LARGE SYNOPTIC SURVEY TELESCOPE: FROM SCIENCE DRIVERS TO REFERENCE DESIGN

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SUMMARY: In the history of astronomy, major advances in our understanding of the Universe have come from dramatic improvements in our ability to accurately measure astronomical quantities. Aided by rapid progress in information technology, current sky surveys are changing the way we view and study the Universe. Next-generation surveys will maintain this revolutionary progress. We focus here on the most ambitious survey currently planned in the visible band, the Large Synoptic Survey Telescope (LSST). LSST will have unique survey capability in the faint time domain. The LSST design is driven by four main science themes: constraining dark energy and dark matter, taking an inventory of the Solar System, exploring the transient optical sky, and mapping the Milky Way. It will be a large, wide-field ground-based system designed to obtain multiple images covering the sky that is visible from Cerro Pachón in Northern Chile. The current baseline design, with an 8.4 m (6.5 m effective) primary mirror, a 9.6 $\deg^2$ field of view, and a 3,200 Megapixel camera, will allow about 10,000 square degrees of sky to be covered using pairs of 15-second exposures in two photometric bands every three nights on average. The system is designed to yield high image quality, as well as superb astrometric and photometric accuracy. The survey area will include 30,000 $\deg^2$ with $\delta < +34.5°$, and will be imaged multiple times in six bands, $ugrizy$, covering the wavelength range 320–1050 nm. About 90% of the observing time will be devoted to a deep-wide-fast survey mode which will observe a 20,000 $\deg^2$ region about 1000 times in the six bands during the anticipated 10 years of operation. These data will result in databases including 10 billion galaxies and a similar number of stars, and will serve the majority of science programs. The remaining 10% of the observing time will be allocated to special programs such as Very Deep and Very Fast time domain surveys. We describe how the LSST science drivers led to these choices of system parameters.

Key words. Astronomical data bases: miscellaneous – Atlases – Catalogs – Surveys – Solar system: general – Stars: general – Galaxy: general – Galaxies: general – Cosmology: miscellaneous

1. INTRODUCTION

1.1. Large scale surveys: a new way of seeing

Major advances in our understanding of the Universe have historically arisen from dramatic improvements in our ability to "see". We have developed progressively larger telescopes over the past century, allowing us to peer farther into space, and further back in time. With the development of advanced instrumentation – imaging, spectroscopic, and polarimetric – we have been able to parse radiation detected from distant sources over the full electromagnetic spectrum in increasingly subtle ways. These data have provided the detailed information needed to construct physical models of planets, stars, galaxies, quasars, and larger structures.

Until recently, most astronomical investigations have focused on small samples of cosmic sources or individual objects. This is because our largest telescope facilities have rather small fields of view, typically only a few square arcminutes – a tiny fraction (few parts per hundred million) of the sky, and those with large fields of view could not detect very faint sources. With all of our existing telescope facilities, we have still surveyed only a minute volume of the observable Universe.

Over the past two decades, however, advances in technology have made it possible to move beyond the traditional observational paradigm and to undertake large-scale sky surveys. As vividly demonstrated by surveys such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), the Two Micron All Sky Survey (2MASS, Skrutskie et al. 2006), and the Galaxy Evolution Explorer (GALEX, Martin et al. 2006), to name but a few, sensitive and accurate multi-color surveys over a large fraction of the sky enable an extremely broad range of new scientific investigations. These results, based on synergy of advances in telescope construction, detectors, and above all, information technology, have dramatically impacted nearly all fields of astronomy – and many areas of fundamental physics. In addition, the recent world-wide attention received by Google Sky[1] (Scranton et al. 2007) demonstrates that the impact of sky surveys extends far beyond fundamental science progress and reaches all of society.

Motivated by the evident scientific progress made possible by large sky surveys, three recent nationally endorsed reports by the U.S. National Academy of Sciences[2] concluded that a dedicated ground-based wide-field imaging telescope with an effective aperture of 6–8 meters is a high priority for planetary science, astronomy, and physics over the next decade. The Large Synoptic Survey Telescope (LSST) described here is such a system. The LSST will be a large, wide-field ground based telescope designed to obtain multi-band images over a substantial fraction of the sky every few nights. The survey will yield contiguous overlapping imaging of over half

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[1] http://earth.google.com/sky/

[2] 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.

the sky in six optical bands, with each sky location visited about 1000 times over 10 years.

The purpose of this paper is to provide a summary of the main LSST science drivers and how they led to the current system design parameters, as described in §2. A project status report and concluding remarks are presented in §3. For detailed and up-to-date information, please consult the LSST website (www.lsst.org).

2. THE LSST REFERENCE DESIGN

The most important characteristic that determines the speed at which a system can survey a given sky area to a given depth (faint flux limit) is its étendue (or grasp), the product of its primary mirror area and the field-of-view area (assuming that observing conditions such as seeing, sky brightness, etc., are fixed). The effective étendue for LSST will be greater than 300 m^2 deg^2, which is more than an order of magnitude larger than that of any existing facility. For example, the SDSS, with its 2.5-m telescope (Gunn et al. 2006) and a camera with 30 imaging CCDs (Gunn et al. 1998), has an effective étendue of only 7.5 m^2 deg^2.

