The LSST Science Requirements Document, v3.2, Oct 3, 2005

1. Introduction

Three recent nationally endorsed decadal surveys[1] concluded that a dedicated wide-field imaging telescope with an effective aperture of 6–8 meters is a high priority for US planetary science, astronomy, and physics over the next decade. The Large Synoptic Survey Telescope (LSST) described here is such a system. LSST is envisioned to be a large, wide-field ground based telescope designed to obtain sequential images of the entire visible sky every few nights. The baseline design (for details see Appendix A) involves a 3-mirror system with an 8.4 m primary mirror, which feeds three refractive correcting elements inside a camera, providing a 10 deg^2 field of view sampled by a 3 Gigapixel focal plane array. The total effective system throughput (étendue) is expected to be greater than 300 m^2 deg^2, which is nearly two orders of magnitude larger than that of any existing facility. The survey will yield contiguous overlapping imaging of $\sim$20,000 square degrees of sky in at least five optical bands covering the wavelength range 300–1100 nm. Detailed simulations that include measured weather statistics and a variety of other effects which impact observations predict that each sky location can be visited about 100 times per year, with 30 sec exposure time per visit.

The range of scientific investigations that could be enabled by such a dramatic improvement in survey capability is extremely broad, and, at this early stage of the program, it would not be feasible to make an exhaustive study of the scientific requirements appropriate to all of them. Therefore, in this document, we limit our attention to four main science themes:

1. Dark Energy and Dark Matter
2. Solar System Map
3. Transient Optical Sky
4. Milky Way Map

Each of these four themes itself encompasses a variety of analyses, with varying sensitivity to instrumental and system parameters. It is our belief that those analyses fully exercise the technical capabilities of the system, such as photometric and astrometric accuracy and image quality. The working paradigm at this time is that all such investigations will utilize a common database constructed from an optimized observing program. An example of such a program is described in Appendix B.

Below, we include short summaries of the science goals in each of these four theme areas and the assumptions that have been invoked in translating these into the minimum and design

[1] Astronomy and Astrophysics in the New Millennium, NAS 2001; Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, NAS 2003; New Frontiers in the Solar System: An Integrated Exploration Strategy, NAS 2003.

specification parameters. This document concludes with Tables of Science Requirements, in which we have integrated the constraints from the different programs.

2. The LSST Science Drivers

The LSST collaboration has identified four science programs as the key drivers of the science requirements for the project. Their selection was the result of discussions within the consortium and reflects the input of

- the three NRC studies that have endorsed the LSST,
- the report of the LSST Science Working Group (SWG), an independent committee formed by NOAO to represent community interests
- the scientific interests of the partners in the LSSTC, and the physics and astrophysics community.

The SWG report[2] (also known as the Strauss report), the LSST NSF proposal, and the LSST Dark Energy Task Force report should be consulted for a more detailed discussion of the major scientific advances that can be expected from the construction of a wide-field telescope that is dedicated to repeated deep multi-color imaging of the sky.

For each of the four primary science drivers selected by the LSSTC, this Section briefly describes the science goals and the most challenging requirements for the telescope and instrument that are derived from those goals (a separate document will deal with the data management requirements). Tables are also provided in the subsequent Section, which integrate the detailed requirements of these four programs. If these requirements are met by the LSST – and indications of the preliminary engineering studies undertaken to date indicate that they can be – then the LSST will not only enable all four of these major scientific initiatives but will also make it possible to pursue many other research programs. Some examples are described in the SWG report, but the long-lived data archives of the LSST will have the astrometric and photometric precision needed to support entirely new research directions, which will inevitably develop during the next several decades.

2.1. Dark Energy and Dark Matter

Driven by observations, current models of cosmology require the existence of both dark matter and dark energy (DE). One of the primary challenges for fundamental physics is to understand these two major components of the universe. The primary DE science drivers for LSST come from a suite of two and three point cosmic shear tomography analyses coupled with galaxy power spectrum and baryon acoustic oscillation (BAO) data, as well as from the use of supernovae as standard candles. Due to its wide area coverage, LSST will be uniquely capable of measuring at least 7 parameters related to DE: the lowest 6 eigenmodes of the DE equation of state vs. redshift $w(z)$ and any directional dependence. DE exerts its largest effects at moderate redshift; LSST's redshift coverage will bracket the epoch of DE dominance. When combined with Planck CMB data,

[2] Available as http://www.lsst.org/Science/docs/DRM2.pdf

these data from LSST will sharply test models of DE, whether due to new gravitational physics, vacuum energy, or other sources of dark energy.

2.1.1. Weak Lensing Studies

Weak lensing (WL) techniques can be used to map the distribution of mass as a function of redshift and thereby trace the history of both the expansion of the universe and the growth of structure. These use common deep wide area multi-color imaging with stringent requirements for the shear systematics in at least two bands and photometry in all bands. These requirements are covered in more detail in the LSST DETF report and references therein.

The shear systematic errors can be mostly corrected by use of foreground stars. The PSF within each exposure must be mapped, fit, and corrected. The precision of this correction depends on how many stars are available, and thus depends on the angular scale. The overall scale of the combined errors is set by the requirement of distinguishing models of the origin of DE: unique sensitivity to the cosmic shear power spectrum from arcminute to 100 degree scales and wide redshift range, the ability to probe at least five DE eigenfunctions, and any variation over the sky. This leads to an etendue requirement for *areal coverage times depth* (several billion source galaxies to z=3), as well as photometric precision and wide angular coverage (¿ 90 deg).

The power of the LSST relative to existing weak lensing surveys derives from its ability to survey much larger areas of the sky to faint limiting surface brightness while maintaining exquisite control of systematic errors in the galaxy shapes. Therefore, characterizing dark energy places particularly strong requirements on the total area of sky covered, the depth of the stacked image, the number of revisits to each field, the ellipticity and sampling of the point spread function (PSF), and the choice of filters, which must be suited to obtaining accurate photometric redshifts. At least five bands are required. Photometric precision of at least 1% is required, as well as calibration of photometric redshifts over the redshift interval 0.1 – 1.

The scale of residual shear errors should be set by the statistical error floors, not systematics. The two components of statistical shear errors vary oppositely with angular scale. On small angular scales (< few arcminutes) the source galaxy shear error is dominated by the random "shot" noise of the galaxy intrinsic ellipticities (about e=0.3 rms per galaxy) and the finite areal density of source galaxies. On large angular scales the source shear error is dominated by large scale structure cosmic variance. The cross-over point varies with source redshift. For all redshifts in projection, over the range of angular scales for LSST WL science the two sum to nearly a constant statistical shear error of 5×10^{-5}, or a source rms residual ellipticity of 0.001. We must make the residual shear systematics vs. angular scale (after PSF corrections) less than 30% of the statistical shear errors. This includes correlations between angle bins. To do this we must at least make sure that the residual shear power systematics (after corrections) track the statistical errors but a factor of $\sim$3 lower. But the statistical error is uncorrelated with angular scale (source galaxies randomly oriented) whereas systematic errors will typically be correlated. Therefore statistical errors beat down when averaged over a broad angular band, but systematics do not unless they are chopped or are stochastic from seeing.

2.1.2. Supernovae

Supernovae (SN) provided the first evidence that the expansion of the universe is accelerating. LSST will be a powerful SN factory. Operating in a standard mode of repeated scans of the sky with images taken every few days and with exposures of 30 seconds, LSST will discover 250,000 Type Ia SN annually. Their mean redshift will be $z \sim 0.45$ with a maximum redshift of ~ 0.7. These data, when combined with priors from other experiments, can constrain the lowest eigenmode of w (i.e. the mean value) in the nearby universe to 1 percent, and given the dense sampling on the sky, can be used to search for any dependence of w on direction, which would be an indicator of new physics. Some SN will be located in the same direction as foreground galaxy clusters; a measurement of the magnification of the SN will make it possible to model the cluster mass distribution. Core-collapse SN will provide estimates of the star formation rate during the epoch when star formation was changing very rapidly. Longer exposures (10-20 minutes/band) of a small area of the sky could extend the discovery of SN to a mean redshift of 0.7 with some objects having $z \sim 1.4$. The added statistical leverage on the "pre-acceleration" era will narrow the confidence interval on both w and its derivative with redshift.

