Science Driven Optimization

of the LSST Observing Strategy

Prepared by the LSST Science Collaborations,
with contributions from the LSST Project.

Contents

Preface

This is a community white paper outlining various science cases and the impacts that observing strategy will have on them, quantified using the Metric Analysis Framework. We will describe various strategies and tradeoffs that impact the observing cadence (visit sequence), the current cadence baseline, and future directions for the optimization of the survey strategy. We aim to publish this white paper on arXiv, and invite community feedback.

The timescale for producing this white paper, started before and finished after the Observing Strategy workshop at the August 2015 LSST Project and Community workshop, is many months.

Messages

The main points we will aim to convey in this white paper are as follows:

- We have a pretty good idea of how we would deploy LSST: there is a baseline strategy and example cadences, with which it can be demonstrated that the data required for the promised science can be delivered.

- The baseline strategy can and will be optimized – even small improvements can be significant. Most importantly, the strategy is not set in stone and it will evolve.

- The cadence optimization process will be as open and inclusive as technically possible. All stakeholders will participate in this process.

Project start: July 2015.

0.1 Guidelines for Authors

Phil Marshall

Since this is a community white paper, contributions are welcome from everyone. Read on for how to make a contribution, and how you should structure that contribution.[1]

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[1]These notes on the white paper design are pasted from `whitepaper/notes/chapter-template.md`

0.1.1 How to get involved

The first thing you should do is read and absorb the current version of the white paper, which you should be able to view on GitHub. (You can also download the "raw" PDF, which is hyper-linked for easier navigation.) You will then be able to provide good feedback, which you should do via the GitHub issues. Browse the existing issues first: there might be a conversation you can join. New issues are most welcome: we'd like to make this white paper as comprehensive as possible.

To edit the white paper, you'll need to "fork" its repository. You will then be able to edit the paper in your own fork, and when you are ready, submit a "pull request" explaining what you are doing and the new version that you would like to be accepted. It's a good idea to submit this pull request sooner rather than later, because associated with it will be a discussion thread that the writing community can use to discuss your ideas with you. For help getting started with `git` and `GitHub`, please see this handy guide.

0.1.2 Chapter and section design

The first section of each science chapter needs to be an *introduction* that outlines, very briefly, the commonality of the key science cases contained in it: what is to be measured, in broad-brush terms, and why this is of interest. Then, suppose we were to design an LSST survey to enable these measurements: qualitatively, what might it look like, in terms of the choices we are able to make? This chapter introduction can eventually (when the results are in!) summarize, again, in very broad brush terms, the results of a number of investigative sections, one on each science case.

The individual sections following this introduction will need to describe the particular discoveries and measurements that are being targeted in each *science case*. It will be helpful to think of a "science case" as a "science project" that the section leads *actually plan to do*. Thinking this way means that the sections can follow the tried and tested format of an observing proposal: a brief description of the investigation, with references, followed by a technical feasibility piece. This latter part will need to be quantified using the MAF framework, via a set of metrics that need to be computed for any given observing strategy to quantify its impact on the described science case. Ideally, these metrics would be combined in a well-motivated figure of merit. The section can conclude with a discussion of any risks that have been identified, and how these could be mitigated.

The following two sections are an example chapter introduction and science case section for you to work from. The latter is checked into the repository as `section-template.tex`.

0.2 Example Introduction

General introduction to the chapter's science projects.

Overview of observing strategy needed by those projects, bringing out common themes or points of tension.

0.3   Example Science Project

Author Name(s)

A short preamble goes here. What's the context for this science project? Where does it fit in the big picture?

0.3.1 Target measurements and discoveries

Describe the discoveries and measurements you want to make.

Now, describe their response to the observing strategy. Qualitatively, how will the science project be affected by the observing schedule and conditions? In broad terms, how would we expect the observing strategy to be optimized for this science?

0.3.2 Metrics

Quantifying the response via MAF metrics: definition of the metrics, and any derived overall figure of merit.

0.3.3 OpSim Analysis

OpSim analysis: how good would the default observing strategy be, at the time of writing for this science project?

0.3.4 Discussion

Discussion: what risks have been identified? What suggestions could be made to improve this science project's figure of merit, and mitigate the identified risks?

1 Introduction

Zeljko Ivezic, Beth Willman, ...

Preamble.

1.1 The Baseline Observing Strategy

Synoptic Surveying with LSST - the basic observing strategy determined by key projects described in the LSST Science Requirements Document, and constrained by the LSST's design (Ivezic et al. 2008).

Optimizing the Observing Strategy - what perturbations can we introduce, to maximize the system's science capabilities?

1.2 Some Simulated Alternative Observing Strategies

Zeljko Ivezic

Please see http://www.astro.washington.edu/users/ivezic/lsst/cadexp2.pdf for a summary of the LSST 2015 OpSim runs. We'll import much of the material from this document soon.

1.3 Evaluation and Optimization

The first step towards a science-based optimization of the LSST observing strategy is a *science-based evaluation of the baseline LSST observing strategy.* Adopting XXXX as this fiducial baseline, we now need to quantify the value of this observing schedule to each science team. This is what the LSST DM Sims team's "Metric Analysis Framework" was designed to enable. Once the fiducial strategy has been evaluated, then any other strategy can be evaluated in the same terms, using the same code, and we will be able to start optimizing the strategy through iterations between OpSim and MAF.

With this program in mind, it makes sense to define *one "Figure of Merit" (FoM) per science project*, that captures the value of the observing strategy under consideration to that science team. This FoM will probably be a function of several "metrics" that quantify lower-level features of the observing sequence. For Figures of Merit to be directly comparable between disparate science projects, they need to be *dimensional, and have the same units.* One natural

choice could be the *information gained* by the science team, in bits. This is a well-defined statistical quantity, albeit not yet one in common use. A given observing schedule's value would then depend on both this information gain, but also *how much that information is worth to the whole community.* It is at this point that the debate could become heated: probably the best we can do in Cadence Diplomacy is to quantify all the information gains implied by each proposed change to the baseline observing strategy, combine them to see whether it makes everyone happy, and iterate. In this way we might hope to minimize the debates about the less quantifiable worth of each piece of information.

We are some way from being able to define information-based Figures of Merit for most science cases – but the metrics that they will depend on will be easier to derive. Writing this white paper is an opportunity to think through the Figure of Merit for each science project that we as a community want to carry out, and how that measure of success is likely (or even known) to depend on metrics that summarize the observing sequence presented to us. Thinking about the problem in terms of science projects, each with a Figure of Merit, encourages us to design *modular document sections,* with one science project and one Figure of Merit per section.

This will have the happy side-effect of allowing the chapters to be straightforwardly re-arranged as we go, to make the white paper easier to read. It will also naturally lead to the definition of a suite of MAF super-metrics, can be evaluated on any future OpSim output database. A table in each section showing the values of the metrics and the FoM, for different schedules, for that science project, will be very helpful. The metric names in these tables should match the metric class names in the `sim_maf_contrib` module. In principle these tables could be auto-generated by the MAF framework, and extended as OpSim is repeatedly reconfigured and run.

For an example of how all this could look, please see the lens time delays section. The MAF subsections are still under development there, but keep checking back to see it come together during the August 2015 workshop week.

2 A Solar System Census

Lynne Jones, David Trilling, Mike Brown, Eric Christensen

2.1 Discovering Solar System Objects

Discovering, rather than simply detecting, small objects throughout the Solar System requires unambiguously linking a series of detections together into an orbit. The orbit provides the information necessary to scientifically characterize the object itself and to understand the population as a whole. Without orbits, the detections of Solar System Objects (SSOs) by LSST will be of limited use; objects discovered with other facilities could be followed up by LSST, but almost the entire science benefit to planetary astronomy would be lost.

Therefore, the primary concern regarding the Solar System is related to the question "Can we link detections of moving objects into orbits?". This requirement poses varying levels of difficulty as we move from Near Earth Objects (NEOs) through the Main Belt Asteroids (MBAs) and to TransNeptunian Objects (TNOs) and Scattered Disk Objects (SDOs), as well as for comets and for other unusual but very interesting populations such as Earth minimoons.

discuss specific challenges for each population; TNOs and SDOs are relatively easy, MBAs are very numerous, NEOs are hard because of speed, comets and minimoons are hard because of nongravitational forces

Much of the answer to this question comes down to the performance of various pieces of LSST Data Management software. In particular, the false positive rate resulting from difference imaging, the compute limitations of the Moving Object Processing System (MOPS) to extend to high apparent velocities, and the capability to unambiguously determine if a linkage is 'real' or not via orbit determination (done as part of MOPS). Additional concerns are related to how well observations widely separated in time can be linked into the 'discovery' orbits (i.e. if we have a discovery in year 1, but do not detect the object again until year 3, could these observations be linked?). The answers to these questions range beyond the limits of the OpSim simulated surveys, but bear on the observing strategy requirements for discovering Solar System Objects.

describe current minimum observation requirements for existing surveys, describe current expected requirements for MOPS, describe current effort to understand if MOPS requirements are realistic in LSST context

If we assume various detection requirements, ranging from XXX to the minimum MOPS requirements, we can characterize the performance of available simulated surveys in terms of their expected detection rates for various known populations.

describe completeness metrics for NEOs/MBAs/TNOs/etc - known populations. what do we do about unknown populations?

