Optimization of LSST deployment strategies

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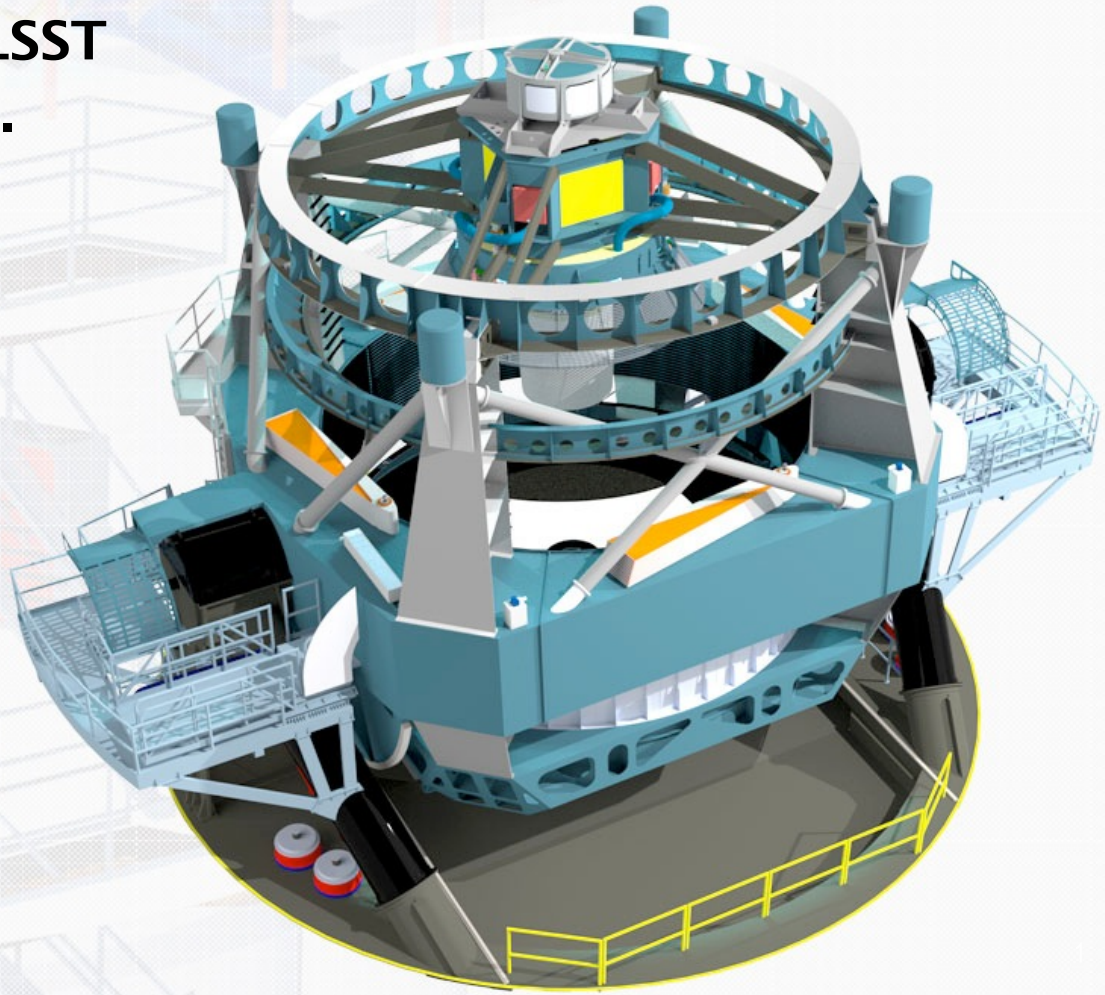
LSST Project Scientist

With special thanks to the LSST Simulations/OpSim team(s).

LSST SAC meeting
Princeton, April 7, 2014



Outline

1) **General cadence considerations**
   - introduction: flow-down of science goals
   - cadence "conservation laws"
2) **Baseline cadence**
   - basic characteristics
   - possible modifications
3) **Tools for further refinements**
   - OpSim and MAF
4) **Mechanisms for changing the cadence**
   - SAC, PST, Project Scientist
5) **Getting community input**
   - cadence workshop series

Flowdown of Science Goals to System Requirements

System

Atmosphere (transmission,refraction, seeing, sky background)

Telescope (collecting area, mirror reflectivity, slew and settle time, contribution to seeing, scattered light, FOV)

Camera (CCD QE curve, optical transmissions and reflections, charge diffusion, readout noise, crosstalk, filters)

Data processing (data throughput, algorithmic errors, speed, bugs)

Science

Dark matter, dark energy, cosmology (spatial distribution of galaxies, gravitational lensing, supernovae)

Time domain (cosmic explosions, variable stars)

The Solar System structure (asteroids)

The Milky Way structure (stars, ISM)

Any given science program drives numerous system parameters

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Data Properties

Image Depth

Delivered Seeing

Number of images

Distributions with respect to time, bandpass and observing conditions

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Key point:
Science goals and technical parameters are connected through, and communicate via, data properties

Science

Dark matter, dark energy, cosmology (spatial distribution of galaxies, gravitational lensing, supernovae)

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SRD specifies data properties needed to achieve science goals

Science Requirements Document (SRD)

At the highest level, LSST objectives are:

1) Obtain about 5.5 million images, 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) 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.

Science Requirements Document (SRD)

At the highest level, LSST objectives are:

1) Obtain about a billion 16 Megapixel images of the sky, with **characteristics as specified in the SRD:**

- ~90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night (one **"visit"** is two back-to-back 15-second exposures)

- after 10 years, half of the sky will be imaged about 800 times (in 6 bandpasses, ugrizy): **a digital color movie of the sky**

- ~24 PB of raw image data, enabling measurements for 37 billion objects

Baseline cadence is defined in terms of data properties and window (sampling) functions (area on the sky, temporal sampling, bandpass sampling, etc.)

Simulated cadence output consists of ~2.5 million values for (mjd, ra, dec, filter, m_5, seeing, sky brightness, etc)

System capability

- The most fundamental parameter (most science metrics scale linearly with it) is the **integrated etendue** (or throughput) over time:
  (Etendue*time) = Field-of-View * Collecting Area * Time

  Ability of the system to collect information (the number of captured photons for a given astronomical sky)
- Baseline: **FOV = 9.6 sq.deg., Time = 10 years**
- 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")

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- Instead of "Collecting Area", a full expression for **5-σ image depth**: coupling of **atmospheric**, **system**, and **deployment** parameters:

$$m_5 = C_m + 2.5*\log[0.7/(\theta_{atm}^2 + \theta_{sys}^2)^{1/2}] + \\ + 1.25*\log(t_{vis} / 30 \text{ sec}) + 0.50(m_{sky}-21) - k_m(X-1)$$

- here m_{sky} is sky brightness, θ is seeing (in arcsec), X is airmass, and k_m is atmospheric extinction coefficient
- **the collecting area, the system throughput, and the system noise enter only via scaling coefficient C_m** (more details in LSE-40)
- N.B. we can increase t_{vis} to go deeper, but then we get fewer visits.

