 usable hours per night for ground-based facilities and 24/24 for SNAP. SNAP will spend 60% of its time on imaging (it will spend the rest doing spectroscopy). Depending on a science program's requirements for wavelength coverage, moonlight, and weather, figures of merit for SNAP should also be multiplied by between 2 and 3 (for the effects of weather & moon brightness relative to ground), and then divided by the ratio of mission lifetimes; this additional factor is about 1 for SNAP's optical efficiency. Because LSST makes such short exposures (10 seconds), the time spent reading the image from the detector reduces ε by about 15% compared with PanSTARRS.

FIGURES OF MERIT OF FUTURE POSSIBLE FACILITIES COMPARED

The following Table 1 lists three figures of merit corresponding to the three types of science mission for each of these facilities, and is followed by a summary (Table 2) of the parameter values adopted for each system. For all science missions, these figures of merit are proportional to the number of objects surveyed to a given depth and signal/noise per unit time, *for those objects which can be detected at all.*

Table 1. Survey Figures of Merit

Science:	***Faint Time window***	***Faint Stellar***	***Faint Galaxies***
FOM	$A\Omega\varepsilon / \Omega_{psf} \tau \beta$	$A\Omega\varepsilon / \Omega_{psf} \beta$	$A\Omega\varepsilon / \beta$
LSST (8.4m)	**16** $\mathrm{m^2\,deg^2\,arcsec^{-2}\,sec^{-1}}$	**160** $\mathrm{m^2\,deg^2\,arcsec^{-2}}$	**79** $\mathrm{m^2\,deg^2}$
*SNAP**(Optical)***	**0.02 – 0.04**	**28 – 50**	**1.1**
PanSTARRS	**0.23**	**23**	**15**
ManySTARRS	**1.6**	**160**	**79**

Table 2. Parameters used in FOM table

	LSST	*SNAP**(Optical)***	*PanSTARRS*
sqrt $4A/\pi$	8.4 m	2 m	Four 1.8 m
$\Omega_{optical}$	7 $\mathrm{deg^2}$	0.34 $\mathrm{deg^2}$	7 $\mathrm{deg^2}$
sqrt $4A_{eff}/\pi$	6.9 m	1.9 m	Four 1.5 m
ε	0.28	0.6	0.33
sqrt Ω_{PSF} (Optical)	0.7 arcsec	0.20 or 0.15 arcsec	0.8 arcsec
τ	10 sec	4x300 sec	100 sec
Av. sky μ at 550 nm	21.8 mag $\mathrm{arcsec^{-2}}$	23.2 mag $\mathrm{arcsec^{-2}}$	21.8 mag $\mathrm{arcsec^{-2}}$

Armed with these figures of merit, we will first discuss several general considerations before comparing the performance of these systems in specific surveys. As noted above, sky background limits the signal-to-noise ratio in imaging. At the near infrared wavelengths used for SNAP's primary high-redshift supernova program, the sky appears much fainter from space, and thus SNAP becomes the facility of choice for stellar photometry, especially if sub-Nyquist photometry apertures can be used. Note that the above figures of merit assume sky noise limited exposures. As the optical throughput decreases, the single exposure time required to reach the sky limit increases, thus impacting the Faint Time Window figure of merit and the pace on the sky (see the discussion and graph in Section C3).

While a given facility can trade filter bandwidth for integration time, for a meaningful intercomparison the same filter bandwidth is assumed for all facilities (V in optical). For the time window FOM, we have chosen a time τ which achieves maximum depth per exposure time.

For the PSF ranges of SNAP, this corresponds to the 4x300 sec adopted exposure pattern. For PanSTARRS we use the shortest exposure for sky noise limit in V, given as 100 seconds in the PanSTARRS *Efficiency Notes* document (http://pan-starrs.ifa.hawaii.edu/project/people/kaiser/efficiency_notes.pdf). While one could employ shorter exposures with Pan-STARRS, the efficiency of the survey would not increase: fewer objects would be detected. Clearly, this would affect bright targets less than fainter ones, but it is precisely the fainter targets that are the goal of any survey; otherwise one would have built a smaller, less-expensive system in the first place.

OPERATIONAL MODES

High throughput permits shorter exposures (to a given signal to noise ratio and limiting flux) and thus a more rapid survey pace. In turn, this leads to the ability of returning to the same patch of sky on a wider range of timescales. It also permits very wide and deep sky coverage in multiple standard filters, a requirement for some science. For systems with throughput below a critical value, a variety of science programs can no longer share the same data and it becomes more cost effective to undertake a series of surveys or even focus on a single limited patch of sky.

Over time, LSST will cover up to 20,000 deg^2 to 24-27 mag in 5 optical filters using multiple, 10 second exposures. This range in limiting magnitude tracks the corresponding event timescales, from 10 seconds to many years. For weak lens photometry of galaxies with measurable shapes, to make cosmological measurements it is better to cover a large area on the sky rather than observe a smaller area to great depth, since wide area coverage is required to reach power at large scales for cosmic shear and for probes of the directional variation of w. SNAP will concentrate on 20 deg^2 at the north ecliptic pole, in a variety of filters from 400 nm to 1700 nm, with multiple 300 second images going as faint as 29 mag for co-added stacks of images. SNAP may also undertake a 300 deg^2 shallower lensing survey. PanSTARRS may pursue sequential surveys using different filters for different programs, focusing on a swath along the ecliptic for NEA detection with multiple 30-60 sec images reaching 24 V+R mag. If sequential surveys are done, ε for each survey should be multiplied by the fraction of time for that survey in order to compare with facilities which operate in the same mode all of the time.

Viewed from this perspective, LSST, SNAP, and PanSTARRS are complementary in several respects. This is not an accident. The designs of LSST and SNAP were driven by very different science missions. SNAP was specifically designed for stellar photometry at infrared wavelengths where ground-based sky is very bright. It does not need to cover wide areas of the sky as high-redshift supernovae are fairly common.

As described below, a system with the capabilities of LSST is required for all-visible-sky, multi-color surveys addressing a wide variety of phenomena ranging from dark energy to detection of a significant fraction of potentially hazardous NEAs. PanSTARRS, in its current configuration with 18% of LSST's collecting area and 40% of LSST's resolution on the sky, might be considered an LSST precursor. It is a less-ambitious solar system survey in one color, focused on finding Kuiper Belt Objects and the most massive NEAs. The PanSTARRS approach can be scaled to a larger number of telescopes until its distributed design has the same collecting area and detector resolution as LSST. Such a system (ManySTARRS in the table above), would have the same figures of merit for faint resolved and unresolved sources. It would still be limited, however, by the time it takes a single telescope and camera to reach the sky brightness. Even if scaled to LSST's aperture, ManySTARRS' time window FOM would remain a factor of ten below that of a single-telescope LSST. A single-telescope design is clearly optimal for NEA searches and finding brief optical transients.

CURRENT WIDE FIELD FACILITIES

In the following Table 3 we list the figures of merit for existing wide-field imaging facilities in the optical (300-1000 nm) and infrared. The widest-field camera is used for each facility (MOSAIC for the NOAO 4-m, ACS WFC for HST, Mega Prime for CFHT, etc.). In order to directly compare with the first table, the efficiency ε is *not* that for current or planned operations. Rather it is assumed that each of these facilities would be used 100% of the time in a single imaging survey. As in the first table, ε includes effects of daylight, with $\varepsilon = 0.3$ for ground based systems and $\varepsilon = 1$ for space. For the PSF footprint Ω_{psf}, a value of 0.7 arcsec for ground-based and 0.1 arcsec for space is used. Also as in the first table, a relative sky noise factor β at 600 nm of 1 for ground based and 0.53 for space is used. Camera readout times are from engineering memos or existing camera specifications, and τ is the greater of 5 times the read time or time to sky noise limit (the square root of sky counts is greater than 5 times the read noise). From these data one can see that the next generation of facilities represents a significant leap in figures of merit and will enable significant new science.

Table 3. Other Wide Field Imaging Facilities (Existing or under construction)

Science:	***Faint Time window***	***Faint Stellar***	***Faint Galaxies***
FOM	$A\Omega\varepsilon / \Omega_{psf} \tau \beta$	$A\Omega\varepsilon / \Omega_{psf} \beta$	$A\Omega\varepsilon / \beta$
CFHT	**0.18** m^2 deg^2 $arcsec^{-2}$ sec^{-1}	**5.4** m^2 deg^2 $arcsec^{-2}$	**2.7** m^2 deg^2
Subaru	**0.007**	**4.4**	**2.2**
SDSS	**0.02**	**1.0**	**1.7**
MMT	**0.07**	**3.0**	**1.5**
VST	**0.01**	**2.8**	**1.4**
NOAO 4m	**0.02**	**1.8**	**0.9**
HST	**0.003**	**1.3**	**0.013**
VISTA (IR)	**0.06**	**1.9**	**0.93**

RELATIVE FIGURES OF MERIT

It is useful to compare the relative figures of merit for current facilities and possible future wide field survey facilities on one chart. The relative FOMs for the three programs (opening the time window, stellar, and resolved galaxies) are summarized in the chart below.

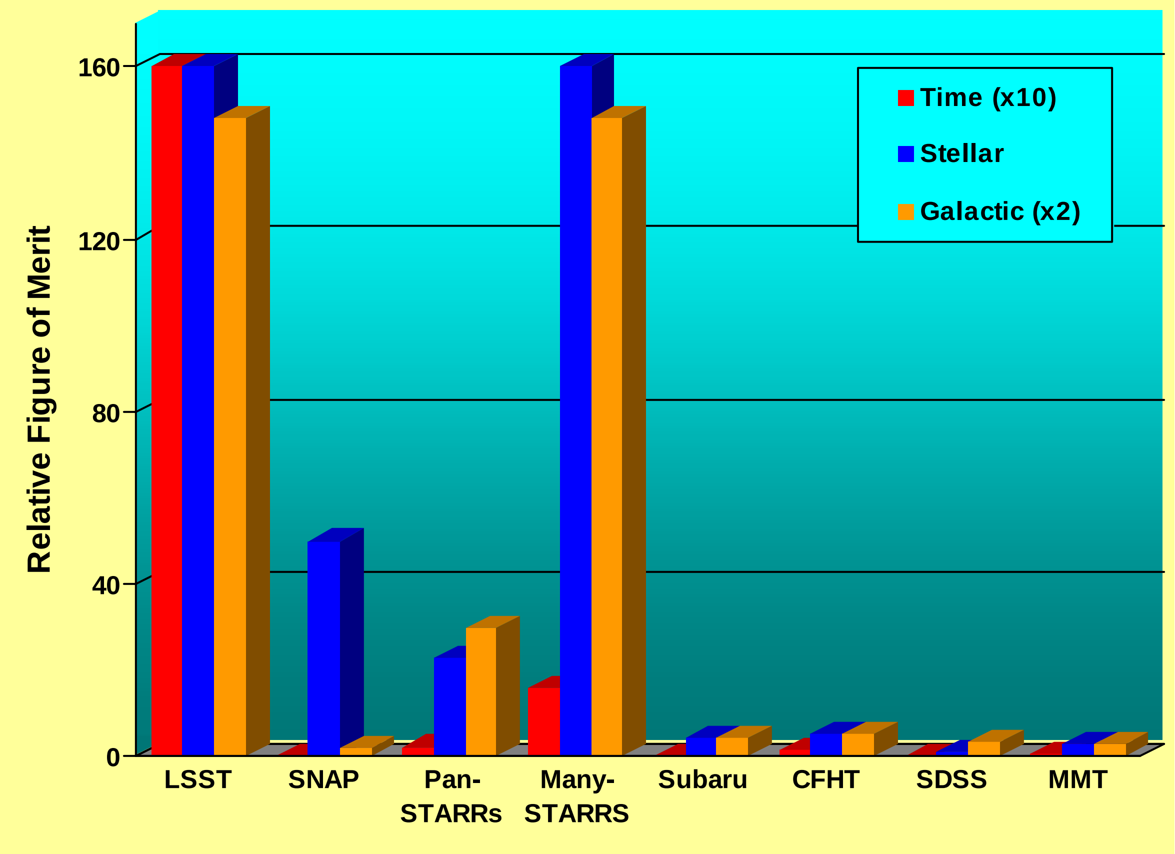


Figure 1. Comparison of present and future survey facilities. Subaru, CFHT, SDSS, and MMT are current facilities, but taken as operating as full-time survey facilities with their most effective instrumentation. LSST, SNAP, and PanSTARRS are the proposed facilities discussed in the text. ManySTARRS is the PanSTARRS approach scaled up to the collecting area of LSST, with 22 1.8-m telescopes operating simultaneously.

SCIENCE IMPLICATIONS

In the next two sections we briefly outline the relative strengths of the three proposed facilities in the context of determining the nature of dark energy and opening the faint time window for detecting potentially hazardous objects and discovering new classes of optical transient. Our conclusion is that LSST and SNAP are both needed and are completely complementary. PanSTARRS is a very useful LSST precursor project. It can begin to address some of the LSST science in both fields. Its scaling properties are not as advantageous as those of a single-telescope system.

POTENTIALLY HAZARDOUS ASTEROIDS

Potentially hazardous asteroids are nearby and move quickly across the sky. An efficient search will cover large areas of the sky rapidly, with frequent revisits to allow discovery of motion at all rates and for the accurate determination of orbits. Exposures must reach the sky limit in less than 15 seconds, and the system must be capable of covering 14,000 square degrees of sky in a few nights. A survey system with high throughput, AΩ greater than 200, is required simply to cover so much sky, so rapidly.

SNAP is clearly not designed as a wide-area survey system; it has an AΩ of one. With an AΩ of 50, and a time window FOM 0.23, PanSTARRs represents a 30% improvement over the most capable system extant, the CHFT (FOM 0.18). No matter what the throughput, however, to go deep and discover the far more numerous smaller hazardous bodies, there is no substitute for larger aperture. Smaller apertures simply become read-noise limited for fast-moving objects. Despite its high throughput, PanSTARRS' small individual apertures will only be able to achieve 90-percent completeness for km-sized objects. Smaller objects are simply too faint to detect in the time it takes their image to trail across the PSF. Scaling the PanSTARRS approach to more telescopes improves this situation, but very slowly. In the read-noise-dominated limit, adding telescopes increases the signal to noise ratio as the square root of the number of telescopes. Since the amount of light reflected from a body (the signal) decreases inversely as the square of its size, the size detection limit of a multiple telescope system decreases only as the inverse fourth root of the number of telescopes. A 22 telescope PanSTARRs would still be limited to detecting 500 m objects.

LSST has an AΩ of 260, but as all of the increase is in A, it is more than just five times more capable than PanSTARRS. For a single-telescope system working in the sky background limit, the detectable radius scales inversely with the telescope aperture. LSST will detect 90% of all objects to 250m diameter and 80% of objects to 140m. For faint transients and rapidly-moving objects, a single-aperture design clearly has superior scaling properties. Instead of a 30% improvement in time window FOM over CFHT, *LSST is 89 times more capable* than the most capable current system. A large, single-telescope system like LSST is thus required for a significant increase in PHA detection capability.

