LSST & NOAO
Observing Cadences Workshop

Phoenix, Arizona

August 11 – 15, 2014

Observing Cadences Workshop

Summary

This first observing cadence workshop brought together project and community scientists concerned with the scheduling of the imaging visits that will constitute the LSST survey. The objectives were:

1. Establish the boundary conditions for possible LSST cadences;
2. Lay the foundation for future cadence exploration by establishing quantitative metrics for the performance of a given cadence for specific science cases, tied to LSST cadence simulations; and
3. Generate ideas for future cadence explorations and establish the goals of the next workshop on cadences.

The workshop was preceded by a half-day tutorial on the LSST schedule Metrics Analysis Framework (MAF) which is a powerful software environment and tool collection for study of data sets in general, and the LSST schedule in particular.

The main program began with a small number of prepared introductory talks, which described the boundary conditions on LSST schedules, and the status of schedule simulations. Steve Kahn, LSST Director, described in detail the current view on how the scheduling principles and priorities will be developed and applied to cadence decisions.

The workshop then began a series of breakout sessions. On the first day, the main breakouts were for consideration of Static targets and of Transient and Variable targets, and each of these large groups subdivided in a number of science-oriented topics for in-depth discussion of target types and observation requirements. Each discussion group considered the metric algorithms that could be used to evaluate simulated schedules for the targets of interest, and in some cases developed actual metrics code for the MAF environment and applied it to existing simulations.

The first breakout groups reported back to the plenary. Additional breakouts addressed a multiplicity of topics including: Mini-surveys, survey optimization, thinking outside the box, and coordination with other surveys.

At the last plenary, participants discussed the content of the oral report to the parallel LSST 2014 meeting, and of this report. Contributions provided by speakers and participants have been merged in the present document.

The workshop finally discussed the sequel to the workshop and planning for a next workshop. It was agreed that a nominally time for Observing Cadences Workshop II is approximately 1 year after the first. In addition, to provide a suitable technical basis for that workshop, the LSST schedule simulator should be by then producing rich variety of schedule options, including developments such as rolling cadences and look ahead, and the simulator should be available with documentation for community members who are willing to invest the effort to create simulations with it.

Observing Cadences Workshop

Table of Contents

Organizing Committee

- Richard Dubois (SLAC)
- Eric Gawiser (Rutgers)
- Zeljko Ivezic (U. Washington)
- Ashish Mahabal (CalTech)
- Stephen Ridgway (NOAO)
- Knut Olsen - Chair (NOAO)
- Michael Strauss (Princeton)
- Beth Willman (Haverford)

Basic Reference Materials

LSST Science Book, available from links at http://www.lsst.org/lsst/scibook.

LSST: from Science Drivers to Reference Design and Anticipated Data Products, available at http://arxiv.org/abs/0805.2366.

Metrics Analysis Framework documentation, available at https://confluence.lsstcorp.org/display/SIM/MAF+documentation.

LSST Science Requirements Document, available at http://www.lsst.org/files/docs/SRD.pdf

Workshop home page at https://project.lsst.org/meetings/ocw/.

Workshop presentations and reports at https://project.lsst.org/meetings/ocw/node/6.

Registered Participants

Marcel Agüeros
Lori Allen
Yusra AlSayyad
Gabriella Alvarez
George Angeli
Timo Anguita
Eric Aubourg
Deborah Bard
Felipe Barrientos
Andrew Becker
Eric Bellm
Dominique Boutigny
Patricia Burchat
Nat Butler
Guillermo Cabrera
Yi Cao
Srinivasan
Chandrasekharan
Nan-Chen Chen
Jim Chiang
Nora Chisari
Eric Christensen
David Ciardi
David Cinabro
Will Clarkson
Chuck Claver
Andrew Connolly
Kem Cook
Mike Cooper
Michael Coughlin
Bozena Czerny
Luiz da Costa
Peter Darch
Francisco Delgado
Richard Dubois
Gregory Dubois-Felsmann
Angelo Fausti
Henry Ferguson
Francisco Forster
Sebastien Foucaud
Emmanuel Gangler
Mark Giampapa
John Gizis
V. Zach Golkhou
Tommy Grav
Carl Grillmair
Robert Gruendl
Alan Harris
Arne Henden
Isobel Hook
Steve Howell
Jedidah Isler
Zeljko Ivezic
Savannah Jacklin
Darko Jevremovic
Ning Jiang
Hannibal Joma
Lynne Jones
Mario Juric
Jason Kalirai
Bryce Kalmbach
Vicky Kalogera
Shashi Kanbur
Mansi Kasliwal
Richard Kessler
Alex Kim
Peter Kurczynski
Tod Lauer
Michael Liu
Michael Lund
Ashish Mahabal
Renu Malhotra
Phil Marshall
Jennifer Marshall
Thomas Matheson
Walter Max-Moerbeck
Peregrine McGehee
Dave Meyer
Joshua Meyers
Dave Monet
Kavilan Moodley
Jonathan Myers
Scot Olivier
Knut Olsen
Kaike Pan
John Peterson
Catherine Petry
Francesco Pierfederici
Jane Price
Jayadev Rajagopal
Andy Rasmussen
John Rector
Jeonghee Rho
James Rhoads
Stephen Ridgway
Steve Ritz
Alexandre Roman-Lopes
Abhijit Saha
Evan Scannapieco
Robert Seaman
Jacques Sebag
David Silva
Warren Skidmore
R. Chris Smith
Verne Smith
William Smith
Gretchen Stahlman
Michael Strauss
Christopher Stubbs
Sherry Suyu
John Thorstensen
Tony Tyson
Kathy Vivas
Michal Vrastil
Lucianne Walkowicz
Beth Willman
Michael Wood-Vasey
Xiuqin Wu
Lin Yan
Peter Yoachim
Hu Zhan
Zhenya Zheng

Workshop Report

1 Introduction

The LSST design is driven by high-level requirements such as sky coverage, number of visits, stacked depth, image quality, efficiency, and so forth. Likewise, the Science Requirements Document, which governs the LSST development at the highest level, addresses primarily the "static" performance of the facility.

With the essential design decisions of the LSST thoroughly explored and approved, the major remaining science-driven decisions in the survey are the schedule of pointings and integrations – that is, the cadence of visits. The conceptual observing strategy for the LSST has been described in terms of a *universal cadence*, in which all parts of the sky in the wide-fast-deep survey are observed similarly – most simply in a pattern this is uniform through the full 10 years of the survey.

However, as a synoptic survey, in which the temporal variation of targets is of essential interest, the cadence options are very great even within a universal cadence, and much greater if some elements of uniformity are reconsidered.

Decisions on the LSST observing cadence will derive from the key science requirements, from simulations of performance and analysis, and from science community deliberations and input to the LSST project team. This workshop is the first, but will not be the last, venue for the community to review progress, contribute metrics, and formulate both formal and informal input to the project.

2 Workshop Motivation and Goals – Stephen Ridgway

2.1 Nature of the survey and the observing schedule

As a synoptic survey, the LSST science return will depend in large part on the temporal sequence of observations. As will be emphasized several times in this workshop, the actual observation sequence has not yet been determined. The high level requirements are explicit or implicit in the LSST Science Requirements Document, but great schedule flexibility remains in the detailed visit sequence, or cadence, which is so essential to study of time-variable targets. In fact, given the advanced status of the project at this time, the development of the telescope observing schedule is the principle opportunity for science input to the survey execution.

A schedule simulator (the Operations Simulator, or OpSim) has been in use since early in the LSST project, first to demonstrate survey feasibility, and subsequently to support engineering design and cost/performance trade-offs. Now as the project enters its formal construction phase, the lessons learned from the simulator will be used to construct the telescope scheduler. The simulator functionality will be needed throughout the survey, and the current plan is to utilize identical code for the scheduling algorithm heart of simulator and scheduler.

Scheduler/Simulator development is now at a level of maturity where participation of a wider community is timely – in fact it is essential, because currently existing requirements documents do not fully define the schedule metrics – in particular, the cadence metrics. This workshop is the first of an expected several, at which the project will report on the status and plans for the scheduler, solicit community advice and engage community participation.

2.2 Workshop goals

The workshop has explicit goals:

1. *Establish the boundary conditions for possible LSST cadences.* These are both physical (telescope design, location, etc), and scientific (required key science products)

2. *Lay the foundation for future cadence exploration by establishing quantitative metrics for the performance of a given cadence for specific science cases, tied to LSST cadence simulations.* For a synoptic survey, there is obvious merit in linking the cadence to the variability characteristics of the targets observed. For LSST, the richness of the phenomena precludes a simple, single analysis of the cadence requirement. The approach favoured for LSST is to utilize multiple merit functions designed by you, the science experts. These merit functions will be utilized to develop performance metrics – probably quite a few of them – which will serve to score the relative performance of simulated schedules, and hence to tune the scheduling algorithms to deliver the strongest possible cadence.

3. *Generate ideas for future cadence explorations and establish the goals of the next workshop on cadences.* Although OpSim has been in use for a number of years, the development of the algorithms is active and entering an important phase, with new capabilities. This is the time for innovative thinking. This workshop constitutes an invitation and a venue for contributing. Another workshop is planned as follow-up and to carry the work to the next level.

2.3 Workshop methods

A small number of prepared talks will communicate the cadence opportunities offered by the LSST survey.

The workshop will consist mainly of breakout sessions. The objective is to access scientific expertise for the critical evaluation of schedule products, and for tools to carry out that evaluation. The most successful outcome will be to develop metrics to measure the productivity of schedules for science. The metrics you provide *will* be used in testing scheduling algorithms and parameterization.

Of course the LSST survey will not do everything. The work of the next few days will help to identify competing objectives and define the measures which can support trades between them.

By the end of the workshop, we look forward to having the nucleus of an informed community that can contribute to and support the scheduling decision process.

Finally, one additional point will be emphasized several times. This workshop is not the time and place for scheduling decisions. At this time we are establishing the boundary conditions, building the tools and discussing the calculus. Shortly, Steve Kahn will discuss what is known about the timescale and process for bringing these components together for scheduling decisions.

But first, we will have a presentation by Andy Connolly on the use of simulations at LSST, and the history of OpSim.

3 Introduction to OpSim and Metrics planning – Andrew Connolly

The objective of the Operations simulator (OpSim) is to provide a tested and validated scheduler for the LSST that will be delivered prior to the start of commissioning in 2019. To accomplish this, OpSim is required to be able to test and evaluate scheduling strategies that prioritize which fields the LSST should observe during a night and over the duration of the survey. This prioritization must account for prior observations, weather (current and predicted), visibility of the fields, overhead in reaching a field (e.g. slew time, and filter exchange time), observing overrides for targets of opportunity, scheduled and unscheduled down time, and the optimization of a broad range of science merit functions. The cadence generated by these scheduler algorithms must also meet the requirements laid out for the survey in the LSST System Science Requirements Document (Document LPM-17: http://www.lsst.org/files/docs/SRD.pdf).

To accomplish this objective OpSim is being designed as a framework; one that can simulate the LSST observatory environment and telemetry and into which scheduling algorithms, that will subsequently be used by the Observatory Control System (OCS), can be integrated. The current requirements on OpSim are that it:

- provide a parameterized model for the observatory that describes the LSST opto-mechanical performance
- simulate the OCS telemetry streams that describe the state of the LSST system, the current and predicted weather, the astronomical sky conditions, prior observation history, and any over ride requests
- implement an API and communication model that is consistent with that used by the scheduler in the OCS.
- be capable of expressing and optimizing a broad range of technical and science metrics that have been provided by and/or vetted by the science community
- provide a framework for testing, validating and optimizing the scheduler module, and that can be installed and run by the science community

3.1 The development timeline for OpSim

OpSim development is phased to meet the needs of the project for the delivery of a tested and validated algorithm for scheduling the LSST prior to the start of commissioning. This includes the creation of the metrics and associated tools to evaluate the performance of the scheduler, a framework that generates the appropriate telemetry for the telescope, a pluggable scheduler that can be integrated with the OCS, the capability to generate sequences of simulated observations with different scheduling algorithms and configu-ations, and the ability for external users to be able to install and run OpSim and analyse its outputs.

3.1.1 FY2014 development

The FY2014 development focused on the first of these objectives; the ability to characterize and visualize the performance of a scheduler through the definition of a suite of science metrics. The prioritization of this component was driven by prior experience in scheduler development that stressed the need to be able to quantify how well an algorithm is performing through a set of cost functions or metrics, and for these metrics to be science-based, and developed and vetted either by the scientific community or in collaboration with the science community.

To accomplish this the Metric Analysis Framework (MAF) was created. MAF is an open-source python framework designed to provide a user-friendly, customizable, and easily-extensible set of tools for analyzing data sets from OpSim. The primary components of MAF are "metrics" (algorithms to analyze a given quantity of data), "slicers" (methods to subdivide a list of observations into smaller subsets that are appropriate for each metric), and database classes that can access and manipulate the outputs of OpSim runs. The design of MAF is described in MAF_documentation (https://confluence.lsstcorp.org/display/SIM/MAF+documentation) and tutorials for using, and developing with MAF are available at https://confluence.lsstcorp.org/display/SIM/MAF+Tutorials+for+Cadence+Workshop.

MAF was released to the LSST community in July 2014 and a tutorial session on the use of MAF was held during the 2014 cadence workshop.

3.1.2 FY2015 development

The current year of development (leading up to the 2015 cadence workshop) is focused on four areas: the refactoring of OpSim to provide a pluggable architecture that enables the OpSim scheduling code to be run by the OCS, the continued support of MAF and the enhancement of its capabilities for use by the science collaborations, the release of a new set of simulated cadence runs that can be analyzed with the MAF, and the delivery of OpSim to the LSST science community as a tool that they can install, configure, and run.

3.1.2.1 The refactoring of OpSim

The primary objective for 2015 is the redesign of OpSim to change it from a monolithic simulation program into a modular simulator of the LSST envronment and data streams, together with an associated scheduler. OpSim will replicate the API's and communication layers expected for the OCS scheduler. Communication will be based on the DDS (Data Distribution Service) protocol used by the OCS. Modules within OpSim will simulate the telemetry for current weather and forecasts, previous observations, and observatory status and provide a dynamical model of the LSST. The design of OpSim will be such that the code developed for the scheduler module will be capable of being plugged directly into the OCS. Delivery of the first implementation of the refactored simulator is expected in July 2014.

3.1.2.2 Improvements in the scheduling algorithms

Concurrent with the redesign of OpSim will be the expansion of the available scheduler algorithms and cadences deployed by OpSim. The working assumption for the LSST has been a universal cadence in a WFD (wide-fastdeep) main survey, in which all fields are observed with a similar cadence and pattern. A natural extension to this universal pattern is the "rolling cadence" where the region surveyed shifts as a function of time (Recent Cadence Experiments, in this report). This provides a denser time sampling for each region on the sky for part of the survey duration, at the cost less dense sampling during the rest of the survey. OpSim will be enhanced to support a rolling cadence (defined by regions on the sky or particular LSST pointings) with an expected delivery of March 2015

Extending beyond rolling cadence the current greedy algorithm deployed in OpSim will be enhanced with "look ahead". This enables the scheduler to

determine whether a proposed sequence of visits to a field can be completed within the time available (e.g. a revisit is required in 45 minutes but astrnomical twilight ends before hand). It is expected that look ahead should improve the efficiency of the scheduler (especially for observations later in the survey). Delivery of look ahead is scheduled for July 2015.

3.1.2.3 Optimization of Auxliary Proposals

OpSim currently uses one main proposal covering 18,000 square degrees where it attempts to deliver the SRD requested number of visits, two of the hard numbers in the SRD. OpSim can achieve the requested number of visits over the 18,000 square degrees in about 8 years, which leaves 20% of the survey time available for other survey strategies. OpSim currently implements non-Wide Fast Deep (WFD) science strategies with a variety of straw man auxiliary proposals. One proposal covers the ecliptic north of the equator (the north ecliptic spur, NES) to better catalog NEOs and PHOs. One proposal, covers the south celestial pole (SCP) region to sample the Magellanic Clouds and various south pole cosmology survey regions. Another proposal covers the Galactic plane (GP) with much fewer visits than the WFD because of the confusion limit in these dense stellar regions. Finally, there are a number of different Deep Drilling proposals which request large numbers of visits to a few fields in a short amount of time to sample the time domain and sample very faint variability (high-z supernovae). A significant effort in 2015, will be to optimize the use of the 20% of time available for auxiliary proposals. The current Deep Drilling proposals are based on the efforts of the Deep Drilling Working Group, but more interaction should lead to evolution of these cadences. Efforts to optimize the science from the NES, SCP and GP areas will be made with input from the community, and an overall optimization of the time allocation between the various auxiliary proposals will be sought. It should be noted that continuing optimization of various rolling cadences may address many of the science issues addressed by the auxiliary proposals.

3.1.2.4 Support of the MAF and OpSim communities

Development and support of MAF for the project and science community will continue. This includes the creation of a repository for storing and accessing metrics designed by the science collaborations (see https://github.com/LSST-nonproject/sims_maf_contrib).

com/LSST-nonproject/sims_maf_contrib) and a mechanism by which user defined metrics will be incorporated automatically within the analysis of subsequent OpSim runs. The core metrics for the project will be extended to include SRD metrics that will capture the science and cadence requirements as defined within the SRD.

In January 2015 a new set of OpSim runs will be released to the science collaborations using the latest version of OpSim (v3.2). These runs, collectively known as “Tier 1” are listed at https://confluence.lsstcorp.org/display/SIM/Cadence+Workshop+Simulated+Surveys. They provide a set of runs of OpSim using the existing v3.2 scheduling algorithm where the parameterization of survey (e.g. integration time, airmass limits, number of pairs of visits etc) are modified. The outputs from the MAF will be released with the Tier 1 runs.

In July 2015 a further sequence of runs will be released using the “rolling cadence” scheduling algorithms. These, “Tier 2” runs will be used to evaluate how the size of the rolling cadence patches and their sampling as a function of region on the sky and time interval effect the baseline metrics. As part of the delivery of the Tier 2 cadence runs OpSim will be released to the community with instructions for how it can be installed, configured, and run.

3.1.2.5 Support of the cadence 2015 workshop

The simulation team will continue to support MAF and OpSim and its use by the science collaborations leading up to and through the 2015 cadence workshop.