The range of scientific investigations which will be enabled by such a dramatic improvement in survey capability is extremely broad. Guided by the community-wide input assembled in the report of the Science Working Group of the LSST[3], the LSST design is focused to achieve goals set by four main science themes:

(1) Constraining Dark Energy and Dark Matter
(2) Taking an Inventory of the Solar System
(3) Exploring the Transient Optical Sky
(4) Mapping the Milky Way

Each of these four themes itself encompasses a variety of analyses, with varying sensitivity to instrumental and system parameters. These themes fully exercise the technical capabilities of the system, such as photometric and astrometric accuracy and image quality. The working paradigm is that all scientific investigations will utilize a common database constructed from an optimized observing program, such as that discussed in Section 3. Here we briefly describe the science goals and the most challenging requirements for the telescope and instruments that are derived from those goals, which led to the overall system design decisions discussed below. For a more detailed discussion, we refer the reader to the LSST Science Requirements Document[4], as well as to the numerous LSST poster presentations at the recent 211th Meeting of the AAS[5].

2.1. The Main Science Drivers

The main science drivers are used to optimize numerous system parameters. Ultimately, in this high-dimensional parameter space, there is a one-dimensional manifold defined by the total project cost. The science drivers must both justify this cost, as well as provide guidance on how to optimize various parameters while staying on the cost manifold. Here we summarize a dozen most important interlocking constraints on data properties imposed by the four main science themes:

o The depth of a single visit (an observation consisting of two back-to-back exposures of the same region of sky)
o Image quality
o Photometric Accuracy
o Astrometric Accuracy
o Optimal exposure time
o The filter complement
o The distribution of revisit times (i.e. the cadence of observations)
o The total number of visits to a given area of the sky
o The coadded survey depth
o The distribution of visits on the sky, and the total sky coverage
o The distribution of visits per filter
o Data processing and data access (e.g. time delay for reporting transient sources and the software contribution to measurement errors)

We present a detailed discussion of how these science-driven data properties are transformed to system parameters below.

2.2. Constraining Dark Energy and Dark Matter

Current models of cosmology require the existence of both dark matter and dark energy to match observational constraints (Spergel et al. 2007). Dark energy affects the cosmic history of both the Hubble expansion and mass clustering. If combined, different types of probes of the expansion history and structure history can lead to percent level precision in dark energy and other cosmological parameters. These tight constraints arise because each technique depends on the cosmological parameters or errors in different ways. These probes include weak gravitational lens (WL) cosmic shear, baryon acoustic oscillations (BAO), supernovae, and cluster counting – all as a function of redshift. Using the cosmic microwave background as normalization, the combination of these probes can yield the needed precision to distinguish between models of dark energy (Zhan 2006, and references therein). In addition, time-resolved strong galaxy and cluster lensing probes the physics of dark matter. This is because the positions

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

[4]Available at `http://www.lsst.org/Science/docs.shtml`

[5]Available at `http://www.lsst.org/Meetings/AAS/2008/AAS211.shtml`

and profiles of multiple images of a source galaxy depend sensitively on the total mass distribution, including the dark matter, in the lensing object.

While LSST WL and BAO probes will yield the strongest dark energy and dark matter constraints, two major programs from this science theme that provide unique and independent constraints on the system design are

o Weak lensing of galaxies, and
o Type Ia Supernovae.

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 (e.g. Hu and Tegmark 1999, Wittman et al. 2000, for a review see Bartelmann and Schneider 2001). These investigations require deep wide-area multi-color imaging with stringent requirements on shear systematics in at least two bands, and excellent photometry in all bands. The strongest constraints on the LSST image quality come from this science program. In order to control systematic errors in shear measurement, it is mandatory to obtain the desired depth with many short exposures (which effectively enables "randomization" of systematic errors). Detailed simulations of weak lensing techniques show that, in order to obtain a sample of $\sim$3 billion lensing galaxies, the coadded map must cover $\sim$20,000 deg^2, and reach a depth of $r \sim 27.5$ (5σ for point sources), with several hundred exposures per field and sufficient signal-to-noise in at least five other bands to obtain accurate photometric redshifts (Zhan 2006). Because of their low surface brightness, this depth optimizes the number of detected galaxies in ground-based seeing, and allows their detection in significant numbers to beyond a redshift of two. It is anticipated that optimal science analysis of weak lensing will place strong constraints on data processing software, such as simultaneous analysis of all the available data (Tyson et al. 2008).

Type Ia supernovae (SN) provided the first evidence that the expansion of the universe is accelerating (Riess et al. 1998, Perlmutter et al. 1999). To fully exploit the supernovae science potential, light-curves sampled in multiple bands every few days over the course of a few months are required. This is essential to search for systematic differences in supernovae populations which may masquerade as cosmological effects, as well as to determine photometric redshifts from the supernovae themselves. Unlike other cosmological probes, even a single object can provide useful constraints and, therefore, a large number of SN across the sky can enable a high angular resolution search for any dependence of dark energy properties on direction, which would be an indicator of new physics.

Given the expected SN flux distribution, the single visit depth should be at least $r \sim 24$. Good image quality is required to separate SN photometrically from their host galaxies. Observations in at least five photometric bands are necessary to ensure that, for any given supernova, light-curves in several bands will be obtained (due to the spread in redshift). The importance of K-corrections to supernova cosmology implies that the calibration of the relative offsets in photometric zero points between filters and the knowledge of the system response functions, especially near the edges of bandpasses, must be accurate to about 1% (Wood-Vasey et al. 2007). Deeper data ($r > 26$) for a small area of the sky can extend the discovery of SN to a mean redshift of 0.7, with some objects beyond $z \sim 1$. The added statistical leverage on the "pre-acceleration" era would improve constraints on the properties of dark energy as a function of redshift.

2.3. Taking an Inventory of the Solar System

The small-body populations in the Solar System, such as asteroids, trans-Neptunian objects (TNOs) and comets, are remnants of its early assembly. The history of accretion, collisional grinding, and perturbation by existing and vanished giant planets is preserved in the orbital elements and size distributions of those objects. In the main asteroid belt between Mars and Jupiter collisions still occur, and occasionally objects are ejected on orbits that may take them on a collision course with the Earth.