Deployment optimization: cadence "conservation laws"

How can we optimize the main deployment parameters: exposure time and depth per visit, the mean revisit time, and the number of visits?

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

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

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

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

How to allocate the total observing time per position of ~8 hours to ugrizy, and how do we split allocations into individual visits?

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

20 sec < t_{vis} < 40 sec for the main survey **t_{vis} = 30 sec as default**

(see section 2.2.2 in "overview" paper, arXiv:0805.2366)

Deployment optimization

Constraints on exposure time per visit (20-40 sec):

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:

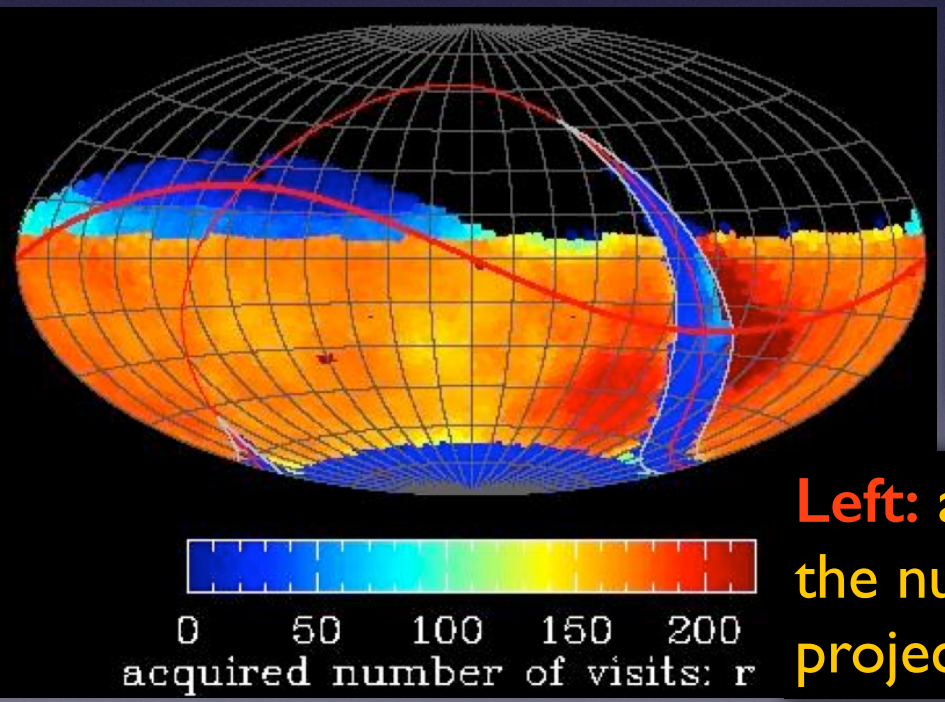
the mean revisit time cannot be too long
(SNe, NEOs)

the number of visits must be large enough
(light curves, systematics, proper motions)

trailing losses for moving objects

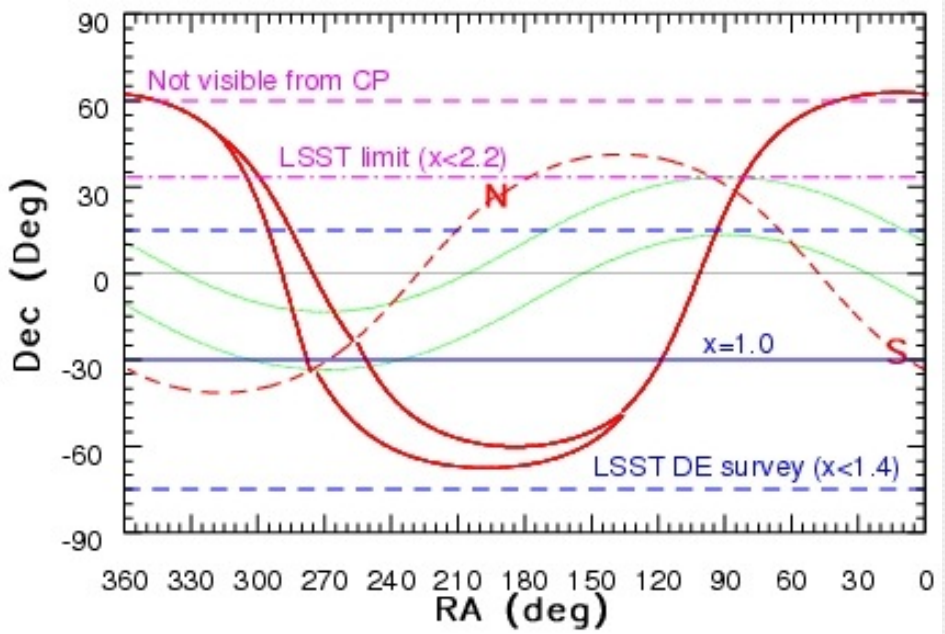
What is LSST? A uniform sky survey.

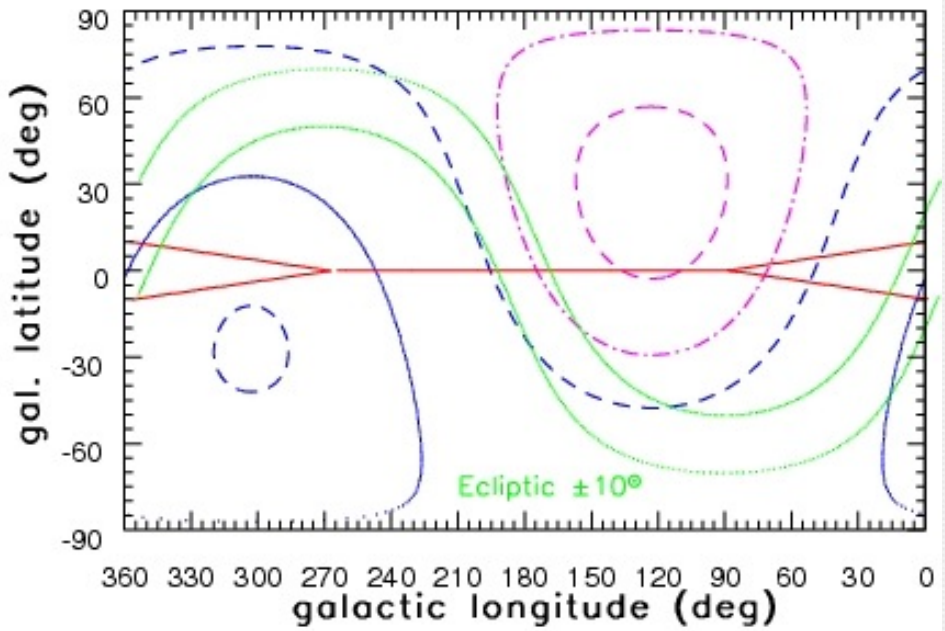
- ~90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night
- after 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky
- ~100 PB of data: about 2.5 million 3.2 Gpix images (visits), enabling **measurements for 40 billion objects**



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.**

Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)





Sky coverage:

for the main survey, maximize the number of objects (area vs. airmass tradeoff)

X<1.4 corresponds to

$-75^o < Dec < +15^o$

(25,262 sq. deg.)

