

Science Driven Optimization of the LSST Observing Strategy

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

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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 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 a corresponding simulated visit sequence, with which it can be demonstrated that the data required for the promised science can be delivered.
- However, the baseline strategy is not set in stone, and can and will be optimized. Even small changes could result in significant improvements to the overall science yield.
- These improvements can be predicted via analysis of the outputs of the LSST Operations Simulator, OPsim, using the Metric Analysis Framework (MAF). Once the baseline visit sequence has been evaluated with a given science case's metrics, all other proposed visit sequences can be compared against it, automatically.
- The LSST observing strategy evaluation and optimization process will be as open and inclusive as possible. We invite all stakeholders to participate.

Project start: July 2015.

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.

0.0.1 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](#).

0.0.2 Chapter and Section Design

For a high-level justification of the following design, please see [Section 1.3](#). In short, we’re aiming for modular sections (that are easy to write in parallel, and then re-arrange within chapters later) focused on one science project each, and quantified by one (or maybe two) figures of merit (which will likely depend on other, lower-level metrics). Each section can be thought of as an observing proposal, demonstrating the performance achievable given various assumptions about the time awarded.¹⁸

The first section of each science chapter needs to be an *introduction* that outlines, very briefly, the commonality of the key science projects 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 then 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

¹⁸These notes on the white paper design are adapted from the notes at [whitepaper/notes/chapter-template.md](#)

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 chapter shows a template introduction and science case section for you to work from. The latter is checked into the repository as `section-template.tex`. For an example of a section being developed according to the above guidelines, please take a look at [Section 7.3](#).

0 Template Science Chapter

Editor Name(s)

0.1 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.

0.2 Example Science Project Section

Author Name(s)

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

0.2.1 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?

0.2.2 Metrics

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

0.2.3 OpSim Analysis

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

0.2.4 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?

Go to: • [the start of this section](#) • [the start of the chapter](#) • [the table of contents](#)

1 Introduction

Phil Marshall, Zeljko Ivezic, Beth Willman, ...

The Large Synoptic Survey Telescope (LSST) is a dedicated optical telescope with an effective aperture of 6.7 meters, currently under construction on Cerro Pachón in the Chilean Andes. The telescope and camera will have a huge field of view, 9.6 deg^2 , and the étendue, i.e., the product of collecting area and field of view will be significantly larger than any other telescope. Thus this telescope is designed for wide-field deep imaging of the sky; its mantra is “Wide-Deep-Fast”, i.e., the ability to cover large swaths of sky (“Wide”) to faint magnitudes (“Deep”) in a short amount of time (“Fast”), allowing to scan the sky repeatedly.

The science case for the LSST is based broadly on four science themes:

- Dark energy and dark matter (via strong and weak lensing, large-scale structure, and supernovae);
- Exploring the transient and variable universe;
- Studying the structure of the Milky Way galaxy and its neighbors via resolved stellar populations;
- An inventory of the Solar System, including Near-Earth Asteroids and Potential Hazardous Objects, Main-Belt Asteroids, and Kuiper-Belt Objects.

These themes, together with *many* other science applications, are described in detail in the [LSST Science Book](#), produced by the LSST Project Team and Science collaborations in 2009. The present white paper represents an important next step in science planning beyond the Science Book. In particular, we now need to quantify how well the LSST (for a given realization of its cadence) will be able to carry out its science goals; indeed, we will use this quantification to refine and optimize the cadence itself.

The Science Book is six years old. In those six years, some of the science themes described in there have evolved or become obsolete, while new science opportunities and ideas have arisen. Moreover, our understanding of the capabilities (such as system response and therefore depth, telescope optics, and so on) have matured considerably. The present document endeavors to explore the principal science themes as described in the Science Book, but is not slaved to them, and where appropriate, we will point out relevant updates to the Science Book.

1.1 Synoptic Sky Surveying at Universal Cadence

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](#)).

1.2 Beyond the Baseline Observing Strategy

Optimizing the Observing Strategy: what perturbations are we permitted to introduce, to maximize the system’s science capabilities? What are our constraints? And our opportunities?

1.3 Evaluation and Optimization of the LSST Observing Strategy

The first step towards a science-based optimization of the LSST observing strategy is a *science-based evaluation of the baseline LSST observing strategy*. After simulating a sample observing schedule consistent with this strategy (see [Chapter 2](#)), we then need to quantify its value 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 in this way, 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. Templates for the chapters and sections can be found in [Chapter 0](#).

1.4 Outline of This Paper

The rest of this white paper is structured as follows. In [Chapter 2](#) we describe a number of OPSIM simulated observing schedules (“cadences”) explored by the LSST Sims team in summer 2015 in preparation for this paper: they include a “baseline cadence”, and then some small but interesting perturbations to it. Then, we present the science cases considered so far, organised into the following chapters:

- [Chapter 3: Solar System](#)
- [Chapter 4: The Galaxy](#)
- [Chapter 5: Mapping Our Galaxy: Positions, Proper Motions and Parallax](#)
- [Chapter 6: Variables and Transients](#)
- [Chapter 7: Cosmology](#)
- [Chapter 8: Deep Drilling Fields](#)
- [Chapter 9: Special Surveys](#)

Finally, in [Chapter 10](#) we bring the results of all the science metric analyses together and discuss the tensions between them, and the trade-offs that we can anticipate having to make.

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2 Some Example Observing Strategies

Željko Ivezić and the LSST Simulations Team, LSST Project Science Team, and Others

Summary: In this chapter (which was originally prepared as the standalone report available from <http://www.astro.washington.edu/users/ivezic/lsst/cadexp2.pdf>) we analyze and compare the performance of a number of simulated LSST observing strategies (“cadences”) which were developed in support of the LSST 2015 Observing Strategy Workshop. A candidate new Baseline Cadence, [enigma_1189](#), was found adequate and is proposed as a replacement for the previous Baseline Cadence ([opsim3.61](#)). Simulations that only implemented Universal Cadence proposal imply a margin of about 40% relative to the design specifications for the main survey sky coverage and the number of visits per field from the Science Requirements Document. This margin can be used to increase the sky coverage of the main survey, the total number of visits per field, or to implement special programs, such as deep drilling fields and Galactic plane coverage. Several simulations analyzed here quantitatively explore these strategic options. Additional simulations show that the effects of variations of the visit exposure time in the range 20-60 seconds on surveying efficiency can be predicted using simple efficiency estimates. Various modifications of baseline cadence (e.g. Pan-STARRS-like cadence, no visit pairs, sequences with 3 and 4 visits) indicate a large parameter space for further optimization, especially for time-domain investigations and detailed coverage of special sky regions.

2.1 Introduction

With the release of the latest version of Operations Simulations (hereafter OPSIM) code (version 3.2.1) for simulating LSST deployment, and the active development of Metrics Analysis Framework (MAF, currently version 0.2) for analyzing OPSIM outputs, we can now begin to undertake systematic and massive investigations of various LSST deployment strategies.

The optimization of the ultimate LSST observing strategy will be done with significant input from the community. To facilitate this process, the first of a series of meetings, named “LSST & NOAO Observing Cadences Workshop”, was held during the [LSST 2014 meeting](#) in Phoenix, AZ, August 11-15, 2014. The next workshop, named “LSST Observing Strategy Workshop”, will be held [after the LSST 2015 meeting](#) in Bremerton, WA, August 20-22, 2015.

In part as a preparation for this upcoming workshop, the LSST Simulations Team and the Project Science Team have designed, executed and analyzed a number of simulated surveys. The cadence strategies for these surveys, while similar to Baseline Cadence, are modified to study the impact of various strategy variations on the scientific potential of LSST. The cadence set also includes a candidate baseline cadence replacement.

An initial analysis of these simulated surveys is presented here. [MAF](#) reports for all simulated cadences are available from

<http://tusken.astro.washington.edu:8080/?runId=2>

OPSIM databases investigated in this section:

enigma_1189 — the new Baseline Cadence.	18
ops2_1098 — Only Universal Cadence, with pairs of visits.	25
ops2_1092 — A Pan-STARRS-like observing strategy.	26
ops2_1093 — Only Universal Cadence, no visit pairs.	27
kraken_1032 — Baseline Cadence, but with no visit pairs.	29
ops1_1163 — Baseline Cadence, but with 33% shorter exposure time.	29
ops1_1164 — Baseline Cadence, but 100% longer exposure time.	30
ops1_1162 — Baseline Cadence, but with doubled u-band exposure time.	31
ops1_1161 — Baseline Cadence, but with doubled u-band exp. time and Baseline NE Spur.	32
ops2_1096 — Only Universal Cadence, with relaxed airmass limit.	32
ops2_1097 — Only Universal Cadence, with stringent airmass limit.	33
ops2_1094 — NEO test: no request for pairs of visits.	34
enigma_1257 — NEO test: pairs of visits (as in the Baseline Cadence).	34
enigma_1258 — NEO test: triplets of visits.	34
enigma_1259 — NEO test: quads of visits.	34

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2.2 The Baseline Observing Strategy

The current “official” (managed by the LSST Change Control Board) Baseline Cadence, `opsim3.61`, was produced with an old version of OPSIM code. We first introduce a candidate replacement simulation that was produced using the latest version (v3.2.1) of OPSIM code, and then proceed with the analysis of other simulations that modify observing strategy in various informative ways. Suggestions for further tool development, and a summary of the main cadence questions addressed here are available at end of this document.

[enigma_1189](#)

the new Baseline Cadence.

The candidate replacement “Baseline Cadence” candidate, [enigma_1189](#), has the following basic properties¹:

¹See <http://tusken.astro.washington.edu:8080/summaryStats?runId=1>

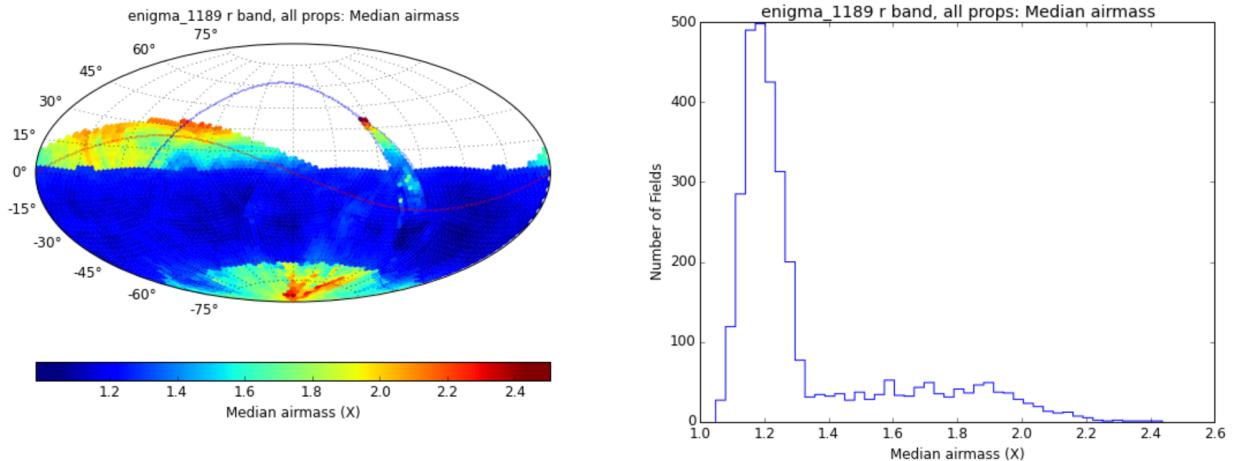


Figure 2.1: The median airmass in the r band across the sky for simulated cadence [enigma_1189](#) is shown in Aitoff projection of equatorial coordinates in the left panel. The corresponding histogram is shown in the right panel. For the main survey area, the maximum allowed airmass was set to 1.5.

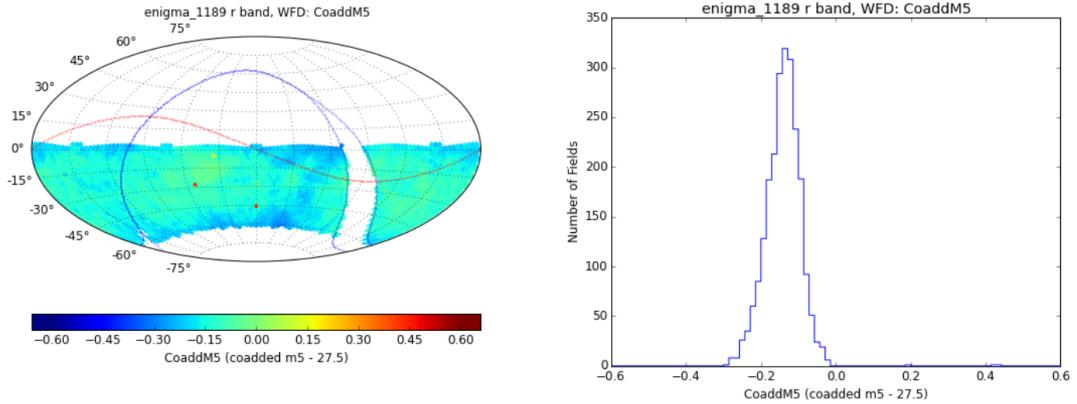
1. The total number of visits is 2,469,307, with 85.4% spent on the Universal proposal (the main deep-wide-fast survey), 6.4% on the North Ecliptic proposal, 1.7% on the Galactic plane proposal, 2.1% on the South Celestial pole proposal, and 4.5% on the Deep Drilling cosmology proposal.
2. The median number of visits *per night* is 815, the range is 35 to 1104, with 3062 observing nights. The mean slew time is 6.9 seconds (median: 4.8 sec) and the total open shutter time is 4.06 Msec. The median total open shutter time (per night) as a fraction of the observing time (the ratio of the open shutter time and the sum of the open shutter time, readout time and slew time) is 73%. The 25%-75% quartiles for the number of filter changes per night are 2 and 7, with the mean of 4.6. The total number of filter changes is 15,364.
3. In the r band, the median seeing is 0.77 arcsec, the median airmass is 1.23, and the median 5σ depth for point sources is 24.5. The variation of the median airmass for the r band observations with the position on the sky is shown in [Figure 2.1](#).
4. For the 2,293 fields (somewhat overlapping) from the Universal Cadence area (also known as WFD – wide, fast, deep), the median number of visits in the $ugrizy$ bands is (63, 89, 202, 202, 182, 181), respectively. Not only that these medians exceed the requested number of visits (design specification from the SRD²) of (56, 80, 184, 184, 160, 160) in the $ugrizy$ bands, but the minimum number of visits per field over this area does so, too. This result is quite encouraging given that only 85% of observing time was spent on the Universal Cadence proposal. The mean number of visits over the Universal Cadence area, summed over all bands, is 920.
5. The coadded 5σ depth³ for point sources in the $ugrizy$ bands is (26.1, 27.3, 27.4, 26.7, 25.4,

²The LSST Science Requirements Document (SRD) is available as <http://ls.st/lpm-17>

³Note that these values depend on externally supplied values for fiducial single-epoch 5σ depths; the following values were used in analysis described here: (24.45, 25.17, 24.67, 24.27, 23.57, 22.36) in the $ugrizy$ bands, respectively. These values are progressively deeper towards the blue bands and shallower towards the red bands, compared to the values listed in Table 2 from the latest version (v3.1) of the LSST overview paper: (23.68, 24.89, 24.43, 24.00,

:

CoaddM5 OpsimFieldSlicer r band, WFD npz JSON



Coadded depth in filter r, with design value subtracted (27.5), for all WFD proposals. More positive numbers indicate fainter limiting magnitudes.