4 Brief history of cadence simulation and development – Andrew Connolly

4.1 Why build a simulation facility?

- Understanding the science performance
  - Extensive engineering simulation tools are used to develop the design of the LSST based on the science and system requirements
  - Detailed design tools but not coupled to the astrophysics of the sky
  - The simulator provides a representation of the LSST for science communi2es to develop their analyses prior to operations
- Prototyping the analysis
  - Detailed parametric, catalog, and image based simulations (coupled with existing data sets) are used to evaluate the performance of the analysis algorithms and the scaling of the compute systems
- Evaluating the as-delivered system
  - Understanding the impact of a single as-delivered component is complicated depending on astrophysics as well as the performance of the full system). Often the simplest approach through simulation

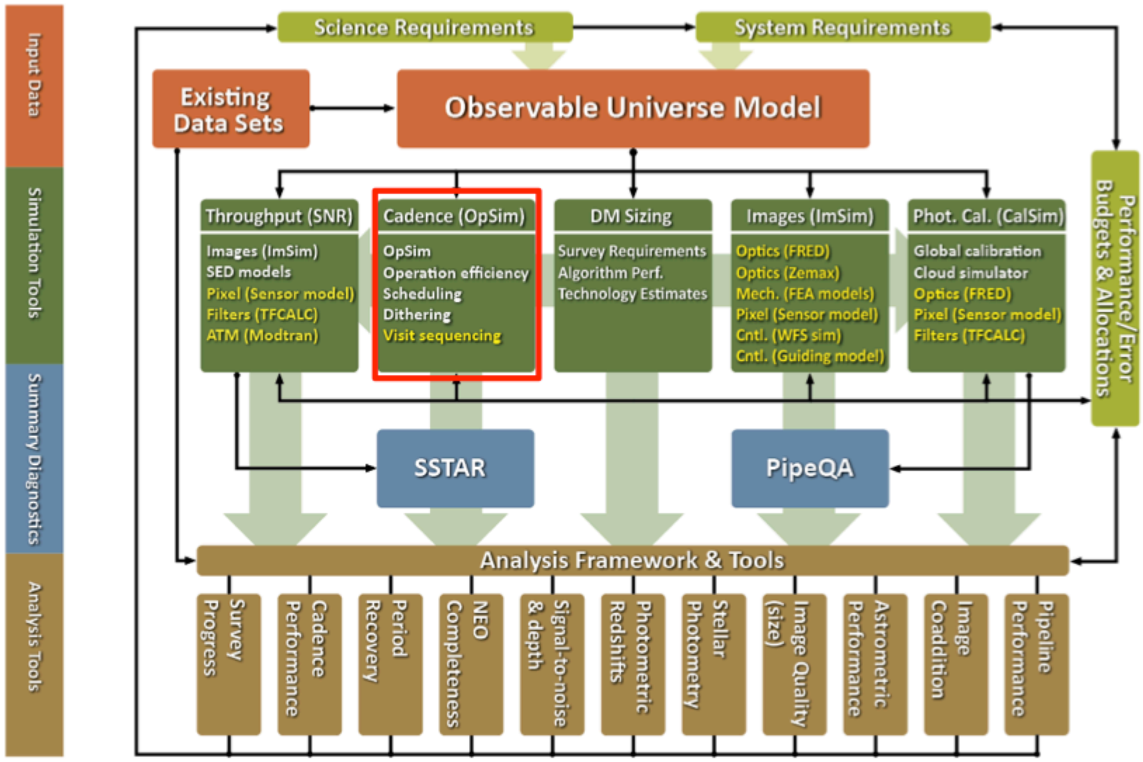


Figure. What is the LSST simulation framework?

4.2 The need for an operations simulation

- LSST survey is a 10 year observing campaign where an integrated set of observations address a variety of science goals requiring:
  - Area coverage (18000 sq degrees) and 'stacked' depth (824 visits per field)
  - Temporal cadence and baseline requirements
  - Photometric uniformity and accuracy
- Can such an observation set be delivered?
  - Must: Goals in the Science Requirements Document (SRD) – Desired: Additional meritorious goals
  - Simulations to find optimal strategy and maximize 'margin'
- How will such a survey be scheduled and conducted?
  - A real time Scheduler for the actual survey based on lessons learned from above

4.3 An adaptive simulation tool

- High fidelity model for limitations and operational overheads of telescope and instrument
- Ephemeris: time windows when a particular observation is possible – predictable time constraints
- `Models' for observing restrictions placed by weather and other downtime
- Optimization methods and algorithms that make operational decisions that maximally

deliver the desiderata given the constraints of telescope, instrument and environment
- Mechanism(s) for specifying science driven desiderata
- Metrics Analysis Framework:
  - tools that help diagnose the mechanics of the simulator in delivering the desiderata and can be used to develop figures of merit, metrics, and other representational forms
  - Tools that will be deployed to the community

4.4 OpSim Scheduler

4.4.1 Prototype implementation - greedy algorithm (search all fields and select one with the highest weight)

- Each science proposal selects candidate targets that comply with requirements for airmass, sky-brightness and seeing.
- Each proposal computes the scientific merit for each target according to distribution and cadence requirements.
- The observation scheduler combines all the targets and computes slew cost for each one
- Computes the overall rank and selects the best.

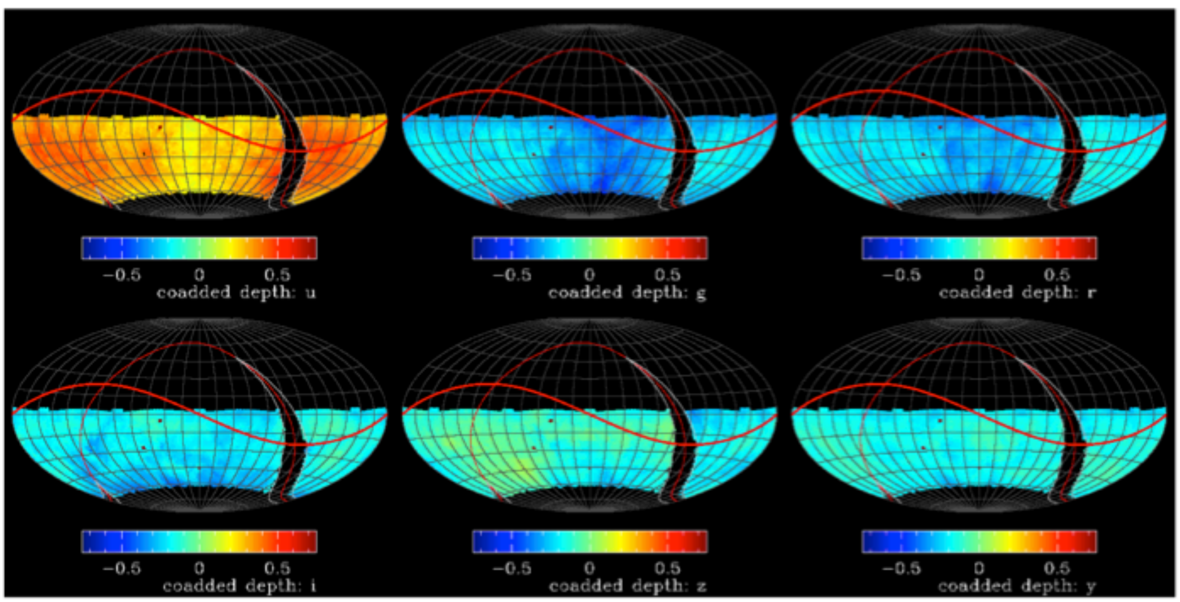


Figure. The prototype scheduler produces uniform distributions that meed many of the SRD goals

4.4.2 OpSim V3

- Optimization of the cost function is an open question for development over the next couple of years
- Dithering of the LSST fields

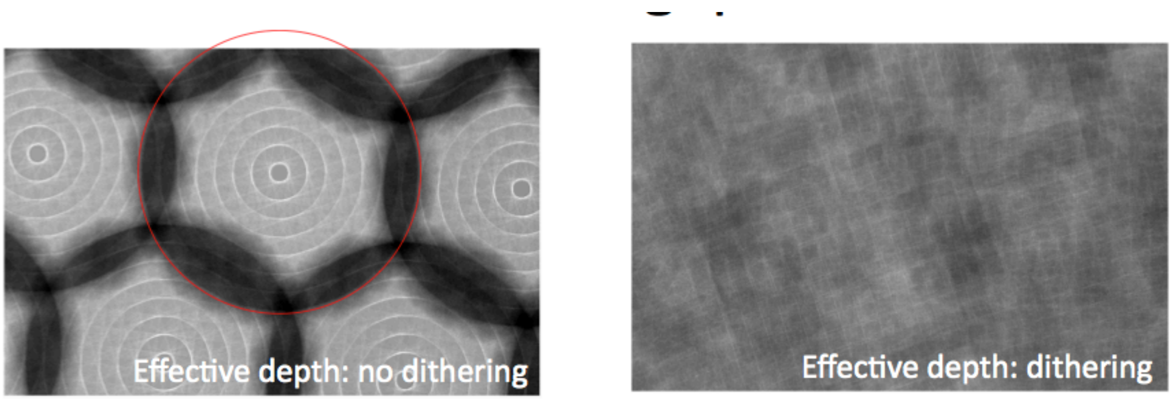


Figure. The dithering question. (Left) relative stacked image depth at the end of the survey without dithering, showing the effect of field overlaps. (Right) the relative depth with dithering, as revealed with MAF HEALpix analysis.

4.4.3 Status and future plans

- Release and support of MAF (August 2014)
    - Basic metrics and functionality
    - Extensible in terms of metrics and OpSim runs
    - We want you to work to develop and deliver metrics (a hosting
    - mechanism will be provided to support these metrics)
- Release of photometry and SNR packages (November 2014)
    - Generation of photometric measurements for sources in LSST bands
- Documentation and release of OpSim (June 2015)
    - Installation and documentation
    - Support for changes to the configuration parameters
    - Possible implementation of a facility to run OpSim

5 Process for deciding on cadence – Steve Kahn

LSST is first and foremost a time-domain facility. We have designed the telescope and camera to enable a large number of “visits” (~ 1000) over ten years for nearly every part of the southern sky. However, we have a lot of freedom as to how we distribute those visits in time. We can cover large areas of sky at slower cadence, or smaller areas of sky at higher cadence, or some combination of both. The science enabled by this facility is broad, ranging from studies of small objects in the solar system to the structure and evolution of the universe as a whole. Different science investigations will be helped or hurt by different cadence choices. Therefore, the strategy that we adopt will involve some compromises, and will necessarily involve an optimization over a diverse array of criteria.

We want to work with the community to understand how to perform that optimization. This meeting is the start of that process.

A somewhat remarkable aspect of the LSST design is that we can accomplish a broad range of science investigations with a single common survey, i.e. that we do not have to divide up the observing time into separate surveys optimized for different science goals. We call this "massively parallel astrophysics". This is a direct consequence of the high etendue. At slower survey speed, we would either suffer from inadequate depth or too long intervals between visits for many of the key science programs.

To verify that this works in detail, we developed the Operations Simulator we currently have, taking explicit account of the statistical properties of the weather and seeing conditions on the site, and the time inefficiencies associated with slews to subsequent fields, changes of filter, etc. The original Operations Simulator constructed a "uniform survey", optimizing the uniformity in the number of visits across the sky in the various colors with maximum efficiency.

The resulting visits are approximately Poisson-distributed in time. As hoped, this exercise showed that it is feasible to achieve the desired visit distribution with our hardware design.

Further investigation has now shown that while the uniform survey meets many of our science goals, it is not optimal for some. That has caused us to reconsider our cadence strategy. Nevertheless, the basic concept of having most of the LSST observing time devoted to "one survey" remains an important guiding principle.

5.1 Process moving forward

- Work with the community to define quantitative metrics for different science investigations.
- Experiment with different cadence strategies to develop a heuristic understanding of how these metrics depend on particular approaches.
- Use the results of those investigations to develop a global metric that can be optimized by the scheduler.
- Investigate the technical issues involved in trying to construct a scheduler that can optimize that global metric. May require a "vernier approach". This is not a trivial problem, and may not be feasible within the resource envelope that the Project can devote to the scheduler. If that turns out to be the case, we will use the heuristic understanding we have gained to come up with a more manageable approach.
- Define a process to evolve the cadence strategy with community input over the life of the mission.

5.2 How will we arrive at a concrete plan?

- The appropriate weighting of metrics associated with the global optimization is question of science policy, not a technical question. The Project will formally engage the community in making such policy decisions through its Science Advisory Committee. The membership and deliberations of the SAC will be public, so there is ample room for community input to them as well as directly to the Project leadership.
- The Project Science Team will provide the primary internal body within the LSST Project that will evaluate the trades between the science gain associated with the choice of a given global metric and the technical difficulties in building a scheduler that can optimize that metric. This requires an understanding of both the scientific and technical issues,

and the PST provides the appropriate mix of expertise.

- The Telescope & Site Team within the Project has formal responsibility for developing and implementing the actual scheduler. They must respond to programmatic constraints in addition to the science guidance coming from the PST. If there are conflicts, the Director, Project Manager, and Project Scientist will make the decision.
- Once a clear plan has been established, we will present it back to the Science Advisory Committee for comment and endorsement
- During operations, the performance of the system and the discoveries coming from LSST data must be taken into account. That will increase the complexity of the decision-making process. At that point, we might appoint a standing Cadence Optimization Committee to review the plan on an annual or subannual basis. The details of how this might work need further definition, and are likely to be clarified in the operations proposal that we submit to the agencies in the 2016-17 timeframe.

5.3 Conclusion

- Do not be concerned that crucial "cadence decisions" have already been made by LSST. This is not true. We have worked some strawman examples, but there is plenty of time for further iteration.
- There are very few (but not zero) elements of the hardware design that strongly constrain the cadence strategy. We designed for flexibility, and we have largely achieved that goal.
- However, the technical challenges of designing a scheduler that can optimize a complex global metric should not be underappreciated. Once we have arrived at an understanding of what we want to do, we still need to figure out how to do it, and what it will cost to do it. That is where programmatic constraints may come in.
- There are both formal and informal mechanisms for interested members of the community to engage with us in these investigations. It is an interesting and exciting problem. We look forward to working with you.

6 Constraints on LSST cadence parameters – Ẑeljko Ivezić

6.1 The main goal

To review the most important cadence constraints, how we arrived to the current "baseline cadence", and why we (Project and stakeholders) want to explore its modifications.

6.2 What is LSST? A uniform sky survey

LSST in one sentence: An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 1000 visits over a 10-year period: deep wide fast.

- ~90% of time will be spent on a uniform survey: every 3-4 nights,
- The whole observable sky will be scanned twice per night !
- After 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky!
- ~100 PB of data: about 2.5 million 3.2 Gpix images (visits), enabling measurements

for 40 billion objects

Parts of this chapter have been abridged. For details of this and the following sub-sections, see the Constraints on Cadence Parameters slide set –

https://project.lsst.org/meetings/ocw/sites/lsst.org.meetings.ocw/files/IvezicCW.pdf

6.3 Flowdown of science goals to system requirements

Any given science program drives numerous system parameters. Any given system parameter can have impact on numerous science programs. Science goals and parameters are connected through and communicate via, data properties. The Science Requirements Document (SRD) specifies data properties needed to achieve science goals.

6.4 Science Requirements Document (SRD) specifications for cadence

At the highest level, the LSST objectives are:

1. Obtain about 2.5 million visits, with 189 CCDs (4k x 4k) in the focal plane; this is about *** a billion 16 Megapixel images of the sky ***, with characteristics as specified in the SRD (2 images/visit)
2. Calibrate these images (and provide other metadata), with characteristics as specified in the SRD
3. Produce catalogs ("model parameters") of detected objects (37 billion), with characteristics as specified in the SRD
4. Serve images, catalogs and all other metadata, that is, LSST data products to LSST users and other stakeholders.

The ultimate deliverable of LSST is not just the telescope, nor the camera, but the fully reduced science-ready data as well.

As a result of early cadence studies, the adopted baseline design(Appendix A of the SRD) assumes a 10-year duration with about 90% of the observing time allocated for the main LSST survey.

Section 3.4 of the SRD, "The Full Survey Specifications", is *intentionally vague.* We plan to optimize the ultimate LSST cadence to reflect the state of the field at the time of system deployment (but note that it is anticipated that the deep-wide-fast aspects of the main survey will not change much).

6.4.1 Ennumerated specifications

SRD Table 22 (below). The sky area uniformly covered by the main survey will include Asky square degrees:

Quantity	Design Spec	Minimum Spec	Stretch Goal
Asky (deg^2)	18,000	15,000	20,000

SRD Table 23 (below). The sum of the median number of visits in each band across the sky area specified by

Asky, will not be smaller than Nv1:

Quantity	Design Spec	Minimum Spec	Stretch Goal
Nv1 sum all filters	825	750	1000

SRD Table 24 (below) provides an *illustration* of the distribution of the number of visits as a function of band-pass, obtained by detailed simulations of LSST operations that include realistic weather, seeing and sky brightness distributions, as well as allocation of about 10% of the total observing time to special programs. The median number of visits per field for all bands is 824. For convenience, the numbers in parentheses show the corresponding gain in depth (magnitudes), assuming √N scaling. The last row shows the total idealized coadded depth for the design specification median depth of a single image (assuming 5σ depths at X = 1 of u = 23.9, g = 25.0, r = 24.7, i = 24.0, z = 23.3 and y = 22.1, from Table 6), and the above design specification for the total number of visits. The coadded image depth losses due to airmass greater than unity are not taken into account. For a large suite of simulated main survey cadences, they are about 0.2-0.3 mag, with the median airmass in the range 1.2-1.3.

Quantity	U	G	R	I	Z	y
Nv1 per filter (Design spec)	56 (2.2)	80 (2.4)	184 (2.8)	184 (2.8)	160 (2.8)	160 (2.8)
Idealized depth	26.1	27.4	27.5	26.8	26.1	24.9

Photometric redshifts: random errors smaller than 0.02, bias below 0.003, fewer than 10% >3σ outliers.

These photo-z requirements are one of the primary drivers for the photometric depth and accuracy of the main LSST survey (and the definition of filter complement)

Photo-z requirements correspond to r~27.5

The distribution of visits in time is intentionally vague. As described in SRD Table 25, at least RVA1 square degrees will have multiple observations separated by nearly uniformly sampled time scales ranging from 40 sec to 30 min:

SRD Table 25 (below). The minimum area with fast (40 sec – 30 min) revisits.

Quantity	Design Spec	Minimum Spec	Stretch Goal
Rva1 (deg^2)	2,000	1,000	3,000

The distribution of visits in time is also implicitly constrained by the astrometric requirements, as the measurement of proper motion benefits from visits early and late in the survey, and the measurement of parallax benefits from visits early and late in the observing season for each target.

SRD Table 26 (below). The required trigonometric and proper motion accuracy.

Quantity	Design Spec	Minimum Spec	Stretch Goal
SIGpara (mas)	3.0	6.0	1.5
SIGpm (mas/yr)	1.0	2.0	0.5
SIGparaRed (mas)	6.0	10.0	3.0

6.5 Cadence conservation laws

How can we optimize the main deployment parameters: exposure time per visit, $\mathbf{t_{vis}}$, single-visit depth, $\mathbf{m_5}$, the mean revisit time, $\mathbf{n_{revisit}}$, and the number of visits, $\mathbf{N_{vis}}$?

While each of these four parameters has its own drivers, they are not independent (scaled to nominal LSST):

$\mathbf{m_5}$ = 24.7+1.25*log($\mathbf{t_{vis}}$ / 30 sec)

$\mathbf{n_{revisit}}$ = 3 days * ($\mathbf{t_{vis}}$ / 30 sec)!

$\mathbf{N_{vis}}$ = 1000 * (30 sec / $\mathbf{t_{vis}}$) * (**T** / 10 years)

The total observing time per position is ~7 hours for ugrizy.

6.5.1 How do we split allocations into individual visits?

Direct and indirect constraints on the shortest and longest acceptable exposure time per visit span a remarkably narrow range.