Beyond this basic but absolutely critical requirement to actually discover SSOs across the Solar System, we can start to look at other science goals: detecting activity, determining colors for moving objects, and measuring shapes and spin states for objects.

describe requirements and challenges for these; why colors are hard, how many objects will we actually be able to determine shape/spin for, how lightcurves may differ from shape/spin

Note: take a look at `https://github.com/rhiannonlynne/MafSSO/blob/master/SSO_Analysis.ipynb` (an extremely messy ipython notebook, but starting to point at some of the ideas I have for metrics – let's expand on this)

3 The Galaxy

Will Clarkson, Kathy Vivas, and others to follow

3.1 Introduction

LSST will significantly advance Milky Way science, on lengthscales from the galactic halo and local volume, right down to sensitive surveys for faint nearby objects to uncover the true state of the Solar Neighborhood. Much more detail about most of these science cases, and specific science questions to be answered, can be found in the LSST Science Book (particularly chapters 6 and 7) and Ivezic et al. (2008 arXiv 0805.2366, in particular Sections 2.1.4 and 4.4); in this chapter we outline the impact of the MW science cases on the LSST observing strategy, both for the main survey and for the ancillary observing campaigns. For the latter, many first-order questions (for example, how many exposures to take per filter over LSSTs operational lifetime) remain unanswered; this document is intended to be a step towards their resolution.

For many of the science goals within the general area of Milky Way science,[1] the main survey is already quite well-matched to requirements (for example, see Ivezic et al. 2008 Section 2.1.4-5). However, there are many important science cases - most obviously, but not exclusively, investigations towards the Galactic Plane - for which either no observations in the main survey are planned, or the main surveys by themselves are not sufficient to meet the science cases. For spatial areas like the Plane that are not currently covered by the main survey, considerable optimization remains to be done to define the observations.

This Chapter is organized as follows: Because of the very large diversity in observing strategies, particularly for regions not in the main survey, we first summarize in Sections **??-??** the science cases in terms of scientific and observational requirements, focusing on items for optimization, the LSST discovery space, and the areas in which observations will be required in addition to the baseline survey. Once these quantities are reported, the flow-through to optimization should become clear. Then, observational considerations particular to the Solar Neighborhood and Galactic Plane are developed in detail (Sections 3.4 onwards, led by Monet et al.). Finally, recommendations are made in Section YY.

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[1] *The Local Volume is not currently included in this chapter. Suggestions are welcome.*

3.2 Milky Way campaigns in relation to the main LSST surveys

Before embarking on strategy considerations for the different science cases, we remind the reader that the baseline performance figures from previous documentation may not apply for all (or any!) spatial regions of interest to a given Milky Way science case. Or, assumptions one might make in planning may be violated just by moving to different spatial regions within the same science case. An example might be surveys of the Solar Neighborhood: populations that happen to lie in front of the Galactic Disk will likely have many fewer visits per filter per year than their equally-close counterparts that happen to lie in front of the main survey area, no matter how the available observations are ordered within the strategy. [2] We identify the following classes:

- *Science cases including the main-survey area:* For some science cases (e.g. finding the most metal-poor stars in the Halo), the cadence and total number of visits in the main survey can be assumed for most fields. In these cases, optimization of observing strategy can proceed within the general parameters of the main survey - there might be some small changes to suggest in terms of the distribution of visits throughout the 10-year main survey, but the photometric and astrometric performance listed in the LSST Science Book can be assumed.

- *Science cases involving more intensive monitoring:* For cases in which many more exposures might be required than for the main survey (possibly in one or two filters only), the deep-drilling sub-surveys are probably the natural channel to take data; see Chapters 6 & 7.

- *Science cases towards areas outside the main survey regions:* For science cases not in regions currently slated for the main-survey, the total time allocation will be much lower than the main-survey baseline. In the present chapter, the main examples are regions in or in front of the Galactic Plane [3]. For cases such as this, the total allocation per field might on average be on the order of 20 exposures per field per filter, over ten years, if spread over all six filters evenly. For such an optimization, certain assumptions one might make when planning a science case (e.g. can average through local distortion by dithering across many chip-regions) will be violated. In most science cases within this general category, optimization using tools such as MAF will be essential.

  - **Note:** Care should be taken during the planning process to ensure that these cases are not artificially down-graded for software reasons. An example might be: searches in the Plane for variability on a timescale of months-years, would be compromised if a small-allocation field were pushed entirely into the first three years by OpSim in order to complete the short projects first.

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[2]This is quite aside from performance issues that are particular to crowded regions like the Galactic Plane, which are developed in some detail in Sections 3.4 onward.

[3](Although we point out that there may also be regions in the main survey that might not currently be observed in the best way for some cases, for example if the population of interest to MW science is so nearby and bright that it would strongly saturate in the main survey.)

3.3 Observing strategies for Milky Way science cases

In the following subsections, we outline the science cases within each science area, in rough order of increasing distance from the Sun. For each science case, we list the broad requirements, an attempt to translate these into observation strategy requirements, an indication of the discovery space open to LSST, and an indication of whether dedicated new observations will be required.

To aid in optimization, we also list any technical drivers that do <u>not</u> need to be optimized for a given science area.

Note: the parameters in this section are a first-cut, to be updated by the experts in each science case!

[Summary table would come here once we have updated content.]

3.3.1 The Solar Neighborhood

(Note: this is not yet a complete list of science cases, the Solar Neighborhood working group was quite thorough in its Phase I roadmap!)

Summary: generally the cases in this science area require deep photometry, particularly (though not exclusively) at red bandpasses, and sufficient per-image precision and distribution of observing times in at least one filter to measure parallax and/or proper motion. The main-survey area is not sufficient for this science area: dedicated observations are required for all science cases to fill in angular coverage (apart from photometric variability of cool dwarfs).

Drivers NOT required for this science area: variability (for all apart from photometric variability of cool dwarfs).

Co-moving groups (new groups or objects that are members of already-known groups)

- **Observing requirement:** proper motions at better than 100 mas/yr in at least one filter; 10% photometry in at least two further filters for object identification.

- **Strategy requirement:** Observations spread over time for proper motion sensitivity; best choice of filter for proper motions; minimum exposure time for other filters for photometry.

- **Discovery space for LSST:** objects too faint for gaia to measure sufficiently precise proper motions.

- **New observations required?** Yes - area coverage of main survey is insufficient.

Volume-complete astrometric sample of extended Solar Neighborhood

- **Observing requirement:** Parallax measurements with LSST, deep photometry out to y-band.
- **Strategy requirement:** Minimum accumulated exposure time per filter; minimum spread in observing epochs to achieve parallax goals.
- **Discovery space for LSST:** LSST will likely lead this science case; gaia has little sensitivity in the red bandpasses needed for low mass objects (L/T/Y dwarfs).
- **New observations required?** Yes - area coverage of main survey is insufficient.

Discovery of ultracold brown dwarfs (late-T and Y)

- **Observing requirement:** Very deep photometry in y
- **Strategy requirement:** Minimum exposure time in y
- **Discovery space for LSST:** Objects not already detected by WISE (and Spitzer). Suggests specific spatial regions (where crowding has prevented those facilities setting useful limits). May need WISE-observed regions for cross-calibration and survey completeness estimation.
- **New observations required?** Yes - perhaps only for selected fields inaccessible to WISE and Spitzer.

The endpoints of stellar evolution in the Solar Neighborhood

- **Observing requirement:** Deep (u,g,r) photometry (required), sufficient proper motion precision for reduced proper motion diagnostics (preferred)
- **Strategy requirement:** Minimum exposure times; distribution of observations through time to increase proper motion sensitivity.
- **Discovery space for LSST:** White dwarfs intrinsically faint: in all noncrowded regions, the sheer field of view and collecting area of LSST makes it the winner for this science case.
- **New observations required?** Yes - perhaps only for selected fields inaccessible to WISE and Spitzer.

Photometric variability of cool dwarfs

- **Observing requirement:** Photometry (do we know in which filters?) of sufficient sampling to measure starspot variability and also measure (to remove) transits and eclipses (fractional amplitude 1% OK?).
- **Strategy requirement:** Minimum number of exposures, minimum exposure time, subset of filters, particular cadence distribution.
- **Discovery space for LSST:** Use LSST-detected objects as calibrators for stellar astronomy, or use LSST-detected objects to better understand the population based on results from other facilities. *(WIC & KV; input needed!)*
- **New observations required?** TBC - even for main-survey areas, might need better time coverage for variability sensitivity. Is the intent here to study calibrator objects well (e.g. in the main survey) or to chart this variability for all reachable stars near the Sun?

3.3.2 Star clusters

Summary: Science mainly motivated by precise magnitudes and colors for members of the various stellar populations in clusters in various parts of the survey. Main requirement is for well-behaved (characterizable) photometric and astrometric measurements. Studies are still ongoing within the Star Clusters subgroup to determine whether main survey-like observations will be sufficient for the science goals.

NOT required for optimization: variability, parallax

Formation History and Evolution of the Milky Way as traced by star clusters

- **Observing requirement:** Deep {ugrizy} photometry down to 2 magnitudes below the main sequence turn-off (required); astrometric precision to remove foreground contamination in regions too crowded for gaia (preferred).

- **Strategy requirement:** Minimum photometric precision; filter-set for population constraints (is y needed?)

