



LARGE SYNOPTIC SURVEY TELESCOPE

Large Synoptic Survey Telescope (LSST)

# Call for White Papers on LSST Cadence Optimization

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## Abstract

The LSST community is invited to play a key role in the definition of LSST's Observing Strategy by submitting white papers to help refine the 'main survey' and fully define the use of 10-20% of time expected to be devoted to various 'mini surveys' (including the 'Deep Drilling mini surveys' and 'Target of Opportunity' programs). The LSST Science Requirements Document (SRD) places minimal constraints on the observing strategy, recognizing that science evolves and that the initial (by now more than a decade old) survey strategy would have to be redefined closer to first light. With LSST first light expected in 2020, and the LSST operations phase starting in 2022, now is the time to undertake the final planning for the initial LSST observing strategy. While the existing candidate baseline survey strategy has been primarily defined by the LSST Project, the final planning must be undertaken hand-in-hand with the community. We seek science-driven input for observing strategy properties such as the sky coverage, per-bandpass imaging depth, temporal coverage, and various detailed observing constraints. There are no specific limitations on what kind of science programs will be considered, except that the four primary LSST science themes must remain the cornerstones of the LSST survey. This document is a solicitation for white papers to help plan these aspects of the LSST survey strategy. The deadline for white paper submission is November 30, 2018.



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## Contents

<b>1 Introduction</b>	<b>1</b>
1.1 Ongoing community feedback: The LSST Community Observing Strategy Evaluation Paper (COSEP) . . . . .	5
1.2 Motivation for this white paper call . . . . .	6
1.3 General guidelines . . . . .	7
1.4 Review process and timeline . . . . .	8
<b>2 White paper submission guidelines</b>	<b>11</b>
2.1 Who can submit a white paper? . . . . .	11
2.2 Requested input . . . . .	11
2.3 TeX template for submission . . . . .	12
<b>3 White paper ranking criteria</b>	<b>13</b>
<b>A Examples of open survey strategy optimization questions</b>	<b>15</b>
A.1 The main Wide-Fast-Deep survey . . . . .	15
A.2 “Deep Drilling” mini surveys . . . . .	18
A.3 Galactic plane mini survey . . . . .	18
A.4 Southern Celestial pole mini survey . . . . .	19
A.5 Northern Ecliptic spur mini survey . . . . .	20
A.6 Twilight survey . . . . .	20
<b>B Constraints on survey strategy imposed by the LSST system</b>	<b>21</b>
B.1 Hardware and software constraints . . . . .	21
B.2 Observing efficiency constraints . . . . .	24
B.3 Limiting depth and uncertainty estimates . . . . .	25
<b>C Supplementary materials</b>	<b>27</b>
C.1 Useful publications and websites . . . . .	27
C.2 Communication about the LSST survey strategy . . . . .	29
C.3 Additional Simulated Survey Strategies . . . . .	31

# Call for White Papers on LSST Cadence Optimization

## 1 Introduction

The Large Synoptic Survey Telescope (LSST) will provide an unprecedented optical imaging dataset that will support investigations of our Solar System, Galaxy and Universe, across half the celestial sphere and over ten years of repeated observation. LSST observations will be scheduled automatically, with the scheduling algorithm designed to address all science goals and maximize observing efficiency for given observing constraints. Please see Appendix C for a list of most relevant references describing LSST and its operations. LSST is constructing a flexible scheduling system that can respond to the unexpected and be re-optimized as the survey progresses.

Any implementation of LSST's 10-year observing strategy must meet the basic requirements described in the LSST Science Requirements Document (SRD<sup>1</sup>) for the core LSST science goals:

- constraining dark energy and dark matter,
- taking an inventory of the Solar System,
- exploring the transient optical sky, and
- mapping the Milky Way.

However, in practice, the SRD intentionally places minimal quantitative constraints on the observing strategy, primarily requiring:

- A footprint for the 'main survey' of at least  $18,000 \text{ deg}^2$ , which must be uniformly covered to a median of 825 30-second visits per  $9.6 \text{ deg}^2$  field, summed over all six filters, *ugrizy* (see SRD Tables 22 and 23). This places a minimum constraint on the time required to complete the main survey. Simulated surveys indicate that the main survey typically requires 85–90% of the available time (10 years) to reach this benchmark; even with

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<sup>1</sup>The LSST Science Requirements Document (SRD) is available at <http://ls.st/srd>

scheduling improvements, it is unlikely that the goals of the main survey could be met with a time allocation significantly below 80%.

- Parallax and proper motion  $1\sigma$  accuracies of 3 mas and 1 mas/yr per coordinate at  $r = 24$ , respectively, in the main survey (see SRD Table 26), which places a weak constraint on how visits are distributed throughout the lifetime of the survey and throughout a season.
- Rapid revisits (40 seconds to 30 minutes) must be acquired over an area of at least 2000 deg<sup>2</sup> (see SRD table 25) for very fast transient discovery; this requirement can usually be satisfied via simple field overlaps when surveying contiguous areas of sky.

This leaves significant flexibility in the detailed cadence of observations within the main survey footprint, including the distribution of visits within a year (or between seasons), the distribution between filters and the definition of a ‘visit’ itself. Furthermore, these constraints apply to the main survey; the use of the remaining time (i.e., in mini surveys) is not constrained by the SRD.

A brief introduction to the baseline survey strategy, expanded background of the primary LSST science goals, and concise descriptions of how these goals drive the basic survey strategy and data processing requirements are provided in the LSST Overview paper<sup>2</sup>. The Project has developed a comprehensive survey operation simulations tool (‘OpSim’), which has been used to develop full survey simulations (for more details see Section 2.7.1 in the Overview paper and references listed in Section C.1 here). This current candidate baseline survey strategy, as represented in the reference survey simulation (baseline2018a), includes the main survey and several candidate mini surveys (for more details, please see Appendix A):

- The **main “wide-fast-deep” survey**, which covers  $\sim 18,000$  deg<sup>2</sup> of sky within the equatorial declination range  $-62^\circ < \delta < +2^\circ$ , and excluding the central portion of the Galactic plane. Within the main survey, two visits<sup>3</sup> per 9.6 deg<sup>2</sup> field (in either the same or different filters) are acquired in each night, to allow identification of moving objects and rapidly varying transients, and to improve the reliability of the alert stream. These pairs of visits are repeated every three to four nights throughout the period the field is visible

<sup>2</sup>The LSST Overview paper is a living document available at <http://ls.st/lop>.

<sup>3</sup>A ‘visit’ here is an LSST default visit, which consists of two back-to-back 15 sec exposures, for a total of 30 sec of on-sky exposure time. These back-to-back exposures are always in the same filter, separated only by the 2 second readout time.

in each year (other nights are used to maximize the sky coverage). Each field in the main survey receives about 825 visits throughout the ten years of the LSST survey, spread over the six LSST filters *ugrizy*. The quantitative SRD constraints on area coverage, number of visits, parallax and proper motion errors, and rapid-revisit rate (40 seconds – 30 minutes) apply to visits obtained in the main survey. In the current reference simulation, the main survey uses 86.4% of the available time.

- The set of five **Deep Drilling Field candidate mini surveys**, consisting of five specific field pointings for a total of  $\sim 50 \text{ deg}^2$ , which are observed with a much denser sampling rate. These mini surveys use a similar sequence of visits; the fields are observed every three to four days, but in a sequence of multiple *grizy* exposures during gray and bright time, and then multiple sequential *u* band exposures during dark time. The current deep drilling mini survey fields are aimed at extragalactic science, providing a ‘gold sample’ to calibrate the main survey, and to discover Type Ia supernovae. As implemented in the current reference simulation, the Deep Drilling Fields mini surveys use about 4.6% of the available time and the resulting co-added depth is typically about 1 magnitude deeper than the main “wide-fast-deep” survey.
- The **Galactic Plane candidate mini survey** covers the central portion of the Galactic plane that is not included in the main survey, centered around  $|l| = 0^\circ$  and covering  $\sim 1860 \text{ deg}^2$ . It is observed at a much reduced rate compared to the main survey, and with a smaller total number of observations per field (30 visits per field and per filter, in *ugrizy*), so as to provide astrometry and photometry of stars toward the Galactic center but without reaching the confusion limit in the coadded images. There is no requirement for pairs of visits in each night in this area. As implemented in the current reference simulation, the Galactic Plane mini survey uses about 1.6% of the available time.
- The **North Ecliptic Spur candidate mini survey** covers the area north of  $\delta = +2^\circ$  to  $10^\circ$  north of the Ecliptic plane and is intended to observe the entire Ecliptic plane for the purpose of inventorying the minor bodies in the Solar System. This area ( $\sim 4160 \text{ deg}^2$ ) is observed on a schedule similar to the main survey, although with a smaller total number of visits per field and only in filters *griz*. As implemented in the current reference simulation, the North Ecliptic Spur mini survey uses about 5.5% of the available time.
- The **South Celestial Pole candidate mini survey** covers the region south of the main survey, to the South Celestial Pole,  $\sim 2315 \text{ deg}^2$ , including the Magellanic Clouds. This mini survey is observed with a strategy similar to the Galactic Plane mini survey, with 30



visits per field per filter in *ugrizy*, and without requiring pairs of visits. This provides coverage of the Magellanic clouds, but without committing extensive time as these fields are at high airmasses from the LSST site. As implemented in the current reference simulation, the South Celestial Pole mini survey uses about 2.0% of the available time.