X=2.2 corresponds to Dec < +33º, but note that the telescope can reach Dec = +40º (X=2.9)

Maximize the number of objects (area vs. airmass)

Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.9; g = 25.0; r = 24.7; i = 24.0; z = 23.3; y = 22.1
Photometric calibration	< 2% absolute, < 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	< 60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

From photo-z

Valid for baseline cadence: t_{vis}=30 s

- **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)

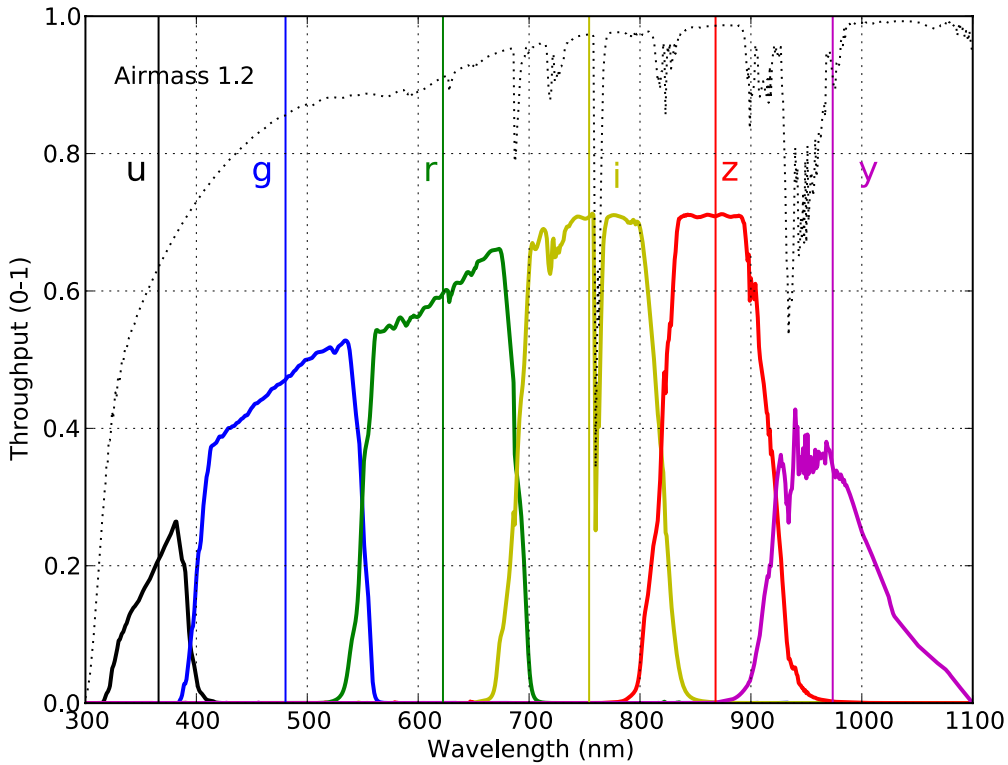


Photo-z requirements correspond to r~27.5 with the following per band time allocations:

u: 8%; g: 10%

r: 22%; i: 22%

z: 19%; y: 19%

Consistent with other science themes (stars)

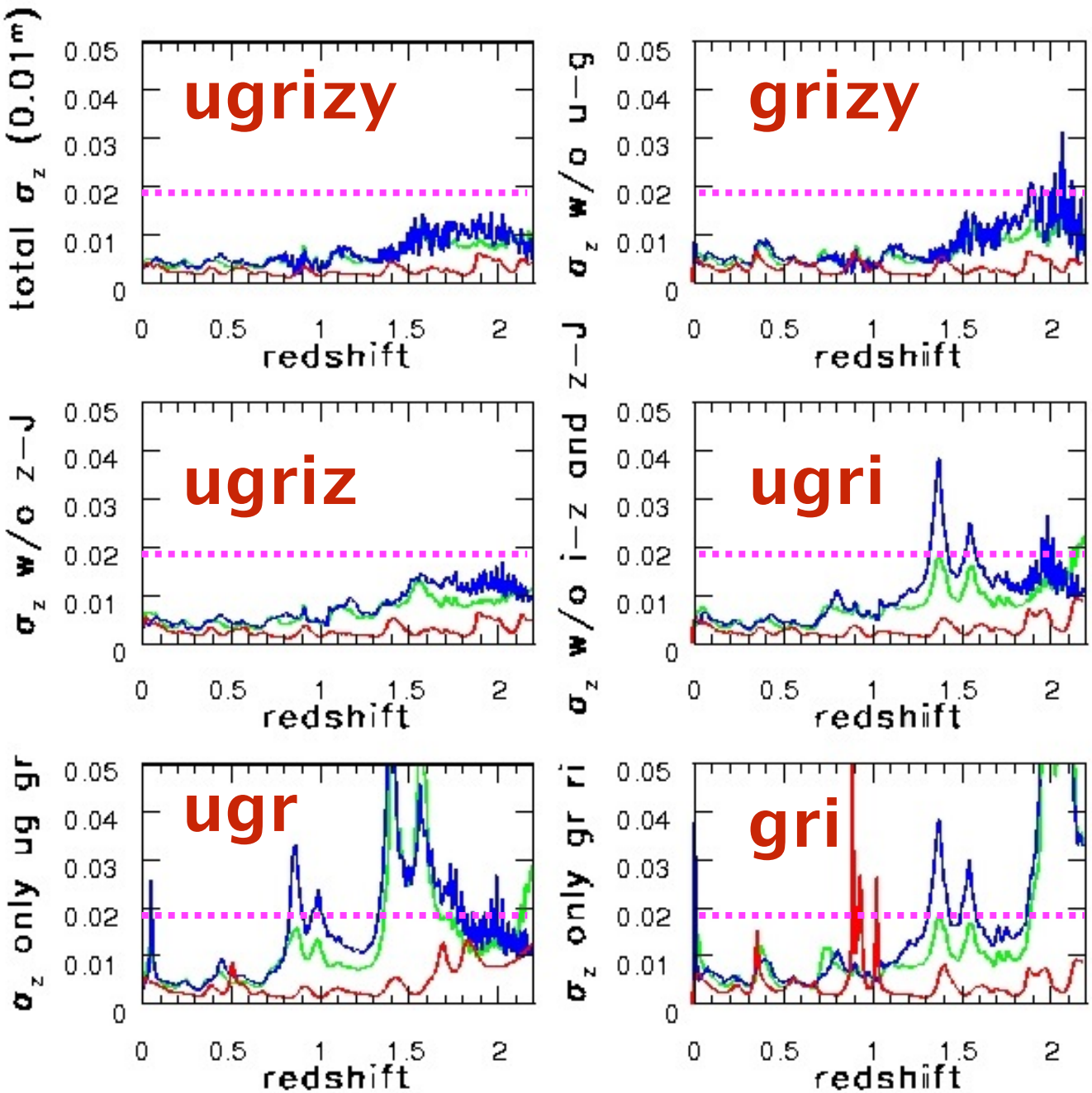


Photo-z:

6 bands are needed!