- **Discovery space for LSST:** The full set of observable clusters within the MW, observed in as uniform a manner as possible; highly spatially-extended clusters (tidal interactions; dissolution into the MW); cluster bulk properties out to distance X kpc.

- **New observations required?** TBC - Clusters within main-survey area, likely not. Clusters at the edge of or in the plane; dedicated observations likely required, configured properly to reach required precision in brightness and color in the presence of crowding.

Stellar Mass function, metallicity, ages

- **Observing requirement:** Deep {ugrizy} photometry down to 4 magnitudes below the main sequence turn-off (required); astrometric precision to remove foreground contamination in regions too crowded for gaia (preferred).

- **Strategy requirement:** Minimum photometric precision; filter-set for population constraints (to do the mass function down to low-mass objects, is y required?)

- **Discovery space for LSST:** Populations of nearby clusters down to mass limit X. *Broad question: survey all clusters in this way, or pick a few representative targets for new observations?*

- **New observations required?** TBC - Clusters within main-survey area, likely no. Clusters at the edge of or in the plane; dedicated observations likely required, configured properly to reach required precision in brightness and color in the presence of crowding.

3.3.3 The Galactic Bulge

Summary: Nearly entirely in LSSTs classical region of avoidance, thus dedicated observations will be needed. Want to optimize for photometry and astrometry, as well as variability on a timescale of hours or longer (for RR Lyrae and other tracers of structure). Quite sensitive to crowding. At the longer timescale, microlensing with a wide-area facility like LSST could be transformative if affordable.

NOT required for optimization: parallax

(Note: the final science case, microlensing, might be a good candidate for a deep-drilling-like survey, e.g. pick a 2×2 set of LSST pointings and monitor those with microlensing-friendly cadence in two filters (to help weed out false positives). This is one science case that should be revisited anyway.)

Bulge structure and stellar populations

- **Observing requirement:** Multi-color photometry in all bands to disentangle constituent bulge populations (required); sensitivity to RR Lyrae for distance and also extinction mapping (required); relative proper motion sensitivity for kinematic population separation (preferred; requires proper motion precision at the 0.5-1mas/yr level).

- **Strategy requirement:** *Maximum* individual exposure time in these crowded fields; minimum exposure time for u-band sensitivity; cadence sufficient for proper motions; cadence sufficient for sensitivity to variables on ∼hour-long timescales.

- **Discovery space for LSST:** Populations down to the main sequence turn-off (most fields); balance of populations across the entire structure; discovery of new RR Lyrae and improvement of extinction map. Gaia cannot make precision measurements down to a couple of magnitudes or so above the turn-off in these fields *(do we have more quantitative information than this yet?).*

- **New observations required?** Yes - the bulge is outside the main LSST survey area. In addition, observations of disk-calibration fields will be needed for statistical subtraction of the foreground. Short exposures will also be needed to constrain nearby bright objects or at least characterize their effect on the deep exposures.

Stellar kinematics in the Bulge and foreground

- **Observing requirement:** Proper motion sensitivity better than 0.5 mas/yr, in at least one band.

- **Strategy requirement:** *Maximum* individual exposure time in these crowded fields; cadence distributed to maximize proper motion precision.

- **Discovery space for LSST:** Proper motions both internally to LSST and externally to earlier epochs from previous campaigns. Gaia cannot make precision measurements down to a couple of magnitudes or so above the turn-off.

- **New observations required?** Yes - the bulge is outside the main LSST survey area. Short exposures will also be needed to constrain nearby bright objects or at least characterize their effect on the deep exposures.

Low-mass microlens events towards the Bulge

- **Observing requirement:** Main-survey-like monitoring in a subset of filters.

- **Strategy requirement:** <u>*Maximum*</u> individual exposure time in these crowded fields (likely different from the previous two science cases due to different analysis techniques); preferred filter choice for monitoring; cadence for sensitivity to microlensing events.

- **Discovery space for LSST:** Detection of microlensing events at the low-mass end, including free-floating planets, at levels inaccessible to smaller-aperture trigger surveys. These objects would later be followed up by dedicated observations with other facilities.

- **New observations required?** Yes - the bulge is outside the main LSST survey area. Short exposures will also be needed to constrain nearby bright objects or at least characterize their effect on the deep exposures.

  Note: this might be a good candidate for a deep-drilling-like survey, e.g. pick a 2×2 set of LSST pointings and monitor those with microlensing-friendly cadence in two filters (to help weed out false positives).

3.3.4 The Milky Way Disk

Summary: precise colors and magnitudes, with the ability to disentangle populations in crowded regions. Sufficient cadence for variability down to minutes-hours variations.

NOT required for optimization: proper motion, parallax.

Thin disk/thick disk structure and stellar populations

- **Observing requirement:** Precise magnitudes and colors; proper motions for reduced proper motion analysis. *(To what level of precision?)* Sensitivity in variability to RR Lyrae, δ Scuti variables, eclipsing binaries.

- **Strategy requirement:** <u>*Maximum*</u> individual exposure time to avoid crowding per exposure; minimum total exposure time. Cadence sufficient for proper motions; cadence sufficient for variability down to a timescale of minutes-hours.

- **Discovery space for LSST:** Regions too crowded for gaia

- **New observations required?** Yes - these are observations of the Galactic Plane. Short exposures will also be needed to constrain nearby bright objects or at least characterize their effect on the deep exposures.

Star formation in the Galactic Disk

Summary: this important topic does not seem to have been developed in previous versions of the LSST science book or Ivezic et al. (2008). LSST gives the opportunity to survey extensive areas around star formation regions in the Southern hemisphere. Among others, it would allow to study the Initial Mass Function down to the sub-stellar limit across different environments. Young stars are efficiently identified by their variability.

NOT required for optimization: parallax, relative proper motion.

- **Observing requirement:** Precise magnitudes and colors, appropriate cadence for T Tauri variability (days).
- **Strategy requirement:** filter set for population constraints; redder bands (z, Y) important for the lowest mass stars; u band for accretion rates
- **Discovery space for LSST:** Only optical survey in the galactic plane. It will produce an unbiased map of the young stellar populations in the Southern Hemisphere. Possibility of early alerts for outbursts of young stars.
- **New observations required?** Yes, most regions are within the galactic plane (outside the LSST main survey area). Constraints in spatial coverage can be done by defining the areas of star formation.

Spiral structure in the Milky Way disk

Note: science case could use some development. This is based on LSST Science Book section 7.3.2.

- **Observing requirement:** Colors, photometry, proper motions
- **Strategy requirement:** Minimum filter-set; cadence sufficient for proper motion; exposure time and strategy optimized to crowding in the preferred fields (e.g. $l \sim 270$).
- **Discovery space for LSST:** Large, coherent structures in phase space that would be difficult for smaller-etendue surveys to efficiently probe. Regions too crowded for gaia.
- **New observations required?** Yes - the galactic plane is not part of the LSST main survey.

3.3.5 Dust throughout the Milky Way

Summary: deep {ugriz} observations required; usefulness appears to depend mainly on the depth achieved in each filter.

NOT required for optimization: variability, parallax, proper motion, y-band photometry [? - not according to the LSST Science book 7.5]

Spatial distribution of dust

- **Observing requirement:** As deep as possible in {ugrizy} to allow reddening-free indices to be constructed for stars, in order for the intrinsic and true colors to be compared to estimate reddening.
- **Strategy requirement:** Minimum exposure-time accumulated in each filter; minimum filter-set *(Is y-band needed for this? Presumably would help, but doesn't seem to be mentioned in the Science book 7.5.)*.
- **Discovery space for LSST:** 3D dust maps out to much greater distance than previously possible (e.g. with SDSS)
- **New observations required?** Yes, but only for regions in the Galactic plane.

Variation in extinction laws

- **Observing requirement:** As deep as possible in {ugrizy} to estimate changes in reddening vector as a function of position and depth.
- **Strategy requirement:** Minimum exposure-time accumulated in each filter; minimum filter-set; 2% photometric accuracy in {ugriz}. (Again, is y required?)
- **Discovery space for LSST:** F-turnoff stars with $g > 19$ (fainter than gaia will measure).
- **New observations required?** Yes, but only for regions in the Galactic plane.

3.3.6 The Halo

Summary: with one exception (stellar streams and overdensities), most halo cases appear to be adequately met by the main survey. A representative sample of halo cases are included here for completeness. Main requirements: brightness and color precision; proper motion (some cases); variability (some cases).

NOT required for optimization: parallax

Halo stellar streams and overdensities

- **Observing requirement:** Deep photometry, with sufficient color precision to identify main sequence objects. Variability sufficient to discern RR Lyrae.
- **Strategy requirement:** Minimum filter-set required; minimum exposure time in these filters; variability sufficient for RR Lyrae.
- **Discovery space for LSST:** Objects too faint for gaia or PanSTARRS (seems to be most of the sample); structures with a very large extent on the sky; structures close to the Galactic Plane.
- **New observations required?** Not for most of the sky, since the main survey has been shown to be sufficient for RR Lyrae. However, overdensities close to the Galactic Plane (like the Monoceros Ring) may be located outside the main survey, and then require dedicated observations. These observations would then need to be optimized carefully to achieve sufficient coverage for the desired tracers.