<i>Median:</i>	27.39
<i>Mean:</i>	27.39
<i>Rms:</i>	0.05
<i>N(-3Sigma):</i>	2.00
<i>N(+3Sigma):</i>	3.00
<i>Count:</i>	2293
<i>25th%ile:</i>	27.36
<i>75th%ile:</i>	27.42
<i>Min:</i>	27.24
<i>Max:</i>	27.97

Figure 2.2: A screen grab from web-based MAF analysis of simulated cadence [enigma_1189](#). The coadded 5σ depth for point sources in the *r* band across the main survey area (WFD=“wide-fast-deep”) is shown in the top left corner, in Aitoff projection of equatorial coordinates. The red line shows the Ecliptic and the blue line shows the Galactic equator (it bifurcates around the so-called “Galactic confusion zone”). The distribution of the limiting depth across this area is shown as a histogram in the top right corner. The basic statistics for this distribution are listed in the bottom left.

24.4), respectively. The distribution of coadded depth across the sky is fairly uniform; for an example see [Figure 2.2](#).

6. For the 2,293 fields from the Universal Cadence area, the median seeing is 0.75 arcsec in the *r* band and 0.74 arcsec in the *i* band. The median airmass in the *urz* bands is 1.25, 1.20 and 1.26 (the maximum allowed airmass for the Universal Cadence area was set to 1.5). The median sky brightness in the *ury* bands is 22.0 mag/arcsec², 21.1 mag/arcsec², and 17.3 mag/arcsec², respectively.
7. Restricted to the Universal Cadence fields, a unique area of 18,000 sq.deg. received at least 898 visits (summed over bands; the SRD design value is 825).

23.45, 22.60). This discrepancy is due to the Project software evolution falling behind continuing improvements in the system performance estimates and will be rectified by introducing automated version control system across the Project.

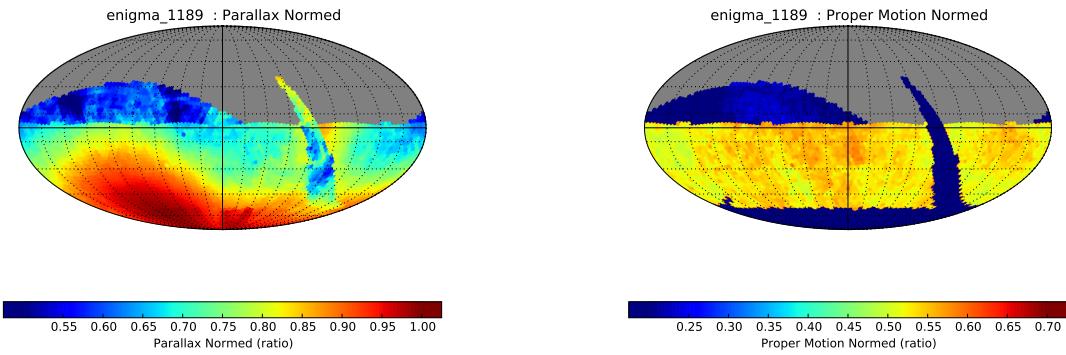


Figure 2.3: The trigonometric parallax errors (left) and proper motion errors (right), normalized by the values for idealized perfectly optimized cadences (parallax: all the observations are taken at maximum parallax factor, resulting in a peak at the South Ecliptic pole; proper motion: a half of all visits are obtained on the first day and the rest on the last day of the survey), obtained for simulated cadence `enigma_1189` are shown in Aitoff projection of equatorial coordinates.

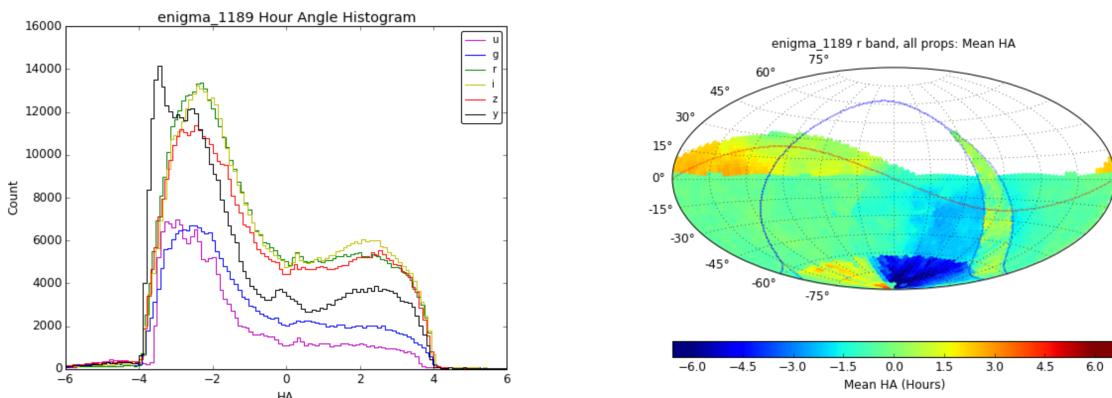


Figure 2.4: Histograms in the left panel show the distribution of hour angles (HA) in 6 bands for all proposals from simulated cadence `enigma_1189` (the distributions are similar for WFD fields considered alone). Note the bias towards observations west from the meridian. The right panel shows the distribution across the sky of the mean HA for all observations in the *r* band.

8. The median trigonometric parallax and proper motion errors are 0.57 mas and 0.16 mas/yr, respectively, for bright sources (limited by assumed systematic errors in relative astrometry of 10 mas), and 5.5 mas and 1.6 mas/yr for points sources with $r = 24$ (assuming flat spectral energy distribution), over the Universal Cadence fields. The variation of parallax and proper motion errors across the sky is visualized in Figure 2.3.

For comparison, the current Baseline Cadence, `opsim3.61` (obtained with old OpSim code), delivered 2,651,588 visits, or 7.4% more than `enigma_1189` (this is due to known effects and changes in the code, such as more pre-scheduled down time in the new version). Perhaps the most important (and undesired!) difference between the two simulations is that the new candidate Baseline Cadence spent 6.4% of the observing time on North Ecliptic Spur proposal (vs. 4% spent on corresponding Universal North proposal in `opsim3.61`), and less than 90% of time on the Universal proposal (the main wide-deep-fast survey).

Analysis of the hour angle distribution, shown in Figure 2.4 and Figure 2.5, reveals a strong bias

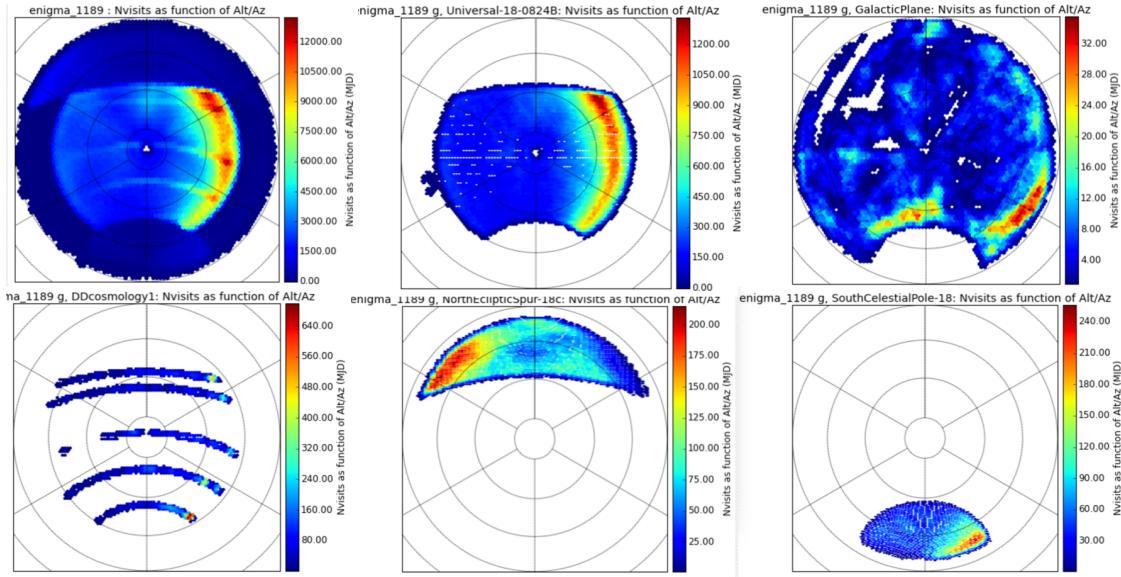


Figure 2.5: The color-coded map in the top left panel shows the g band visit count from Baseline Cadence simulation [enigma_1189](#) in the equal-area Lambert projection of the horizontal coordinate system (altitude-azimuth), with north on top and west towards the right. The horizon corresponds to the largest circle. Five implemented proposals are shown separately in other panels (top row: Universal and Galactic Plane, bottom row: Deep Drilling fields, North Ecliptic Spur, and South Celestial Pole region). The Universal cadence was limited to airmass below 1.5, while other proposals sampled higher airmass, too (see the histogram in [Figure 2.1](#)). Note the strong propensity of Universal fields for westward observations (the median airmass is about 1.2).

towards observations west from the meridian for the main survey. *This pattern is not fully understood at this time* and may be caused by specific features of the cost function implemented in the OpSim code.

Another potentially undesirable feature, seen in practically all simulations analyzed here, is that up to about a quarter of visits in the main survey area represents the third, the fourth and sometimes even the fifth visit to a field in the same night. For a large number of time-domain programs, these visits could be used instead to decrease the field inter-night revisit time. For

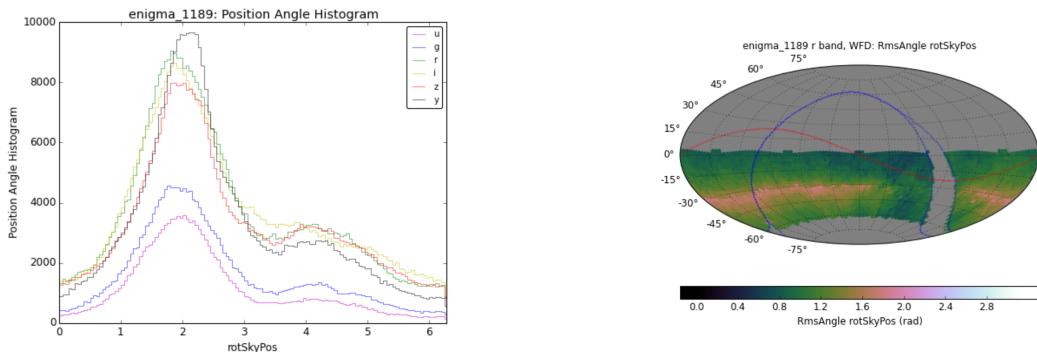


Figure 2.6: The left panel shows the position angle distribution (in radians) in each band for the main survey fields in [enigma_1189](#). The position angle is the angle between “up” in the image and North on the sky. The variation of the root-mean-square scatter of the r band distribution across the sky is shown in the right panel.

2.2 The Baseline Observing Strategy



Figure 2.7: The median inter-night gap (or revisit time) is shown in Aitoff projection for all proposals and all filters for candidate Baseline Cadence [enigma_1189](#). On average, fields in the main survey get revisited about every 3 days.



Figure 2.8: The median inter-night gap for r band visits is shown in Aitoff projection for all proposals and all filters for candidate Baseline Cadence [enigma_1189](#). On average, fields in the main survey get revisited in the r band about every 15 days.

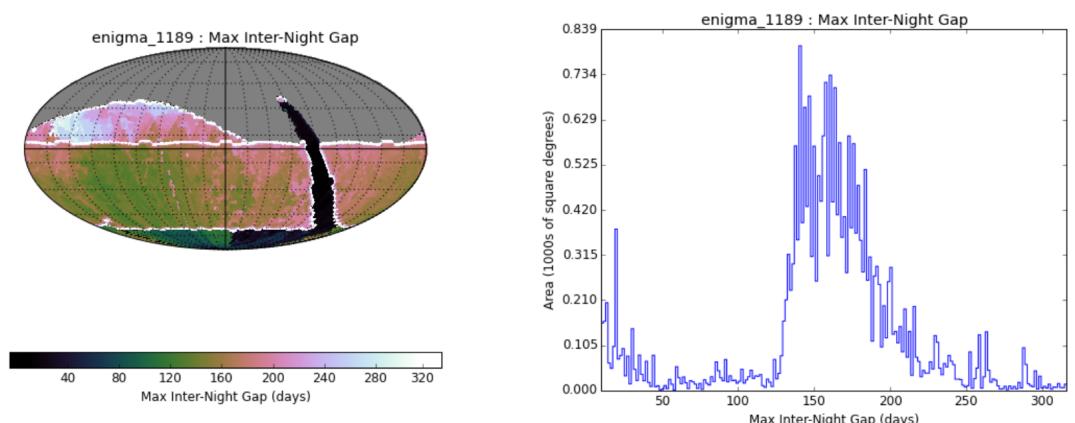


Figure 2.9: The maximum inter-night gap (or revisit time) is shown in Aitoff projection for all proposals and all filters for candidate Baseline Cadence [enigma_1189](#).



Figure 2.10: The fraction of simulated Type Ia SNe at a redshift of 0.5 detected pre-peak in any filter for candidate Baseline Cadence [enigma_1189](#). About 40% of all such SNe from the main survey will be detected before their maximum brightness.

more details, see [Section 2.4](#). The position angle distributions for this simulation are shown in [Figure 2.6](#).

Time-domain metrics

The analysis of metrics designed for time-domain science has not been performed yet in detail, except for the analysis of asteroid completeness discussed in [Section 2.4](#). MAF already includes several sophisticated metrics, e.g., period recovery for variable stars, which will be described in a later version of this report.

As a brief illustration of time-domain analysis, [Figure 2.7](#) shows the median revisit time distribution when all bands are considered, and [Figure 2.8](#) shows the median revisit time distribution in the band. On average, fields in the main survey get revisited about every 3 days using all filters, and every 15 days when using only r band visits (30 days when using only u band visits is the longest median revisit time). [Figure 2.9](#) shows the maximum inter-night gap, which on average is about 5-6 months.

The temporal sampling for this simulation is sufficient to enable a large recovery fraction for SNe. [Figure 2.10](#) shows that a large fraction of LSST SNe will be detected before their maximum brightness. Similar MAF metrics that explore various quality cuts on SNe light curves (e.g. “detected at least 6 times, at least 3 pre-peak, at least 3 post-peak, with observations in at least 3 filters”).

Intra-night revisit time distribution is discussed in more detail in §[2.4](#).

Special Proposals

Regarding the special proposals, here we only provide the basic performance parameters. With the exception of the Deep Drilling proposal, these proposals are essentially strawman placeholders. The North Ecliptic proposal (6.4% of the observing time) obtained an additional 300 visits per field, summed over *griz* bands. These fields are placed along the northern part of

the Ecliptic. The Galactic plane proposal (1.7%) obtained 30 visits per band in all six bands, across the region extending in Galactic latitude 10 degrees from the Galactic center, with the boundary approaching the Galactic equator linearly with longitude, and the zone ending at $l = 90$ deg. and at $l = 270$ deg. The South Celestial pole proposal (2.1%) obtained 30 visits per band in all six bands, for fields centers with Dec < -62.5 deg. The Deep Drilling cosmology proposal (4.5%) included 5 fields, with each obtaining several thousand visits per band. The coadded 5σ depths for these fields are much fainter than for the main survey: the medians values are (28.5, 28.6, 28.8, 28.2, 27.7, 26.0) in the *ugrizy* bands, respectively.

Conclusions:

The candidate Baseline Cadence, [enigma_1189](#), appears to be an adequate replacement for the current baseline cadence ([opsim3.61](#)). Based on this preliminary analysis, there are no major problems with its performance. While there are patterns which are not fully understood (most notably the observing bias towards west), or undesired (unnecessary revisits of the same field in the same night), [enigma_1189](#) is used as a benchmark cadence, and referred to as “Baseline Cadence”, in the rest of this document⁴

An important feature of [enigma_1189](#) simulation is that the mean slew time of 6.9 sec is very close to the minimum possible slew time of about 4.5 sec. The implication is that the surveying efficiency, assuming 30 sec exposure time per visit, can be increased by at most about 6% (that is, the total open-shutter time is within about 6% from its possible maximum, given everything else unchanged). Nevertheless, there are other survey aspects, including sky coverage and temporal sampling functions, that can be further optimized, as discussed in ??.