As a result, the Earth orbits within a swarm of asteroids; some number of these objects will ultimately strike Earth's surface. In December 2005, the U.S. Congress directed[6] NASA to implement a near-Earth object (NEO) survey that would catalog 90% of NEOs larger than 140 meters by 2020. About 20% of NEOs, the potentially hazardous asteroids or PHAs, are in orbits that pass sufficiently close to Earth's orbit, to within 0.05 AU, that perturbations with time scales of a century can lead to intersections and the possibility of collision. In order to fulfill the Congressional mandate using a ground-based facility, a 10-meter class telescope equipped with a multi-gigapixel camera, and a sophisticated and robust data processing system are required (Ivezić et al. 2007). The search for NEOs also places 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 exposures should be shorter than about 1 minute each to minimize the effects of trailing for the majority of moving objects. The images must be well sampled to enable accurate astrometry, with absolute accuracy of at least 0.1 arcsec. The images should reach a depth of at least $\sim$24.5 (5σ for point sources) in the r band in order to probe the ~ 0.1 km size range at main-belt distances, and to fulfill the Congressional NEO mandate. The photometry should be better than 1-2% to enable color-based taxonomic classification.

2.4. Exploring the Transient Optical 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, and many other projects

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[6]For details see `http://neo.jpl.nasa.gov/neo/report2007.html`

at the forefront of astrophysics (Tyson 2006, and references therein). A wide-area dense temporal coverage to deep limiting magnitudes would enable the discovery and analysis of rare and exotic objects such as 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 and stellar disruptions by black holes. It is likely that such a survey would detect numerous microlensing events in the Local Group and perhaps beyond, and open the possibility of discovering planets and obtaining spectra of lensed stars in distant galaxies as well as our own.

Time domain science requires large area coverage to enhance the probability of detecting rare events; good time sampling, since light curves are necessary to distinguish certain types of variables and in some cases to infer their properties (e.g. determining of 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 discerning of images, especially in crowded fields; and rapid data reduction, classification and reporting to the community in order to flag interesting objects for spectroscopic and other investigations with separate facilities. Time scales ranging from 1 min (to constrain the properties of fast faint transients such as optical flashes associated with gamma-ray bursts (Kaspi et al. 2007) and transients recently discovered by the Deep Lens Survey, Becker et al. 2004) to 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 faint magnitude limits in individual visits (at least the Deep Lens Survey limit of $r \sim 24.5$).

2.5. Mapping the Milky Way

A major objective of modern astrophysics is to understand when and how galaxies formed and evolved. Theories of galaxy formation and evolution can be tested and influenced by a significantly improved understanding of the distribution and kinematics of stars in our own Galaxy, the Milky Way, which is a complex and dynamical structure that is still being shaped by the infall (merging) of neighboring smaller galaxies. We still lack robust answers to two basic questions about the Milky Way Galaxy:

o What is the detailed structure and accretion history of the Milky Way?
o What are the fundamental properties of all the stars within 300 pc of the Sun?

Key requirements for mapping the Galaxy are large area coverage, excellent image quality to maximize the photometric and astrometric accuracy, especially in crowded fields; photometric precision of at least 1% to separate main sequence and giant stars; astrometric precision of about 10 mas per observation to enable parallax and proper motion measurements; and dynamic range that allows measurements of astrometric standard stars at least as bright as $r = 16$. In order to probe the halo out to its presumed edge at ~ 100 kpc using numerous main-sequence stars, the total co-added depth must reach $r > 27$, with a similar depth in the g band. To study the metallicity distribution of stars in the Sgr tidal stream (see e.g. Majewski et al. 2003) and other halo substructures at distances beyond the presumed inner vs. outer halo boundary (at least ~ 40 kpc), the co-added depth in the u band must reach ~ 24.5. To detect RR Lyrae stars beyond the Galaxy's tidal radius at ~ 300 kpc, the single-visit depth must be $r \sim 24.5$. In order to constrain the tangential velocity of stars at a distance of 10 kpc, where halo dominates over disk, to within 10 km/s needed to be competitive with large-scale radial velocity surveys, the required proper motion accuracy is at least 0.2 mas/yr. The same accuracy follows from the requirement to obtain the same proper motion accuracy as Gaia (Perryman et al. 2001) at its faint limit ($r \sim 20$). In order to produce a complete sample of solar neighborhood stars out to a distance of 300 pc (the thin disk scale height), with 3σ or better geometric distances, trigonometric parallax measurements accurate to 1 mas are required. To achieve the required proper motion and parallax accuracy with an assumed astrometric accuracy of 10 milliarcsec per observation per coordinate, approximately 1,000 observations are required. This requirement on the number of observations is in good agreement with the independent constraint implied by the difference between the total depth and the single-visit depth.

2.6. A Summary and Synthesis of Science-driven Constraints on Data Properties

The goals of all the science programs discussed above (and many others, of course) can be accomplished by satisfying the following minimal constraints[7]

o *The single visit depth* should reach $r \sim 24.5$. This limit is primarily driven by the NEO survey and variable sources (e.g. RR Lyrae stars), and by proper motion and trigonometric parallax measurements for stars. Indirectly, it is also driven by the requirements on the coadded survey depth and the minimum number of exposures placed by weak lensing science.
o *Image quality* should maintain the limit set by the atmosphere (the median seeing is 0.7 arcsec in the r band at the chosen site), and not be degraded appreciably by the hardware. In addition to stringent constraints from weak lensing, good image quality is driven by required survey depth for point sources and by image differencing techniques.