Halo structure: main sequence stars out to 300 kpc

- **Observing requirement:** Deep photometry, with sufficient color precision to identify main sequence objects.
- **Strategy requirement:** Minimum filter-set required; minimum exposure time in these filters
- **Discovery space for LSST:** Objects too faint for gaia or PanSTARRS
- **New observations required?** No - baseline survey should be sufficient (e.g. Ivezic et al. 2008 2.1.5).

Hypervelocity stars in and in front of the Halo

- **Observing requirement:** Proper motion precision at the 1 mas/yr level; brightness and color precision sufficient to constrain luminosity class
- **Strategy requirement:** Minimum filter-set required; minimum exposure time in these filters; cadence for proper motions
- **Discovery space for LSST:** Old main sequence turn-off stars at about 10kpc (r ¡ 20; brighter than this is accessible to gaia)
- **New observations required?** No - LSST science book 7.7

The most metal-poor stars in the Galaxy

- **Observing requirement:** Color, brightness precision in the full {ugrizy} set for photometric selection of candidate metal-poor stars out to 100kpc from the Galactic Center.
- **Strategy requirement:** Minimum filter-set required; minimum exposure time in these filters; cadence for proper motions
- **Discovery space for LSST:** A much larger sample of metal-poor stars over a wider area than previously possible.
- **New observations required?** No - LSST science book 6.7.

4 Mapping Our Galaxy: Positions, Proper Motions and Parallax

Dave Monet, Dana Casetti, John Gizis, Michael Liu

While astrometry is not a science case, high astrometric accuracy enables a large number of science cases. Hence, the LSST Observing Strategy needs to be examined for systematic trends that might mitigate or even preclude precise measures of stellar positions, proper motions, parallaxes, and perturbations that arise from unseen companions. To highlight the various astrometric impacts of the strategy, three science cases have been chosen for particular attention:

- The tie between the Radio and Optical realizations of the International Celestial Reference System.

- Identification of Streams in the Galactic Halo using proper motions.

- The specific and ensemble agreement between LSST and Gaia parallaxes.

Each of these cases stresses different aspects of the LSST hardware, software, and observing strategies.

The measurement of stellar parallax puts the most constraints on the observing cadence. There are two major issues:

- Sampling over a wide range of parallax factor.

- Breaking the correlation between Differential Color Refraction and parallax factor.

The parallax factors characterize the ellipse of the star's apparent motion as seen during the year. The shape of the ellipse is given by the Earth's orbit and is not a free parameter in the astrometric solution. The amplitude of the RA parallax factor is close to unity while the amplitude of the Dec parallax factor is dominated by the sine of ecliptic latitude. The RA parallax factor has maximum amplitude when the star is approximately six hours from the Sun, so the optimum time for parallax observing is when the star is on the meridian near evening or morning twilight. Atmospheric refraction displaces the star's apparent position in the direction of the zenith by an amount characterized by both the wavelength of the light and the distance to the zenith. Whereas the measured position of star is a function of the total refraction, the measurement of parallax and proper motion depends on the differences in the refraction as a function of the color of each star and the circumstances of the observations. This dependence is called Differential Color Refraction (DCR). The combination of parallax factor and DCR leads to the these two rules well known to those who make astrometric observations.

1 Observations need to cover the widest possible range in parallax factor.

  2 The correlation between parallax factor and hour angle in the observations needs to be minimized.

The search for faint proper motion stars has two key components. The first is the need to identify stars that move from the ensemble of other image features that can cause confusion. For example, a compact group of stars that contains one or more stars of variable brightness can confuse the catalog correlation algorithm. The other is the need to establish the zero point. For the case of relative astrometry, meaning the measurement of relative positions in an image, the question remains on how to remove the mean motion of the reference frame. For example, astrometry on certain classes of galaxies might produce a zero point of sufficient accuracy. This leads to a third constraint on the observing cadence.

  3) Observations must cover a sufficient range of epochs so that stars with linear or periodic motions can be identified at a high level of confidence.

The tie between the radio and optical reference frames relies on measuring accurate positions for objects visible in both wavelength regimes. Whereas there are optical variable stars with radio emission, most have associated optical nebulosity that degrades the accuracy of the optical positions. The typical radio+optical object is a QSO. Unfortunately, many QSOs have detectable optical or radio structures that degrade the positions or suggests a displacement between the location of the sources of the radio and optical radiation. The major contribution from LSST will be the identification of a large number of QSOs based on their colors that have minimal (if any) spatially extended structure. The impact of this search has no obvious impact on the cadence other than temporal coverage to identify variability.

In summary, there are three metrics for the observing strategy that have direct relevance on the quality of LSST astrometric measurements. These were identified years ago and are already in the suite of MAF utilities, but they should be reviewed prior to making final decisions.

  A) For each LSST field, the parallax factors at each epoch of observation need to be computed. The ensemble of these must be checked for sufficient coverage of the parallactic ellipse. In particular, the number of measures with RA parallax factor less than -0.5 and greater than +0.5 needs to be tallied because these carry the most weight in the solution for the amplitude (parallax).

  B) For each LSST field, the hour angle of the observation needs to be computed, and the correlation between hour angle and parallax factor needs to be examined for significance. The observing strategy must minimize the number of fields with this correlation.

  C) The epochs of observation for each field must be checked for a reasonable coverage over the duration of the survey and to avoid collections of too many visits during a few short intervals.

Finally, it must be noted that these MAF metrics are only part of the study of LSST's predicted astrometric performance. Detailed simulations and studies need to be done in many other areas as part of the prediction and verification of LSST's astrometric performance. Among the most important are the following.

- Can we use galaxies as reference objects, and if so are certain shapes or colors better than others?

- Can we identify QSOs and sense optical structure that might mitigate using certain ones in the Radio-Optical reference frame link?

- Given the LSST exposure time, site, and physical characteristics, how can we mitigate the limitations on astrometric accuracy imposed by the seeing and local atmospheric turbulence?

- At what star densities does the measurement of a centroid become difficult or impossible, and does difference imaging allow us to work in these crowded areas?

- What tools do we need to compare the general and specific agreement between the *Gaia* results and the LSST results?

- Does the "brighter-wider" effect in the deep depletion CCDs introduce a magnitude term into the centroid positions?

5 Variable and Transient Sources in the Galaxy and Beyond

Mike Lund, Ashish Mahabal, Stephen Ridgway, Lucianne Walkowicz, Rahul Biswas, Michelle Lochner, Jeonghee Rho...

Confirmed leads for Stellar variability and Fast Stellar Transients: Mike Lund, Ashish Mahabal, Stephen Ridgway, Lucianne Walkowicz

Confirmed leads for cosmological SNe: Rahul Biswas, Michelle Lochner, Jeonghee Rho

Confirmed leads for extragalactic transients: Ashish Mahabal

Confirmed leads on rolling cadence: Stephen Ridgway

5.1 Introduction

The observation of variable targets investigates the time domain, and thus realizes the essence of a synoptic survey. Variable and transient studies are all about sampling, and different types and time scales of phenomena benefit from different sampling strategies - sometimes significantly different. Competing objectives described in this chapter are at the heart of LSST observing strategy and cadence design.

Target types are here grouped in subsections by variability characteristics, but as will be seen, this does not mean that all targets in a group require a common cadence, since the times scales may vary dramatically. Acquiring suitable data for a wide range of time scales presents a fundamental problem for LSST, since the available 800 visits to a field over the survey cannot be deployed so as to usefully sample all time scales at all times. This fact leads to the concept of a non-uniform survey, in which parts of the sky are visited more frequently part of the time. The merits of such options must be traded against the benefits of a more uniform survey strategy.

5.2 Periodic Variable Stars

Author Name(s)

Some stars may be strictly periodic, or sufficiently so to be treated as such for some purposes, in which case data from different cycles can be combined according to phase to provide a more fully sampled light curve. It is unreasonable to suppose that LSST visits will be synchronized with variable stars, and visits will occur effectively at random phases. In a 10-year survey, most

periodic stars of almost any period will benefit from excellent phase coverage in all filters. Only a very small period range close to the sidereal day will be poorly observed. There is no reason to believe that any likely LSST observing strategy could seriously disturb good sampling of periodic variables.

Eclipsing binaries are discussed here with variable stars, as detection of eclipses is dependent on adequate sampling of the phase curve. However, study of the features of an eclipse, particularly one of short duration in phase, may require sampling more appropriate to the discussion of transients.

5.2.1 Nearly Periodic Variables

Stars with a drifting period will be served well with sampling which constrains period variations frequently through the survey. For targets with a wide range of periods, this will be most effectively accomplished with sampling that is rather uniform through the survey. A considerable degree of uniformity is needed for many science objectives, and distribution of visits over the full survey is more important than the exact timing.

Some variable stars do not exhibit a strictly repeating light curve, and show variations in light curve structure from period to period. For observational purposes, these targets are better described as periodic transients, discussed in a later section.

5.2.2 Targets and Measurements

Periodic Variable Type	Examples of target science
Eclipsing binaries	Physical properties of stars, distances, ages, evolution, apsidal precession, mass transfer induced period changes, Applegate effect
RR Lyrae	Galactic structure, distance ladder, RR Lyrae properties
Cepheids	Distance ladder, cepheid properties
Long Period Variables	Distance ladder, LPV properties
Rotational Modulation	Gyrochronology, stellar activity

These targets share the requirement for good sampling over the variation phase curve.