Both u and y bands are needed for photo-z.

Both are also required by stellar science.

Baseline cadence (OpSim3.61)

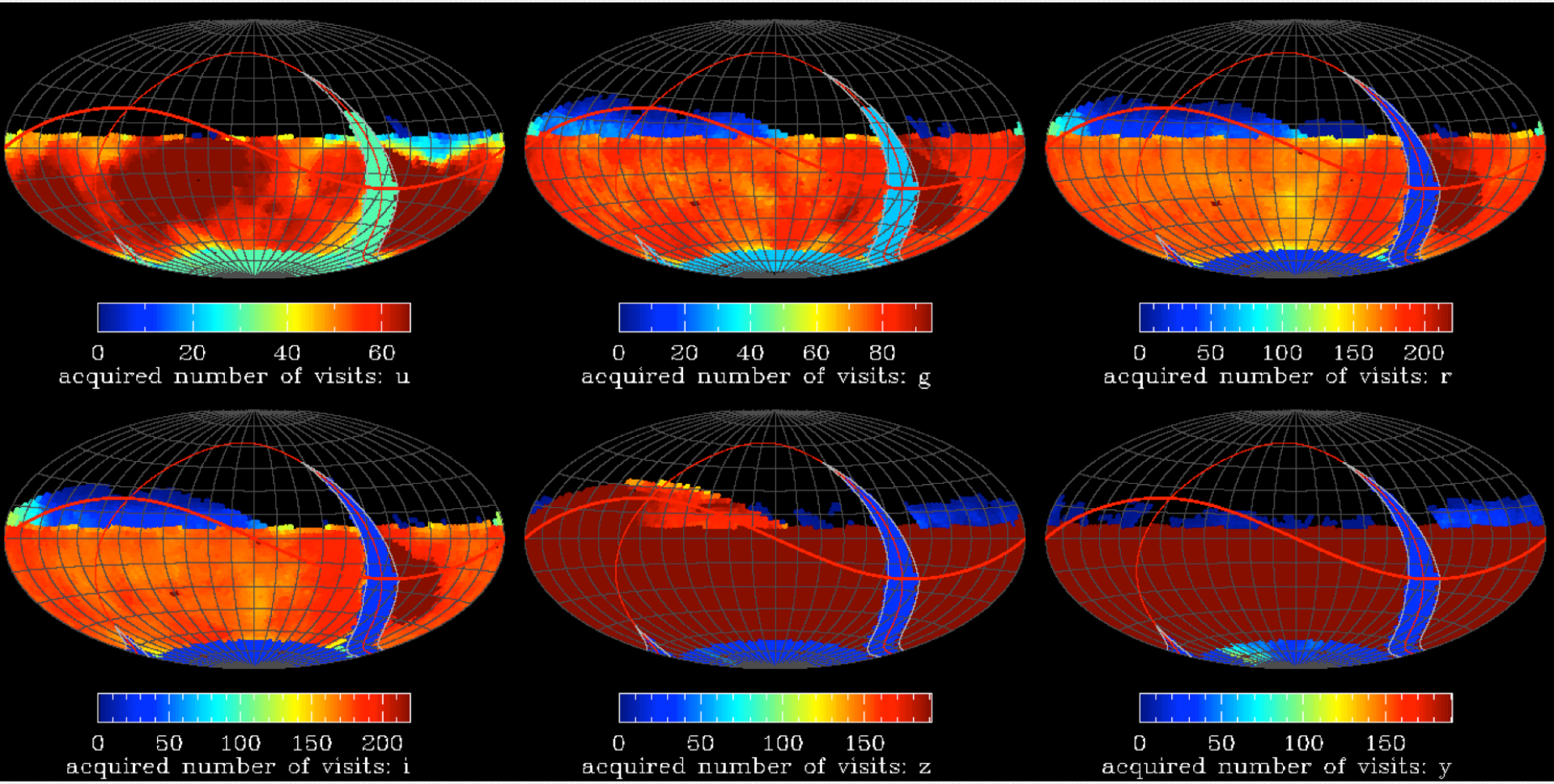
A 10 year simulation: "existence proof" for an LSST survey

Basic characteristics:

- 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 passband
  - 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 t_{vis} = 30 seconds!**

Baseline cadence (OpSim3.61)

SSTAR report: http://opsimcvs.tuc.noao.edu/runs/opsim3.61/design/opsim3_61_design.html



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.

Baseline cadence (OpSim3.61)

- 2,651,588 total visits,
- 20,000 square degrees: 75% in Wide-Fast-Deep (WFD)
  - 1030 requested visits in ugrizy
  - 656,687 pairs of griz with 15-60 minute separation
  - ~ 6 pairs per field per lunation
- 4,000 square degrees: 12% in the Northern Ecliptic (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
- 1,300 square degrees: 6% in the South Celestial Pole (SCP)
  - 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)

Baseline cadence (OpSim3.61)

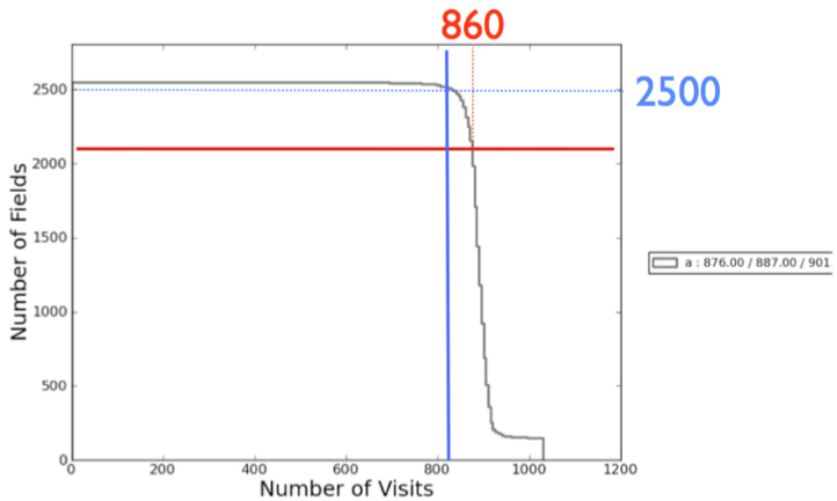


Figure 6: *(opsim3_61_cvisits_allfilters_all.png)* The cumulative distribution of Figure 4 showing the number of fields having visits $\geq x$. Only visits acquired by modes designed to meet the WFD number of visits are included. The inset box contains the values of the 25th, 50th (median), and 75th percentiles for each curve.

FIG. 4.— An approximate estimate of f_O using figure 6 from the opsim3.61 SSTAR report. The curve shows the number of fields on the y axis that have at least the number of visits shown on the x axis. The median number of visits for all 2549 fields considered for the main survey is 887. The red line corresponds to the SRD requirement for 2107 fields; all these fields have at least 860 visits, with a median of ~890. The blue line corresponds to "at least 825 visits" (different and more stringent than the SRD requirement for the "median of 825 visits") and is satisfied by ~ 2500 fields.