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2.3 Some Simulated Alternative Observing Strategies

We now describe some alternatives to the Baseline Cadence that were explored. These OPSIM databases are all available for further testing with science-based MAF metrics.

ops2_1098

Only Universal Cadence, with pairs of visits.

Motivation and description: Formally, ~90% of observing time is allocated to the main Universal Cadence program (WFD). The remaining observing time is allocated to other programs, such as “Deep Drilling” programs (see Section 3.4 and Tables 22-26 in the SRD). With this simulation, we wished to find out what would be the effect of ignoring special programs and spending all of the observing time on the main Universal Cadence program.

⁴ Assuming that additional analysis will not uncover any major deficiencies, this simulation will be discussed by the Project Science Team and proposed for adoption as the new Baseline Cadence to the Change Control Board. The target date for this proposal is late September 2015.

Expectations: About 2.11 million visits (85% of 2.47 million visits) from Baseline Cadence ([enigma_1189](#)) were allocated to WFD cadence. Here we expect that all of these 2.47 million visits will be allocated to WFD cadence.

Analysis Results: This simulated cadence is named [ops2_1098](#). Compared to the Baseline Cadence [enigma_1189](#):

1. The total number of visits is close to the expected value: 2.45 million. The minimum number of visits per field for the 2,293 WFD fields in Baseline Cadence is 968 for this simulation, compared to 898 for Baseline Cadence.
2. The median number of visits per night and the mean slew time are essentially the same as for Baseline Cadence (810 vs. 815 and 7.2 sec vs. 6.9 sec).
3. The median seeing, sky brightness and airmass in the r and i bands are essentially the same as for WFD fields in Baseline Cadence.
4. The median trigonometric parallax and proper motion errors are improved by about 8%, with improvements commensurate with the increase in the number of visits.
5. This simulation also shows observing bias towards west (that is, additional special programs in [enigma_1189](#) are not responsible for this bias).

Conclusions: [ops2_1098](#), using only uniform cadence proposal, delivered 99.2% of the number of visits obtained by Baseline Cadence. Therefore, *the “filler” aspect of other proposals does not have a major impact on the surveying efficiency*. The minimum number of visits per field for the 2,293 WFD fields in Baseline Cadence is 968 (the SRD design value is 825 and the stretch goal value is 1000). Although the sky coverage of these 2293 fields is about 18,000 sq.deg., their cumulative area is 22,000 sq.deg. With proper dithering, the effective number of visits could be increased to $968 \times 22 / 18 = 1183$ (or the WFD area increased from 18,000 sq. deg.; see analysis of [ops2_1092](#) below). This increase is an improvement of 43% relative to the SRD design specification of 825 visits over 18,000 sq.deg. However, note again that there are no other programs in this simulation (i.e., if other programs were allocated 10% of the observing time, the implied overall “over-performance” in the number of visits would be about 30%).

[ops2_1092](#)

A Pan-STARRS-like observing strategy.

Motivation and description: ”Pan-STARRS-like cadence attempts to apply a uniform cadence strategy throughout the survey region, which is maximized and defined by $\text{Dec} < +15$ deg (about 27,400 deg²). The maximum acceptable airmass is kept at its default value of 1.5 (which excludes fields with $\text{Dec} < -78$ deg and $\text{Dec} > +18$ deg. This simulation utilizes uniform cadence and no other proposal, and requires pairs of visits as in Baseline Cadence.

Expectations: The total number of visits should be roughly the same as in Baseline Cadence, but spread over a 42% larger sky area (3,255 fields instead of 2,293), with fewer visits per field.

Analysis Results: This simulated cadence is named [??](#). Compared to the Baseline Cadence [enigma_1189](#):

1. The total number of visits is 2.47 million, and essentially identical to the number of visits in Baseline cadence.
2. The mean number of visits per field is 758.5, which is 98% of the number of visits for WFD fields obtained by Baseline Cadence (but here the sky area is 42% larger).
3. The median number of visits per night and the mean slew time are essentially the same as for Baseline Cadence.
4. The median seeing, sky brightness and airmass in the r and i bands for WFD fields are essentially the same as in Baseline Cadence.
5. The median trigonometric parallax and proper motion errors show uniform behavior over the entire enlarged area (see [Figure 2.11](#)), with the values similar to those obtained for Baseline Cadence.
6. This simulation also shows observing bias towards west.

Due to increased sky area, which samples regions that can never achieve low airmass, the median coadded depth is about 0.15 mag shallower for this simulation than for Baseline Cadence. As a result, the counts of galaxies per unit area down to a fixed SNR would decrease by about 15-20%. At the same time, the area outside the Galactic plane is increased by about 30%, and thus the total number of galaxies would be increased by about 10%, compared to WFD fields in Baseline Cadence. However, the increased median airmass also results in larger seeing, especially for the borderline regions, as illustrated in [Figure 2.12](#). The increased median seeing would decrease the number of galaxies effectively resolved for weak lensing by about 3-5%. In addition, the additional area has somewhat larger extinction due to interstellar dust which further decreases the galaxy counts (this impact of dust extinction is not yet implemented in MAF). As a result of these effects, the two strategies result in similar weak lensing galaxy samples.

Conclusions: When only the Universal Cadence proposal is employed, the survey area could be increased by about 40%, while still delivering the mean number of fields at the level of 98% of that in Baseline Cadence (or 92% of the SRD design value of 825). Hence, simulations [ops2_1092](#) and [ops2_1098](#) demonstrate that the “survey reserve”, relative to the Universal Cadence design specifications from the SRD, can be used to i) increase the number of visits per field over the WFD area, or ii) increase the surveyed area while keeping the number of visits per field statistically unchanged, or iii) increase both area and the number of visits, and/or iv) execute additional programs (the current baseline).

[ops2_1093](#)

Only Universal Cadence, no visit pairs.

Motivation and description: The main goal of this simulation was to assess the impact of the requirement for visit pairs on the survey efficiency (Baseline Cadence requests two visits per night to the same field, separated in time by about an hour, and driven by asteroid orbit determination). It is plausible that the removal of this requirement could result in a more efficient survey. In order to allow as simple analysis as possible, only the Universal Cadence proposal is requested. Hence, this simulation should be directly compared to simulation [ops2_1098](#).

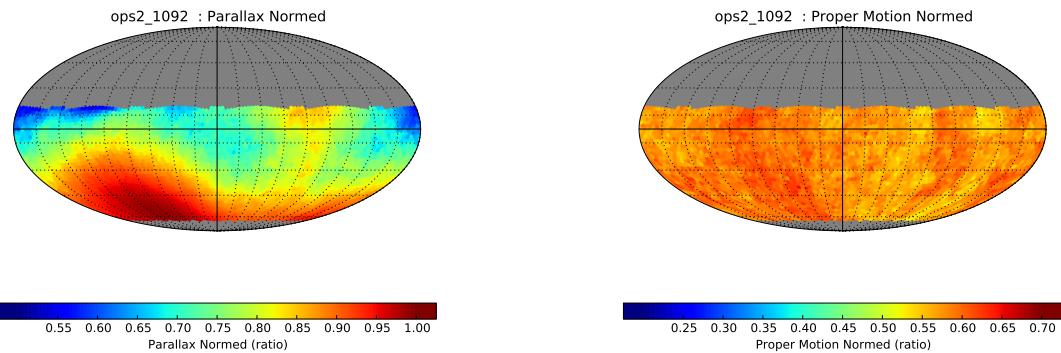


Figure 2.11: The trigonometric parallax errors (left) and proper motion errors (right) for simulated cadence ops2_1092 (“Pan-STARRS-like” cadence), normalized by the values for idealized perfectly optimized cadence, are shown in Aitoff projection of equatorial coordinates (compare to Figure 2.3).

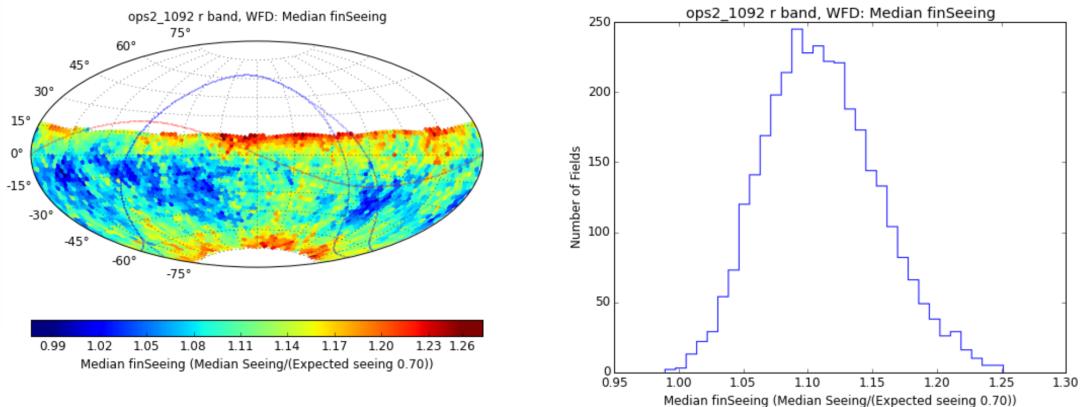


Figure 2.12: The median seeing in r filter, for simulated cadence ops2_1092 (“Pan-STARRS-like” cadence), normalized by expected value (0.70). Note that fields with the most positive and most negative declination have on average larger values. For comparison, the median normalized seeing for WFD fields in Baseline Cadence is 1.08, with a negligible fraction of fields with values above 1.18.

Expectations: If the requirement for visit pairs decreases surveying efficiency, then this simulation should deliver more than 2.45 million visits delivered by [ops2_1098](#).

Analysis Results: This simulated cadence is named [ops2_1093](#). Compared to [ops2_1098](#):

1. The total number of visits is 2.45 million, identical to [ops2_1098](#).
2. The median slew time, and the median coadded depth and seeing in the r band are essentially identical, too.
3. The median airmass in the r band of 1.26 is a bit higher than 1.20 obtained for [ops2_1098](#).
4. The median fraction of revisits faster than 30 minutes of 0.35 is smaller than 0.39 for [ops2_1098](#), and is consistent with the absence of pair contributions (that is, such revisits are due to field edge overlaps, and unintentional revisits, in case of [ops2_1093](#)).

Conclusions: The comparison of this simulation and [ops2_1098](#) shows that requiring pairs of visits (in a given observing night) does not result in an appreciable loss of surveying efficiency.

Indeed, pairs of visits result in a better short-timescale coverage that would enhance many types of time-domain science (and, of course, it's crucial for asteroid science).

kraken_1032

Baseline Cadence, but with no visit pairs.

Motivation and description: The main goal of this simulation was to assess the impact of the requirement for visit pairs on the survey efficiency. Instead of the idealized case above which compared only the Universal Cadence proposal fields, in this more realistic case *all proposals from Baseline Cadence are executed*. Hence, this simulation should be compared to Baseline Cadence ([enigma_1189](#)).

Expectations: A slight, or no, increase in surveying efficiency and thus the total number of visits is expected when compared to Baseline Cadence.

Analysis Results: This simulated cadence is named [kraken_1032](#). Compared to [enigma_1189](#),

1. The total number of visits is 2.53 million, or 2.4% more than in Baseline Cadence.
2. The mean slew time is 5.8 sec, or 16% shorter than for Baseline Cadence. This decrease in the mean slew time implies an efficiency increase of 2.8% and explains the actual 2.4% improvement implied by the total number of visits. Note that this simulation has the shortest mean slew time of all simulations investigated here (the nominal shortest slew and settle time is about 4.5 sec).
3. The median airmass in the r band is slightly larger for this simulation than for Baseline Cadence: 1.29 vs. 1.23.

Conclusions: Unlike the comparison of [ops2_1093](#) and [ops2_1098](#), here the removal of visit pair requirement results in a 16% shorter mean slew time and consequently in 2.4% more visits.

ops1_1163

Baseline Cadence, but with 33% shorter exposure time.

Motivation and description: The optimal exposure time per visit for the main survey, in the limit of a single value for all bands and at all times, is in the range of about 20–60 seconds (see Section 2.2.2 in the LSST overview paper, arXiv:0805.2366, version 3.1). This simulation investigates the effect of decreasing the exposure time per visit to 20 seconds (from its nominal value of 30 seconds). The shorter exposure time results in 0.22 mag shallower faint limit per visit (the effect is larger in the u-band, see [ops1_1162](#)).

Expectations: The total number of visits is expected to increase by about 50%, compared to [enigma_1189](#), to 3.70 million, for the same survey efficiency. However, the shorter exposure time will have a significant impact on the survey efficiency: assuming a slew time of 7 sec, the efficiency drops from 73% to 65% (comparing $30/(30+4+7)$ vs. $20/(20+4+7)$). Therefore, the expected increase in the number of visits is about 32% and the expected number of visits is 3.2 million.

Analysis Results: This simulated cadence is named [ops1_1163](#). Compared to Baseline Cadence:

1. The total number of visits is 3.29 million, representing an increase of 33% that is very close to the expected value of 32%.
2. The median number of visits per night is 1091, or about 34% more than for Baseline Cadence. The total open shutter time is 11% smaller for this simulation, and easily understood as due to expected 11% decrease due to smaller surveying efficiency (the mean slew time is practically the same as in Baseline Cadence, 6.8 sec vs. 6.9 sec).
3. The main survey (WFD, 18,000 sq. deg.) fields received 32% more visits than in Baseline Cadence. The increase in the minimum number of visits over that area is 7% (from 898 to 961). In addition, another 1,000 sq. deg. (6% of the nominal WFD) area has more than 961 visits.
4. Most other performance parameters are essentially unchanged: the fraction of visits spent on the main survey (84% vs. 85%), the median seeing in the r band (0.78 arcsec vs. 0.77 arcsec), and the median airmass (1.24 vs. 1.23).

Conclusions: The comparison of [ops1_1163](#) and [enigma_1189](#) simulations demonstrates that the effect of shorter exposures can be easily understood using simple efficiency estimates. With the visit exposure time is decreased from 30 sec to 20 sec, the surveying efficiency and the total open shutter time drops by $\sim 10\%$, while the number of (shorter exposure time) visits (for all proposals) increases by 33%.

[ops1_1164](#)

Baseline Cadence, but 100% longer exposure time.

Motivation and description: This simulation investigates the effect of increasing the exposure time per visit to 60 seconds (from its nominal value of 30 seconds). The longer exposure time results in 0.38 mag deeper faint limit per visit (the effect is larger in the *u*-band, see [ops1_1162](#)).

Expectations: The total number of visits is expected to decrease by about a factor of 2 in case of no significant impact on the survey efficiency. However, the longer exposure time improves efficiency by a factor of $2*(34+7)/(64+7)-1=15\%$, and thus the expected total number of visits is $0.5*1.15 = 58\%$ of the the number of visits in Baseline Cadence (assuming the same mean slew time of 7 seconds).

Analysis Results: This simulated cadence is named [ops1_1164](#). Compared to Baseline Cadence:

1. The total number of visits is 1.42 million or 58% of the visits obtained with Baseline Cadence, and the total open-shutter time is 15% higher than for Baseline Cadence. Both results are in good agreement with above expectations.
2. The median number of visits per night is 472, or 58% of the value obtained with Baseline Cadence. The mean slew time is 0.1 sec longer than that obtained with Baseline Cadence.
3. This simulation has significantly different time allocation per proposal, compared to Baseline Cadence: 69% spent on the Universal proposal (vs. 85%) and 18% spent on the North Ecliptic proposal (vs. 6%) (with smaller and less important differences for other proposals). Because of these differences, *the results of this test may not be very robust*.

Conclusions: Simple estimates of the total number of visits and the improvement in efficiency are in good agreement with delivered values. Of course, the increased efficiency comes at the cost of fewer visits, which is disadvantageous for time-domain science.

