The Large Synoptic Survey Telescope (LSST)

Letter of Intent
for Consideration by the
Experimental Program Advisory Committee
Stanford Linear Accelerator Center

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ABSTRACT

The Large Synoptic Survey Telescope (LSST) will be a large, wide-field ground-based telescope designed to obtain sequential images of the entire visible sky every few nights. The optical design involves a novel 3-mirror system with an 8.4 m primary, which feeds three refractive correcting elements inside a camera, thereby providing a 7 square degree field of view sampled by a 2.3 Gpixel focal plane array. The total system throughput, $A\Omega = 270\ m^2\ deg^2$, is nearly two orders of magnitude larger than that of any existing facility.

LSST will enable a wide variety of complementary scientific investigations, all utilizing a common database. These range from searches for small bodies in the solar system to the first systematic monitoring campaign for transient phenomena in the optical sky. Of particular interest to high energy physics, LSST images can be co-added to provide a weak lensing survey of the entire sky with unprecedented sensitivity. Measurement of the dark matter power density spectrum through weak lensing will provide tight constraints on models of dark energy, such as the equation of state parameter, *w*, and its derivative with respect to cosmic time. These constraints are complementary to those which will come from other approaches to studying dark energy (such as the apparent magnitude redshift relation of Type 1a supernovae), but are sensitive to different aspects of the cosmological model and involve quite different systematics.

A collaboration has been formed to launch a design and development program for the LSST, leading to commencement of operations in 2011. This collaboration involves both NSF and DOE funded groups, working together under a common management structure. The DOE effort, which will be led by SLAC with significant components at BNL, LLNL and university-based HEP groups, will take overall responsibility for the LSST camera, the data acquisition system, and aspects of the pipeline software.

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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 10,000 primitive objects in the Kuiper Belt, which contains a fossil record of the formation of the solar system. It will also contribute to the study of the structure of the universe by observing thousands of supernovae, both nearby and at large redshift, and by measuring the distribution of dark matter through gravitational lensing."
>
> *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 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 8.4-m 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 > 10 Terabytes per night) will catalyze significant developments in computational science and engineering.

This *Letter of Intent* proposes SLAC involvement in the design and development phase of the LSST project. As currently envisioned, a team supported by DOE-OS, led by SLAC with significant involvement at BNL, LLNL, and university-based HEP groups, will take overall responsibility for the LSST camera, the data acquisition system, and aspects of the pipeline software systems. The telescope itself, the enclosure, the site, and other components of the software and operations, will be developed with funding from the NSF and from private sources. The LSST Corporation, whose members 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 there are still many technical challenges associated with this project, we expect to establish that they can be solved with confidence and, provided funding is available, that first light can be achieved by 2011.

The following sections of this Letter of Intent provide the scientific motivation for LSST as a whole; the requirements placed on the telescope, instrument, and software by the scientific goals; the comparison to other anticipated wide-field telescopes, 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.

2. Science Drivers for the LSST

The unprecedented sky coverage, cadence, and depth of the 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 > 10 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.

DOE-OS interest in the LSST program is driven by its implications for cosmology, and especially for the constraints it will provide on models of dark energy. We therefore discuss this topic in some detail below. Since the overall design of the LSST telescope and camera system has been optimized over a broad range of scientific applications, we also briefly cover the science drivers in other fields as well.

2.1 Constraints on 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 developed 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 the dynamical importance of this component evolves strongly in redshift across the prime LSST range of sensitivity. The various 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. These multiple methods are sensitive to different forms of systematic errors, meaning that complementary 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. Fortunately, the photometric redshifts need not be superbly precise--even 5-10% in $(1 + z)$ is adequate--but extending the range of redshifts over which the results are robust is very important.

2.1.1 The Large-Angle Cosmic Shear Power Spectrum

The principal of weak lensing (WL) is illustrated in Figure 1: Light from background galaxies passes through concentrations of dark matter in the intervening medium on its way toward the solar system. Due to gravitational lensing, the images of these galaxies are subtly distorted as the light moves through the dark matter gravitational potential. Since the background galaxies are randomly oriented, these distortions are imperceptible for images of individual objects, but they do produce correlations in galaxy orientations as a function of angular separation. The Fourier transform of the correlation function is the cosmic shear power spectrum, which can be theoretically related to the power spectrum of mass fluctuations in the dark matter distribution.

The evolution of the mass power spectrum with redshift is a sensitive function of the underlying cosmology, and of the influence of dark energy, in particular. Using photometric redshifts of the lensed galaxies, we can tomographically decompose the power spectrum as a function of redshift, thereby measuring the growth of structure directly in the low z universe, where dark energy has its most significant effect (Hu 1999; Hu & Keeton 2002). 3D lensing tomography using photometric redshifts has been recently demonstrated (Wittman et al. 2003). With LSST, we can apply this technique to the entire sky, thereby constraining the matter power spectrum down to the lowest multipole moments.

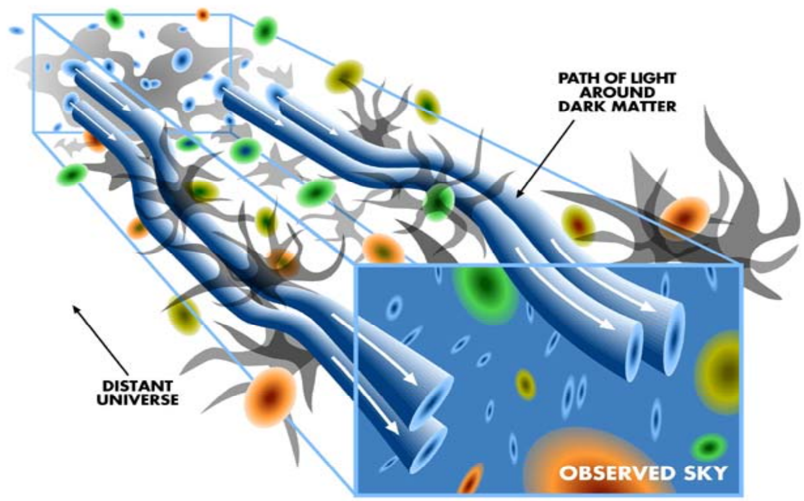

Figure 1 An illustration of the effect of weak gravitational lensing on the appearance of background galaxies.

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 could cause the LSST-measured shear power spectrum to be tilted in scale relative to the CMB prediction. For cosmological tests involving anomalies in broad-band shape and amplitude of the power spectrum, weak lensing measurements will become the method of choice in the coming decade. Heretofore, such searches have used galaxy redshift surveys, but uncertainties in the bias associated with using luminous matter will limit these surveys to 10% (plus statistics error) accuracy. Only by probing the dark matter directly with full-sky weak lensing will we be able to push these searches to the few percent level. For fixed growth at some redshift the degeneracy line is $4w - \Omega_M = const$, where $w = p/\rho$ is the ratio of pressure to energy density in the dark energy component, and Ω_M is the fraction of closure density in matter. Figure 2 shows an estimate of the precision achieved in the cosmic shear survey of 20,000 square degrees to sources at $z = 2$. A density of 70 sources per square arcminute and a shear floor of 0.0001 was used.

2.1.2 Cluster Counting Statistics: *dN/dz* versus *z*

The runaway collapses initiated by gravitational instability offer another way to probe cosmological perturbations, this time on smaller scales. The number density of dark matter clusters depends very sensitively on the amplitude of density fluctuations and on the cosmic distance scale. Both depend on the details of dark energy. Massive clusters provide large enough shear signals as to be easily detectable in LSST mass maps. The counting of clusters thus provides a superb way to constrain w. However, because of the exponential sensitivity to mass it is important to avoid mass proxies. Other techniques for surveying for clusters are baryon biased. That bias is complex and scale dependent.

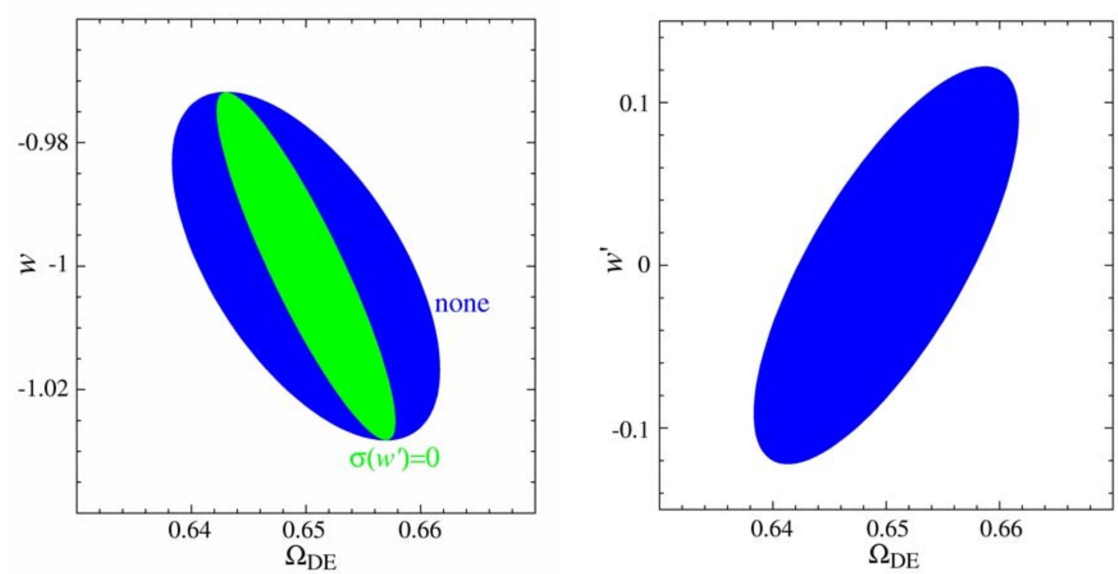

Figure 2 Error ellipsoids (1σ) in the planes of some DE parameters for the 8.4m LSST 15,000 sq.deg tomographic survey. *Left:* w for two priors on $w' = dw/d\ln(1+z)$ (Hu 2003). *Right:* Limits on w' and the fraction of closure density in dark energy from shear power spectrum tomography alone.