Spectroscopic follow-up for so many SN is impossible. Therefore, exploitation of the data from LSST will require both colors and good coverage of the light curves to enable template fitting; the development of methods for the use of photometric data alone is currently being pursued by several community groups. Good image quality is required to separate SN photometrically from their host galaxies. At least four photometric bands, and preferably five, are required. Absolute photometric calibration to 1 percent is adequate, but the calibration of the zero points between filters remains a serious issue. The bandpasses must be sufficiently stable to allow the required levels of photometric calibration accuracy.

2.2. Solar System Map

The Earth is embedded within a swarm of asteroids, and some small number of these objects will ultimately impact the Earth's surface. The U.S. Congress has mandated that by the year 2008, 90% of the near-Earth asteroids (NEAs) with diameters greater than 1 km be discovered and their orbits determined. Impacts of NEAs of this size have the potential to change the Earth's climate and cause mass extinctions such as the one that presumably caused the extinction of the dinosaurs. A NASA report published in 2003 estimates conservatively that with current search techniques, about 70% of the NEAs with diameters larger than 1 km will be cataloged by 2008. This same report quantifies the risk of impacts by smaller bodies, which have the potential of causing significant ground damage and recommends as a reasonable next goal reduction of the residual hazard by another order of magnitude. Achieving this goal would require discovery of about 90% of the potentially hazardous asteroids (PHAs) down to diameters of about 140 m. While it is unlikely that any currently planned facility could achieve this goal within a decade or two, modeling suggests that the LSST could find about 90% of the PHAs with diameters larger than 250 m within ten years.

The search for PHAs puts strong constraints on the cadence of observations, requiring closely spaced pairs of observations two or preferably three times per lunation in order to link observations unambiguously and derive orbits. Individual xposures should be shorter than about 15 seconds each to minimize the effects of trailing. Because of the faintness and the large number of PHAs and other asteroids that will be detected, LSST must provide the follow up required to derive orbits rather than relying, as current surveys do, on separate telescopes. The observations should be obtained within ±15 degrees of the Ecliptic. The images should be well sampled to enable accurate astrometry, with absolute accuracy not worse than 0.1 arcsec. There are no special requirements on filters, although bands such as V and R that offer the greatest sensitivity are preferable. The images should reach a depth of at least 24 (5σ for point sources) in the r band in order to probe the < 1 km size range at the main-belt distances. The photometry should be better that 1% to allow for color-based taxonomic classification and light-curve measurements.

The LSST can also make a major contribution to mapping Kuiper Belt Objects (KBOs). The orbits of the KBOs provide a fossil record of the early history of the solar system; their eccentricities and inclinations contain clues to past perturbations by giant planets. The sizes of the KBOs hold clues to the accretion events that formed them and to their subsequent evolution through collisional grinding, etc. The compositions of KBOs are not identical and are correlated with their dynamical state; the reasons for the differences are not known. Light curves can be used to constrain the angular momentum distribution and internal strengths of the bodies. A more complete sample of KBOs and determination of their properties can assist with selecting targets for future NASA missions. The survey for PHAs can simultaneously provide the joint color-magnitude-orbital distribution for all bright ($r < 24$) KBOs. The 100 or so observations obtained for each bright KBO can be searched for brightness variations, but modeling will be required to determine how well periods can be extracted from observations made at random times. At the very least, it will be possible to determine amplitudes for many thousands of KBOs, and periods can likely be derived for many of them.

Long exposures would be required to push the detection of KBOs to smaller sizes and reach the erosion dominated regime in order to study the collisional history of various types of KBOs. KBO science would be greatly amplified if a small fraction of the observing time were devoted to hour-long observations in the ecliptic. This same mode of observation may have applications to the study of variable and transient objects. Apart from exposure time and the requirement for multiple filters (at least two) to classify objects according to composition, the requirements for the KBO science are essentially similar to the requirements for the detection and orbital determination.

2.3. Transient Optical Sky

The LSST will open a new window on the variable sky. Recent surveys have shown the power of variability for studying gravitational lensing, searching for supernovae, determining the physical properties of gamma-ray burst sources, etc. The LSST with its wide area coverage to deep limiting magnitudes will enable the discovery and analysis of rare and exotic objects such as accreting neutron star and black hole binaries; gamma-ray bursts and X-ray flashes, at least some of which apparently mark the deaths of massive stars; AGNs and blazars; and very possibly new classes of transients, such as binary mergers. LSST can also provide multi-wavelength monitoring over time of objects discovered by the Gamma-Ray Large Area Space Telescope (GLAST) and the Energetic X-ray Imaging Survey Telescope (EXIST). With its large aperture, the LSST is well suited to conducting a Deep Supernova Search in selected areas. LSST will also provide a powerful new capability for monitoring periodic variables, such as RR Lyrae stars, which can be used to map the Galactic halo and intergalactic space to distances exceeding 400 kpc. Since LSST extends time-volume space times 1000 over current surveys, the most interesting science may well be the discovery of new classes of objects.

Exploiting the capabilities of LSST for time domain science requires large area coverage to enhance the probability of detection of rare events; time coverage, since light curves are necessary to distinguish certain types of variables and in some cases infer their properties (e.g. determining the intrinsic luminosity of supernovae Type Ia depends on measurements of their rate of decline); accurate color information to assist with the classification of variable objects; good image quality to enable differencing of images, especially in crowded fields; and rapid data reduction and classification in order to flag interesting objects for spectroscopic and other follow up with facilities other than the LSST. Time scales ranging from $\sim$1 min (to constrain the properties of fast faint transients such as those recently discovered by the Deep Lens Survey) to $\sim$10 years (to study long-period variables and quasars) should be probed over a significant fraction of the sky. It should be possible to measure colors of fast transients, and to reach r 24 in individual visits. Fast reporting of likely transients to the community is required in order to facilitate followup observations.

2.4. Milky Way Map

The LSST is ideally suited to answering two basic questions about the Milky Way Galaxy: What is the structure and accretion history of the Milky Way? What are the fundamental properties of all the stars within 300 pc of the Sun?

Standard models posit that galaxies form from seeds planted by the Big Bang with accretion over time playing a significant role in determining their structure. Detailed study of the Milky Way can provide rigorous tests of these ideas, and the LSST will be able to map the 3-D shape and extent of the halo of our Galaxy. Specifically, the LSST will detect F turn-off stars to distances of 200 kpc; isolate stellar populations according to color; and determine halo kinematics through measurement of proper motions at distances exceeding 100 kpc. The LSST dataset can be used to identify streams of stars in the halo that are thought to provide a fossil record of discrete accretion events. The LSST in its standard surveying mode will be able to detect RR Lyrae variables and classical novae at a distance of 400 kpc and hence can explore the extent and structure of our own halo out to half the distance to the Andromeda Galaxy. The proper motions and photometric parallaxes for these stars can be used to characterize the properties of the dark matter halo in which the Milky Way is embedded.

Is our solar system with its family of planets unique? Or are there many more that contain Earth-like planets within the so-called habitable zone? How do solar systems form? Detailed exploration of our local neighborhood is key to answering this question. The LSST will obtain better than 3σ parallax measurements of hydrogen-burning stars to a distance of 300 pc and of brown dwarfs to tens of parsecs. These measurements will provide basic information on candidate stars that merit further study in the search for companions, including planets. Residuals from the fits for position, proper motions, and parallax will be searched for the signature of Keplerian motion to identify stars and brown dwarfs with companions and provide fundamental estimates of the mass of the primaries. LSST data will be used to determine the initial mass functions for low mass stars and sub-stellar mass objects and to test models of brown dwarf structure. The age of the Galactic disk can be inferred from white dwarf cooling curves.