For each target, the coverage of the phase curve sampling will accumulate randomly, and particular measurements or discoveries will become possible at a rate that is somewhat linear with number of acquired visits (hence linearly with time in a uniform survey).

With millions of different periods, it is difficult to imagine designing the survey to optimize this sampling, but the sampling achieved can be predicted with appropriate metrics.

5.2.3 Metrics

Metric	Description
Eclipsing binary discovery	Fraction of discoveries vs fractional duration of eclipse
Transiting exoplanets (depth dependent)	Fraction of discoveries vs fractional duration of eclipse
Phase gap	Histogram vs period of the median and maximum phase gaps achieved in all fields
Period determination (period dependent)	Fraction of targets vs survey duration, for which the period can be determined to 5-sigma confidence
Period variability (period dependent)	Fraction of targets vs survey duration, for which a period change of 1% can be determined with 5-sigma confidence

The period metrics can be based on a standard variable curve (e.g.sinusoid) of fiducial amplitude and brightness, and/or a realistic model population of a particular variable type. These metrics can be informative for science programs. However, it is not clear that the survey strategy can or should attempt to control these metrics, as the requirements are specific to each target, and all targets benefit from a generally uniform distribution of visits.

5.2.4 OpSim Analysis

Current simulations show for the main survey a broad uniformity of visits, with thorough randomization of visit phase per period, giving very good phase coverage with minimum phase gaps.

5.2.5 Discussion

For periodic variable science, two cadence characteristics should be avoided:

- an exactly uniform spacing of visits (which is anyway virtually impossible);

- a very non-uniform distribution, such as most visits concentrated in a few survey years.

A metric for maximum phase gap will guard against the possibility that a very unusual cadence might compromise the random sampling of periodic variables.

In each case, it would help to jump-start science programs if some fraction of targets had more complete measurements early in the survey.

5.3 Non-periodic Variable Stars

Author Name(s)

Some variable star types are not strictly periodic. These include multi-period stars, for which Fourier analysis may be useful, but only if the underlying frequencies are at least critically sampled. Irregularly variable stars may have so little repeatable structure that neither phase stacking nor harmonic analysis is very useful, but patterns may become evident over observing intervals of years or decades.

Non-periodic variable stars may benefit from complete phase coverage over a single cycle, or other time interval of of interest, repeated in consecutive intervals, or in intervals distributed over the survey. Variable stars for which thorough sampling of limited duration is required, including eruptive variables, are considered below with transients.

Active galactic nuclei are mentioned here as well, as they may vary as transients and/or variable, in most cases with no or only weak periodicity.

5.3.1 Targets and Measurements

The class of non-periodic variables includes a heterogeneous assortment of objects and phenomena.

Variable Type	Examples of target science
Long Period Variables	Pulsation modes, internal structure, evolution
Multimode pulsation	Pulsation mechanisms, internal structure
Semi-regular variables	Pulsation mechanisms, convection
Pulsating irregular variables	Chaotic dynamics
Epsilon Aurigae systems	Circumstellar material, dark companions
FU Ori systems	Accretion events, jets
Young Stellar Objects	Accretion, jets, disks, binarity, flaring, rotation, spots, magnetic phenomena
Active galactic nuclei	Galaxy evolution, reverberation mapping, black hole physics

In each case, the observational challenge is to discover and then to characterize the targets, utilizing the power of the LSST survey to increase by orders of magnitude the number of well-studied targets known. Most of the targets in the table have variation time scales of $\simeq 1$ week or greater, and will receive sampling commensurate with the time scale of variation under a natural LSST cadence ($\sim$800 visits over 10 years). Where a higher sampling rate is needed, these will need customized attention to the time scale and the number and duration of sampled intervals.

5.3.2 Metrics

Metric	Description
Non-periodic variables	Histogram of median visit series length vs maximum visit spacing within the series

5.3.3 OpSim Analysis

Current simulations provide reasonable sampling ($\sim$2 samples per time constant) for variables that change brightness on a time scale of >1 week. For faster variations, an enhanced sampling rate should be studied.

5.3.4 Discussion

Special cadences offer the opportunity to extend LSST studies to non-periodic phenomena with time scales $\leq$1 week, rather than the >1 week that is naturally achieved with a uniform survey.

The need for contemporaneous color information has not been addressed, and needs consideration, as with novel targets and non-repeating signals, it may not be possible to infer color relations.

5.4 Periodic Transient Events

Author Name(s)

This section is a place holder in case periodic transients deserve focus. However, they may fit into the previous sections.

5.4.1 Targets and Measurements

Describe the discoveries and measurements you want to make for a generic transient, with additional comment on specific variable types which have any special requirements.

Example events: eclipsing binary stars, exoplanet eclipses

Now, describe their response to the observing strategy. Qualitatively, how will the science project be affected by the observing schedule and conditions? In broad terms, how would we expect the observing strategy to be optimized for this science?

5.4.2 Metrics

Quantifying the response via MAF metrics: definition of the metrics, and any derived overall figure of merit.

5.4.3 OpSim Analysis

OpSim analysis: how good would the default observing strategy be, at the time of writing for this science project?

5.4.4 Discussion

Discussion: what risks have been identified? What suggestions could be made to improve this science project's figure of merit, and mitigate the identified risks?

5.5 Transient Events

Author Name(s)

Transient events may benefit from substantial temporal sampling (matched to the time constant of the event) with color information (perhaps contemporaneous) to support characterization and classification, obtained over the limited duration of interest. Transient events slower than $\sim$ weeks may be adequately sampled by a uniform LSST cadence. Faster events may require special scheduling strategies. For some event types, LSST can only be expected to provide a discovery service, and followup will necessarily be performed elsewhere.

5.5.1 Targets and Measurements

The class of transients includes a heterogeneous assortment of objects and phenomena.

Transient Type	Examples of target science
Flare stars	Flare frequency, energy, stellar age
Cataclysmic variables & novae	Interacting binaries, stellar evolution, compact objects, explosive events
Supernovae	SN physics, mass loss, distance scale, cosmology
Active galactic nuclei	Galaxy evolution, reverberation mapping, black hole physics
Stellar microlensing	Exoplanet statistics
Gamma ray bursts	Optical discovery and characterization
LIGO detections	Source position and characterization
Serendipity	Discovery and characterization

Among the targets in this list, only AGN are likely to be sampled with sufficient resolution by a uniform LSST cadence - in fact for AGN, a challenge may be to spread visits sufficiently in time to avoid excessive seasonal gaps.

For very short lived phenomena (stellar flares, CV outbursts, GRBs, LIGO events) it appears that the function of LSST will be to provide discoveries and/or simple characterization. Followup to discovery/identification, if required, will surely take place elsewhere.

For events requiring intensive monitoring (stellar microlensing, exoplanet transits), the followup will certainly take place elsewhere.

Supernovae fall in an intermediate time range. LSST will provide multiple visits in multiple filters during the typical SN duration. This sampling may be insufficient for many (including key) science objectives. However, a moderate, and feasible, change to LSST observing strategy, may enhance the sampling for part of the sky part of the time, greatly enhancing the usefulness of SN observations.

Serendipitous discoveries are of course harder to plan for. An ideal transient discovery survey would include heavy coverage of all time scales. LSST will cover longer time periods well, but will have to make some choices of emphasis in coverage of shorter time-scales.

5.5.2 Metrics

Metric	Description
SNe	Number of events adequately sampled
Serendipity	Histogram of median visit series length vs maximum visit spacing within the series

The metrics for SNe will be highly specialized and based on the best available understanding of SN light curve analysis and the expected event population.

The suggested metric set for serendipity is based on the simple-minded idea that a novel transient will be characterized by a band-limited, finite waveform, and that a useful observation series will consist of a series of samples extending over the duration of the event, with at least

critical sampling of the fastest variations. Since for some event durations the number of useful time series will be small, it may be useful to look not at the median length, but the median length of a subset size preselected as possibly useful (e.g. the10^3 longest series).

5.5.3 OpSim Analysis

Analysis shows that current simulations provide poor coverage in any one filter for transient events longer than a deep drilling session ($\sim$30 minutes) and shorter than $\sim$ weeks.

Simulated performance for SN observations must be analyzed for both main survey and mini-survey (deep drilling) productivity. It is considered that current simulated schedules give inadequate performance for SN science.

5.5.4 Discussion

Community studies are providing improving SNe metrics, and continuing communication between the SN and LSST communities is essential to tuning the observing strategy to deliver the SN time series that are needed and possible.

Improving LSST science return for SNe will also improve sampling of all transients with similar or somewhat shorter characteristic times. Non-uniform survey strategies (rolling cadence) can significantly improve the LSST performance for faster transients. Interpretation of multiple filters for novel events may be powerful, or problematic, since color may be uncertain.

Some insight into fast transients may be available from image pairs or triples (as opposed to more complete series). These include the pair of images in a visit - which could be useful in studying the rise time of an extremely fast event. This includes the characteristic grouping of visits (typically 0.5 to 1.0 hour separation) planned for purposes of identifying asteroids. It also includes fortuitous multiple sampling due to field overlap, providing additional sampling, which may be random or systematic, depending on the scheduling, on a time scale of minutes to hours. The sampling benefits of this fortuitous overlap have not yet been investigated.

5.6 Rolling Cadence

Stephen Ridgway, . . .