The locations of four of the Deep Drilling mini survey fields, which are included among the five DD mini surveys in the current reference simulation, have been finalized and announced to the community<sup>4</sup> in 2012, while any remaining field locations have yet to be specified. The locations of these four deep fields<sup>5</sup> were the result of a community driven process with the goal of obtaining multi-wavelength coverage by ground and space-based facilities, some of which may not exist at the start of the LSST survey<sup>6</sup>. These fields are intended to coincide with multi-wavelength surveys targeting the ELAIS-S1, XMM-LSS, Extended Chandra Deep Field-South, and COSMOS pointings. The cadence of observations within these (or any) deep drilling mini surveys is not finalized, although the coadded depth may be expected to be at least one magnitude deeper than the LSST main survey in each filter.

Beyond the SRD constraints and commitment to the location of four deep drilling fields, the survey strategy as implemented in the candidate baseline above should not be considered guaranteed, and candidate mini surveys present in the current baseline may not be carried forward to the initial operations survey strategy; for illustrative examples of some alternate survey strategies, please see Appendix C.3. All of the candidate mini surveys and the cadence in the main survey will be re-evaluated on the basis of community input in the next step of planning for the initial LSST survey strategy. Much of the existing survey strategy has been based on a mix of community and project input, but the overall balance has been project-driven. The detailed cadence of visits in the main survey, the detailed footprint for the main survey (beyond a minimum of 18,000 deg<sup>2</sup>), the footprint for any other mini survey (except the location of the four pre-announced deep drilling fields), and the cadence or number of visits in any mini survey are open topics for optimization. The main purpose of this call for white papers is to solicit detailed input from the community interested in LSST science in order to design the optimum overall survey strategy.

<sup>4</sup>For details, including the field center coordinates, please see <http://ls.st/bki>

<sup>5</sup>Note that three of these four fields are closely spaced in Right Ascension: 0<sup>h</sup>38<sup>m</sup>, 2<sup>h</sup>23<sup>m</sup>, and 3<sup>h</sup>33<sup>m</sup>.

<sup>6</sup>This approach indeed worked: a lot of additional Spitzer and XMM-Newton data were gathered!



## 1.1 Ongoing community feedback: The LSST Community Observing Strategy Evaluation Paper (COSEP)

The LSST community is already playing a key role in the refinement of LSST’s observing strategy by developing and analyzing metrics for quantifying the performance of simulated surveys generated by the LSST project. This work is being assembled in an open github community<sup>7</sup>, in the form of a large cross-community survey evaluation paper titled ‘Science-Driven Optimization of the LSST Survey Strategy’<sup>8</sup>, which will be referred to here as the Community Observing Strategy Evaluation Paper (COSEP). Chapter 1 and 2 of the COSEP provide a useful overview of the considerations involved in modifying the LSST survey strategy, as well as more details of the baseline survey strategy and examples of some possible variations in survey strategy, implemented in various simulated surveys.

The COSEP explores the effects of relatively small changes to the LSST survey strategy on the detailed performance of the anticipated science investigations. The main lessons learned from the first (2017) version of this paper are:

1. The LSST Project should simulate, analyze and optimize the rolling cadence idea (a non-uniform sampling in time in the wide-fast-deep survey designed to increase the frequency of observations for better coverage of variable phenomena on time scales of a few months, driven by supernovae, asteroids, and short-timescale stellar variability, at the cost of decreasing the frequency slightly on longer timescales), and
2. The LSST Project should execute a systematic effort to further improve the ultimate LSST survey strategy (e.g., sky coverage optimization, u band depth optimization, mini surveys).

The baseline survey simulation used in the COSEP was carried out in 2016, using the version of OpSim available then; the simulation software has been significantly improved and used to recently produce baseline2018a, a new candidate baseline simulation. The two simulations are statistically consistent, especially in terms of time spent on various mini surveys and their footprints. The main improvements in baseline2018a simulation include optimizations in observing closer to the meridian and better balancing of the rate of observations in the mini

<sup>7</sup> <https://github.com/LSSTScienceCollaborations/ObservingStrategy>

<sup>8</sup>The first version of this community observing strategy evaluation paper was published as arXiv:1708.04058 in August 2017.

surveys over the survey lifetime.

Through the end of construction and commissioning, the COSEP will remain a living document to which the community continues to be welcome to contribute, as the main vehicle for the community to broadly communicate to the LSST Project regarding the scientific repercussions of various observing strategies. It will serve as a repository of metrics, with performance evaluations of existing simulated surveys. Periodically, the LSST Project Scientist, with support from the Project Science Team (PST) and the Science Advisory Committee (SAC), will review these metrics and evaluations, to fold updates into the survey optimization efforts.

While the COSEP will continue to provide the means to update evaluations of the survey strategy, the white papers solicited in this call are intended to provide the LSST science community with an opportunity to propose more significant, and detailed, modifications of the LSST survey strategy, including broad changes in the mini surveys.

We anticipate that the performance evaluation components of the white papers solicited here will also be added to the COSEP, to provide a comprehensive reference point for survey strategy evaluation.

## 1.2 Motivation for this white paper call

Guided by the community input summarized in the COSEP and further advice from the Science Advisory Committee (SAC), the LSST Construction Project has decided to solicit detailed technical white papers for specific modifications of the current baseline survey strategy.

As discussed in more detail in Appendix A, analysis to date indicates that the baseline candidate survey strategy, while meeting the basic science requirements for the LSST survey, can be meaningfully improved<sup>9</sup>. The LSST SRD provides minimal constraints on the survey strategy details because it recognized that science evolves and that the initial, by now more than a decade old, survey strategy will have to be re-optimized closer to first light. With LSST first light expected in 2020, now is the time to undertake the final pre-commissioning optimization<sup>10</sup> of the LSST baseline observing strategy. We seek science-driven input for cadence

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<sup>9</sup>For details, see Sections 1.1 and 2.3 in the COSEP.

<sup>10</sup>“Optimization” used here does not imply its strict mathematical meaning. We are attempting to create the best survey strategy possible, but this is not a formal optimization effort of an objective function in part because the concept of an “optimized” survey depends in part on a subjective weighting of different science goals.

properties such as per-bandpass imaging depth, the sky coverage, temporal coverage, observing rules, etc., as summarized in Appendix A. Investigations of a limited number of such survey strategy modifications are reported in Chapter 2 from the COSEP (and discussed in various supplementary materials listed in Appendix C).

### 1.3 General guidelines

We solicit detailed white papers for specific modifications of the current baseline survey strategy, including both the main survey and the deep drilling fields and other mini surveys. There are no specific limitations on what kind of science programs will be considered, but please note that the primary four LSST science themes remain the cornerstones of the LSST survey and must be maintained. Indeed, the LSST SRD states that “the adopted observing strategy will not jeopardize the goals of any of the four main science themes”. Each white paper should include detailed metrics to evaluate the scientific performance and impact of the suggested changes; these metrics do not need to be comprehensive across all science use cases<sup>11</sup>. Descriptions of these metrics should be sufficiently detailed for the Project team to be able to implement them. While the code for computing metrics is not required, Python 3 implementations will be welcome.