Key requirements for mapping the Galaxy are large area coverage; excellent image quality to maximize the accuracy of the photometry and astrometry, especially in crowded fields; photometric accuracy of at least 1 percent to separate main sequence and giant stars; stringent astrometric accuracy to enable parallax and proper motion measurements; and dynamic range that allows measurement of astrometric standards at least as bright as r = 15. In order to probe the halo out to distances of 100 kpc using numerous main-sequence stars, the total depth has to reach $r \sim 27$ (assuming 5% photometry in the r band at $r = 25.6$; the SDSS has demonstrated such studies out to distances of 15 kpc using data with $r < 21.5$). To study metallicity distribution of stars in the Sgr tidal stream and other halo substructures at distances out to at least $\sim$40 kpc, the total depth in the u band has to reach ~ 24.5. In order to constrain tangential velocity at a distance of 10 kpc to within 10 km/s the proper motion accuracy has to be at least 0.2 mas/yr. The same requirement follows from a desideratum to obtain the same proper motion accuracy as GAIA at its faint end ($r \sim 20$). The LSST will then represent an "extension" of GAIA proper motion measurements to a 4 magnitude deeper level. In order to produce a complete sample of the solar neighborhood stars out to a distance of 300 pc (the thin disk scale height), with 3σ or better geometric distances, the parallax measurements accurate to 1 mas are required. In summary, these requirements imply that the LSST will enable studies of the distribution of numerous main-sequence stars beyond the presumed edge of the Galaxy's halo, of their metallicity distribution throughout most of the halo, of their kinematics beyond the thick disk/halo boundary, and will obtain direct distance measurements below hydrogen-burning limit for a representative thin disk sample.

3. Detailed Description of Science Requirements

The purpose of this Section is to lay out a common set of science requirements necessary to achieve a set of concrete scientific measurements of specified accuracy in the four main science areas described above. It will serve as a primary starting point to derive engineering requirements that can be flowed down to the various technical subsystems that comprise the LSST. Note that some of these requirements are not fully independent of the existing baseline design (see Appendix A), and of realities such as seeing distribution at the candidate sites (at the time of writing, three candidate sites are under consideration: San Pedro Martir in Mexico, and Cerro Pachon and Las Campanas in Chile).

3.1. The Definitions of Specified Parameters

For each quantity of interest or system parameter, we identify two quantitative values: a *minimum specification*, and a *design specification.*

The minimum specification shall represent the minimum capability or accuracy required of the system in order to achieve its scientific aims. If it becomes clear that the as-constructed system is in danger of not meeting its minimum specification, then the rationale for moving forward toward the construction of the LSST will need to be reevaluated.

The design specification represents the system design point, and will be used as the basis for the adoption of engineering tolerances. At this juncture, we believe that the design specification should be achievable in the context of the existing baseline concept for the LSST. However, as the development proceeds, it is conceivable that there may be some change in capability away from these values.

In some cases, it may be appropriate to also consider a set of stretch goals that would enhance scientific performance if they can be achieved. To avoid some complications and ambiguity, we do not list those in every instance, although it will remain understood that where improved capability is easily achievable, it should be pursued. Situations where enhanced capability beyond the design specification requires trade-offs in cost, schedule, or other system parameters must be evaluated on a case by case basis to decide whether they make sense in the context of the whole system. In addition to numerical requirements, a brief reference to the science program that provided the strongest constraints is also provided.

3.2. Distinction between Single Image Specifications and the Full Survey Performance

Detailed simulations show that LSST will be capable of obtaining about 200,000 10 deg^2 large images per year, assuming 30 sec total exposure per image and realistic observing conditions. For each of these images, a decision involving at least three free parameters (position on the sky and filter) will have to be made. With a simplifying assumption of only 2,000 allowed sky positions (i.e. a fixed grid of 10 deg^2 large field centers over an area of 20,000 deg^2) and 5 filters, there will be over 10^{10} different ways to execute the LSST observations over its projected 10-year long lifetime. Hence, the optimization of LSST observing strategies is a formidable problem that will require significant further analysis. For this reason, only weak constraints for observing cadence are listed here (though integral quantities such as total depth and sky coverage are specfied). On the contrary, the required properties of individual images (also known as *visits*) are specified in detail because they directly constrain the capabilities of hardware and software systems. The error budget distribution between the hardware and software systems is not considered here and will be addressed in a separate Engineering Requirements document.

3.3. Single Image Specifications

The fundamental image properties that are specified here are

- Bandpass characteristics
- Image depth (attained magnitude at some fiducial signal-to-noise ratio)
- Image quality (size and ellipticity)
- Astrometric accuracy
- Photometric accuracy

There are several factors that increase complexity of these specifications. Many of the image properties may depend on quantities such as zenith angle (airmass), wavelength, sky brightness, relative positions on the sensor and within the field of view, and attained signal-to-noise ratio. Most of these quantities are actually distributions, and can be specified by a single number only in special cases, such as that of a perfect Gaussian.

These effects are addressed as follows. For quantities with strong wavelength dependence, the requirements are specified in each band. Where relevant, fiducial seeing and airmass are specified. For quantities with a strong dependence on the signal-to-noise ratio (SNR), the requirements are specified at the *bright end*, defined here as the magnitude range between 1 mag and 4 mag fainter than the saturation limit in a given bandpass. Assuming that the faint end of this range corresponds to $r = 20$, and that 5σ depth is achieved at $r = 24.5$, the photon statistics limits on photometric and astrometric accuracy are 3 millimag and 2 milliarcsec for a fiducial delivered seeing of 0.7 arcsec. Both of these limits are sufficiently small as to allow required overall photometric and astrometric accuracy described below (which include the effects such as sky brightness and instrumental noise, as well as various calibration uncertainties). About 1% of all the sources detected in a typical LSST image will be brighter than $r = 20$. At this magnitude, the surface densities of galaxies and high-galactic-latitude stars are similar: about 1000 per square degree (implying a typical nearest neighbor distance of the order 1 arcmin).

The FWHM means *the full width at half maximum*, and the rms means *the root-mean-square scatter*. For a Gaussian distribution FWHM $= 2.35\,\mathrm{rms}$.

3.3.1. Filter Set Characteristics

The filter complement is modeled after the SDSS system because it has demonstrated success in applications such as photometric redshifts of galaxies, separation of stellar populations and photometric selection of quasars.

Quantity	Design Spec	Minimum Spec	Stretch Goal
Filter complement	ugrizY	grizY	ubgrizY

Table 1: The filter complement.

The extension of the SDSS system to longer wavelengths (Y band) is mandated by the increased effective redshift range due to deeper imaging. The optimal wavelength range for the Y band is still under investigation. A narrow blue b filter may increase the photometric redshift accuracy, but the quantitative effects of its addition are also under investigation. Current design of the bandpasses is illustrated in Appendix C.

At the time of writing, it is not known whether significant UV sensitivity is technically feasible. The addition of the u band would improve the robustness of photometric redshifts of galaxies, of stellar population separation, and of quasar color selection, and would provide significant additional sensitivity to star formation histories of detected galaxies (e.g. GALEX bands are red-shifted to the u band for galaxies at redshifts of about 1, about the median redshift for galaxies detectable in deep LSST images).

Filter Changes within a Night

The number of filters, *Nfilters*, within the same night, is equivalent to the number of filters that can be simultaneously housed within the camera. It is assumed that other filters from the filter complement can be inserted during the daytime.

Quantity	Design Spec	Minimum Spec	Stretch Goal
Nfilters	5	3	6

Table 2: The number of filters that can be simultaneously housed within the camera

Specification: The maximum time allowed to elapse between two visits in different filters is specified as *TFmax*.