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[7]For a more elaborate listing of various constraints, including detailed specification of various probability distributions, please see the LSST Science Requirements Document (http://www.lsst.org/Science/docs.shtml).

o *Photometric repeatability* should achieve 5 millimag precision at the bright end, with zero-point stability across the sky of 10 millimag and band-to-band calibration errors not larger than 5 millimag. These requirements are driven by the photometric redshift accuracy, the separation of stellar populations, detection of low-amplitude variable objects (such as eclipsing planetary systems), and the search for systematic effects in type Ia supernova light-curves.

o *Astrometric precision* should maintain the limit set by the atmosphere, of about 10 milliarcsec per visit at the bright end (on scales below 20 arcmin). This precision 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 a 10 year long survey.

o *The single visit exposure time* should be less than about a minute to prevent trailing of fast moving objects and to facilitate control of various systematic effects induced by the atmosphere. It should be longer than ~ 20 seconds to avoid efficiency losses due to finite readout and slew time.

o *The filter complement* should include at least six filters in the wavelength range limited by atmospheric absorption and silicon detection efficiency (320–1050 nm), with roughly rectangular filters and no large gaps in the coverage, in order to enable robust and accurate photometric redshifts, and stellar typing. An SDSS-like u band is extremely important for separating low-redshift quasars from stars, and for estimating metallicity of F/G main sequence stars. A bandpass with an effective wavelength of about 1 micron would enable studies of sub-stellar objects, high-redshift quasars, and regions of the Galaxy that are obscured by interstellar dust.

o *The revisit time distribution* should allow SN light curves to be sampled every few days; this constraint is needed to obtain orbits of Solar System objects as well, while accomodating constraints set by proper motion and trigonometric parallax measurements.

o *The total number of visits* of any given area of sky, when accounting for all filters, should be of the order of 1,000, as mandated by weak lensing science, the NEO survey, and proper motion and trigonometric parallax measurements. Studies of transient sources also benefit from a larger number of visits.

o *The coadded survey depth* should reach $r \sim 27.5$, with sufficient signal-to-noise ratio in other bands to address both extragalactic and Galactic science drivers.

o *The distribution of visits per filter* should enable accurate photometric redshifts, separation of stellar populations, and sufficient depth to make detection of faint extremely red sources posible (e.g. brown dwarfs and high-redshift quasars). Detailed simulations of photometric redshift estimates suggest an approximately flat distribution of visits among bandpasses (because the system throughput and atmospheric properties are wavelength dependent, the achieved depths are different in different bands). The adopted time allocation (see Table 1) gives a slight preference to the r and i bands because of their dominant role for star/galaxy separation and weak lensing measurements.

o *The distribution of visits on the sky* should extend over at least $\sim 20{,}000$ deg² to obtain the required number of galaxies for weak lensing studies, with attention paid to "special" regions such as the Ecliptic, Galactic plane, and the Large and Small Magellanic Clouds.

o *Data processing, data products and data access* should enable efficient science analysis without a significant impact on the final uncertainties. To enable a fast and efficient response to transient sources, the processing latency should be less than a minute, with a robust and accurate preliminary classification of reported transients.

It is remarkable that, even with these joint requirements, none of the individual science programs is severely overdesigned. That is, despite their significant scientific diversity, these programs are highly compatible in terms of desired data characteristics. Indeed, any one of the four main science drivers could be removed, and the remaining three would still yield very similar requirements for most system parameters. As a result, the LSST system can adopt a highly efficient survey strategy where *a single dataset serves all science programs* (instead of science-specific surveys executed in series). One can think of this as *massively parallel astrophysics*. The vast majority (about 90%) of the observing time will be devoted to a deep-wide-fast survey mode, with the remaining 10% of observing time allocated to special programs which will also address multiple science goals. Before describing these surveys in more detail, we discuss the main system parameters.

2.7. The Main System Design Parameters

Given the minimum science-driven constraints on the data properties listed in the previous section, we now discuss how they are translated into constraints on the main system design parameters: the aperture size, the optimal exposure time, and the filter complement. We also briefly describe the LSST reference design.

2.8. The Aperture Size

The product of the system's étendue and the survey lifetime, for given observing conditions, determines the sky area that can be surveyed to a given depth, where the étendue is the product of the primary mirror area and the field-of-view area. The LSST field-of-view area is maximized to its practical limit, 10 deg², determined by the requirement that the delivered image quality be dominated by atmospheric seeing at the chosen site (Cerro Pachón in Northern Chile). A larger field-of-view would lead to unacceptable deterioration of the image quality. This leaves the primary mirror diameter and survey

lifetime as free parameters. The adopted survey lifetime of 10 years is a compromise between a shorter time that leads to an excessively large and expensive mirror (15 m for a 3 year-long survey and 12 m for a 5-year long survey), and a smaller telescope that would require more time to complete the survey, with the associated increase in operations cost.

The primary mirror size is a function of the required survey depth and the desired sky coverage. By and large, the anticipated science outcome scales with the number of detected sources. For practically all astronomical source populations, in order to maximize the number of detected sources, it is more advantageous to maximize the area first, and then the detection depth. For this reason, the sky area for the main survey is also maximized to its practical limit, 20,000 deg^2, determined by the requirement to avoid large airmasses (which would substaintily deteriorate the image quality and the survey depth).

With the adopted field-of-view area, the sky coverage and the survey lifetime fixed, the primary mirror diameter is fully driven by the required survey depth. There are two depth requirements: the final (coadded) survey depth, $r \sim 27.5$, and the depth of a single visit, $r \sim 24.5$. The two requirements are compatible if the number of visits is several hundred (per band), which is in good agreement with independent science-driven requirements on the latter.