- Lower limit:
  - Surveying efficiency must be high enough
    - (readout time, slew & settle time)
  - Depth per visit must be deep enough
    - (SNe, RR Lyrae, NEOs)
- Upper limit:
  - The mean revisit time cannot be too long
    - (SNe, NEOs)
  - The number of visits must be large enough
    - (light curves, systematics, proper motions)
  - (Trailing losses for moving objects)
- These bounds determine: 20 sec < $\mathbf{t_{vis}}$ < 40 sec for the main survey. (See section 2.2.2 in the “overview” paper, arXiv:0805.2366)
- The default is taken as $\mathbf{t_{vis}}$ = 30 sec
- However, *there is no fundamental reason why* $\mathbf{t_{vis}}$ *should be exactly the same for all*

visits (i.e. filters, programs)

- *Out of the box thinking is highly encouraged!*
- But there are short-exposure boundaries
  - The fastest sustained frame rate to guarantee standard performance is about one exposure per 13 sec.
  - The shortest possible exposure time will be about 1 sec (SRD stretch goal; design spec. is 5 sec).
  - A faster frame rate may cause a loss in data quality (due to heat dissipation, etc).
  - The project will not do detailed studies of these effects until a strong science case is identified that would be enabled by faster sustained frame rates.

6.5.2 How do we determine the sky area observed?

For the main survey, maximize the number of objects (area vs. airmass tradeoff). X< 1.4 corresponds to -75° < Dec < +15° (25,262 deg^2).

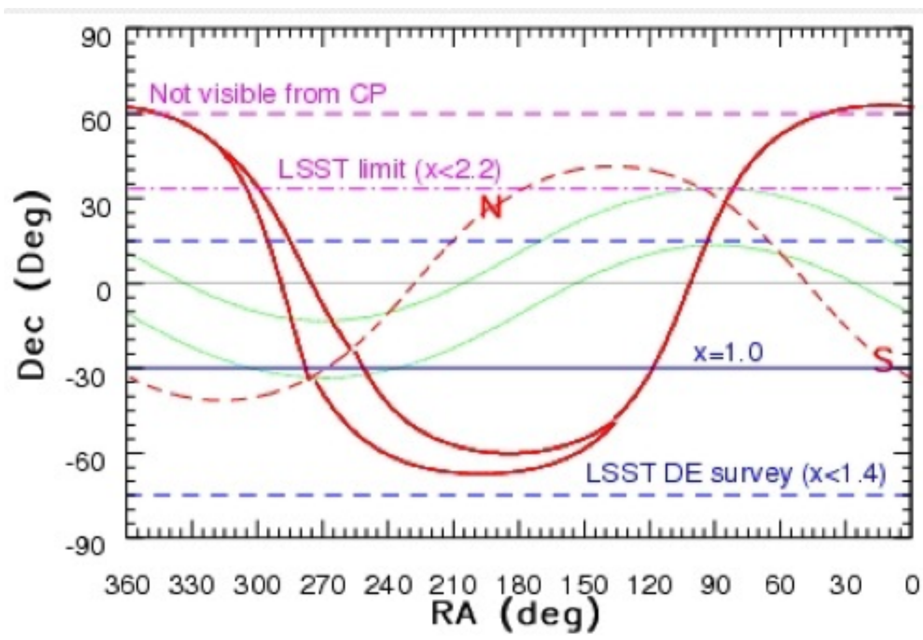


Figure. The LSST sky in equatorial coordinates.

6.6 Current baseline cadence

The current baseline cadence is designated opsim3.61 (the 61st simulation run on computer opsim3).

This is a 10-year simulation "existence proof" for an LSST survey.

6.6.1 Basic characteristics of simulation opsim3.61

- Observing starts/stops at 12 degree twilight
- CTIO 4m weather log as weather model

- Telescope model and scheduled downtime for maintenance - u filter in camera ~ 6 days per lunation
  - Utilizes 5 science proposals:
  - WideFastDeep: Universal Cadence
  - Galactic plane: collect 30 visits in each filter
  - North ecliptic: Universal Cadence
  - South Pole: collect 30 visits in each filter
  - 6"deep drilling" fields for SNe (100-day sequences with visits every 5 days in grizy)
- Baseline cadence always uses $\mathbf{t_{vis}}$ = 30 seconds!

6.6.2 Features of the opsim3.61 simulated schedule

- 1,651,588 total visits
- 20,000 square degrees: 75% Wide-Fast-Deep (WFD)
  - 1030 requested visits in urgizy
  - 656,687 requested pairs in ugrizy
  - ~6 pairs per field per lunation
- 4,000 square degrees: 12% in the Northern Ecliptic spur (NES)
  - 41.774 pairs of griz with 15-60 minute separation
  - ~2 pair per field per lunation
- 1,900 square degrees: 7% in the Galactic bulge/Plane (Gal)
  - 30 visits in ugrizy each
- 23 perfect deep 100 day supernova sequences (SN), 170 incomplete for 7 fields
- Excellent period recovery for periodic variables
- Quite efficient: 6.4 second average slew (1.02 seconds due to filter change). OpSim3.61 produced 2.65 million visits. This gives a margin (to the SRD requirement_ of ~18% (not including margins form expected depths)

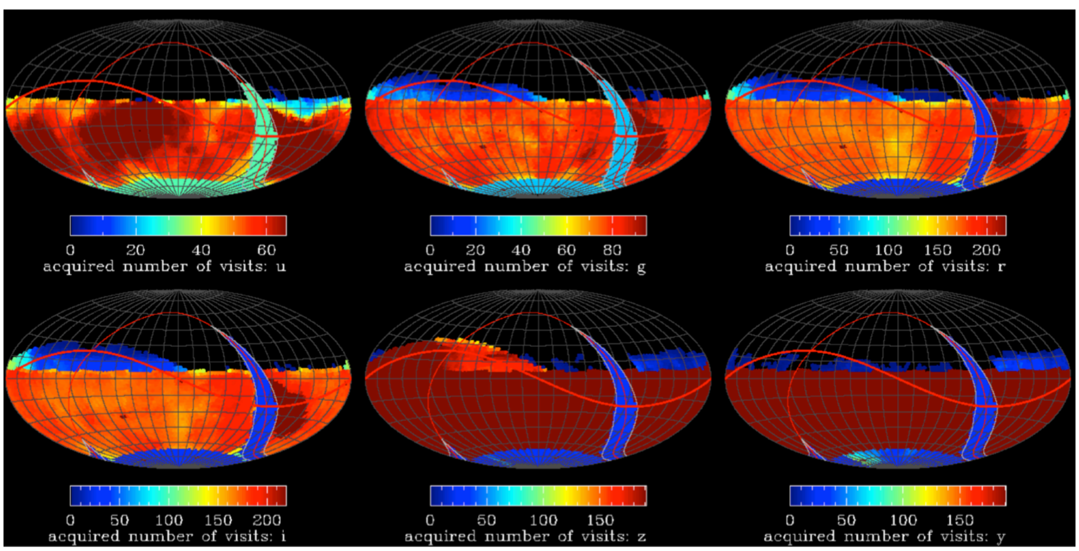


Figure. The number of visits acquired for each field is plotted in Aitoff projection for each filter. All visits

acquired by all observing modes are included in this plot.

- Median 5-σ depth (for all visits). OpSim give variation around the nominal depth due to seeing, sky brightness, and airmass variations. The nominal value is given as input to OpSim, with the best C_m estimates (see below). The following figure shows the achieved median depths with respect to the nominal.

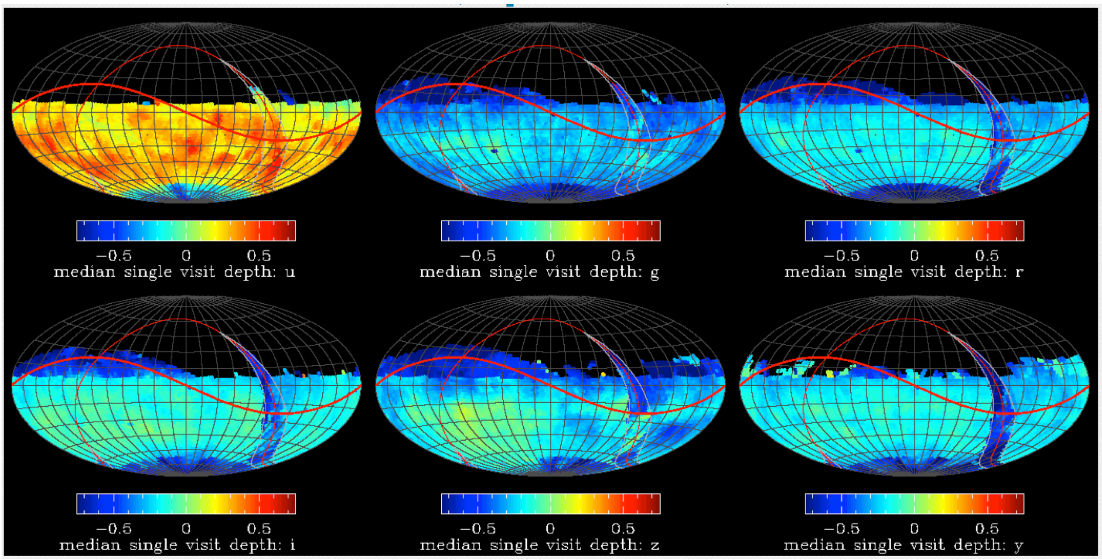


Figure. The median single visit depth for all visits to all fields in simulation opsim3.61, with respect to the SRD nominal values.

- The limiting image depth (for point sources)
  - The limiting image depth (ability to detect faint sources) includes a complex interplay between system capability, system deployment, and observing conditions (generalization of "collecting area")
  - Instead of "Collecting Area", a full expression for 5-σ image depth: coupling of atmospheric, system, and deployment parameters:
  - $\mathbf{M_5} = \mathbf{C_m} + 2.5*\log[0.7/(\theta_{atm}^2 + \theta_{sys}^2)^{1/2}] +$

    $+ 1.25*\log(\mathbf{t_{vis}}/ 30\text{ sec}) + 0.50(\mathbf{m_{sky}}-21) - \mathbf{k_m}(X-1)$
  - here $\mathbf{m_{sky}}$ is sky brightness, θ is seeing (in arcsec), X is airmass, and $\mathbf{k_m}$ is atmospheric extinction coefficient
  - **the collecting area, the system throughput, and the system noise enter only via a scaling coefficient Cm** (more details in LSE-40)
  - N.B. we can increase $\mathbf{t_{vis}}$ to go deeper, but then we get fewer visits.
  - given the difference between $\mathbf{C_m}$ and its nominal value, and all other parameters at their nominal values, then an "effective open-shutter time" metric is

log(f2) = 0.8*($\mathbf{M_5}$ - $\mathbf{M_5}$nominal)

- excellent high-level metric for engineering and science tradeoffs
    - caveat: $\mathbf{C_m}$ for the u band depends a bit on $\mathbf{t_{vis}}$ (readout noise)

- Progress toward survey goals – main performance metrics as a function of time
    - Co-added survey depth:
        - m5(t) = m5Final +1.25*log(t / 10 yr)
    - Photometric errors at i=25 (4 billion galaxy sample):
        - σph(t) = 0.04 mag * (t / 10 yr)(-1/2)
    - Trigonometric parallax errors at r=24:
        - σπ(t) = 3.0 mas * (t / 10 yr)(-1/2)
    - Proper motion errors at r=24:
        - σμ(t) = 1.0 mas/yr * (t / 10 yr)(-3/2)
    - DETF FOM (FOMFinal ~750):
        - FOM(t) = FOMFinal * (t / 10 yr)
    - NEO (140m) completeness (tNEO~4 yrs; CNEO~93%):
        - C(t) = CNEO* (1-exp[-(t / tNEO)(3/4)])
    - And many other (e.g., the faint limit for period recovery of short-period variables, KBO and main-belt asteroid completeness)...
    - LSST design and performance analysis is based on sophisticated simulations but these scaling laws and resulting trade-offs offer basis for quick and robust multi-dimensional trade analysis of various "what if" scenarios.
- Performance as a function of survey duration

Table. Various science metrics as functions of survey duration

Quantity	Year 1	Y3	Y5	Y8	Year 10	Y12
r_5 coadd[a]	26.3	26.8	27.1	27.4	27.5	27.6
$\sigma(i{=}25)$[b]	0.12	0.07	0.06	0.05	0.04	0.04
color vol.[c]	316	20	6	1.7	1	0.6
# of visits[d]	83	248	412	660	825	990
σ_π $(r{=}24)$[e]	9.5	5.5	4.2	3.3	3.0	2.7
σ_μ $(r{=}24)$[f]	32	6.1	2.8	1.4	1.0	0.8

- Between years 1 and 10: 1.2 mag deeper, 30x better proper motions
- While unprecedented science outcome will definitely be possible even with a first few years of LSST data, the complete planned and designed for science deliverables will require 10-years of data, with a tolerance of at most about 1-2 years.
- Should we "front load" some science programs?

6.7 Continuing baseline cadence optimization

6.7.1 Drivers for baseline cadence modifications

- Improved knowledge of the system (now due to simulations, eventually due to performance measurements)
- Changing science landscape on timescales of a few years
- Unscheduled technical delays or substandard performance (e.g. broken filter, dead CCD, extra noise)
- Even 10% improvement in surveying efficiency would be significant accomplishment (c.f. entire DD observing time)

6.7.2 Potential optimization directions

- Minimizing the impact of read-out noise (mostly in u band)
- Optimizing sky coverage (Galactic plane, south celestial pole, LMC/SMC, Ecliptic)
- Temporal sampling (SNe, variable stars, asteroids)
- Interplay between sky coverage and temporal sampling - deep drilling fields
- Dynamic cadence (in response to expected SNR)
- Evolving cadence (in response to science drivers)
- Minimizing the impact of read-out noise (mostly in u band)
- Optimizing sky coverage (Galactic plane, south celestial pole, LMC/SMC, Ecliptic)
- Temporal sampling (SNe, variable stars, asteroids)
- Interplay between sky coverage and temporal sampling - deep drilling fields
- Dynamic cadence (in response to expected SNR)
- Evolving cadence (in response to science drivers)

6.7.3 Summary

- The Project aims to empower the community with tools to explore all of these possibilities. Out-of-the-box thinking is strongly encouraged, but at the same time we need to have a process and tools to communicate and test new ideas. Hence this workshop, and other to follow...
- The LSST baseline cadence, and various implemented assumptions, are NOT sacrosanct! The Project and the community will continue cadence optimization. While there are some “conservation laws” set by the integrated etendue, thinking “out-of-the-box” might result in significant performance improvements!
- The most important conclusion of the preliminary cadence explorations (c.f. Cook’s talk) is that the upper limit on possible efficiency improvements for baseline cadence is not larger than 10% and probably close to 6%. This conclusion is by and large based on the fact that the mean slew time for (candidate) baseline cadence is 7.0 sec, and thus only slightly larger than the design specifications for the system slew and settle time of 5 sec. Nevertheless, it is likely that the performance for time-domain science can be significantly improved (e.g. rolling cadence for SNe survey).

7 Recent Cadence Experiments – Kem Cook

The OpSim group runs a lot of cadence simulations, mostly for simulator development and to answer specific engineering and science questions. As preparation for this workshop, we prepared a grid of simulations proposed by Ẑeljko.

7.1 Candidate new baseline cadence

From time to time, a simulation from a stable version of the simulator has been designated a "reference simulation", meaning that it is believed to provide a fair representation of LSST performance as currently understood with the current level of development of the simulation capability.

The most recent reference simulation, opsim3.61, is now several years old, and the simulator has been improved in a number of respects, culminating in the release of v3.0. Also, major changes to the simulator are now beginning to merge its development with the scheduler development, so a new reference simulation is timely.

We need a replacement for the current baseline cadence (opsim3.61) produced with the new (v3.0) version of OpSim code First try: opsimblitz2.1035

- 2.47 million visits (2.65 in opsim3.61); OK
- mean slew time: 7.0 sec; OK
- For WFD: the mean number of visits is 95% of the SRD design value 1 satisfactory airmass distribution
- problem: as much as 16 of time spent on North Ecliptic Spur (NES) 1 1035 has design area and design visits
- 3.61 has stretch area and stretch visits

It is unlikely that opsimblitz2.1035 will replace opsim3.61. Check the confluence page (Cadence Workshop Simulated Surveys) for the current candidate – the best to date is ops2.1075 (NES de-emphasized).

7.2 Maximum performance for the main survey

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

- ops2.1064
    - Exceeded the design specification for the number of visits by 56% (1050 visits without dithering, 1283 with perfect dithering over the design specification for the sky area of 18,000 sq.deg.

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?

- ops1.1144

- This “Pan1STARRS1like” cadence results in a 48% larger sky coverage (26,600 sq.deg), with the mean number of visits at 92% of the SRD design specification.

How much extra time would be available in a 10 year survey if only use the WFD

- ops2.1040
    - When running the WFD with design visits and design area, survey is complete after 8 years—extra 20% used for auxiliary proposals in baseline cadence.

7.3 Effects of auxiliary programs

What is the effect of auxiliary proposals (deep drilling fields, North Ecliptic Spur, etc) on surveying efficiency?

- A comparison of simulations ops1.1140 (all proposals) and ops2.1064 (only WFD) shows that the former has higher surveying efficiency by about 3.4% due to shorter slewing time (6.7 sec vs. 8.2 sec). Note, the Pan-STARRS-like, WFD only, had a 7.2 sec average slew.

Adding “more choices” for the “next field” improves the survey efficiency by 4 .%

7.4 Effects of requiring pairs of visits

What is the effect of the requirement for visit pairs (two visits per night to the same field, separated in time by about an hour, and driven by asteroid orbit determination) on the survey efficiency?

- ops2.1065'
    - compared to ops2.1064, which was also WFD-only simulation and required pairs of visits, this simulation obtained 2% more visits due to shorter slew times.
- ops2.1066'
    - compared to ops1.1140, with all proposals and requiring pairs of visits, this simulation obtained 2.3% more visits due to shorter slew times.

Relinquishing the visit pair requirement results in about a 2% improvement of the surveying efficiency.

7.5 Effects of varying visit exposure time

Can the effects of variations of the visit exposure time on the surveying efficiency be predicted using simple efficiency estimates? E.g. the visit efficiency for baseline cadence is 30/(34+6.7ti=74

- A comparison of simulations ops1.1140 (baseline with 30 sec visit exposure time) and ops2.1072 (20 sec) confirms a simple estimate of the efficiency decrease by 12% (3.32 million visits)
- A comparison of simulations ops1.1140 (baseline with 30 sec visit exposure time) and ops2.1074 (60 sec) confirms a simple estimate of the efficiency increase by 15% (1.43 million visits)

The effects of variations of the visit exposure time on the surveying efficiency can be predicted using simple efficiency estimates.

7.6 Improving the u band performance

The contribution of read-out noise in the u band for 30 sec exposures is not as small as in other bands because the sky is much darker. Doubling the visit exposure time in the u band would mitigate this effect and result in 0.2 mag deeper coadded images (assuming the same total exposure timeti. What is the impact on the survey efficiency? What if the number of visits is not halved?