Quantity	Design Spec	Minimum Spec	Stretch Goal
TFmax (min)	2	10	1

Table 3: The maximum time, in minutes, allowed to elapse between two visits in different filters.

The ability to switch active filters in a short amount of time will allow the color measurements of fast transients.

Filter Out-of-Band Constraints

Specification: The filter must not transmit more than Fleak % in any 10nm interval at any wavelength beyond one FWHM of the central wavelength. The integrated transmission at all wavelengths beyond one FWHM of the central wavelength must be below FleakTot %

Quantity	Design Spec	Minimum Spec	Stretch Goal
Fleak (%)	0.01	0.02	0.003
FleakTot (%)	0.05	0.1	0.02

Table 4: Filter Out-of-Band Constraints (transmission in % in any 10nm interval outside $3 \times FWHM$ range).

This requirement assures reasonable photometric accuracy for objects with extreme colors. For example, for a source with the color $u - i = 5$, the effect of a u band read leak confined to the i band (e.g. see Appendix C) is limited to a 0.05 mag bias in the u band measurement.

The temporal change of bandpasses (aging) must be sufficiently small to enable required photometric calibration accuracy (specified below, see §3.3.4).

3.3.2. Image Depth and the Minimal Exposure Time

An *exposure* means a single readout of the camera (one of the two back-to-back exposures, designed for cosmic ray rejection, that represent a *visit* of a given field of view). Image properties, such as depth (attained magnitude for point sources at some fiducial SNR, here taken to be 5), **are defined per visit**. The image depth depends on total exposure time, bandpass, delivered image quality (dominated by atmospheric seeing as per image quality requirement), the sky brightness and its spatial structure, and the system efficiency. For a chosen exposure time, and fiducial seeing and sky brightness, the required image depth is an indirect constraint on the system's efficiency (assuming a fixed effective primary mirror diameter).

The overall image depth distribution

Specification: The distribution of the 5σ (SNR=5) detection depth for point sources for all the exposures in a given band (the implication of many exposures only formally violates the paradigm of a single image specification; this requirement can be understood as a probability distribuion for the attained depth) will have a median not brighter than D1 mag, and no more than DF1% of images will have the 5σ depth brighter than Z1 mag.

All science programs would benefit from improved image depths and there is no threshold value. The science drivers described in §2 and correspoding image depths have motivated the baseline design parameters listed in Appendix A. The design specification values for D1 are computed for those baseline design parameters, and are verified using Subaru observations described by Kashikawa et al. 2002 (astro-ph/0209445). The uncertainty of these estimates is about 0.1-0.2 mag. The bandpasses used in computations are illustrated in Appendix C. A preliminary version

Quantity	Design Spec	Minimum Spec	Stretch Goal
D1 (mag)	24.5	24.2	24.7
DF1 (%)	10	20	5
Z1 (%)	24.2	23.8	24.5

Table 5: Single image depth in the r band (SNR=5 for point sources). The D1 and Z1 values are expressed on the AB magnitude scale and assume an A0V star, fiducial seeing of 0.7 arcsec (FWHM), the sky brightness of 21 mag/arcsec^2, airmass of 1.2, and a total exposure time of 30 sec. For the same fiducial parameters, the depth is approximately the same in the g band, about 1.0-1.5 mag brighter in the u band (very sensitive to lunar phase and mirror coatings; aluminium is assumed for the latter and 3 day old moon for the former), and brighter by about 1.0 and 1.5-2.0 mag in the i and z band, respectively. The throughput in the Y band is still being investigated; the depth may be 2.5-3.0 mag shallower than in the r band.

of the LSST Exposure Time Calculator was used to compute the depth in Y band. Note that there is no requirement that exposure time be same for all the bands.

The variation of the image depth over the field of view

Specification: For an image representative of the median depth (i.e. with the 5σ detection depth of D1 mag), the depth distribution over individual devices will have no more than DF2% of the sample brighter by Z2 mag than the median depth.

Quantity	Design Spec	Minimum Spec	Stretch Goal
DF2 (%)	15	20	10
Z2 (mag)	0.2	0.4	0.2

Table 6: Image depth variation over the field of view. These values apply to all the bands.

While the depth depends on the delivered image quality, the implied requirements are less stringent than the direct requirements on the image quality variation over the field of view specified below. The primary purpose of these image depth requirements is to define allowed variation in detector sensitivity.

The Minimum Exposure Time

Specification: The required exposure time will not be shorter than ETmin seconds.

Quantity	Design Spec	Minimum Spec	Stretch Goal
ETmin (sec)	5	10	1

Table 7: The minimal exposure time (in seconds).

The specified value allows a saturation level ~1 mag brighter than for the nominal 15-sec exposures (~3 mag brighter for the stretch goal). The ability to accurately measure the brightness and positions to a brighter level may improve calibration.

3.3.3. The Delivered Image Quality

The delivered image quality depends on atmospheric seeing and distortions introduced by the system, and can be parametrized by the equivalent Gaussian width (see below), and image ellipticity. The deviations of the image profile from the implied Gaussianity are parametrized by the radii enclosing specified fractions of the total energy (light).

The weak lensing studies are particularly sensitive to the delivered image quality (other science programs are only indirectly affected, e.g. through the dependence of the image depth on image size). As there is no particular threshold to be achieved, the benefit is a monotonous function of improvements in delivered image quality.

The delivered image size distribution

The delivered image size, hereafter delivered seeing (as opposed to atmospheric seeing), is expressed using the "equivalent Gaussian width" computed from

$$\text{seeing} = 0.663\,\text{pixelScale}\,\sqrt{n_{eff}}\ \text{arcsec}. \tag{1}$$

Here pixelScale is the pixel size in arcsec (0.2 for the baseline design) and n_{eff} is the effective number of pixels computed from

$$n_{eff} = \frac{(\sum f_i)^2}{\sum f_i^2}, \tag{2}$$

where f_i is the image intensity (i.e. the sum is over a bright star). In the limit of a perfect single Gaussian profile, seeing computed using these expressions is equal to the FWHM ($n_{eff} = 2.27\,(seeing/pixelScale)^2$ for a single Gaussian). Note that this approach is insensitive to the detailed image profile, and accounts for the fact that atmospheric seeing cannot be described by a single Gaussian at the required level of accuracy (∼1 %).

The image size is specified for three values of fiducial atmospheric seeing: 0.44, 0.60 and 0.80 arcsec. These values are chosen as the three quartiles of the seeing distribution measured at the Cerro Pachon site using DIMM at 500 nm, and corrected using the outer scale parameter of 30 m. Of course, these are simply fiducial values and are independent of the particular site choice. The atmospheric seeing distribution at the Cerro Pachon site is illustrated in Appendix D. The atmospheric seeing distributions at other two candidate sites (Las Campanas and San Pedro Mártir) are similar.

Specification: The delivered seeing distribution across the field of view will have a median not larger than S1 arcsec, with no more than SF1% of images exceeding SX*S1 arcsec.

The required image size is derived from assumption that the delivered image quality will be dominated by atmospheric seeing effects, and not the system. The design specification values reflect an error budget of 0.3 arcsec (for both telescope and camera, and including static and dynamic

Quantity	Design Spec	Minimum Spec	Stretch Goal
S1 (0.44)	0.53	0.59	0.51
S1 (0.60)	0.67	0.72	0.65
S1 (0.80)	0.85	0.89	0.84
SF1 (%)	10	10	5
SX	1.1	1.2	1.1

Table 8: The delivered seeing distributions for three fiducial values of atmospheric seeing. These values apply to the r and i bands.

errors), which is added in quadrature. The minimum specification and stretch goal are computed using error budgets of 0.4 and 0.25 arcsec, respectively.

The seeing spatial profile

Specification: For a delivered seeing of 0.67 arcsec, at least 80% of the energy will be encircled within SR1 arcsec, at least 95% of the energy will be encircled within SR2 arcsec, and at least 99% of the energy will be encircled within SR3 arcsec.