The same arguments are true wherever the faint time window FOM applies. Little is known about the faint, dynamic sky because we do not have facilities that can survey *faint, fast, and wide* simultaneously. While examples exist of optical bursters (GRB afterglows) and fast moving faint objects, the relative FOM for LSST shows that this virtually unexplored phase space will be opened dramatically to discovery. There are already hints from existing surveys that other classes of rare optical bursts exist. LSST will supply unique access to the sky and the needed statistics for rare events. This is a very exciting frontier that will surely yield surprises. There are also new and exciting public outreach opportunities for this *celestial cinematography.*

DARK ENERGY

Dark energy affects the time history of the expansion of the universe, with the largest effect around a redshift of 0.5. Observations of distances (luminosity distance, angular diameter distance) or co-moving volume over a range of redshift bracketing 0.5 will constrain theories of the physical nature of dark energy, in particular the equation of state w. The key observations are listed here.

High-redshift Supernovae

If type 1a supernovae can be calibrated as "standard candles," they may be used to measure luminosity distance as a function of redshift. With enough measurements over a wide range of redshift and careful attention to the control of systematic errors, several percent level precision on w could be achieved. A generic prediction of concordance cosmology (Λ=0.7, Ω_M=0.3) is a turn-over in the $d_l - z$ relation at $z > 1.5$. Also, any systematic errors in the standard candle could be revealed by an investigation of high-z SN. To detect and follow high redshift supernovae in the rest-frame optical, one needs to observe in the near infrared where the sky background is high. A space mission is thus required. While SNAP has an infrared stellar FOM comparable to LSST, LSST cannot observe in the infrared. There is an additional SNAP complementarity to a large-volume LSST weak-lensing mass cluster and cosmic shear survey: The SN derived error ellipsoids in w - Ω_M space are nearly *orthogonal* to those from cluster counts or cosmic shear.

Moderate-redshift Supernovae

Supernova surveys over a wide redshift range are needed. While it is probable that much moderate redshift supernova work relating to the average value of *w* will have been done by 2013 using existing ground-based telescopes (including CFHT, PanSTARRS, and HST), LSST will discover 100,000 supernovae per year in the range $0.1 < z < 1$. Statistics of color and light curves, together with sample spectra, will enable studies of "third parameter" dependencies, shedding light on any systematic errors in supernova measurements. More interestingly, with hundreds of thousands of SN spread all over the sky, anisotropies may be detected: flows and spatial and temporal variations of *w* would be revealed. If it were found that *w* is different in different directions, this result would have very important implications for fundamental physics.

In this area, the faint stellar FOM applies. SNAP will provide a large number of supernova detections in this redshift range, but over only a small region of the sky. PanSTARRS will prove 15% as powerful as LSST, but unless very long exposures are employed, the supernovae found by PanSTARRS will be over a much smaller range in distance.

Weak Lens Tomography

There are two ways in which measuring the gravitational shear of background galaxies as a function of their redshift may be used to pin down cosmological parameters: measuring the co-moving volume versus redshift via massive cluster counting, and measuring mass structure growth via the redshift dependence of cosmic shear. Both of these rely on imaging as much of the sky as possible in order to reach a large volume with resolved sources and to measure structure on small scales. Both measurements are both free of astrophysical systematics.

Co-moving volume and mass over-density are exponentially sensitive to *w,* and they change much more rapidly as a function of redshift than the luminosity distance measured by supernovae. It is critical to do mass measurements in a way that measures total mass directly and is not biased toward the visible baryons. One can accomplish this goal with weak gravitational lens 3-D mass cluster tomography using color-redshifts of billions of background galaxies and their shear, but one needs a large sample of clusters in to get to percent level precision on *w*. To obtain maximum volume, it is better to go wide in a survey than deep; this insures resolved source galaxies at redshifts greater than two, and trades the number density of sources for brighter galaxies (< 26 V mag) and depth for area on the sky. It also guarantees detection of any directional dependence of *w*. With 200,000 massive clusters in a decade-long survey of 20,000 square degrees, LSST is the facility of choice as is clearly shown by a comparison of the galactic figures of merit.

While SNAP surveys a far smaller area, it can resolve and measure shear in fainter galaxies in 1% of LSST's survey area thus increasing the source density and mass resolution, as will HST's Advanced Camera for Surveys, but such systems cannot reach the required LSST weak lens survey volume. By time-sharing with its single, wide-band planetary survey, PanSTARRS may undertake a shallow wide area weak lens survey with limited color-z, which nevertheless could be state of the art by 2010. With its lower resolution and brighter limiting magnitude, a PanSTARRS weak lens survey will be to LSST what the COBE mission was to WMAP in measuring the microwave background.

One can combine measurements of the microwave background anisotropy with weak lens measurements of cosmic shear and mass tomography of lenses over the redshift range $0.1 < z < 1$. This will enable precision measures of *w* as well as of the spectrum of the primeval density fluctuations. While the CMB anisotropy is not sensitive to the dark energy, it is helpful for probing dark energy when combined with LSST because of the degeneracies it breaks: With the dark matter density determined well from CMB data, departures of LSST data from the CMB prediction can be ascribed to dark energy. Combining these two measurements will pin down *w* to the percent level as well as tightly constrain the initial power spectrum. These two weak lens techniques are subject to somewhat different systematics, and their degeneracy line in w - Ω_M space is orthogonal to that of SN based measurements of luminosity distance vs. z. Again, weak lens shear data over 20,000 deg^2 is crucial, as is reaching fainter sources to extend the range in redshifts. With a figure of merit more than five times that of PanSTARRS, only LSST can provide sufficient coverage of the sky as deeply as required.

PRACTICAL CONSIDERATIONS

We have commented on the poor performance of a scaled-up ManySTARRS design in the time window FOM. This approach to obtaining large collecting area may have other shortcomings as well.

A first multi-gigapixel camera, essential to both designs, is likely to cost tens of millions of dollars. To be cost-competitive over a single-telescope design, the cost per camera would have to be reduced by a least a factor of ten in quantities of twenty-two. While such economies of scale might be realized in producing the raw silicon detectors (going, e.g., from 1000 devices to 22,000 devices), the cost of these detectors is probably rather less than 90% of the total cost of a camera; fabrication costs will likely remain high.

Extrapolating from current observatory experience, the maintenance and operations cost of 22 1.8-m telescopes is significantly greater than that of a single 8-m telescope. The complexity, in terms of the number of operating components, of the multi-telescope system would be more than ten times higher than a single 8-m class telescope. Given the current mean time between failure for large telescope systems, without significant advances in reliability the ManySTARRS approach would require building and operating several telescopes as spares.

Without a strong scientific case for dividing aperture among many detectors, one must conclude that associating all of the available aperture on a camera system is the most effective, and cost effective, approach.

APPENDIX II: LSST SUPPORTING TECHNICAL INFORMATION

OPTICAL DESIGN

BASELINE PRESCRIPTION

Surface	Description	Radius (Meters)	Thickness (Meters)	Glass	Clear Aperture (Meters)	k	Aspheric Coeffs.		
							r^6	r^8	r^{10}
1		∞	0.91141						
2		∞	4.71446						
3	Primary	-17.7597	-4.71446	Mirror	8.4	-0.9603	-1.04 E-10		
4		∞	-0.91141						
5	Secondary	-6.15723	0.91141	Mirror	3.36	-0.1604	-1.32 E-05	2.41 E-08	-9.78 E-08
6		∞	4.03945						
7		∞	0.53076						
8		∞	3.79256						
9	Tertiary	-8.41245	-3.69256	Mirror	5.0	0.01685	4.22 E-07	6.50 E-09	
10		∞	0.0						
11	L1 (front)	-1.73861	-0.06948	Silica	1.34	0.0			
12	L2 (back)	-2.68891	-0.28794		1.34	2.05297	1.96 E-02	1.45 E-05	
13		∞	0.0						
14	L2 (front)	-4.09767	-0.03000	Silica	1.02	0.0			
15	L2 (back)	-1.29129	-0.03040		1.02	-0.6460	-5.95 E-02	-7.10 E-02	
16		∞	0.0						
17	Filter	-3.35600	-0.01467	Silica	0.68	0.0			
18	Filter	-3.35600	-0.02299		0.68	0.0			
19	L3 (front)	-2.01828	-0.03094	Silica	0.64	0.0			
20	L3 (back)	-12.4694	-0.05000		0.64	0.0			
21	Image	∞			0.55				

SENSITIVITY ANALYSIS

The position sensitivity of the primary, secondary, tertiary mirrors, and the instrument assembly was investigated. This was not a tolerance analysis. Instead, the goal was to identify how precisely the major telescope components must be held during the measurement cycle. The telescope is assumed perfect at the outset. Perturbations were applied singly to each component and were uncompensated. The perturbations on the mirrors were all rigid body motion about the vertex (real or virtual) of the individual surfaces. The instrument assembly was also subject to rigid body motion, with the origin

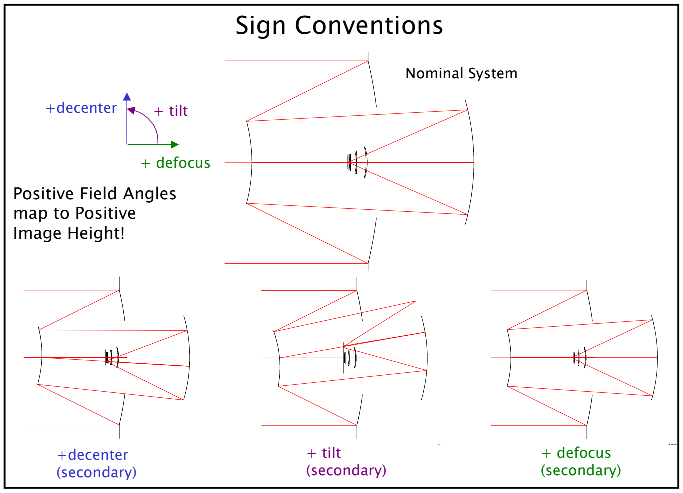
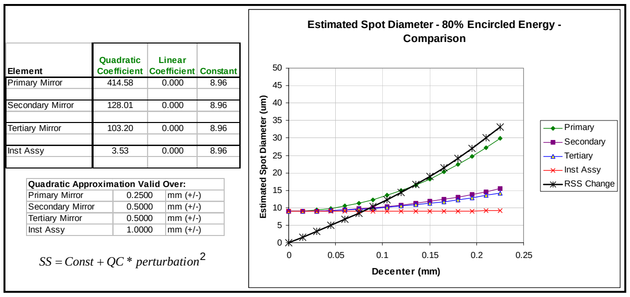


Figure 1 Rigid body perturbations and sign conventions

being coincident with the front surface vertex of Element 1.

The perturbations applied to each element were lateral decenter, axial decenter (defocus), and tilt about an axis perpendicular to the optical axis (see Figure 1). Nine field points, distributed across the entire field of view, were used to assess image quality, boresight error (for tilt and decenter), and, for defocus, the resulting plate scale variation. Image quality was assessed as the growth in the blur diameter for both the 50% and 80% diffraction encircled energy spots. Boresight error is simply the change from zero of the on-axis ray intercept at the target plane divided by the focal length. Plate scale error was assessed as the change in the effective focal length of the telescope.

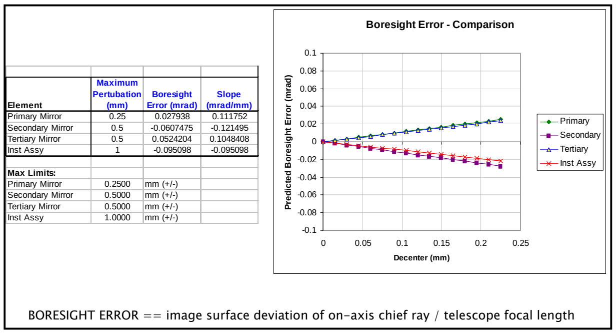


Element	Quadratic Coefficient	Linear Coefficient	Constant
Primary Mirror	414.58	0.000	8.96
Secondary Mirror	128.01	0.000	8.96
Tertiary Mirror	103.20	0.000	8.96
Inst Assy	3.53	0.000	8.96

Quadratic Approximation Valid Over:		
Primary Mirror	0.2500	mm (+/-)
Secondary Mirror	0.5000	mm (+/-)
Tertiary Mirror	0.5000	mm (+/-)
Inst Assy	1.0000	mm (+/-)

$$SS = Const + QC * perturbation^2$$

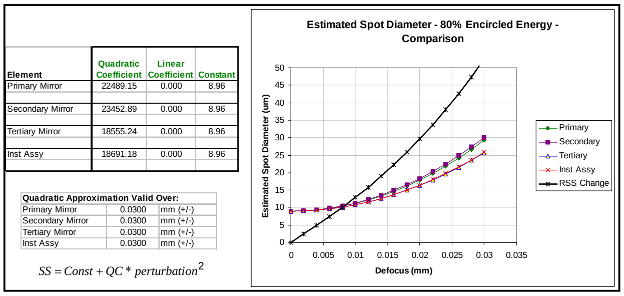
Figure 2. Element decenter (mm) and 80% diffraction encircled energy spot size degradation.



Element	Maximum Pertubation (mm)	Boresight Error (mrad)	Slope (mrad/mm)
Primary Mirror	0.25	0.027938	0.111752
Secondary Mirror	0.5	-0.0607475	-0.121495
Tertiary Mirror	0.5	0.0524204	0.1048408
Inst Assy	1	-0.095098	-0.095098
Max Limits:			
Primary Mirror	0.2500	mm (+/-)	
Secondary Mirror	0.5000	mm (+/-)	
Tertiary Mirror	0.5000	mm (+/-)	
Inst Assy	1.0000	mm (+/-)	

BORESIGHT ERROR == image surface deviation of on-axis chief ray / telescope focal length

Figure 3. Element tilt (mrads) sensitivity and 80% diffraction encircled energy spot size

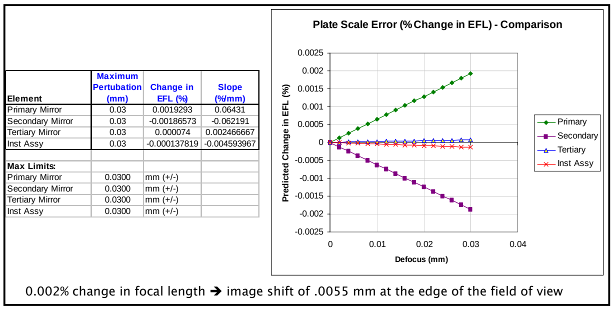


Element	Quadratic Coefficient	Linear Coefficient	Constant
Primary Mirror	22489.15	0.000	8.96
Secondary Mirror	23452.89	0.000	8.96
Tertiary Mirror	18555.24	0.000	8.96
Inst Assy	18691.18	0.000	8.96

Quadratic Approximation Valid Over:		
Primary Mirror	0.0300	mm (+/-)
Secondary Mirror	0.0300	mm (+/-)
Tertiary Mirror	0.0300	mm (+/-)
Inst Assy	0.0300	mm (+/-)

$$SS = Const + QC * perturbation^2$$

Figure 4. Defocus (mm) sensitivity and 80% diffraction encircled energy spot size degradation.