LSST is expected to find about 200,000 clusters in its mass maps; by using photometric redshifts, this offers 2-3% precision on w (Tyson et al. 2002). The shape of the observed distribution with mass and redshift can be compared with N-body simulations. Cluster counting as a method achieves its best accuracy at $z < 1$, where the dark energy is thought to have its most important effect. This distinguishes the method from higher redshift probes such as $z > 1$ supernovae or high-z redshift surveys for acoustic peaks.

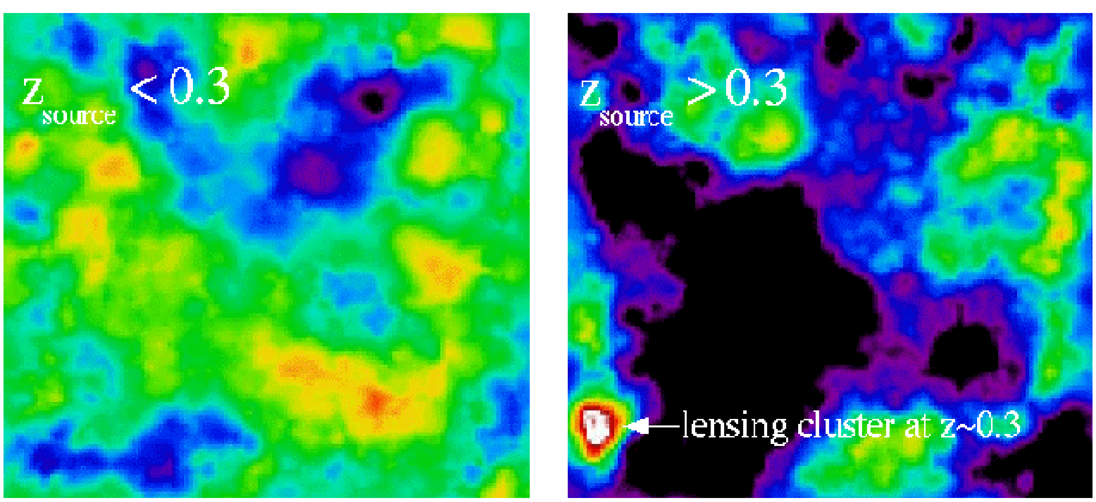

Figure 3 3-D mass tomography from the Deep Lens Survey. These mass maps of a 40' field show two slices in redshift. Similar 3-D mass tomography has found clusters up to $z = 1$.

2.1.3 Higher-Order Moments Using Galaxies at Multiple Redshifts

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, one can achieve highly precise measurements of the distance-redshift relation (Bernstein & Jain 2003), yielding a few percent precision on w. 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 merely on measuring relative cosmological distances. The potential systematic effects are quite different from those of other weak lensing analyses. The recent appearance of this apparently powerful analysis method suggests that we do not yet know the full power of the LSST data set. The methods in hand provide percent level precision on the dark sector, but the richness of the data set is such that we may well find better methods as the decade advances. Application of this technique will be limited by the stringent requirements on shear systematics (below 0.0001) and color-z nonlinearity (0.001) as well as decorrelation of mass and light on the scale of clusters.

In general, the non-Gaussian deviations of the density field on 10 Mpc scales makes the mass maps both complicated and rich. In galaxy redshift surveys, the non-linear evolution of clustering is seen as a contaminant that obscures the window into the early universe that the linear regime power spectrum provides. However, because weak lensing mass maps avoid the complications of redshift distortions and non-linear bias, these mass maps will allow us to compare the quasi-linear regime directly to the accurate predictions of cosmological simulations. Higher-order statistics such as the skewness of the shear may also provide a sensitive method for constraining Ω_M. We expect that the full utility of the mass maps has not yet been fully understood theoretically.

2.1.4 Combining LSST Shear with Cosmic Microwave Background (CMB) Measurements

Combining CMB anisotropy measurements with weak lens cosmic shear and mass tomography of lenses over the redshift range $0.1 < z < 1$ will enable precision measures of w as well as the spectrum of the density fluctuations. Dark energy influences mass structure formation (via changes on 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. For example, 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 the two measurements will pin down w to the 5% level as well as tightly constrain the dark matter power spectrum. Weak lens shear data over 15,000-20,000 deg^2 is required. This LSST survey will also constrain the time derivative of w to better than 0.08 (Knox & Song 2003) as shown in Table 1. The LSST estimates are based on realistic depths, seeing, noise, systematics, and areal coverage: source density of 70 arcmin^{-2} and a shear floor of 0.0001. In this table w_a is twice the usual derivative $w' = dw/d \ln(1 + z)$, n_S is the scalar index and $n_S' = dn_S/d\ln k$ is the running of the scalar index. These errors are for a simultaneous fit to a full set of cosmological parameters, and include marginalization over all parameters except curvature. Cluster counting gives similar errors, and combining the several DE probes will result in smaller overall errors.

Table 1 Estimates of Precision

	m_ν (eV)	w	w_a	n_S	n_S'
WMAP	1.2	2.4	—	0.06	0.02
WMAP +LSST	0.09	0.12	0.23	0.01	0.003
Planck +LSST	0.07	0.05	0.08	0.004	0.002

2.1.5 Joint Constraints

With an Ω_M prior from Planck, what are the error ellipsoids expected in the plane of w and w_a? To a depth of 26.5 R mag there will be over 60 useful resolved sources per square arcminute, and with 5 band color-z the shear tomographic estimates can be made for each of the WL tests. Figure 4 below shows the error ellipsoids for one of the above WL probes: the cosmic shear vs. z test, for the planned LSST and SNAP WL (Refrigier et al. 2003) surveys for an Ω_M prior as above (Knox & Song 2003).

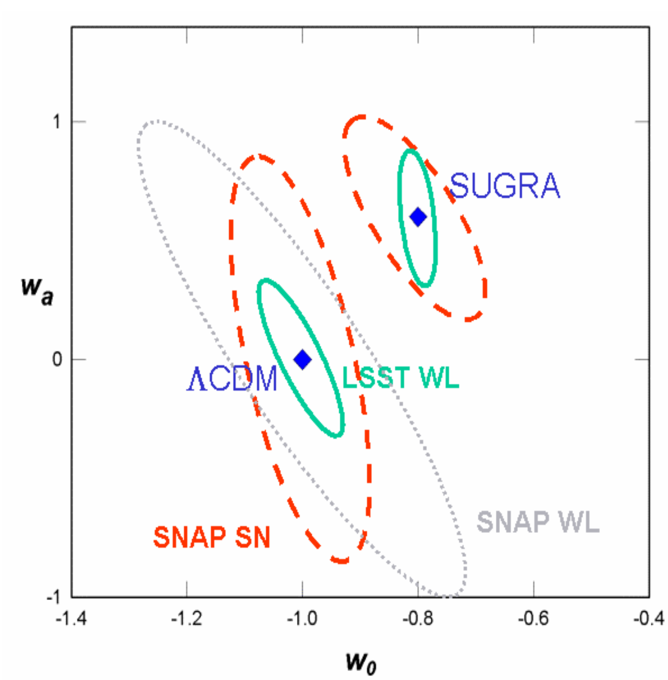

Figure 4 Error ellipsoids (1σ) in the planes of the relevant DE parameters for the 8.4m LSST 15,000 deg^2 tomographic survey and for SNAP. This LSST survey and SNAP SN and 300 deg^2 WL surveys in the $w - w_a$ plane are shown for two cosmological models. $w_a = 2\,w'$.

Cluster counting and WL cross-correlation cosmography are expected to produce equally good or better errors and with independent systematics. In fact cluster counting alone promises 2% precision on w when combined with a CMB prior. Two cosmologies are shown in Figure 4 indicating the required precision for reliably distinguishing between them. Also shown are the estimated SNAP SN errors. Combining all the WL probes may lead to a factor of two improvement for LSST over that shown in Figure 4. The difference between the two models of dark energy presented parameterizes our current level of ignorance in the overall cosmological model.

2.1.6 An independent measure of Ω_M

The above WL probes of dark energy use an Ω_M prior. Currently the most accurate is that obtained from the WMAP mission, and it is expected that the precision will increase with Planck. It is worth pointing out that all-sky deep WL data has the potential of determining Ω_M independently from the CMB observations. This will be a useful cross check. Each of the cosmological probes constrains a degenerate mix of Ω_{DE} and Ω_M. CMB, SNe, and $z = 0$ structure (including 2-D cosmic shear) each produce highly elongated error ellipsoids. While the WL error ellipsoid in Ω_{DE} - Ω_M space will be determined to perhaps 5% precision prior to LSST (via normalization to the mass fluctuation amplitude σ_8 at z=0), an all-sky WL cosmic shear survey vs. source redshift could shrink this elongated ellipsoid to a small region. As the source redshift is raised the error ellipsoid rotates counter-clockwise. The maximum likelihood solution, using only cosmic shear vs. z, will be a small region with error comparable to that of the width of the CMB ellipsoid.