The required coadded survey depth provides a direct constraint, independent of the details of survey execution such as the exposure time per visit, on the minimum primary mirror diameter, as illustrated in Fig. 1.
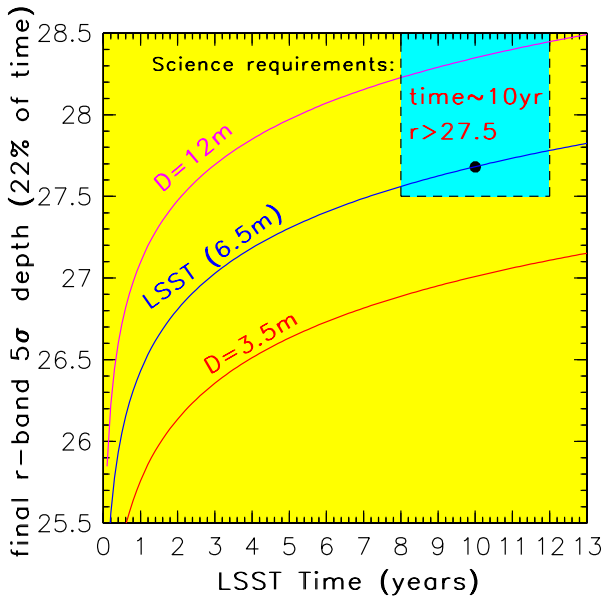
Fig. 1. *The co-added depth in the r band vs. aperture and the survey lifetime ($r \sim V$, where V is the Johnson visual magnitude). It is assumed that 22% of the total observing time (corrected for weather and other losses) is allocated for the r band, and that the ratio of the surveyed sky area to the field-of-view area is 2,000.*

2.9. The Optimal Exposure Time

The single visit depth depends on both the primary mirror diameter and the chosen exposure time. In turn, the exposure time determines the time interval to revisit a given sky position and the total number of visits, and each of these quantities has its own science drivers. We summarize these simultaneous constraints in terms of single-visit exposure time:

o The single-visit exposure time should not be longer than about a minute to prevent trailing of fast Solar System moving objects, and to enable efficient control of atmospheric systematics.

o The mean revisit time (assuming uniform cadence) for a given position on the sky, n (days), scales as

$$n = \left(\frac{t_{\exp}}{10 \sec}\right)\left(\frac{A_{\text{sky}}}{20,000 \deg^2}\right)\left(\frac{10 \deg^2}{A_{\text{FOV}}}\right),$$

$$(1)$$

where the losses for realistic observing conditions have been taken into account. Science drivers such as SN and moving objects in the Solar System require that $n < 4$, or equivalently $t_{\exp} < 40$ seconds for the nominal values of A_{sky} and A_{FOV}. Note that normalization by 20,000 deg^2 is equivalent to two visits per night over 10,000 deg^2.

o The number of visits to a given position on the sky, N_{visit}, with losses for realistic observing conditions taken into account, is given by

$$N_{\text{visit}} = \left(\frac{3000}{n}\right)\left(\frac{T}{10 \,\text{yr}}\right).$$

$$(2)$$

The requirement $N_{\text{visit}} > 800$, again implies that $n < 4$ and $t_{\exp} < 40$ seconds if the survey lifetime, $T \sim 10$ years.

o These three requirements place a firm upper limit on the optimal exposure time of $t_{\exp} < 40$ seconds. Surveying efficiency (the ratio of open-shutter time to the total time spent per visit) considerations place a lower limit on $t_{\exp}$ due to finite read-out and slew time (the longest acceptable read-out time is set to 2 seconds, and the slew and settle time is set to 5 seconds, including the read-out time for the second exposure in a visit):

$$\epsilon = \left(\frac{t_{\exp}}{t_{\exp} + 9 \sec}\right).$$

$$(3)$$

To maintain efficiency losses below 30% (i.e. at least below the limit set by the weather patterns), and to minimize the read noise impact, $t_{\exp} > 20$ seconds. Taking these constraints simultaneously into account, as summarized in Fig. 2, yielded the following reference design:

1. A primary mirror effective diameter of ~ 6.5 m. With the adopted optical design, described below, this effective diameter corresponds to a geometrical diameter of ~ 8 m. Motivated by characteristics of the existing equipment at the Steward Mirror Laboratory, which is casting the primary mirror, the adopted geometrical diameter is set to 8.4 m.

2. A visit time of 30 seconds (using two 15 second exposures to efficiently reject cosmic rays; $\epsilon = 77\%$).

3. A revisit time of 3 days on average per 10,000 deg^2 of sky, with two visits per night.

To summarize, the chosen primary mirror diameter is the *minimum* diameter that simultaneously satisfies the depth ($r \sim 24.5$ for single visit and $r \sim 27.5$ for coadded depth) and cadence (revisit time of 3-4 days, with 30 seconds per visit) constraints described above.
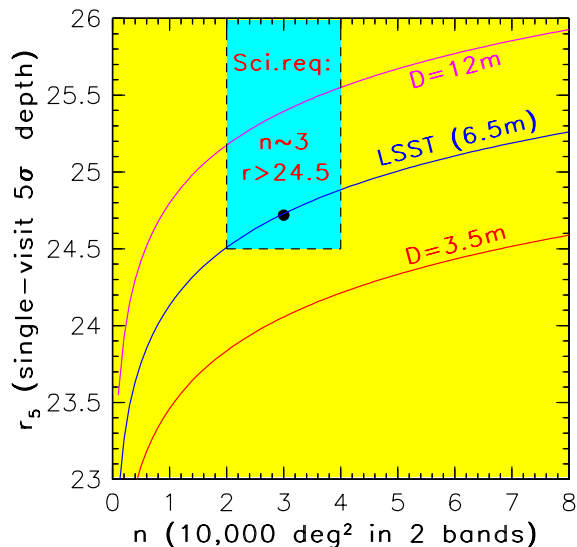
Fig. 2. *The single-visit depth in the r band (5σ detection for point sources) vs. revisit time, n (or exposure time, $t_{\exp} = 10\,n$ seconds), as a function of aperture size. In addition to direct constraints on optimal exposure time, $t_{\exp}$ is also driven by requirements on the revisit time, n, the total number of visits per sky position over the survey lifetime, $N_{\rm visit}$, and the survey efficiency, ε (see eqs.1-3). Note that these constraints result in a fairly narrow range of allowed $t_{\exp}$ for the main deep-wide-fast survey.*