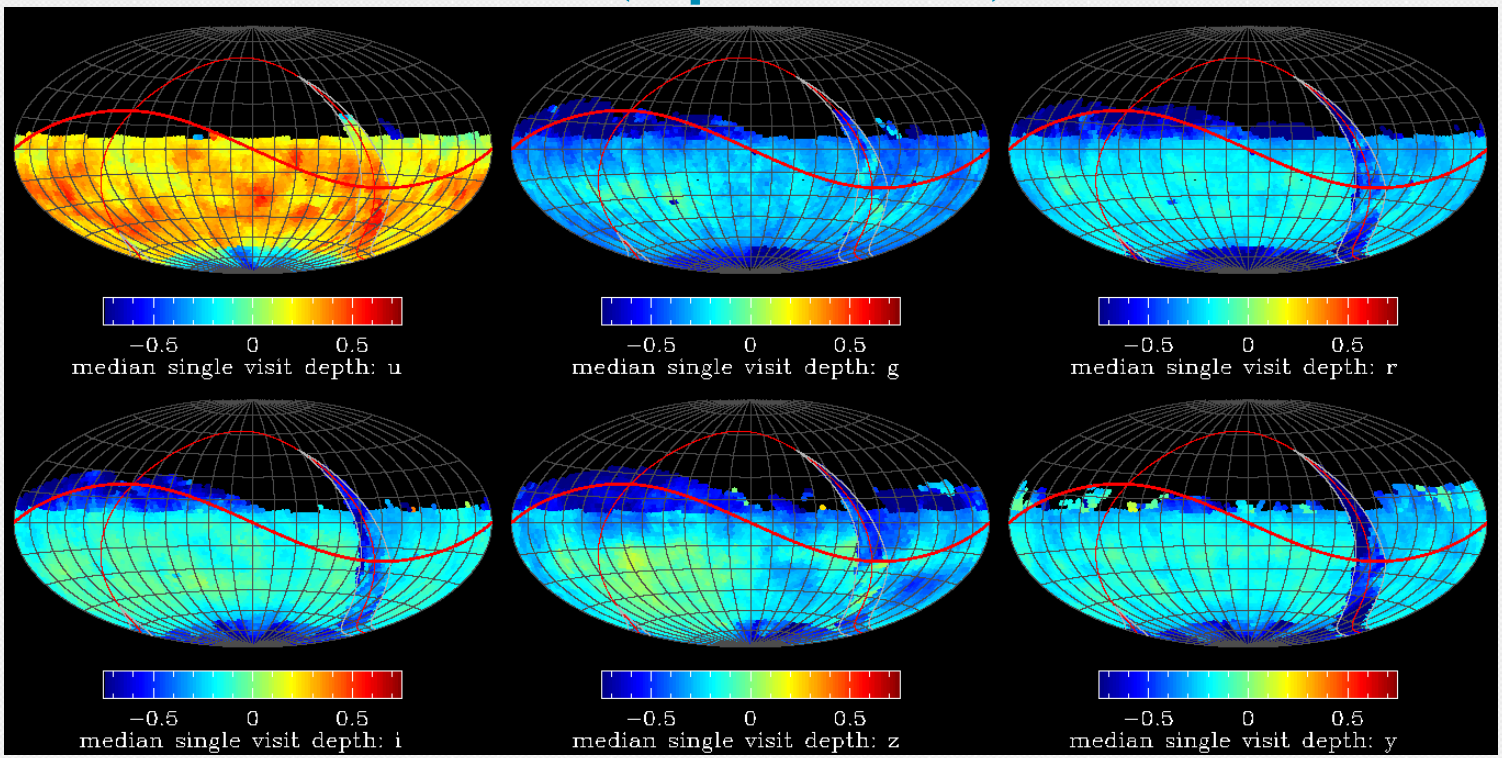
OpSim3.61 produced 2.65 million visits.

The minimum number of visits, with a nominal FOV, to satisfy the SRD (including 10% for DD) is 1.93 million.

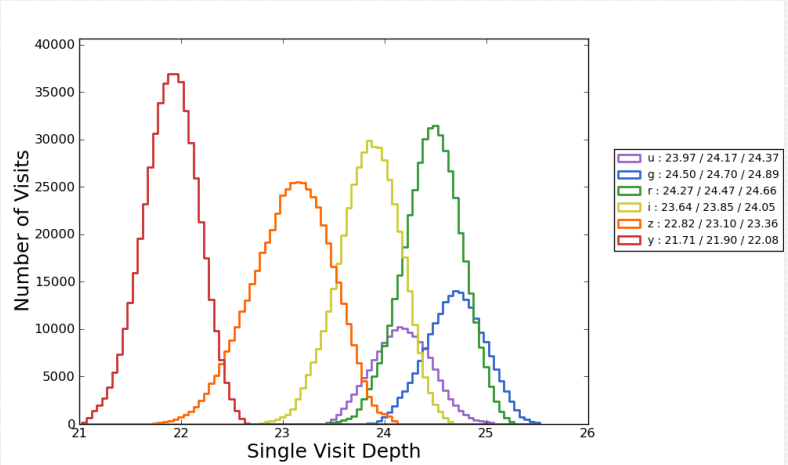
With the FOV filling factor of ~0.86, we have **a reserve of ~18%.**

(also, some margin from expected depths)

Baseline cadence (OpSim3.61)



Median 5-sigma depth (for all visits)



OpSim gives variation around the mean depth due to seeing, sky brightness, and airmass variations.

The mean value is inserted as input to OpSim (best Cm estimates)

Progress towards the survey goals

Main performance metrics as functions of time:

Co-added survey depth:

$$m_5(t) = m_5^{Final} + 1.25 * \log(t / 10\ yr)$$

Photometric errors at i=25 (4 billion galaxy sample):

$$\sigma_{ph}(t) = 0.04\ mag * (t / 10\ yr)^{(-1/2)}$$

Trigonometric parallax errors at r=24:

$$\sigma_{\pi}(t) = 3.0\ mas * (t / 10\ yr)^{(-1/2)}$$

Proper motion errors at r=24:

$$\sigma_{\mu}(t) = 1.0\ mas/yr * (t / 10\ yr)^{(-3/2)}$$

DETF FOM (FOM^{Final} ~750):

$$FOM(t) = FOM^{Final} * (t / 10\ yr)^{(-1)}$$

NEO (140m) completeness (t_{NEO}~4 yrs; C_{NEO}~93%):

$$C(t) = C_{NEO} * (1-\exp[-(t / t_{NEO})^{(-3/4)}])$$

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

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?