2.1.7 The Integrated Sachs-Wolfe Effect

Microwave background photons suffer a net blueshift when passing through regions of mass overdensity in an accelerating universe. This is called the integrated Sachs-Wolfe effect (ISW). 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 effect is primarily dominated by sample variance, as it is only seen on large angular scales. To significantly improve upon the SDSS-WMAP detection of the ISW effect will require more sky coverage (going linearly with area). One must also control the photometric accuracy. 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. The only survey combination that will provide these improvements is LSST +Planck.

2.1.8 Moderate Redshift Supernovae

LSST will discover 100,000 SNe per year in the range $0.1 < z < 1$. It will follow up on these supernovae with lightcurves which 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 SNe spread all over the sky, anisotropies may be detected: flows and spatial and temporal dependence of w would be revealed. If it were found that w is different in different directions that 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 ISW observations, ideally complementing constraints from lensing.

2.2 Opening the Optical Time Window

Characterization of the variable optical sky is one of the few remaining 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 ten 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 throughput (defined as the product of collecting area and solid angle) in a single exposure that exceeds 200 $m^2 \, deg^2$. With a smaller throughput (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 would survey 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 5).

2.2.1 Explosive Events

Known types of catastrophic stellar explosions, such as supernovae and gamma-ray bursts (GRBs), 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

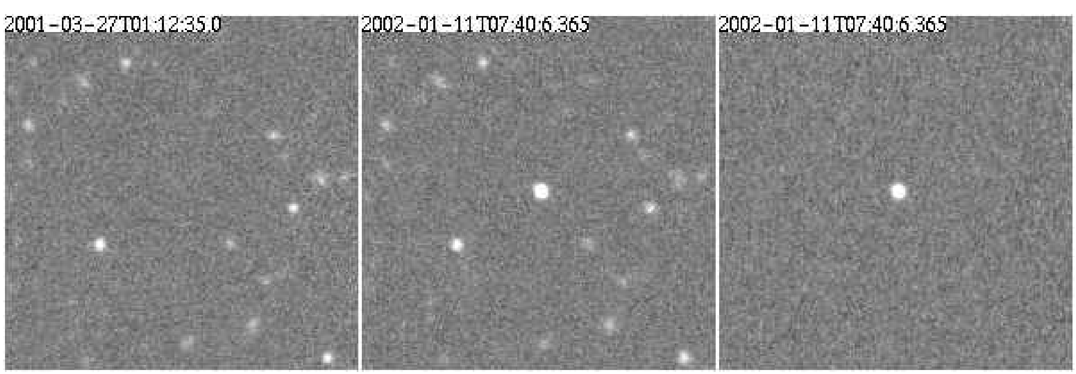

Figure 5 Optical burst detected by difference imaging in the Deep Lens Survey

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 1998). If LSST succeeds in detecting optical counterparts to the in-spiraling compact pairs that produce detectable gravity waves, it can measure their locations on the sky, providing an important constraint on the fit to the gravity wave time series.

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 quasars. With the basic cosmological parameters determined from other experiments, and lens masses obtained from either weak lensing or velocity dispersion data, these systems can be considered as tests of gravity on kiloparsec length scales, a range not easily tested by other means.

2.2.2 Extreme Physics

In upcoming decades, the space experiments GLAST (in the GeV band) and EXIST (in the hard X-ray) will observe the high-energy sky with unprecedented sensitivity and with very large (several steradian) fields of view. EXIST will monitor accreting black holes on all scales, from the stellar to the super-massive, while GLAST will observe the massive high-energy blazars. LSST provides the ideal complement in the optical. EXIST will survey most of the sky in a single 90-minute orbit, obtaining X-ray lightcurves for thousands of black holes on timescales of minutes to weeks. By monitoring large regions of the sky, LSST will provide the crucial optical lightcurves sampled on day 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.

2.2.3 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 luminous blue variable (LBV) outbursts, the shedding of giant dust clouds or naked thermal pulses during late active giant branch (AGB) evolution, disk instabilities during both inflow (cataclysmic variables), outflow (Be stars), or 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.

2.3 Strong Lensing with LSST

The large scale weak lensing survey performed by LSST is well-suited to strong lensing investigations. Using LSST to find and measure strong gravitational lensing by galaxies, groups and clusters will provide a wealth of complementary information on the properties of the dark matter on small scales.

An LSST survey covering 20,000 square degrees to a limiting magnitude ~ 27 in five filters will generate a very large sample of new wide-separation gravitational lenses. Of the 2×10^5 or so galaxy clusters discovered and mapped in the weak lensing survey, we estimate that upwards of 1000 should exhibit luminous arc systems. By comparison, the RCS survey, covering just 100 square degrees to a depth of 25 magnitudes, has discovered arcs in 8 out of 48 clusters (Gladders et al. 2003). The weak lensing tomography and multi-color optical selection capability will allow focused searches for such arc systems. The strong lensing constraints will greatly enhance the precision of the mass estimates of this cluster subsample, and allow the dark matter halo profile to be measured over a larger range of length scales. Figure 6 gives an impression of the image quality to be expected from the LSST cluster images.

The source population numbers to the survey limiting magnitude may be estimated from the Hubble Deep Field (HDF), suggesting some 3×10^5 galaxies per square degree at $z > 1$ (Metcalfe et al. 2001, Fernandez-Soto et al. 1999). We may reasonably expect of order 10^7 multiple image systems to be present in the survey, using a lensing rate of 10^{-3} as found in the CLASS survey (Browne et al. 2003); however, only a fraction of these lenses will be identified by LSST alone. The lensing cross-section is dominated by massive elliptical galaxies at redshifts $0.3 < z < 1$ (e.g. Fukugita & Turner 1991, Blandford et al. 2001); again from the HDF, we may expect approximately 10,000 such “clean lens” galaxies per square degree, providing in the region of 30 square degrees of lensing cross-section in the whole survey. By targeting these ellipticals and searching for achromatic excesses, a substantial fraction of these lenses may be detected; note the great importance of multi-color LSST imaging in this task. The resulting large sample of wide separation lenses will allow high precision statistical tests of the level of small-scale and non-axisymmetric structure in galaxies and groups.

Figure 6. *Left:* HST image of the inner regions of C10024+1652 (from Colley et al. 1996). *Right:* An approximate simulation of the LSST view of the same field, generated by convolution with a seeing disk of width 0.7 arcsec, rebinning into LSST pixels, and degrading with a small amount of noise. The lensed images are still partially resolved, providing information about the lens structure on small scales.

The prospect of discovering a significant number of higher-order catastrophe lenses in the LSST sample is an exciting one: as an example, the "quintuple quasar" lens system has six lensed images, with the lens model predicting two more (Winn et al. 2003, Keeton & Winn 2003). Such multiple image systems will provide much information on lens galaxy structure, while the very high magnifications attainable will provide us with a very powerful "cosmic telescope" indeed. The LSST optical data on sources observed in this way will provide very important complementary information to that available in similar scale low cadence surveys across the rest of the electromagnetic spectrum, including those by EXIST in the X-ray band and the Square Kilometer Array in the radio.

2.4 Small Bodies in the Solar System

2.4.1 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 Kuiper Belt Objects (KBOs) are our only chance to study directly this phase of planetary system formation; similar 10-1000 km objects in other planetary systems are likely to remain beyond observation for many decades.

The history of accretion, collisional grinding, and perturbation by existing and vanished giant planets is preserved in the KBO's orbital elements and size distributions. 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.

2.4.2 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. The impact of an asteroid larger than a kilometer or so in diameter would produce a major climatic disaster. 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 diameter, asteroids striking Earth would explode low enough in the atmosphere to have the effect of a large nuclear explosion of from 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 than the area damaged decreases, 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 and capable of causing ground damage. The frequency of such events, similar to the Tunguska event over Siberia in 1908, is once in a few hundred to a thousand years. 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.

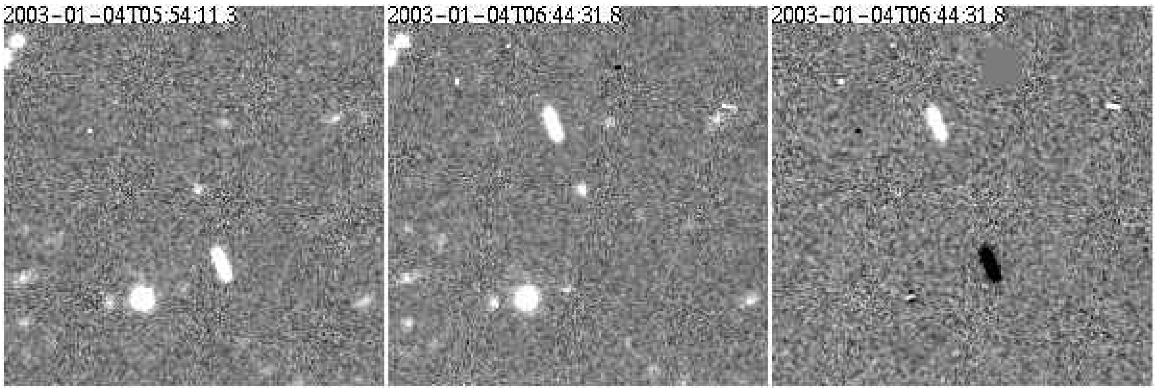

Figure 7 Asteroid detected in difference imaging from the Deep Lens Survey

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 asteroids larger than 250 m diameter, and about 80% completion down to the 140 m diameter called for by the NASA report.

2.4.3 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 severely affected (increased) by coma. There is hope that by detecting comets farther from the Sun, their bare nuclei can be observed and thereby provide 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.