2.10. The Filter Complement

The LSST filter complement (*ugrizy*, see Fig. 3) is modeled after the Sloan Digital Sky Survey (SDSS) system (Fukugita et al. 1996) because of its demonstrated success in a wide variety of applications, including photometric redshifts of galaxies (Budavári et al. 2003), separation of stellar popula-

tions (Lenz et al. 1998, Helmi et al. 2003), and photometric selection of quasars (Richards et al. 2002). The extension of the SDSS system to longer wavelengths (the y band at ~ 1 micron) is driven by the increased effective redshift range achievable with the LSST due to deeper imaging, the desire to study substellar objects, high-redshift quasars, regions of the Galaxy that are obscured by interstellar dust, and the scientific opportunity offered by modern CCDs with high quantum efficiency in the near infrared.
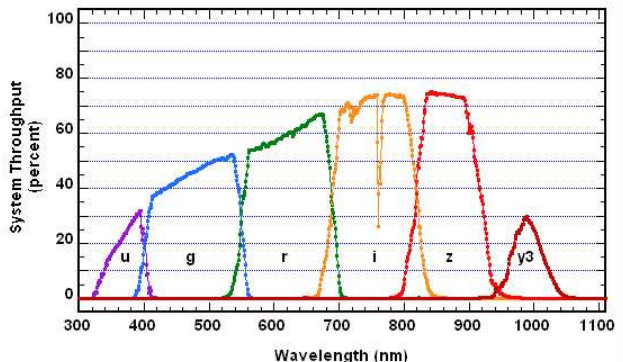
Fig. 3. *The current design of the LSST bandpasses. The vertical axis shows the overall system throughput. The computation includes the atmospheric transmission, optics, and the detector sensitivity.*

2.11. The LSST Reference Design

We briefly describe the reference design for the main LSST system components. Detailed discussion of the flow-down from science requirements to system design parameters, and extensive system engineering analysis can be found in Claver et al. (2008, in prep.). Additional discussion of science drivers, description of data products and examples of science programs can be found in Ivezić et al. (2008, in prep.). Both publications will be maintained at the astro-ph site[8], and should be consulted for the detailed and most up-to-date information about the LSST system.

2.12. Telescope and Site

The large LSST étendue is achieved in a novel three-mirror design (modified Paul-Baker, Davison and Angel 2002) with a very fast f/1.25 beam. The optical design has been optimized to yield a large field of view (9.6 deg^2), with seeing-limited image quality, across a wide wavelength band (350–1050 nm). Incident light is collected by the primary mirror, which is an annulus with an outer diameter of 8.4 m (an effective diameter of 6.5 m), then reflected to a 3.4 m convex secondary, onto a 5 m concave tertiary, and finally into three refractive lenses in a camera (see Fig. 4). All three mirrors will be ac-

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tively supported to control wavefront distortions introduced by gravity and environmental stresses on the telescope.
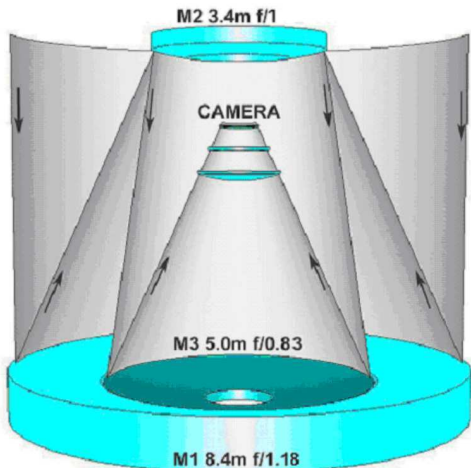
Fig. 4. *The LSST baseline optical design with its unique monolithic mirror: the primary and tertiary mirrors are so positioned that they form a continuous compound surface, allowing them to be polished into a single substrate.*

The telescope mount is a compact, stiff structure with a fundamental frequency of nearly 10 Hz, which is crucial for achieving the required fast slew-and-settle times. The telescope sits on a concrete pier within a carousel dome that is 30 m in diameter. The dome has been designed to reduce dome seeing (local air turbulence that can distort images) and to maintain a uniform thermal environment over the course of the night. The LSST Observatory will be sited atop Cerro Pachón in northern Chile, near the Gemini South and SOAR telescopes (latitude: S 30° 10' 20.1"; longitude: W 70° 48' 0.1"; elevation: 2123 m; the median r band zenith seeing: 0.7 arcsec).
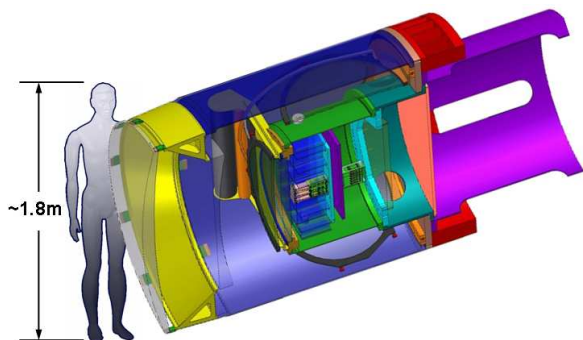
Fig. 5. *The LSST camera with a person to indicate scale size. The camera is positioned in the middle of the telescope and will include a filter mechanism and shuttering capability.*