The detailed cadence of visits in the main survey, the footprint for any other mini survey (except the location of the four pre-announced deep drilling fields), and the cadence or number of visits in any mini survey are open topics for optimization. The existence of a particular survey strategy for a given mini survey in the current baseline should not be taken to imply that it will be present in the same way in the final survey strategy. Science justification and accompanying scientific performance metrics that support a given mini survey are highly encouraged.

Detailed white papers are also solicited for novel ideas, such as twilight observing (see Appendix A.6), as well as changes to the survey strategy that would create synergies with other major surveys (*e.g.*, WFIRST, Euclid). In addition, white papers describing even very small programs are welcome and encouraged. White papers should emphasize programs leveraging LSST’s unique large étendue. At this time we are not soliciting proposals to optimize observations during the commissioning period.

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<sup>11</sup>The LSST Project will provide metrics to evaluate the SRD-required quantities, as well as run a combination of metrics contributed by the general science community (as described in the COSEP) to cover a wide range of science goals.

Technical constraints imposed by the system and observing conditions are summarized in Appendix B. Links to the description of LSST data processing and pipelines are included in Appendix C. If a proposed dataset will require special processing beyond what standard LSST software will provide, a plan to obtain necessary software and computational resources must be provided in the white paper. In cases that require more detail, or in case of specific questions not addressed in this document, please start a discussion at [community.lsst.org](https://community.lsst.org)<sup>12</sup>.

The LSST Science Requirements Document states that “the adopted baseline design assumes a nominal 10-year duration with about 90% of the observing time allocated for the main LSST survey”, and further clarifies that “The remaining 10% of observing time will be used to obtain improved coverage of parameter space...”. While the detailed time allocation will eventually depend on currently unknown system performance parameters, it is unlikely that the goals of the main survey could be met with a time allocation significantly below 80%. In the current baseline reference survey simulation, the main survey requires 86% of the total time. In other words, it is plausible that the time allocated to programs other than the main survey could significantly exceed 10% (perhaps by as much as a factor of two), but no firm commitments beyond this statement of plausibility can be made at this time.

The data from any given specialized survey will be treated in exactly the same way as all LSST data: there is no special proprietary access or ownership for any subset of the data from LSST. The final set of deep-drilling fields and other mini surveys are likely to be based on an amalgam of ideas from different white papers; a survey strategy described in a given white paper need not be accepted or rejected without adaptation.

## 1.4 Review process and timeline

The deadline for submitting white papers is November 30, 2018. For submission instructions, please see the next section.

Soon after the November 2018 submission deadline, members of the LSST Science Advisory Committee (SAC), with technical support from the Project, will undertake an initial review and decide which submitted white papers meet the criteria of scientific excellence and technical feasibility for further analysis. These criteria are discussed in Section 3. The SAC will publish a short summary of the results of this initial review, including a list of all white papers to be

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<sup>12</sup><https://community.lsst.org/c/sci/survey-strategy>

considered for further simulations, by April 2019.

The input from the submitted white papers will be used to design multiple options in observing strategies, and the Project team will generate a series of simulations based on these survey strategies. These multiple simulated surveys will address varying science drivers and will form a “menu” of possible survey strategies (e.g., a main survey with 18,000 deg<sup>2</sup> of sky coverage vs. a main survey with sky coverage of 23,000 deg<sup>2</sup>, perhaps to a somewhat shallower depth). The performance evaluation criteria submitted as part of the white papers and in the COSEP will be used to generate quantitative assessments to compare these strategies. During this process, the Project team will keep a public list of simulations in progress and notify authors of the submitted white papers as to how their suggested survey strategy has been implemented in these simulated surveys or combined with other suggested survey strategies. We will also publish monthly updates on the LSST Community<sup>13</sup> forum, an open and searchable forum platform for communication between the LSST Project and the astronomical community.

We anticipate that the list of observing strategies that will be simulated and analyzed (the “menu” above) will be available by April 2019. Simulated survey outputs, generated via the LSST Operations Simulator (OpSim) and the LSST Metric Analysis Framework (MAF) analyses will become available by the end of 2019 (see Appendix C for more information about OpSim and MAF).

A Survey Strategy Committee (SSC) will be established by the LSST Operations Director in 2020. An advisory report on the performance of the survey strategies developed as a result of this call for white papers, based on performance metrics provided in the white papers and the COSEP, will be prepared by the Project for this committee in early 2020. The SSC will undertake the work of balancing the overall scientific performance between the individual science goals, and will advise the Project on the specific survey strategy to be used at the start of full LSST operations, as well as on guidelines for the strategy throughout all ten years of the survey. In developing their recommendations to the Director, the SSC will be guided by selection criteria set by the Project Science Team and discussed in Section 3 (e.g., restrictions based on technical criteria, such as those discussed in Appendix B). The Director can further consult with the Project Science Team about the SSC survey strategy recommendations. A baseline simulation that reproduces the adopted strategy, and its detailed performance analysis, will be published in 2021. The start of LSST operations is anticipated in 2022. The SSC will continue to regularly

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<sup>13</sup><http://community.lsst.org/c/sci/survey-strategy>

explore cadence and survey progress throughout the lifetime of survey. It is likely that the observing strategy will be further refined as the LSST system becomes better understood, and science goals further evolve.

An overall aim of the Project and all stakeholders is to make this process transparent to the community and to base all decisions on quantitative input and pre-defined criteria to the maximum extent possible. The Project will organize a dedicated session at the LSST 2018 Project and Community Workshop (Tucson, Aug 13-17) about this call for white papers, to further clarify details, exchange ideas, discuss simulated surveys, and coordinate teams that plan to submit white papers. In addition, LSST Corporation and the Simons Center for Computational Astrophysics will organize an LSST Cadence Hackathon at the Flatiron Institute in Manhattan, on September 17 and 18, 2018, with an optional third day on September 19. At the Hackathon, participants from different LSST Science Collaborations will work together in small teams to explore creative cadence strategies with the help from Project experts for the OpSim and MAF software packages. Members of teams that come up with the most promising strategies will each receive a modest honorarium for writing up their ideas as white papers. There is no registration fee for this workshop and travel support will be provided for attendees from LSSTC member institutions, and for other attendees as funds allow. To apply for the workshop, please fill out the application form at <http://ls.st/cwg> by July 20, 2018.

TABLE 1: **Timeline for survey strategy work**

Call for white papers	June 30, 2018
2018 Project and Community Workshop	Aug 13-17, 2018
White paper submission deadline	Nov 30, 2018
List of to-be-simulated survey strategies	April 2019
Simulated survey strategies available	End of 2019
Survey Strategy Committee (SSC) established	Early 2020
Advisory report from Project to SSC	Early 2020
SSC report on official initial LSST survey strategy	Early 2021
Baseline simulation of initial LSST survey strategy	Mid 2021
Start of LSST Operations	2022
Regular survey reviews by the SSC	2022-2032

## 2 White paper submission guidelines

### 2.1 Who can submit a white paper?

All members of the scientific community interested in LSST science<sup>14</sup> can submit a white paper. We encourage the LSST Science Collaborations to submit white papers resulting from collaborative work among their members. We reiterate that the data from any given specialized survey will be treated exactly the same way as all LSST data: the authors of white papers will have no proprietary access to it.

### 2.2 Requested input

The current candidate baseline survey strategy (as represented in the reference survey simulation baseline2018a) includes:

1. **Committed Surveys** (white papers should be submitted to optimize the design of these):
  - the main Wide-Fast-Deep (WFD) survey,
  - four of the Deep Drilling (DD) mini surveys,
2. **Candidate Mini Surveys** (must be proposed and selected in white paper process):
  - additional Deep Drilling (DD) mini surveys,
  - the candidate Galactic Plane (GP) mini survey,
  - the candidate Northern Ecliptic Spur (NES) mini survey, and
  - the candidate South Celestial Pole (SCP) mini survey.

Quantitative, science-driven optimization input is requested for each of the above, as well as for survey strategy questions such as optimal visit exposure time, co-added per-bandpass imaging depth, the sky coverage, temporal coverage, observing rules, etc. For a detailed discussion, please see Appendix A. The existence of a particular mini survey, sequence of observations, or exposure time in the current baseline does not guarantee its existence in the same or any form in the final survey strategy.

<sup>14</sup>Note that there is no requirement to have LSST data rights to submit a white paper.



