Constraints on LSST cadence parameters

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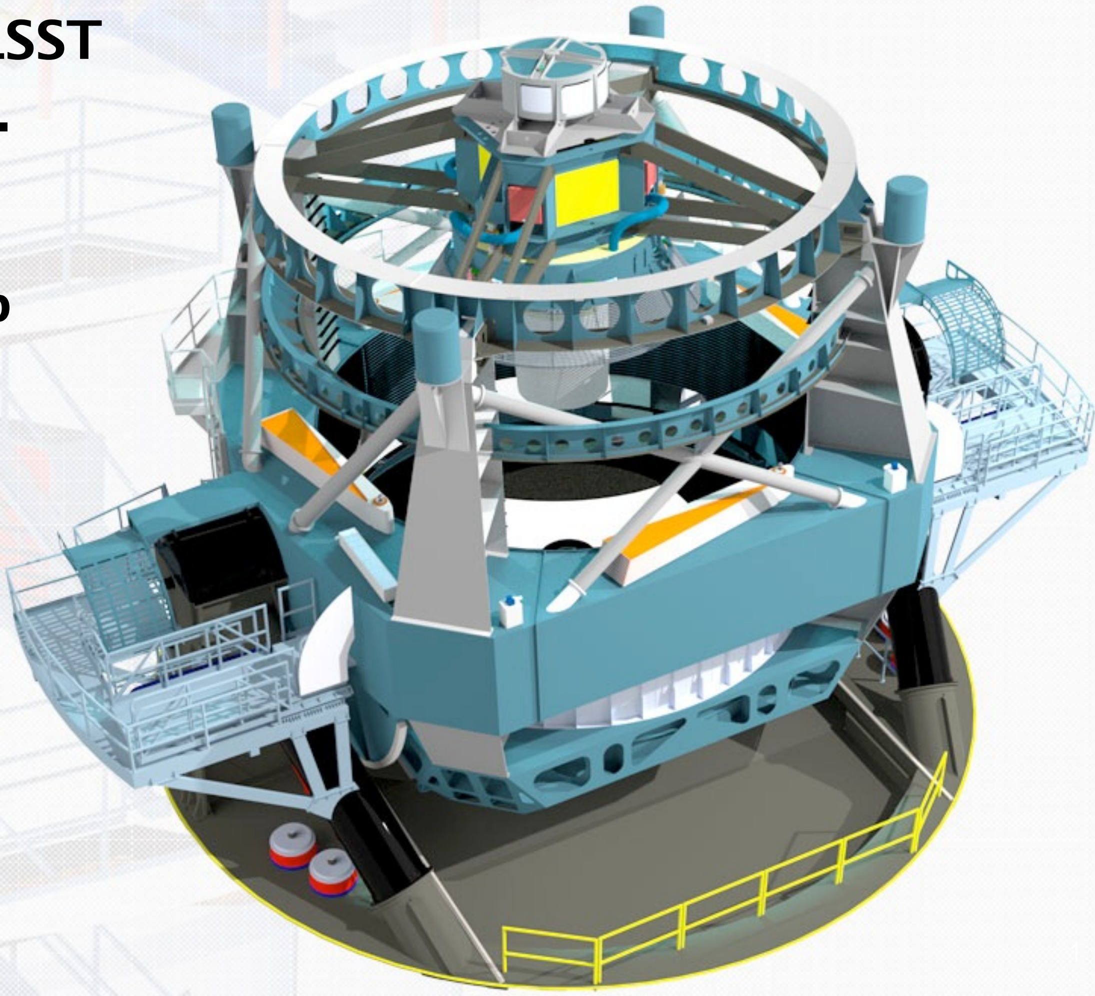
With special thanks to the LSST Simulations/OpSim team(s).