2.5 Galactic Structure and Astrometric Studies

2.5.1 Astrometry and the Solar Neighborhood

The unique characteristics of the LSST make it particularly powerful for studies of local stellar populations. Repeated observations of the sky will yield parallaxes, proper motions, and variability characteristics, and the summed observations will provide very deep photometry.

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 achieve a major advance in this field. 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 pass bands, 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 and in turn allow selections of interesting classes of binaries to be made from the database. Combining the parallax and binarity data will greatly advance understanding of star formation. 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.

2.5.2 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 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.

2.5.3 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 8 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.

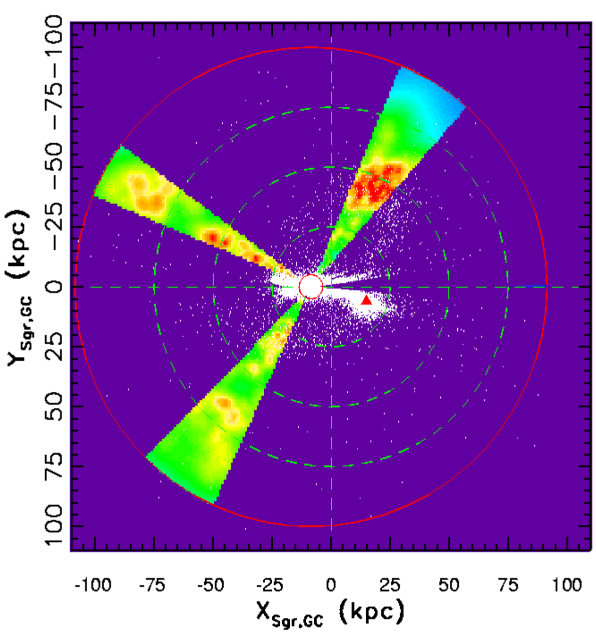

Figure 8 A plot of the product of stellar density and the cube of galactocentric radius derived from SDSS observations of RR Lyr stars within 10 degrees of the Sgr dwarf tidal stream plane

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.

2.6 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 these science drivers will also support a wide variety of other projects, and examples already proposed include: 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 at the universe; Nature is surely ready for us to begin.

3. Telescope and Instrument Requirements

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 data that could be used by any science program that requires optical photometry and astrometry. Some 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. Some potential conflicts are highlighted in the discussion of requirements that follows. Reconciliation of these requirements and optimization of the scheduling algorithm is one of the goals of the design and development phase.

3.1 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 $A\Omega > 200$ m^2 deg^2 can measure 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 27 AB. 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 a 1 micron band would be most important as it would extend the reach of diagnostics such as the 4000Å and Balmer breaks out to $z \sim 1.3$. 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 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. Short exposures optimize reconstruction of the high resolution image stack.

3.2 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 beyond $z = 1$ 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 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.

3.3 Strong Lensing Science

Using LSST as a finder for wide-separation strong gravitational lenses places requirements on the survey very similar to those from the weak lens tomography project. Good sampling of the PSF is needed for the lensed image analysis, while the wide range of colors needed for weak lensing source photometric red shift measurements are also essential for identifying multiple image systems in the presence of large, bright and dusty elliptical lens galaxies. Likewise, a survey cadence of a few days, as driven by the Near Earth Object search, will allow the time delays of the lensed images to be estimated, providing additional statistical leverage when exploring the properties of the lenses.

3.4 Solar System Census

The Near Earth Object (NEO) search places 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 to within 10° 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.

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 much less than 10 seconds, and the telescope must be able to move to a new field several degrees away and settle in this time, 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 AΩ of more than 200 m^2 deg^2. 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 throughput to be useful for the NEO search.

A survey for Trans-Neptunian Objects and other faint contents of the solar system makes demands that are somewhat at odds with those of an NEO search. Exposures of one hour are necessary 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 geographical requirements on the LSST site.

3.5 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. An AΩ of over 200 m^2 deg^2, as provided by the LSST, would 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.

3.6 Contents and History of the Galaxy

Mapping the assembly of our Galaxy via stellar streams requires photometry to r = 26, 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 several 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. Neutral density filters might be needed, or sensor technology might allow for magnitude compensation by fast readout of subarrays.

3.7 Putting It All Together

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 specified amounts of time to satisfy the cadence requirements. These requirements have optical throughput implications for the telescope/camera. Figure 9 charts the relative speeds of a survey to V = 24 for two values of the telescope/camera throughput: 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 must greatly exceed the noise of the detector. For the lower throughput

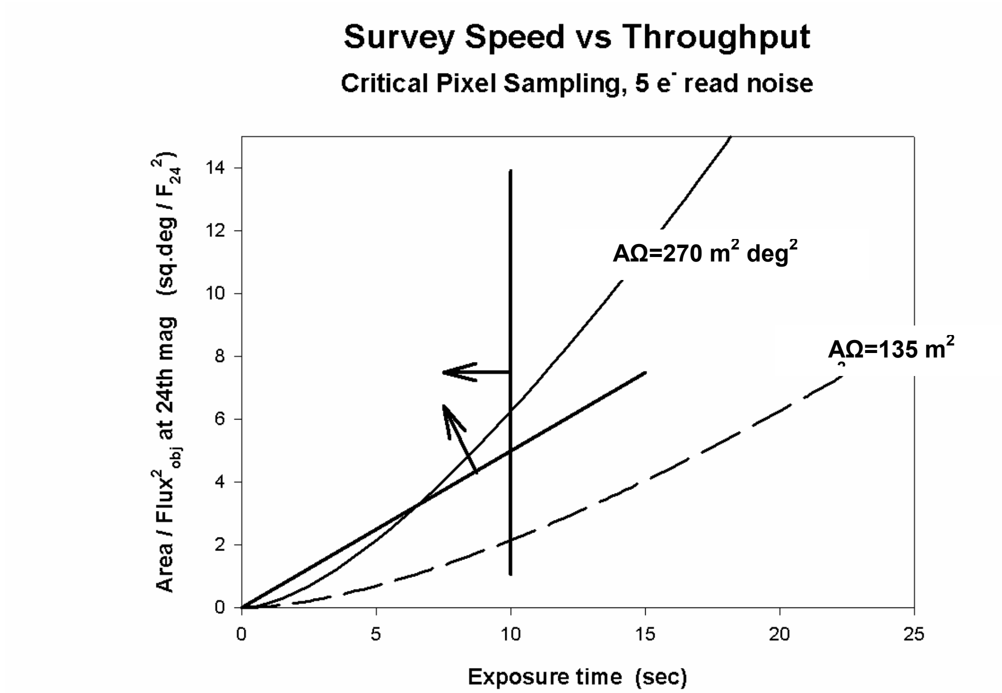

Figure 9 This plot shows the effect of telescope plus camera optical throughput (AΩ) on the survey efficiency as a function of exposure time, for a given detector noise. Two throughputs are shown: the upper curved line represents LSST at AΩ=270 m^2 deg^2; the lower curved line represents a system with half the LSST throughput (AΩ=135 m^2 deg^2). A 2.3 Gpixel camera (critically sampling) is assumed. The ordinate is the sky area surveyed to a given depth per exposure, normalized to 24th V mag. Survey speed increases with AΩ. But for the low throughput telescope the sky noise limit is never reached for exposure times less than the maximum (vertical line at 10 sec) set by the science requirements. Other science drivers require deep coverage of the entire visible sky every few days (upper left region), giving a minimum data rate.

system, the sky noise is not reached for exposure times less than 10 seconds. Small AΩ systems 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. The 8.4-m LSST with standard filters and current detector performance at –40 C reaches 24^{th} 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 minimization of 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 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 throughput) 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 section 5 below. A key advantage of this concept is that its high throughput makes it possible to cover the entire visible sky several times per month, thus enabling multiple parallel science programs.

3.8 Operational Strategy

Observation planning is a key element in the design of the overall LSST 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 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.

4. Facility Figures of Merit: Comparing LSST to SNAP and Pan-STARRS

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

SNAP is a proposed 2m 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 is sized to detect km-sized near-Earth asteroids (NEAs): an array of four 1.8m telescopes, each with a CCD array covering 7 square degrees of sky. The idea is that mass production of smaller telescopes and cameras may achieve economies of scale inaccessible to large, single telescopes. The approach is designed to be scaled to larger numbers of telescopes, so we compare both the current project and a potential larger version with 22 telescopes which we 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 8.4m single telescope with a detector array which 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.

4.1 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 these systems are so flexible as to cover a wide range of possible science, we define three figures of merit, corresponding to three important survey missions: opening 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 which change brightness or position on short timescales: optical flashes and NEAs. The faint stellar FOM applies to surveys which 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 which 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. The factors that determine the value of the figures of merit for each facility are:

• *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 will not collect sufficient signal to enable detecting a faint source in the available time.

• *Noise.* The noise in an image is determined by 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. 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.

• *Point-Spread Function*. 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 done in practice, but the projected 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 (Bernstein 2002).

• *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 and 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.