In addition to existing surveys listed above, we also seek input on new mini survey ideas to replace, supplement, and/or enhance the current programs, including special “Target of Opportunity” (ToO) programs. We also solicit novel ideas, such as twilight observing (see Appendix A.6), as well as observing synergies with other major surveys (e.g., WFIRST, Euclid).

We reiterate that the observing time allocated to **all** the mini surveys (including all DD mini surveys) is “about” 10%, per SRD design, and is unlikely to exceed 20% of the total available observing time; in the current candidate baseline, the mini surveys use about 14% of the available time. We note that implementation details for mini surveys (especially DD mini surveys) are coupled at some level to the main survey: more time for the former means less for the latter, and some of the design decisions for the latter affect the science case for the former. For example, some rolling cadence strategies for the main survey may allow some variable and transient science to happen that would otherwise be the focus of a deep drilling field, and changes in the main survey footprint will affect the definition of a Galactic Plane survey. The Project will provide additional alternative survey simulations with this call for white papers (please see the list in Appendix C.3) to help illustrate some of these potential crossovers.

## 2.3 TeX template for submission

Each proposed modification of the survey strategy must contain a Scientific Motivation, Technical Description, and Performance Evaluation section, instructions for which are expanded in the white paper submission template. The Scientific Motivation section is intended to explain why this survey strategy modification is important and what could be learned if the proposed observations were obtained, relative to some baseline. The Technical Description section details what observations are being requested and should provide enough detail to enable proper simulations<sup>15</sup> to be created, as well as additional information that can help in the process of combining similar but separate survey strategy modification requests.

The Performance Evaluation section must contain methods to evaluate the effectiveness of the survey strategy modifications, particularly in light of the potential effect of survey strategy changes proposed in other white papers. It is unlikely that any proposed cadence modification suggested in white papers will be carried out in its original form; thus metrics (along with threshold values for these figures of merit) to evaluate the science performance of non-ideal

<sup>15</sup>For more information on how survey simulations are created, please see the documentation on OpSim at [https://lsst-sims.github.io/sims\\_ocs/](https://lsst-sims.github.io/sims_ocs/).

simulations are crucial. Note that each white paper does not need to solve or address the global optimization problem, nor does it need to supply performance criteria across all science goals<sup>16</sup>. The TeX submission template gives further instructions for each of these areas.

The submission template and an example of the submission, with instructions about all the required information, can be found in the git repository hosted at `lsst-pst/survey_strategy_wp`<sup>17</sup>. To submit white papers, please email the compiled PDF to `lsst-survey-strategy@lists.lsst.org`. An acknowledgement of the receipt of each white paper will be returned within 48 hours.

The Project will organize a dedicated session at the LSST 2019 Project and Community Workshop (mostly likely during August 2019 in Tucson) to discuss submitted white papers and follow-up deliberations and work. LSST Corporation is committed to provide funds to help waive registration fee for this meeting for one person per submitted white paper (or at least a fraction of the registration fee in case of a large number of submitted white papers).

For additional help or questions, please ask on LSST Community<sup>18</sup>.

### 3 White paper ranking criteria

The LSST observing strategy will aim to deliver a cutting-edge data set to enable the four cornerstone scientific programs, while at the same time maximizing the science possible with specialized observing modes using about 10% of the total observing time.

We anticipate that the adopted observing strategy will be based on an amalgam of ideas from different white papers; therefore, there will be no formal “acceptance” or “rejection” of proposed ideas. The overall ranking priority advice provided to the Project by the Science Advisory Committee will be based on the following considerations:

- **Science** Importance and legacy value of the proposed science program, including its match to the unique abilities of the LSST system, and its consistency with the four main LSST science themes. This could be a single strong science goal, synergies with other

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<sup>16</sup>Note that the Project team cannot support individuals or groups wishing to run the Operations Simulator themselves. It is not required that authors of white papers run the proposed simulations themselves.

<sup>17</sup>[https://github.com/lsst-pst/survey\\_strategy\\_wp](https://github.com/lsst-pst/survey_strategy_wp)

<sup>18</sup><http://community.lsst.org/c/sci/survey-strategy>

astronomical facilities, or a multitude of science goals enabled by the same survey strategy.

- **Feasibility** Programs must be feasible from the hardware and software point of view (see Appendix B), specifically including any special data processing required. The complexity of the program, in terms of additional requirements on hardware and software beyond the baseline requirements, will also be considered. The Project Science Team will conduct a technical check on submitted white papers.
- **Time requested** The amount of time (including overheads) required should be justified by the associated science.

As always, the science program properties such as importance and robustness are open to interpretation. It is inevitable that some science drivers will be in conflict, and even observing efficiency may not be defined in an absolute sense. The Project, the Science Advisory Committee and the Survey Strategy Committee will strive to make the white paper ranking process transparent to the maximum extent possible.

*Acknowledgments:* this document has greatly benefited from discussions between the LSST Project Science Team, the LSST Science Advisory Committee and Kem Cook, Phil Marshall, Steve Ridgway, Daniel Rothchild, Peter Yoachim and numerous other members of the LSST Science Collaborations.

## A Examples of open survey strategy optimization questions

The quantitative optimization of the LSST observing strategy requires many detailed decisions to be made, often with only an indirect science justification, or with conflicting science drivers. The current most significant open questions and associated tradeoffs are listed below for the main survey and each mini survey. White papers are specifically encouraged to address these questions.

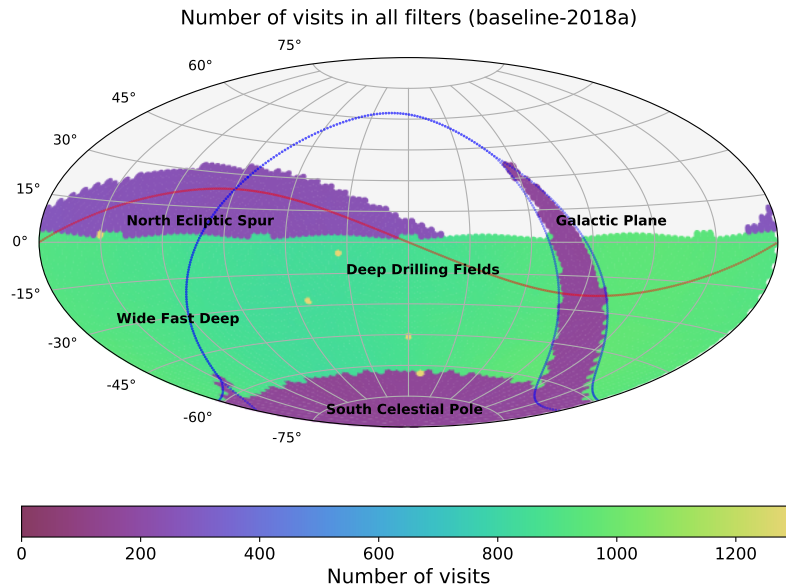


FIGURE 1: The current baseline survey includes the main Wide-Fast-Deep survey and eight candidate mini surveys: the North Ecliptic Spur, the Galactic Plane, the South Celestial Pole, and the five fields of Deep Drilling mini surveys. This figure demonstrates their footprint in the current baseline simulated survey and the total number of visits in all bands. We are seeking suggestions for modification of the survey strategy, especially suggestions for changes to the mini surveys.

### A.1 The main Wide-Fast-Deep survey

The baseline survey strategy optimizes the amount of sky covered in any given night (subject to the constraint of gathering pairs of visits in each night - generally, but not always, in a single filter), and allows the entire sky visible at any time of the year to be covered in about three nights. The basic strategy is designed to give roughly uniform coverage over the sky at any given time, and to reach the survey goals for measuring stellar parallax and proper motion,

and the number of visits per field (825 visits, summed over the six filters). In the baseline implementation, the main survey covers about 18,000 deg<sup>2</sup> of high Galactic latitude sky, and uses about 86% of the available observing time (based on current survey simulations).