- simulation ops1.1147 shows that doubling the u band exposure time, while halving the number of visits, decreases the survey efficiency by 3.8%
- simulation ops1.1141 shows that doubling the u band exposure time, while keeping the number of visits unchanged, results in 9.5% fewer visits in other bands. Thus, the u band coadded depth could be improved by 0.6 mag at the expense of 0.04 mag shallower data in other bands

7.7 Effects of airmass limit (and a 'feature')

The current baseline cadence places a hard limit on airmass, X<1.5.

Is this an optimal value?

- Simulations using airmass limits of 2.0 and 1.2 (ops1.1146 and ops2.1068 & 1069) show that the median airmass is controlled by the airmass limit. Relaxing the latter is thus a bad idea! The baseline cadence should be produced with a smaller airmass limit (X<1.25 or X<1.30).
- "The'10th-year'Panic" effect: some simulations, e.g. ops1.1065, 1068, 1069, display a significant decrease of the surveying efficiency during the 10th year of the survey. It seems that vigorous filter change activity is happening, though longer slew time could be responsible too. Needs more analysis!

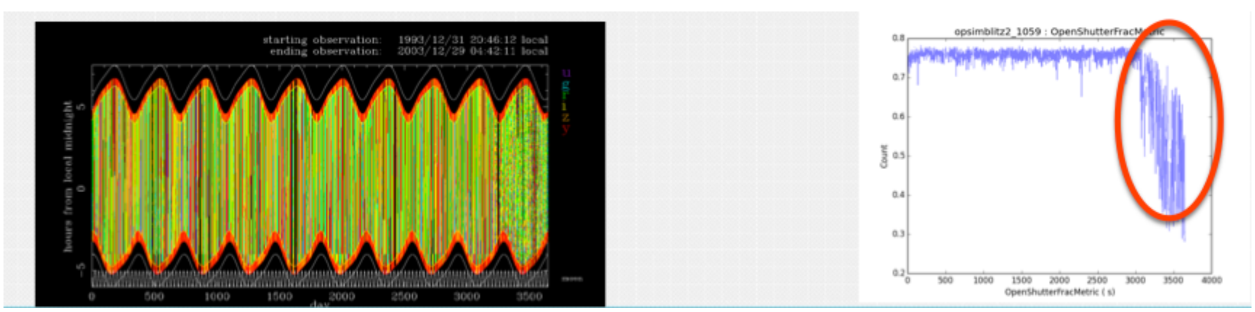


Figure. (Left) the filter-change map, showing for the full 10-year survey, for each night, the time that each filter is in use. Note the change in "texture" in the 10th year, as filter changes become very frequent. (Right) the open shutter fraction vs tiem, showing the efficiency cost of the frequent filter changes seen at left.

7.8 Rolling cadences

Rolling cadences allow different time sampling over limited area and over limited time. They are motivated by trying to yield better SN light curves, variable star light curves and transient sampling

The seemingly straight forward rolling cadence of defining RA and Dec limits for a more densely sampled survey over some portion of the total survey, yielded 3 subtle bugs in the operation simulator. All of these have been fixed as of late last week.

The 'swiss cheese' model for a rolling cadence is on the confluence page as ops1.1122 and ops2.1078. This simulation has 10 proposals which run for different 1 year periods with 1/10th the number of fields and 1/10th of the total, SRD, visits. And there is a continuous WFD with 90% of SRD visits requested. These simulations are early tests.

Mixed cadences with different cadences in rolling areas have yet to be investigated, but are similar to some Deep Drilling proposals

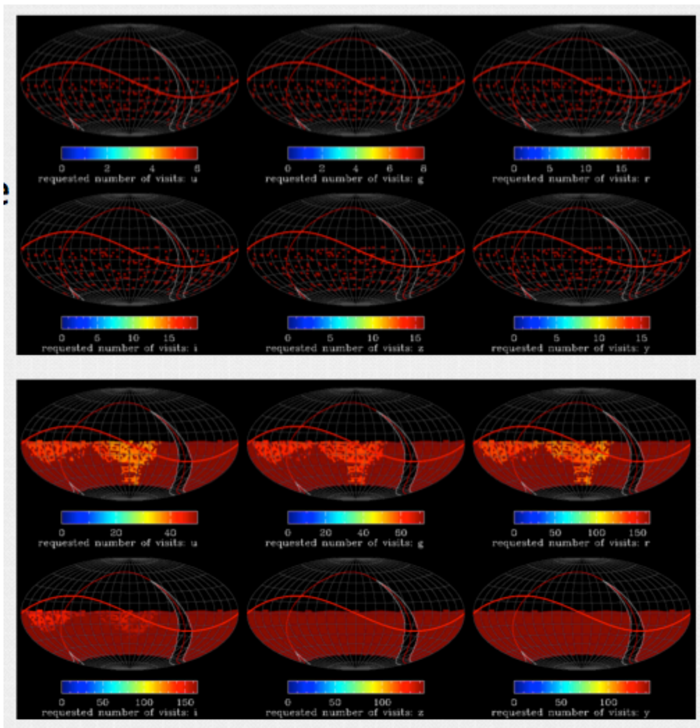


Figure. The "swiss cheese" rolling cadence, first test. (Above) 'Random 1/10th of WFD fields whose proposal is active for 1 year with an arbitrary cadence (say optimized for 60 day light curves). There are 10 of these. (Below) WFD proposal with 90% of SRD visits requested running for all ten years.

7.9 Summary

The LSST baseline cadence, and various implemented assumptions, are NOT sacrosanct! The Project and the community will continue cadence optimization. While there are some "conservation laws" set by the integrated etendue, thinking "out-of-the-box" might result in significant performance improvements!

The most important conclusion of this preliminary cadence exploration is that the upper limit on possible efficiency improvements for baseline cadence is not larger than 10% and probably close to 6%. This conclusion is by and large based on the fact that the mean slew time for (candidate) baseline cadence is 6.7 sec, and thus only slightly larger than the design specifications for the system slew and settle)me of 5 sec. Nevertheless, it is likely that the performance for time1domain science can be significantly improved (e.g. rolling cadence for SNe survey).

8 External surveys and facilities

9 Metrics and Metrics Analysis Framework (MAF) – Peter Yoachim

(Note: the main presentation of the Metrics Analysis Framework occurred on the morning of the first day of the conference, in a separate tutorial session. Materials from that session are collected at: https://confluence.lsstcorp.org/display/SIM/MAF+documentation).

9.1 The operations simulator (OpSim) and Metrics Analysis Framework (MAF)

OpSim generates realistic 10-year LSST pointing histories

– 2.5 million visits

– For each visit, record Nme, airmass, ra, dec, seeing, sky brightness, filter, etc.

− MAF provides a framework for visualizing and analyzing the scientific usefulness of a survey

9.2 Simple metrics

Combine:

- Single columns from OpSim output table, like:
  - airmass, seeing, sky brightness
- Simple algorithms like: Mean, Median, Coadded depth, RMS, etc

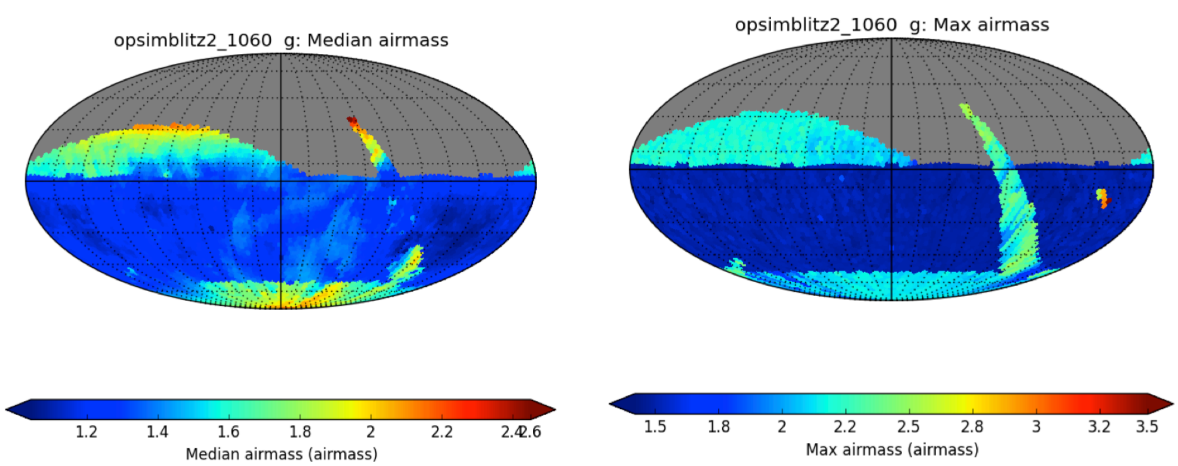


Figure. Example simple metrics. (Left) median airmass of all visits to each field. (Right) Maximum airmass of

all visits to each field.

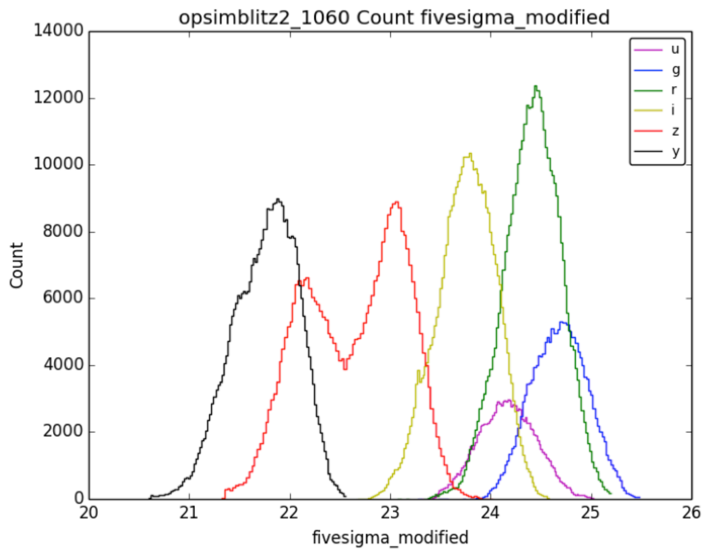


Figure. Example metrics graphic – histogram of single visit depths to all fields in all filters.

9.3 New cadence metrics

- Astrometry

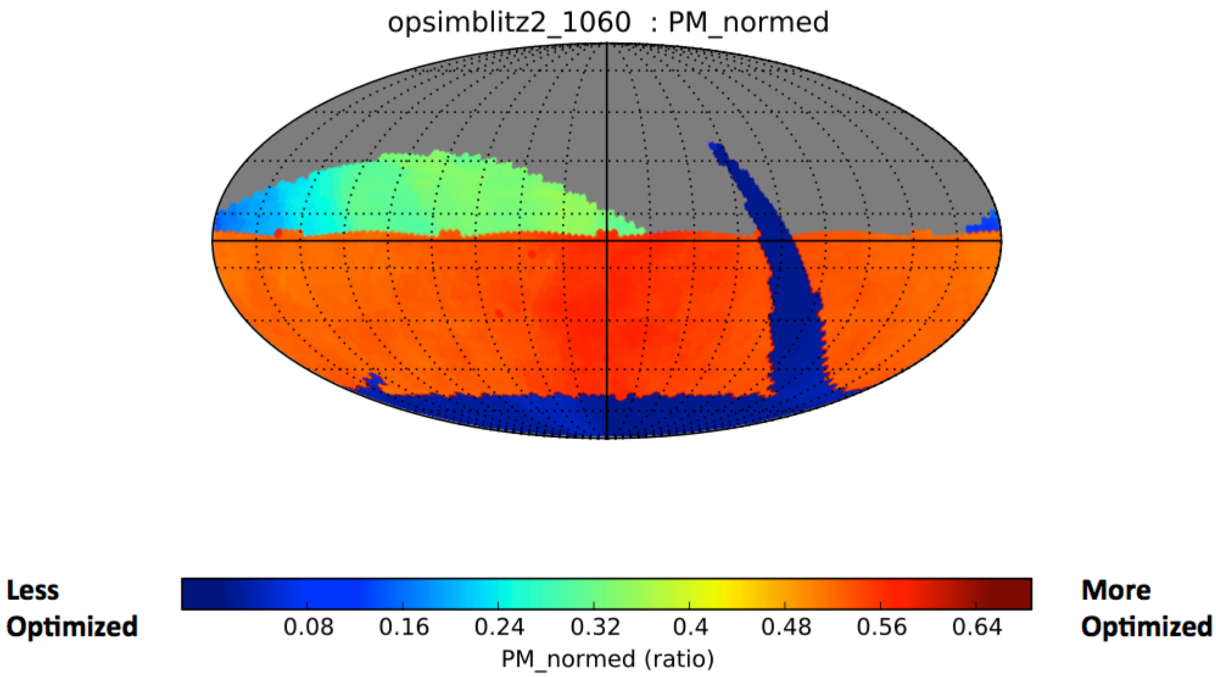


Figure. A metric for proper motion, with actual distribution normalized to the best possible distribution, to show the relative performance.

- Supernova sampling

Figure. Supernova merit function, showing relative number of events for which good sampling of the light curve is obtained

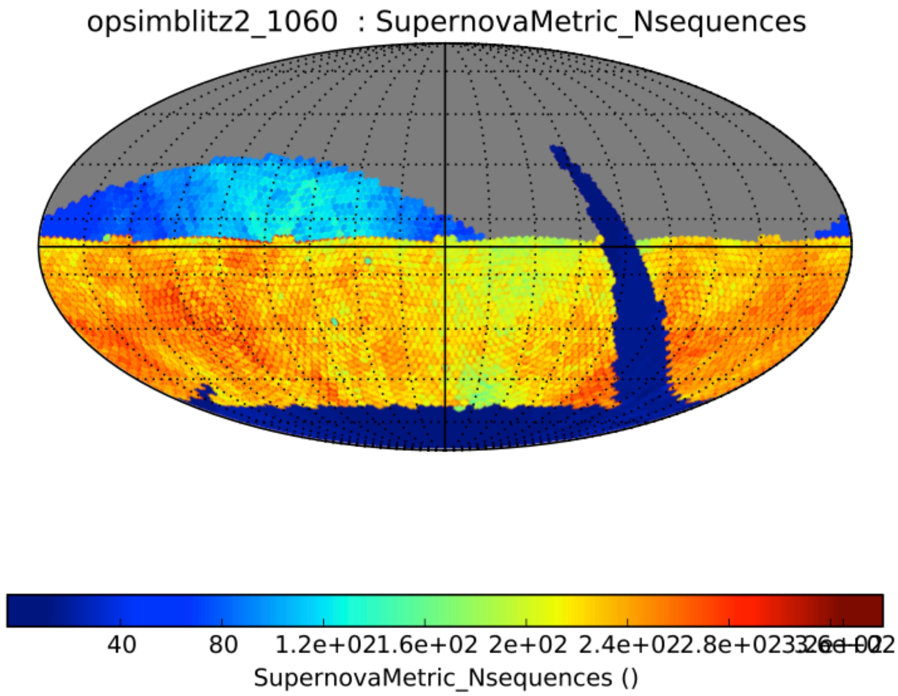


Figure. Supernova merit function, showing the relative number of events for which good sampling is obtained.

- Fraction of fields with good templates

For image differencing, it is necessary to have a pre-existing image with similar or better seeing, in the same filter. These metrics evaluate what fraction of field shave such templates as a function of progress in the survey.

- Uniformity

There are many possible metrics to measure uniformity in the survey.

10 Workshop Process – Knut Olsen

10.1 Organization and agenda

10.1.1 Plenaries and breakouts

- In the plenary sessions, there will be a modest number of introductory and overview talks.
- Most of the workshop time will be in breakout sessions.
- We will have breakout reports to the plenary.
- Thursday will end with plenary discussion of a workshop report and plans for continuing activity

10.1.2 Top level agenda

- **Monday**
  - **Metrics Analysis Framework tutorial**
- **Tuesday Breakouts – science – Static science**
  - **Transients and Variables**
- **Wednesday Breakouts - operations – Main Survey**
  - **Mini-surveys**
- **Thursday**
  - **MAF hack session – Deep drilling**
  - **Workshop report**

10.2 Breakout group deliverables

10.2.1 What do we want to achieve in breakouts

- We are looking for quantitative input on how a given LSST schedule performs for specific science cases
  - This is the way for your input to have impact
- Remember that schedule has some broad constraints
  - Must serve four key science goals
  - Hardware constraints, e.g. total number of filter changes
- Input on alternate scheduling strategies, questioning assumptions, and other strategic advice also welcome (on Wednesday in particular), but most useful if it follows from the quantitative work that we are starting now

10.2.2 Breakout group deliverables

- A list of science cases for which the groups would like to provide metrics
- For those science cases, a list of variables that would enter into their metrics
- A translation of those variables into the output columns delivered by OpSim
- Performance metrics in rough analytical (or pseudocode) form
- A list of assumptions made in constructing the performance metrics
- Identification of e.g. modeling work needed in order to construct a metric that can be calibrated to provide absolute performance for a given science case
- A brief oral report of the breakout group discussion
- A brief wriOen report (few paragraphs) for the workshop report
- Coded performance metrics in Python and MAF
- Input for main survey optimization, mini-‐surveys, deep drilling, commissioning

11 Breakout Group Results

11.1 Static Science - Cadence considerations for the LSST static science cases

Group leads and editors: Michael Strauss and Tony Tyson

Subgroup leaders:

- D. Bard (Weak Lensing)
- H. Zhan (LSS)
- M. Cooper (Galaxies)
- C. Grillmair (Stellar Populations)

The universal consideration for the static science cases is control of systematics. In this spirit, all the subgroups agreed that dithering of exposures (as opposed to imaging at a fixed hexagonal grid of pointing centers) was much preferred. Without dithering, the depth of the survey is considerably greater (~0.3 mag) on the regular pattern of overlap between grid cells[1], and the angular power spectrum of galaxy counts shows considerable excess power on scales corresponding to the radius of a cell (~1.8°, or l~120). While this is correctable to first order in large-scale structure measurements (e.g., by simply rejecting the excess exposures in the overlap regions, which is a waste), it would be better not to have such a pattern, and the dithering pattern that has been incorporated into OpSim removes it almost entirely, giving a nearly featureless angular power spectrum (see Figure 1). Further work is needed to incorporate effects such as chip gaps into OpSim, which will also be mitigated by dithering.

For weak lensing, the most important systematic to control is the measurement of the PSF. Dithering is important here, so that each star (and associated galaxies for that exposure) is imaged at a range of positions on the focal plane and at different camera rotations (position angles), thus allowing us to measure and remove any systematics due to the camera optics and CCD effects as well as some atmosphere effects. Observing each galaxy at a range of position angles is particularly important, as galaxy shape measurement is inherently a directional quantity. Some of this field rotation will come about naturally as a given point of the sky is observed at a range of hour angles, but additional rotation of the field is desirable using the camera rotator. The weak lensing folks are designing metrics that measure the randomness of the rotation angle over the sky. Both dithering and field rotation will also help with identifying and removing sources of scattered light, allowing low-surface brightness extensions of galaxies to be measured accurately.