Element	Maximum Pertubation (mm)	Change in EFL (%)	Slope (%/mm)
Primary Mirror	0.03	0.0019293	0.06431
Secondary Mirror	0.03	-0.00186573	-0.062191
Tertiary Mirror	0.03	0.000074	0.002466667
Inst Assy	0.03	-0.000137819	-0.004593967
Max Limits:			
Primary Mirror	0.0300	mm (+/-)	
Secondary Mirror	0.0300	mm (+/-)	
Tertiary Mirror	0.0300	mm (+/-)	
Inst Assy	0.0300	mm (+/-)	

0.002% change in focal length ➔ image shift of .0055 mm at the edge of the field of view

Decenter Sensitivity

Spot size growth is assumed to be purely quadratic over the range of motion evaluated. The quadratic coefficients of each element and the range over which the approximation is valid is shown in Figure 2. The primary mirror is the most sensitive to centration errors.

Tilt Sensitivity

As was the case with decenter, the change in the encircled energy spot size grows quadratically with angle. Once again, the primary mirror has the highest sensitivity (Figure 3). Of note is that the tilt angles, while small, introduce a displacement error at the edge that can be resolved using current sensing technology.

The boresight error resulting from element decenters and tilts is linear.

Defocus Sensitivity

The sensitivity analysis for defocus showed that all major components contribute nearly equally to spot size growth and that the sensitivity coefficients are quite high, meaning that small perturbations lead to rapid change. It also shows that moving any one major component is as effective as any other for focus compensation.

Plate scale change was assessed by calculating the new paraxial focal length after each perturbation. Because the range of motion turns out to be quite small, the change in focal length is not significant, as shown in the following figure. Both the primary and secondary mirrors contribute in nearly equal magnitude, although the sign is different, indicating that motion in the same direction causes a reduction for one mirror and an increase for the other. For reference, a change in the focal length of 0.002% shifts the image 5.5 microns at the edge of the field of view. This calculation is based on the following relationship between focal length and paraxial object height.

$$\partial H = \left(1 + \frac{\Delta\%}{100}\right) \cdot EFL_0 \cdot \tan(1.5)$$

The paraxial focal length of the telescope used in the calculation is 10500 mm.

Preliminary Baffle Design

The analysis conducted by Photon Engineering Inc. includes the evaluation of baffle concepts and to identify possible baffle locations and their impact on fractional throughput. Of concern is the identification of specular illumination paths that reach the image surface. This task does not include either scatter or ghost image analyses. To complete this task, an optical system model was imported into FRED, Photon Engineering's commercially available optical engineering software (Figure 6). FRED is a generalized non-sequential raytrace analysis program that allows for the creation and analysis of optical and opto-mechanical system models.

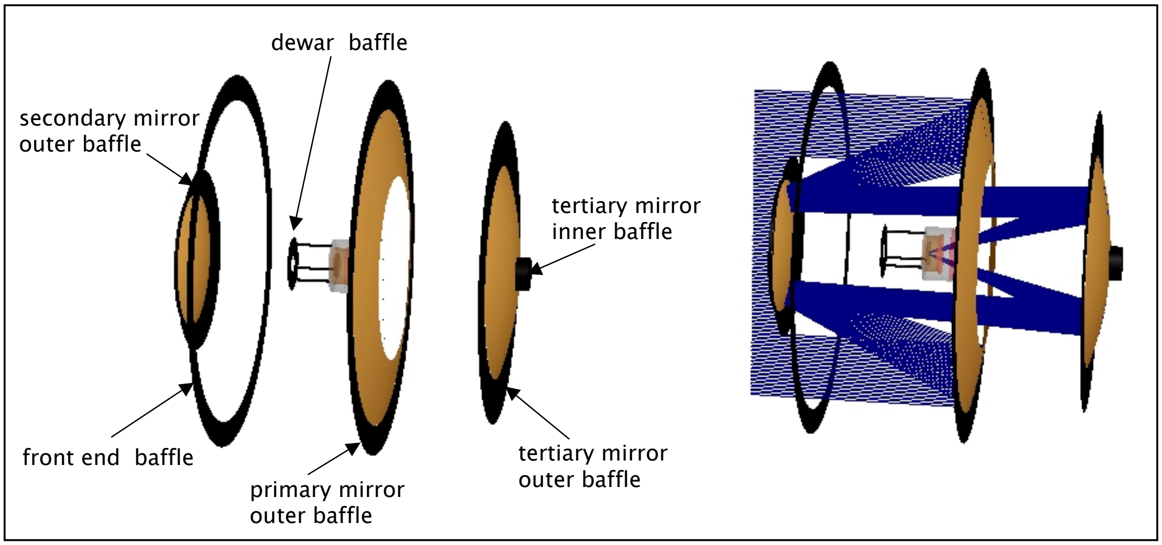


Figure 6. FRED model of a baffled telescope showing suggested baffle configuration

The most efficient way to identify potential stray light paths is to launch rays from the detector surface backwards through the optical system. Doing so provides a first look at what the detector 'sees.' This technique identifies one potential specular path from outside of the field of view, shown in Figure 7 below. Figure 8 shows the raytrace of this path. Light incident on the telescope near an object space angle of 7.5 degrees strikes the primary and secondary mirrors in normal fashion. It then strikes the tertiary mirror, and, because the angle of incidence on the tertiary is nearly normal, is reflected back towards the secondary mirror. From the secondary mirror, light is reflected back again towards the tertiary mirror. The instrument assembly blocks most of the light on its return to the tertiary, but the remaining portion passes by and eventually reaches the detector along the normal imaging path. Although the net flux is quite low (~0.14%) and the image formed on the detector is diffuse, light traveling along this path would likely be detected by the instrument, resulting in measurement artifacts and erroneous data. Figure 9 shows the irradiance distribution arising from an extended source to give an indication of the breadth of the problem. Point objects would not produce the same result, as they illuminate substantially less area.

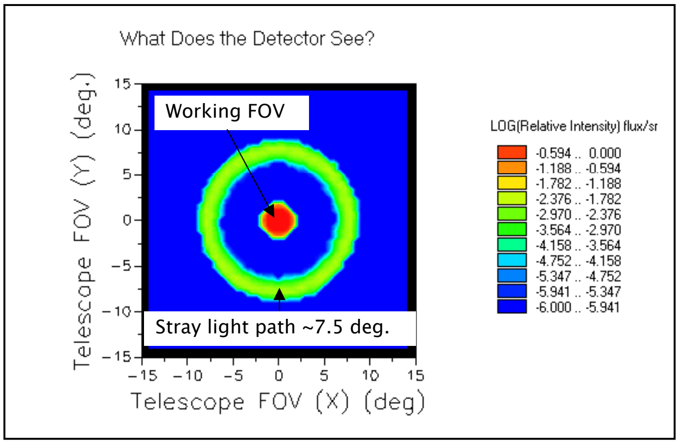


Figure 7. Relative intensity plot (in object space) shows a significant stray light path occurring at ~7.5 degrees off-axis. Tracing rays out from the detector generated these results.

A single baffle located between the back side of the instrument assembly and the secondary mirror is all that is needed to suppress this path (Figure 15). It does not affect the fractional throughput because it is located in the shadow of the primary mirror obscuration. An alternative would be to place an annular baffle around the instrument assembly itself, but this baffle could potentially block light incident inside the field of view, thereby lowering throughput. Another advantage of moving the dewar baffle away from the instrument assembly is that it can be oversized slightly to block rays from striking the assembly at near grazing incidence, where most surfaces, even those painted black, exhibit high reflectivity.

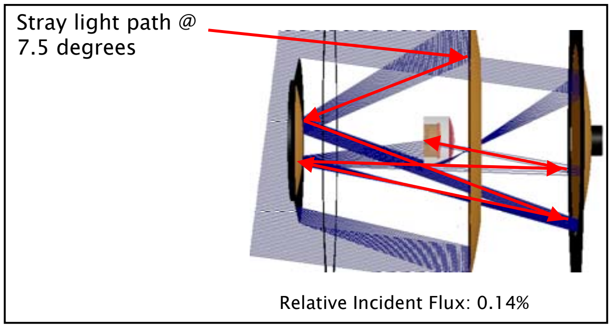


Figure 8. Illustration of stray light path.

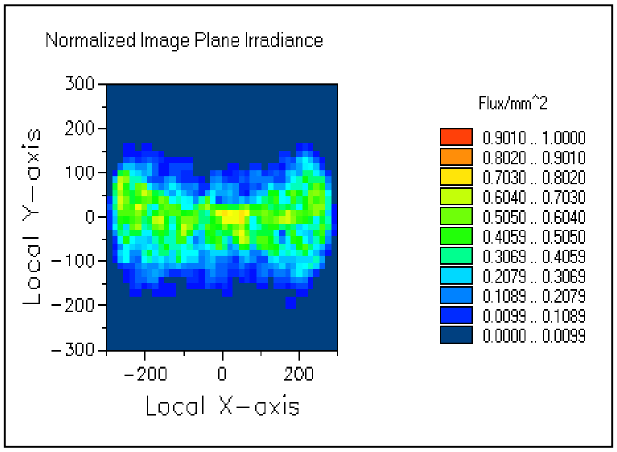


Figure 9. Irradiance distribution on the image plane arising from an extended source tilted 7.5 degrees and emitting into a half angle cone of 1.5 degrees.

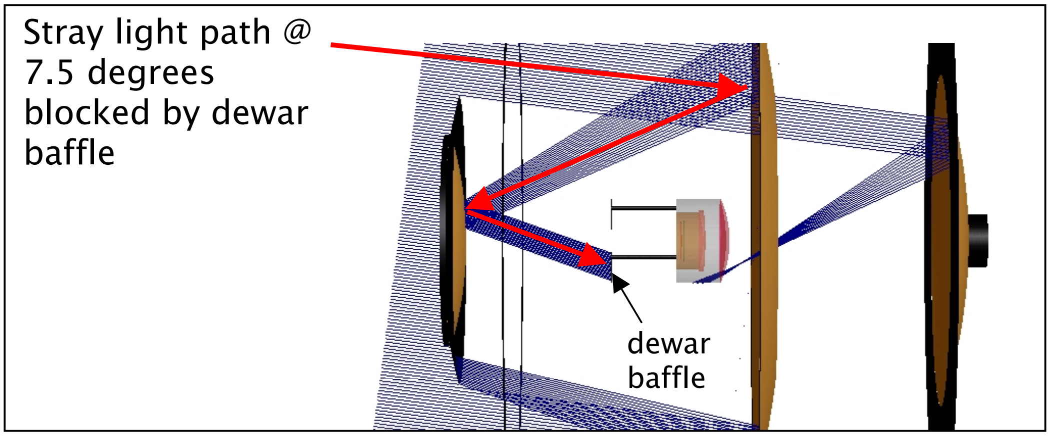


Figure 10. Blocking effect of the dewar baffle.

Other paths exist which may not illuminate the detector directly, but can illuminate areas proximate to the detector active area, thereby increasing susceptibility to scattered light. One such path arises if the secondary mirror baffle (or obscuration if no baffle is used) is smaller than the hole in the primary mirror (Figure 10). Light that misses the secondary mirror and passes through the hole in the primary focuses inside the instrument ensemble. These rays are diverging quickly, but do manage to pass through Element 2. An on-axis source illuminates the inside wall of the inner dewar and perhaps even the active area if the secondary mirror obscuration is much smaller than the hole in the primary mirror. Of more concern is light originating from a source located near the edge of the field of view because the rays that miss the primary and secondary mirrors can form an arc opposite the desired image inside the active area of the focal plane. This problem is again easily remedied by ensuring that the secondary mirror baffle is close to the same size as the hole in the primary.

PHYSICAL OPTICS: FABRICATION

The Secondary Mirror Concept

The LSST secondary mirror baseline design is a 3.42 m (137") diameter, 0.6 m (23.44") thick convex mirror weighing 3260 kg (7177 lbs). The support error allocation is derived from the error budget in use for large optical telescopes at Steward Observatory. The budget for the LSST secondary has been scaled by the difference in the pupil demagnification between the LBT f/5.2 and the LSST secondary. The LBT f/5.2 pupil demagnification is 4.25, that of the LSST is 2.413. The MMT f/15 secondary budget scales to the LSST secondary as shown in Table 2. This budget represents a different allocation of errors but the support allocations are similar for the two cases. The LSST secondary requirement is taken as $255*\cos(\upsilon_{elev})$ cm

Table 1. (left) secondary error budget scaled from the f/5.2 LBT secondary budget. Table 2. (right) secondary error budget scaled from the f/15 MMT secondary budget.

Budgeted Item	Budgeted R0		
	cm		
Polishng	264		
Testing	528		
Wind Forces	493	Pupil Demag	2.413
Ventilation Errors	493		
Homogeneity Errors	493		
Reflective Coating	793		
Axial Support	493		
Lateral Support	493		
Actuator Errors	493		
Total	123		
Support	255		

Budgeted Item	Budgeted R0		
	cm		
Polishng/Testing	190		
Wind Forces	373		
Ventilation Errors	373	Pupil Demag =	2.413
Homogeneity Errors	373		
Reflective Coating	698		
Axial Support	246		
Total	104		
Support	246		

The LSST secondary mirror is shown in Figure 11. This is a 137-inch (3.48 m) diameter mirror with a center thickness of 24.127 inches (0.613 m). The best-fit spherical radius for the optical surface is 261.614 inches (6.645 m). The secondary has a back sheet thickness of 1.5 inches (3.81 cm), and a face sheet of similar thickness except near the OD where the fabrication process requires that the internal surface of the face sheet be parallel to the back surface resulting in an increase in the average face sheet thickness toward the OD. The shape of the machined cells is selected based on the use of a mushroom shaped grinding wheel of 6 inch (15.24 cm) diameter mounted on a 3.0 inch (7.62 cm) shaft (see Figure 12). The mass properties of the LSST secondary are as listed in Table 3.