2.13. Camera

The LSST camera provides a 3.2 Gigapixel flat focal plane array, tiled by 4K x 4K CCD sensors with 10 μm pixels (see Figs. 5 and 6). This pixel count is a direct consequence of sampling the ~ 10 deg^2 field-of-view with 0.2×0.2 arcsec^2 pixels (Nyquist sampling). The sensors are deep depleted, back-illuminated devices with a highly segmented architecture that enables the entire array to be read in 2 seconds.
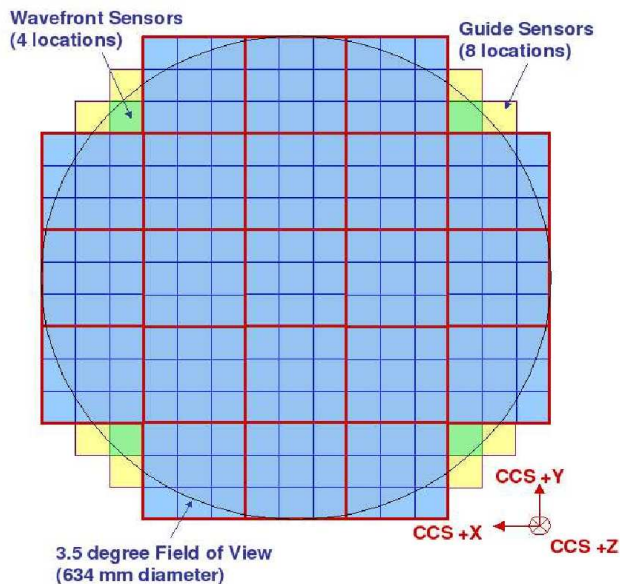
Fig. 6. *The LSST focal plane. Each cyan square represents one 4096×4096 pixel large sensor. Nine sensors are assembled into a raft; the 21 rafts are outlined in red. There are 189 science sensors, each with 16.8 Mpix, for a total pixel count of 3.2 Gpix.*

2.14. Data Management

The rapid cadence of the LSST observing program will produce an enormous volume of data, $\sim$ 30 TB per night, leading to a total database over the ten years of operations of 60 PB for the raw data, and 30 PB for the catalog database. The total data volume after processing will be several hundred PB, processed using substantial computing power (~ 100 TFlops). Processing such a large volume of data, converting the raw images into a faithful representation of the universe, and archiving the results in useful form for a broad community of users is a major challenge.

The data management system is configured in three levels: an infrastructure layer consisting of the computing, storage, and networking hardware and system software; a middleware layer, which handles distributed processing, data access, user interface, and system operations services; and an applications layer, which includes the data pipelines and products and the science data archives. There will be both mountain summit and base computing facilities, as

Table 1. The LSST Baseline Design and Survey Parameters.

Quantity	Baseline Design Specification
Optical/mount Configuration	3-mirror modified Paul-Baker; alt-azimuth
Final f-Ratio, aperture	f/1.25, 8.4 m
Field of view area, étendue	9.6 deg^2, 318 m^{2}deg^2
Plate Scale, pixel count	50.9 μm/arcsec (0.2" pix), 3.2 Gigapix
Wavelength Coverage, filters	320 – 1050 nm, *ugrizy*
Single visit depths (5σ)	$u : 23.9$, $g : 25.0$, $r : 24.7$, $i : 24.0$, $z : 23.3$, $y : 22.1$
Mean number of visits	$u : 70$, $g : 100$, $r : 230$, $i : 230$, $z : 200$, $y : 200$
Final (coadded) depths (5σ)	$u : 26.3$, $g : 27.5$, $r : 27.7$, $i : 27.0$, $z : 26.2$, $y : 24.9$

well as a central archive facility and multiple data access centers. The data will be transported over existing high-speed optical fiber links from South America to the U.S.

2.15. The Baseline Main Deep-Wide-Fast Survey

The fundamental basis of the LSST concept is to scan the sky deep, wide, and fast, and to obtain a dataset that simultaneously satisfies the majority of science goals. This concept, so-called "universal cadence", will yield the main deep-wide-fast survey and use about 90% of the observing time. The observing strategy will be optimized to maximize the scientific throughput by minimizing slew and other downtime and by making appropriate choices of the filter bands given the real-time weather conditions. As often as possible, each field will be observed twice, with visits separated by 15-60 minutes. This strategy will provide motion vectors to link detections of moving objects in the Solar System, and fine-time sampling for measuring short-period variability. The resulting sky coverage for LSST baseline cadence, based on detailed operations simulations, is shown for the r band in Fig. 7. The anticipated total number of
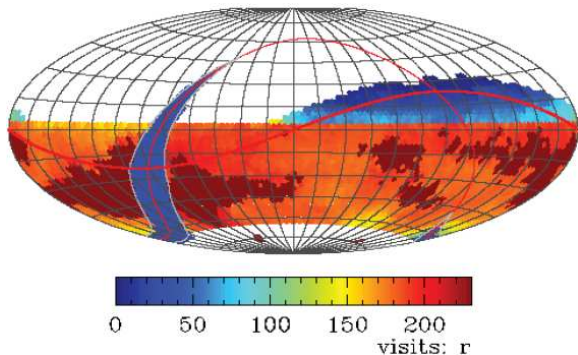