Baseline cadence (OpSim3.61)

Drivers for baseline cadence modifications:

- 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)

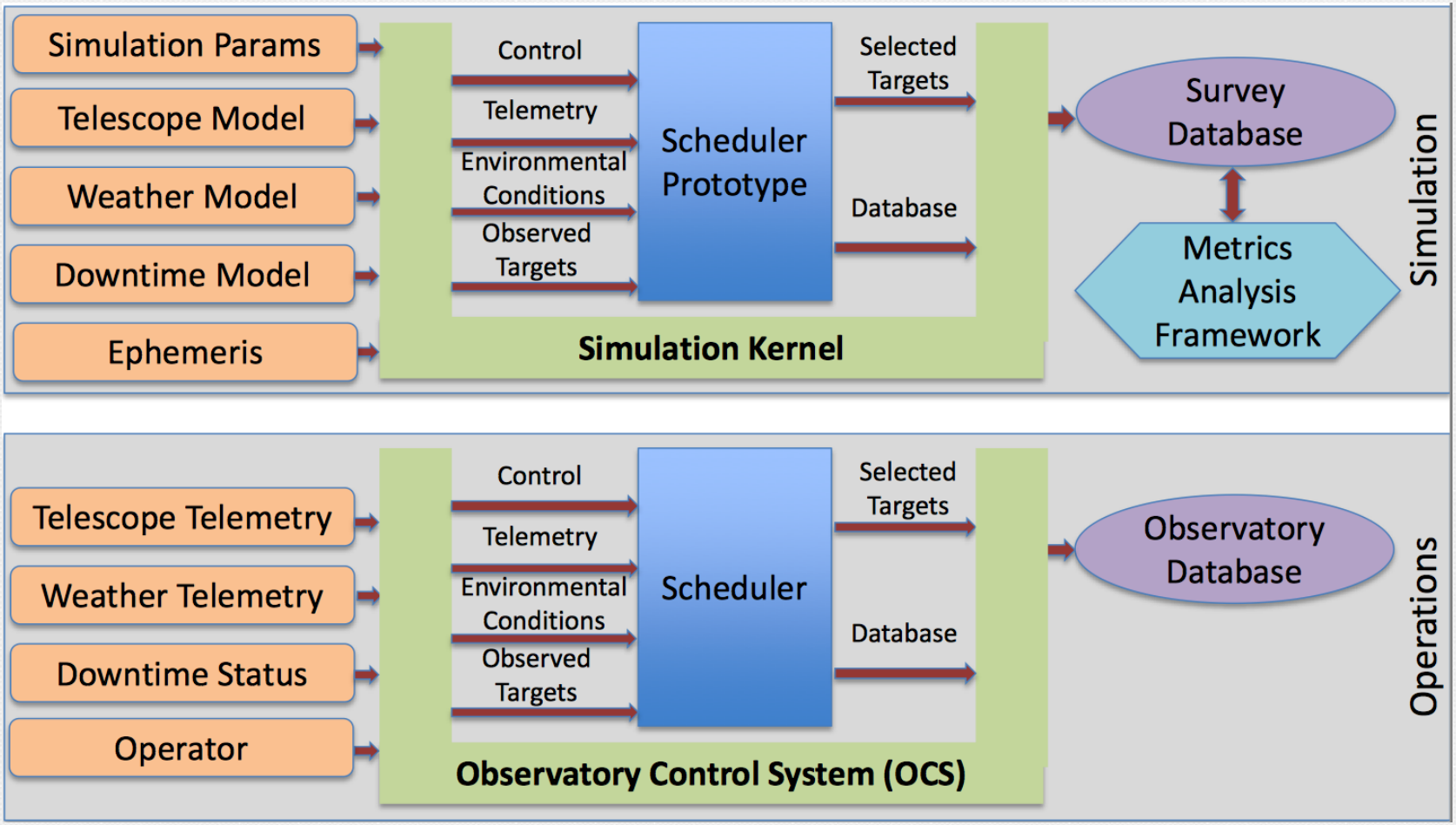
Potential optimization directions:

- 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)

Tools for further cadence refinement

OpSim (Operations Simulator)

- the main tool for simulating LSST cadence
- also a prototype for the scheduler



Tools for further cadence refinement

OpSim (Operations Simulator)

- the main tool for simulating LSST cadence
- also a prototype for the scheduler (14k of python code)
- developers mostly at NOAO; recently, the entire LSST Simulation effort was consolidated as a single group (led by Andy Connolly).
- Priorities for the development of OpSim (next 1-2 years):

Release of the Metrics analysis framework and support for cadence studies
Implementation of rolling cadence and marching army cadences within the OpSim framework
Improvement in speed of the code to run in hours instead of days
Development of the scheduler algorithms within the OpSim framework

OpSim code will be open source on April 15th, and with install instructions by the cadence workshop in August

The OpSim documentation is available from
http://www.noao.edu/lsst/opsim/docs/simulator/

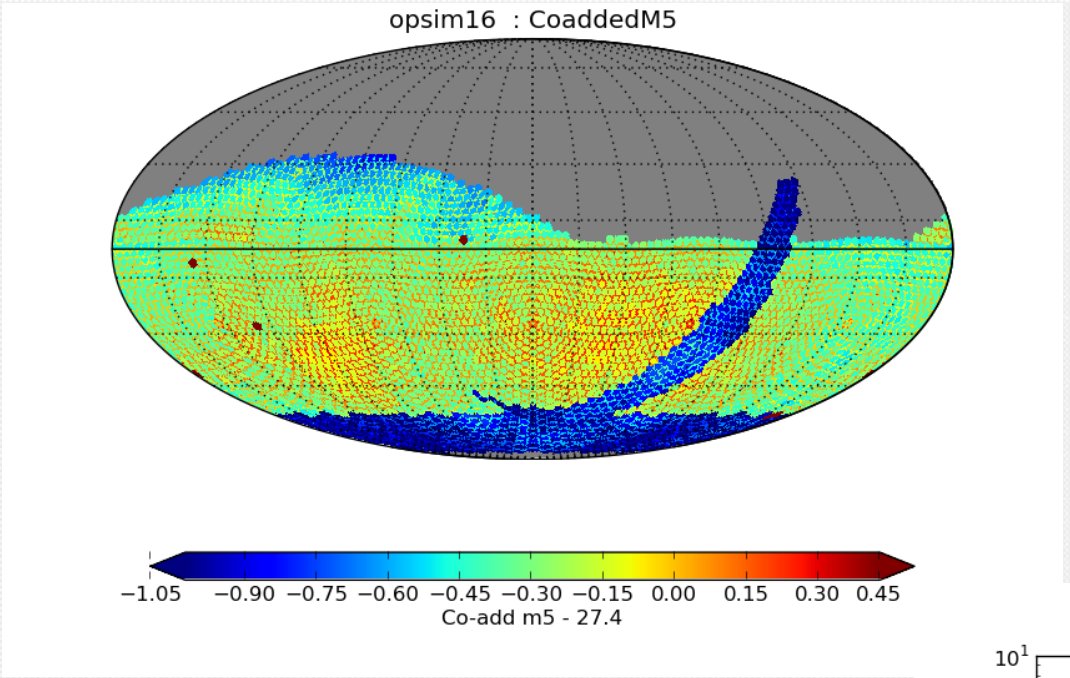
Tools for further cadence refinement

OpSim (Operations Simulator)