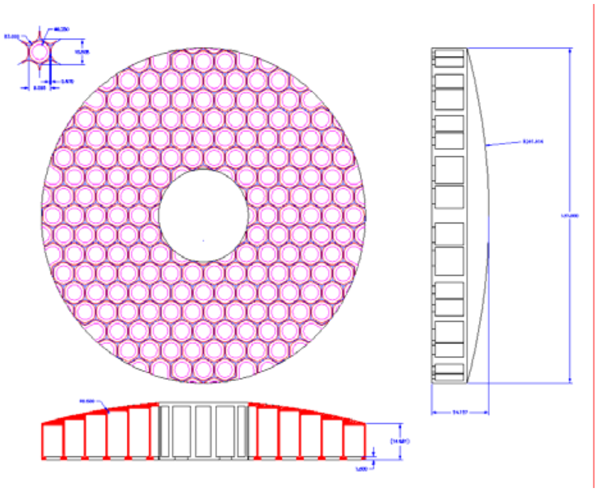


Figure 11. LSST Secondary mirror blank layout

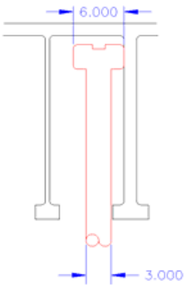


Figure 12. Machining Concept for the mirror.

Weight	7176	lbs	3262	Kg	
CG	11.494	inches	29.195	cm	Forward of the back surface
Ixx, Iyy	26,590	in-lb-sec^2			
Izz	45,340	in-lb-sec^2			(Izz is about the optical axis)

Figure 13. LSST Secondary baseline mass properties.

The LSST secondary is supported through load spreaders bonded to the back of the mirror as shown in Figure 14. Eighteen three puck and 22 two puck load spreaders are used. Three puck load spreaders carry axial and lateral loads, two-puck load spreaders carry axial loads only. Three of the triple puck load spreaders are fixed in position relative to the secondary cell. Force break-away mechanisms will be implemented at these locations to prevent overloading during seismic events, handling or axis acceleration. A normally non-contacting spring support system adapted from UA 6.5 and 8.4 m mirror support systems will provide backup support for loads in the cross-lateral (parallel to the elevation axis) direction and to support the mirror during installation and maintenance of the operational supports. One of the spring support elements is shown in Figure 15.

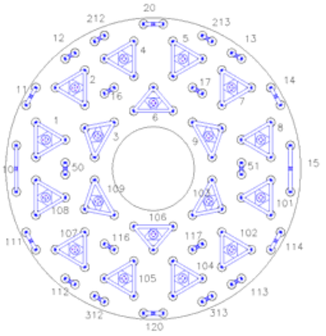


Figure 14. Load spreader layout for the LSST baseline secondary.

The axial force actuators can be equipped with load cells and an active force capability if this is required (as for the compensation of thermal distortion due to thermal expansion in-homogeneity). The axial units must provide sin(υ_{elev}) and cos(υ_{elev}) force components so two separate counterweights in the same pivot axis are employed permitting the sine and cosine components to be separately adjusted as required at each location. The axial actuator provides a compressive rod load when oriented as shown. If a tensile load is required, the counterweight beam is placed above the connecting rod. Tapered roller bearings are used at all rotating joints including the two universal joints in the connecting rods.

It is normal practice to figure the mirror based on testing performed with the mirror nadir pointing and supported at the same locations with the same forces as will be used in the telescope at this orientation (telescope zenith pointing). This procedure results in telescope zenith pointing gravity effects being polished out of the secondary so that the best optical performance is achieved for this orientation. As the telescope slews toward the horizon, distortion due to lateral gravity reacted by the actuators appears along with distortion resulting from the reduction of axial gravity and axial support forces. More distortion is allowed away from zenith pointing, as was discussed above, so the mirror figure error from mounting and gravity effects remains less than the budgeted limits as will be shown below.

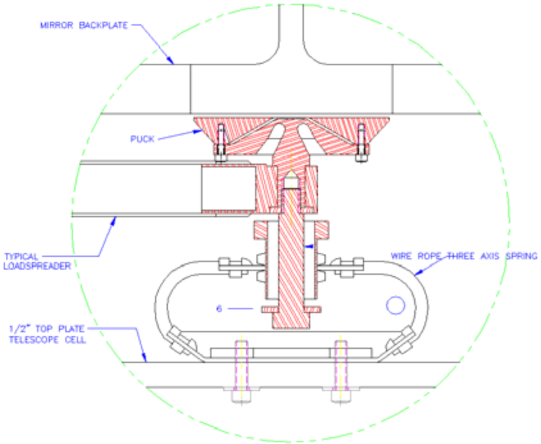


Figure 15. Normally Non-Contacting Auxiliary Support, Located at Each Puck on the Triple Puck Load-Spreaders

Secondary Mirror Fabrication

The basic steps required to fabricate the LSST secondary are given in the table below. Included in this table are the process stage, tools required, and metrology type for the required precision.

Process	Tools	Metrology	Precision
Blank Fab.	Diamond Generate	Direct measure	0.5mm
Form best fit sphere	Tile faced rigid lap	Spherometer, test plate	2.0μm
Aspherize	Numerically controlled stressed lap using metal pads	Profilometry	0.1μm
Polish Figure	Numerically controlled stressed lap using pitch pads	Stitched interferometry	0.02μm

We start work on the optical surface by grinding it to the best-fitting spherical surface. This is done for several reasons. First, it is easy to achieve a good sphere using a large rigid tile-faced tool. Large grits and long running times can be used to achieve rapid removal and the sphere can be readily figured to a few microns. As long as we support the mirror correctly, it will take a spherical shape after running with the large rigid tool. We count on this surface to be free of azimuthal variations, as we have no good way to make a full surface map until the part has been aspherized and can be measured optically. The shape during spherical grinding is monitored with spherometers and subaperture test plates. We will verify that the part does not have large azimuthal errors using a large bar spherometer and making profilometer scan across several diameters, but we will not be able to see the small-scale figure errors until the interferometric test can be performed when the mirror is near completion. It is important that we start with a good sphere.

The convex secondary mirror of the LSST requires a large amount of positive spherical aberration, meaning that material must be removed from the 70% zone relative to the center and edge. We will use both large, flexible laps and smaller computer controlled active laps for asphering. The rough-ground surfaces are measured using a swing-arm profilometer. The profilometer is mounted to the secondary polishing machine to allow rapid measurements for guiding asphering and rough figuring. The instrument at the University of Arizona's Optical Science Center – Steward Observatory Mirror Lab measures surface profiles with 50 nm rms accuracy so it also provides verification of the interferometric CGH test.

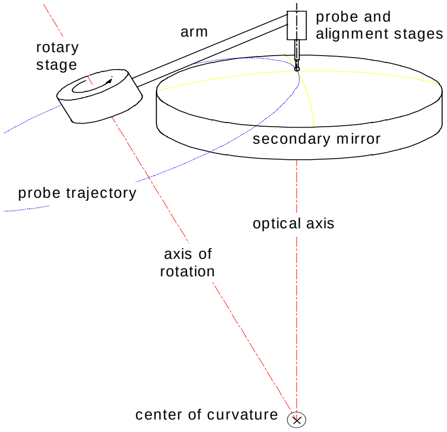


Figure 16. Geometry for the swing arm profilometer

The swing-arm profilometer uses an LVDT indicator at the end of an arm to make mechanical measurements of the optical surface. The geometry for this test is shown in Figure 16. The probe is mounted at the end of an arm that swings across the test optic such that the axis of rotation goes through the center of curvature of the optic. The arc defined by the probe tip trajectory (for no change in probe reading) lies on a spherical surface defined by this center. This is the geometry used for generating spherical surfaces using cup wheels. For measuring the aspheric optics, the probe, which is aligned so its travel is in the direction normal to the optical surface, reads only the surface departure from spherical.

The accuracy of the profilometer was assessed using two methods. When the Sloan mirror was nearly spherical, the same arc on the surface was scanned with the arm mounted at different orientations on the rotation stage. The difference between these scans shows the expected bearing errors of 40 nm rms. Also the profilometry of the nearly finished mirror shows agreement with the data from the holographic test plate of about 50 nm rms. Since the profilometer always measures relative to a virtual reference sphere, it does not give the absolute radius of curvature of the part. We control the radius by measuring it carefully when the part is ground spherical using a sub-aperture concave test plate. We grind small dimples into the surface of the mirror, one at the center, and the other outside the clear aperture. The profilometer is used to measure the depths of these while the part is spherical. Then, during asphering, the dimple depths are measured routinely and a direct calculation gives the radius of curvature of the asphere given the initial radius of the sphere, the change in dimple depths due to material removal, and the aspheric departure of the mirror. We track the asphering progress by plotting the vertex radius of curvature R against the conic constant K.

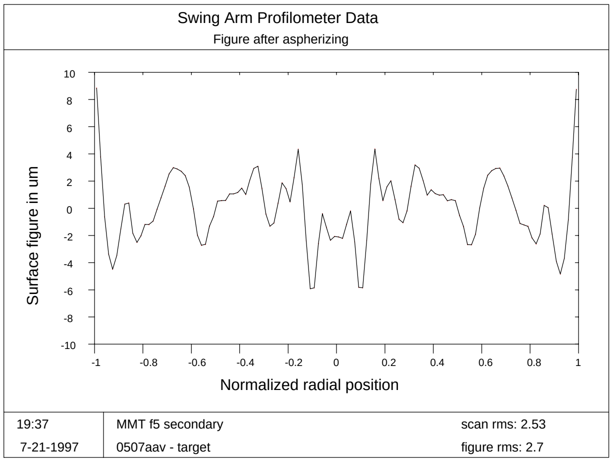


Figure 17. Profile of figure errors after asphering the MMT *f*/5 secondary mirror. This is computed by subtracting the ideal shape.

The final stage of fabrication is polishing and figuring the surface to meet its specifications in surface quality and aspheric terms. The key to this final stage is controlling the polishing process and being able to test the resulting surface interferometrically. The Steward Observatory Mirror Lab has demonstrated a high degree of surface control on convex aspheric secondaries using its numerically controlled stressed lap polishing. Some scaling of this technology will be necessary to accommodate the LSST secondary's large 3.5m diameter, but this does not represent any fundamental impediment. Thus, the challenge is in the interferometry.

G. Sommargren (LLNL) studied the feasibility of measuring the LSST secondary with interferometry. Full aperture interferometry of the LSST is prohibitively difficult for two reasons. First, the fringe density would require a large digital camera to capture with enough precision the full fringe pattern. No such camera is commercially available and would have to be custom built and would greatly increase the fabrication cost of the LSST secondary. Second, in order to generate the reference wave front optics that are comparable in size to the secondary mirror (3.5m in diameter) would have to fabricated. This too would drive the cost and complexity of fabricating the LSST secondary.

G. Sommargren has proposed using sub-aperture interferometry stitched together to form a full aperture test. Figure 18 shows the proposed sub-aperture relative to the full aperture interferograms. This geometry requires a minimum of 12 sub-apertures for complete coverage of the secondary. There is approximately 32% of overlap of an individual aperture with its neighbors. This over lap is used to determine a global least squares solution to determine the full aperture estimate from the sub-apertures. Sommargren has analyzed several sources of errors and their effect on the estimation of the full aperture surface and are summarized in Table XX. The total RSS error from these sources of the final estimated full aperture surface is 15.2nm.

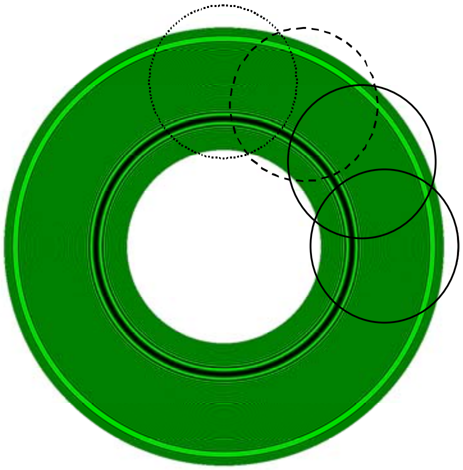


Figure 18. The sub-aperture stitch pattern shown over the full aperture interferogram.

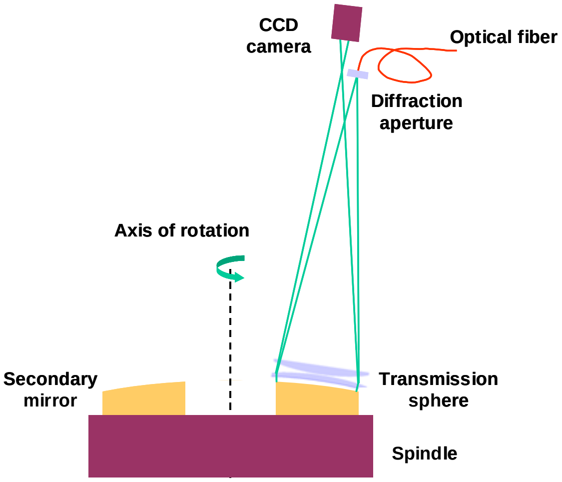


Figure 19. Geometry for the sub-aperture interferometer.

Error Source	Error Magnitude	RMS Error in Estimated Surface
Random noise:	Phase=10nm, Piston=1μm, titlts=1μradian	1.9nm
Magnification:	0.0005	4.3nm
Distortion:	0.0005	2.4nm
Location of rotation axis:	200μm	5.9nm
Non-concentricity	200μm	5.9nm
Air bearing wobble (random):	3μm	6.7nm
Air bearing wobble (sinusoidal):	5μm	7.0nm
Low order interferometer errors:	10nm each for spherical, astigmatism and coma	6.2nm

Transmissive Optics

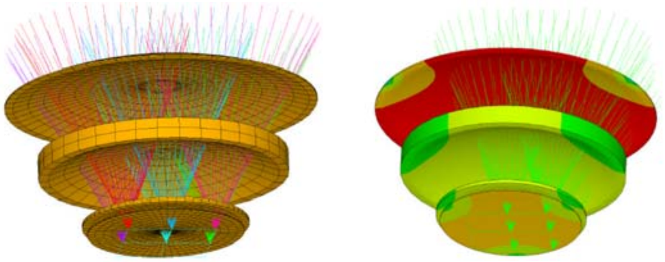


Figure 20. The Finite element model (left) used in the deformation analysis. The three-point boundary condition example (right) is the worse case model.

We have investigated two fundamental issues regarding the feasibility of the large trasmissive optics in the LSST optical design. First, the lenses in the LSST optical design are large by any standard. They are also relatively thin, most notably the first refractive element. This leaves the potential for self-deformation from gravity as an uncorrectable figure error. Under contract from NOAO, ROM Engineering Inc. conducted a detailed finite element and raytrace analysis to evaluate the sensitivity of image quality on the deformation of the LSST lenses. In this analysis eight boundary conditions were examined in two orientations with respect to gravity to explore the range of deformations under different assumptions on how the lenses were supported. Each model was evaluated for total transmitted wavefront error, image degradation and field distortion through the system of 4 deformed tranmissive elements. Additionally, each element was analyzed to determine the maximum internal stress with respect to the yield strength of fused silica and the condition for birefringence.