Note to OpSim team: this simulation should be repeated with the requested number of visits per field set to 60% of the values used for Baseline Cadence for all proposals. For example, instead of (75, 105, 240, 240, 210, 210) for Universal-18-0824B proposal, (45, 63, 144, 144, 126, 126) should be used. This way the additional observing time due to improved surveying efficiency will be allocated to all proposals, including Universal Cadence. *This simulation will be repeated with the same North Ecliptic Spur proposal as used for [enigma_1189](#), and with the modified requested number of visits.*

ops1_1162

Baseline Cadence, but with doubled u-band exposure time.

Motivation and description: The read-out noise in the u band is not negligible compared to the background noise as in other bands, due to darker u band sky. The current best estimates for survey performance (see Table 2 in the LSST overview paper, arXiv:0805.2366, version 3.1) indicate that the coadded depth in the *u* band could be improved by 0.24 mag by increasing the exposure time per visit from 30 seconds to 60 seconds⁵ (assuming the same total exposure time, which implies a decrease in the number of visits by a factor of two). To keep the total exposure time in the *u* band unchanged, the requested number of visits in this simulation is decreased by a factor of 2 relative to Baseline Cadence specification.

Expectations: The total exposure time in the *u* band should remain unchanged. The single visits depth should be 0.38 mag deeper due to twice as long exposure time (the gain of 0.24 mag related to read-out noise effects is not yet implemented in the OPsim code so MAF outputs may be a bit confusing).

Analysis Results: This simulated cadence is named [ops1_1162](#). Compared to Baseline Cadence ([enigma_1189](#)):

1. The total number of visits is 2.21 million or 89.5% of the Baseline Cadence values. The fraction of time allocated to the main survey is 77% vs. 85% for Baseline Cadence, and for the NE spur proposal 14% vs. 6%. Given that the NE spur proposal was different than for [enigma_1189](#), this simulation needs to be rerun.

Conclusions: The *u* band exposure time can be increased from 30 seconds to 60 seconds without a significant impact on the survey efficiency. This change would result in a gain of about 0.2 mag in the coadded depth. However, the number of visits in the *u* band would be decreased by about a factor of two, with a negative impact on time-domain science. *This simulation will be repeated with the same North Ecliptic Spur proposal as used for [enigma_1189](#) to make conclusions more robust and precise.*

⁵In the background-limited case, a factor of two increase of the exposure time results in 0.38 mag deeper data. Since in the *u* band the read-out noise is not negligible compared to the background noise, the total noise increases by less than a factor of $\sqrt{2}$ and there is an extra depth improvement of 0.24 mag (see eq. 7 and Table 2 the overview paper). Conversely, when exposure time is shorter than 30 seconds, there is an extra penalty of 0.16 mag, in addition to a loss of depth of 0.22 mag due to shorter exposure time in the limit of negligible read-out noise.

ops1_1161

Baseline Cadence, but with doubled u-band exp. time and Baseline NE Spur.

Motivation and description: This simulation is similar to [ops1_1162](#), which increased the exposure time per visit in the *u*-band from 30 seconds to 60 seconds, with the requested number of visits decreased by a factor of 2. This change resulted in a gain of about 0.24 mag in the coadded depth. Since the number of *u* band visits in [ops1_1162](#) was decreased by about a factor of two, with a negative impact on time-domain science, this simulation does not change the nominal requested number of visits per field. Hence, the coadded depth in the *u* band in this simulation would be improved by about 0.6 mag.

Expectations: Given that about 5% of all visits are allocated to the *u* band, the total number of visits may decrease by up to about 5%, resulting in about 0.03 mag shallower data in bands other than *u* band.

Analysis Results: This simulated cadence is named [ops1_1161](#). Compared to Baseline Cadence ([enigma_1189](#)):

1. The total number of visits is 2.36 million or 95.5% of the Baseline Cadence values. The fraction of time allocated to the main survey is 78% vs. 85% for Baseline Cadence, and for the NE spur proposal 13% vs. 6%. Given that the NE spur proposal was different than for [enigma_1189](#), this simulation needs to be rerun.

Conclusions: When the *u* band exposure time is increased from 30 seconds to 60 seconds, and the number of visits is kept unchanged, the single-visit and coadded depths would be improved by 0.6 mag. This improvement would come at the expense of about 6% fewer visits in other bands (with about 0.03 mag shallower coadded depths).

ops2_1096

Only Universal Cadence, with relaxed airmass limit.

Motivation and description: What is the effect of changing the airmass limit from 1.5 to 2.0? To avoid complicated analysis, use only Universal Cadence proposal and thus compare to [ops2_1098](#).

Analysis Results: This simulated cadence is named [ops2_1096](#). Compared to [ops2_1098](#), it collected 98.0% visits. This fraction is identical to the loss of efficiency due to slightly longer mean slew time: 8.1 sec vs. 7.2 sec. In addition, [ops2_1096](#) has much worse airmass distributions than [ops2_1098](#), extending to the allowed maximum of 2.0. For example, the median for the *r* band and WFD fields is 1.33, compared to 1.20 for [ops2_1098](#).

Conclusions: This simulation confirms that it's a bad idea to relax airmass limit: as a result, the airmass distribution always widens. In addition, relaxed airmass limit tends to result in a longer mean slew time. For a given proposal, the airmass limit has to be as tight as possible, while still allowing observations of all requested fields.

ops2_1097

Only Universal Cadence, with stringent airmass limit.

Motivation and description: What is the effect of changing the airmass limit from 1.5 to 1.3? To avoid complicated analysis, we use only the Universal Cadence proposal and thus compare to ops2_1098.

Analysis Results: This simulated cadence is named ops2_1097. Compared to ops2_1098, it collected essentially the same number of visits. The mean slew time is also essentially unchanged (7.4 sec vs. 7.2 sec). The airmass distributions is improved compared to ops2_1098. For example, the median for the r band and WFD fields is 1.14, compared to 1.20 for ops2_1098. The limiting coadded depth in u and g bands is about 0.1 mag deeper than for Baseline Cadence.

Conclusions: It is possible to achieve the same surveying efficiency with much more stringent airmass limit than 1.5, which was used in most simulations to date. *Given this encouraging behavior, an analogous experiment should be executed for Baseline Cadence (i.e. a simulation like enigma_1189, with airmass limit for the main survey set to 1.3) – after the “Western bias” is fixed’.*

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2.4 Analysis of NEO/PHA completeness

Continuing our analysis of some alternatives to the Baseline Cadence, we now investigate a suite of observing strategies for their suitability in supporting Near-Earth Object (NEO) science. As in the previous section, these OPSIM databases are all available for further testing with science-based MAF metrics.

The U.S. Congress has given a mandate to NASA to implement a Near-Earth Object (NEO) Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter⁶. The goal is to achieve a completeness of 90%. In recent practice, adopted here, the completeness is evaluated for a subset of NEOs called Potentially Hazardous Asteroids⁷ (PHAs), with $H \leq 22$, where H is the absolute magnitude⁸ in the Johnson’s V band. While LSST is very competitive in this context, it will also enable analysis of many other Solar System populations (e.g. main-belt asteroids, comets, trans-Neptunian objects). Nevertheless, we focus analysis here on NEOs/PHAs completeness.

Motivation and description:

The baseline cadence implements observing strategy with two visits to a field obtained per night, separated in time by a fraction of an hour. Motivation for a simulation that does require pairs of visits is to gauge its impact on the survey efficiency and other performance parameters.

⁶See <http://www.gpo.gov/fdsys/pkg/PLAW-109publ1155/pdf/PLAW-109publ1155.pdf>

⁷ Potentially Hazardous Asteroids (PHAs) are defined as asteroids with a minimum orbit intersection distance (MOID) of 0.05 AU or less.

⁸Absolute magnitude is the magnitude that an asteroid would have at a distance of 1 AU from the Sun and from the Earth, viewed at zero phase angle. This is an impossible configuration, of course, but the definition is motivated by desire to separate asteroid physical characteristics from the observing configuration.

Motivation for simulations with more than two visits to a given field per night is to investigate the feasibility of a more robust approach to linking individual detections into a plausible object track. Although detailed simulations of the performance of image differencing software and orbital determination software indicate that two visits per night are likely to be sufficient, quantitative analysis of other strategies is clearly within the purview of the cadence optimization program. Five simulations are analyzed in this section:

`ops2_1094`

NEO test: no request for pairs of visits.

`enigma_1257`

NEO test: pairs of visits (as in the Baseline Cadence). . .

`enigma_1258`

NEO test: triplets of visits.

`enigma_1259`

NEO test: quads of visits.

Expectations: Analysis of all simulations is repeated three times, with different conditions for what constitutes an object’s “discovery”: two, three or four detections per night are required, together with at least three such sequences in a 15-day window. When only two detections per night are required, a modest decrease in PHA completeness is expected for simulations that request more than two visits per night because some visits “don’t live up to their full potential”. On the other hand, when more than two detections per night are required, a naive expectation is that PHA completeness for runs with fewer requested visits will drop significantly.

Analysis Results: First, we emphasize that “requested” is not the same as “delivered”: even the “no pairs” simulation `ops2_1094` ends up having multiple visits in a given night to the same fields, and when multiple visits per night are requested, not all fields get to have completed sequences. The statistics of how many fields are combined into sequences of a given number of visits is shown in [Figure 2.13](#). As evident, the highest peak is at the requested number of visits in a sequence, but not all visits are incorporated into requested sequences: some are in both shorter and longer sequences. In particular, even “no pairs” simulation includes multiple visits to some fields, essentially because the current version of the algorithm is not told not to do so. As illustrated in [Figure 2.14](#), such revisits typically happen within 10 minutes from the first visit. This (unintended) behavior implies that the naive expectation above is probably incorrect, as we discuss in more detail below.

For baseline reference, the PHA completeness for `enigma_1189` is shown in [Figure 2.15](#). The baseline cadence achieves a cumulative completeness of 73% for $H \leq 22$ PHAs. This cumulative completeness for $H \leq 22$ is 17% higher than differential completeness at $H=22$ of 56% due to

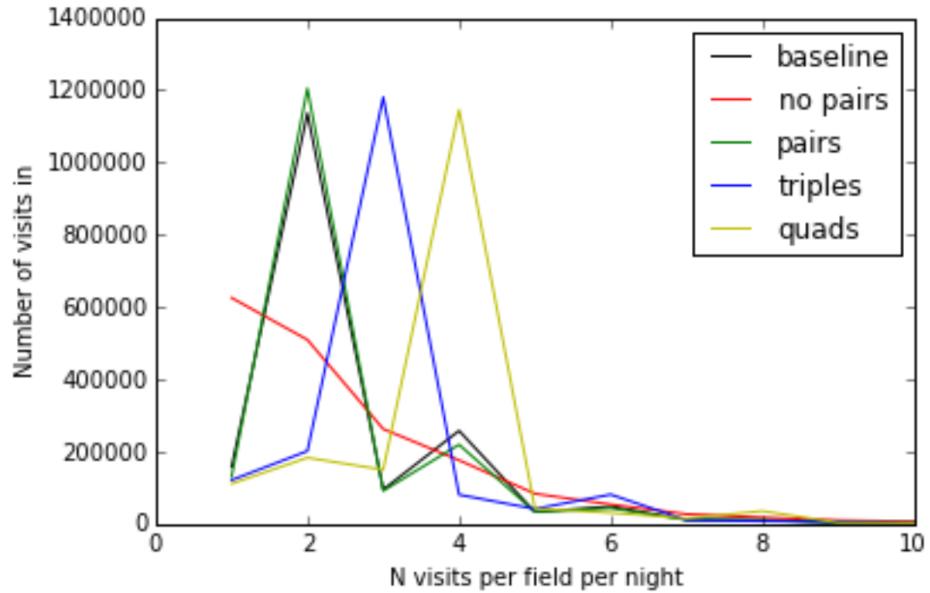


Figure 2.13: The distribution of the number of visits used for nightly sequences of length given on the horizontal axis. Only *griz* bands are used. Note that even “no pairs” simulation ([ops2_1094](#)) includes multiple visits. The highest peak is at the requested number of visits in a sequence.

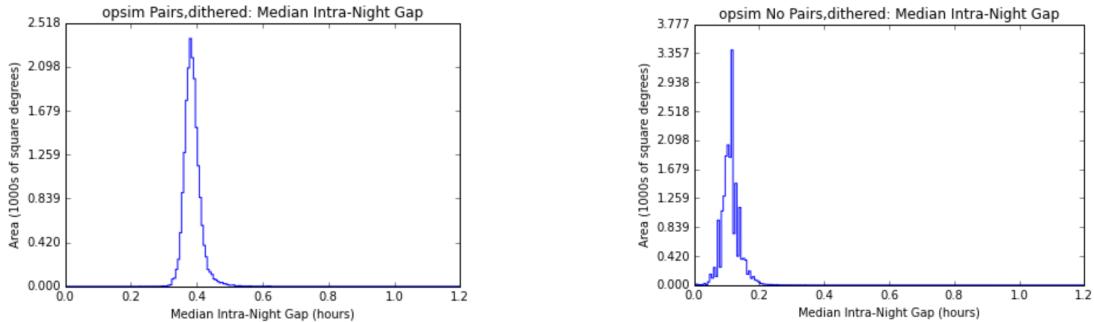


Figure 2.14: The comparison of the median intra-night gap distributions for Baseline Cadence (left) and simulation [ops2_1094](#), which did not request pairs of visits per night. Despite no need for pairs, simulation [ops2_1094](#) produced them “spontaneously”, as well as longer sequences (see Figure 2.13). The mean field revisit time is much shorter (about 6 minutes, see the right panel) than for Baseline Cadence (22 minutes).

increasing completeness towards smaller H (larger objects). Both differential and cumulative completeness are relevant metrics: the former provides more insight in the behavior of a particular simulation, while the latter is a metric given to NASA by the U.S. Congress. Analysis of results illustrated in Figure 2.16 can be summarized as follows:

- When NEO discovery algorithm requires pairs of visits, all runs have very similar PHA completeness, with quads run only about 2% lower than the baseline (a differential completeness of 56% at H=22 for [enigma_1189](#))
- When NEO discovery algorithm requires 4 detections per night, the simulation with quads achieves a differential completeness of about 27% at H=22, or about 30% lower completeness than Baseline Cadence.

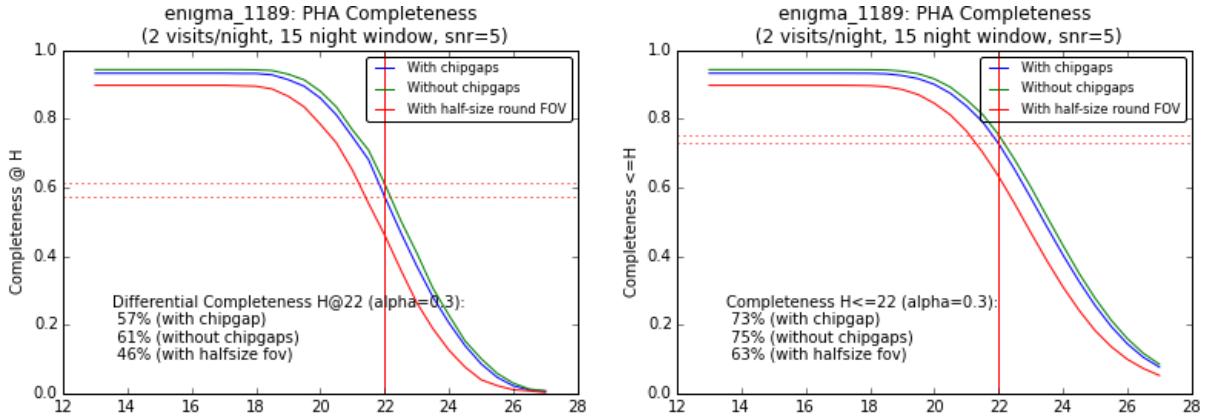


Figure 2.15: The PHA completeness for [enigma_1189](#), as a function of the object's absolute visual magnitude H on the horizontal axes (left: differential completeness at a given H ; right: cumulative completeness for all objects brighter than a given H). The completeness for $H \leq 22$ NEOs (those with diameters larger than 140m) for this simulation is 73% (blue line in the right panel). The panels also show the effects of ignoring chip gaps (a 2% effect for cumulative $H \leq 22$ completeness) and of decreasing the field-of-view size to a half (i.e. to 4.8 sq. deg; a 10% effect).