Spurious correlations in the measured shear of stars are known to decrease inversely with exposure time, as atmospheric fluctuations are averaged over (see Figure 2). For this reason, weak lensing is interested in exploring cadences in which the exposure times in r and i (the two bands in which the weak lensing signal will be measured) is increased from 15 seconds to perhaps 20 seconds. This also has the advantage of increasing the S/N of the measurement of PSF stars at any given magnitude (or equivalently, increasing the number of stars available for PSF measurement above a given S/N threshold).

With the standard 15-second exposure time, the u-band images will be marginally read-noise limited, thus there is also interest in increasing the u-band exposures to perhaps 30 seconds. This deeper u-band data could be particularly valuable for photometric redshifts, and for metallicity determinations of stars.

---

[1] Given the deep drilling fields which will go much fainter still, the extra depth in the overlap region is not particularly valuable to galaxy studies

All static science areas will benefit from a rolling cadence, in which at any given time, observations are carried out not over all the sky available, but over a smaller area of sky, that then gradually tiles the full LSST footprint over the year and the full survey. While the initial motivation for a rolling cadence was to improve the short timescale sampling of the variable universe, it has the additional benefit that the average airmass of the observations will be lower, improving depth and seeing for all static science. It will also decrease the effects of atmospheric chromatic aberration, which is a boon to the weak lensing and astrometric folks. The rolling cadence could naturally target special regions of sky early in the LSST survey (for example, the ~2000 deg^2 of the WFIRST survey), enhancing the early science return of the LSST and its synergy with other facilities. Of course, there is also the desire to get a (relatively shallow) uniform coverage of the LSST footprint early in the survey, and to have uniform coverage over the footprint as the survey progresses, and there is work to do to balance these considerations. If the rolling cadence ends up more-or-less uniformly covering the sky on year-long timescales (i.e., the timescales of the data releases) the impact of the rolling cadence on wide-angle science will be minimal. In any case, all static science cases agree that whatever area of sky is covered early in the survey, it is desirable to get coverage in all six bands. Perhaps some of this work could take place as part of commissioning. The notion of a 1-second exposure pre-survey, for calibration and to put well-studied bright stars on the LSST photometric system, received some support.

All science is enhanced by good seeing data. Stellar populations at the faint end will depend on the accuracy of our star-galaxy separation, a problem that certainly gets easier with better seeing. It is also true that crowding at low latitudes is mitigated by better seeing, and the stellar population folks are particularly interested in metrics that explore the distribution of seeing at both low and high latitudes. Thus, there is the desire to make a coadd of the subset of the images with the best seeing, particularly in the r-band and i-band, and to observe in those bands preferentially when the seeing is good.

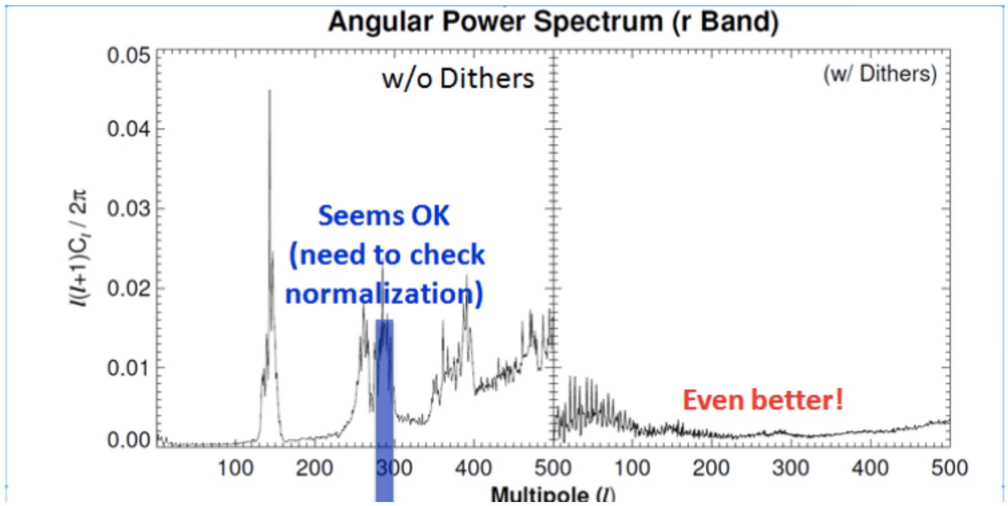


Figure 1: Angular power spectrum of the depth distribution, with and without dithering.

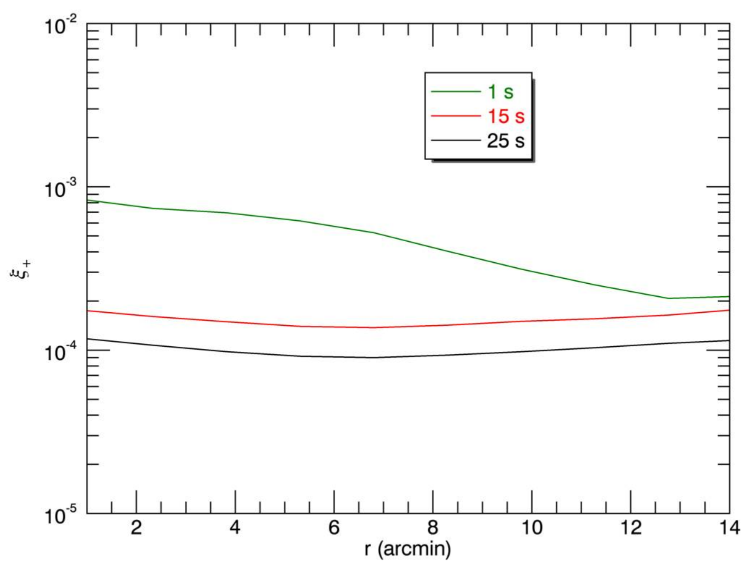


Figure 2: the spatial correlation function of PSF shear as a function of exposure time. This spurious shear is significantly smaller for longer exposure times.

11.2 Transients and Variables

Group lead and editors: Steve Howell

Subgroup leaders:

- J. Gizis, M. Liu (Astrometry)
- L. Walkowicz, M. Kasliwal (Fast Transients and Variables)
- A. Mahabal, J. Thorstensen(Slow Transients and Variables)
- M. Wood-Vasey, A. Kim (Supernovae)
- L. Allen, E. Christensen(Moving objects)

11.2.1 Introduction

This short report presents a brief summary of the Transients and Variables working groups culled from the face-to-face discussions and workshop presentations that occurred during the LSST cadence meeting held in Phoenix, AZ on 11-14 August 2014.

11.2.2 Goals for Breakout Sessions

In order to lay a foundation and some common themes for our breakout sessions, a few goals were identified ahead of time. These goals were based on a pre-reading of the workshop planning and were modified and changed in real-time as the breakouts progressed. You will see the changes and final results in the subgroup sections below, but for posterity, here are the common goals that were laid out before the workshop participants.

- Identify the science cases for which we wish to provide metrics, and characterize the success criteria for each case
- Turn these criteria into metrics that can be quantified, from the output of the Operations Simulator
- Identify any additional work (i.e. modeling) that needs to be done before useful metrics can be created or calibrated
- Subgroup leaders should distill the discussions into a short report to the workshop
- If possible, begin to create metrics on the MAF platform

11.2.3 Case Studies

In addition to the initial goals, a few case studies were presented to start the creative juices flowing in the T&V participants. These are by no means exhaustive, but were an attempt to provide a range of thinking for the group and to present, right up front, the premise that all science cases are still in the running. Thinking outside the box and in a different manner for

LSST was encouraged.

To prompt collaborative work among the groups, many of which had never worked together before, these bullet points were laid out as case study examples – a starting point for early discussion. The subgroup leaders and their teams were asked to think about these example cases and provide their own.

LSST Sample Case Studies:

- Representative science cases - Perhaps applicable to a number of object types
- Specific science use cases – of interest to you or "unique"
- Leverage other projects or missions (current and future)
- Think about filter, sky coverage, time coverage, cadence, seeing, S/N,…
- Think toward your desired science results.
- Think broadly – LSST science cases are not "an observing run"
- There will likely be overlapping subgroup cases – e.g., Stellar pops (Astrometry), AGN variability (Slow T&Vs) – feel free to mingle
- Are additional subgroups needed?
- Are additional topics to discuss

11.2.4 Common Themes

During the deliberations, discussions, cross-subgroup interactions and final presentations, a number of common themes were identified by all the T&V subgroups as desirable. A number of these themes involve simulations and their follow-on catalogues. Simon Krughoff kindly spent time discussing these items with me and has read over the accounts below related to this topic to make sure of their correctness and applicability.

The highest interest common theme was to provide a mechanism to have a "more formal" relationship between the T&V subgroups and the community with the ImSim/OpsSim groups. In particular, a number of the T&V folks would like to provide inputs (e.g., variable star light curves, astrometric motions) to the simulators. The ability to input specific light curves in one filter band, exists as code at least. How exactly this can be used from the outside is yet to be determined/ implemented. The ability to simulate photometry including the contribution from single band light curves (with simple, but realistically motivated photometric errors) exists. There is a framework that can produce catalogs with these values. The piece that might be missing is that this framework has not been implemented inside MAF metrics. These two frameworks share some common code, thus this merging should not be hard to do. An initial bit of documentation for the catalog framework high level documentation is available here: https://confluence.lsstcorp.org/display/SIM/Catalog+Simulations+Documentation The documentation is a work in progress. The outputs of such runs would then lead to 1) transient alert simulations and T&V users to "see" what they might receive from LSST and 2) photometric catalogues that could be examined and searched to truly begin to examine science use cases. Such an input stream and analysis metrics will/might require users to write software (MAF code), hopefully software that can be useful to many groups and shared. Simulated catalogues are far easier for the community to manipulate and make use of simply sue to their far smaller size.

The above simulation desires might be best presented to the T&V public as some sort of web-based simulator with photometry and catalogue outputs available (highly desired) as well. The simulations team has been been leaning toward building frameworks instead of providing applications, but they do see the utility of a web-based system. If the scope of such an application could be defined, the simulation team would be interested in building such a tool. For example, can a user actually identify a sample of RR Lyrae stars from a specific cadence run? Or will there be many variable sources but not enough coverage to differentiate classes? Example of this process were developed and presented in the *LSST Science Book*, (Ver. 2.0, Nov. 2009), section 8.6. Such a process would be a way to allow the community to “roll their own” LSST science case, to move from observational detection to discovery to classification.

The use of existing and near-term LSST-like surveys (DECCAM, PFT, etc.), and/or early LSST commissioning science containing well sampled (time/color) light curves as training set was seen as highly desirable precursors to LSST. Such datasets can be used as LSST science case trainers as well as a methodology to learn from prior experience, yielding a better LSST with better science goals as it begins operations.

11.2.5 Slow Transients and Variables

Chairs: Ashish Mahabal, John Thorstensen

Attendees: Dave Meyer, Eric Bellm, Kathy Vivas, Phil Marshall, Mark Giampapa, Timo Anguita, Walter Max-Moerbeck

The slow transients and variables subgroup, where slow was taken as a change occurring on a time scale of >3 days, examined a number of variable sources. The list included Lensed QSO, AGN, Cataclysmic Variables, Compact Binaries, Extragalactic Microlensing, RR Lyrae, Cepheids, Late-type dwarf stars, and Generic variable and transient classification schema. Some subtopics in the above discussed were Gyrochronology, Transiting exoplanets, Star spots, AGN QPOs and tidal disruption flares, Stellar activity cycles, and the general panoply of variable stars (Ellipsoidal binaries, Mira, LPV, …).

11.2.5.1 Possible Metrics

In general, this subgroup found that very few to no existing metrics are oriented toward time-domain science! In fact, this was a theme repeated in some of the other T&V subgroups as well. One strategy for light curve metrics might be to *summarize* a given light curve sampling pattern for a given cadence run (e.g., an OPSIM MJD time series), and then try to understand your LSST science case in terms of that summary and derive metrics for success. As an example we present the following figure.

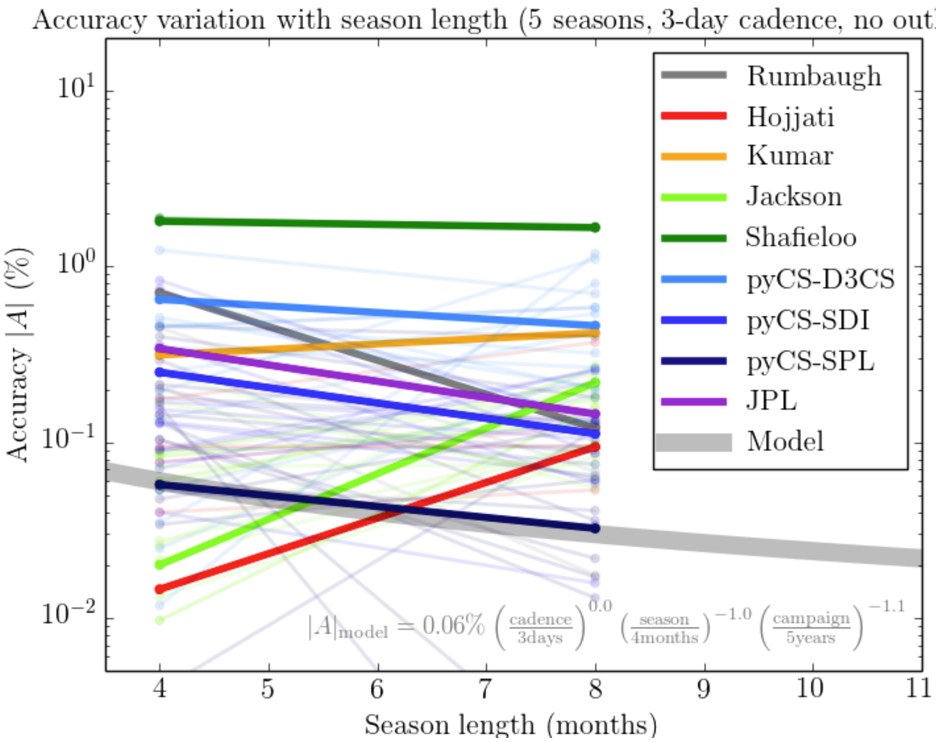


Figure. The DESC Strong Lens Time Delay Challenge returns an estimate of the average time delay accuracy expected for a realistic sample of LSST lensed quasars, as a function of three summary metrics: mean night-to-night cadence, season length, and campaign length

Variability or light curve metrics might also be products of:

- **Sensitivity** (visit? coadd?) by filter (especially u and g), needed for several (many? all?) variable types
- **Phased uniformity** (periodic variables): for a given period how uniformly would the light curve be sampled? E.g., the largest gap as a function of intrinsic period:
  ftp://ftp.noao.edu/pub/ridgway/MetricReports/Variables.pdf
  Other uniformity measures possible.
- **Window function** (per filter/all filters) FWHM, ...
- Statistics of **revisit time histogram** (per filter/all filters) e.g. min/max/median/5th & 95th percentiles
- **Hour angle distribution** (to check aliasing), at a given sky position, maximum difference, rms ...

The steps in such a metric setting procedure might be to write pseudocode,

see if stackers can be used (e.g. for hour angle, time-since-last-obs), avoid loops (in python) as they will be time-consuming, get representation from more variability types, assess population statistics and science case. New OpSim output columns might include hour angle (good for science case assessment as well as useful for computing follow-up potential from other observatories), time since last observation of the same sky location, including filter.

Below we present some example metrics in graphical form to allow a better assessment of their importance in T&V light curve production and science case success. These represent a sampling pattern and its associated window function, a sampling summary using the FWHM of the sampling window function and the distribution of hour angle.

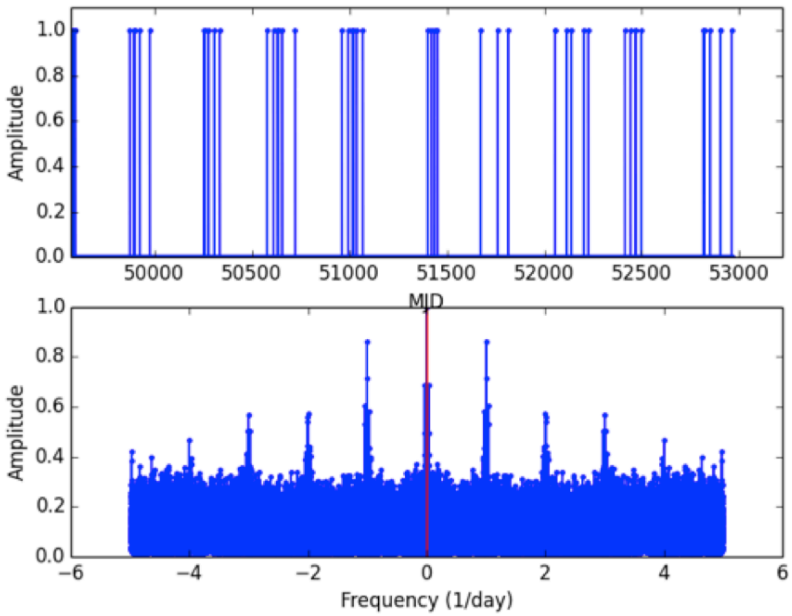
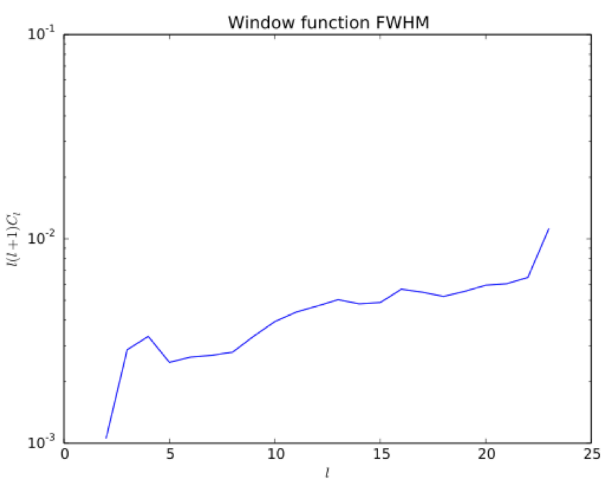


Figure. An example sampling function and the associated window function.



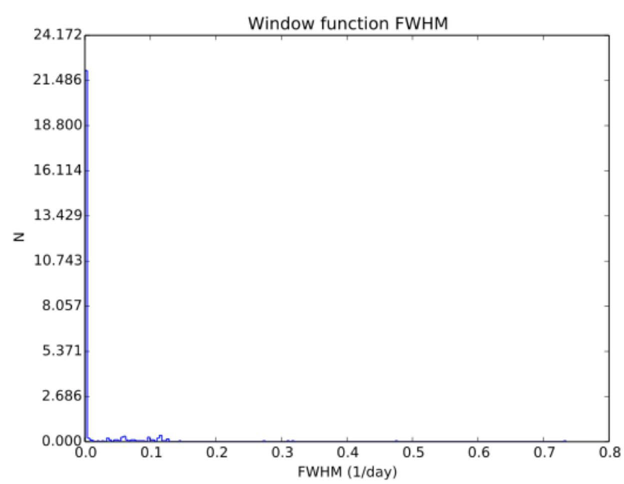


Figure. Window function FWHM.