Open questions and optimization options associated with the main survey are as follows:

- With the current declination boundaries at  $\delta = -62^\circ$  and  $\delta = +2^\circ$ , the main survey area includes about 18,000 deg<sup>2</sup> (without the Galactic plane confusion zone, see Appendix A.3). These boundaries were set to optimize the number of detected galaxies useful for cosmological studies, including weak lensing, with the declination limits defined by an airmass limit of 1.18 (the maximum value of the minimum achievable airmass; the maximum allowed observation airmass is set to 1.4). These galaxy counts stay within 5-10% of the current baseline values even with a much larger survey area. For example, Section 2.4 in the COSEP describes a simulated survey that covers 27,400 deg<sup>2</sup> to about 0.15 mag shallower co-added depth than in the baseline survey (the declination boundaries are at  $\delta = -78^\circ$  and  $\delta = +18^\circ$ , relaxing the airmass limit to 1.5, and resulting in a mean number of visits per field about 20% smaller than in the baseline survey). This trade-off between the sky coverage and number of visits is still open to optimization, subject to the SRD constraints of a minimum 18,000 deg<sup>2</sup> footprint with at least 825 visits per field. It is important to receive science-driven optimization arguments from all science programs.
- The observing time allocation per band (number of visits per filter) listed in the Science Requirements Document (Table 24) is given only as an illustration. Further optimization of this allocation for the main survey, and different fractional allocations for mini surveys, are possible.
- Concentrating a fraction of the observations for a given field into a shorter period of time (a.k.a. a “rolling cadence”) can provide enhanced sampling rates over a part of the survey for a designated time, at the cost of reduced sampling rate the rest of the time (while maintaining the nominal total visit counts). This would mean that LSST would not simply aim to cover all the visible sky every three nights, as the current baseline cadence does. While it is likely that science programs such as supernovae, asteroids, and short-timescale stellar variability would benefit from rolling cadence, detailed cadence parameters have not been optimized yet (e.g., how much of the survey area to “roll” at once and how long to “roll” for, or whether to “roll” in right ascension or declination). The optimization of “rolling cadence” simulations will be driven by submitted white papers.

- The current baseline survey strategy obtains two visits per night (within 15-60 minutes) in order to enable easy linking of asteroid detections, and robust identification of rapid photometric transients. Whether the two visits on the same night should be obtained in the same filter or in different filters has not been decided yet (e.g., in the context of photometric transients, same filters would provide a more accurate measurement of the brightness change, while different filters would provide a color constraint). The current baseline survey strategy places no preference on whether pairs are obtained in the same or different filters, which results in most pairs being in the same filter due to the additional time penalty in changing the filter. The candidate baseline survey has just under 11,000 filter changes over the ten years of the survey, with an average of 3 filter changes per night; about 7000 of these changes can be attributed to the WFD portion of the survey.
- The current strategy for the main survey which obtains two visits per night could be modified to obtain a single visit, or more than two visits, per night.
- The current baseline survey strategy assumes that a visit is composed of two 15-second exposures, the so-called snaps. While 2x15 sec visits enable search for very rapid variability, and help with cosmic ray rejection, there are compelling technical arguments – including observing efficiency – to adopt single-exposure 30 second visits. The effect of varying the exposure time and number of snaps in a visit can be calculated from details available in the LSST overview paper, but a summary of the effect on the  $5\sigma$  limiting magnitude is shown in Table 2. Arguments for or against retaining the 2x15 sec visits would be very useful in further optimization of the main survey strategy. The impact of read-out noise and other parameters on limiting depth is quantitatively discussed in the LSST Overview paper (see Section 3.2.1).

White papers addressing all or some of these optimization efforts are strongly encouraged.

TABLE 2: Changes in  $5\sigma$  limiting magnitude when varying the exposure time and number of snaps per visit.

$N_{exp} \times T_{exp}$	u	g	r	i	z	y
2x15	0.000	0.000	0.000	0.000	0.000	0.000
1x20	-0.129	-0.186	-0.202	-0.207	-0.211	-0.214
1x30	0.216	0.078	0.044	0.033	0.023	0.017
1x40	0.447	0.259	0.214	0.199	0.186	0.179
2x30	0.601	0.460	0.425	0.413	0.402	0.396

## A.2 “Deep Drilling” mini surveys

The Deep Drilling (DD) mini surveys are a set of mini surveys, each consisting of a field (a single pointing) that is observed in extended sequences, potentially with specified dithering patterns. In the first call for white papers in 2011 on survey strategy optimization, the Project received 8 white papers from the community<sup>19</sup>. These white papers described excellent early ideas that helped design the current baseline cadence simulation; however, to receive full consideration, these ideas will have to be resubmitted as new white papers. Many of these early proposals include specific filter combinations to ensure that near-simultaneous color information is available for variable and transient objects. While science programs suggested in DD proposals are ideally well matched to the size of LSST field of view ( $9.6 \text{ deg}^2$ ), it is plausible that some programs may require several fields.

Four of the LSST DD mini survey field locations have been selected and announced<sup>20</sup> (Elais S1, XMM-LSS, Extended Chandra Deep Field-South, and COSMOS). It is guaranteed that they will be observed with deeper coverage and more frequent temporal sampling than the main survey fields, but details are still open and no minimums have been set. Thus four mini surveys, representing these four DD fields, are required. White papers detailing additional DD mini surveys and their requirements are solicited with this call (a plausible but not prescriptive range is 5-10).

The observing sequences and coadded depths for these DD mini surveys are not yet decided. The current baseline cadence includes sequences of *grizy* observations during bright and gray time, and sequences of *u* band observations during dark time. The large number of filter changes in the bright time sequences are inefficient and the large gap in multi-color sampling during dark time is likely problematic for variable and transient characterization. White papers addressing improved cadences in the DD mini surveys are desirable.

## A.3 Galactic plane mini survey

The baseline main survey excludes observations at low Galactic latitudes, where the high stellar density leads to a confusion limit at much brighter magnitudes than those attained at high Galactic latitudes. Assuming median seeing, this confusion limit corresponds to a source density of about 1-2 million per  $\text{deg}^2$ . The current boundary of this “Galactic confusion zone”

<sup>19</sup>These white papers are available from <https://project.lsst.org/content/whitepapers32012>

<sup>20</sup>Please see <http://ls.st/bki>



starts at  $|b| = 10^\circ$  towards  $l = 0^\circ$  and linearly drops to  $b = 0^\circ$  at  $l = 90^\circ$  and  $l = 270^\circ$ . Along this boundary, the confusion limit is reached at a depth of  $i \sim 26$ ; therefore, the useful coadded depth is at least 1-2 magnitudes shallower than for the main survey and the total number of visits in this region is thus fewer. Within this boundary, the fraction of galaxies is only a few percent (due to flux extinction by interstellar dust) and an assumption that all sources are stars works quite well. Crowding is not expected to significantly impact the quality of data products derived from difference images (*i.e.* Prompt data products).

While the confusion limit is relevant for the coadded depth and is the reason the current version of this mini survey contains so few total visits (30 per field in each of the six filters), time-domain studies using photometry from single images could still benefit from additional visits in this region. Science driven input is needed for both “static science” and time domain surveys. White papers exploring this science case are encouraged.

As guidance, stellar count simulations with the TRILEGAL code (Girardi et al. 2005, arXiv:astro-ph/050404) show that to the depth of  $r = 27.5$  there are about 4 billion stars in the main survey area, with another 13 billion stars in the Galactic confusion zone. Of the latter, about 6 billion are brighter than  $r = 24.5$ .

The footprint in the current baseline survey strategy extends to the far north along the Galactic plane, to the region that can only be observed at relatively large airmass from the LSST site at Cerro Pachón ( $X > 1.4$  at  $\delta = +15^\circ$ ). Originally, this extension was designed to extend longitudinal coverage of the Galactic plane with Galactic structure studies in mind. With the advent of other surveys (e.g., Pan-STARRS and DECAPS<sup>21</sup>), the reasons for obtaining these less efficient observations (due to unavoidable high airmass) are less compelling. Unless a strong case is made in submitted white papers, the Project is likely to limit the coverage of the Galactic plane to  $\delta < +2^\circ$ .

## A.4 Southern Celestial pole mini survey

Due to its southern declination limit ( $\delta > -62^\circ$ ), the main survey misses a large fraction of both the Magellanic Clouds. To allow coverage of the Large and Small Magellanic Clouds, the baseline survey strategy uses relaxed limits on airmass and seeing for the  $\sim 2,000 \text{ deg}^2$  region around the South Celestial Pole, but with fewer observations than for the main survey.