Quantity	Design Spec	Minimum Spec	Stretch Goal
SR1 (arcsec)	0.72	0.78	0.68
SR2 (arcsec)	1.17	1.27	1.11
SR3 (arcsec)	1.62	1.76	1.54

Table 9: These values apply to all the bands, as they are defined for a fiducial delivered seeing. For a different fiducial seeing, the SRx/seeing ratio (i.e. the *shape* of the delivered image) need be preserved.

The specified values were computed using a double-Gaussian profile that is a good description of both typically observed seeing profiles, and that expected for Kolmogoroff turbulence

$$p(x) = G(0, \sigma) + 0.1\, G(0, 2\sigma), \tag{3}$$

where $G(\mu, \sigma)$ is a two-dimensional Gaussian. For this profile, n_{eff} is 31% larger than for a single Gaussian with the same FWHM. For a seeing of 0.67 arcsec described by this profile, the radii enclosing 80%, 95% and 99% of the energy are 0.65, 1.06, and 1.47 arcsec, respectively (note that it would be grossly incorrect to assume that the seeing can be described by a single Gaussian, as the corresponding radii are 0.51, 0.69, and 0.86 arcsec).

The design specifications were determined by multiplying the above radii by 1.1, and by 1.2 for the minimum specifications. For the stretch goal specifications, the multiplication factor is 1.05. These requirements limit the deviations from the above canonical profile, and in particular, the amount of power in the expected power-law wings, due to the system. The power-law wings observed for free atmospheric seeing have a much smaller amplitude ($\sim$10 times, relative to the central intensity) than the upper limit implied by the above requirements.

The image ellipticity distribution

The image *ellipticity* is defined as $e = (\sigma^2_{maj} - \sigma^2_{min})/(\sigma^2_{maj} + \sigma^2_{min})$, where σ^2_{maj} and σ^2_{min} are the 2^{nd} moments of the stellar image along the major and minor axes, respectively.

Specification: For a delivered seeing of 0.67 arcsec, the ellipticity distribution across the field of view for unresolved sources will have a median not larger than SE1, with no more than EF1% of images exceeding the ellipticity of SE2. After fitting a smooth function, such as a low-order polynomial, to the ellipticity dependence on the position within the field of view, the distribution of residuals will have a median not larger than SE3, with no more than EF2% of images exceeding the ellipticity of SE4.

Quantity	Design Spec	Minimum Spec	Stretch Goal
SE1	0.04	0.05	0.03
EF1 (%)	5	10	5
SE2	0.07	0.1	0.05
SE3	0.002	0.003	0.001
EF2 (%)	10	15	10
SE4	0.003	0.005	0.002

Table 10: These values apply to the r and i bands.

The specified values are required by the weak lensing science, which aims to achieve a median ellipticity of the order 10^{-4} using several hundred exposures of the same field.

3.3.4. Photometric Quality

The photometric requirements are defined for bright unresolved sources (i.e. those whose measurements are not dominated by photon statistics, see § 3.3). The photometric accuracy is specified through the requirements on relative photometry (repeatability), the system stability across the sky, color zeropoints, and the transfer to physical flux scale (i.e. calibration onto the AB magnitude scale).

The relative photometry

Specification: The rms of the unresolved source magnitude distribution around the mean value (repeatability) will not exceed PA1 millimag (median distribution for a large number of sources). No more than PF1% of the measurements will deviate by more than PA2% millimag from the mean.

The specified requirements are driven by the photometric redshift accuracy, the separation of stellar populations, and detection of low-amplitude variable objects (such as eclipsing planetary systems). To verify that this requirement is fulfilled, samples of predominantly non-variable stars will have to be selected using appropriate color selection. Note that is sufficient to have only two observations to verify this requirement.

Quantity	Design Spec	Minimum Spec	Stretch Goal
PA1 (millimag)	5	8	3
PF1 (%)	10	20	5
PA2 (millimag)	15	15	10

Table 11: These values apply to the g, r and i bands. The PA1 and PA2 values in the u, z and Y bands may be 50% larger.

The internal absolute photometry

Specification: The distribution width (rms) of the internal photometric zeropoint error (the system stability across the sky) will not exceed PA3 millimag, and no more than PF2% of the distribution will exceed PA4 millimag.

Quantity	Design Spec	Minimum Spec	Stretch Goal
PA3 (millimag)	10	15	5
PF2 (%)	10	20	5
PA4 (millimag)	15	15	15

Table 12: These values apply to the g, r and i bands. The accuracy may be somewhat worse (but not by more than a factor of two) in the u, z and Y bands.

The specified requirements are driven by the photometric redshift accuracy and the separation of stellar populations. To verify that this requirement is fulfilled, samples of standard stars may be needed (an alternative is to track the shifts of morphological features in the color-color diagrams). Note that this requirement also places an upper limit on various systematic errors, such as, for example, a correlation of internal photometric zeropoint error with the position on a sensor, and within the field of view.

The band-to-band absolute photometric calibration

Specification: The absolute band-to-band zeropoint transformations (color zeropoints, e.g. for constructing the spectral energy distribution, SED) for main-sequence stars must be known with an accuracy of PA5 millimag.

Quantity	Design Spec	Minimum Spec	Stretch Goal
PA5 (g-r and r-i)	5	10	3
PA5 (other colors)	10	15	5

Table 13: The accuracy of color zeropoints (in millimag).

These requirements are primarily driven by the desired accuracy of photometric redshift estimates.

The overall external absolute photometry

Specification: The LSST photometric system must transform to a physical scale (e.g. AB magnitude scale) with an accuracy of PA6 millimag.

Quantity	Design Spec	Minimum Spec	Stretch Goal
PA6	20	50	10

Table 14: The accuracy of photometric system transformation to a physical scale (in millimag).

The requirements are driven by the accuracy of absolute determination of quantities such as luminosity and asteroid size for objects with well determined distances. Note that the internal band-to-band transformations are required to be much more accurate (as they may be calibrated and controlled by other means, and are not sensitive to errors in overall flux scale of photometric calibrators).

Further notes on photometry

The photometry of resolved sources, and of sources with non-stellar SEDs, must have comparable accuracy (not worse than a factor of 2 in rms sense, with the same fraction of sources in the distribution tails, as per above requirements) to unresolved stellar sources. The photometric measurements for resolved sources (galaxies) have to include several standard magnitudes, such as Petrosian magnitudes, as well as appropriate model magnitudes.

It is noteworthy to point out that the technical aspects of how the required photometric accuracy will be achieved (e.g. calibration schemes, flat-field determination, corrections for atmospheric effects) are purposedly left out as they belong to the Engineering Requirements Documents (for example, an all-sky cloud camera, or new software algorithms, may be needed to achieve the required photometric accuracy). The same approach is taken when specifying astrometric requirements, described next.

3.3.5. Astrometric Quality

The astrometric requirements are defined for bright unresolved sources (i.e. those whose measurements are not dominated by photon statistics, see § 3.3). The astrometric accuracy is specified through the requirements on relative astrometry (repeatability) and absolute astrometry.

The relative astrometry

Specification: The rms of the astrometric distance distribution for stellar pairs with separation of D arcmin (repeatability) will not exceed AM milliarcsec (median distribution for a large number of sources). No more than AF% of the sample will deviate by more than AD milliarcsec from the median. Specify AM, AF and AD for D=5, 20 and 200 arcmin (marked as 1,2, and 3, in the same order).

The three selected characteristic distances reflect the size of a chip, raft, and camera. The

Quantity	Design Spec	Minimum Spec	Stretch Goal
AM1 (milliarcsec)	10	20	5
AF1 (%)	10	20	5
AD1 (milliarcsec)	20	40	10
AM2 (milliarcsec)	10	20	5
AF2 (%)	10	20	5
AD2 (milliarcsec)	20	40	10
AM3 (milliarcsec)	15	30	10
AF3 (%)	10	20	5
AD3 (milliarcsec)	30	50	20

Table 15: The three blocks of values correspond to D=5, 20 and 200 arcmin, and to astrometric measurements performed in the r and i bands.

required median astrometric accuracy is driven by the desire to achieve a proper motion accuracy of 0.2 mas/yr, and parallax accuracy of 1.0 mas, over the course of the survey. These two requirements correspond to relative astrometric accuracy for a single image of 10 mas.