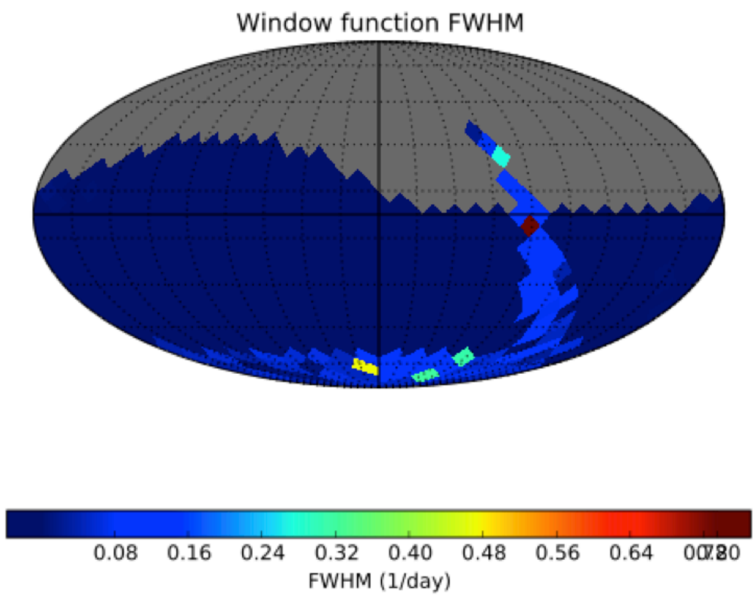


Figure. A merit function based on the FWHM of the sampling window function.

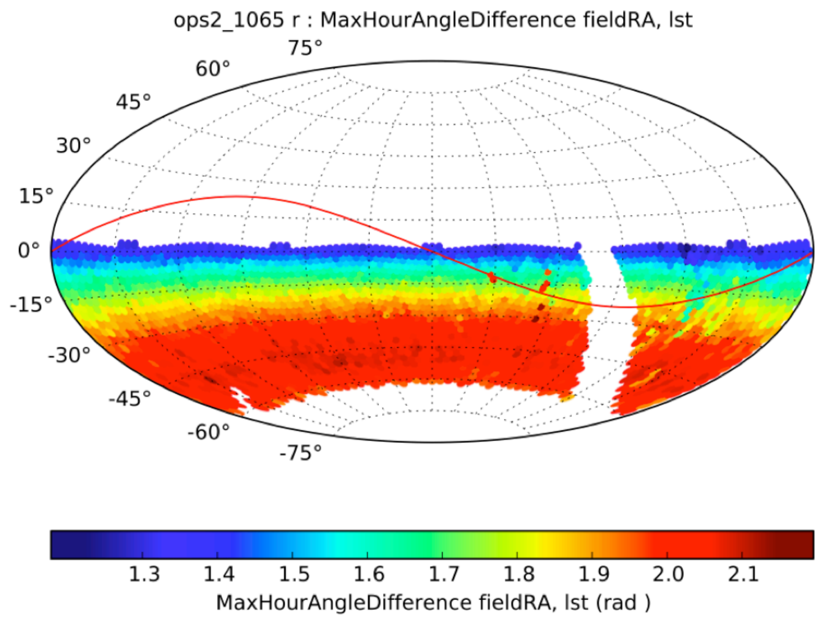


Figure. An example merit function based on the range of HA differences

As a specific example, we look at the case of AGN variability, specifically a reverberation study. Reverberation studies (the measurement of the line delay with respect to the continuum) were usually done using the spectroscopic monitoring. However, multi-color photometry also allows for such measurements (Chelouche et al. 2014). Estimates of the reverberation accuracy in a spectroscopic monitoring was done for example in Czerny et al. 2013 by creating artificial light curves and assuming the form of line response and the sampling pattern. This can be generalized to the case of pure photometry, and various sampling patterns.

Model Parameter	A	B	C	D	E
Photometric accuracy	5 %	1%	5 %	5 %	5 %
Spectroscopic accuracy	10 %	1%	10 %	10 %	10 %
Width of the BLR response	10 %	10%	10 %	10 %	10 %
No of photometric points/year	18	18	18	100	18
No of spectroscopic points/year	5	5	5	5	18
Dispersion of the photometry date	3 days	3 days	3 days	1 day	3 days
Dispersion of the spectroscopy date	14 days	14 days	14 days	14 days	3 days
Observational gap/year	3 months	3 months	3 months	3 months	3 months
Campaign duration	5 years	5 years	20 years	5 years	5 years
ICCF					
Obtained delay	605 ± 285	605 ± 251	660 ± 94	605 ± 279	605 ± 246
Spread	220	192	55	220	165
χ^2					
Obtained delay	671 ± 113	652 ± 20	673 ± 31	671 ± 111	671 ± 76
Spread	84	9	40	93	47
ZDCF					
Obtained delay	622 ± 200	666 ± 38	661 ± 405	604 ± 200	641 ± 206
Spread	141	20	62	137	119

11.2.6 Fast Transients and Variables

Chairs: Lucianne Walkowicz, Mansi Kasliwal

Attendees: Marcel Agueros, Andrew Becker, David Ciardi, Francisco Forster, Zach Golkhou, Jedidah Isler, Savannah Jacklin, Vicky Kalogera, Mike Lund, Tom Matheson, James Rhoads, Stephen Ridgway, Warren Skidmore, Przemek Wozniak, Lin Yan

The fast transients and variables subgroup, where fast was taken as a change occurring on a time scale of <3 days, examined a number of transient and rapidly variable sources. These included along with their relevant time scales:

- Minutes: Stellar Flares, Exoplanet Transits, Exotic Microlensing, Dwarf Novae
- Hours: NS-NS Mergers, NS-BH Mergers, Orphan Afterglows, Stellar Rotation, Shock Breakouts, Eclipsing Binaries, Exoplanet Phase Curves
- Days: Exploding Asteroids, WD-WD Mergers, WD-NS Mergers
- Unknown Variables & Transients

11.2.6.1 Possible metrics

This subgroup divided their metric discussion into discovery metrics and classification metrics.

11.2.6.1.1 Discovery Metric (driven by true transients):

Discovery would be far more robust of triplets of observations were available for every transient event. That is, quiescence, detection and confirmation. For discovery, the sampling time is of highest use when it is of comparable magnitude to the event rise/fall time itself. Thus, ranging between 10^2 s and 10^5 s. To generate an interesting sample case, one might condense the transient “discoveries” into a histogram of N triplets in four logarithmic time bins. The minimum number of observations required in each bin to generate interesting samples will be source-specific. A filter constraint metric would be to have the triplets drawn from a single filter or a specific set of filters.

11.2.6.1.2 Classification/characterization metric:

A color evolution constraint metric might be a specification of triplets of observations to be in a specific filter or even more so, a requirement of two triplets taken in multiple filters. Production of products yielding time difference between observations constituting a triplet that list parameters such as delta t, filter etc. will be important discriminators.

Some early MAF code runs based on Opsim 3.6.1, Field 1402, 1500 observations, a and 330000 triplets with consecutive delta-t's less than three days, yielding the following graphical results.

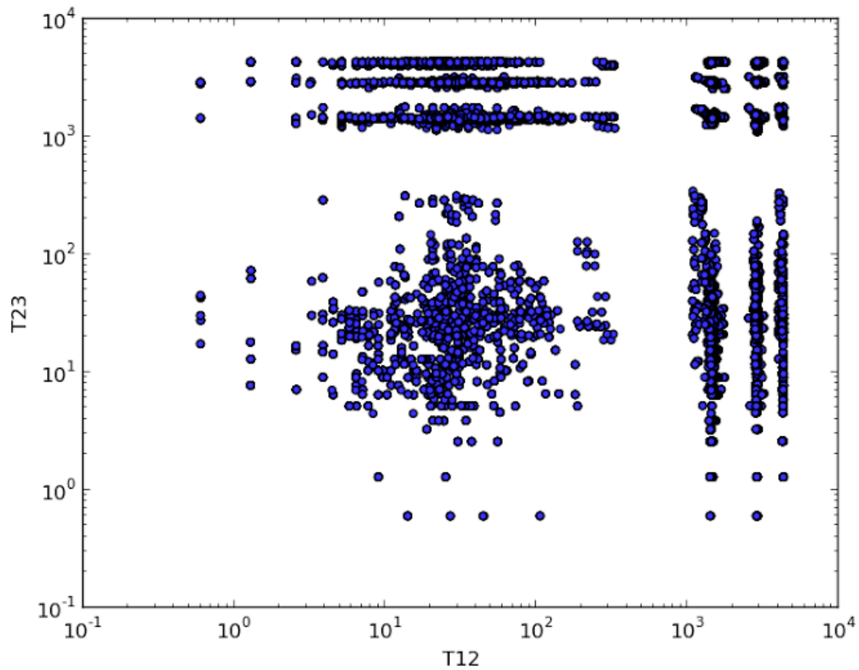


Figure. Example triplets merit function for rapid transients and variables. For a sequence of three visits, the axes show the interval between the 1st and second visits, and between the 2nd and 3rd.

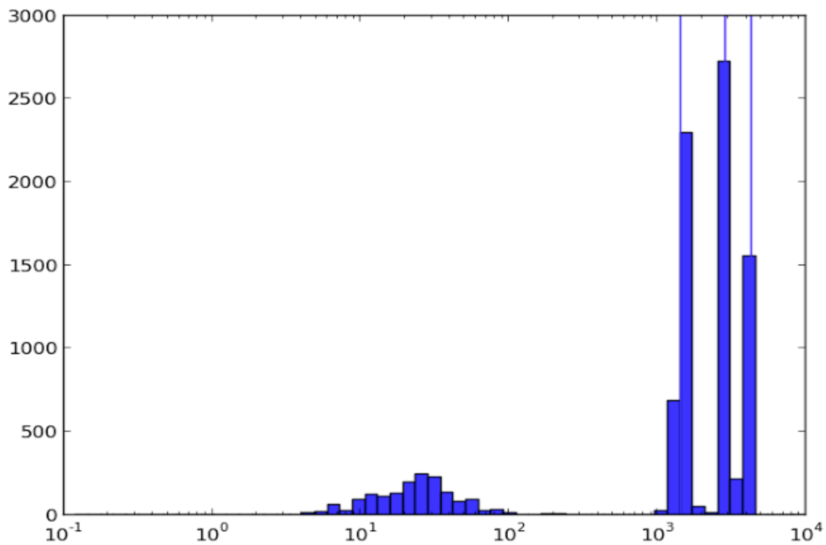


Figure. A triplet merit function derived from the figure above, showing a histogram of the number of triplets with the interval between the first pair having the value shown.

Some additional considerations from the Fast T&V group, that would be helpful or necessary for classification, are:

*Have the change in magnitude in a given visit saved to the database

*Present a light curve history in difference images

*Provide the reference image of the nearest neighbors (star/galaxy/nothing)

*Maximize contiguous set of observations when observing at faster cadence

*Splitting two consecutive 15 sec exposures in a given visit to a larger separation, perhaps minutes to hours (rather than back-to-back)

*Have a Deep-drilling or mini-survey call for proposals

11.2.7 Astrometry

Chairs: John Gizis, Michael Liu

Attendees: Will Clarkson, Dave Monet

The astrometry sub-group, while small, was very active and presented many detailed aspects of how the LSST could best be used for astrometry. They started with a general statement of astrometric cases and divided these into parallax and proper motion as follows.

Parallaxes

- Complete stellar census out to 300 pc
- Brown dwarfs

- White dwarfs
- Young moving groups
- Crowded fields

LSST is expected to measure parallaxes comparable to the very best ground-based optical measurements ever obtained. *(~0.3 mas parallax uncertainty → 300 pc)*. LSST will do this over ~half the sky, as compared to previous work that targeted individual objects. *(cf. Pan-STARRS 1)*

Proper Motions

- Halo tidal streams
- Magellanic clouds
- Galactic Bulge
- Star clusters
- Stellar populations
- Hypervelocity stars
- AGN/star separation

11.2.7.1 Possible metrics

The following metrics already exist in the LSST simulation and database entries.

The proper motion uncertainty in fine as is and comes for “free”. However, parallax uncertainty, while necessary, is insufficient at present. The existing metric assumes objects with flat SED but the LSST science “sweet spot” is for low-luminosity objects detected only in a subset of filters. For example, brown dwarfs detected in red filters, white dwarfs detected in blue filters, etc.. These types of metrics would be a desired upgrade for the parallax uncertainty as a function of spectral type. Ideally, this subgroup would like to inject astrometric objects directly into an ImSim.

Some new astrometric metrics might be the correlation of parallax factor with zenith angle. This would be a gauge of systematic errors. The actual degradation of parallax with this particular metric is future work. A listing of the fraction of visits with abs(parallax factor) > 0.5 would also be useful and both of these metrics should be measured as a function of spectral type.

For the Solar neighborhood census, some metrics might be

- “Parallax-detectable” volume @ S/N~10 (as a function of Spectral Type)
    - *Stellar/substellar luminosity function*
    - *Yield of young free-floating planets*
- All-sky completeness metric - TBD
    - *Are key regions of interest covered well?*
- Incompleteness of Galactic Plane - TBD
- False alarm rate for parallax rate discoveries - TBD

and for the Galactic Bulge & Plane (also LMC)

- Purity of kinematic-selected samples, e.g. fraction of non-Bulge stars at MSTO.

Future work for this subgroup consists of detailed reading of the code for Project’s existing metrics. Compile some SEDs for low-luminosity objects and add to ImSim (single objects, entire solar neighborhood, Galactic Bulge) including astrometric information. Refine the science-based metrics (false alarm, crowded fields).

How and when will DM add astrometry (e.g. DCR correction) to the simulations is of high interest to this subgroup. Astrometry subgroup is interested in establishing a living document for LSST astrometry issues.

11.2.8 Moving Objects Subgroup

Chairs: Eric Christensen, Lori Allen

Attendees: Lynne Jones, Renu Malhotra, Jon Myers, Al Harris, Tommy Grav, Rob Seaman

The Moving Object subgroup started with some details of their science goals. They listed four major themes and provided some metric related information for each as follows:

- Solar System population studies
  - Census of small bodies: LSST has the potential to reach ~3 magnitudes fainter than current solar system surveys
  - How many model MBAs, TNOs, Sedna-like objects, distant planets or dwarf planets, free-floating planets, irregular satellites of giant planets, high-perihelia Oort Cloud comets are detected?
- NEO population
  - NASA pursuing the goal of finding 90% of 140-m NEOs. How will LSST contribute?
  - Sample small NEO population, including "death plunge" impactors
- Asteroid Light curve / Shape models from sparse photometry
  - How many objects are observed >100 times in a single filter over 10 years?
- Asteroid family relationships
  - How many objects will have contemporaneous multi-color observations?

In order to write metrics for any of these themes, enhancements must be made to MAF to include a model solar system population overlay. While the current incarnation of MAF is powerful to understand how a particular RA, Dec coordinate (or healpixel) is observed over the lifetime of the survey, any solar system science depends on how and how often a particular *moving object* is observed.

11.2.8.1 Moving Object Detection

Keeping in mind that one of the four prime science drivers for LSST is "Taking an Inventory of the Solar System", it is important to emphasize that *all moving object science follows from reliable and efficient detection*. There is also interest from other science projects in removing moving objects as a source of confusion from the transient stream.

The conventional wisdom (based on many years' experience with all-sky asteroid surveys) recommends a minimum of 4 observations in a night for efficient moving object detection. Successful asteroids surveys have traditionally used either no filter, or broadband R or VR filters. Furthermore, deriving a minimally useful orbit requires detection at least 3 epochs with a total time baseline of at least week. Initial detection is optimized by collecting 3-5 astrometric points within 1-2 hours in a single filter (preferably g or r), but subsequent epochs can possibly tolerate fewer visits and different filters. The baseline cadence adopted by LSST assumes that moving object detection can be done with much sparser sampling. In order for this to work, it will require new and unprecedented software efforts.

Within the moving object subgroup, there is significant concern about the LSST assumed detection criteria: 3 pairs of observations separated by 15-30 days (2+2+2) is a novel, unproven technique with significant computational challenges. In order for this to work, significant resources will need to be invested, and the following issues will need to be addressed.

- The cost to develop and demonstrate the 2+2+2 detection pipeline (MOPS) *on real data* should not be underestimated. Some progress has been made in showing that moving object detection with a sparse cadence is theoretically possible, but these simulations have generally been based on low-fidelity simulated data, without considering inescapable real-world issues like correlated noise. The 2+2+2 cadence and detection criteria have never been shown to work in the real world.
- The cost of failing to solve the 2+2+2 problem must be clearly understood. Little to no solar system science can be done without first detecting and linking moving objects, and unlinked moving objects will become a source of noise that must be dealt with by other projects.
- If moving objects cannot be efficiently detected with a 2+2+2 cadence, then the cadence may need significant alterations in order to meet the “Inventory of the Solar System” science requirement. The cost of re-balancing the cadence to meet this requirement must be understood well before commissioning begins.
- Moving object detection is very sensitive to chip gaps. Previous simulations have ignored the mosaic focal plane array, potentially leading to over-estimates in LSST’s efficiency at detecting moving objects. Higher fidelity simulations are required to estimate LSST’s true efficiency as a function of cadence and detection requirement.

In addition, the 2+2+2 detection criteria presents additional challenges to moving object detection, compared to traditional single-night detection with 3-5 observations. The moment of “discovery” will be delayed until the last pair of observations is obtained and the full set of observations is linked together. Practically speaking, this means that some moving object observations will not be removed from the transient stream until up to 30 days after the images are obtained, and asteroid observations that are never linked due to an insufficient number of further detections will potentially never be removed. It is important for other science interests to understand the effects these orphaned asteroids will have on their science cases.

The next steps in the moving object planning to develop and assess metrics are to enhance MAF to include a model Solar System population overlay and provide plotting capabilities not tied to pointings on sky. This can easily assess how many *objects* will meet particular metric criteria. Specific OpSim cadences prioritizing 4-5 visits per night would be very helpful to examine. We can use them to develop metrics for solar system science assuming a variety of detection criteria, from optimistic (2+2+2) to conservative (5+5+5). Finally, moving object optimal cadences should be examined to evaluate their impact on other science goals.

11.3 Supernova Group

The breakout participants were:

- Jeonghee Rho
- Yi Cao
- Isobel Hook
- Rick Kessler
- Alex Kim
- Michael Wood-Vasey
- David Cinabro
- Tom Matheson
- Yan Lin
- Emmanuel Gangler
- Evan Scannapieco

11.3.1 Science Cases

We identified the following suite of science cases that can benefit from and should therefore inform both LSST Main and Deep Drilling Surveys.