:

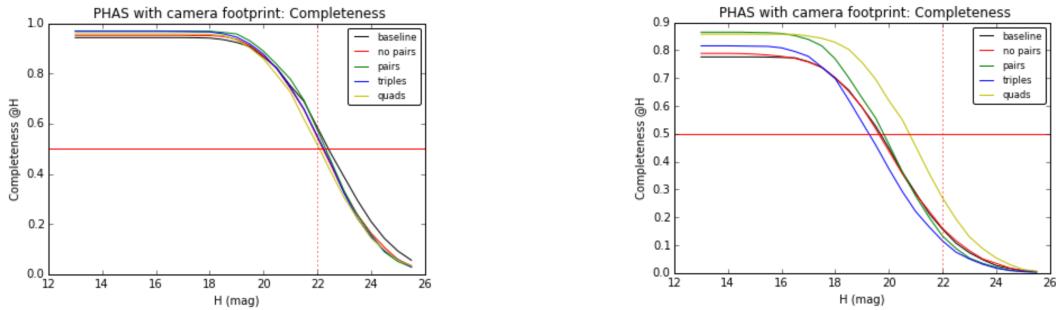


Figure 2.16: The comparison of differential PHA completeness for the five analyzed simulations when requiring two detections per night (left) and four detections per night (right). With two detections per night, all simulations perform similarly but when four detections per night are required, the simulation that has the largest number of such sequences (see [Figure 2.13](#)), performs the best although at an inferior level compared to the left panel (see also [Figure 2.15](#)).

- When NEO discovery algorithm requires 4 detections per night, Baseline Cadence reaches a differential completeness of about 15% at $H=22$ (some quads are unintentionally produced by chance, see [Figure 2.13](#)).
- When NEO discovery algorithm requires 3 detections per night, runs which requested triples and quads achieve a differential completeness of about 40% at $H=22$ (corresponding to a cumulative completeness of about 57% for $H \leq 22$).

Therefore, going from pairs of visits to triples (both for cadence and NEO detection) reduces completeness (both differential and cumulative) for PHAs with $H \leq 22$ by about 15-20% (and by about 30% for quads).

Impact on other science programs

The impact of requesting sequences with 3 or 4 visits to the same field on other science programs is not yet analyzed in detail. The impact on static science should be minimal, except perhaps for a bit worse behavior of various systematic errors (because fewer nights, with their observing conditions, are sampled).

For time-domain science, the mean revisit time will increase by about 50% if we go from pairs to triples, and by about a factor of two for quads. This change will have a negative impact on time-domain science programs based on SNe, variable stars, and transient objects, which remains to be quantified.

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2.5 Ongoing and Future Work

2.5.1 Ongoing: Extended time-domain metrics

A number of very sophisticated time-domain metrics have been implemented in recent MAF development cycle (and some were contributed by the community) but they have not been systematically run yet on all available simulations. Time-domain metrics, together with metrics for analyzing special programs (e.g. deep drilling programs), will be further expanded in the next development cycle.

2.5.2 Ongoing: Rolling Cadence experiments

Analysis of a few prototype runs (`ops2_1102`, `enigma_1260`, `enigma_1261`), which implemented the so-called “swiss cheese rolling cadence” is in progress.

2.5.3 Future work

Based on analysis presented here, several recommendations for further cadence exploration, can be made.

1. Further optimization of the main survey (e.g., exposure time in general, and u band exposure time in particular; fixing western bias; optimizing airmass limit and sky coverage; investigations of variable, perhaps SNR-driven, exposure time).
2. Exploration and optimization of temporal sampling function in general, and of Rolling Cadence in particular.
3. NEO completeness studies: what would it take for LSST to reach 90% completeness for 140m and larger NEOs? Based on previous analysis, directions to explore are deeper visits along the Ecliptic and longer survey duration (about 12 years).

4. Exploration of extending the main survey to the Galactic plane (per A. Gould's proposal, arXiv:1304.3455) and further optimization of Galactic plane and Bulge science programs.
5. Optimization of LMC/SMC coverage (and somewhat less importantly, the South Celestial Pole coverage).
6. Deep drilling optimization (detailed analysis of existing proposals; investigation of gains from going to a larger observing time allocation, e.g. 20%).
7. Twilight short-exposure time observing (per internal Stubbs proposal).
8. Planning commissioning observations (e.g. the tension between going wide to enable self-calibration and dense temporal sampling to obtain various light curve templates and fine tune image differencing and multi-epoch data processing and data analysis software tools).
9. Dynamic cadence explorations (the main goal at this time is to answer: are our tools good enough to act and react swiftly and robustly in operations?).

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2.6 Summary

The most important conclusion of this study is that the upper limit on possible scheduling efficiency improvements for Baseline Cadence is close to 6%. This conclusion is by and large based on the fact that the mean slew time for (candidate) Baseline Cadence is 6.9 sec, and thus only slightly larger than the design specifications for the system slew and settle time of 4.5 sec. Nevertheless, there are a number of features to understand, and some to fix, and there is substantial optimization potential in temporal sampling functions and further optimization of the sky area and observing strategy details, that can result in enhanced science even with the same integrated open-shutter time (e.g. by obtaining deeper data through an improved sampling of observing conditions).

The main other questions addressed here are:

1. *By what factor could we exceed the SRD design specification for the number of visits if only Universal Cadence proposal was implemented?*

A simulation that only implemented Universal Cadence proposal exceeded the design specification for the number of visits by about 40% (over the design specification for the sky area of 18,000 sq.deg.)

2. *By what factor could we exceed the SRD design specification for the sky coverage if only Universal Cadence proposal was implemented with the design specification for the number of visits?*

This Pan-STARRS-like strategy results in about 40% larger sky coverage (about 25,000 sq.deg.), with the mean number of visits at 92% of the design specification. The total number of visits is the same as for Baseline Cadence, implying similar surveying efficiency.

Therefore, the available “margin” relative to the SRD design specifications for the main survey is equivalent to about 30-40% larger sky coverage, or about 30-40% more visits per field. The SRD assumes that 10% margin will be available for other programs. The implied “survey reserve”, relative to the Universal Cadence design specifications from the SRD, can be used to:

- a) increase the number of visits per field over the WFD area, or
 - b) increase the surveyed area while keeping the number of visits per field statistically unchanged, or
 - c) increase both area and the number of visits, and/or
 - d) execute additional programs (the current baseline).
3. *What is the effect of auxiliary proposals on surveying efficiency?*

A comparison of simulations which only implemented Universal Cadence proposal to those that included all other programs did not show a significant change of efficiency (older simulations, not analyzed here, showed increases in surveying efficiency of up to about 3% due to shorter slewing time).

4. *What is the effect of visit pairs on surveying efficiency?*

Relinquishing the visit pair requirement results in up to 2-3% improvement of the surveying efficiency. The impact on some time-domain science would be positive, while for NEO and main-belt asteroid science it would be strongly negative.

5. *Can the effects of variations of the visit exposure time on surveying efficiency be predicted using simple efficiency estimates?*

Simple estimates based on comparing exposure (open shutter) and total visit times are in good agreement with simulations. Decreasing the visit exposure time to 20 seconds decreases the total open shutter time by 10%, and increasing it to 60 seconds increases the total open shutter time by 16%, relative to Baseline Cadence and standard exposure time of 30 seconds. The number of visits changes by factors of 1.35 and 0.58.

6. *What are the effects of doubling the exposure time only in the u band?*

The effect of doubling the exposure time only in the u band, while simultaneously halving the number of requested visits, has no significant effect on the survey efficiency.

The effect of doubling the exposure time only in the u band, with the number of requested visits unchanged, is a decrease in the number of visits in other bands by about 6%.

7. *What is the impact of hard airmass limit, $X < 1.5$, on the surveying efficiency?*

It is a very bad idea to relax airmass limit! It is possible to achieve the same surveying efficiency with much more stringent airmass limit than 1.5, which was used in most simulations to date.

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3 A Solar System Census

Lynne Jones, David Trilling, Mike Brown, Eric Christensen

3.1 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)

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4 The Galaxy

Will Clarkson, Kathy Vivas, Peregrine McGehee, and others to follow

4.1 Introduction

[(To be refactored following the template per chapter...)]

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 Ivezić et al. (2008 arXiv 0805.2366, in particular Sections 2.1.4 and 4.4); in this chapter we (aim to) present metrics that will allow various observing strategies to be quantitatively assessed in terms of their impact on science cases falling under the general rubric of “The Milky Way.”

Our intention is to decouple the technical issue of coverage on-sky from the science accomplished; for example, if a science case includes regions both inside and outside of the “Wide-Fast-Deep” (WFD) survey, then the metric for a particular science case should produce a quantitative assessment of the science outcome no matter what the distribution of pointings on the sky actually was. As a result, issues to do with areal coverage (for example, whether a census of all nearby brown dwarfs that neglects “low-latitude” fields is scientifically unacceptable) should in theory drop out of the metrics assessment process.

By assessing metrics across the range of MW science cases, guidance could then be given (if requested) on first-order questions that remain to be resolved for Milky Way science (such as: what percentage of LSST’s total exposure manifest must be devoted to observations outside WFD in order for LSST to deliver Milky Way science?)

Because of the very large diversity in science case and the “ideal” observing strategy one might desire in each case, we summarize the science cases in terms of scientific and observational requirements, focusing on items for optimization, the LSST discovery space, and the areas in which at this time we expect observations to be mainly taken outside the WFD survey. We also include our assessment at this time of whether the performance estimates in the SRD are likely to be sufficient for the science case, and finally some strawman science metrics.

Need more precise metrics!

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In the following subsections, we attempt to translate the science cases into strawman metrics. The key features of the science cases relevant to metrics are listed in bullet form.

(**Hierarchical metrics (e.g. Issue #79):** since others are developing detailed metrics for fine-grained issues of detectability, in this Chapter we focus our candidate metrics mostly on high-level metrics that might call the variability metrics as functions. **To be worked out...**)

To aid in optimization, we also list any technical drivers that do not 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.]

4.2 The Solar Neighborhood

Author Name(s)

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

4.2.1 Target measurements and discoveries

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).

Three representative science cases identified (more are in the Phase I Science Roadmap):

- Volume-complete astrometric sample of extended Solar Neighborhood: requires parallax and proper motion, deep multi-filter photometry to classify objects.;
- Discovery of ultracold brown dwarfs (late-T and Y); requires very deep photometry in (i,z,Y)
- Photometric variability of cool dwarfs; requires sufficient time baseline sampling to chart variability; photometry at other bands to classify object.

4.2.2 Metrics

Organized by broad science case within this area:

- Volume-complete astrometric sample of extended Solar Neighborhood:
 - Bias and scatter in distance distribution of extended Solar Neighborhood objects;
 - Bias and scatter in individual source T_{eff} , $\log(g)$ as a function of spectral type;
 - Bias and scatter in population constraints (e.g. mass function slope) for candidate mass functions of local populations;
 - Fraction of local-volume population recovered *and* correctly identified (e.g. spectral subtype error?).
- Discovery of ultracold brown dwarfs (late-T/Y):
 - Bias and scatter in individual source T_{eff} , $\log(g)$ as a function of spectral type;
 - Bias and scatter in the brown dwarf/exoplanet (?) mass function parameters.
 - Fraction of objects within X pc from the Sun recovered *and* correctly identified (e.g. spectral subtype error?).
- Photometric variability of cool dwarfs
 - (*Note: hierarchical metric?*) E.g. classification of $X\%$ of starspot variability in local volume, which calls Variability Metric Y as a method.

4.2.3 OpSim Analysis

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

4.2.4 Discussion

One useful output of MAF for Solar Neighborhood work, will be the extent to which the small part of the sky in front of crowded regions in this general science area will make an impact.

Comparison of the science metrics for cases when Galactic Plane observations are / are not included as part of the OpSim run, will directly address the degree to which LSST should consider Solar Neighborhood science in its galactic plane strategy.

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4.2.5 The Solar Neighborhood

4.2.6 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.

4.2.7 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 \sim 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:** *Maximum* 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).

4.2.8 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:** *Maximum* 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.

In order to assess the ability of LSST to 1) identify and 2) classify YSO we need to quantify the variability timescales and amplitudes of both Class I/II (stars with disks) and Class III (WTTS). Inclusion of eruptive variables (FUor/Exor) is appropriate as well - see section 8.10.2 in the Science Book.

In brief, WTTS are quasi-periodic with amplitudes of 0.1 to 0.3 mag and periods 1 to 15 days - so comparable to gamma Dor stars (see Figure 8.17 in the SB). Given the temporal evolution of cool spots, a period recovery analysis such as shown for RRL stars (se Figure 8.20 in the SB) is likely difficult. The embedded systems and CTTS are irregular variables but shown have distinctive colors due to extinction + UB/blue excess arising from to accretion shocks.

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.

4.2.9 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.

4.2.10 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. Ivezić 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 ($r \gtrsim 20$; 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.

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5 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?

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6 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

6.1 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.

6.2 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.

6.2.1 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.

6.2.2 Targets and Measurements

Periodic Variable Type	Examples of target science	Amplitude	Timescale
Periodic binaries	Eclipses, physical properties of stars, distances, ages, evolution, apsidal precession, mass transfer induced period changes, Applegate effect	small	hr-day
RR Lyrae	Galactic structure, distance ladder, RR Lyrae properties	large	day
Cepheids	Distance ladder, cepheid properties	large	day
Long Period Variables	Distance ladder, LPV properties	large	weeks
Short period pulsators	Instability strip, white dwarf interior properties, evolution	small	min
Rotational Modulation	Gyrochronology, stellar activity	small	days

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.

6.2.3 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.

6.2.4 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.

6.2.5 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.

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6.3 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 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.

6.3.1 Targets and Measurements

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

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

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 (~ 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.

6.3.2 Metrics

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

6.3.3 OpSim Analysis

Current simulations provide reasonable sampling (~ 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.

6.3.4 Discussion

Special cadences offer the opportunity to extend LSST studies to non-periodic phenomena with time scales ≤ 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.

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6.4 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.

6.4.1 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?

6.4.2 Metrics

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

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?

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6.5 Transient Events

Stephen Ridgeway, Ashish Mahabal, Ohad Shemmer

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.

6.5.1 Targets and Measurements

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

Transient Type	Examples of target science	Amplitude	Time Scale
Flare stars	Flare frequency, energy, stellar age	large	min
Cataclysmic variables	Interacting binaries, stellar evolution, compact objects, explosive events	small	min
Supernovae	SN physics, mass loss, distance scale, cosmology	large	days
Active galactic nuclei	Galaxy evolution, reverberation mapping, black hole physics	large	weeks
Stellar microlensing	Exoplanet statistics	large	hours
Gamma ray bursts	Optical discovery and characterization	large	min
LIGO detections	Source position and characterization	unknown	min
Serendipity	Discovery and characterization	unknown	unknown
Tidal Disruption Events	Discovery and characterization	large	days

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.

For Tidal Disruption Events, where the fading time-scale is much more gradual (over weeks to months) than the rise time-scale it will be worth checking - through a metric - how many will be missed (as alerts). Ref. Science Book: 10.6.1. Also ref. recent papers.

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.

6.5.2 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. the 10^3 longest series).

6.5.3 OpSim Analysis

Analysis shows that current simulations provide poor coverage in any one filter for transient events longer than a deep drilling session (~ 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.