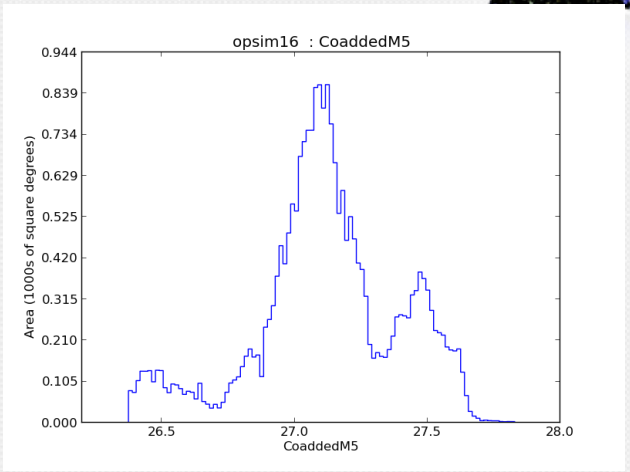
- the main tool for simulating LSST cadence

MAF (Metrics Analysis Framework)

- recent effort (since late 2013)
- aims to replace and extend SSTAR, as well as to provide a user-friendly framework (python) for developing new science-based metrics and other cadence analysis tools
- development part of overall simulation effort (currently development led by Lynne Jones and Peter Yoachim)
- delivered to alpha testers in February
- full public release at the cadence workshop in August

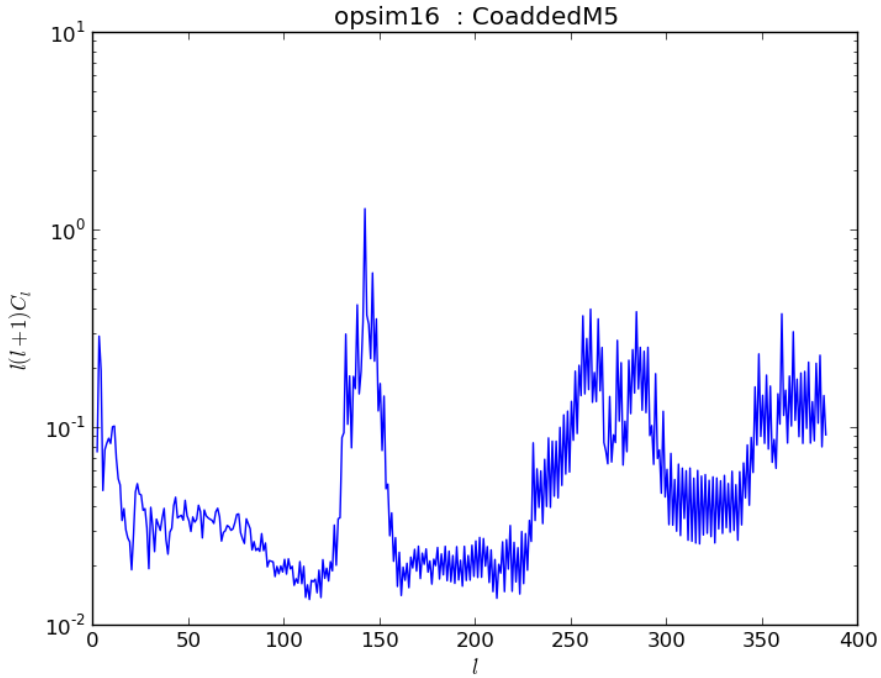


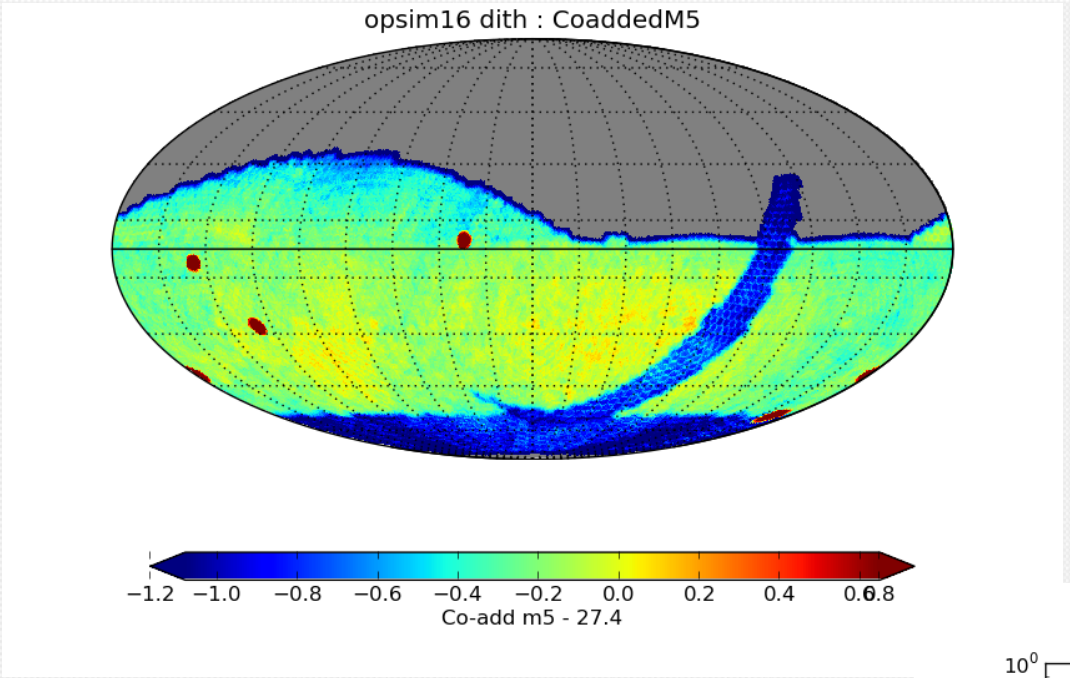
no dither



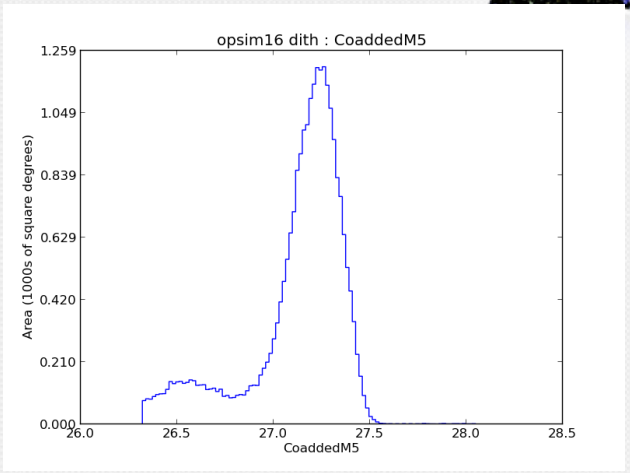
MAF examples

- coadded depth
- sky plots, histograms, power spectrum etc.
- dithered vs. not
- user friendly
- @ cadence workshop