Fig. 7. *The distribution of the r band visits on the sky for the baseline main survey. The sky is shown in Aitoff projection in equatorial coordinates and the number of visits for a 10-year survey is color-coded according to the inset. The two regions with smaller number of visits than the main survey are the Galactic plane (arc on the left) and the so-called "northern Ecliptic region" (upper right). It is likely that the region around the South Celestial Pole will also receive substantial coverage.*

visits for a ten-year LSST survey is 2,767,595 (~ 5.5 million 15-second long exposures). The per-band allocation of these visits is shown in Table 1. The remaining 10% of observing time will be used to obtain improved coverage of parameter space such as very deep ($r \sim 26$) observations, observations with very short revisit times (~ 1 minute), and observations of "special" regions such as the Ecliptic, Galactic plane, and the Large and Small Magellanic Clouds.

3. CONCLUSIONS

Until recently, most astronomical investigations have focused on small samples of cosmic sources or individual objects. Over the past decade, however, advances in technology have made it possible to move beyond the traditional observational paradigm and to undertake large-scale sky surveys, such as SDSS, 2MASS, GALEX and many others. This observational progress, based on synergy of advances in telescope construction, detectors, and above all, information technology, has a dramatic impact on nearly all fields of astronomy, many areas of fundamental physics, and the society in general.

The LSST builds on the experience of these surveys and addresses the broad goals stated in several nationally endorsed reports by the U.S. National Academy of Sciences. The realization of the LSST involves extraordinary engineering and technological challenges: the fabrication of large, high-precision optics; construction of a huge, highly-integrated array of sensitive, wide-band imaging sensors; and the operation of a massive data management facility handling tens of terabytes of data each day. The project is scheduled to have first light in 2014 and the beginning of survey operations in 2015.

The LSST survey will open a movie-like window on objects that change brightness, or move, on timescales ranging from 10 seconds to 10 years. The survey will have a data rate of about 30 TB/night (more than one complete Sloan Digital Sky Survey per night), and will collect over 60 PB of raw data over its lifetime, resulting in an incredibly rich and extensive public archive that will be a treasure trove for breakthroughs in many areas of astronomy. About 10 billion galaxies and a similar number of stars will be detected – *for the first time in history, the number of cataloged celestial objects will exceed the number of living people!*

LSST has been conceived as a public facility: the database that it will produce, and the associated object catalogs that are generated from that database, will be made available to the world's scientific community and to the public at large with no proprietary period. LSST will be a significant milestone in the globalization of the information revolution. The LSST data management system will provide user-friendly tools to access this database and to support user-initiated queries, run on LSST computers, either at the archive facility or at the data access centers. We expect that many, perhaps even the majority of LSST discoveries will come from research astronomers with no formal affiliation to the project, from students, and from interested amateurs, intrigued by the accessibility to the universe that this facility uniquely provides.

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LSST: ОД НАУЧНИХ ЦИЉЕВА ДО ДИЗАЈНА

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У историји астрономије, велики помаци у нашем разумевању Васионе често су произлазили из драматичног напретка у могућностима прецизног мерења астрономских величина. Захваљујући брзом развоју информационих технологија, савремени прегледи неба мењају начин на који посматрамо и проучавамо Васиону. Прегледи неба следеће генерације наставиће овим путем револуционарног напретка. У овом раду усредсређујемо се на најамбициознији планирани пројекат прегледа неба у видљивом делу спектра, Велики синоптички телескоп за преглед неба (скр. LSST, од енг. Large Synoptic Survey Telescope). LSST ће имати јединствене могућности

прегледа у кратким временским интервали-
ма. Дизајн LSST одређују четири примарна
научна задатка: ограничавање на параметре
везане за тамну енергију и тамну материју,
прављење инвентара објеката Сунчевог сис-
тема, истраживање краткотрајних појава на
небу у видљивом делу спектра и мапирање
Млечног пута. Телескоп ће представљати ве-
лики, земаљски, широкоугаони систем дизајни-
ран за добијање вишеструких снимака који би
у потпуности покрили небо видљиво из места
Cerro Pachón у северном Чилеу. Актуелни
основни дизајн предвиђа примарно огледало
пречника 8.4 m (ефективно 6.5 m), видно
поље од 9.6 квадратних степени и камеру са
3200 мегапиксела, што ће омогућити да се у
две експозиције од по 15 секунди, у два фо-
тометријска филтера, за три ноћи у просе-
ку, покрије укупно 10 000 квадратних степени
неба. Систем је дизајниран тако да обезбеди
висок квалитет снимака, као и изузетну ас-
трометријску и фотометријску тачност. Пре-
глед ће покрити укупну површину од 30 000
квадратних степени, у области деклинација
$\delta < +34.5°$, снимајући више пута у шест фил-
тера, *ugrizy*, који покривају области талас-
них дужина од 320–1050 nm. Око 90% посма-
трачког времена биће искоришћено за рад у
тзв. дубоком-широком-брзом моду, при чему
ће се, током предвиђених 10 година рада
телескопа, отприлике 1000 пута у шест фил-
тера посматрати област од 20 000 квадрат-
них степени. Прикупљени подаци ће бити похра-
њени у базу која ће укључивати око 10
милијарди галаксија и приближно исти број
звезда, и која ће служити већини научних про-
грама. Преосталих 10% посматрачког времена
предвиђено је за посебне програме као што су
Врло Дубоки и Врло Брзи прегледи. Овде
описујемо како се од научних задатака про-
грама LSST дошло до ових избора параметара
система.