With a total of 800 visits spaced approximately uniformly over 10 years, and distributed among 6 filters, it is not clear that LSST can offer the sufficiently dense sampling in time for study of transients with typical durations less than or $\simeq$ 1week. This is particularly a concern for key science requiring well-sampled SNIa light curves. Rolling cadences stand out as a general solution that can potentially enhance sampling rates by $2\times$ or more, on some of the sky all of the time and all of the sky some of the time, while maintaining a sufficient uniformity for survey objectives that require it.

5.6.1 The Uniform Cadence

Current schedule simulations allocate visits as pairs separated by 30-60 minutes, for the purposes of identifying asteroids. For most science purposes, the 30-60 minute spacing is too small to reveal temporal information, and a pair will constitute effectively a single epoch of measurement. If the expected 824 (design value) LSST visits are realized as 412 pairs, and distributed uniformly over 10 observing seasons of 6 months each, the typical separation between epochs will be 4 days. The most numerous visits will be in the r and i filters, and the repeat visit rate in either of these will be $\simeq 20$ days.

The possibility is still open that, for asteroid identification, visits might be required as triples or quadrupoles, in which case the universal temporal sampling will be further slowed by 1.5 or $2\times$.

Under a strict universal cadence it is not possible to satisfy a need for more frequent sample epochs. This leads the simulations group to investigate the options opened up by reinterpreting the concept of a universal cadence. Instead of aiming for a strategy which attempts to observe all fields "equally" all the time, it would allow significant deviations from equal coverage during the survey, returning to balance at the end of the survey.

Stronger divergence from a universal cadence, allowing significant inhomogeneities to remain at the end of the survey, is of course possible, but is not under investigation or discussed here.

There is currently considerable interest in the community in strategies that provide enhanced sampling over a selected area of the sky, and rotating the selected area in order to exercise enhanced sampling over all of the survey area part of the time. The class of cadences that provides such intervals of enhanced visits, with the focus region shifting from time to time, is termed here a rolling cadence. As a point of terminology, observing a single sky area with enhanced cadence for a period of time will be described as a "roll".

5.6.2 Rolling Cadence Basics

Assume a fixed number of observing epochs for each point on the sky, nominally distributed uniformly over the survey duration. A subset of these can be reallocated to provide improved sampling of a sky region. This will have the inevitable effects of: (1) reducing the number of epochs available for that sky region during the rest of the survey, and (2) displace observations of other sky regions during the time of the improved temporal sampling. In short, the cadence outside the enhanced interval will be degraded.

The essential parameters of rolling cadence are: (1) the number of samples taken from the uniform cadence, and (2) the enhancement factor for the observing rate. The LSST document 16370, "A Rolling Cadence Strategy for the Operations Simulator", by K. Cook and S. Ridgway, contains more detailed discussion and analysis.

5.6.3 Supernovae and Rolling Cadence

Author Name(s)

Supernovae as a science topic are addressed elsewhere. In this section, the demands of SN are used to directly constrain or orient the rolling cadence development.

Pending more quantitative guidance, the SN objective for rolling cadence is to obtain multicolor time series significantly longer than the typical SN duration, with a cadence significantly faster than uniform. As an example we discuss the option of a rolling cadence with the regular distribution of filters.

As a simple example, consider improving the cadence by a factor of 2 or 3. Is we accept that some regions of the sky will be enhanced every year, and that uniform sky coverage will only arrive at the end of 10 years, then we could use, e.g., 10% of the total epochs in a single roll. If the enhancement is $2\times$, each roll would last for $\simeq 6$ months, with high efficiency for capture of complete SN events. If the enhancement is $4\times$, each roll would last for 2 months, with lower efficiency.

If it is important to achieve survey uniformity after 3 years, the available visits for each roll would be reduced also. With a $2\times$ enhancement of epoch frequency, a roll would last 2 months.

Some leverage would be gained by using more than 10% of the available visits for a single roll. However, this begins to impact the sampling of slow variables reduce schedule flexibility and robustness, and should be approached with caution.

From these examples, it appears that a $2\times$ enhancement with uniformity closure after 10 years is relatively feasible and promising. Much higher gains, or more rapid closure, require additional compromises.

5.6.4 Fast Transients and Rolling Cadence

Author Name(s)

Fast transients as a science topic are addressed elsewhere. In this section, the demands of fast transients are used to directly constrain or orient the rolling cadence development.

By "fast transients", we are referring to events that are sufficiently fast that they are not addressed by the rolling cadence designed for SN observations, and slow enough that they are not covered in "deep drilling" type mini-surveys. For higher tempo rolls, it is quite difficult to obtain full color data, because of the constraints on filter selection. For this example, we will examine a rolling cadence utilizing only the r and i filters, as they are used for most visits. They are close in wavelength, and we assume that sufficient color information will be obtained by the "background" uniform survey that continues during a roll.

Again using 10% of the available visits from the full 10 year survey for a single roll, we find that there would be enough epochs for each roll to acquire 1 visit per day for 21 consecutive days, giving an enhancement of $10\times$.

Alternatively, the same epochs could be used to observe a target every 20 minutes for 12 hours during a single night (here it is assumed that visit pairs are not required, doubling the available epochs) for an enhancement of $300\times$.

Several different possible redeployments of portions of a uniform survey have been described, each using 10% of available time. Of course it is possible in principal to implement multiple options, sequentially or maybe in parallel in some cases. This may pose considerable challenges to the scheduling strategy design by introducing incompatible boundary conditions.

While rolling cadences are powerful, they have limitations. For example, sampling events that last longer than $\simeq 1$ day and less than $\simeq 1$ week have the obvious problem of diurnal availability. In this example, intermediate cadences could be implemented in the circumpolar region, where diurnal access is much extended. This is an example of a case in which a mini-survey of a limited number of regions could be considered as an alternative to a rolling cadence applied to the entire main survey.

5.6.5 Constraints, Trades and Compromises for Rolling Cadences

While rolling cadences offer some attractive benefits, it is important to realize that rolling cadences are very highly constrained, and that they do bring disadvantages and compromises.

There are strong arguments against beginning a rolling cadence in the first, or even the second year of the survey. Early in the survey, it is important to obtain for each field/filter combination, an adequate number of good quality photometric images, and at least one image in excellent seeing, to support closure of photometry reductions and to support generation of template images.

Since major science goals require a significant degree of survey homogeneity, it may be advisable to implement a strategy that brings the survey to nominal uniform depth at several times, e.g. after 3 or 5 years. This would strongly constrain rolling cadences.

Some science objectives favor certain distributions of visits. For astrometry, visits early and late in the survey and at large parallax factors, are beneficial. Slow variables may benefit from uniform spacing. Rolling cadences might impact these constraints either favorably or unfavorably.

Many objectives are served by randomization of observing conditions for each field. Some rolling cadences could tend to reduce this randomization, for example by acquiring a large number of observations during a meteorologically favorable or unfavorable season, or during a period of instrument performance variance.

Dithering does not work gracefully with a rolling cadence, reducing temporal coverage at the boundaries of the selected sky region. This is negligible for small dithers, but important for large dithers, which are under consideration.

These cautions illustrate that evaluation of rolling cadences must be based on the full range of schedule performance metrics, and not just those targeted by rolling cadence development.

6 Keeping It Even: Accurate Cosmological Measurements on the Largest Scales

Eric Gawiser, Peter Kurczynski, Phil Marshall, Ohad Shemmer, Timo Anguita and others to follow

6.1 Introduction

Cosmology is one of the key science themes for which LSST was designed. Our goal is to measure cosmological parameters, such as the equation of state of dark energy, or departures from General Relativity, with sufficient accuracy to distinguish one model from another, and hence drive our theoretical understanding of how the universe works, as a whole. To do this will necessarily involve a variety of different measurements, that can act as cross-checks of each other, and break parameter degeneracies in any single one.

The Dark Energy Science Collaboration (DESC) has identified five different cosmological probes enabled by the LSST: weak lensing (WL), large scale structure (LSS), type Ia supernovae (SN), strong lensing (SL), and clusters of galaxies (CL). In all cases, the primary concern is residual systematic error: the shapes and photometric redshifts of galaxies, and the properties of supernova and lensed quasar light curves, will all need to be measured with extraordinary accuracy in order for LSST's high statistical power to be properly harnessed. This accuracy will come from the abundance and heterogeneity of the individual measurements made, and the degree to which they can be modeled and understood. This latter point implies a need for uniformity in the survey, which enables powerful simplifying assumptions to be made when calibrating on the largest, cosmologically most important scales. The need for heterogeneity also implies uniformity, in the sense that the nuisance parameters that describe the systematic effects need to be sampled over as wide a range as possible (examples include the need to sample a wide range of roll angles to minimize shape error, and observing conditions to understand photometric errors due to the changing atmosphere).

In this chapter we look at some of the key measurements planned by the Dark Energy Science Collaboration, and how they depend on the Observing Strategy.

6.2 Strong Gravitational Lens Time Delays

Phil Marshall

The multiple images of strongly lensed quasars and supernovae have delayed arrival times: variability in the first image will be observed in the second image some time later, as the photons take different paths around the deflector galaxy, and through different depths of gravitational potential. If the lens mass distribution can be modeled independently, using a combination of high resolution imaging of the distorted quasar/SN host galaxy and stellar dynamics in the lens galaxy, the measured time delays can be used to infer the "time delay distance" in the system. This distance enables a direct measurement of the Hubble constant, independent of the distance ladder.