6.5.4 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.

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6.6 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 $\simeq 1$ week. 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.

6.6.1 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”.

6.6.2 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.

6.6.3 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. If 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.

6.6.4 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 principle 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.

6.6.5 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.

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

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

7.1 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.

7.2 Dithering Patterns and Timescales

Humna Awan, Eric Gawiser, Peter Kurczynski, Lynne Jones

Three of the key cosmology probes available with LSST represent “static science” insensitive to time-domain concerns. These are Weak Lensing, Large-Scale Structure, and Galaxy Clusters. Nonetheless, due to the need to track and correct for the survey “window function” in all of these probes, cosmology with LSST will benefit greatly from achieving survey depth as uniform as possible over the WFD area. OpSim tiles the sky in hexagons inscribed within the nearly-circular LSST field-of-view. It has been shown in [Carroll et al. \(2014\)](#) that the default LSST survey strategy implemented in OpSim runs leads to a strongly non-uniform “honeycomb” pattern due to overlapping regions on the edges of these hexagons receiving double the observing time. A pattern of large dithers proves sufficient to greatly reduce these overlaps, leading to an increase in median survey depth in each filter of 0.08 magnitudes.

In this section, we report results from an investigation by Awan et al. (in preparation) of several geometrical patterns for dithers performed on timescales varying from once per observing season to once per night to every visit.

EG: Flesh out WL, LSS, and Clusters dependence on survey uniformity to make this section more clearly science-driven.

7.2.1 Dithering Patterns and Timescales

7.2.2 Metrics

Our primary metric is total uncertainty in the derived window function over relevant angular scales, modeled via variations in the angular power spectrum of fake galaxy fluctuations between *gri* bands. Intermediate metrics include the number of galaxies in each pixel, fluctuations in this number, total power in the angular power spectrum of a skymap of those fluctuations, and residual power that angular power spectrum after subtracting a smooth fit to it.

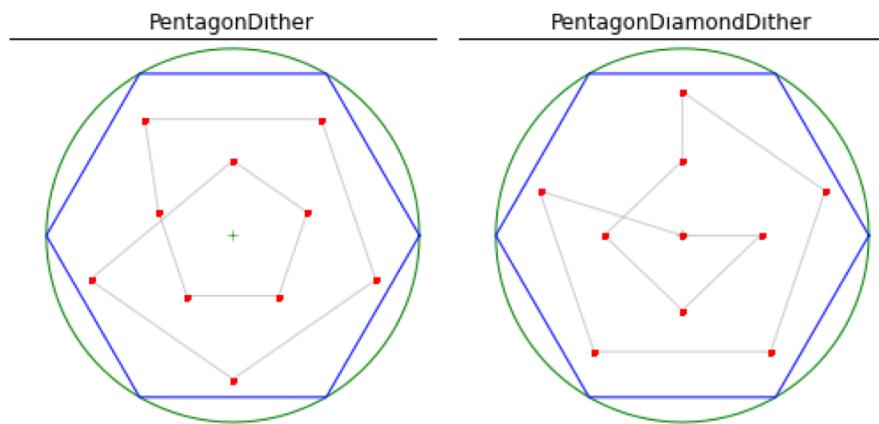
7.2.3 OpSim Analysis

In this section we present our ongoing OPSIM/ MAF analysis, as we try to answer the question “what dithering strategies produce acceptable variations in survey uniformity, and which appears optimal?”

7.2.4 Results

EG: Improve figures to originals rather than screen-captures.

EG: Input fuller results and text from Awan et al. draft.



: Fig. 1.— Geometries for by season dithering strategies.

Figure 7.1:

7.2.5 Discussion

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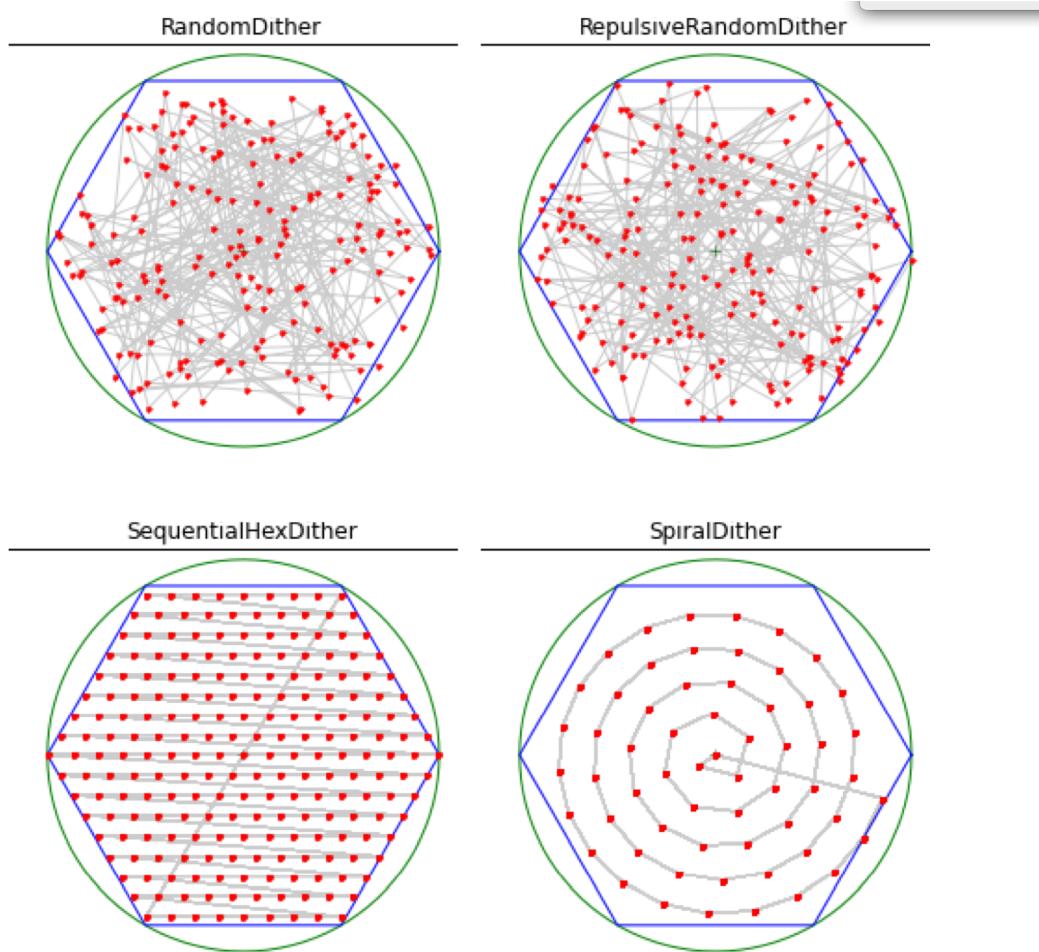


Fig. 2.— Geometries for by visit and by night dithering strategies.

Figure 7.2:

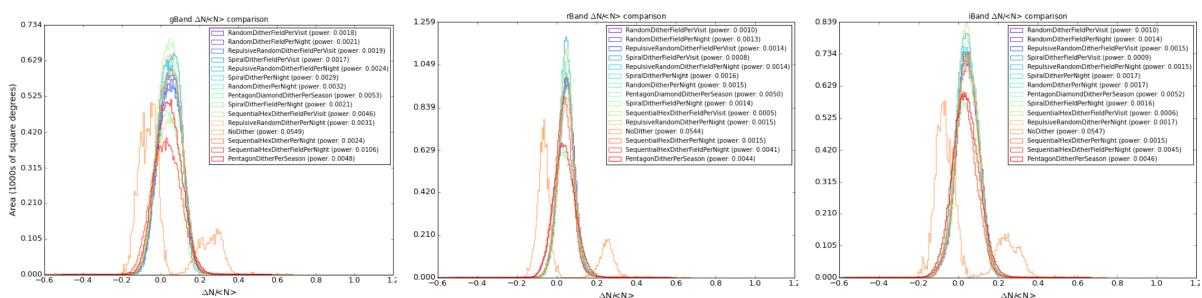


Fig. 4.— Histograms for artificial fluctuations in galaxy counts in gri bands for various dithering strategies.

Figure 7.3:

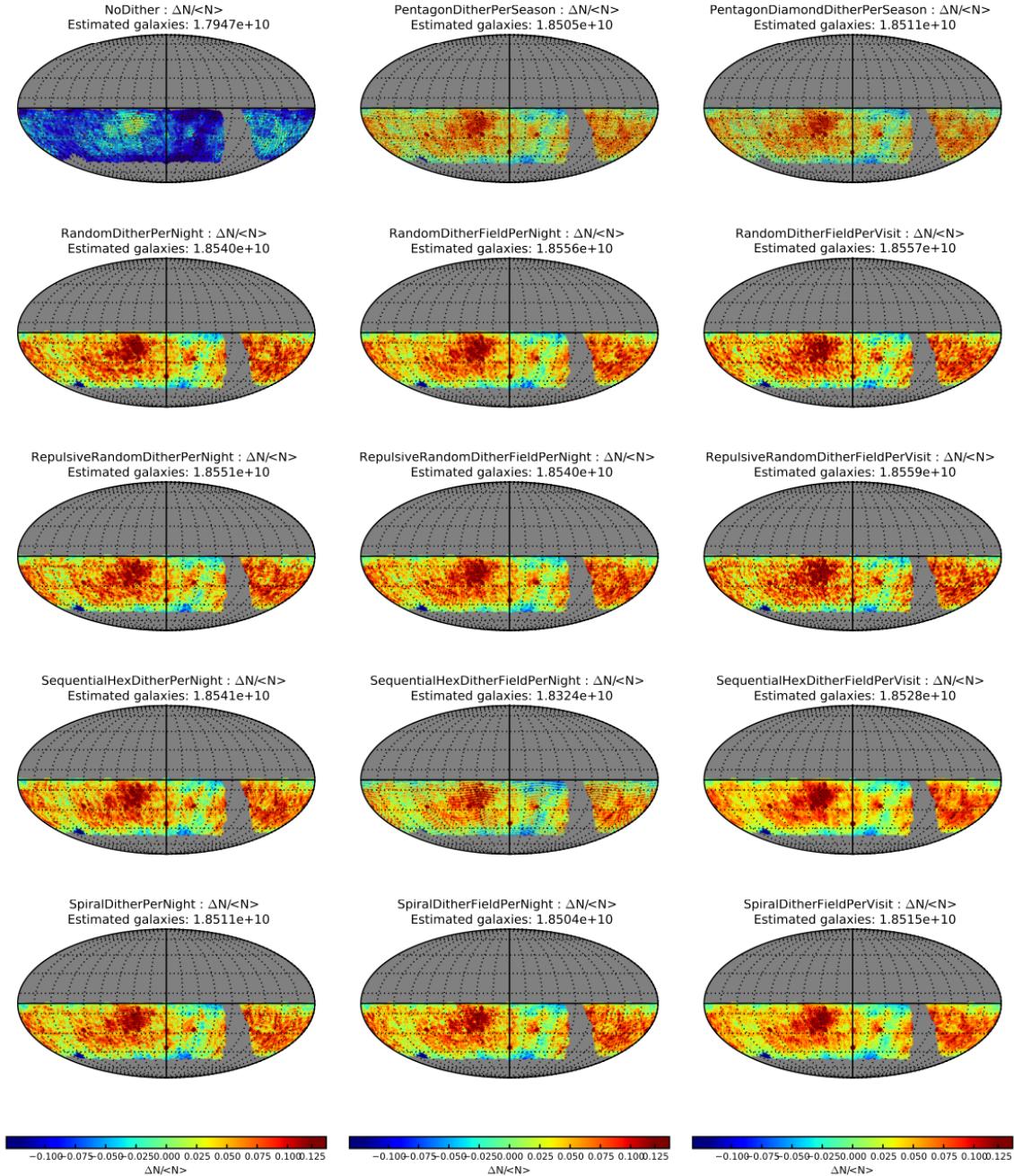


Fig. 5.— Skymaps for r-band differential galaxy counts from various dithering strategies.

Figure 7.4:

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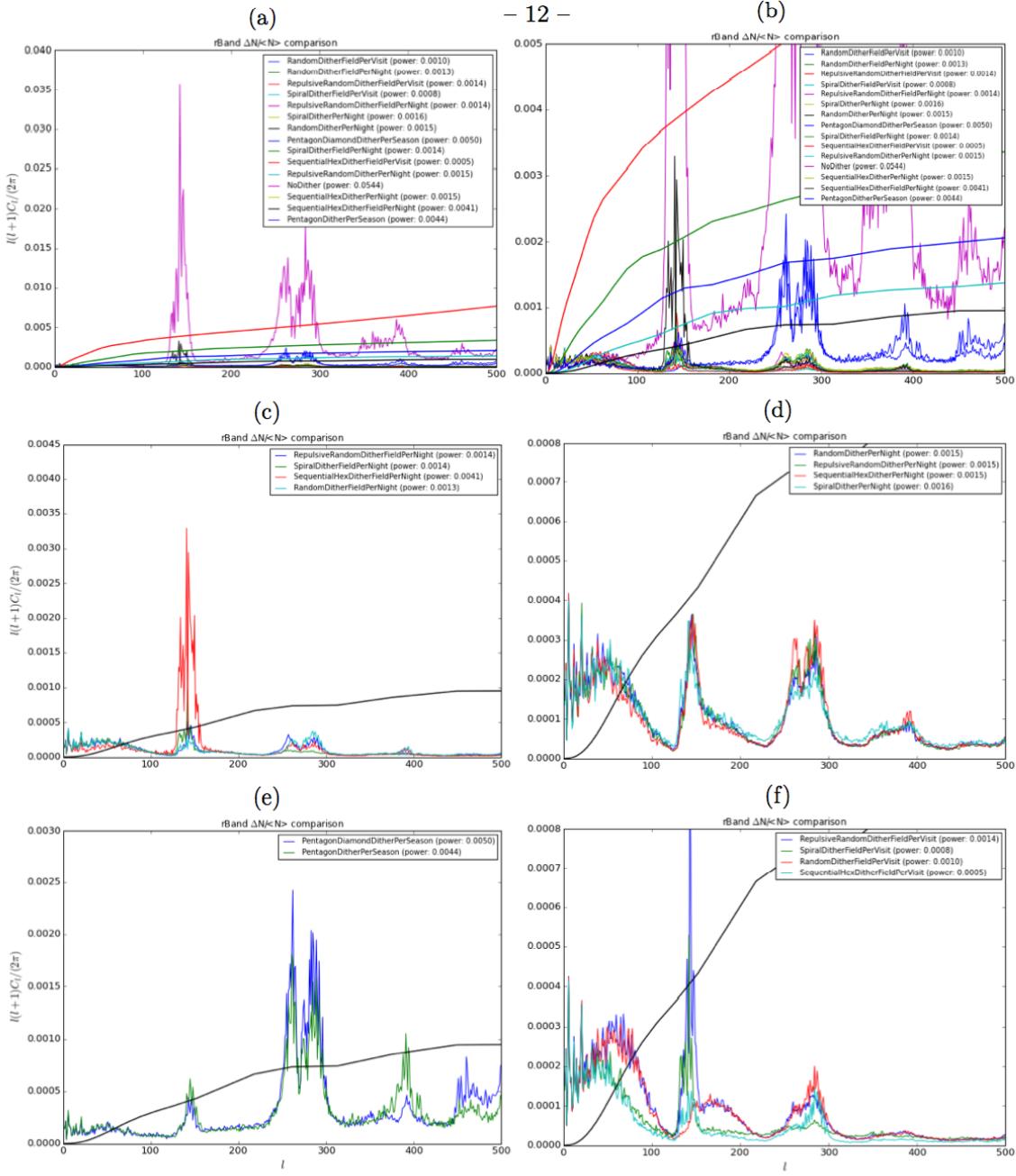


Fig. 6.— Angular power spectra for artificial fluctuations in r-band galaxy counts from various strategies. Panel (a) includes the spectra for all strategies, with its zoomed version shown in Panel (b). Panel (c) includes those for FieldPerNight strategies, Panel (d) for PerNight, Panel (e) for PerSeason, and Panel (f) for FieldPerVisit strategies. Thick curves are an example BAO signals, where the red one is for $0.15 < z < 0.37$, green for $0.37 < z < 0.66$, blue for $0.66 < z < 1$, cyan $1 < z < 1.5$, and black for $1.5 < z < 2$.