It should be stressed that about 25% of blue stars ($g - r < 1$) and 50% of red stars brighter than $r = 20$ have proper motions greater than 10 mas/yr. Thus, to verify that these requirements are met, it may be necessary to use quasars, which have a sky surface density of about 60 per square degree for $r < 20$ (implying a mean separation of $\sim$4 arcmin).

Specification: The astrometric reference frame for an image obtained in a band other than r will be mapped to the corresponding r band image such that the rms of the distance distribution between the positions on the two frames will not exceed AB1 milliarcsec (for a large number of bright sources). No more than ABF1% of the measurements will deviate by more than AB2 milliarcsec from the mean. The dependence of the distance between the positions on the two frames on the source color and observing conditions will be explicitly included in the astrometic model.

Quantity	Design Spec	Minimum Spec	Stretch Goal
AB1 (milliarcsec)	10	20	5
ABF1 (%)	10	20	5
AB2 (milliarcsec)	20	40	10

Table 16: The requirements on the band-to-band astrometric transformation accuracy (arbitrary band, relative to the r band reference frame).

The requirements on the band-to-band astrometric transformation accuracy are driven by the detection of moving objects, deblending of complex sources, and astrometric accuracy for sources detected in a single-band (e.g. high-redshift quasars detected only in the Y band).

The absolute astrometry

Specification: The LSST astrometric system must transform to an external system (e.g.

ICRF extension) with the median accuracy of AA1 milliarcsec.

Quantity	Design Spec	Minimum Spec	Stretch Goal
AA1 (milliarcsec)	50	100	20

Table 17: The median error in the absolute astrometric positions (in milliarcsec).

The accuracy of absolute astrometry is driven by the linkage and orbital computations for solar system objects. A somewhat weaker constraint is also placed by the need for positional cross-correlation with external catalogs. Note that the delivered absolute astrometric accuracy may be fundamentally limited by the accuracy of astrometric standard catalogs.

Auxiliary System Characteristics

The weak lensing science may be jeopardized by systematics in the shape measurements. To enable tests of systematics, it should be possible to perform measurements in a variety of observing conditions and setups. It is required that the camera can rotate by ± 90 degrees.

The effects of ghosting, which can also contribute to systematics in the shape measurements, are partially addressed through photometric requirements (e.g. the fraction of objects with substandard photometry). Further constraints, such as on spatial derivatives of the ghost brightness, cannot be made more quantitative at the time of writing than to require that the number and brightness of ghosts need be minimized.

Other issues, such as maximum sensor area loss and up/down time will be addressed through the considerations of efficiency and projected length of the survey.

3.4. The Full Survey Specifications

By obtaining numerous images of the same area on the sky, LSST will be able to significantly extend the scientific reach of single images described above. The required total number of images depends on a particular science program. Studies of LSST science capabilities performed to date have demonstrated that:

1. It is possible to design a universal cadence that would result in a common database of observations to be used by all science programs (see Appendix B).

2. The required survey lifetime is of the order 10 years. The strongest constraints on the lower limit come from the required number of images to perform robust weak lensing analysis, and from the minimum time baseline to obtain sufficiently accurate proper motion measurements. A somewhat less quantitative constraint on the upper limit for the survey lifetime comes from the desire to avoid “stale science”.

As a result of these studies, the adopted baseline design (see Appendix A) assumes a nominal 10-year long lifetime for the LSST survey. The same assumption was adopted here to derive requirements described below.

Note that some quantities relevant for science analysis are indirectly defined. For example, the accuracy for photometric redshifts is not specified, but it follows from the bandpass selection, required photometric accuracy per single visit, and the number of visits. Simulations show that the requirements described here will result in photometric redshift accuracy in the range 4-7% (fractional rms for 1+z over the redshift range 0.2-3.0, the fraction of catastrophic failures is still being investigated; also, a training sample of galaxies with spectroscopic redshift may be needed in order to limit systematic errors). This performance is consistent with t he level required by the science drivers. Similarly, the proper motion and parallax accuracies follow from required relative astrometric accuracy per single visit, and the number and distribution of visits (see below).

Distribution of visits vs. bandpass

Detailed simulations show that, during its nominal 10-year long lifetime, LSST will be capable of obtaining about 2,000,000 10 deg^2 large images. Assuming an effective sky area of 20,000 deg^2 (less than maximum observable area because of airmass constraints), this implies that each position on the sky can be visited about 1000 times (ignoring field overlaps). The distribution of these visits among the bandpasses (filters) will have a direct impact on the science of the full LSST survey.

The r and i bands should be preferentially selected over other bands because they will be used for shape measurements. Yet, other bands cannot be neglected because a broad wavelength coverage is required to achieve desired photometric redshift accuracy. The impact of the visit distribution across bands can be gauged from the following two cases. If all 1000 visits are distributed equally to the r and i bands, their final depth, assuming $\sqrt{N}$ scaling, would be 3.4 mag deeper than the single image depth (see §3.3.2). If the visits are distributed equally over 6 bands, then the final depth would be 2.8 mag deeper than the single image depth. Note that the depth difference between these two scenarios is only 0.6 mag.

Specification: The median of the distribution of the number of visits across the sky will not be smaller than Nv1.

It is assumed that the 6 bands are allocated the following fractions (in %) of the total number of visits: 1 (u), 4 (g), 40 (r), 30 (i), 10 (z) and 15 (Y). The total number of visits is 1000 for design specification, 800 for minimum specification, and 1200 for stretch goal. Note that the r and i bands are the deepest and have the largest numbers of visits, and that the r band is about 1 mag deeper than the adjacent bands (which would greatly help the faint source detection). These depths meet the requirements imposed by the required photometric redshift accuracy (the Y band depth may be too shallow by 0.5-1.0 mag, the impact of this difference is under investigation), and the total number of visits in the r and i bands meets the requirements imposed by the weak lensing drivers.

The above table specifies the *median* number of visits. The actual number of visits may vary across the sky. For example, the regions close to the Ecliptic may have a larger than median number of visits. On the other hand, the Galactic plane regions may have smaller than median number of visits (e.g. very deep images may be confusion limited). Details of such variations are not specified here, with an understanding that the adopted observing strategy will not jeopardize goals of any of the four main science themes (e.g. the full avoidance of the Galactic plane would have a severe

Nv1	u	g	r	i	z	Y
Design Spec	10 (1.3)	40 (2.0)	400 (3.3)	300 (3.1)	100 (2.5)	150 (2.7)
Minimum Spec	8 (1.1)	32 (1.9)	320 (3.1)	240 (3.0)	80 (2.4)	120 (2.6)
Stretch Goal	12 (1.3)	48 (2.1)	480 (3.4)	360 (3.2)	120 (2.6)	180 (2.8)
Design Depth	24.3	26.5	27.8	26.6	25.5	24.7

Table 18: The number of visits as a function of bandpass. For illustration, the numbers in parentheses show the corresponding gain in depth (magnitudes), assuming $\sqrt{N}$ scaling. The last row shows the total depth for the design specification median depth of a single image (assuming 5σ depths of $u = 23.0$, $g = 24.5$, $r = 24.5$, $i = 23.5$, $z = 23.0$ and $Y = 22.0$, from Table 5), and the above design specification for the total number of visits. The total depth is computed using a preliminary version of the LSST Exposure Time Calculator, with realistic observing conditions (the values are within 0.1 mag from the simple $\sqrt{N}$ scaling predictions, which is a consequence of the fact that the sky and source photon noise are dominating noise contributors in all the bands). Note, however, that the variation of the sky brightness due to solar cycle is *not* taken into account! At the time of writing, the listed values cannot be trusted to better than $\sim$0.2 mag.

impact on the Galactic structure studies).