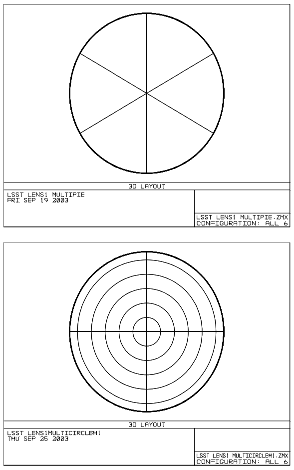


Figure 21 Model geometries used in homogeneity study

For all metrics the worse case model was a simply supported boundary condition at three descete location about the lens edge. Maximum deformation occurs in the case where the optical axis is parallel to the gravity vector. Because of its high aspect ratio first lens shows the greatest deformation of approximately 45μm. However, because both font and back surface of the lens deform nearly identically the wavefront error produced is quite small and tolerable, roughly 0.1 wave at λ=0.5μm. The diffraction encircled energy in the worse case increases by <5% over the entire field of view independent of wavelength over the unperturbed design. The maximum geometric distortion of the unperturbed design is 0.2249%, the worse case distortion is essentially unchanged at 0.2252%. In summary, this study shows that self deformation of the lenses under the influence of gravity has negligible effects in the optical performance of the LSST optical system.

The second issue studied was the availability of suitable material for the lenses. Due to their size it was uncertain whether fused silica of sufficient quality is available for the fabrication of the LSST lenses. Schott Glass Inc. rates fused silica in homogeneity classes H1-H4 based on the variations of the index of refraction across the substrate, where the higher grade number indicates higher uniformity. M. Liang (NOAO) has examined the effects of varying homogeneity classes in two possible segment geometries (Figure 21). For each case a Monte-Carlo simulation was carried out assigning each segment an index of refraction value within the range allowed for the given homogeneity class. The resulting lenses was then inserted into a raytrace model and evaluated for image quality. The worse case (circular zoned segments) results for homogeneity classes H1, H2 and H3 are shown in Figure 22. These results show that is possible to maintain reasonable control over image quality with a homogeneity class as low as H2, however H3 is preferred.

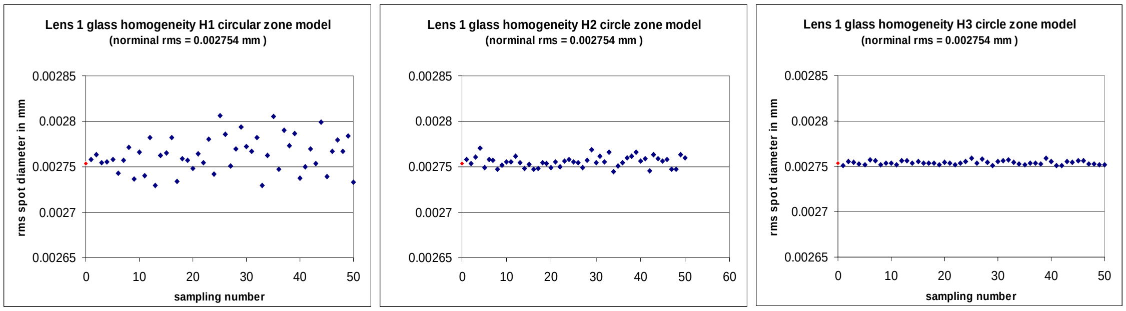


Figure 22. Variations in RMS spot size for 50 Monte-Carlo models of L1 using the H1 (left), H2 (center) and H3 (right) homogeneity specifications.

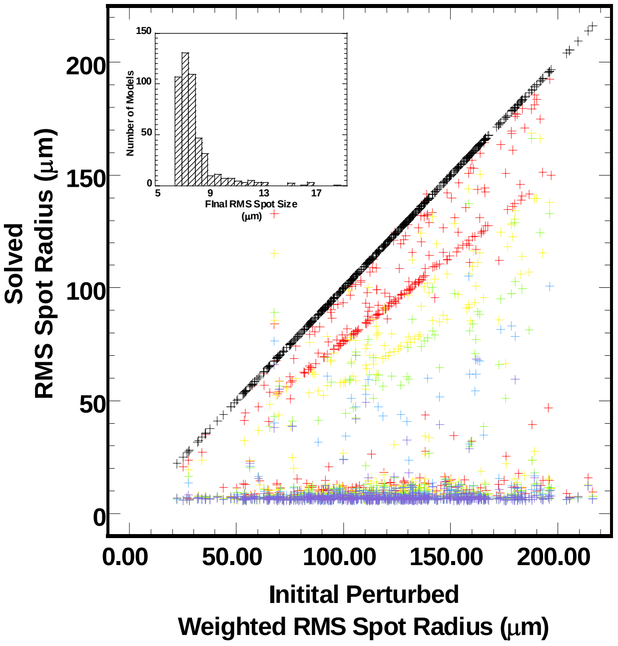


Figure 23. Successive solutions based on wavefront analysis to the LSST optical system as it has been perturbed in 48 degrees of freedom are shown. Each of 500 models is followed through 5 iterations (black = initial, red = 1st, yellow = 2nd, green = 3rd, blue = 4th and purple = 5th) relative to their initial perturbed image quality. The histogram inset shows the distribution in system image quality after 5 iterations.

Alignment Strategy

The fast optical system of the LSST places stringent requirements on alignment and surface tolerances that raises two questions: First, can the optical system once made be assembled to the level of precision as to deliver the required image quality? Second, once assembled, can the optical system be maintained in such away as meet the image quality requirements?

In answer to the first question a preliminary Monte-Carlo analysis on the effects of perturbing 48 degrees of freedom (rigid body position of the three mirror plus surface bending modes 9 each on the secondary and tertiary and 15 on the primary) shows that within a few iterations least square fitting of wavefront aberrations measured in 5 positions through out the field of view can be used to converge the LSST optical system. Acceptable performance from initial errors in assembly and fabrication are typically achieved with fewer than 5 iterations (see Figure 23).

DETECTOR ARRAY TECHNOLOGY

An ongoing NSF supported effort will evaluate state-of-the-art technologies including thick high-resistivity silicon back-illuminated CCDs and hybrid silicon photodiode-CMOS array detectors to develop a suitable candidate detector for the FPA. We describe here in more detail the program for this study leading into this D&D phase.

Recent advances in CMOS and CCD plus ASIC hybrid imagers can now be applied to this 2.3 Gpixel camera. Parallel multiplexing many discrete modules allows for fast readout, which will be critical for efficiency, as exposure times must be short. The clocking electronics will be integrated with the individual detectors, and there are several attractive options for analog and digital ULSI packaging that minimize the interconnections. Each module will consist of a thick silicon detector for high QE over the full wavelength range from 350 nm to 1050 nm.

The LSST's large focal plane and the required short exposure times make the traditional approach of CCD plus mechanical shutter difficult to implement. LLNL has developed a shutter concept for the LSST that would be capable of at least one million exposures, or more than one year of LSST operations. However, hybrid CMOS detector arrays with integrated ASIC electronics, originally developed for IR arrays, are now being produced for visible-wavelength applications and would eliminate the need for a mechanical shutter. Work is in progress on both monolithic and hybrid CCD array + readout electronics solutions to our module requirements. Bump bonding of the photodiode array to the CMOS readout chip requires facilities currently available only at a very few select commercial sources. The design of the high performance photo diode array will require expertise from collaborating research institutions. This will be primarily in the areas of the dark current noise, guard rings, maximizing the active area, and the entrance windows. Collaborating research institutions will be largely responsible for the CMOS design with very low noise (~5 rms e) and for the design of readout architecture allowing fast data acquisition with minimal digital noise. There has been significant recent progress in CMOS-CMOS imager-ASIC fabrication. The initial NSF funded LSST detector technology assessment program now being aggressively pursued and will end in the middle of the D&D phase with a single vendor and detector module design.

During the D&D phase, we propose to design the focal plane and complete the tests of a cost-effective imager module, whether based on CCD or CMOS technology. We will undertake the engineering for the FPA, including module parallelism and flatness tests. We will also design the necessary testing and quality assurance programs that will be crucial during the imager module delivery and acceptance phase. The full requirements specifications are shown on the next two pages.

CMOS Specifications:

LSST CMOS Array Requirements

Priority

High	🟩
Moderate	🟨
Low	🟥

				Allowable Range	Target	Units
	Physical:					
🟨		**Format(1-side)**		>= 2048	>= 2048	**pixels**
🟩		**Pixel size**		8-12	10	**microns**
🟩		**Flatness Deviation**		<=10	<=5	**microns**
🟥		**Outgassing**		<10	<5	**10^-11**
		Packaging				
🟨			**X-axis Metrology**	<100	<=25	**microns**
🟨			**Y-axis Metrology**	<100	<=25	**microns**
🟩			**Z-axis Metrology**	<10	<=5	**microns**
🟥			**Rotational Metrology**	<0.035	<0.025	**degrees**
🟩			**Parallelism**	<20	<10	**microns**
🟩			**non-radoactive material**		yes	
🟩		**Agrigate fill factor (over full array)**		>90%	>95%	**percent**
🟨			**Buttablity**	4	4	**side**
🟨			**Butting gap (3 sides)**	<500	<=250	**microns**
🟨			**Butting gap (1 side)**	<1500	<=500	**microns**
		Temperture				
🟥			**Storage**	-60 - +50		**C**
🟩			**Operating**	-60 - -30	-50	**C**
🟥			**Cycling Range**	-55 - +30		**C**
🟥			**Total Cycles**	>150	>200	
	Electrical:					
🟩		**Full well**		>=70000	>=90000	**electrons**
		Non-linearity				
🟩			**Absolute**	<7	<5	**%**
🟩			**Stability**	<1	<0.5	**%**
🟩		**Dark Signal (95th percentile @-50C)**		<4	<2	**e-/pixels/sec**
		Cosmetics				
🟨			**Bright Pixels**	1:4000	1:10000	**pixels**
🟨			**Dark Pixels**	1:4000	1:10000	**pixels**
		Charge Memory (residual image)				
🟩			**after 1 reset**	<0.05	<0.02	**percent**
🟨			**after 10 resets**	<0.005	<0.002	**percent**
🟨			**after 100 resets**	<0.005	<0.001	**percent**
		Readout				
🟩			**Frame Read Time**	<3	<2	**seconds**
🟩			**Sub-Array**		Any	
🟩			**Output-output Crosstalk**	<0.05	<0.01	**percent**
🟩			**Output-output Crosstalk stability**	<0.02	<0.01	**percent**
🟩			**Pixel-to-pixel Crosstalk**	<5	<3	**percent**
🟩			**Incomplete settling**	t_RC<t_sample/5	t_RC<t_sample/10	**seconds**
🟩			**Random noise**	<10	<=6	**electrons**
🟩			**Fixed pattern additive offset**	<50	<30	**electrons**
🟩			**Fixed pattern jittter**	<3	<=2	**electrons**
🟩			**Max. Pixel rate per output**		0.5	**Mhz**
🟨			**Conversion Gain**	4-20	5	**u-volt/electron**
	Optical:					
		A-R Coating			broad-band	
		DQE				
🟩			**400nm**	>55	>60	**%**
🟩			**600nm**	>80	>85	**%**
🟩			**800nm**	>80	>85	**%**
🟩			**900nm**	>60	>85	**%**
🟩			**1000nm**	>25	>45	**%**
🟨			**Pixel-to-pixel variations**	<5	<2	**% rms**
🟨			**Variations across device**	<15	<10	**%**
		Device DQE Stability				
🟨			**1 hour**	<2	<1	**% p-p**
🟨			**1 month**	<4	<2	**% p-p**
🟨			**1 year**	<10	<5	**% p-p**
		Fringing (within centered 100nm bandpass)				
🟥			**800nm**	<10	<5	**% p-p**
🟥			**900nm**	<15	<5	**% p-p**
🟥			**1000nm**	<20	<5	**% p-p**

CCD Specifications:

LSST CCD Array Requirements

Priority

High	🟩
Moderate	🟨
Low	🟥

				Allowable Range	Target	Units
	Physical:					
🟨		**Format(1-side)**		>= 2048	>= 2048	**pixels**
🟩		**Pixel size**		8-12	10	**microns**
🟩		**Flatness Deviation**		<=10	<=5	**microns**
🟥		**Outgassing**		<10	<5	**10^-11**
		Packaging				
🟨			**X-axis Metrology**	<100	<=25	**microns**
🟨			**Y-axis Metrology**	<100	<=25	**microns**
🟩			**Z-axis Metrology**	<10	<=5	**microns**
🟥			**Rotational Metrology**	<0.035	<=0.025	**degrees**
🟩			**Parallelism**	<20	<10	**microns**
🟩			**non-radoactive material**		yes	
🟩		**Agrigate fill factor (over full array)**		>90%	>95%	**percent**
🟨			**Buttablity**	4	4	**side**
🟨			**Butting gap (3 sides)**	<500	<=250	**microns**
🟨			**Butting gap (1 side)**	<1500	<=500	**microns**
		Temperture				
🟥			**Storage**	-60 - +50		**C**
🟩			**Operating**	-60 - -30	-50	**C**
🟥			**Cycling Range**	-55 - +30		**C**
🟥			**Total Cycles**	>150	>200	
	Electrical:					
🟩		**Max. Pixel rate per ouput**			0.5	**Mhz**
🟩		**Frame Read Time**		<3	<2	**seconds**
🟩		**CTE (per shift @500 electrons on each output)**				
🟩			**Parallel**	>0.999990 (<2%)	>0.999995 (<1%)	
🟩			**Serial**	>0.999980 (<4%)	>0.999990 (<2%)	
🟩		**Read Noise**		<10	<=6	**electrons**
🟩		**Full well**		>=70000	>=90000	**electrons**
🟩		**Output-output Crosstalk**		<0.05	<0.01	**percent**
🟩		**Output-output Crosstalk stability**		<0.02	<0.01	**percent**
		Non-linearity				
🟩			**Absolute**	<7	<5	**%**
🟩			**Stability**	<1	<0.5	**%**
🟩		**Dark Signal (95th percentile @ -50C)**		<4	<2	**e-/pixels/sec**
		Cosmetics				
🟨			**Bright Pixels**	1:4000	1:10000	**pixels**
🟨			**Dark Pixels**	1:4000	1:10000	**pixels**
🟨			**Traps**	<20	<10	**pixels**
🟨		**Blooming Control (above full well)**		>10E5	>10E6	**electrons/sec**
		Charge Memory (residual image)				
🟩			**after 1 readout**	<0.05	<0.02	**percent**
🟨			**after 10 readout**	<0.005	<0.002	**percent**
🟨			**after 100 readout**	<0.005	<0.001	**percent**
🟨		**Conversion Gain**		4-20	5	**u-volt/electron**
🟨		**Pixel FWHM (charge spreading)**		<10	<7.5	**microns**
	Optical					
		A-R Coating			broad-band	
		DQE				
🟩			**400nm**	>55	>60	**%**
🟩			**600nm**	>80	>85	**%**
🟩			**800nm**	>80	>85	**%**
🟩			**900nm**	>60	>85	**%**
🟩			**1000nm**	>25	>45	**%**
🟨			**Pixel-to-pixel variations**	<5	<2	**% rms**
🟨			**Variation across device**	<15	<10	**%**
		Device DQE Stability				
🟨			**1 hour**	<2	<1	**% p-p**
🟨			**1 month**	<4	<2	**% p-p**
🟨			**1 year**	<10	<5	**% p-p**
		Fringing (within centered 100nm bandpass)				
🟥			**800nm**	<10	<5	**% p-p**
🟥			**900nm**	<15	<5	**% p-p**

APPENDIX III – DATA MANAGEMENT

THE LSST DATA SYSTEM

As discussed in the proposal, the LSST data system presents significant challenges which must be addressed during the D&D phase of the project. The system will have to move large quantities of data rapidly from the camera to the rest of the data processing system, reliably, and possibly over long distances. A variety of real-time analyses must be carried out; candidate algorithms for these analyses must be refined and tested in practice before final selections are made. In addition to executing these algorithms, the analysis piplines must coordinate the data flow among these processes and monitor the accuracy and calibration of the results and the overall performance of the system. The resulting data must be stored in a manner which makes future access convenient and efficient. The body of this proposal has presented an architectural view of the data system; in this appendix we present a functional view and describe some of the issues we must face in greater detail.