4.2 Comparison of the Figures of Merit

Table 2 lists three figures of merit corresponding to the three types of science mission for each of these facilities, and is followed by a summary 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 2a Survey Figures of Merit

Science:	**Faint Time window**	**Faint Stellar**	**Faint Galaxies**
FOM	$A\Omega\varepsilon / \Omega_{psf}\,\tau\,\beta$ m^2 deg^2 $arcsec^{-2}$ sec^{-1}	$A\Omega\varepsilon / \Omega_{psf}\,\beta$ m^2 deg^2 $arcsec^{-2}$	$A\Omega\varepsilon / \beta$ m^2 deg^2
LSST (8.4m)	16.0	160	79
SNAP (Optical)	0.02 – 0.04	28 – 50	1.1
PanSTARRS	0.23	23	15
ManySTARRS	1.6	160	79

Table 2b Parameters used in FOM table

	LSST	SNAP (Optical)	PanSTARRS
sqrt $4A/\pi$	8.4 m	2 m	Four 1.8 m
$\Omega_{optical}$	7 deg^2	0.34 deg^2	7 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 $arcsec^{-2}$	23.2 mag $arcsec^{-2}$	21.8 mag $arcsec^{-2}$

Armed with these figures of merit, we must consider 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.

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 which are the goal of any survey; otherwise one would have built a smaller, less-expensive system in the first place.

4.3 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 trade area on the sky for 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 design of LSST and SNAP was driven by very different science missions. SNAP was specifically designed for stellar photometry at infrared wavelengths where the 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 weak lensing 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-detector design is clearly optimal for NEA searches and finding brief optical transients.

5. The LSST System Reference Design

With few exceptions the 8-m class telescopes that have come into operation over the past decade have all had relatively narrow fields of view. The design and development phase of the LSST effort will establish the feasibility of breaking this paradigm with the intent of maximizing the telescope étendue (the AΩ product) and operational efficiency for the single purpose of conducting the deep synoptic surveys discussed in the previous sections. Below, we describe 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 design phase.

5.1 The Telescope

5.1.1 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˚ field of view (FOV) covering a 55-cm diameter flat focal plane, as tabulated in Table 3 and illustrated in Figure 10.

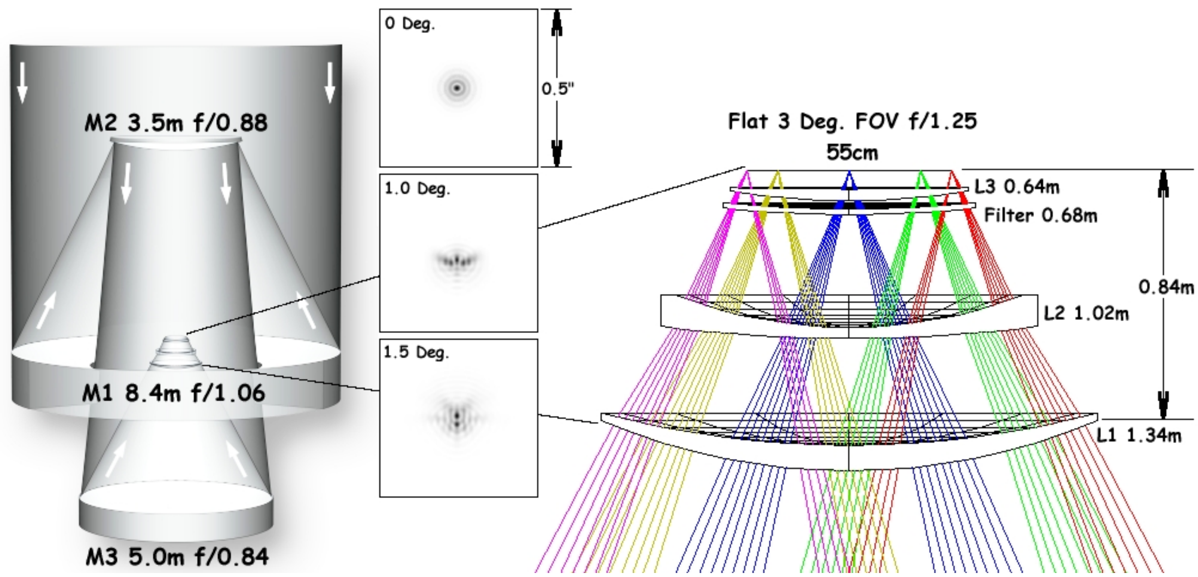

Figure 10 The overall optical path for the LSST baseline design (left) along with a more detailed view through the corrective camera optics (right). Insets show the diffraction PSFs at 650nm for three field radii.

Table 3 Optical Design Summary

Optical Configuration:	3-mirror modified Paul-Baker
Aperture:	8.4 m
FOV:	3.0 degrees
Étendue (AΩ)	278 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
Final F-Ratio:	1.25
Plate Scale:	50.9 microns/arcsec

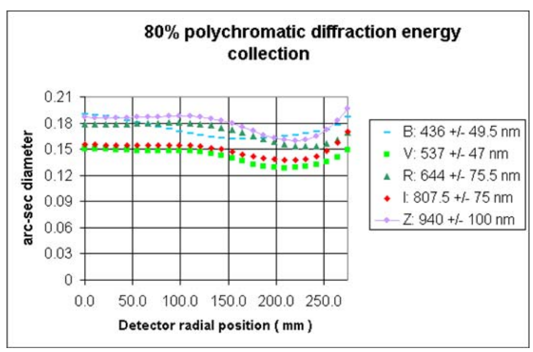

Figure 11 Estimated point spread function performance vs. position in the field.

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. As a fallback, the LSST can use standard aluminum reflective coatings on the three mirrors. The three refractive elements will be made from optical-grade fused silica. The convex surfaces of the first two lenses, L1 and L2, are 8^{th} 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. In Figure 11, the image sizes that include 80% of the polychromatic diffracted energy are plotted vs. radial position on the detector for each spectral band. For comparison, the diffraction-limited 80% image for the Z-band is about 0.083 arc-sec.

5.1.2 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 12.

5.1.3 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 for handling the large mirrors. The concept is illustrated in Figure 13.

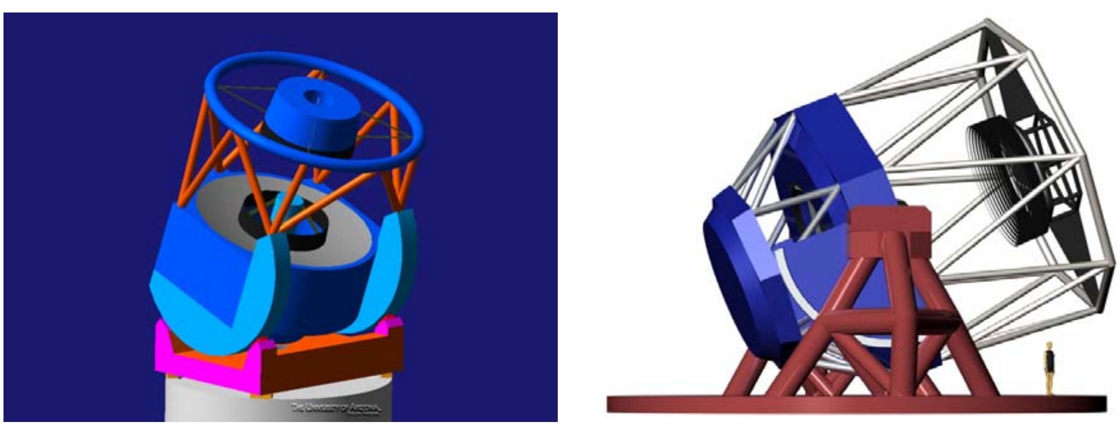

Figure 12 LSST Alt-Az Telescope concepts. At left is the dual "C" ring concept by W. Davison (UA, Steward Obs.). The right panel shows a concept by Claver and Muller (NOAO) based on a Gemini-like fork configuration.

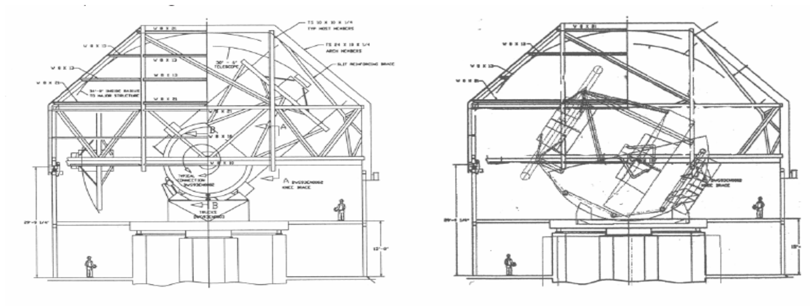

Figure 13 A dome concept showing a comparison between the 8.4-m LSST (right) and one of the 6.5-m Magellan telescopes utilizing a Magellan style dome.

5.2 The Camera and Focal Plane Assembly

5.2.1 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 14. 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 10) 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 as currently laid out can only accommodate four 60-cm filters at one time. 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.

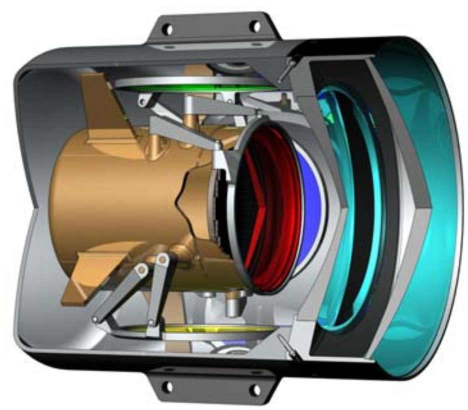

Figure 14 A sectional view of the camera dewar-in-dewar concept. The outer dewar houses the refractive elements for the wide field correction as well as the filter mechanism. The inner dewar holds the focal surface with detectors and interface electronics.

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.