- Cosmology: Both Type Ia and core-collapse supernovae can be used as distance indicators to probe the expansion history of the Universe. LSST will discover and obtain multi-band light curves of supernovae. LSST supernovae will be used to search for better standardization of their absolute magnitudes and to serve as tracers of the cosmic expansion.
- Rates: Redshift-dependent supernova rates can be measured precisely with the large number of supernovae discovered by LSST.
- Bulk Flows: Peculiar velocities can be measured through observed supernova redshifts and distances. With their large number and broad sky coverage, LSST-discovered supernovae can be used to measure coherent bulk flows at low redshift.
- Supernova Subpopulations: Among the large pool of LSST supernova discoveries, super- and under-luminous supernovae will appear in much greater numbers than today. High-statistics studies of relatively rare objects will be enabled.
- Supernova Science: The fundamental physics of supernovae, particularly Type Ia's, is not well understood: e.g., their progenitor systems, relation with their environment, and their explosion mechanism. These can be studied with the large number of LSST supernovae, or through special "gold" objects that happen to be accessible for detailed observation. Among the special discovery potential of LSST are objects that are discovered shortly after explosion, potentially as early as the shock breakout. At the other extreme, extensive time coverage will allow measurements long into the nebular phase of the light curves of nearby supernovae, providing another handle on the physical processes associated with the variation/scatter in the light curves.
- Light Echos: The reflection of primary supernova light off of circumstellar material provides a unique view of the progenitor environment.
- Strongly Lensed Supernovae: LSST should observe 10–100 strongly-lensed Type Ia supernovae. These objects will provide magnification and time-delay information that will

constrain the lens system and allow precision measurements of the Hubble constant.

11.3.2 The Two Key Metrics for LSST Supernova Science

Across this diverse range of science cases, we identified two classes of metric that generically capture the strength of an LSST survey for supernova science: metrics for the numbers of transient discoveries and metrics for transient light-curve quality (and other data from non-LSST resources). Metrics for transient discovery and follow-up capability include the control time, equivalent to the expected number of transient discoveriesti the distributions of the time gap between observations in the same or any band, the number of external resources (e.g., Euclid, WFIRST, spectroscopy) available to observe discoveries, the availability of derived data, including deep and timely reference images, galaxy pho- tometric redshift catalogs. Metrics for light curve quality include transient classification efficiency and false-positive rates, data uniformity within the light curve of a single object and amongst all objects, and primary science metrics such as the Dark Energy Task Force Figure of Merit. Sensitivity to anisotropy, which is related to the angular distribution of discoveries, can be derived from analyses of maps of these metrics.

Two metrics have been implemented within the MAF. The first is a metric that is maximized for a survey that is uniform in depth and in observing cadence. Given the redshift depth and light-curve quality requirements of a supernova survey, a quality re- quirement (or goal) can be given for the signal-to-noise ratio for band α (SNRα) for some fiducial magnitude mα, and a target cadence δt. The parameter τ is a supernova property (not of the survey) that describes the SN time evolution. For a realized survey, the quality of a given visit i observed in band α is efficiently expressed as the signal-to-noise ratio SNRα,i for the fiducial magnitude mα and the dates of the visits ti over the duration of the survey T. For the purposes of the DES and LSST surveys under consideration, SNR□,i is per night rather than per exposure. The time separation between visits is Δti = ti+1 − ti and min ({Δt}) □ 1 day. The solid-angle of the survey field covered by the observation is Ω. The number of observations in a season for band α is Nα. The metric for the survey field is

$$\Omega\left(T-(1+z_{max})T_0\right) \times \sum_{\alpha\in Bands}\left\{\sum_{i\in visits}\left[\min\left(\frac{SNR^2_{\alpha,i}}{SNR^2_\alpha},1\right)\frac{\tau}{T}\left(1-e^{-\Delta t_{\alpha,i}/\tau}\right)\right]-a\left(\frac{\tau(1-e^{-\frac{\delta t}{\tau}})}{\delta t}\right)\frac{\mathrm{Var}\left(\min\left(SNR_{\alpha,i},SNR_\alpha\right)\right)}{SNR^2_\alpha}\right\} \tag{1}$$

if (T − (1 + zmax)T0) > 0, and zero otherwise. The MAF output for an LSST OpSim output is provided in the Figure 1. This metric is described in more detail in a document available at:

https://github.com/DarkEnergyScienceCollaboration/surveymetrics/blob/master/docs/latex/snmetric.tex

The second metric implemented within the MAF is a control-time calculator. Given a user-input observer light curve, the control time of a survey is calculated. The control time is the time duration over which a new occurrence of a transient will be detected: the total number of discoveries is simply the product of the control time and the transient rate. Details of this metric can be found at:

https://github.com/DarkEnergyScienceCollaboration/surveymetrics/blob/master/surveymetrics/ctmetric.py

The MAF output for this control-time metric is illustrated in in Figure 2.

Note that for these metrics, only the ordinality within a metric has meaning and that it makes no sense to compare values across metrics.

11.3.3 Recommendations and Future Work

The MAF framework could provide tools that ease the implementation of these metrics. A map and dust extinction models for the Milky Way were used in both of the above

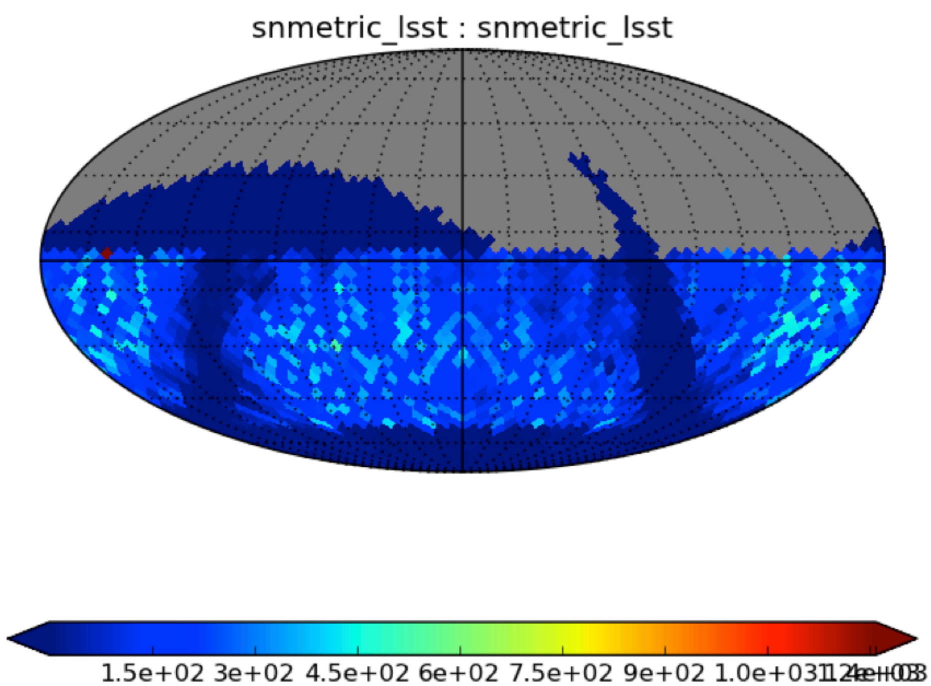


Fig. 1.— Sky map of the metric describing the uniformity of a survey as given in Eqn. 1 for an OpSim output. At the low resolution for which this was run, only one deep drilling field achieves a high metric value.

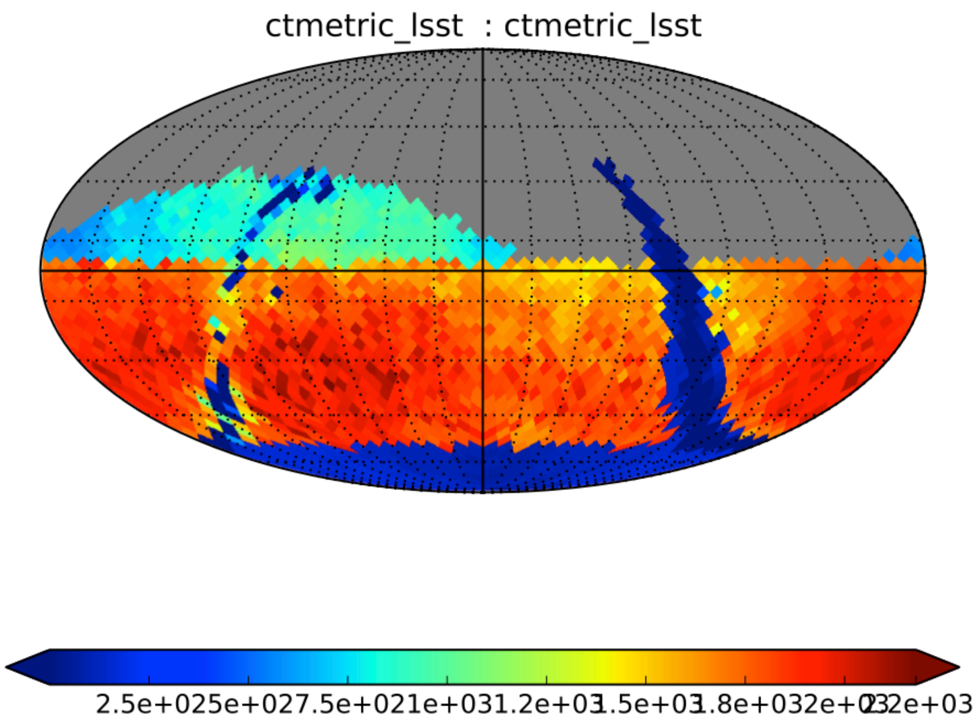


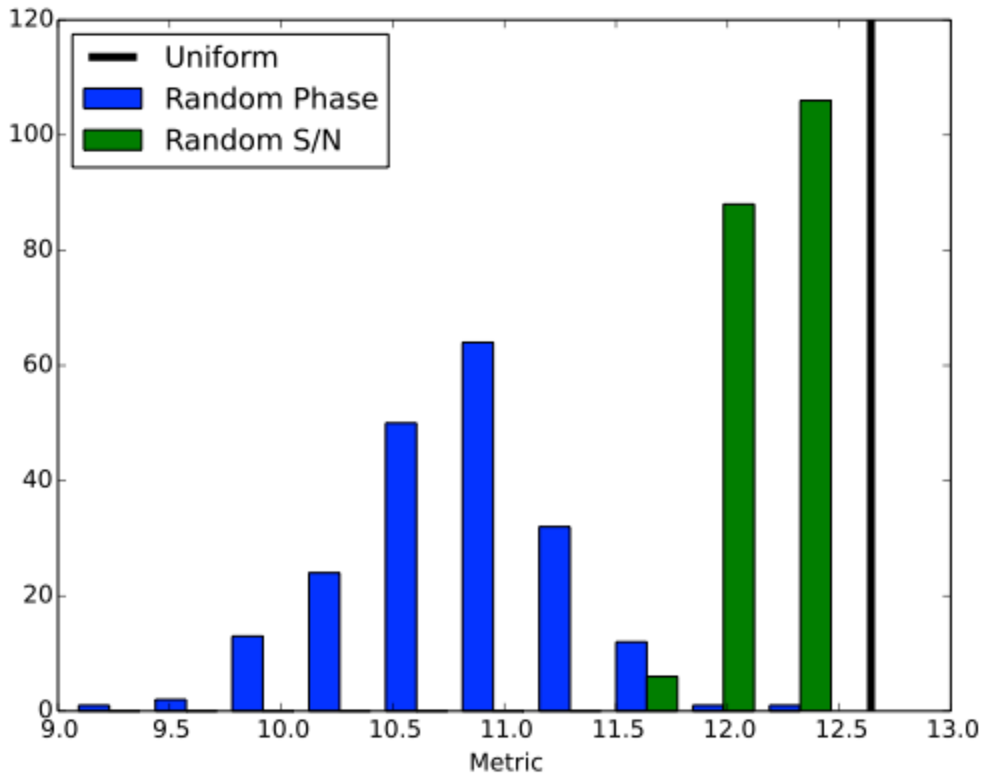
Fig. 2.— Sky map of the metric describing the control time over the sky for the discovery of z = 0.3 supernovae within 5 days of explosion, for an OpSim output.

metrics. Having this functionality easily accessed would be useful for metrics describing extra-galactic sources. It would be useful to have a calendar in which external resources (observing or processed data) are loaded and upon which metric decisions can be based. Of critical importance for supernova cosmology is photometric calibration, indeed calibration uncertainties are the largest source of uncertainty in current SN results. It is anticipated that calibration uncertainties will depend on survey strategy. It is necessary to have some form of the LSST calibration covariance matrix from which we can derive good supernova metrics.

No plans for continuing work were made. The production of MAF metrics will come from specific interested parties, not the group with diverse interests that assembled at the Workshop. Parties with specific scientific interests can take on responsibility for ensuring that their science is represented.

It would be beneficial for some supernova surveys to work on preferred pieces of sky, defined by high galactic latitudes and seasons. Full optimization of the LSST survey strategy could benefit from a balkanized splitting of the sky based on Galactic, ecliptic, and equatorial latitudes.

The benefit of some observing strategies cannot be quantified, for example making LSST the source of WFIRST supernova follow-up could boost the power of both observatories. Synergy with other surveys must be explored in the future.



The above figure shows some results from Monte Carlo Realizations of Random Dates and S/N.

11.4 Mini Surveys – The Magellanic Clouds

Reporter: Kathy Vivas (CTIO)

The Magellanic Clouds (MC) are the largest of the satellite galaxies of the Milky Way. Being at the Southern Hemisphere and at a distance of only 50 kpc, they are a prime target for any telescope in the South. The capabilities of LSST will provide unique views of these galaxies with many new and exciting science outcomes. The MC are close enough to aim for exquisite studies of their multiple stellar populations, but at the same time they are not that close that saturation will be a major problem.

Three main (non-exclusive) strategies for observations of the Clouds were discussed in this breakout session: (1) A high cadence survey; (2) A legacy survey of the stellar populations in the clouds, and (3) a study of the extended stellar populations and periphery of the clouds. Each one of these strategies addresses different (and multiple) science cases that range from the study of the origin and evolution of the MC to investigations of variable stars.

Metrics that may help to determine the success in reaching the different science goals for the strategies above follow.

11.4.1 A high cadence survey of the clouds:

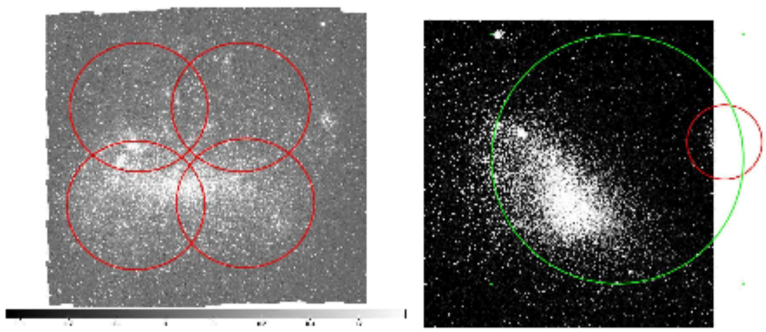


Figure. Possible field selection for observation of the Magellanic Clouds

There is already a White Paper for a Deep-Drilling Field Observations (Szkody et al) proposing a high cadence survey on the Clouds to unveil and characterize the many different type of short period variables expected in the clouds. In summary, the MC present a unique opportunity to obtain a high concentration of well-sampled light curves of many different types, covering stars in an ample range of masses, ages and metallicities. These include RR Lyrae stars, δ Scuti, eclipsing binaries, cataclysmic variables, Flare stars, pulsating white dwarfs, T Tauri stars, extra-galactic planets, and more. With only a few LSST pointings (4 in the LMC and 1 in the SMC, see Figure 1 with Szkody et al's suggestion) the main bodies of the galaxies can be covered. This high return of variables in a small area suggests that it may be a good project to do early in the survey, as it may provide good templates for discovering variables elsewhere.

Metrics needed to quantify this survey includes:

- Variable stars metrics: Many of these metrics were discussed, or even written, during the breakout sessions on transients and variables (fast and slow). An example of this is a metric that measures how uniform observations are distributed in phase for a given period (for example, what is the maximum gap in the phased light curve for stars of a given period)
- Discovery metrics: There is a need to quantify the expected number of the different type of variables in the MC. This was also partially discussed in the Transients and Variables breakouts.
- Simulations for discovering planets in the MC. There is ongoing work in this subject and a journal paper is already available (Lund et al, 2014, arXiv:1408.2305)

11.4.2 A legacy survey of the stellar population of the MC

LSST provides a chance to produce exquisite color-magnitude diagrams of the MCs down to very low masses. The key aspect of this science case is the effect of crowding. These are very crowded fields and hence, only observations with good seeing are to be stacked. Alternatively, specific constraints on seeing conditions when observing the MCs may be set. A metric of limiting magnitudes with different seeing constraint is needed. This calculation should include the confusion limits introduced by the single resolution element of the telescope and the surface brightness profile of the galaxy. Knut Olsen has started work on this issue. His preliminary results show a dramatic decrease of the limiting surface brightness (errors<0.1 mag) when going from 0.5 to 1.0 arcsec seeing (see Figure 2).

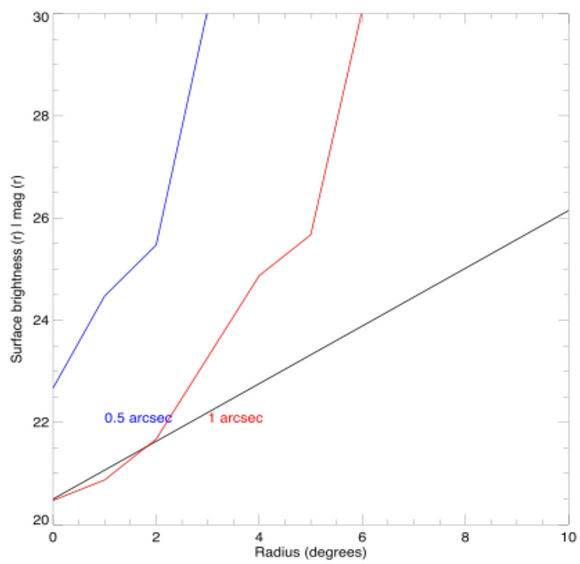


Figure. The improvement of surface brightness limit with improved seeing.

11.4.3 Extended Structure of the Clouds

In recent years it has become clear that MC's population may be found far away from the center of the galaxies. LSST will cover uniformly regions around the galaxies to unveil their true extension and shape as well as material stripped off the galaxies due to interactions between themselves and/or with the Milky Way. The population of the clouds may be traced either by using main sequence stars or with special tracers such as RR Lyrae or dwarf Cepheid stars. Relevant metrics include the calculation of the limiting magnitude as a function of position in the sky (in the case of main sequence stars) and metrics for variables discussed in (1) and in the Transients and Variables Breakout. Figure 3 shows the limiting magnitude reached by the current OpSim over all the sky. The limiting magnitude, even in the less observed part of the sky at high negative declinations (SMC has a declination of -72.8 deg), is deep enough to ensure

CMDs which will reach several magnitudes below the MC's turnoff. This technique may then be used with the current proposed cadence, although it would be interesting to investigate how soon in the survey the goals may be achieved. Techniques with other tracers will require study of other metrics.