Data will flow from the camera at 2.3 Gbps into the analysis pipelines and the raw image archive. At the same time, a complete description of the telescope and camera, from motor voltages and dewar temperatures to UT and position on the sky, will be stored in a corresponding telescope archive and passed to a system which monitors the "health" of the hardware. Provision will also be made to distribute data (on site) to projects whose analysis needs cannot be met by the default system. This and all subsequent stages in the data system need to be managed in a fault-tolerant manner, requiring hardware redundancy and a robust software architecture. We are likely to be guided during development by project partners such as Google with extensive experience designing reliable high data rate and data volume systems at low cost.

The first element of the data processing pipeline performs flat field correction with high signal-to-noise cross-talk, bias, flat field and other library calibrations. This portion of the system can be highly parallel as these corrections are independent for each physical device in the detector. Knowledge of the next field to be observed allows pre-fetching calibration data from the appropriate database during exposure, helping to spread out the I/O load.

Having removed the instrumental response, the data system will detect sources and match them against an astrometric catalog so that a coordinate system can be attached to each image. This is necessary for identifying sources from catalogs, for removing geometric distortion, and for registering multiple images for co-addition or subtraction. Once the image is calibrated astrometrically, a photometric catalog will be referenced for flux calibration, and the final, reduced images will emerge.

At this point, the pipeline will divide into three logically distinct paths: an image subtraction pipeline which detects transient sources, an object characterization pipeline which determines appropriate parameters for all objects (transient or not) in the image, and a detection-efficiency pipeline. Image subtraction will identify transient sources by subtracting a high signal-to-noise template created by co-addition of previous images of the field. Subtraction is a critical algorithm we discuss further, below. New sources in the image will be compared to a catalog of known variable sources, new transients will be identified and cataloged, and subscribers throughout the world will be alerted via the web and email. The object characterization pipeline will measure parameters of all detected objects in the image. This involves another set of central algorithms; a discussion of these is found in a later section on classification. These two pipelines will be monitored for their efficiency and quality by injecting synthetic transients, objects, and noise events into the data stream.

Detection of synthetic events will monitor the system's detection efficiency and the quality of source characterization. Rejection of synthetic noise will measure the system's susceptibility to noise. The injection may be done in identical, parallel pipelines to avoid "polluting" the real data, or, with careful bookkeeping and rigid control, they may be injected into the "real" pipelines themselves. This is one of the many choices which will be made during the Design and Development phase. It will be based upon an evaluation of the software needed to insure there is no corruption of real data versus the compute power and complexity needed to replicate pipelines. Experience has shown that real-time efficiency determination is important not only to the timely production of science, but also as a diagnostic of overall system performance.

The data on transients, object characteristics, and efficiency determined in these pipelines will then be loaded into a data store whose details are yet to be determined, but will almost certainly be a combination of databases and flat file storage systems. The quality of each incoming reduced image will be assessed and, if sufficient (see the discussion below on image addition), the image will be added to one or more of the images of the current field used as templates and which form one of the primary data products of LSST: very deep images of the whole sky. These and the individual images themselves will almost certainly be stored as plain files, while the derived data will likely go into a variety of more complex database systems.

Once the characterizations are loaded into the database, it will be necessary to perform an additional set of near-real-time analyses. One process will work to aggregate new detections into known objects, either variable sources or moving objects. Another will insert synthetic data into catalog and database query output and perform extensive Monte Carlo calculations on the detection efficiency and quality. Yet another will measure real-time detection efficiency, efficiency and accuracy at aggregation, and a host of other data-quality measures. These efficiency calculations are complementary to those occurring earlier in the pipeline; one can inject far more synthetic events into database queries than into the images themselves.

The reduction, archiving, and analysis pipelines and processes will be managed by a highly parallel and redundant software architecture which incorporates fault-tolerance and self-diagnosis. A key effort during the Design and Development phase of the LSST will be the specification of the requirements for this system. A number of possible architectures have been developed for previous astronomy and high energy physics experiments which merit investigation. Some are "light-weight," in the sense that there is a minimal framework managing the algorithmic calculations, while others are more "heavy-weight" with an extensive framework and many layers of software and protocols. The former have the utility of speed of execution and ease of design, while the latter may be robust and may require less detailed knowledge of the overall system by the science algorithm designers.

A number of data processing systems capable of handing aspects of the LSST data volume and analysis effort exist today. The following table details these capabilities for a sampling of astronomy and high energy physics experiments. It is clear from this table that although no single past experiment has simultaneously managed the LSST data flow, analysis rate, database capability, or real-time requirements, all of the LSST requirements have been met individually within different experiments. The LSST will not require conquering new volumes of data management parameter space.

	Astronomy					High Energy Physics		
	LSST	**SDSS**	**2MASS**	**MACHO**	**DLS**	**BaBar**	**Atlas**	**RHIC**
First year of operation	2011	1998	2001	1992	1999	1998	2007	1999
Run-time date rate to storage (MB/sec)	5000 Peak 500 Av	8.3		1	2.7	60 (zero-suppressd) 6*	540*	120* ('03) 250* ('04)
Daily average data rate (TB/day)	15	0.02	0.008	0.008	0.012	0.6	60.0	3 ('03) 10 ('04)
Annual data store (TB)	2000	3.6	6	1	0.25	300	7000	200 ('03) 500 ('04)
Total data store capacity (TB)	20,000 (10 yrs)	20.0	24.5	8	2	10,000	100,000 (10 yrs)	10,000 (10 yrs)
Peak computational load (GFLOPS)	9200			1.00	0.600	2,000	100,000	3,000
Average computational load (GFLOPS)	1700			0.700	0.030	2,000	100,000	3,000
Comp granularity (1-10) 1 -> fully serial 10 -> fully parallel	9	9	5	7	5	-	-	-
Data release delay acceptable (.)	1 day moving 3 months static	2 months	6 months	1 year	6 hrs (trans) 1 yr (static)	1 day (max) <1 hr (typ)	Few days	100 days
Real-time alert of event (.)	30 sec	none	none	<1 hour	1 hr	none	none	none
Type/number of processors			450MHz Sparc 28	60-70MHz Sparc 10	500MHz Pentium 5	Mixed/ 5000	20GHz/ 10,000	Pentium/ 2500
Data Management operating budget($M/yr)	~7.0		3.0	<0.1	0.5	5	>10	7

*after real-time trigger filtering of raw detector data stream

Science Algorithm Development

In this and the following sections we describe some of the science algorithms which must be developed and refined to enable LSST to achieve its full potential. This development appears quite tractable, but will require significant effort to achieve optimal results. Problems include image addition to reach fainter magnitudes, astrometric and flux calibration, object measurement and classification, and automated quality assessment. In all of these areas, the algorithms must embody some of the human judgment involved in data analysis. How to make the computer reliably distinguish an artifact like a cosmic ray track from a true brief transient, and do so in a way which does not compromise the use of the data for other purposes, is not simply a matter of mathematics. Rather, it will require building upon the wealth of experience accumulating in current LSST precursor surveys and significant experimentation on real and simulated data sets.

PSF Determination

It is crucial to know the instrumental spatial response, the point spread function (PSF), when analyzing an image. This information is needed for, among other tasks, correct deblending of overlapping sources, image classification, measurements of cosmic shear, and image quality assessment. (Interestingly, the PSF is not needed for the image subtraction problem.) The usual approach is to identify isolated stars, to use them to characterise the spatial variation of the PSF (using *e.g.* a Karhunen-Loeve decomposition), and then to use some interpolation scheme to determine the PSF at any point of interest. If necessary, it is then possible to `clean' the initial stars by clipping their profiles using the model PSF, and iterate. An alternative procedure (used by HST) is to model the PSF, but this seems unlikely to be useful for LSST (or any ground-based telescope), even given exact wavefront sensing around the edge of the camera.

Photometric Calibration

Photometric calibration of a large-field survey telescope is not easy. Although the software to perform the calibration is straightforward, the detemination of the parameters to use in the calibration is not. Because these parameters are only needed for the pipeline calibrations, a discussion of the problem in determining them is appropriate here. The problem can be split into three parts: determining the detector+filter's characteristics, determining the flat-field response of the detectors, establishing suitable standard stars, and tying the survey exposures to the standards

None of these are especially difficult in theory, but all require careful attention to detail and, potentially, a significant outlay in telescope time. We need to know the sensitivity of the detector+filter combination, and the non-linearity of the chips. The sensitivity is likely to vary with time, and we must be able to follow these variations.

The pixel-to-pixel variation of the detectors can probably be determined using a dome flat, but because the lamp doesn't have the same SED as astronomical objects, and (especially) due to problems with scattered light, the overall flatfield structure must be determined from measurements on a large number of dis-registered exposures. The other area of concern is fringe removal over the entire field; it is not clear that a single `fringe frame' is really applicable-- but this is something that we can find out. The design of the telescope and dome must include a satisfactory flatfield screen, and a system to illuminate it; the D&D phase is the time to ensure that this happens.

Establishing a standard system must wait until we have a prototype camera, as we shall need to match the detector characteristics to the main camera as accurately as possible. In the D&D stage of the project, we will determine whether it is best to set up the LSST standard system using the LSST camera and telescope itself, or by using an auxiliary telescope and camera. In either case, the number of standard fields and the nature of the standards will be determined. These fields will be used both to provide zeropoints and to allow us to measure our flat fields using stellar photometry.

Image Co-Addition

Co-added images play a crucial role in LSST science. With the exception of studies of moving objects, all science programs will use the co-added images either as the primary input or as the starting point for measurements on the individual exposures. This is because the co-added image is much less noisy in the Poisson sense than the individual exposures, and it has screened out other sources of "noise" such as asteroids, which one would not want to creep into lensing statistics, for example. Development of a co-addition algorithm which meets the needs of diverse science programs will thus be a key activity in the D&D phase.

The main issue in image co-addition is how to handle different PSFs. The PSF of a telescope varies with time because conditions such as seeing (blurring due to atmospheric turbulence), temperature, focus, gravity load, and tracking/guiding performance are all variable. As a result, no two exposures are the same. In addition the PSF will vary across the LSST 3-deg field of view differently for each exposure of the same field.

In principle, an algorithm for optimal image co-addition is fairly simple, as recently shown in an unpublished paper by Kaiser which implies that (for faint, constant sources) there is a unique correct way to add the data that preserves all the information about the true sky. While the Kaiser algorithm is optimal in theory, in practice there are many details to be considered which will make the algorithm considerably more complex, and likely no longer optimal. In the face of changing conditions, is the procedure stable in practice? Even if stable, the formalism presented implies that all data, taken in arbitrarily bad conditions, should be included; this violates most astronomers' intuition, but is it nonetheless correct? If not, where should the "bad data" cutoff be placed? Is the cutoff different for different science goals?

In addition, there are practical issues of implementation. How finely should we sample the sky? At what point should we remove putative cosmic rays and other image "defects"? Going beyond these, how should we deal with variable sources? How do we preserve all the uncorrupted information about point sources which are bright enough to saturate the detector in better seeing, but remain unsaturated in worse seeing? How do we face the fact that almost all the Galactic stars detected by the LSST are going to move by detectable amounts over the course of the survey? Should we include per-pixel color information in the estimation, thereby allowing for differential chromatic aberration? How well does the algorithm work for bright sources, for which the noise is dominated by the photon noise in the object?

To explore just one of these issues in more depth, consider the elimination of the "noise" of asteroids and other moving and varying phenomena. A common way of doing this is by taking the median of a series of exposures, but this "solution" has several problems of its own. It is statistically noisier than the mean if one has more than a handful of exposures, and it basically throws away the best-seeing images, which have intensities too low on the outskirts of a point source, and too high at the peak. Another way of doing this is by taking a clipped mean, but this can change the photometry of point sources, as one generally clips the peak values of the best-seeing images. The most rigorous way of doing this is to identify the transient objects and mask them out beefore the stacking begins. To date, this has been too computationally intensive in practice, as transient identification involves differencing each exposure with a template such as a first-pass stack. With LSST, transient identification will be available as an input to the stacking process, so this may be a viable solution. However, much work remains on defining the specific pixels to be masked around each transient, and indeed in which cases to mask at all. We would not like to mask out all pixels in all exposures of variable stars, for example.

Depending on the science goal, optimal measurements may need to be performed on the individual exposures. For example, lensing benefits greatly from a smaller PSF which more accurately preserves the original shape of small, faint galaxies, and it may be that shape measurements are best done on the individual exposures and then combined with weights that depend on the PSF size. Even so, the co-added image will be crucial, both as a starting point for basic galaxy parameters, and as a basis for photometric redshifts, which require only accurate photometry of the galaxy as a whole.

During the D&D phase, we will pursue development of image co-addition schemes guided by theory, but also grounded on extensive, real-world experience. A key activity will be to define the scope: Which science goals can be met by the co-added image and which must be passed on to the individual exposures? Can science goals be met more efficiently by providing a few different types of co-added images stacks rather than a single one?

Optimized image subtraction.

The optimal subtraction of two astronomical images does not require the processing for the optimal addition of images, but does have a number of prerequisites. Instrumental and atmospheric distortions must be matched between the images to be subtracted, but they do not need to be corrected. First, the images must be brought into registration, in order to correct for telescope pointing errors, and exhibit the same distortions due to atmospheric refraction and optical distortions in the apparatus. Next, the images must be scaled appropriately, with both an additive (sky) and multiplicative (transparency) correction. Finally, the point spread function (PSF) must be matched by applying an appropriate convolution kernel to one of the frames. Practical algorithms already exist to determine the necessary quantity, the ratio of two PSFs, even in arbitrarily crowded fields.