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<sup>21</sup>See <http://decaps.skymaps.info>

Detailed optimization of this strategy has not been done yet. Given recent informative observations obtained by the SMASH survey (Nidever et al. 2017, *Astronomical Journal*, 154, 199), as well as calibration and legacy aspects of this mini survey, a white paper with more detailed cadence prescriptions (e.g., is it necessary to extend the coverage all the way to the South Celestial pole?) would greatly inform further cadence optimization.

## A.5 Northern Ecliptic spur mini survey

The main survey footprint provides most of LSST’s power for detecting Near Earth Objects (NEO) and TransNeptunian Objects (TNOs) and naturally incorporates the southern half of the Ecliptic within its 18,000 deg<sup>2</sup> sky area. The additional coverage of a crescent reaching to +10 degrees of the Northern Ecliptic plane in the North Ecliptic Spur (NES) mini survey provides observations of small bodies, particular TNOs, throughout the full range of ecliptic longitude. The baseline survey strategy covers this region using the *griz* filters only, with about 300 visits per field and a cadence generally similar to that of the main survey (but with more relaxed limits on airmass and seeing due to the northern location of the fields). With fewer visits per field, it is not possible to maintain a complete main survey time sampling over the full ten years of the survey. Previous simulations ended observations in the NES by approximately year seven; the current baseline simulation runs observations over the full ten years at the cost of a lower sampling rate (the mean inter-night gap falls from approximately every 3 nights in *minion\_1016* to approximately every 5 nights in the current baseline, *baseline2018a*).

A more detailed and robust science-driven justification addressing both outer Solar System (e.g., sampling of the full longitudinal distribution of TNOs) and inner Solar System (e.g., light curve sampling for main-belt and NEO asteroids) populations is needed to maintain and optimize the observing strategy for this mini survey.

## A.6 Twilight survey

LSST’s short read-out time (2 sec) enables efficient taking of short-exposure images during twilight time that would otherwise go unused. Science drivers and technical details are discussed in Section 10.3 in the COSEP (arXiv:1708.04058); the former include a bright star survey for Galactic science, obtaining light curves for nearby supernovae, and observations of near-Earth asteroids towards so-called “sweet spots” (on the Ecliptic, at Solar elongations of  $\sim 60^\circ$ ). This cadence has not been simulated yet.

The Project plans to simulate twilight observing in late 2018. Assuming exposure times of 1 second (the stretch goal from the LSST Science Requirements Document, which is already met and corresponds to the Camera baseline requirement), the saturation limit would be about 3 mag brighter than for 15-sec exposures; in the  $r$  band from about  $r = 16$  to  $r = 13$ , with about 1.5 mag loss of limiting depth. In morning twilight, the improvement in dynamic range of 1.5 mag would gradually diminish and eventually dynamic range would vanish as the sky brightness increases. About 20-30 minutes of additional observing time could be utilized during twilight before the dynamic brightness range becomes too small. Assuming 7-sec visits (1 sec exposure + 1 sec for shutter + 5 sec for read and slew), about 2,000 deg<sup>2</sup> of sky could be imaged in 25 minutes in a given filter. Alternatively, over 350 exposures (1 sec + 1 sec + 2 sec) of the same field could be obtained instead. Detailed strategies should consider limitations on the number of filter changes (see Appendix B.1). White papers addressing the science justification and strategies for using twilight time are desired.

The shortest exposure stretch goal in the Camera baseline requirements is set to 0.1 sec. Science-driven studies that would advocate pursuing this goal would be a welcome contribution to further system optimization; twilight observing could especially benefit from shorter exposures.

## B Constraints on survey strategy imposed by the LSST system

### B.1 Hardware and software constraints

#### Hardware constraints

Several hard constraints prevent observations in certain alt-az directions. The telescope altitude limit prevents observations at altitudes below 20°. As a consequence of the alt-az mount, there is also a zenith exclusion zone with a radius of 3.5°.

The LSST telescope mount uses direct drive motors and there should not be any mechanical limits on slewing from the mount. However, there are observing efficiency considerations: the minimum slew time (as soon as the telescope moves at all) is 3 seconds, due to readout (2s) plus settle time requirements (1s). Otherwise, the slew time depends on slew distance.

Approximately<sup>22</sup>, in the azimuth direction,

$$t_{slew}^{Az} = 0.66 \text{ sec/deg} * \delta Az(\text{deg}) + C^{Az} \quad (1)$$

$$t_{slew}^{Az} \text{ min} = 3 \text{ sec} \quad (2)$$

where  $C^{Az} = -2 \text{ sec}$  (this is negative because of dome crawl; however, the minimum slew time is still 3 seconds due to readout and telescope settle time). For slewing in altitude

$$t_{slew}^{Alt} = 0.57 \text{ sec/deg} * \delta Alt(\text{deg}) + C^{Alt}, \quad (3)$$

where  $C^{Alt} = 3 \text{ sec}$  for slews below  $9^\circ$  and  $C^{Alt} = 37 \text{ sec}$  for longer slews (because of the need to recompute optics corrections for slews larger than 9 degrees in altitude). The dome is assumed to crawl in the azimuth direction, but not in altitude. In the baseline simulated survey, about 2% of slews move in altitude more than  $9^\circ$ .

The shortest exposure time is assumed to be 1 second, with the shortest exposure stretch goal in the Camera baseline requirements set to 0.1 sec. For exposures shorter than about 10 sec, the seeing due to atmospheric turbulence may be harder to characterize (the profiles are more irregular) than for longer exposures, and moving objects may trail in long exposures (for more details see Section 5.1.4 in Jones et al. 2018; Icarus 303, 181). Short exposures will have a low observing efficiency due to the finite read-out time (2 sec).

There are important constraints on the filter exchange strategy. As the system is not yet completely built and characterized, the following represents current understanding of the limitations on filter loads (swaps in and out of the carousel, done during the daytime) and filter changes (swaps within the carousel, done between exposures within a night), based on the design and on engineering judgement. As such, some of the details should be considered preliminary and subject to change. Expanded ranges could be possible if there are strong scientific motivations along with sufficient resources during operations.

- LSST has 6 filters (*ugrizy*), of which 5 can be loaded into the filter exchange carousel. Only 5 out of the 6 filters will be available on any given night.
- Filter load operations (swapping a filter into or out of the carousel, to change the set of five available filters) will be done during daytime. The system is designed for 3000 loads over its lifetime.

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<sup>22</sup>These expressions are approximate linear fits to the precise model behavior used in OpSim.

- The currently implemented filter load strategy is to replace during the day one of the  $z$  or  $y$  by the  $u$  band at the start of dark time, when the lunar phase reaches 20%. The process is reversed at the end of dark time when the lunar phase is above the same threshold.
- During a given observing night, the system could support as many filter changes (changes within a night, involving the 5 filters already loaded in the carousel) as desired, without any practical limitation beyond the two-minute change interval (which consists of 90 seconds for the exchange plus up to 30 seconds to put the camera into the required orientation).
- The carousel filter change mechanism is designed to undergo a total of 100,000 filter changes over its lifetime (an average of about 17 changes per night of the survey, after accounting for necessary calibration activities).
- Each individual filter is designed to support up to 30,000 changes over its lifetime.
- A maintenance cycle to the filter exchange mechanism is anticipated, and this would nominally occur after 10,000 filter changes or one year, whichever is reached first.

## Software constraints

The LSST Science Requirements Document specifies that “As a general principle, the measurement errors for fundamental quantities, such as astrometry, photometry and image size, should not be dominated by algorithmic performance.” Data products that LSST will produce are described in LSST Data Products Definition Document ([ls.st/dpdd](https://lsst.st/dpdd)) and more algorithmic detail is provided in LSST Data Management Science Pipelines Design document ([ls.st/dm-151](https://lsst.st/dm-151)).

The Project will not take formal responsibility for specialized data reduction algorithms needed to process data, including that taken in “non-standard” modes; detailed discussion is available in the Data Management and LSST Special Programs document ([ls.st/dmtn-065](https://lsst.st/dmtn-065)) and should be perused when proposing non-standard observing sequences. In addition, we strongly recommend that white paper authors consult Sections 5 and 6 in the LSST Data Products Definition Document. If a proposed dataset will require special processing, a plan to obtain necessary software and compute resources must be provided in the white paper.