:

Figure 7.5:

7.3 Strong Gravitational Lens Time Delays

Phil Marshall, Lynne Jones

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.

7.3.1 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.

7.3.2 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 7.1](#). 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 7.6](#), 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 7.1: 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:

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

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

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

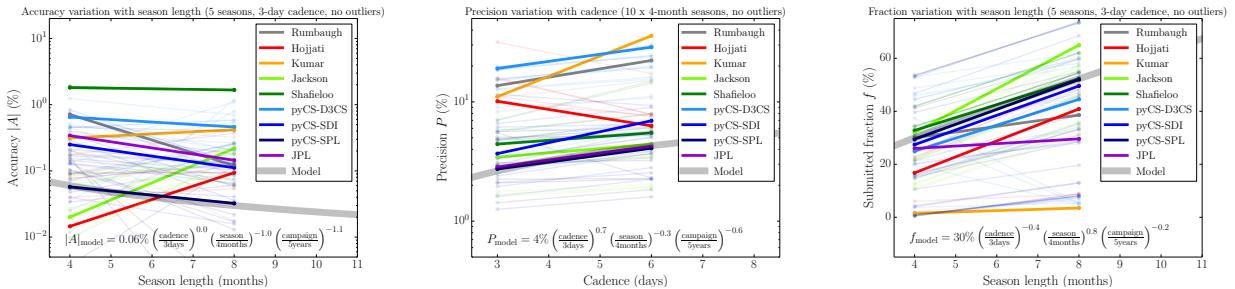


Figure 7.6: Examples of changes in accuracy A (left), precision P (center) and success fraction f (right) with schedule properties, as seen in the different TDC submissions. The gray approximate power law model was derived by visual inspection of the pyCS-SPL results; the signs of the indices were pre-determined 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.

Table 7.2: Lens Time Delay Metric Analysis Results.

OPSIM run	Filters	cadence	season	campaign	Accuracy	Precision	Fraction	timedelayFoM
enigma_1189	<i>ri</i>	XXX	XXX	XXX	XXX	XXX	XXX	???
enigma_1189	<i>ugrizy</i>	XXX	XXX	XXX	XXX	XXX	XXX	???
ops2_1075	<i>ri</i>	XXX	XXX	XXX	XXX	XXX	XXX	???
ops2_1075	<i>ugrizy</i>	XXX	XXX	XXX	XXX	XXX	XXX	???

Notes: see the text for the definitions of each metric, and sky maps and histogram plots of them. The Figure of Merit is still under development.

7.3.3 OpSim Analysis

In this section we present the results of our ongoing OPSIM/ MAF analysis, as we try to answer the question “how good would the proposed observing strategies be, for time delay lens cosmography?”

We used the `SeasonStacker` to work with seasons.

We used `ops2_1075` for most of our tests, but we need to now re-run on `enigma_1189`, and others from ??.

PJM: Correct the above paragraphs and add more links to MAF code.

Figure 7.7 shows the results of our MAF analysis of one OPSIM database, `ops2_1075`, where we have assumed that all filters were able to be used in the light curve analysis (as was implicitly assumed when applying the results of Liao et al.). These sky maps show that, over the main (WDF) survey area, the time delay accuracy, time delay precision and time delay lens success fraction are consistently maintained, indicating that the global average values of these metrics could conceivably be used as higher level metrics or even figure of merit.

Table 7.2 shows the global (i.e. al-sky) average values of our metrics, for two different OPSIM databases and two different filter set assumptions.

PJM: Compute global average lens time delay metrics and discuss.

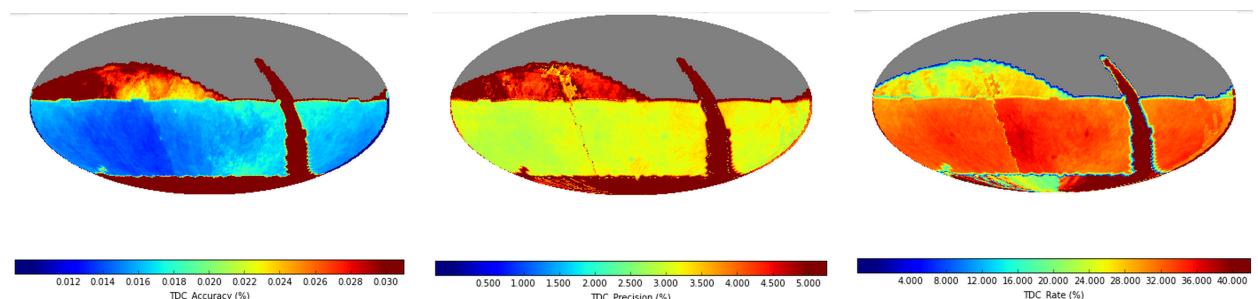


Figure 7.7: Sky maps of the accuracy A (left), precision P (center) and success fraction f (right) metrics, for the `ops2_1075` OPSIM database and assuming all filters (*ugrizy*) are used in the analysis according to the assumptions described in the text.

7.3.4 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?

PJM: Write lens time delays discussion section.

Go to: • [*the start of this section*](#) • [*the start of the chapter*](#) • [*the table of contents*](#)

7.4 AGN Science

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

7.4.1 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) AGN. 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 ([Kaczmarszak et al. 2009](#)). The DCR effect is more pronounced at higher airmasses. Therefore, it'd be advantageous to have at least one visit, per source, at airmass greater than about 1.4. 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.

7.4.2 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.

7.4.3 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 (PSD) 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 (for 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 ([Section 7.3](#)).

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 will be placed. 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 α : $R_\lambda \propto \lambda^\alpha$ implies source crossing time $t_s \propto \lambda^{1/\alpha} \rightarrow t_u = t_i \times (\lambda_u/\lambda_i)^{1/\alpha}$. For a Shakura-Sunyaev slope of $\alpha = 0.75$ this would correspond to $7.3 \times (3600/8140)^{4/3}$ months which is ≈ 2.5 months in the *u*-band.

In terms of the cadence, at least three evenly sampled data points per band within two to three 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 ([Section 6.3](#)).

7.4.4 Metrics

AGN Selection: Need to compute the mean Y band magnitude across the sky for the nominal OpSim. Compare this magnitude to the one required for identifying ≥ 1000 quasars at $z \geq 6$. Currently, for enigma_1189, the single-epoch 5-sigma depth in Y is 22.36 mag, and for the final co-added 5-sigma depth is $Y = 24.4$. These limits are deeper than the original predictions (see AAS poster from 2013). Need to compare these numbers to the output from other OpSims.

PRM: Need to compute the average and the dispersion in the number of visits, per band, across the sky for the nominal OpSim (during the entire survey). Since PRM works best for uniform sampling, need to compare the distributions of the number of visits in each band, averaged across the sky, and identify ways to minimize any potential differences between these distributions. By running PRM simulations, identify the 1) minimum number of visits (in any band) that can yield any meaningful BELR-continuum lag estimates, and 2) the largest difference in the number of visits between two different bands that can yield any meaningful BELR-continuum lag estimates. Repeat these simulations by doubling the nominal number of DDFs. Assess the number of meaningful BELR-continuum time delays that can be obtained with the nominal OpSim, and point out potential perturbations in the cadence to improve the number and quality of such time delays.

Microlensing: Need to compute the dispersion in the time gap between visits in the same band, across the sky, in order to assess the fraction of microlensing events that might be missed (on top of seasonal gaps).

7.4.5 Discussion

Some additional considerations/thoughts that came up during the workshop:

- 1) Assuming we will have 10 DDFs, perhaps one of those fields could be sampled more heavily than the others and would be visited nightly (or even more frequently) per band. This can be justified by the fact that a) very few AGNs have been monitored at these frequencies on such a long baseline, leaving room for discovery, and b) this may probe intermediate-mass black holes ($\sim 10^4 - 10^5 M_\odot$) via PRM or PSDs.
- 2) Need to assess the effects of the LSST cadence on the ability to detect periodic AGNs and quasi-periodic oscillations (QPOs) in AGNs.

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7.5 Supernova Cosmology and Physics

Jeonghee Rho, Michelle Lochner, Rahul Biswas

This section is concerned with the detection, characterization of supernovae over time using the Large Synoptic Sky Telescope (LSST) and the use of these supernovae for a number of science applications. The most important science application is the use of supernovae Type Ia (SNIa)

and potentially some core-collapse SN (like Type IIP) to trace the recent expansion history of the universe, and confront models of the physics driving the late time accelerated expansion of the universe.

This objective of supernova cosmology follows (at least for SNIa) several highly successful surveys; improvement in that knowledge could come from substantially larger numbers of well-characterized supernovae and potentially useful redshift distributions of such detected supernovae. In this sense, this goal is not directly tied to the large survey area that is an unprecedented characteristic of the LSST. However, we shall argue that in practice, even this goal would be largely helped by the spatial scale offered by the Wide Fast Deep (WFD) component of the LSST.

On the other hand, the WFD component of the LSST survey is potentially the first single survey to scan supernovae across the very large area of the entire Southern sky. Therefore, supernovae detected and well characterized (a) probing the isotropy of the universe, or (b) using peculiar velocities of supernovae to probe the growth of structure and finally (c) this may be the best avenue for a highly complete sample of supernovae that will enable further sharpening of our understanding of the properties of the supernova population of different types. This last point is extremely important for supernova cosmology goals: The success of supernova cosmology has always been based on the empirical model of intrinsic peak brightnesses being related to the certain observable characteristics of supernovae. While the spatial location of the supernovae is not important, the WFD has the potential to dramatically increase the size of the sample available to train such an empirical model, as well understand the probability of deviations and scatter from this model. Aside from issues like calibration which need to be addressed differently, a larger sample size of such well measured supernovae is probably the only way to address deviations from the empirical model usually discussed as ‘systematics’. This can be thought of in two components: the low redshift sample of supernovae which is more likely to be complete, and the higher redshift sample that might be able to constrain evolution.

7.5.1 Target measurements and discoveries

Supernovae of different types are visible over a time scale of about a few weeks (eg. Type Ia) to 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 (WFD) Cadence, and certain specific locations of the sky called the Deep Drilling Fields (DDF) with special enhanced cadence.

This spatio-temporal window should contain millions (RB: remember to check) of supernovae, that will have apparent magnitudes brighter than the single exposure limiting magnitude of LSST, for at least some time. 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 detected and 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. For LSST, this goal entails (a) detection of supernovae (b) photometric typing of supernovae, (c) 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, and finally use these data in addressing our science goals of cosmological inference, etc. 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. While these steps are not necessarily independent, it is useful to think of the requirements on some of these steps separately; it is not unlikely that combining some of these steps would still be affected by similar requirements.

Our first objective is to detect such supernovae. By ‘detection of supernovae’, we mean a process that detects transients from the subsets of LSST detection, and classify them as supernovae (as opposed to an AGN, or an asteroid). In brief, this process consists the identification of a set of image subtractions between high resolution ‘template’ image of a sky section, and a set of single exposures at different times (usually of lower resolution) of the same region, after attempting to correctly account for the different resolutions of images, and alignments. These sets of image subtractions associated with a single object will be used to detect the object as a transient and then classify the transient as a supernova . Clearly, this step of detecting a supernova depends on the number of such images recorded per object, the number of filters and the signal to noise ratio of these images. One might expect that the efficiency of this step may be summarized as a threshold on the joint properties of an astrophysical candidate (apparent brightness, light curve characteristics, background) as well as observing conditions (Seeing etc.).

Our second objective is to photometrically classify different kinds of supernovae **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.

Our third objective is to characterize supernovae in terms of empirical light curve models

The ultimate goal of using supernovae for a cosmology analysis (either SNIa or SNIIP) requires an estimate of the intrinsic brightness of the supernova. The first (and sometimes only step depending on the light curve model) to this, is to fit the calibrated fluxes to a light curve model with a set of parameters. According to the ansatz used in supernova cosmology, the intrinsic brightness of supernovae is largely determined by the parameters of the light curve model; hence the uncertainties on the inferred parameters largely determine the uncertainties on the inferred peak intrinsic brightness or distance moduli of the supernovae.

7.5.2 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

7.5.3 OpSim Analysis

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

As noted above the science goal of trying to characterize supernovae is largely dependent on how well the light curves of individual supernovae are sampled in time and filters. To study this, we reindex the opsim output on spatial locations rather than use the temporal index. There are different methods (which will be merged), and here we will first illustrate this in terms the cadence in an example LSST field.

7.5.4 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?

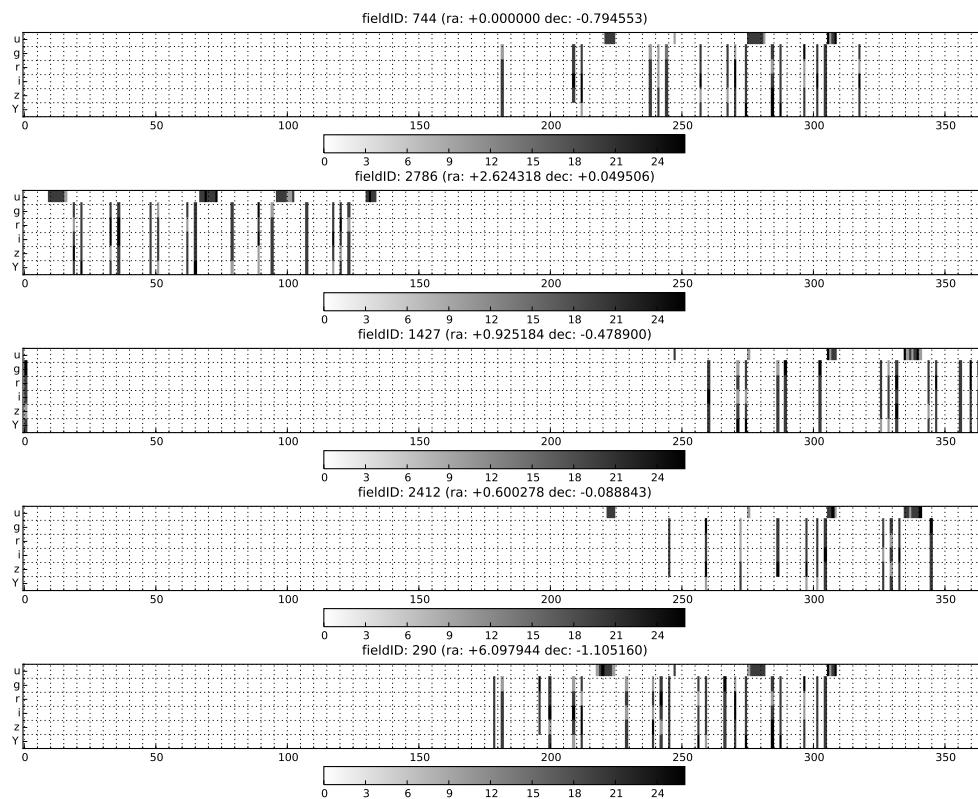


Figure 7.8: Cadence in different filters for a few LSST deep drilling fields in the the ouptut of OpSim version Enigma 1189. This ignores issues of chip gaps or overlaps between LSST. These issues have been addressed in ([Carroll et al. 2014](#)) and [Awan et.al. 2015, in preparation](#). We will add these to this analysis.