LSST and NOAO
Observing Cadences Workshop
Phoenix, August 11-14, 2014



Outline

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

1) Flowdown of LSST science goals to LSST system requirements
2) SRD specifications for cadence
3) Cadence "conservation laws"
4) Current baseline cadence
5) Progress towards survey goals
6) Baseline cadence optimization

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)

Time domain (cosmic explosions, variable stars)

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SRD specifies data properties needed to achieve science goals

I.2 Science Requirements Document (SRD) Specifications for Cadence

At the highest level, 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.

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:**

Section 3.4 from the SRD

Early cadence studies

As a result of these studies, the adopted baseline design (see Appendix A) assumes a nominal 10-year duration with about 90% of the observing time allocated for the main LSST survey. The same assumption was adopted here to derive the requirements described below.

Section 3.4 from 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).

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:**

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

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

Table 22: The sky area uniformly covered by the main survey.

Specification: The sum of the median number of visits in each band, Nv1, across the sky area specified in Table 22, will not be smaller than Nv1 (Table 23).

Quantity	Design Spec	Minimum Spec	Stretch Goal
Nv1	825	750	1000

Table 23: The sum of the median number of visits in each band across the sky area specified in Table 22.

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:**

Quantity	u	g	r	i	z	y
Nv1 (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

Table 24: An *illustration* of the distribution of the number of visits as a function of bandpass, 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 $\sqrt{N}$ 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. Note: 824 visits with two 15-sec exposures is 6.9 hours (~1 night/field).

- **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)