6.2.1 Target measurements and discoveries

For this cosmological probe to be competitive with LSST's others, the time delays of several hundred systems (which will be distributed uniformly over the extragalactic sky) will need to be measured with bias below the sub-percent level, while the precision required is a few percent per lens. In galaxy-scale lenses, the kind that are most accurately modeled, these time delays are typically between several days and several weeks long, and so are measurable in monitoring campaigns having night-to-night cadence of between one and a few days, and seasons lasting several months or more.

To obtain accurate as well as precise lensed quasar time delays, several monitoring seasons are required. Lensed supernova time delays have not yet been measured, but their transient nature means that their time delay measurements may be more sensitive to cadence than season or campaign length.

6.2.2 Metrics

Anticipating that the time delay accuracy would depend on night-to-night cadence, season length, and campaign length, we carried out a large scale simulation and measurement program that coarsely sampled these schedule properties. In Liao et al. (2015), we simulated 5 different light curve datasets, each containing 1000 lenses, and presented them to the strong lensing community in a "Time Delay Challenge." These 5 challenge "rungs" differed by their schedule properties, in the ways shown in Table 6.1. Focusing on the best challenge submissions made by the community, we derived a simple power law model for the variation of each of the time delay accuracy, time delay precision, and useable sample fraction, with the schedule properties cadence, season length and campaign length. These models are shown in Figure 6.1, reproduced from Liao

Rung	Mean Cadence (days)	Cadence Dispersion (days)	Season (months)	Campaign (years)	Length (epochs)
0	3.0	1.0	8.0	5	400
1	3.0	1.0	4.0	10	400
2	3.0	0.0	4.0	5	200
3	3.0	1.0	4.0	5	200
4	6.0	1.0	4.0	10	200

Table 6.1: The observing parameters for the five rungs of the Time Delay Challenge. Reproduced from Liao et al. (2015).

et al. (2015), and are given by the following equations:

$$|A|_{\mathrm{model}} \approx 0.06\% \left(\frac{\mathrm{cad}}{3\mathrm{days}} \right)^{0.0} \left(\frac{\mathrm{sea}}{4\mathrm{months}} \right)^{-1.0} \left(\frac{\mathrm{camp}}{5\mathrm{years}} \right)^{-1.1}$$

$$P_{\mathrm{model}} \approx 4.0\% \left(\frac{\mathrm{cad}}{3\mathrm{days}} \right)^{0.7} \left(\frac{\mathrm{sea}}{4\mathrm{months}} \right)^{-0.3} \left(\frac{\mathrm{camp}}{5\mathrm{years}} \right)^{-0.6}$$

$$f_{\mathrm{model}} \approx 30\% \left(\frac{\mathrm{cad}}{3\mathrm{days}} \right)^{-0.4} \left(\frac{\mathrm{sea}}{4\mathrm{months}} \right)^{0.8} \left(\frac{\mathrm{camp}}{5\mathrm{years}} \right)^{-0.2}$$
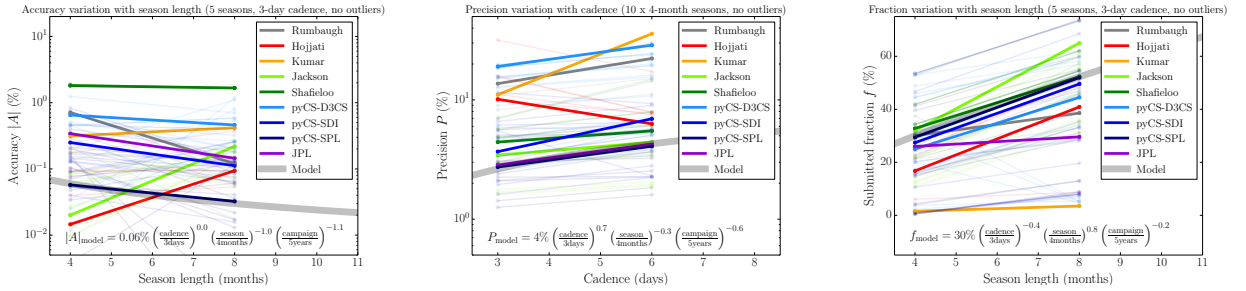

Figure 6.1: Examples of changes in accuracy A (left), precision P (center) and success fraction f (right) with schedule properties, as seen in the different TDC submissions. The gray approximate power law model was derived by visual inspection of the pyCS-SPL results; the signs of the indices were pre-determined according to our expectations. Reproduced from Liao et al. (2015).

All three of these metrics would, in an ideal world, be optimized: this could be achieved by decreasing the night-to-night cadence (to better sample the light curves), extending the observing season length (to maximize the chances of capturing a strong variation and its echo), and extending the campaign length (to increase the number of effective time delay measurements). A combined figure of merit should therefore be readily available. The quantity of greatest scientific interest is the accuracy in cosmological parameters: efforts to derive such a figure of merit in terms of the Hubble constant are underway.

6.2.3 OpSim Analysis

In this section we will present the results of our OpSim analysis, answering the question "how good would the current default observing strategy be for time delay lens cosmography?"

6.2.4 Discussion

Discussion: what risks have been identified? What suggestions could be made to improve this science project's figure of merit, and mitigate the identified risks?

6.3 AGN Science

Ohad Shemmer, Timo Anguita, Niel Brandt, Gordon Richards, Scott Anderson(?), Phil Marshall(?)

6.3.1 AGN Selection and Census

About $10^7 - 10^8$ AGNs will be selected in the main LSST survey using a combination of criteria, split broadly into four categories: colors, astrometry, variability, and multiwavelength matching with other surveys. The LSST observing strategy will affect mostly the first three of these categories.

Colors: The LSST observing strategy will determine the depth in each band, as a function of position on the sky, and will thus affect the color selection of AGNs. This will eventually determine the AGN $L - z$ distribution and, in particular, may affect the identification of quasars at $z \gtrsim 6$ if, for example, Y-band exposures will not be sufficiently deep.

Variability: AGNs can be effectively distinguished from (variable) stars, and from quiescent galaxies, by exhibiting certain characteristic variability patterns (e.g., Butler & Bloom (2011)). Non-uniform sampling may "contaminate" the variability signal of AGN candidates.

Astrometry: AGNs will be selected among sources having zero proper motion, within the uncertainties. The LSST cadence may affect the level of this uncertainty in each band, and may therefore affect the ability to identify (mostly fainter) AGNs. Differential chromatic refraction (DCR), making use of the astrometric offset a source with emission lines has with respect to a source with a featureless power-law spectrum, can help in the selection of AGNs and in confirming their photometric redshifts (Kaczmarczik et al. 2009). The DCR effect is more pronounced at higher airmasses. AGN selection and photometric redshift confirmation may be affected since the LSST cadence will affect the airmass distribution, in each band, for each AGN candidate.

6.3.2 AGN Clustering

Measurements of the spatial clustering of AGNs with respect to those of quiescent galaxies can provide clues as to how galaxies form inside their dark-matter halos and what causes the growth of their supermassive black holes (SMBHs). The impressive inventory of LSST AGNs will enable the clustering, and thus the host galaxy halo mass, to be determined over the widest range ranges of cosmic epoch and accretion power. The LSST cadence will not only affect the overall AGN census and its $L - z$ distribution, but also the depth in each band as a function of sky position that can directly affect the clustering signal.

6.3.3 AGNs and the Time Domain

AGN Variability: A variety of AGN variability studies will be enabled by LSST. These are intended to probe the physical properties of the unresolved inner regions of the central engine. Relations will be sought between variability amplitude and timescale vs. L, z, λ_{eff}, color, multiwavelength and spectroscopic properties, if available. The LSST sampling is expected to provide high-quality power spectral density functions for a large number of AGNs; these can be used to constrain the SMBH mass and accretion rate/mode. Furthermore, LSST AGNs exhibiting excess variability over that expected from their luminosities will be further scrutinized as candidates for lensed systems having unresolved images with the excess (extrinsic) variability being attributed mainly to microlensing.

Photometric reverberation mapping (PRM), measuring the time-delayed response of either the flux of the broad emission line region (BELR) lines to the flux of the AGN continuum or between the continuum flux in one (longer wavelength) band to the continuum flux in another (band with shorter wavelength), will be one of the cornerstones of AGN research in the LSST era (e.g., Chelouche (2013); Chelouche & Zucker (2013); Chelouche et al. (2014)). For example, LSST is expected to deliver BELR line-continuum time delays in $\sim 10^5 - 10^6$ sources, which is unprecedented when compared to $\sim 50 - 100$ such measurements conducted via the traditional, yet much more expensive (per source) spectroscopic method. Sources in the deep-drilling fields (DDFs) will benefit from the highest quality PRM time-delay measurements given the factor of ~ 10 denser sampling. The PRM measurements will probe the size and structure of the accretion disk and BELR, in a statistical sense, and may provide improved SMBH mass estimates for sources that have at least single-epoch spectra.

The PRM method is very sensitive to the sampling in each band, therefore the ability to derive reliable time delays can be affected significantly by the LSST cadence. The best results will be obtained by having the most uniform sampling equally for each band. Additionally, there is a trade-off between the number of DDFs and the number of time delays that PRM can obtain (Chelouche et al. 2014). For example, an increase in the number of DDFs, with similarly dense sampling in each field, can yield a proportionately larger number of high-quality time delays, down to lower luminosities, but at the expense of far fewer time delays (of relatively high luminosity sources) in the main survey.