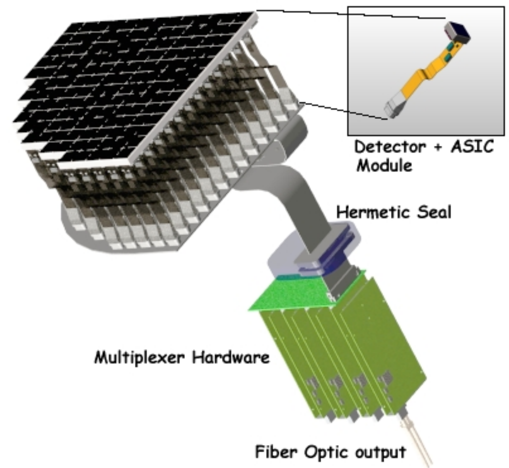

Figure 15 A quarter section of the detector array concept.

5.2.2 Detector Array Concept

The development of the 2.3 Gpixel camera should benefit from recent advances in CMOS and CCD plus ASIC hybrid imagers. 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 array + readout electronics solutions to our module requirements. Our concept for the focal plane array is shown in Figure 15.

5.3 Facility Operations

The basic concept for operating the LSST is to carry out an initial deep multi-color survey in the early years of commissioning and operation, followed by a survey more tailored to the time domain science. The early survey will be one that focuses on depth and wavelength coverage and will serve as the baseline reference for the time domain survey. Because the LSST will survey far fainter than any other survey before it, the LSST will have to provide its own base line survey of the static sky.

The baseline time-domain mode will provide multi-wavelength data. The LSST will initiate a series of adjacent telescope pointings; at each pointing a pair of short (10-15 second) exposures will be obtained in the reference filter color (*e.g.* Sloan r′). This sequence will go for 20-30 minutes, after which the LSST will repeat the series of pointings in a second filter color. This cadence of visits will be replicated throughout a night covering as much sky as possible. The same patch of sky will be revisited several times per lunation, where each new visit will use the same reference filter color but a different secondary color.

The actual cadence of observations will be optimized by means of a sophisticated scheduler utilizing a set of scientific merit functions to determine pointing priorities. Each of the principal science goals will have a merit function that contains strategic and tactical elements. Strategic elements would include long-term requirements for the aggregate data set over the lifetime of the survey (*e.g.* total area covered, amount of area that is contiguous, filter band passes etc.). Tactical elements would include those requirements that influence science goals on short time scales (*e.g.* image quality, cloud cover, sky brightness, transparency etc.). After each pointing the scheduler will evaluate the merit functions based on input it receives from the observatory control system containing information about the current sky conditions and data quality plus past history of the survey. For example, the LSST observing cadence may be altered to optimize the weak lensing science when the seeing conditions are exceptional (<0.5 arcseconds).

5.4 Data Processing and Analysis

The data will be processed in near real time to remove the instrumental signatures and to assess data integrity along with the image quality, sky brightness, photometric quality and other on-sky metrics through a series of processing pipelines. Once processed, the data will be analyzed for transient events, which will then be classified and published to the community. At a somewhat slower pace the image data will be processed to produce object catalogs that will be available to the community via an interface through the National Virtual Observatory (NVO).

5.4.1 Data Flow Architecture

Based on the preliminary science requirements and the experience gained from recent large surveys, we have generated a baseline data flow diagram (Figure 16). The first challenge is to move the pixel data from the camera to the reduction and archiving pipeline. The data management system will be responsible for moving more than 2 Gigapixels of data from the camera into the data analysis system in two seconds at a rate of 2.3 gigabytes per second. These data must then move through pipelines that remove instrumental signatures, then through analysis pipelines, and into long term storage in less than 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. The data management system will process and store approximately 6 Tera pixels per night, roughly the same as the whole 2MASS survey.

This data rate and volume is unprecedented in astronomy. When these data are appropriately distributed, however, the actual hardware needs for LSST reductions and analyses could be met with current, albeit a very large number of, commodity computers.

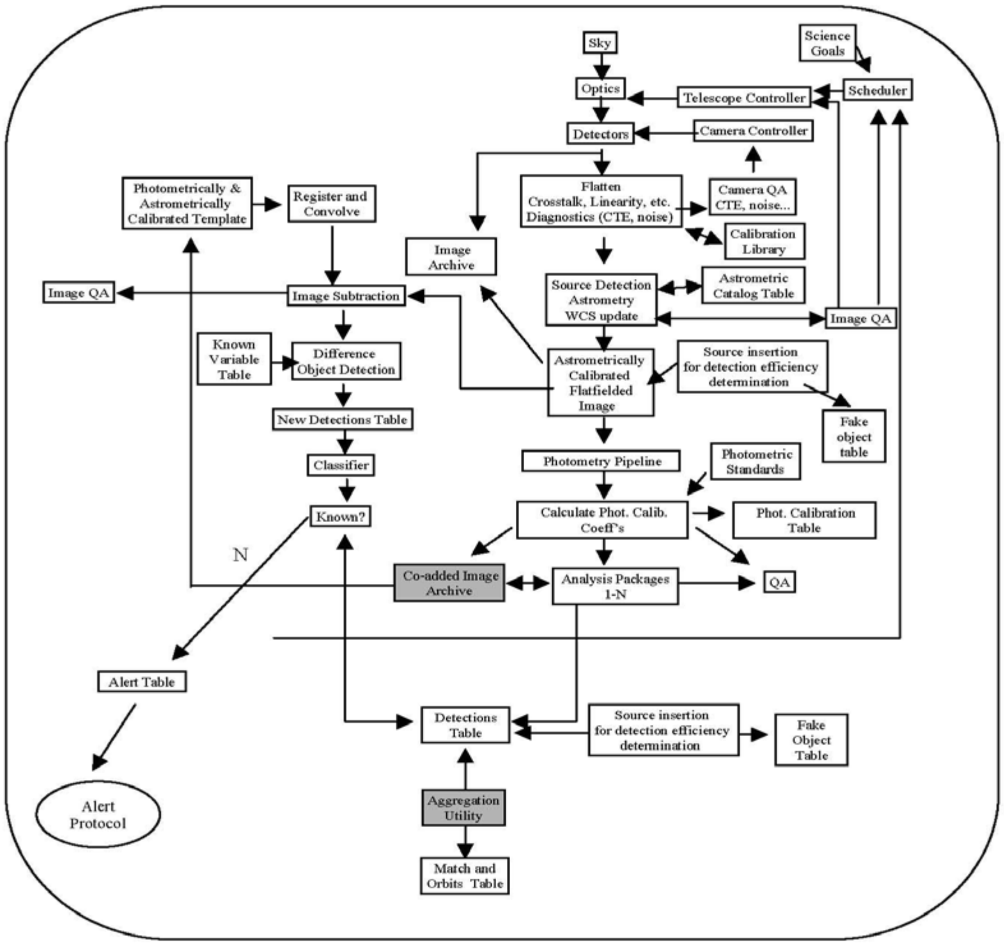

Figure 16 Data flow diagram for the LSST science data.

It is also true that the LSST database does not far exceed current databases in high energy physics or the commercial world and so database technology should be capable of handling the LSST data volume. The challenge, then, is to build upon our current experience and only develop new approaches where these are needed.

Some of the key requirements for the LSST data management system are:

- technology independence – the LSST software will need to operate over a minimum of 10 years;
- the ability to optimize and reconfigure computations;
- the flexibility to optimize and reconfigure data storage-- technologies on which data storage depends will change over the project lifetime and adaptation should be accommodated with ease;
- a computational environment that isolates scientists from the complexity associated with parallel computation;
- accommodation of pluggable and reusable modules;
- maintainability over the lifetime of the project.

The LSST data system will take advantage of the progress over the past decade in analyzing and managing large astronomical data sets. Microlensing surveys, the Sloan Digital Sky Survey, the Deep Lens Survey, and others have made significant advances in understanding image subtraction, automated object classification, automated alert generation, image addition, and distributed pipeline reduction systems. The intimate involvement of many members of our team in these surveys allows us to identify with confidence the key areas of development needed for the LSST data system:

- Optimal co-addition of images in the presence of variable seeing. The issues include: how to handle differential chromatic refraction (DCR); whether the co-addition algorithm which is optimal in an information-theoretic sense is in fact desirable for astronomical processing; and how well we can do astrometry and photometry on the co-added images.
- Careful investigation of the state-of-the-art image-subtraction codes. Open questions include: How much could be gained by integration of astrometric registration, flux conserving distortion-correcting pixel remapping, and psf-matching convolution into a single stage; and what is the best representation of the spatial variation in the PSF.
- The automated classification of transient events.
- Efficient techniques for aggregation of detections of transients into an object catalog; this involves both the linking of multiple detections of moving objects, and the resolution of object lists taken at different times and under conditions of different seeing.

6. Design Challenges, Trades and Tasks

The LSST telescope facility 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 4 summarizes the key trades and design studies that will be undertaken during the design phases for the telescope, supporting facilities, and camera. In the following sections, we describe the issues and how we plan to address them.

6.1 The Telescope

6.1.1 Optical Design

The LSST baseline optical design is fairly mature. During the design phase of the LSST project we will examine this optical design in the context of the scientific drivers. 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.).

Specifically, we will re-evaluate the current baseline design's field of view (FOV). While we expect to maintain a FOV of at least 3˚, 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.

Table 4 Key design and trade studies to be performed in design phase.

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

We will also conduct a detailed perturbation analysis study 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 minimum 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.

6.1.2 Physical Optics

The most challenging optic in the LSST 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.

The LSST program is 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, Phase Shifting Diffraction Interferometry (PSDI); an example is shown in Figure 17. 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.