The required number of visits as a function of bandpass does not reflect a possibility that some fraction of total time is allocated for special programs, such as deep SN and deep KBO search. While uniform observing strategy, enabled by the large étendue, will significantly increase the LSST efficiency, it seems prudent to reserve a small fraction of time for programs that can significantly enhance the science return, but cannot be accommodated by standard observations.

Specification: At least SPTmin (%), and not more than SPTmax (%), of total observing time will be allocated for special programs.

Quantity	Design Spec	Minimum Spec
SPTmin	5	1
SPTmax	10	20

Table 19: The fraction (%) of total observing time to be allocated for special programs.

These requirements are based on the analysis and deliberations performed within the LSST Science Working Group, which argued that some programs would have significant science impact using only 5-10% of total observing time. It is assumed that at least 1% of time is required for such programs, and that more than 20% of time allocated for such programs would have significant impact on the overall observing efficiency.

Distribution of visits in time

The LSST will be capable of observing 20,000 deg^2 of the sky in two bands every three nights. While the data obtained with such a cadence will contribute greatly to studies of optical transients, it is desirable to explore much shorter scales, down to 1 minute. This can be achieved with frequent revisits to the same field, or by utilizing field overlap. The details of the revisit time distribution, and its dependence on the covered area, will greatly depend on the adopted observing strategy and here only a rough guidance is provided.

Specification: At least RVA1 square degrees will have multiple observations separated by nearly uniformly sampled time scales ranging from 30 sec to 30 min.

Quantity	Design Spec	Minimum Spec	Stretch Goal
RVA1 (deg^2)	2,000	1,000	3,000

Table 20: The minimum area with fast (30 sec – 30 min) revisits.

The requirements are derived using the universal cadence described in Appendix B as a minimalistic scenario. It shows that ∼10% of the total area can be revisited on short time scales by utilizing field overlaps.

Strong constraints on the distribution of visits in time come from the goal to accurately measure stellar parallax and proper motion. Irrespective of the delivered astrometric accuracy, parallax measurements will not be of sufficient accuracy if the majority of visits are clustered around the same calendar day. Similarly, proper motion measurements require that a large fraction of observations is spread over as long a baseline as possible.

Specification: At least RVA2 square degrees will have at least 25% of the total number of observations of a given area separated in time by more than 5 years from the rest of the observations of the same area. At least RVA3 square degrees will have at least 25% of the total number of observations of a given area span at least 4 different calendar months.

Quantity	Design Spec	Minimum Spec	Stretch Goal
RVA2 (deg^2)	15,000	10,000	20,000
RVA3 (deg^2)	15,000	10,000	20,000

Table 21: The minimum area with revisit time distribution allowing accurate parallax and proper motion measurements.

The requirements are derived using a proper motion accuracy of 0.2 mas/yr and a parallax accuracy of 1 mas. The adopted design specification guarantees that it will be possible to achieve such measurement accuracies over the RVA2 and RVA3 large areas of the sky.

Distribution of visits vs. observing conditions

Observing conditions include, but are not limited to, seeing, lunar phase, and airmass. It is assumed that observing strategy will follow standard practices when selecting bandpass and sky location of a particular visit (e.g. the blue bands should be preferentially observed around new moon). Weak lensing science mandates that the r and i band observations be performed in the best seeing nights, and at low airmass. It also requires a large range of observing conditions to test for systematics errors.

The overall image ellipticity distribution

Specification: The distribution of ellipticities measured for unresolved bright sources using the full survey data will have a median not larger than TE1, with no more than TEF1% of the sample exceeding the ellipticity of TE2.

Quantity	Design Spec	Minimum Spec	Stretch Goal
TE1	0.0001	0.0002	0.00005
TEF1 (%)	15	25	15
TE2	0.0002	0.0004	0.0001

Table 22: These values apply to the r and i bands.

The specified values are required by the weak lensing science, which aims to achieve a median ellipticity of the order 10^{-4} using several hundred exposures of the same field.

3.5. Data Processing and Management Requirements

Detailed requirements on data processing and management will be described in a separate document, and here only a rough guidance is provided.

Specification: The object catalogs will include an extensive list of measured properties that will allow a variety of science analysis without the need to reprocess images. These catalogs and images corrected for instrumental artefacts, and photometrically and astrometrically calibrated, will be released to public every DRT1 years. The catalogs and images will be released for both single visits and for appropriately coadded data (such as those optimized for depth and for weak lensing analysis). Data on likely optical transients will be released with a latency of OTT1 minutes. The catalogs will be released in a format that will allow efficient data access and analysis (such as a database and query system).

Quantity	Design Spec	Minimum Spec	Stretch Goal
DRT1 (year)	1.0	2.0	0.5
OTT1 (min)	1.0	2.0	0.5

Table 23: Requirements for the data release cadence (DRT1) and for the transient reporting latency.

The requirement on the data release cadence is a compromise between "too often", which may have an impact on the system's efficiency, and "too slow", which may have an impact on the system's science outcome, and its perception within the community. The requirement on the transient reporting latency is essentially driven by the total exposure time, which sets an intrinsic scale for the time resolution of transient sources.

3.6. Further Improvements and Changes

A number of LSST-related design and scientific studies are under way that may affect the requirements described in this document. In addition, it is quite possible that further specifications may be requested during the process of distilling this document into the LSST Engineering Requirements Document. Any such changes to this document need to be brought to the attention of the LSST Science Council, who will review the case and, if appropriate, propose a change to the LSST Change Control Board.

4. Authorship

This document is the result of deliberations by the members of LSST Science Council, listed below, who also benefitted greatly from input from a variety of people, including, but not restricted to: Andy Connolly, Kem Cook, Daniel Eisenstein, Peter Garnavich, Kirk Gilmore, Richard Green, Alan Harris, Jeremy Mould, Knut Olsen, Abi Saha, Mike Shara, Chris Smith, Nick Suntzeff, David Wittman, Sidney Wolff, and Dennis Zaritsky.

The members of the LSST Science Council are: Bill Althouse, Tim Axelrod, Chuck Claver, Željko Ivezić (chair), Steve Kahn, Robert Lupton, Dave Monet, Phil Pinto, Michael Strauss, Chris Stubbs, Don Sweeney (ex officio), Alex Szalay, and Tony Tyson (ex officio).

Appendix A: The LSST Baseline Design

The following tables includes excerpts from the Aug 23, 2005 LSST Baseline Design Summary (available from http://www.lsstcorp.org) that are most relevant to this document.

Quantity	Baseline Design Specification
Optical Configuration	3-mirror modified Paul-Baker
Mount configuration	Alt – azimuth
Final f-Ratio	f/1.25
Aperture	8.4 m
Field of view area	9.6 deg^2
Effective étendue (AΩ)	318 $\mathrm{m}^2\mathrm{deg}^2$
Plate Scale	50.9 microns/arcsec (0.2 arcsec pix)
Pixel count	3.2 Gigapixel
Wavelength Coverage	300 – 1100 nm
Standard exposure sequence	15 s exp + 2 s read + 15 s exp + 2 s read + 5 s slew

Table 24: The LSST September 2005 Baseline Design Parameters

Appendix B: The Universal Cadence Strategy

Strict optimization of each of the numerous science programs that LSST will enable would certainly result in the same number of observing strategies. However, thanks to the large étendue, it is possible to design a universal cadence that would result in a common database of observations to be used by all science programs. An example of such a cadence is described here and presented as a "proof of concept" rather than as a specific requirement on the observing strategy.

This, so-called "universal cadence", has a number of desirable properties, and in particular, samples a wide range of time scales that are necessary for time domain science. Equally important, the proposed cadence is invariant to time translation and reversal, a feature that is desirable for a massive steady-state synoptic sky survey. More details about this proposal are available in the LSST Science Working Group report, and here only its essential characteristics are described.