There is an additional caveat regarding crowded field processing (see also Appendix A.3). A fraction of LSST imaging will cover areas of high object (mostly stellar) density, such as the

Galactic plane, the Large and Small Magellanic Clouds, and a number of globular clusters (among others). LSST image processing and measurement software, although primarily designed to operate in non-crowded regions, is expected to perform well in areas of crowding. The current LSST applications development plan envisions making the deblender aware of Galactic longitude and latitude, and permitting it to use that information as a prior when deciding how to deblend objects. While not guaranteed to reach the accuracy or completeness of purpose-built crowded field photometry codes, we expect this approach will yield acceptable results even in areas of moderately high crowding.

The above discussion only pertains to processing of direct images. Crowding is not expected to significantly impact the quality of data products derived from difference images (i.e., Prompt products).

## B.2 Observing efficiency constraints

The LSST Science Requirements Document “...assumes a nominal 10-year duration with about 90% of the observing time allocated for the main LSST survey.”, and thus 10% of observing time is left for all other programs. However, if the system performs better than expected, or if science priorities change over time, it is conceivable that the 90% could be modified and become as low as perhaps 80%, with the observing time for other programs thus doubled. At this time, details are TBD but the Project is developing flexible scheduling procedures to enable such modifications. In the current baseline survey strategy, the main survey takes about 86% of the time, with the remainder taken by the candidate mini surveys.

We note that the uncertainty in our system performance estimates due to weather and solar activity is about 10%. In addition, the system has not been built yet and many hardware performance parameters are still taken at their design values.

Sustained observing, such as the main survey, with exposures much shorter than standard visits will result in diminished observing efficiency. Given total visit exposure time  $t_{vis}$  (30 sec for standard visits), with two exposures/readouts (snaps) per visit, and assuming a slew and settle time of 5 sec (also including the second readout), the observing efficiency can be computed as

$$\epsilon = \left( \frac{t_{vis}}{t_{vis} + 9 \text{ sec}} \right). \quad (4)$$

To maintain efficiency losses below  $\sim 30\%$  (i.e., at least below the limit set by the weather

patterns), and to minimize the read noise impact,  $t_{vis} > 20$  seconds is required for sustained observing.

Variations in exposure time for the main survey affect not only the limiting depth, but also the total number of acquired visits and revisit time because the total observing time is finite. For more detailed discussion of these tradeoffs, please peruse Section 2.2.2 in the Overview paper.

The number of filter changes (2 minutes per change) and size of slews also affects efficiency.

### B.3 Limiting depth and uncertainty estimates

Methods for estimating individual image depth ( $5\sigma$  point source magnitude limits) for a given exposure time and other observing parameters are discussed in detail in Section 3.2 in the LSST Overview paper (see C.1). Tradeoffs between exposure time per visit, single-visit depth, the mean revisit time, and the total number of visits, as well as justification for the adopted standard exposure time of 30 sec, are discussed in Section 2.2 of the same paper. The improvement in measurement uncertainties as the survey progresses, as a function of time  $t$ , can be approximately summarized as follows.

The co-added depth (the  $5\sigma$  depth for point sources),  $m_5^{\text{co-add}}$ , scales with time as (see eq. 6 in the overview paper)

$$m_5^{\text{co-add}} = m_5^{\text{co-add, Final}} + 1.25 \log_{10} \left( \frac{t}{10 \text{ yrs}} \right) \quad (5)$$

where  $m_5^{\text{co-add, Final}}$  is the target depth achieved with the 10-year survey. With airmass and other losses taken into account,  $m_5^{\text{co-add, Final}} = 27.2$  for the  $r$  band in the baseline simulated survey.

The photometric errors (inverse signal-to-noise ratio) at the faint limit of the so-called “gold” galaxy sample (4 billion galaxies with  $i < 25.3$  which will be used for cosmological programs, see Section 3.7.2 in the LSST Science Book<sup>23</sup>), is computed from (see eq. 5 and Table 1 in the overview paper):

$$\sigma_{i=25} = 0.04 \left( \frac{t}{10 \text{ yrs}} \right)^{-1/2} \text{ mag.} \quad (6)$$

<sup>23</sup>The LSST Science Book is a wide-ranging, detailed description of science cases enabled by LSST. Written in 2009 by the LSST Science Collaborations, it is available online at <https://www.lsst.org/scientists/scibook>.



The volume of the 5-dimensional color error space per source with  $i = 25$ , which controls the ability to classify sources using colors (including photometric redshift estimates for galaxies and star/quasar separation, for example) is computed assuming uncorrelated color errors, as proportional to  $\sigma_{i=25}^5$ , and normalized by the value corresponding to the 10-year survey.

The trigonometric parallax accuracy for a point source with  $r=24$  (see section 3.3.3 in the overview paper) scales with time as

$$\sigma_{\pi} = 3.0 \left( \frac{t}{10 \text{ yrs}} \right)^{-1/2} \text{ mas.} \quad (7)$$

The proper motion accuracy for a point source with  $r=24$  (see section 3.2.3 in the overview paper) scales with time as

$$\sigma_{\mu} = 1.0 \left( \frac{t}{10 \text{ yrs}} \right)^{-3/2} \text{ mas/yr.} \quad (8)$$

Note the very strong dependence of  $\sigma_{\mu}$  on time ( $t^{-1/2}$  comes from the increase in the square root of the number of visits, analogously to  $\sigma_{\pi}$ , and an additional  $t^{-1}$  from the linear increase in temporal baseline). In both expressions, the number of visits is assumed proportional to time, with a value of 825 corresponding to the main wide-fast-deep 10-year survey.

The behavior of these quantities as a function of time is summarized in Table 2. While the co-added depth and  $\sigma(i=25)$  rapidly improve during the first few years, several important quantities continue to show marked improvement between survey years 8 and 10: most notably, the color error volume per source for faint sources ( $i = 25$ ) shrinks by a factor of 1.7. Substantial improvement is also seen for proper motions, with errors larger by 40%, after 8 years than at the end of the 10-year survey.

TABLE 3: Various science metrics as functions of survey duration.

Quantity	Year 1	Y3	Y5	Y8	Year 10
$r_5$ coadd <sup>a</sup>	26.0	26.5	26.8	27.1	27.2
$\sigma(i=25)$ <sup>b</sup>	0.12	0.07	0.06	0.05	0.04
color vol. <sup>c</sup>	316	20	6	1.7	1
# of visits <sup>d</sup>	83	248	412	660	825
$\sigma_\pi$ ( $r=24$ ) <sup>e</sup>	9.5	5.5	4.2	3.3	3.0
$\sigma_\mu$ ( $r=24$ ) <sup>f</sup>	32	6.1	2.8	1.4	1.0

<sup>a</sup> The co-added depth in the  $r$  band (AB,  $5\sigma$ ; point sources).

<sup>b</sup> The photometric error for a point source with  $i = 25$ .

<sup>c</sup> The volume of the 5-dimensional color error space, normalized by the final value.

<sup>d</sup> The number of visits per sky position (summed over all bands).

<sup>e</sup> The trigonometric parallax accuracy for a point source with  $r=24$  (milliarcsec).

<sup>f</sup> The proper motion accuracy for a point source with  $r=24$  (milliarcsec/yr).

## C Supplementary materials

### C.1 Useful publications and websites

*Note that various websites and documents references here are still in development (if not an official LSST document under change control).*

The LSST Overview paper provides a short summary of the four primary science drivers, as well as the expected performance of LSST in terms of throughputs, and calibration. It also discusses high-level survey constraints and tradeoffs. Last updated in 2018 (but a living document that will have future incremental updates), this is available as <http://ls.st/1op>

The LSST Science Book tackles an in-depth view of a broad range of LSST science goals. Written in 2009 by the LSST Science Collaborations, each chapter focuses on investigations relevant to a different area of astronomy. Available at <https://www.lsst.org/scientists/scibook>

The Community Observing Strategy Evaluation Paper (COSEP) is a community-driven paper describing a wide variety of science cases and their implications for survey strategy. This paper is primarily aimed at helping define the main wide-fast-deep survey. Last updated in 2017, the analysis in the COSEP is currently based on older simulations (including a reference simulation similar to the current baseline, but with significant differences in the detailed observations). The COSEP will continue to be a living document, with periodic updates as

provided by authors. This is available as <http://ls.st/3y1>

The LSST Science Requirements Document (SRD) describes the official requirements for LSST science deliverables. Section 3.4 is the most relevant for survey strategy, although other sections are relevant for telescope and camera performance such as throughputs and readout time. This document is under change control, and is not subject to update. Available as <http://ls.st/srd>

The LSST Data Products Definition Document (DPDD) describes the data products that LSST will provide, with some high-level background on how they will be produced. If you want to know what will be contained in various catalogs, this is a good place to look. Available as <http://ls.st/dpdd>

The LSST Data Management Science Pipelines Design (LDM-151) document describes the LSST data management processing pipelines. This provides details of how and when images will be processed and catalogs will be generated, including information on the algorithms used in each processing stage. If you want to know more about the details of a value in an output catalog and how it will be calculated, this is the place to look. This document will be periodically updated as processing algorithms are improved. Available as <http://ls.st/lm-151>

Documentation about the LSST Operations Simulator (OpSim), which consists of the Simulated Observatory Control System (SOCS) and Scheduler is available at [https://lsst-sims.github.io/sims\\_ocs/](https://lsst-sims.github.io/sims_ocs/). Documentation about the LSST Metrics Analysis Framework (MAF) is available at <http://sims-maf.lsst.io>. Documentation about running OpSim and MAF via docker is available at <http://ls.st/40m>.