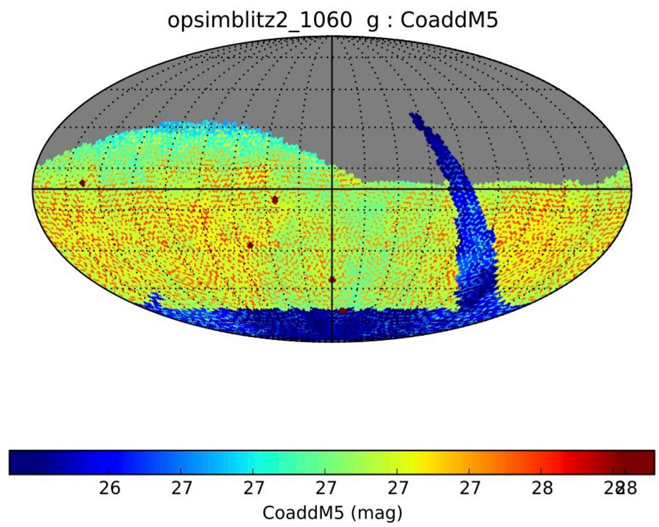


Figure. A metric for the LSST limiting g-magnitude in an example simulation.

11.5 Minisurveys - Galactic Plane Breakout group

Subgroup participants*:

- Will Clarkson
- John Gizis
- Carl Grillmair,
- Jason Kalirai
- Peregrine McGehee
- Warren Skidmore
- Michael Strauss
- Lucianne Walkowicz
- Beth Willman

11.5.1 Abstract:

This document reports the discussion that took place within the “Galactic Plane” subgroup of the Mini-surveys group within the Cadence Workshop at the 2014 LSST meeting. The breakout sessions took place Weds Aug 13 and Thurs Aug 14. While a number of metrics were discussed (and are documented here), the discussion also covered a range of important ways in which Galactic Plane observations are somewhat special from LSST's point of view, and what kinds of effort must be expended to ensure LSST is effective in the presence of these differences. Both metrics and these wider observational issues are documented here.

11.5.2 Introduction and Perspective

Galactic Plane observations differ from the main LSST surveys in a number of important ways. The plots in the OpSim 3.61 SSTAR document dramatically illustrate some of these points:

1. The number of visits per field is likely to be much lower than for the main survey area (OpSim 3.61 indicates 30 visits per filter per field per *decade* compared to ~200 for the main survey area), which makes it dangerous to assume one can average through observing conditions for the Plane.
2. Furthermore, since Galactic Plane observations are not part of the main-survey area, programmatic upper and lower limits on exposure time not set by hardware, may not apply to the plane.
    a. So the adopted strategy becomes more critical with low-N, but there is more flexibility to set the schedule.
    b. For example, your science may require many exposures in one filter and only a few in the others for source characterization.
    c. ***A concern:*** Currently it appears that OpSim always puts Plane observations into the first three years for algorithmic reasons, which even by current metrics significantly disadvantages the Plane. This is a concern that should be addressed before the SAC makes decisions on the relative importance of science cases. No matter what we do with the metrics, at present the Plane would always be down-weighted.
3. In many fields the ability to do one's science at all depends on factors such as source crowding that vary strongly on spatial scales down to the sub-arcminute level. This leads to a need to fold spatial information into the metric in a meaningful way that does not require the end-user to re-run an expensive simulation each time the trial strategy is tweaked.

The discussion during the sessions can be characterized in terms of the level of sophistication at which simulation software is being required to report survey appropriateness for the science.

11.5.3 Level 0: Which science cases cannot be done with the main survey?

The Roadmap process within the Milky Way and Local Volume collaboration (hereafter MWLV) has produced a list of cases organized by science topic, but [as far as I am aware! WIC] has not produced a similar breakdown by operational considerations. MWLV should come to a decision on which science cases cannot be done in the main survey. As a strawman example: if one is interested in faint M-dwarfs that nominally concentrate in the plane, the observable targets may be so close by anyway that they are found essentially all over the sky, and thus they would already be very well-served by the main survey. Existing OpSim metrics should allow the hypothetical investigator to determine how well the main survey already meets their science goals (another example: how close do we really need to get to the Plane in order to constrain, say, the scale height as a function of stellar mass?).

Related: what sets the range on the extent in galactic longitude for galactic plane science? The Plane currently extends quite far North in OpSim runs, what is the science case for this?

There are a number of obvious examples (where the targets are *only* present in the plane, such as Bulge population studies, or for example looking for galactic substructure in the plane using variables as standard candles), but at least a list of cases needs to be culled so that specific metrics can be produced. To start the ball rolling, here are some example cases mostly pulled down from the MWLV Phase I Roadmaps that may or may not fall into the "Galactic Plane" observations as opposed to the main survey:

- Tracing structure in the plane using standard-candle variables
- Comparing thin- and thick-disk populations
- Galactic scale height as a function of stellar mass
- Tracing the large-scale warp in the Milky Way
- Search for phase-space overdensities that may indicate past merger events
- Dissecting the stellar populations within the Milky Way bulge to determine its formation and evolution
- Characterization of star-clusters in the plane
- Detecting candidate microlensing events
- Detecting transiting planets

11.5.4 Level 1: Metrics using OpSim output without calls to external information

Because so many of the Plane science cases would require knowledge of specific regions and/or populations, the ultimate decision of whether investigation X is worthwhile, does depend somewhat on the specific source population, and thus is currently somewhat beyond OpSim's specifications. Remembering that the number of visits per filter may be quite low (~3 per pointing filter per *year* assuming uniform sampling), the investigator may require OpSim-based metrics that they can then use to set up their own tests on their laptop. An example might be the Monte Carlo investigation of the recovery rate of the investigator's favorite object for a large number of fake observation-setsti in this case the investigator would need a parameterization of the observations that could be used as input. Specific examples were discussed of OpSim-based metrics for this case:

1. Allow multiple exposure times to be simulated per filter per pointing, and report as a metric the number (and fraction completed) of exposures, as well as the signal to noise to a range of apparent magnitudes (or coefficients in an analytic scaling) under the same assumptions as the rest of the survey area (i.e. no crowding heroics).
2. Quantify spatial variation of the above within a user-defined area (e.g. user-defined cluster of healpixels). Examples: mean, standard deviation, quartiles of depth over a collection of healpix?
3. Both of the above combined over exposure times in a given strategy.
4. Some discussion of airmass: is the time-series of airmasses at observations sufficient?
    a. Spatially-varying measurement error as a function of airmass needs to be included at some level, since with an assumed low number of exposures per filter per field, we cannot necessarily assume averaging over a range of airmasses.

    b. Ditto for distortion (atmospheric + telescope + camera)ti again with too-low N_exp to average through, the investigator is likely to need to know spatially-dependent perturbations.
5. Investigators are likely to need the time series of exposures and exposure times that they can then fold into their own simulations if needed. This appears to be a natural output from OpSim already - but with investigators likely to focus on spatial regions, tools to extract time-series' from a particular user-defined clump of HEALPIXels would be very welcome.

11.5.5 Level 2: Metrics incorporating crowding and foreground bright stars in a practical way

It seems clear that meaningful metrics in the presence of strong spatial variation requires the ability to bring in external information, whether that be a lookup table based on existing observations, the results of a canned simulation, or analytic fits to existing simulations/observations (that could be called very quickly). Specific metrics/ideas discussed:

1. Spatial crowding:
    a. The number of stars measured more poorly than the SRD requirements for the main survey as a function of apparent magnitude.
        i. This might be coded as a fraction of stars lost to crowding, as a multiplicative factor stored at the resolution of the smallest HEALPIX supported by OpSim.
    b. Incorporate crowding as a correction to the existing OpSim metrics? For example, OpSim already has a proper motion metric that takes seeing, signal to noise at a particular magnitude, and the distribution of exposure dates and times as input. Calling external information or parameterization would allow correction of the inputs to this metric. One can imagine a module that takes OpSim output into to a stored parameterization of typical random and systematic errors for a particular pointing, and outputs the corrected [fwhm, signal to noise, etc.] and also the same metric, with these corrected values as inputs. A couple of notes on this:
        i. We heard from the Magellanic Clouds subgroup that Knut Olsen et al. have already done work quantifying survey efficiency as a function of position and depth near the LMC… might a fit to this data just be dropped in as a parameterization?
        ii. Analytic scalings likely to be the most practical input to OpSim.
2. Bright stars: in this case we know from other surveys where all stars bright enough to cause charge bleeds would be. It may be practical to perform star-injection simulations to quantify the systematic and random error imposed on measurements [for some choice of measurement tool!] as a function of position near bright stars, and store this as a lookup table. This table could then be sampled to produce statistical estimates for the impact of bright stars.
    a. At the OpSim level, could quantify the area of a typical LSST image falling under a charge-bleed if a believable parameterization of bleed size and shape is available.
3. There was some discussion about short exposures. My recollection is that the following three items were discussed at various points:
    a. Exposure strategy for science case X: given spatial crowding, a large number of short exposures may be better than fewer 30s exposures anyway. This feeds back to the discussion of metric 1a above about crowding. Note that since galactic plane

observations are NOT part of the main survey, limits on exposure time driven by the "big four" science drivers may not apply.

b. Calibration: even if a bright star is so saturated it bleeds, the observing team may well wish to quantify its brightness. Example: aperture photometry of charge-bleeding stars may allow variability studies at useful precision (assuming the bleed is entirely contained on-chip), but some calibration of the absolute brightness will still be needed.
c. Compelling case for short exposures lacking? However, from the point of view of *dedicated* short-exposure observations, concern was raised that a compelling scientific reason to add short exposures to the queue has yet to be identified.

11.5.6 Level 3: Metrics describing errors in science parameters as a function of input survey strategy

This item was not discussed much due to time constraints. The idea here would be to take input population parameters (say, a mass function), "observe" them with OpSim/ImSim/PhoSim and then estimate the error in recovered (say, uncertainty and bias in the mass function).

- Concern was expressed at the Breakout Summary session that one does need to know where to stop with this process. Is this best left to the investigator to develop (rather than the LSST program trying to support metrics for all science cases at the operations+image+catalog level)?

11.5.7 Additional strategy notes discussed that do not fit into the by-level characterization above

- For special regions like the Bulge and Plane, some number of excellent-seeing images will be required as a legacy product. [Knut Olsen, Breakout plenary.]
- There was also some discussion about synergy with WFIRST: should LSST devote excellent-seeing observations to support source characterization for WFIRST's microlensing survey, for example?
- e.g. Andy Gould paper on LSST microlensing [need to find this reference]

11.5.8 Actions arising, organized by the level of metrics discussed above

- **Level 0:**
  - **MWLV collaboration to identify which science cases absolutely *cannot* be done by the main survey,** even independently of metrics (looking for 100% cases rather than 10% cases).
  - Connect with external groups to determine what is already being planned with other instruments. E.g. 3D dust mapping teamsti transient surveys in the plane
  - Contact OpSim developers to make them aware of the down-weighting problem
    - WIC: I have discussed with and emailed Lynne Jones, recommendation was to ensure the SAC knows about this issue.
- **Level 1:**
  - Find out / get documented what metrics are currently used or were recommended by other Cadence sub-groups, so that investigators can assess the whole survey for their Galactic Plane science case of interest. This would enable assessment of which cases do not require dedicated GP observations at a more quantitative level. Specific examples discussed:

        - What metrics came out of the Variable Stars and Transients group?
        - What metrics came out of the Astrometry group?
    - Communicate with OpSim developers to determine:
        - if multiple exposure times per field per filter are supported
        - if tools exist to query a set of HEALPIX from OpSim output by user-input area on the sky, and if not, what is involved in making this happen
        - What tools exist to return the time-series of OpSim values for one or few HEALPIX
    - Airmass
        - Examine the airmass limits currently in OpSim input parameters.
        - Recommend different airmass limits if currently too high for GP science.
- **Level 2:**
    - Discuss with OpSim developers: how would crowding and extinction be correctly handled within OpSim?
    - Bright stars: find out from ImSim [?] developers how charge-bleeds are currently parameterized
    - Distortion: ditto
    - Crowding, simulations:
        - Examine the LMC-based work in a bit more detail is this already what we need for metrics that include crowding?
    - Crowding, observations:
        - Produce estimates for crowding impact as function of (l,b) through artificial star tests
        - Examine PSF elongation as a function of airmass and its impact on crowding from real data (DECam engineering? Bulge datasets?)
- **Level 3:**
    - **Short exposures:** MWLV to come to a decision about science cases that require short exposures. Is there a compelling scientific and/or technical case for short exposures?
    - More specific metrics postponed for now until the key science cases are identified.

11.6 Minsurveys – Deep Drilling

Editor and reporter – Lynne Jones

In 2011, white papers solicited from the LSST community describing desired deep drilling strategies for their science. Eight white papers were submitted.

The topics proposed are:

- Large scale structure (Gawiser et.al.)
- Weak lensing (Ma et.al.)
- Galaxies (Ferguson)
- Supernovae (Crotts)
- Transients and Variable Stars (Szkody et.al.)
- Milky and the Local Volume (Dhital et.al.)
- Solar System (Becker et.al.)

Tables of the deep drilling proposals show a total request (after compensating for requests which can be served by shared datasets) of 3923 hours.

Extragalactic fields	grizy observations in each sequence, every few nights (weighted toward z) Add u band exposures during dark time	5 fields with 265 nights of grizy, and additional u band - 1675 hrs
	grizy observations in each sequence, every few nights (weighted toward z) Add u band exposures during dark time	5 fields with 265 nights of grizy, and additional (less) u band - 1547 hrs
Transients/Variable Stars fields	g band continuous for 1 hour, then 7 more hours of observations spaced over next 3 days; repeat in r then repeat in g and r again	6 fields - 192 hrs
Milky Way fields	30 nights of izy/izy/izy sequences every night gri sequences spread over 2 years	3 fields - 407 hrs
Solar System fields	8 nights of 85 minutes of continuous r band observations, spaced at particular intervals over one year Total: 3923	9 fields - 102 hrs hours

Figure. Proposed deep drilling fields, filters and visit counts

12 LSST Main Survey – Optimization and Thinking Outside the Box

Discussion leads: Ẑeljko Ivezić and Jason Kalirai

12.1 Broad topics

12.1.1 What is LSST?

- LSST as a series of large science programs.
  - Science landscape will change
  - The science priorities and needs for specific observations will be different in year XX of LSST
  - An economical model for OpSim (Hogg)
  - Input proposals have certain amount of (virtual) money that they can spend on fields
  - This meeting is focussed on quantifying the outputs from OpSim …do we need to

reconsider the inputs?
    - Maybe, but its probably not worth re-doing everything. Should at least see what these a

12.1.2 Distibution of time and balance among different programs

- Primary survey
    - Maintaining uniformity vs. not
    - Early science vs. uniformity
- Deep drilling fields and other minisurveys
    - Nominally 10% of total
    - What hit to main survey if it is, eg., 13%?
- Early science

12.1.3 Commissioning

What science can be done during commissioning? Need clarification.

Three phases:

- Early system I&T with ComCam (6 months)
- Camera-telescope-DM integration (7 months)
- Science verification through mini surveys to characterize SRD performance (5 months)

12.1.4 Cadence

- Solar system would like two (or more, TBD) observations per night
    - Not needed every night
    - Perhaps not needed away from the ecliptic
- Transients
    - Proposal for triplets per night
    - Could lead to inefficiencies in other programs

12.1.5 LSST in an era of WFIRST, EUCLID, JWST, ELTs

- WFIRST (2.4 m telescope) will survey 2400 deg^2 at 0.1” pixels to Y,J,H,F184 = 26 - 27
    - 25% of WFIRST is unallocated for GO programs (i.e., point anywhere)
    - Instrumentation includes wide-field camera, coronagraph, and an IFU for SN spectroscopy
    - WFIRST needs LSST for photo-z’s and panchromatic baseline
    - LSST needs WFIRST for high resolution imaging, panchromatic baseline, galaxy morphology, and star/galaxy separation
    - Consider overlapping the WFIRST 2400 sq deg. early in LSST, down to sufficient depth
- EUCLID
    - Optical and IR imaging at lower resolution than WFIRST
    - Unclear if there is substantial overlap in survey footprints
- JWST
    - Very valuable for LSST follow up

- Cycle 5 call for proposals in 2022
- Motivation for early science programs

12.2 Other topics

- Constant SNR vs constant exposure time
- Making better use of time that doesn't meet sky brightness and seeing limits
- Dithering

13 Conclusion

13.1 Summary

13.2 Timing and goals for the next workshop

- When: ~1 year from now
- Where: ?
- Pacing item: making OpSim a tool for experimenta7on by community
- Goal: have users experiment with alternate cadence calculations
- Intermediate work: continue work on gettng metrics coded into MAF, recommending directions for cadence exploration

14 Additional materials and information

14.1 Post-workshop survey

The posts-workshop survey drew 31 responses. The responses are summarized here.

How was the balance of plenary and breakout sessions?

I would have preferred more time in plenary sessions	13.3%
The balance was about right	76.7%
I would have preferred more time in breakouts	10.0%

How was the length of the workshop?

The workshop was too short	3.3%
The workshop length was about right	70.0%

The workshop was too long	26.7%

Would you recommend scheduling future Cadence (or other) workshops concurrent with annual LSST "All Hands" meetings?

Yes	67.7%
No	32.3%

How productive was the workshop for you? (Select all that apply)

I didn't attend most of the workshop sessions	6.5%
I attended but didn't find the workshop very productive	0%
I was actively involved in the breakout group discussions	77.4%
I came away with new ideas for metrics for my science	61.3%
I came away with coded metrics for my science	12.9%

Did you attend the tutorial session on the Metrics Analysis Framework (MAF)?

Yes	58.1%
No	41.9%

How useful was MAF at the workshop?

I have no interest in MAF	4.8%
I got stuck on MAF software installation, and didn't make use of it at the workshop	42.9%
I used MAF to try and code my own metrics, but didn't finish	23.8%
I used MAF to successfully code my own metric	14.3%

What are your thoughts about MAF support and development? (Select all that apply)

How was the length of the workshop?

Really, I'm not interested in MAF	8.7%
I have ideas for metrics, but need help coding them in MAF	47.8%
I think I can (mostly) code my own metrics, but I need help to contribute them to LSST	39.1%
MAF is easy, I don't need any help using it	13.0%
I need new capabilities added to MAF (please explain in comments)	4.4%

Do you want to run the Operations Simulator (OpSim) yourself to explore new cadences?

	For sure	Probably	Not Likely	Nope
Even if there is a steep learning curve and little support	13.8%	31.0%	37.9%	17.2%
If it is considerably simplified and/or significant support is available	41.4%	37.9%	17.2%	3.5%
If I could make request for simulations and have someone else run them	48.3%	34.5%	13.*%	3.5%

Assuming the scheduling works for you, will you attend the next Cadence workshop?

Absolutely	43.3%
Probably	46.7%
50/50 chance	10.0%
Not likely	0.0%

14.2 Electronic copies of slides presented at the workshop

https://project.lsst.org/meetings/ocw/node/6

14.3 Metrics Analysis Framework (MAF) documentation

https://confluence.lsstcorp.org/display/SIM/MAF+documentation

14.4 Accessing the schedule simulations referenced at the workshop:

https://confluence.lsstcorp.org/display/SIM/Cadence+Workshop+Simulated+Surveys

14.5 How metrics will be received by the project

Continuing support for MAF – Peter Yoachim and Lynne Jones

- Where to send metrics – preferably check into git repository
  - see https://github.com/LSST-nonproject/sims_maf_contrib – instructions will be in report and on workshop Resource page, or contact anybody in OpSim group
- Provide documentation of algorithm so motivation and logic is clear
- Provide example config file that includes appropriate captions for figures