dithered



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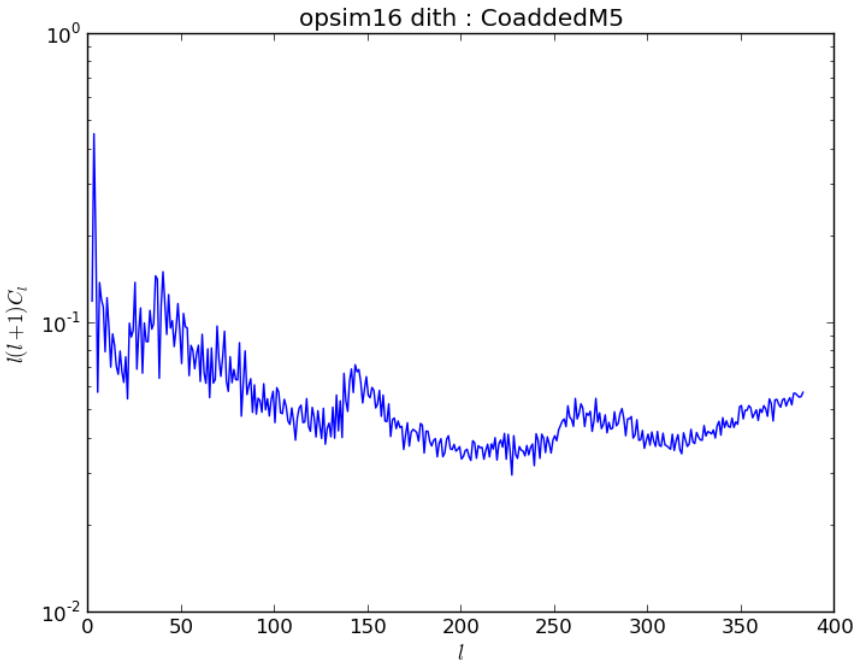

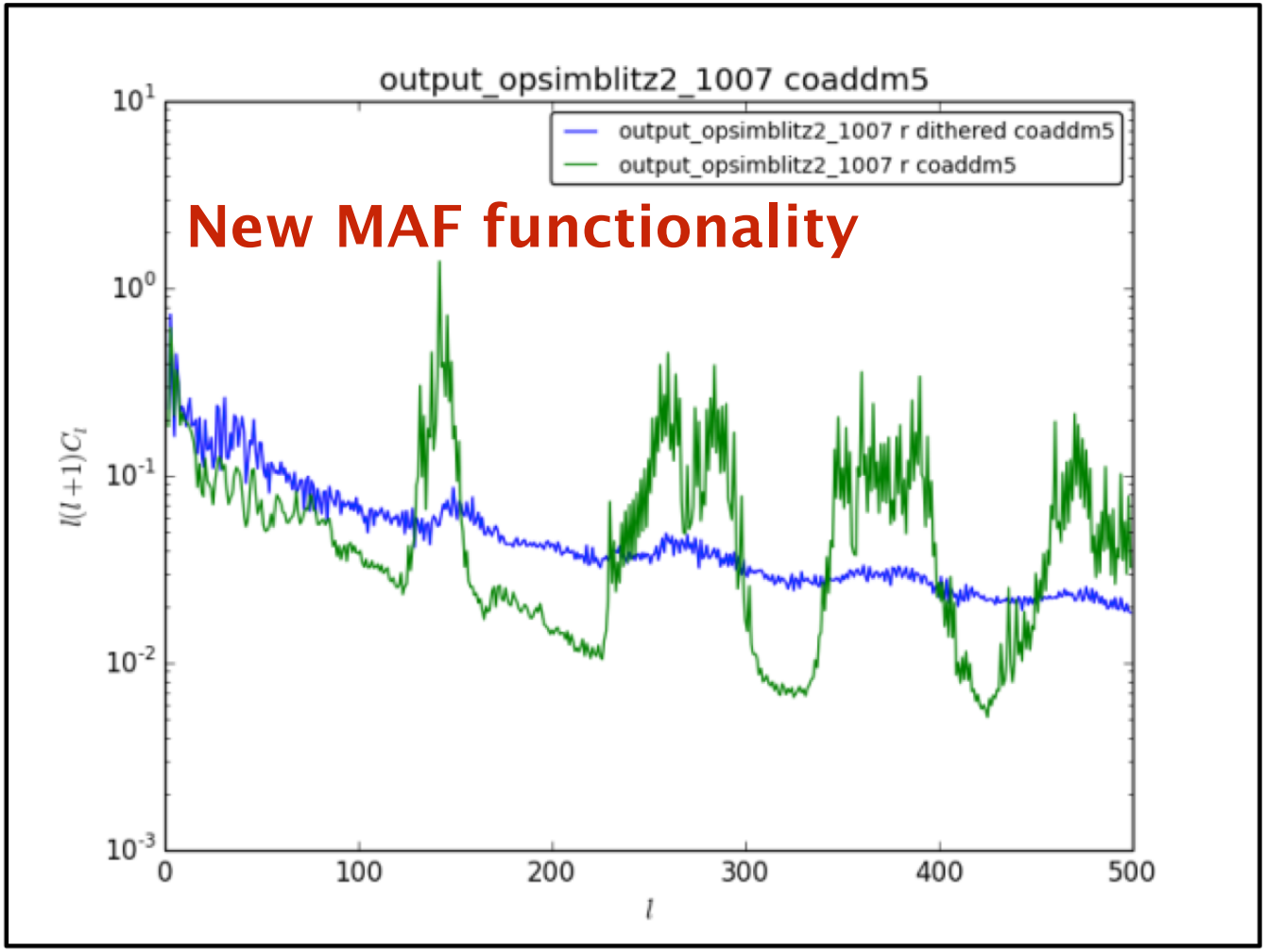

Figure 4: The angular power spectrum of the coadded 5σ limiting magnitude, with and without dithering (blue and green lines, respectively).

MAF
– coad
– sky
power
– dith
– user
– @ ca

Mechanisms for changing the cadence

LSST Science Advisory Council (SAC)

- the main mechanism for officially collecting and delivering community input to the Project.

LSST Project Science Team (PST)

- an operational unit, within the Project, that includes key scientists (Claver, Connolly, Ivezić, Jurić, Kahn, Lupton, Ritz, Stubbs, Tyson). The PST provides input on critical technical decisions as the project construction proceeds.

LSST Project Scientist

- chairs PST, maintains the SRD and supporting documentation, responsible for cadence optimization efforts, reports directly to the LSST Director.

Getting Community Input

LSST Cadence Workshop Series

- a series of annual/biennial meetings: the main goal is systematic optimization of LSST cadence
- the first meeting: Phoenix, Aug 11–15, 2014 (same place and time as "LSST week 2014")
- Organizing Committee: Dubois, Gawiser, Ivezić, Jacoby, Mahabal, **Olsen, Ridgway**, Strauss, Willman
- the main goal for the first meeting:
  - introduction of MAF
  - holistic discussion of baseline cadence and its potential improvements (breakout sessions on "Static science", "Time-domain science", "Deep drilling fields", "Special Milky Way regions")
  - strategic roadmap for future meetings