The strategy proposes two revisits closely separated in time (15-60 min) to enable a robust and simple method for linking main-belt asteroids (MBA). Their sky surface density is about two orders of magnitude higher than the expected density of potentially hazardous asteroids (PHA), and thus MBAs must be efficiently and robustly recognized in order to find PHAs. MBAs move about 3-18 arcmin in 24 hours, which is larger than their typical nearest neighbor distance at the depths probed by LSST (2.3 arcmin on the Ecliptic). Two visits closely separated in time enable linking based on a simple search for the nearest moving neighbor, with a false matching rate of only a few percent.

With this cadence, it is possible to observe 20,000 deg^2 of sky in about three nights, with two visits per field. The colors of transients (such as SNe) and moving objects can also be measured by using two different filters for the two visits (with a preference given to the r band).

Due to the proposed overlap between successive fields of view, about 17% of the observed area represent multiple observations with a variety of time scales. With a representative choice of various free parameters, about 5% of the observed area would be revisited within 25 sec. Another 10% of the area would be reobserved with a fairly uniform sampling of time scales ranging from 25 sec to 15 min.

Appendix C: The LSST Bandpasses

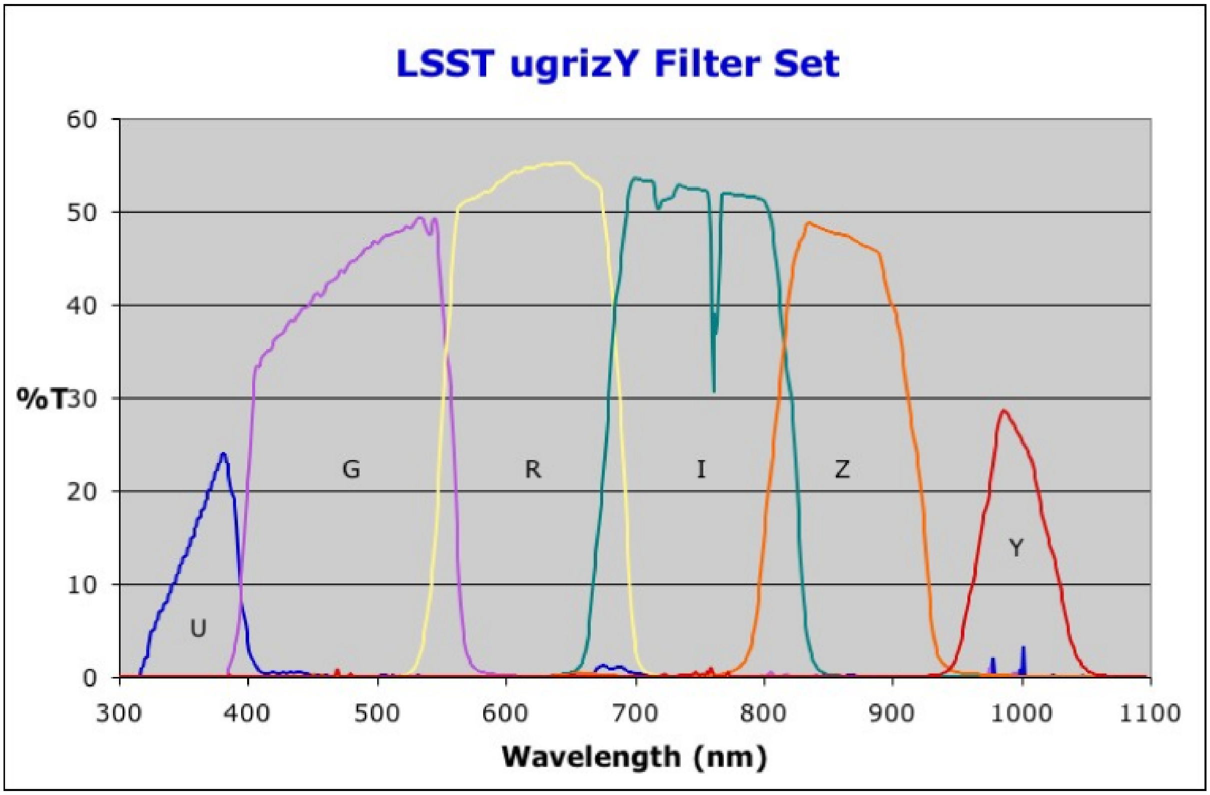

Fig. 1.— The current design of the LSST bandpasses. The y axis shows the overall system throughput (computed by K. Gilmore).

Appendix D: The Seeing Distribution at the Cerro Pachon site

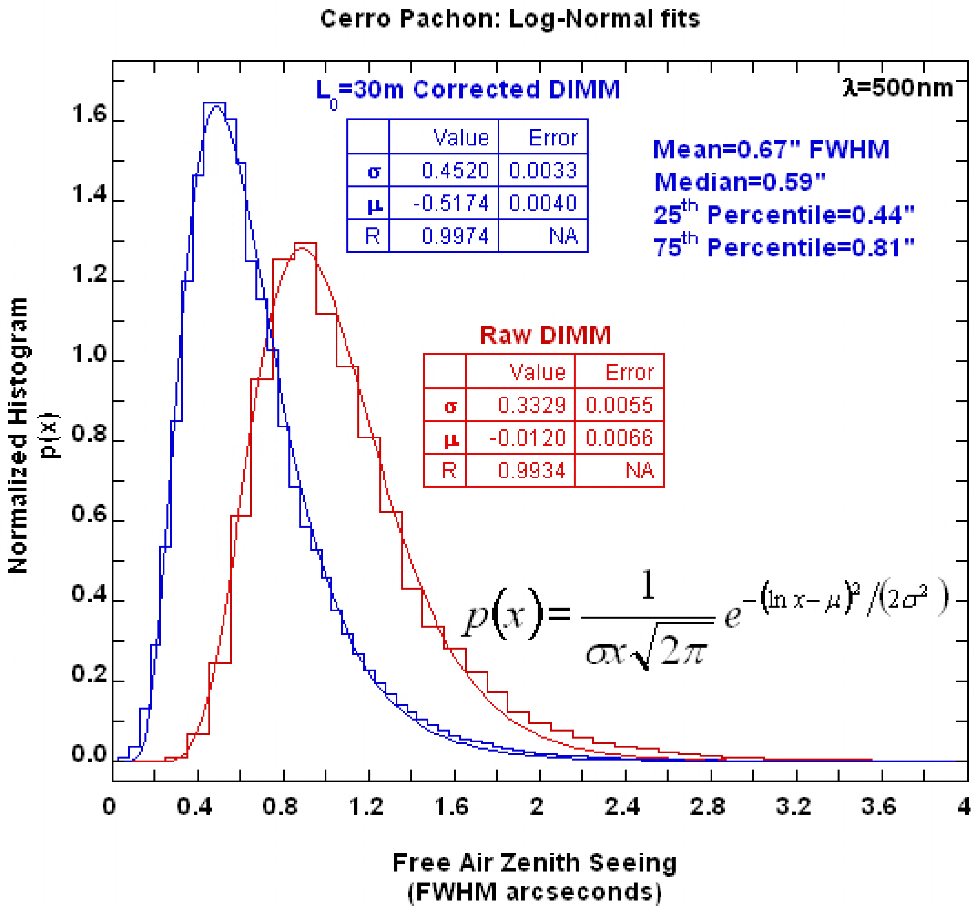

Fig. 2.— The seeing distribution measured at the Cerro Pachon site using DIMM at 500 nm (red histogram), and corrected using the outer scale parameter of 30 m (blue histogram). For details about the outer scale correction see Tokovinin 2002 (PASP, 114, 1156). The lines show best-fit log-normal distributions, with the best-fit parameters as shown in the inset (computed by C. Claver).