At present, these stages are all carried out with distinct code modules, with images written to disk at each intermediate stage. This is an ineffective way to carry out the tasks, and it would be far better to integrate these three stages into a single code module. Unfortunately this is not just a simple coding task. We intend to carefully evaluate the optimal way to determine and apply the optimal convolution kernel that would not only match PSFs, but also accomplish the other subtraction pre-requisites described above.

Object Measurement/Classification

The primary output from the LSST will be catalogues, not images. Experience with other large surveys (Macho; SDSS; 2MASS) shows that almost all science, at least initially, will be done on the lists of objects' properties. Because of its dense time sampling, the LSST object parameter space will be richer than those of other surveys. At least the following aspects must be considered:

- Instantaneous photometric properties in multiple filter bands
- Time dependence of photometric properties (“light curves”)
- Spatial properties of extended objects
- Trajectories of moving objects

For isolated stellar sources, the photometric properties are reasonably straightforward both to define and to measure; fitting a PSF is the optimal way of measuring the positions and brightnesses of faint sources (for bright sources, aperture measures may offer higher precision). The limit to the precision is liable to be set by the quality of the photometric calibration. Extended sources are a different matter; there are many measures of brightness in the literature, and most have their strengths and weaknesses. The traditional measure, an isophotal magnitude, is clearly deeply flawed (a galaxy's surface brightnesses correlate with its other properties; the surface brightness dims with $(1+z)^4$, and thus the isophotal aperture shrinks). Replacements include Kron magnitudes (as used by e.g. 2MASS); Petrosian magnitudes (as used by e.g. SDSS); total magnitudes based upon extrapolating curves of growth; and magnitudes based on fitting analytical models of galaxies (as used by e.g. SDSS). All of these have their strengths (unambiguous interpretation in terms of galaxy properties) and weaknesses (poor signal-to-noise performance; sensitivity to the structure of the galaxies).

While classification of variable star lightcurves is basic to astronomy and has a long history, automating this classification is in its infancy, and is far from straightforward. For periodic lightcurves, standard methods exist to find periods, but they are computationally expensive. Even once periods are found, classification of the myriad waveforms exhibited by stars is difficult to automate.

The analysis of aperiodic lightcurves is in its infancy. No standard classifications exist, let along methods for determining classification automatically. Neural nets have been explored to reproduce human-defined subjective categories, and more objective (if no more instructive) classifications based on clustering or wavelet analysis have been proposed.

When we turn to properties of spatially extended objects, the parameter space broadens still further. One might argue that these extended measures are not needed for the core LSST science, but it turns out that they are needed as soon as we want to ask questions about galaxies as more than point masses (e.g. to split the sample by Hubble type). An example is measures of substructure in an image; the traditional measures, based on non-axial power in an image, are aperture measures that are not applicable to faint sources.

Today, the community employs a wide variety of techniques to quantify these spatial properties. Both parametric (*eg* fitting a galaxy image to an analytic model and deriving a bulge/disk ratio from the fit) and nonparametric (*eg* principal component analysis) descriptions are in widespread use, and new ones are frequently proposed (*eg* Lotz, Primack, and Madau, astro-ph 0311352). It is clear that no single catalog can contain all parameter sets that may be useful in this area. We will need to carefully consider which parameter set should form the core LSST catalog, and strive to make it easy to create additional catalogs that use alternative parameter sets.

So far we have implicitly considered only isolated sources. Many LSST fields will be highly crowded, however, with objects frequently overlapping. Crowded-field photometry algorithms such as those in DAOPhot and DoPhot perform well when almost all objects are known to be stars, but the general case is much more complicated. Despite recent progress (*e.g.* the SDSS deblender), the problem of correctly measuring the properties of close groups of objects has yet to be resolved. The situation is only complicated by attempting to make sense of data taken under different observing conditions. How best to use the information in a stack of images taken under varying conditions?

The Aggregation of Detections into Objects

In each exposure, the LSST will observe, and the analysis pipeline will detect, objects which exhibit variability in their flux or position, or both. These *detections* of variability must then be identified with celestial sources, or *objects*. In instances where the object resides in our own solar system, the various detections will occur over a wide range of apparent positions on the celestial sphere; LSST will detect of order 10^6 such moving objects.

The challenge of extracting solar system objects with orbits from a set of (position,time,flux) detections is an unsolved problem. The scope of the matching task can be restricted with a shrewd choice of observing strategies, but with the number of objects that LSST will detect we will still need to pay careful attention to how this problem is addressed. A related issue is how to most effectively represent the required information in a relational database, and how, for example, to execute queries in a fashion constrained by Kepler’s laws.

Astrometry

A key deliverable for the LSST survey will be accurate astrometry. This astrometry will enable the determination of the parallax of all stars within 200 parsecs, and the most accurate and complete set of proper motions ever proposed. In order to deliver on this promise, there are significant analysis issues which must be addressed.

We know from 20 years of the USNO 61-inch parallax program that we can do astrometry at the few milliarcsecond level in a small field (a few arcminutes, “local astrometry”), but the net experience of the community (2MASS, SDSS, USNO's UCAC) is that fits to the entire field are usually a factor of 10 (or more) worse (“global astrometry”). We need to understand what seeing is doing to the astrometry, and develop algorithms that mitigate the damage.

We must also investigate tying LSST to the International Celestial Reference Frame (ICRF). The optical realization of the ICRF quits where Hipparcos left off at about V=10. The radio realization of the ICRF starts at V=18 (or so) and contains 350 QSOs. LSST is the first experiment that will (must!) observe both sets of objects, and the astrometric pipeline must provide a rigid tie to each.

Translating astrometric accuracy into engineering units will be another challenge. LSST will be specified in terms of Strehl ratio, flexure in microns, spectral energy distribution of vibrations, *etc.*, but we have no models that translate milliarcseconds of astrometric accuracy into these units. To avoid building an astrometrically-challenged LSST, we need to solve this problem early in the design and development phase.

LSST astrometry must be done in potentially wide passbands and certainly at large zenith distances. Many programs, particularly the search for asteroids, could involve very wide passbands such as V+R or even V+R+I to find the faintest possible objects. We know that large zenith distances are involved in chasing the "sweet spots" of objects in earth-like orbits at the beginning and ends of the night. Differential color refraction (DCR) will be a very large effect (up to several arcseconds) and must be mitigated if LSST is to deliver the accuracy needed for linking observations taken many nights apart.

Finally, we need to include astrometric considerations in to the image stacking algorithms. We know that all the stars are moving with respect to the extragalactic objects, either by their proper motions or by the DCR generated by their different spectral energy distributions. A good algorithm for the astrometric alignment of image data during the co-addition process has not yet been proposed. Of particular concern is the elimination of systematic errors that would induce significant structure in the shape of galaxies.

Automated Quality Assessment

The LSST will measure the properties of hundreds of millions of objects, and the majority of the users of LSST data will rely upon the project to ensure that the quality of these catalogs remains reliably high. We shall have to create tools and procedures that constantly, and automatically, check on the operation of the system and the behavior of the data processing pipelines.

Pre-existing surveys such as 2MASS and SDSS have a lot of relevant experience asking the question, "Are the data good enough?". This is a question that can and will be asked at many stages of the data analysis task. For example, is the electronics corrupting the data? Is the raw photometry good? Is the calibrated photometry good? Is the database corrupted?

There are four overlapping sets of questions that the system must continually address: Do these data satisfy some invariant or known property of the system? Examples of this are a CRC checksum, a limit on the number of cosmic rays/pixel/second, or a departure from some property of a typical brightness histogram for a wide field. Are the data internally consistent? Colors of stars should be consistent with expectations, and magnitudes determined by PSF fitting should agree with aperture magnitudes for bright stars. Do the data agree with previous measurements? Stars (objects not deemed to be moving) should be in the same places they were last week. Objects which do move should have orbital elements within the bounds of sense. Finally, when I do science with these data, are the results sensible?

All of these questions are more subtle than they appear; for example too-good seeing can generate too many cosmic rays, and this may imply a problem in the algorithms used – in which case the data *should* fail quality assurance! Stellar colors are affected by galactic reddening; asteroids move; scientific truth can fail to match prejudices.

Previous surveys have generally adopted ad-hoc approaches to QA, and made extensive use of human intervention. We shall not have this luxury, and therefore need to start building experience with data streams similar in complexity, if not volume, to those of the LSST during the D&D phase.

One feature of most previous QA efforts is that the problem may be automatically reported as a problem, but that the diagnosis has taken scarce human resources. With a system as complex as LSST this may well prove to be a severe difficulty. The human touch is undoubtedly essential to resolving some problems, but we must investigate the degree to which analysis can be integrated into our automated testing, for example by employing expert systems.

APPENDIX IV. PROJECT MANAGEMENT

MANAGEMENT OVERVIEW

The LSST plan of record calls for telescope first light in December 2011. To meet this ambitious goal, the LSST team has already begun a Design and Development (D&D) phase. This proposal supports a critical portion of that effort. Overall, the D&D phase budget is approximately $30M with the requested NSF support being about half of the total. The remainder of the D&D funding is from the DOE laboratories, private sponsors, and in-kind contributions from partners.

The LSST construction phase is estimated to cost $162M in 2007 dollars. Of that, we expect private funding of $30M, DOE funding for the camera of $35M, in-kind contributions of $10M, and NSF construction funding of approximately $90M. To meet our goal of first light in December, 2011, the NSF construction funding must begin in October, 2007. This, in turn, means the NSF construction proposal must be submitted in October 2005. A major deliverable of the D&D project is preparation of the fully-costed construction proposal. Private funding for long-lead, critical-path items such as the large mirrors has already started.

A focus of the D&D phase will be the Conceptual Design. A conceptual design review (CoDR) will be held in the first year of the NSF D&D period. Plans to mitigate risk and control costs will be developed during that time. Since the LSST does not need to develop any new technology, the construction proposal can be prepared once the CoDR is complete. Prior to the end of the NSF-sponsored D&D phase, the program will also complete a Preliminary Design.

This Appendix provides additional support information related to the management of the LSST project:

- Figure A4-1 is a management diagram for each sub-task of (a) Data Management, (b) Camera, and (c) Telescope/Site.
- Figure A4-2 is a list of high-level deliverables. The tabular presentation shows the due date, NSF-funded effort level, and in-kind effort level. The total effort indicated in the figure shows the NSF support and in-kind support are approximately equal.
- Figure A4-3 shows the top two-levels of the WBS. A complete WBS is available on the WEB at http//www.lsst.???….

BUSINESS PRACTICES

NSF funding will go directly to the LSST Corporation (LSSTC). The Project Manager will direct the LSSTC financial officer to distribute funds to partner organizations to support the elements of the WBS. Partners will provide reports on work accomplished and funds spent.

The Project Manager has the authority to direct project staff and to plan for, redirect, and control budget expenditures. The Project Manager will have the authority to execute the management plan, subject to normal technical and administrative reviews and approvals. The Project Manager will be accountable for generating and documenting engineering requirements based on science objectives and priorities, and will be responsible for the preparation and organization of formal project reviews as specified by the LSST board and Project Director. Regular reports to management and the community will be made available over the Internet.

The project management will employ standard cost and schedule control system methods to track and control the design and development phase effort. The WBS breaks the work down into categories and subcategories that allow the estimation and tracking of individual elements of the project effort.

By utilizing the project schedule and the WBS, progress and expenditures by individual task can be tracked by comparing the percent complete and the to-date costs. This allows early identification of tasks that are at risk so that action can be taken.

Project status will be assessed weekly. This along with weekly team meetings will allow early identification of problems for critical item tracking. Cost tracking will be done to the 4th and 5th levels of the WBS, as applicable. The charge numbers used in project tracking and reporting will reflect the WBS.

Contract administration will be performed by LSST Corp. and include a contracts administrator, and sufficient support staff to administer and monitor all aspects of contracts and procurements. Personnel familiar with government contracting procedures, federal acquisition regulation (FARs), and NSF contracting policies will administer all contracts.

The subcontract type employed will depend on the nature of the specific task; most contracts, however, will be firm fixed price (FFP). Contracting clauses will be negotiated with the awardees to provide LSST with sufficient protections to ensure contract completion on schedule and within budget.

All purchases over $5K will be made using competitive bidding unless there is an adequate sole source justification. The Project Manager must review and approve all sole-source procurements.

The award of custom design and fabrication work will be based on an evaluation of bid price, ability to meet specifications, ability to meet schedule, experience, resources, personnel, and other similar factors.

Subcontracts will identify tracking data that will be supplied to the project office so that the Project Manager will have early warning of problems relating to schedules, costs and performance. In special cases, where particular activities are critical, the project technical representative may reside for some period at the subcontractor’s facility. The objective is to resolve problems before they impact schedule and provide the project manage with insight into subcontractor progress. The technical representative assigned by the project office will provide technical overview of the subcontract.

The Project Manager and the contract administrator must approve any modifications to a subcontract. Modifications must also be evaluated, negotiated, and formally changed by the contracting officer.

Risk is minimized by the use of sound, demonstrated technology, conservative designs, strict adherence to the error budget specifications, and continues management review of work progress. A formal risk management program will be established for LSST and administered by the project management office.

The project team will prepare a monthly report. This report will cover the monthly activities of the project team and will relate them to schedules for the design and development phase. This report will include program costs by task and subtasks, direct labor hours and dollars itemized by task and subtask, and commitment of funds.

A series of reports, prepared by the project team will provide a record of technical work involved in the design and construction of the telescope, camera, and data management. These reports will document theoretical studies and simulations, and the results of experiments with prototypes. The technical reports will be numbered and a system will be set up to catalog them and make them available to others work in the field of telescope design.