The git repository ([https://github.com/lsst-pst/survey\\_strategy/](https://github.com/lsst-pst/survey_strategy/)) hosting the source of this document also holds additional information relevant to the call for white papers, such as a summary of observing constraints. The contents of the repository are described in the README.

The baseline2018a simulated survey document describes the recent, post-COSEP, features enabled in OpSim, as well as characteristics of the updated baseline simulated survey ('baseline2018a'). This document is available at <http://ls.st/Document-28453>.

The 'next candidate reference run' (*i.e.* the run that is likely to become baseline2018b) sim-

ulated survey document describes recent updates in OpSim to increase simulation fidelity. These updates include simulating dome crawl, which increases the efficiency of observing by about 3%, and updating the optics corrections time delay to the currently expected requirements. This document is available at <http://ls.st/Document-28715>.

A summary of the alternate survey strategy simulations produced as examples for the call for white papers, listed below in Section C.3 is available at <http://ls.st/Document-28716>. Additional plots and metric comparison are available in the `survey_strategy` github repo, at <http://ls.st/blm>.

The full outputs of MAF analyses for the 2018a baseline survey, as well as the example runs generated for the call for white papers, are available at <http://astro-lsst-01.astro.washington.edu:8080>.

A short description of the current Deep Drilling mini surveys and links to further materials (including white papers submitted in response to the 2011 call for input on the DD strategy) are available on the LSST website at <http://ls.st/57q>. Additional posts on LSST Community can be found by searching for 'deep drilling'.

Additional information is available in the following presentations:

- “Overview of the LSST Observing Strategy” (Nov 16, 2015): <http://ls.st/4yh>
- “The LSST Deep-Drilling Fields: White Papers and Science Council Selected Fields” (Aug 15, 2016): <http://ls.st/wzy>
- “Observing Strategy White Paper Status Report” (Mar 5, 2017): <http://ls.st/zj2>
- “LSST Plans for Cadence Optimization” (May 30, 2017): <http://ls.st/ot2>
- “Special Programs” (Aug 15, 2017): <http://ls.st/10o>

## C.2 Communication about the LSST survey strategy

The LSST Project Scientist (Željko Ivezić, e-mail: [ivezic@astro.washington.edu](mailto:ivezic@astro.washington.edu)) is formally responsible for survey strategy optimization efforts and is the formal liaison between the community and the LSST Scheduler and Operations Simulation teams.

The LSST Science Advisory Committee (SAC) (<https://project.lsst.org/groups/sac>) is charged with collecting and delivering various community input to the Project. Strategic and political issues about the LSST survey strategy should be communicated via the SAC (chair: Michael Strauss, [strauss@astro.princeton.edu](mailto:strauss@astro.princeton.edu)).

In addition to this call for white papers, the Community Observing Strategy Evaluation Paper<sup>24</sup>, COSEP, provides a coordinated mechanism for providing scientific input about survey strategy. LSST science collaborations are also official channels for communication with the LSST project — a Data Management liaison<sup>25</sup> is assigned to each Science Collaboration to answer specific questions about data products generated by the project.

An open, searchable resource for asking questions not addressed in this document is available on LSST Community, in the Science category, SurveyStrategy subcategory. Team members will monitor and respond in a timely manner to questions posted there. Please go to <http://community.lsst.org/c/sci/survey-strategy>

There is a mailing list available (email: [lsst-survey-strategy@lists.lsst.org](mailto:lsst-survey-strategy@lists.lsst.org)) to contact the survey strategy team in case of specific questions and/or concerns. Messages posted to the mailing list are broadcasted to the survey strategy team and archived. The same list will be used for white paper submission (see Section 2).

Throughout the survey strategy design process there will be open community meetings. The first of these will be at the LSST 2018 Project and Community Workshop in Tucson, AZ (August 13-17, 2018). More information on this meeting, including the agenda, is available at <https://project.lsst.org/meetings/lsst2018/>; note that the registration deadline is July 9, 2018. Another highly relevant meeting/workshop will be organized by LSST Corporation and the Simons Center for Computational Astrophysics at the Flatiron Institute in Manhattan, NY (September 17-19, 2018). To apply for this workshop, please fill out the application form at <http://ls.st/cwg> by July 20, 2018. Finally, the Project will organize a dedicated session at the LSST 2019 Project and Community Workshop to discuss submitted white papers and follow-up deliberations and work. We anticipate more similar meetings before the formal start of LSST Operations.

<sup>24</sup>A living document (available as <http://ls.st/9fw>) and a community project coordinated at <https://github.com/LSSTScienceCollaborations/ObservingStrategy>

<sup>25</sup>For the list of Science Collaboration contacts and corresponding Data Management Liaisons, please see <https://www.lsstcorporation.org/science-collaborations>.

The Project teams cannot support individuals or groups wishing to run the Operations Simulator themselves. The Project will provide Docker images (as well as the source code) and corresponding documentation on running OpSim; however, the Project does not have resources to provide help desk facilities on this topic.

### C.3 Additional Simulated Survey Strategies

With this call for white papers, we are providing a set of simulated surveys for the community to use as test cases. These simulated survey strategies will include (as of June 30, 2018):

- The baseline survey strategy, with the main survey having a 18,000 deg<sup>2</sup> footprint, the North Ecliptic Spur, South Celestial Pole, Galactic Plane and Deep Drilling mini surveys operating in the current example baseline survey strategy manner (i.e., no “rolling”).
- A slight variation on the baseline survey strategy, extending the main survey by about 1.5 degrees further north and south to improve performance on the SRD requirements about footprint and number of visits.
- A survey with a much larger main survey footprint (27,000 deg<sup>2</sup>), defined by airmass limit  $X < 1.5$  and declination limits  $-78^\circ < \delta < +18^\circ$ , and including only the four-field Deep Drilling mini survey (and no other mini surveys).
- A survey strategy allowing more overall visits by making each visit shorter and without snaps: each visit being 20 sec long with a single exposure per visit in  $g, r, i, z$  and  $y$ , and 40 sec visits in the  $u$  band.
- A survey similar to the current baseline, with the Galactic Plane at the main survey cadence (and the northern portion of the Galactic plane mini survey with  $\delta > 2^\circ$  removed).
- A survey similar to the current baseline, but only observing with single visits per night.
- A survey similar to the current baseline, but adding more Deep Drilling mini surveys to increase the number of DD fields to 9 (from 5).
- A rolling cadence survey with two declination bands that divide the WFD survey area in half and alternate on/off every other year. The non-rolling WFD proposal was completely removed from this survey.

- A rolling cadence survey with two declination bands that divide the WFD survey area in half and alternate on/off every other year. The non-rolling WFD proposal was included in this survey at the 25% level, as a low-level, on-going, background.
- A rolling cadence survey that observed the entire WFD area for the first and last two years of the survey. During the six years in between, the WFD area was divided into three declination bands observed every three years (i.e. each band is observed twice).

A summary of these simulations is available at <http://ls.st/Document-28716>. Additional plots and metric comparison are available in the survey\_strategy github repo, at <http://ls.st/blm>. The full outputs of MAF analyses are available at <http://astro-lsst-01.astro.washington.edu:8080>.

We anticipate that additional sample survey strategies will follow during the remainder of 2018, which may include changes reflecting updates to the scheduling software.