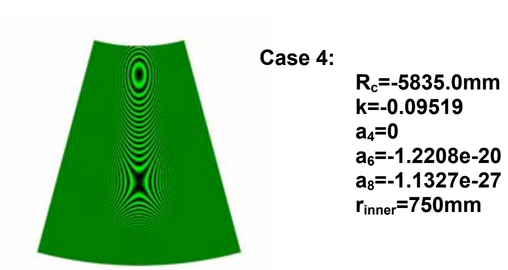

Figure 17 A simulated PSDI interferogram of a 1/12 sector of the LSST secondary mirror.

As presently envisioned the LSST will use spun-cast borosilicate mirrors for both the primary and tertiary. With existing telescopes that use borosilicate mirrors, no distinction is made 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 of both mirrors simultaneously. If it proves that there is a control problem, we will develop an alternate implementation of the tertiary using low expansion glass.

The 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.

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.

6.1.3 Active Optics and the Alignment System

The fast optical system of the LSST places stringent requirements on alignment and surface tolerances and that raises two questions: First, can the optical system once made be assembled to the level of precision needed to deliver the required image quality? Second, once assembled, can the 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: 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 design effort will focus on demonstrating the feasibility of this concept through detailed numerical modeling. An early example is shown in Figure 18.

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 number required will be determined during the design effort. We are currently exploring placing adjacent pairs of small detectors, one in front of, and the other behind, the 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.

6.1.4 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.

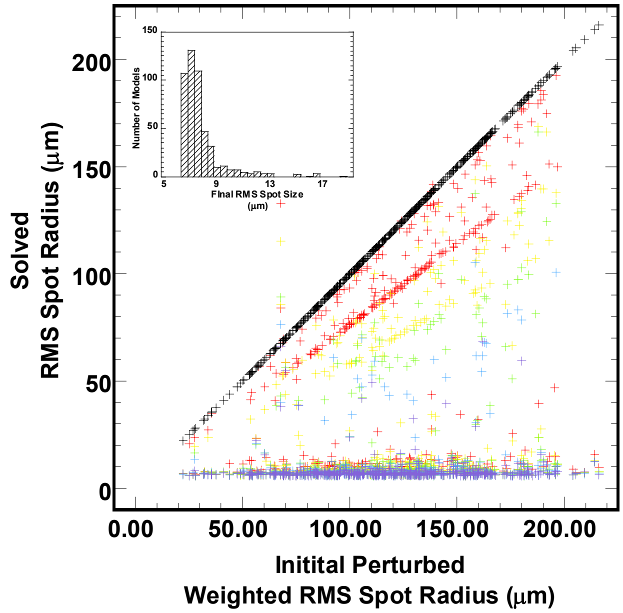

Figure 18 Successive solutions based on wavefront analysis of the LSST optical system as it has been perturbed in 48 degrees of freedom are shown. Each of 500 models is followed through 5 iterations (black = initial, red = 1st, yellow = 2nd, green = 3rd, blue = 4th and purple = 5th) relative to their initial perturbed image quality. The histogram inset shows the distribution in system image quality after 5 iterations.

For a variety of reasons we believe that the equatorial mount configuration is neither feasible under this requirement nor cost effective. During the design 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.

6.1.5 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 design 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.

6.1.6 Control System

The LSST telescope has a number of sophisticated subsystems that will require nested control loop systems to maintain the image quality performance (see Figure 19). These control loops will need a high degree of automation to fulfill the scientific goals of low down-time and high efficiency and to provide a clear feeling of simplicity and "transparency" to the users. Such systems have been developed already for Gemini and the VLT. LSST will take advantage of their success and lessons learned to design the LSST control system. In some aspects, LSST is unlike previous 8-m telescopes mainly because of the number of degrees of freedom that need to be controlled. A control model will be developed to simulate the whole system and to optimize the loop bandwidths. Particular attention will be given to the simultaneous control of the three mirrors. This modeling will be adapted to the various modes of operation that require different types of control.

In the current design, four major components have been identified as illustrated in the simplified control system diagram. Each system is then divided into subcomponents. During the design phase, a very detailed hardware-software control system architecture will be developed to address design, performance, and implementation issues.

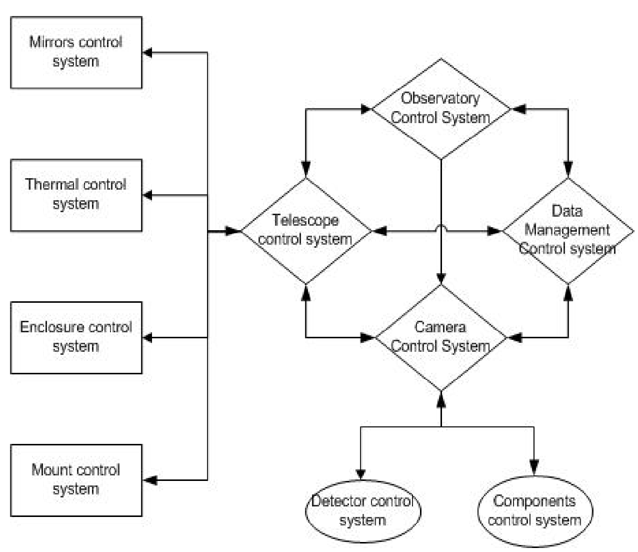

Figure 19 A simplified control system diagram for the LSST

6.1.7 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:

- 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;
- 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;
- sky brightness during the likely operational lifetime of a decade;
- surface winds and wind directions relative to likely observing patterns—it will be necessary to minimize the effects of wind on the secondary; and
- 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:

- establish the science requirements with appropriate weighting factors;
- compile existing data bases, both from remote sensing measurements by satellites and from existing observatory records; and
- model airflow over sites that make the initial cut.

We expect that most potential sites will 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 will form a site selection committee from its community of users. This committee will be supplied with the data and charged to make a final recommendation and ranked order of alternates. 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.

6.1.8 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.

6.2 The Camera and Focal Plane Assembly

6.2.8 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.

During the design 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 (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 key requirements for the LSST detector are:

- 10 µm pixel size.
- >95% fill-factor.
- Pixel full well > 90000 electrons.
- Read noise < 5 electrons with a readout time of < 2 seconds for a 2048 x 2048 detector format.
- High quantum efficiency, > 60% at 400 nm, >85% from 600 to 900 nm, and >45% at 1000 nm.

There are currently no detectors available from a single vendor that meet all the above specifications. The planned design and development 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.

About 100 microns of silicon is required to meet the target specification of 45% quantum efficiency at 1000 nm wavelength. Even with high resistivity material, cooling to -40 °C will be required to suppress dark current noise. Large-format, back-illuminated CCDs on high resistivity silicon can be made thick enough to achieve the high NIR QE (Holland 2003). However, this requires special processing. 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 may be 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 any thick detector there is a tradeoff between NIR QE and crosstalk between pixels due to the long drift distance of photo-generated carriers. While thick detectors have more radiation events and depth of focus issues for long-wavelength light absorbed at significant depths, neither of these present a problem for the 10 sec exposures and 10 μm pixels planned for the LSST.

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.

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. Antiblooming structures will need to be developed that are compatible with back illumination and do not compromise the fill factor or full well capacity. Use of CCDs will require a mechanical shutter in the camera.

The design and development 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. 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.

Collaborating research institutions will also perform evaluation of individual components, technologies, and prototypes obtained from commercial sources. This will involve 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, and the mechanical parameters relevant to the assembly of the focal plane. The evaluation program alone requires a significant investment in measurement equipment and a continuing manpower effort.

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. 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.

6.2.9 Camera Electronic Design

As part of an existing NSF grant, a final set of target specifications for the imager module are being formulated, vendors are being solicited for prototypes, and the IDTL lab will test these. We will then down-select to one vendor each for CCD and hybrid CMOS imager modules. 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.

6.2.10 Camera Opto-Mechanical Design

The baseline opto-mechanical design for the camera will be refined and developed during the design phase. Specific issues for investigation include gravitational distortions as a function of alt-az 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 a 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.

6.2.11 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.

6.3 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 design 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 design 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.

6.4 Data Processing System

We are approaching the LSST data management challenge from 3 perspectives: 1) developing and validating the algorithms needed to do the science, 2) devising an appropriate scalable framework within which these algorithms and associated modules will operate at the LSST data rate, and 3) developing and refining the data distribution mechanisms. Our high-level goals during the design phase are to:

- Build the core team that will implement the LSST data management components.
- Design a data acquisition, reduction, and publication model.
- Ensure that we have validated conceptual solutions in hand for the core pipeline algorithms, focusing on the aspects that are presently high risk.
- Implement an end-to-end prototype that runs at speed and goes from “pixels to SQL”, as we are firm believers in the value of early prototyping.
- Devise and evaluate a scalable framework for the high-data-rate computing that will be needed for LSST data analysis.
- Produce a set of project software requirements, drawing upon the experiences described above, with well-understood cost, scope and schedule, for the LSST construction phase.

6.4.1 Data Management Architecture

The goal for the LSST data management system is to enable concurrent, optimal execution of a diverse set of analysis and data interaction/access tasks. The baseline architecture is hierarchical. The coarsest component is the data processing pipeline. Each pipeline carries out a series of specific tasks or jobs to affect a larger result. For example, there will be a pipeline that is dedicated and tailored to efficiently remove the instrumental signatures from the camera data, another that will assess the quality of the data in terms of on sky metrics and at the engineering level to ensure data integrity. Each pipeline is envisioned as an application or job that is carried out utilizing a 3-component model for execution that includes: 1) a science model (SM) that details the specifics of the algorithm being applied, 2) a compute model (CM) that dictates the means by which a job is designed, constructed, and executed, and 3) a data model that determines how the data and job results are represented.