- Intrinsic Dispersion, environmental effects, newer analysis methods
- Follow-up procedures: What is feasible? Where will our training samples for classification and light curve models come from (other experiments, our own sub-samples with spectroscopic follow-up), spectroscopic follow-up of host galaxies. Can hosts be identified?
- ‘Systematics’: In what ways will the real data not match the assumptions made in analysis. Having a large sample of SN, to understand the astrophysics would be useful for this.

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7.6 Suppressing systematic effects

Much of cosmology science may be limited by systematic errors rather than photon signal-to-noise.

7.6.1 Target Measurements

It is expected that even after maximal optimization of camera optics and electronics, that systematic image shape errors will be associated with the orientation of the camera focal plane. These can be partially reduced by randomization of the orientation of the camera with respect to the sky. This is represented by the parameter RotSkyPos.

Similarly, the telescope optics may harbor systematic aberrations, and these also could be mitigated by recording images with varying parallactic angle. Another relevant parameter, RotTelPos, is indicative of the projected angle of the telescope optics on the sky.

7.6.2 Metrics

A metric is available for RotSkyPos. The metric computes, for any selected filter and simulation, a histogram of the distribution of rms values of RotSkyPos computed per field. It also computes basic statistics of these distributions.

7.6.3 OpSim Analysis

The distribution of rms values by filter is shown in Figure 7.9 for the current candidate baseline simulation, enigma_1189. As shown, the rms values cluster around the value 1 radian, with typical values 1 ± 0.3 radian. This compares to a completely uniform distribution over the half circle with an rms of 1.14.

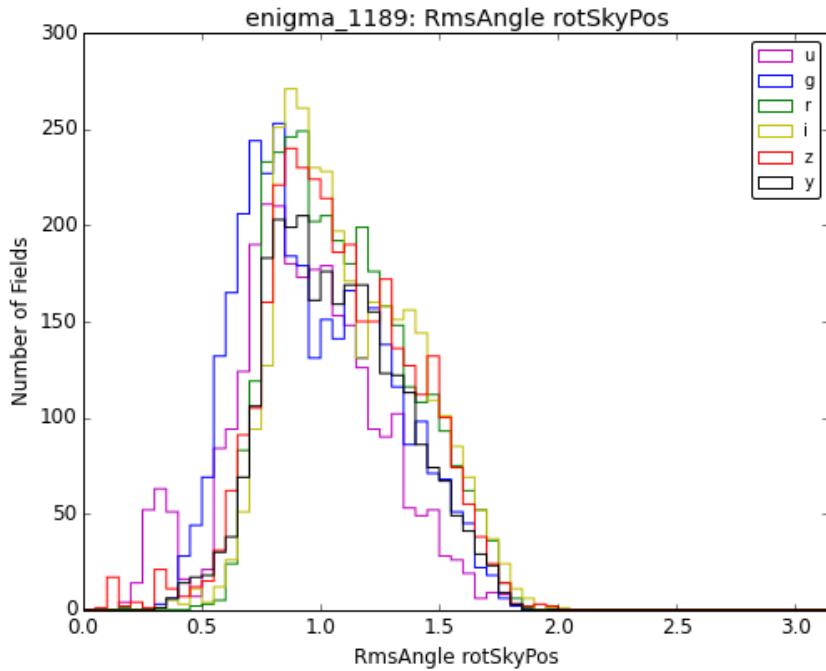


Figure 7.9: The relative angle of the detector plane with respect to the sky, RotSkyPos, as a histogram showing the number of fields vs. rms of the parameter.

7.6.4 Discussion

The RotSkyPos metric analysis shows that the majority of fields have a good randomization of detector angles projected on the sky.

There are several limitations to this observation.

First, we do not have at present a quantitative requirement for randomization of this parameter. In future development of weak lensing analysis, a criterion should be developed.

Second, a significant fraction of fields have median values that are lower or higher than expected for a random distribution, with some far from uniformly distributed. Regardless of the *per field* criterion, it is desirable to avoid the incidence of individual discrepant fields.

The recommended criterion for randomization of RotSkyPos is not the behavior of the majority of the fields, but of the minority with the least random behavior. The number of non-random fields should be minimized. A recommended metric is the count of fields with median RMS less than 0.8 or greater than 1.5 radians (these values to be reviewed again as additional experience is gained with additional OpSim schedule simulations and weak lensing analysis.)

A similar metric for RotTelPos should be developed. Other observing parameters may benefit from randomization, but are not presently recommended for metric analysis.

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

Niel Brandt, Lynn Jones

8.1 Introduction

9 Special Surveys

Knut Olsen, David Nidever, more to come

9.1 Introduction

The four main LSST science themes, as defined by the Science Book, drive the design of LSST’s main Wide-Fast-Deep survey. However, it has always been recognized that many important scientific projects, including some that are highly relevant to LSST’s main science themes, are not well served by the areal coverage and/or cadence constraints placed on the WFD survey. The LSST Project thus set aside a nominal 10% of the observing time to serve what are collectively called “special surveys”. In addition, the LSST commissioning period may be available for use by special programs. Projects that will certainly make use of this 10% time not dedicated to the WFD survey include the Deep Drilling fields and Galactic Plane surveys described separately in this paper, as well as any survey wishing to observe at declinations below -60° , such as the Magellanic Clouds. These special programs heavily oversubscribe the nominal 10% of time assigned to them. It is of thus critical importance for these programs to define compelling science cases, clearly justify their observing requirements, and derive metrics to quantify the performance of a given schedule for the program. An extra degree of freedom that these special surveys

As mentioned previously, the Deep Drilling and Milky Way plane surveys are described separately in this paper. In this section, we describe the goals of two special surveys designed to serve scientific goals related to the Magellanic Clouds. Descriptions of other special surveys, including candidate commissioning programs, are welcome here.

9.2 The Magellanic Clouds

David L. Nidever, Knut Olsen

The Magellanic Clouds have always had outsized importance for astrophysics. They are critical steps in the cosmological distance ladder, they are a binary galaxy system with a unique interaction history, and they are laboratories for studying all manner of astrophysical phenomena. They are often used as jumping-off points for investigations of much larger scope and scale; examples are the searches for extragalactic supernova prompted by the explosion of SN1987A and the dark matter searches through the technique of gravitational microlensing. More than 17,000 papers in the NASA ADS include the words “Magellanic Clouds” in their abstracts or as part of their keywords, highlighting their importance for a wide variety of astronomical studies.

An LSST survey that did not include coverage of the Magellanic Clouds and their periphery would be tragically incomplete. LSST has a unique role to play in surveys of the Clouds. First, its large $A\Omega$ will allow us to probe the thousands of square degrees that comprise the extended periphery of the Magellanic Clouds with unprecedented completeness and depth, allowing us to detect and map their extended disks, stellar halos, and debris from interactions that we already have strong evidence must exist (REFS). Second, the ability of LSST to map the entire main bodies in only a few pointings will allow us to identify and classify their extensive variable source populations with unprecedeted time and areal coverage, discovering, for example, extragalactic planets, rare variables and transients, and light echoes from explosive events that occurred thousands of years ago (REFS). Finally, the large number of observing opportunities that the LSST 10-year survey will provide will enable us to produce a static imaging mosaic of the main bodies of the Clouds with extraordinary image quality, an invaluable legacy product of LSST.

We propose two distinct mini-surveys to meet the goals of LSST Magellanic Clouds science:

- A mini-survey covering the 2700deg^2 with $\delta < -60$ to the standard LSST single-exposure depth and to stacked depths of XXX, with cadence sufficient to detect and measure light curves of RR Lyrae stars
- A mini-survey covering $\sim 250\text{deg}^2$ of the main bodies of the Clouds with cadence sufficient to detect exoplanet transits and other variable objects; a subset of these images should be taken with seeing of $0.5''$, with stacked depth reaching the confusion limits in the Clouds

These surveys will support several important scientific goals:

Two main overarching science themes:

1. **Galaxy formation evolution:** The study of the formation and evolution of the Large and Small Magellanic Clouds (LMC and SMC, respectively), especially their interaction with each other and the Milky Way. The Magellanic Clouds (MCs) are a unique local laboratory for studying the formation and evolution of dwarf galaxies in exquisite detail. LSST's large FOV will be able to map out the three-dimensional structure, metallicity and kinematics in great detail.
2. **Stellar astrophysics & Exoplanets:** The MCs have been used for decades to study stellar astrophysics, microlensing and other processes. The fact that the objects are effectively all at a single known distance makes it much easier to study them than in, for example, the Milky Way. LSST will extend these studies to fainter magnitudes, higher cadence, and larger area.

Many different types of objects and measurements with their own cadence “requirements” will fall into these two broad categories (with some overlap). These will be outlined in the next section.

A very important aspect of the “galaxy evolution” science theme is not just the cadence but also the sky coverage of the Magellanic Clouds “mini-survey”. A common misunderstanding is that the MCs only cover a few degrees on the sky. That is, however, just the central regions of the MCs akin to the thinking of the Milky Way as the just the bulge. The full galaxies are actually much larger with LMC stars detected at $\sim 21^\circ$ (~ 18 kpc) and SMC stars at $\sim 10^\circ$ (~ 11 kpc) from their respective centers. The extended stellar debris from their interaction likely extends to even larger distances. Therefore, to get a complete picture of the complex strucure of the MCs will

require a mini-survey that covers $\sim 2000 \text{ deg}^2$. At this point, it is not entirely clear how to include this into the metrics. Note, that for the second science case this is not as much of an issue since the large majority of the relevant objects will be located in the high-density, central regions of the MCs.

9.2.1 Target measurements and discoveries

1. Deep Color Magnitude Diagrams
2. Proper Motions
3. Variable stars
4. Transients
5. Transiting Exoplanets
6. Astrometric binaries
7. Gyrochronology
8. Astroseismology

9.2.2 Metrics

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

9.2.3 OpSim Analysis

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

9.2.4 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?

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10 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.

References

- Bernstein, J. P., Kessler, R., Kuhlmann, S., Biswas, R., Kovacs, E., Aldering, G., Crane, I., D'Andrea, C. B., Finley, D. A., Frieman, J. A., Hufford, T., Jarvis, M. J., Kim, A. G., Marriner, J., Mukherjee, P., Nichol, R. C., Nugent, P., Parkinson, D., Reis, R. R. R., Sako, M., Spinka, H., & Sullivan, M. 2012, *ApJ*, 753, 152
- Butler, N. R. & Bloom, J. S. 2011, *AJ*, 141, 93
- Campbell, H., D'Andrea, C. B., Nichol, R. C., Sako, M., Smith, M., Lampeitl, H., Olmstead, M. D., Bassett, B., Biswas, R., Brown, P., Cinabro, D., Dawson, K. S., Dilday, B., Foley, R. J., Frieman, J. A., Garnavich, P., Hlozek, R., Jha, S. W., Kuhlmann, S., Kunz, M., Marriner, J., Miquel, R., Richmond, M., Riess, A., Schneider, D. P., Sollerman, J., Taylor, M., & Zhao, G.-B. 2013, *ApJ*, 763, 88
- Carroll, C. M., Gawiser, E., Kurczynski, P. L., Bailey, R. A., Biswas, R., Cinabro, D., Jha, S. W., Jones, R. L., Krughoff, K. S., Sonawalla, A., & Wood-Vasey, W. M. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9149, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 0
- Chelouche, D. 2013, *ApJ*, 772, 9
- Chelouche, D., Shemmer, O., Cotlier, G. I., Barth, A. J., & Rafter, S. E. 2014, *ApJ*, 785, 140
- Chelouche, D. & Zucker, S. 2013, *ApJ*, 769, 124
- Guy, J., Astier, P., Baumont, S., Hardin, D., Pain, R., Regnault, N., Basa, S., Carlberg, R. G., Conley, A., Fabbro, S., Fouchez, D., Hook, I. M., Howell, D. A., Perrett, K., Pritchett, C. J., Rich, J., Sullivan, M., Antilogus, P., Aubourg, E., Bazin, G., Brionner, J., Filhol, M., Palanque-Delabrouille, N., Ripoche, P., & Ruhlmann-Kleider, V. 2007, *A&A*, 466, 11
- Hlozek, R., Kunz, M., Bassett, B., Smith, M., Newling, J., Varughese, M., Kessler, R., Bernstein, J. P., Campbell, H., Dilday, B., Falck, B., Frieman, J., Kuhlmann, S., Lampeitl, H., Marriner, J., Nichol, R. C., Riess, A. G., Sako, M., & Schneider, D. P. 2012, *ApJ*, 752, 79
- Ivezic, Z., Tyson, J. A., Allsman, R., Andrew, J., Angel, R., & for the LSST Collaboration. 2008, ArXiv e-prints
- Jha, S., Riess, A. G., & Kirshner, R. P. 2007, *ApJ*, 659, 122
- Kaczmarszak, M. C., Richards, G. T., Mehta, S. S., & Schlegel, D. J. 2009, *AJ*, 138, 19
- Kessler, R., Bassett, B., Belov, P., Bhatnagar, V., Campbell, H., Conley, A., Frieman, J. A., Glazov, A., González-Gaitán, S., Hlozek, R., Jha, S., Kuhlmann, S., Kunz, M., Lampeitl, H., Mahabal, A., Newling, J., Nichol, R. C., Parkinson, D., Philip, N. S., Poznanski, D., Richards, J. W., Rodney, S. A., Sako, M., Schneider, D. P., Smith, M., Stritzinger, M., & Varughese, M. 2010a, *PASP*, 122, 1415
- Kessler, R., Conley, A., Jha, S., & Kuhlmann, S. 2010b, ArXiv e-prints
- Knights, M., Bassett, B. A., Varughese, M., Hlozek, R., Kunz, M., Smith, M., & Newling, J. 2013, *JCAP*, 1, 39
- Kunz, M., Bassett, B. A., & Hlozek, R. A. 2007, *Phys. Rev. D*, 75, 103508
- Liao, K., Treu, T., Marshall, P., Fassnacht, C. D., Rumbaugh, N., Dobler, G., Aghamousa, A., Bonvin, V., Courbin, F., Hojjati, A., Jackson, N., Kashyap, V., Rathna Kumar, S., Linder, E., Mandel, K., Meng, X.-L., Meylan, G., Moustakas, L. A., Prabhu, T. P., Romero-Wolf, A., Shafieloo, A., Siemiginowska, A., Stalin, C. S., Tak, H., Tewes, M., & van Dyk, D. 2015, *ApJ*, 800, 11
- Mosquera, A. M. & Kochanek, C. S. 2011, *ApJ*, 738, 96
- Newling, J., Bassett, B. A., Hlozek, R., Kunz, M., Smith, M., & Varughese, M. 2011, ArXiv e-prints
- Sako, M., Bassett, B., Becker, A., Cinabro, D., DeJongh, F., Depoy, D. L., Dilday, B., Doi, M., Frieman, J. A., Garnavich, P. M., Hogan, C. J., Holtzman, J., Jha, S., Kessler, R., Konishi, K., Lampeitl, H., Marriner, J., Miknaitis, G., Nichol, R. C., Prieto, J. L., Riess, A. G., Richmond, M. W., Romani, R., Schneider, D. P., Smith, M., SubbaRao, M., Takanashi, N., Tokita, K., van der Heyden, K., Yasuda, N., Zheng, C., Barentine, J., Brewington, H., Choi, C., Dembicky, J., Harnavek, M., Ihara, Y., Im, M., Ketzeback, W., Kleinman, S. J., Krzesiński, J., Long, D. C., Malanushenko, E., Malanushenko, V., McMillan, R. J., Morokuma, T., Nitta, A., Pan, K., Saurage, G., & Snedden, S. A. 2008, *AJ*, 135, 348
- Sako, M., Bassett, B., Connolly, B., Dilday, B., Cambell, H., Frieman, J. A., Gladney, L., Kessler, R., Lampeitl, H., Marriner, J., Miquel, R., Nichol, R. C., Schneider, D. P., Smith, M., & Sollerman, J. 2011, *ApJ*, 738, 162

Chapter 10: References

Sluse, D. & Tewes, M. 2014, *A&A*, 571, A60