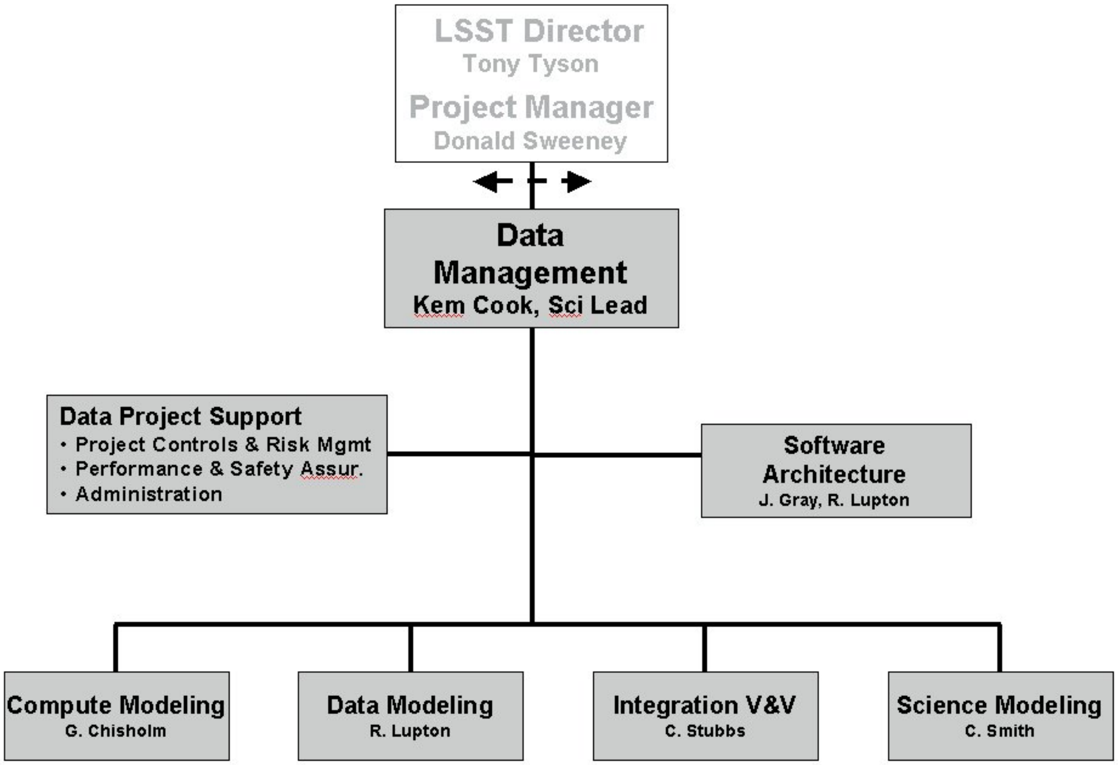


Figure A4-1a. Data Management Subsystem Organization Chart.

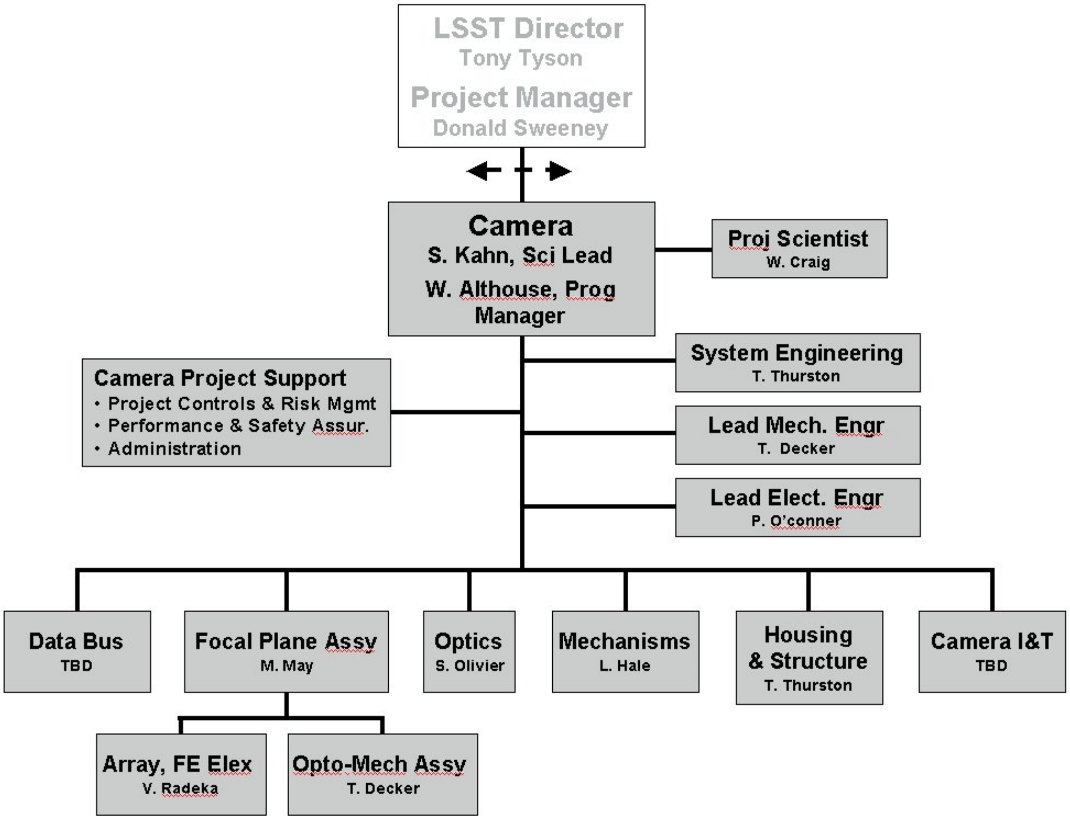


Figure A4-1b. Camera Subsystem Organization Chart.

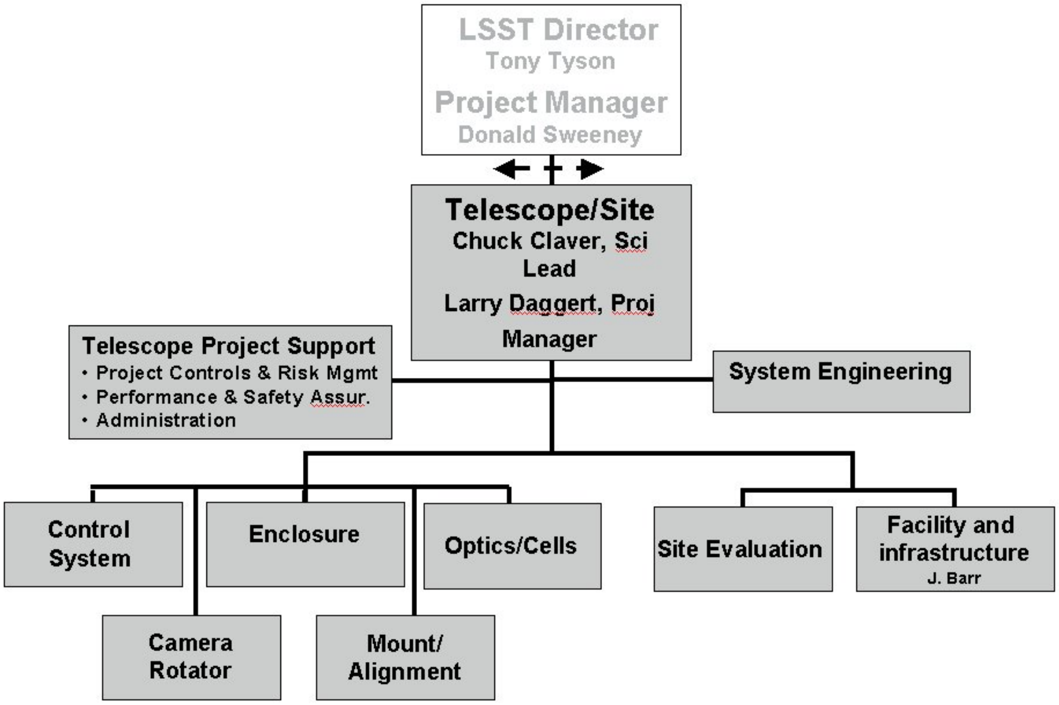


Figure A4-1c. Telescope/Site Subsystem Organization Chart.

DELIVERABLES	Due Date	NSF Effort	In Kind Effor
WBS 1.0 Data Management		Man years	Man years
Design Core System Architecture	4/1/2005	0.75	0.5
Data Management Conceptual Design Review	4/1/2005	2	0.5
Complete the Software Control system Model	10/1/2005	1.5	0.75
Complete the Algorithm Risk Management review	10/1/2005	0.5	0.25
Cost model for construction proposal Complete	10/1/2005	0.5	0.5
Complete the database workshop and SOA report	1/1/2006	0.25	0.25
Complete prototype framework for Data Challenges from Pixel to database	4/1/2006	2.5	0.5
Complete prototype review and tests for architecture and scalability	10/1/2006	1	0.5
Algorithm Development (Review)	10/1/2006	4	1
Integrated Prototype LSST simulator for data challenges Complete	4/1/2007	3	0.5
Preliminary Design Complete	4/1/2007	3	0.5
Continue developing Pipeline algorithms	10/1/2007	4	1.25
Subtotal		23	7
WBS 2.0 Camera			
Focal Plane Assembly Conceptual Design Complete	4/1/2005		1.7
Optics, mechanisms, & structure Conceptual Design Complete	4/1/2005		1.0
Camera system Derived Requirements Complete	4/1/2005		1
Camera Conceptual Design Complete	4/1/2005		1.3
Complete Construction Proposal	10/1/2005		1
Focal Plane Assembly Preliminary Design complete	4/1/2005		8
Optics, mechanisms, & structure Preliminary Design Complete	4/1/2007		8.0
Camera Preliminary Design Complete	4/1/2007		6.2
Camera Critical Design Review	4/1/2007		1
Continue developing final design	10/1/2007		5.8
Subtotal			35
WBS 3.0 Telescope			
Complete a study of alternate mirror material for M3	1/1/2005	0.25	0.25
Complete an Optical Perturbation Model for Alignment	1/1/2005	0.5	0.5
Complete a Conceptual Designs for the Telescope & Observatory Control Systems	4/1/2005	0.5	0.5
Complete two Telescope Mount Conceptual Designs & Trade Study	4/1/2005	1	1
Conceptual Design for M1, M2, M3 including Mirror Cells and Supports Complete	4/1/2005	1.5	1
Camera Rotator Conceptual Design Complete	4/1/2005	1	1.5
Complete Enclosure Conceptual Designs	4/1/2005	1	
Conceptual Design Review Complete	4/1/2005	3	1
Complete Construction Proposal	10/1/2005	4	1.5
Develop the metrology system for testing M2 during polishing	1/1/2006	2	1
Complete Protected Silver Mirror Coating Study	4/1/2006	1	1
Complete prototype alignmmment system tests	4/1/2007	2.2	0.5
Complete telescope system Prelilminary Design review	4/1/2007	4	1
Continue developing final designs	10/1/2007	3	1
Subtotal		24.95	11.75
WBS 4.0 Site			
Site Selection Complete	10/1/2004		
Site plan Conceptual Design Complete	4/1/2005	0.5	0.3
Complete Site Construction Proposal	10/1/2005	1	0.3
Complete the Site Preliminary Design	4/1/2007	1.25	0.3
Continue developing final site designs	10/1/2007	0.75	
Subtotal		3.5	0.9
WBS 6.0 Project Management			
System Error Budgets Complete	4/1/2005		0.5
Complete the systems engineering for the conceptual design review	4/1/2005	0.5	1.5
Conceptual Design Review	4/1/2005	0.5	1
Develop an analytical system model for LSST	4/1/2005	1	1
Complete the systems engineering for the construction proposal	10/1/2005	1	1.5
Submit the Construction Proposal	10/1/2005	1	2
Complete the Preliminary Design Review	4/1/2007	0.5	3
Continue developing final designs	10/1/2007	0.5	1.6
Subtotal		5	12.1
TOTAL Labor Person Years		56.45	66.75

Figure A4-2. Design and Development Deliverables.

LSST WBS

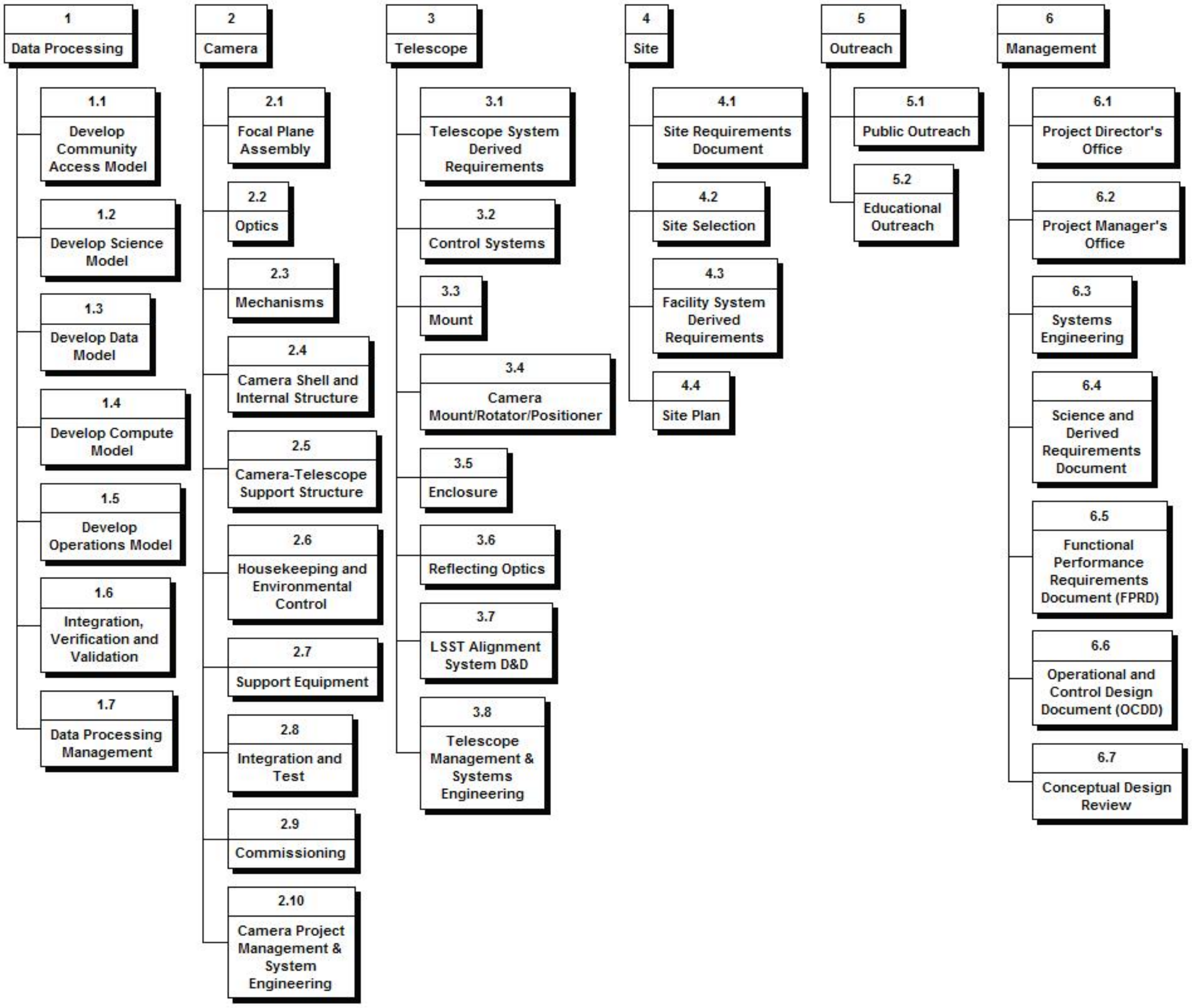


Figure A4-3. LSST Level 2 Work Breakdown Structure