Time Delays in Gravitationally Lensed Quasars: This aspect is discussed in detail in the lens time delays section (§ 6.2).

AGN Size and Structure with Microlensing: Microlensing due to stars projected on top of individual lensed quasar images produce additional magnification. Using the fact that the Einstein radii of stars in lensing galaxies closely match the scales of different emission regions in high-redshift AGNs (micro-arcseconds), analyzing microlensing induced flux variations statistically on individual systems allows us to measure "sizes" of AGN regions. Assuming a thermal profile for accretion disks, sizes in different emission wavelengths will be probed and as such, constraints on the slope of this thermal profile. Given the sheer number of lensed systems that LSST is expected to discover (~ 8000), this will allow us to stack systems for better constraints and hopefully determine the evolution of the size and profile. Due to the typical

relative velocities of lenses, microlenses, observers (Earth) and source AGN, the microlensing variation timescales are between months to a few decades.

The quasar microlensing optical depth is ~ 1, so every lensed quasar should be affected by microlensing at any given point in time. However, measurable variability can occur on longer timescales. Mosquera & Kochanek (2011) did a study using all known lensed quasars. They found the median timescale between high magnification events (Einstein crossing time scales) in the observed *I*-band is of the order of ~ 20 yr (with a distribution between 10 and 40 yr). However, the source crossing time (duration of a high magnification event) is ~ 7.3 months (with a distribution tail up to 3 yr). This basically means that out of all the lensed quasar *images* (microlensing between images is completely uncorrelated) about half of them will be quiescent during the 10 yr baseline of LSST. However, since the typical number of lensed images is either two or four, it means that, statistically, in every system, one (for doubles) or two (for quads) high magnification events should be observed in 10 yr of LSST monitoring.

Note that, the important cadence parameter is the source crossing time, as it is the length of the event to be as uniformly sampled as possible. The 7.3 months crossing time is the median for the observed *i*-band, but this time would be significantly shorter for bluer bands: for a thermal profile with slope $\alpha : R_\lambda \propto \lambda^\alpha$ implies source crossing time $t_s \propto \lambda^{1/\alpha} \to t_u = t_i \times (\lambda_u/\lambda_i)^{1/\alpha}$. For a Shakura-Sunyaev slope of $\alpha = 0.75$ this would correspond to $7.3 \times (3600/8140)^{4/3}$ months ≈ 2.5 months in the *u*-band.

In terms of the cadence, at least three evenly sampled data points per band within 2 to 3 months would be preferred to be able to map the constraining high magnification event(?). Hopefully uniformly spaced. Very tight cadence (e.g., DDFs) would increase the constraints significantly. However, since lensed quasars are not that common, this smaller area would mean only a few (~ 80?) suitable systems monitored in the DDFs. Regarding the season length, the "months" timescale of high magnification events very likely means that we can/will miss high magnification events in the season gaps, at least in the bluer bands. Killer: observations spread on timescales larger than 3 months(??). This would likely miss the high magnification events. In those cases we could perhaps consider close consecutive photometric bands as equivalent accretion disk regions, however this would mean weaker constraints on the thermal profile. Important Note: all this science needs to be done on lensed quasars with measured or very short time delays to remove the intrinsic variability signal, which might significantly reduce the sample.

Microlensing Aided Reverberation Mapping: Given that microlensing mostly affects continuum emission rather than BELR line emission, microlensing may enable disentangling the BELR line + continuum emission in single photometric bands, allowing the use of single broad band PRM measurements (Sluse & Tewes 2014). As with the two-band PRM method discussed above, the denser (and the longer) the sampling, the more accurate are the constraints that can be obtained for the time delays.

Transient AGN and TDEs: This aspect is discussed in detail in the non-periodic variables section (§ 5.3).

6.3.4 Metrics

6.3.5 Discussion

6.4 Supernova Cosmology and Astrophysics

Jeonghee Rho, Michelle Lochner, Rahul Biswas

This section is concerned with the detection and characterization over time of supernovae using the Large Synoptic Sky Telescope (LSST). Supernovae of various types are visible over a time scale of about a few weeks (eg. Type Ia) to a close to a year (Type IIP). During the full ten year survey of LSST, the telescope will scan the entire Southern Sky repeatedly with a universal Wide Fast Deep Candence, and certain specific locations of the sky (the Deep Drilling fields) with special enhanced cadence. This spatio-temporal window should contain millions (RB: remember to check) of supernovae, that should be detected with the limiting magnitude of LSST. However, the actual sequence of observations in LSST defined by series of field pointings as a function of time in filter bands (along with weather conditions) will determine the extent to which each of such supernovae can be characterized well. Characterization of these supernovae is at the core of a number of science programs that use supernovae as bright, abundant objects with empirically determined intrinsic brightness.

The most important of these is the use of SNIa (and potentially core-collapse supernovae like Type IIP) as standardizable candles to measure the distance-redshift relation at cosmological distances to confront models leading to late time acceleration. For LSST, this goal entails (a) photometric typing of supernovae, (b) estimating photometric redshifts of supernovae (or identifying host galaxies, and obtaining their redshifts from photometry or follow-up spectroscopy) (c) estimation of intrinsic brightnesses of the supernovae. The efficacy of Photometric typing, redshifts and estimation of intrinsic brightnesses are all dependent on the amount of information available in the observed light curves of supernovae. It should be noted that goal of using supernovae to constrain the cosmology of a statistically homogeneous and isotropic universe is independent of the spatial extent of the locations of the supernovae, and therefore a target precision in terms of constraining cosmology can be met by using a high cadence sampling in a relatively small subset of the LSST sky. However, there are other science cases using such supernovae as tracers of position, redshift and distance simultaneously to probe quantities like the distribution of peculiar velocities, or to test whether the universe is statistically isotropic at redshifts $z \lesssim 1.5$. Such projects which use supernovae as a tracer of large scale structure with a good measure of "distance" require large spatial extents, that could only be provided by the LSST WFD.

Photometric supernova classification

In the past, only spectroscopically typed supernovae have been used for cosmology. Photometric typing from the light curve alone has only been used to select candidates for spectroscopic follow-up (see for example Sako et al. (2008)). However, LSST will simply produce far too many candidates for any chance of following up even a significant fraction of them. In order to avoid throwing away the majority of the supernova dataset, we need to use techniques capable of determining cosmological parameters from a potentially contaminated photometric supernova dataset.

There have been several techniques proposed in recent literature to solve this problem. One approach proposes applying stringent cuts to the photometric dataset to obtain a nearly pure sample of type Ia supernovae (Bernstein et al. 2012; Campbell et al. 2013) and to run the

standard supernova analysis with this sample. Another approach, BEAMS (Kunz et al. 2007; Newling et al. 2011; Hlozek et al. 2012; Knights et al. 2013), makes use of the full dataset, coping with contamination by using a mixture model for the likelihood, thus allowing for multiple populations. Whatever the technique ultimately used to for cosmological analysis, it will rely on accurate initial classifications of supernova type and unbiased estimates for the probability of each type.

The current state-of-the-art photometric classification techniques rely on fitting empirically determined templates of supernovae to light curves (Jha et al. 2007; Guy et al. 2007; Sako et al. 2011). However in recent years, new approaches have been published in response to the 2010 'Supernova Photometric Classification Challenge' (Kessler et al. 2010b). Many of these use novel light curve parameterisation and employ machine learning algorithms to perform the classification (see Kessler et al. (2010a) and references therein).

While many of these methods have been tested on standard sets of simulated data and (in some cases) on SDSS data, it is still not clear which technique (if any) is superior in all situations. For example, some techniques rely heavily on reliable redshift information being available, while others are less reliant on it. Some techniques may be more robust to non-representative datasets than others and it is not clear how the techniques will respond to changes in cadence, filter sets, SNR etc. With this in mind, we propose the use of a multifaceted classification system which employs several different methods of extracting features from the light curves (e.g. fitting parametric functions or templates) and several different classification algorithms. This system is highly modular, allowing the easy addition of new approaches for direct comparison with existing techniques. This also allows direct analysis of different observing strategies, without having to make an initial choice of classification technique.

6.4.1 Target measurements and discoveries

6.4.2 Metrics

Quantifying the response via MAF metrics: definition of the metrics, and any derived overall figure of merit.

To be added: discussion of the ROC curve as a useful metric for photometric supernova classification

6.4.3 OpSim Analysis

OpSim analysis: how good would the default observing strategy be, at the time of writing for this science project?

6.4.4 Discussion

Discussion: what risks have been identified? What suggestions could be made to improve this science project's figure of merit, and mitigate the identified risks?

7 Drilling Deep: Options for a Small Number of Enhanced Observation Fields

Niel Brandt, Lynn Jones

7.1 Introduction

8 Special Surveys

Knut Olsen, David Nidever

8.1 Introduction

Includes: science programs not served effectively by the main wide-fast-deep program; additional sky regions; special cadences; candidate commissioning surveys

9 Tensions and Trade-offs

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Discussion and conclusions chapter, at the end, highlighting the issues that we will need to figure out. Possible topics include the cost/benefit tradeoffs between competing objectives

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