The challenge is to devise LSST compute, data, and science models that are reliable, robust, platform-independent and maintainable. We must also demonstrate that the system can handle not only the peak data rates off the telescope, but also the re-reductions that are an *inescapable* consequence of software evolution over the LSST project lifetime. A summary of key data management tasks and issues is given in Table 5.

Table 5 Key data management tasks to be performed in design 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

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.

As presently envisioned, 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 will be based on its fundamental interest in the scientific mission of LSST, especially the LSST probe of dark matter and dark energy. The DOE will conduct reviews, audits, and technical briefings coordinated with 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 will commit internal, discretionary funds with an approximate value of $10M during the design phase. 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 everything inside the dewar; this represents about a third of the total project. SLAC will take the lead and act as the primary interface for the project 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. For example, SLAC is the lead for BaBar and GLAST. Brookhaven is the lead for RHIC and a major US partner in LHC. Lawrence Livermore has a major role in the DOE computing initiative called ASCI and unmatched optics and precision engineering capabilities developed in connection with national security programs.

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 of the entire LSST project, including the design and development 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 a well-defined 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 design 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

7.1 Management Structure

Figure 20 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 day-to-day activities. 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 connected with solid lines in Figure 20 denote scientific components led by the LSST Director. Shaded boxes connected with shaded lines denote 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.

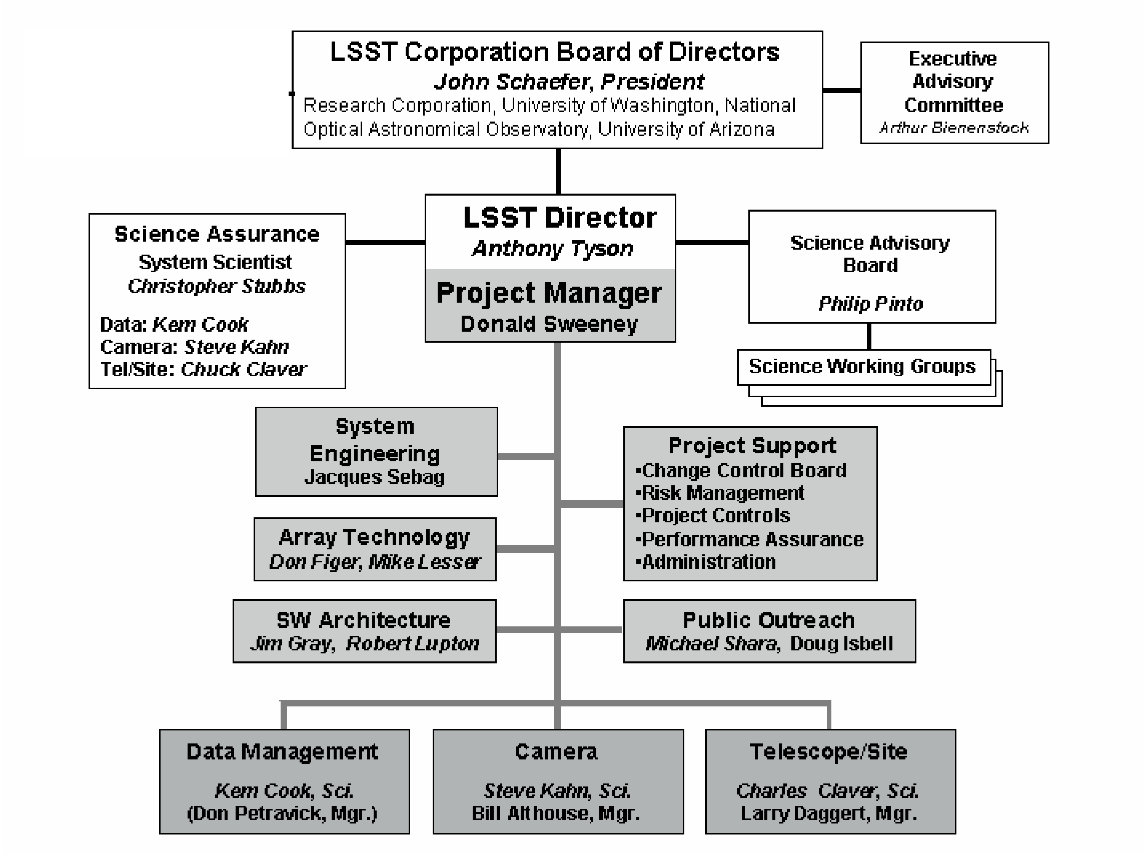

Figure 20 LSST Management Structure (design phase)

As shown in Figure 20, 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 design 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.

The LSST project has the good fortune that its management structure is defined and in place. The Project Director is Prof. Anthony Tyson (Lucent Technologies, Bell Labs and University of California, Davis) 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 and engineering project leaders, as shown in Figure 20.

7.2 Management of DOE Camera and Related Activities

SLAC will take overall responsibility for management of the LSST camera and focal plane data acquisition system, along with related science participation, together with major participation by BNL, LLNL and university-base HEP groups. The activities will be organized and managed in accordance with DOE Order 413.3, in the customary manner for major multi-lab projects. The DOE effort will be led by Prof. Steve Kahn (SLAC).

7.3 Work Breakdown Structure

The top-level of the WBS is divided into seven parts and is directly related to the management structure presented in Figure 20. Table 6 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.

Table 6 LSST Work Breakdown Structure (WBS)

WBS	Title	Management Owner
1.0	Data processing at telescope site	Data Management Team
2.0	Scientific data processing	Data Management Team
3.0	Camera	Camera Team
4.0	Telescope	Telescope/Site Team
5.0	Site	Telescope/Site Team
6.0	Public Outreach	Public Outreach Team
7.0	Management	LSST Director and Project Manager

The project schedule will be based on the WBS and will include all required activities for the design phase regardless of the source of funds or where the activity will be performed.

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.

7.4 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. Once each quarter, there will be a full-day, technical review. 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 NSF grant. All refereed publications will acknowledge support and be placed in the document archive.

7.5 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 four founding 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, Princeton University, and the University of California at Davis. 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 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 NASA with in-kind contributions from organizations in Europe and Asia. All sub-system managers have extensive management experience in their specialties.

7.6 Design and Development Phase

Figure 21 shows the Timeline and Deliverables associated with the proposed three-year, design and development project. The design phase has five, high-level deliverables, including both the conceptual design review (CoDR) and the preliminary design review (PDR). The PDR will be completed near the end of the third year. The site for the telescope will be finalized early in the second year of support. Selection of the site is essential to complete numerical modeling of the dynamic behavior of the telescope and camera.

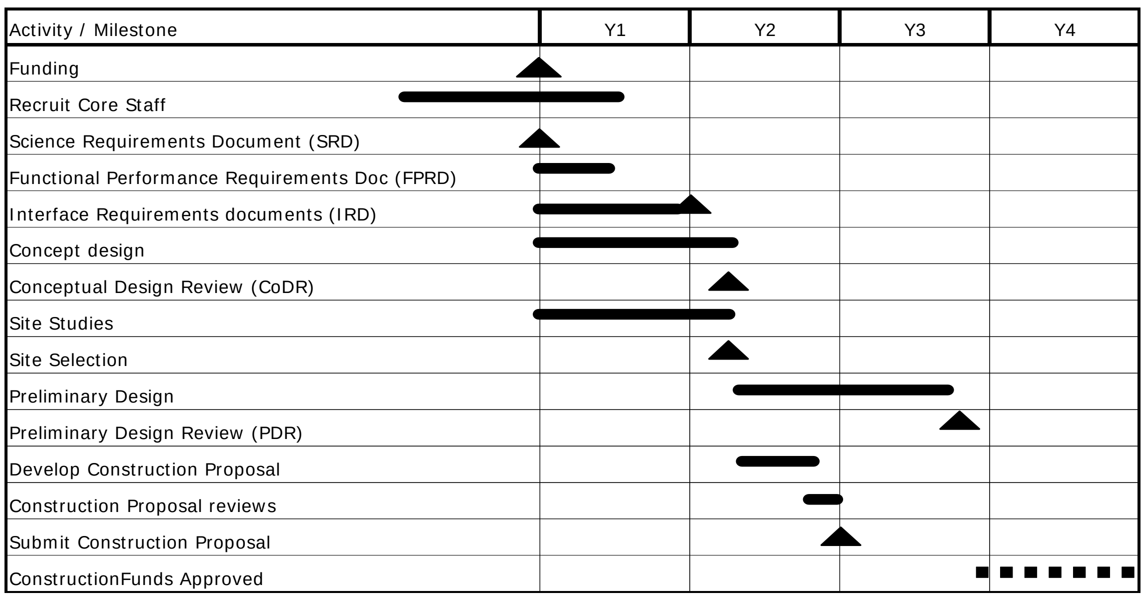

Figure 21 Schedule for Design and Development Phase

A key deliverable will be a nationally vetted science and engineering document that will enable and underpin the LSST construction phase. Moreover, once the project achieves this early milestone we will be in a position to approach individuals, foundations, and federal agencies to fully fund the program.

7.7 Budget 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 their own projects. The Project Manager will maintain and distribute the contingency fund. 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.

7.8 Risk Management Plan

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 subsystem 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.

7.9 Technology Readiness

A considerable effort from a broad community has led to a firm conceptual 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 eighty 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 informed the conceptual 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.

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: design phase engineering completed in the next three years, and “first light” for the telescope, camera, and data system achieved in 2011.

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