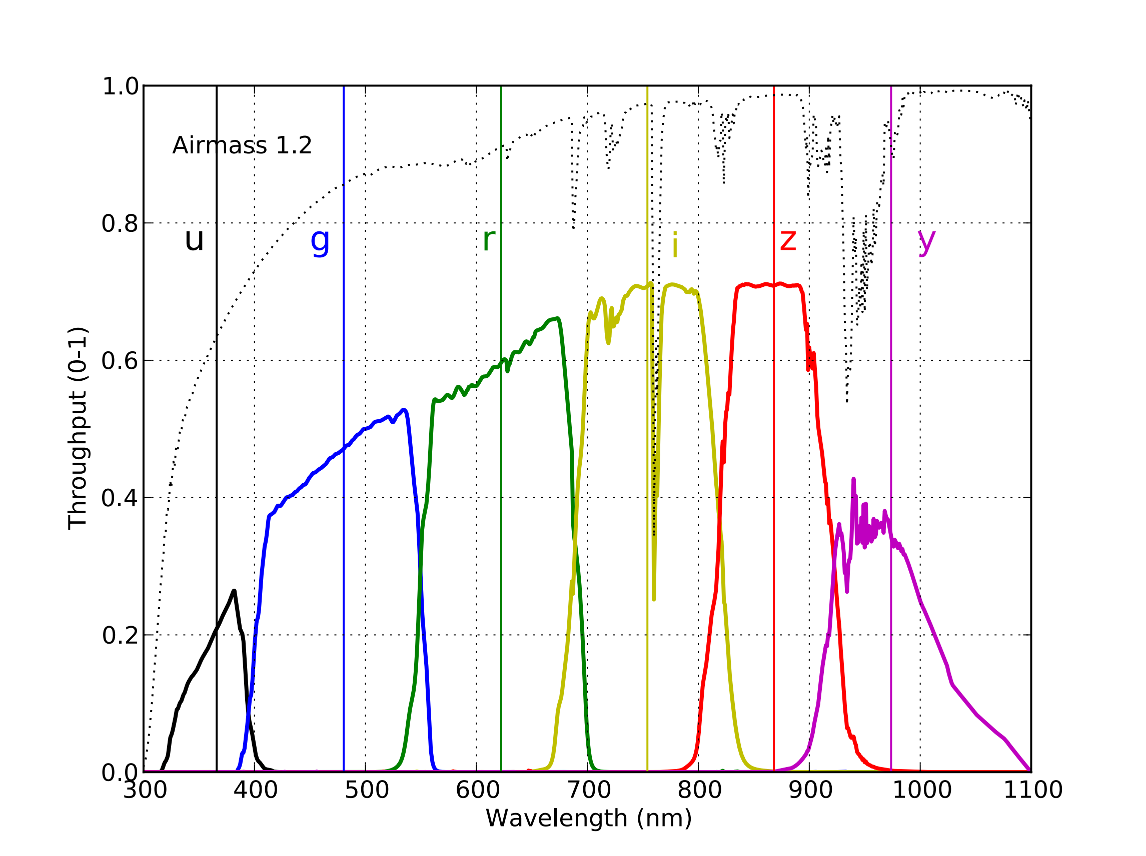

Photo-z requirements correspond to r~27.5 with the following per band time allocations:

u: 8%; g: 10%

r: 22%; i: 22%

z: 19%; y: 19%

Consistent with other science themes (stars)

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:**

Distribution of visits in time → intentionally vague!

Specification: At least RVA1 square degrees will have multiple observations separated by nearly uniformly sampled time scales ranging from 40 sec to 30 min (Table 25).

Quantity	Design Spec	Minimum Spec	Stretch Goal
RVA1 (deg^2)	2,000	1,000	3,000

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

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

Table 26: The required trigonometric parallax and proper motion accuracy.

Distribution of visits vs. observing conditions

I.3 Cadence "conservation laws"

How can we optimize the main deployment parameters:

exposure time per visit, t_{vis}, single-visit depth, m_5, the mean revisit time, $n_{revisit}$, and the number of visits, N_{vis}?

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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 ~7 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 the "overview" paper, arXiv:0805.2366)

I.3 Cadence "conservation laws"

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)

Out-of-the-box thinking is highly encouraged!

There is no fundamental reason why t_{vis} should be exactly the same for all visits (i.e. filters, programs, during the survey)!

I.3 Cadence "conservation laws"

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

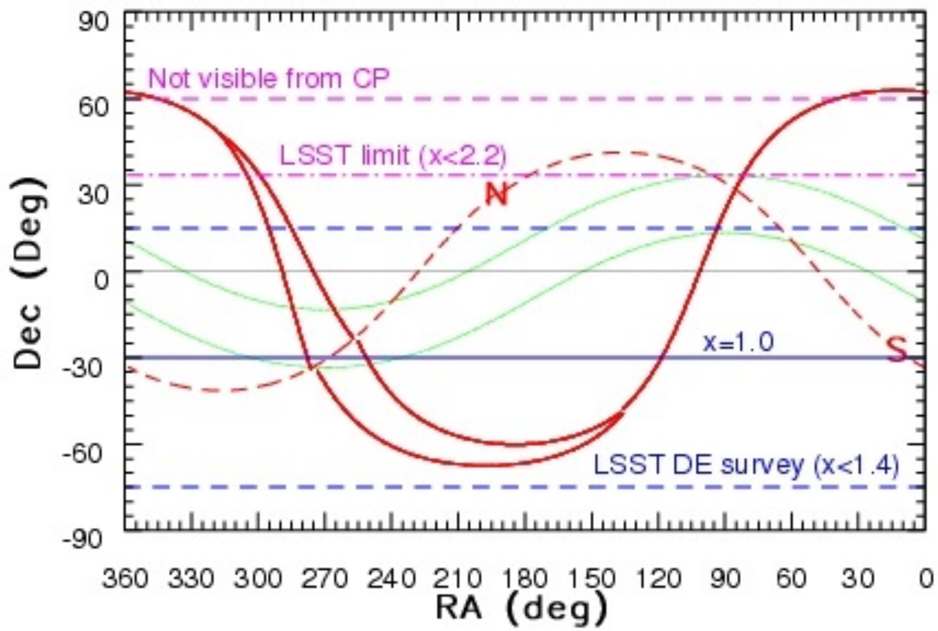
20 sec < t_{vis} < 40 sec for the main survey $\boxed{t_{vis} = 30 \text{ sec as default}}$

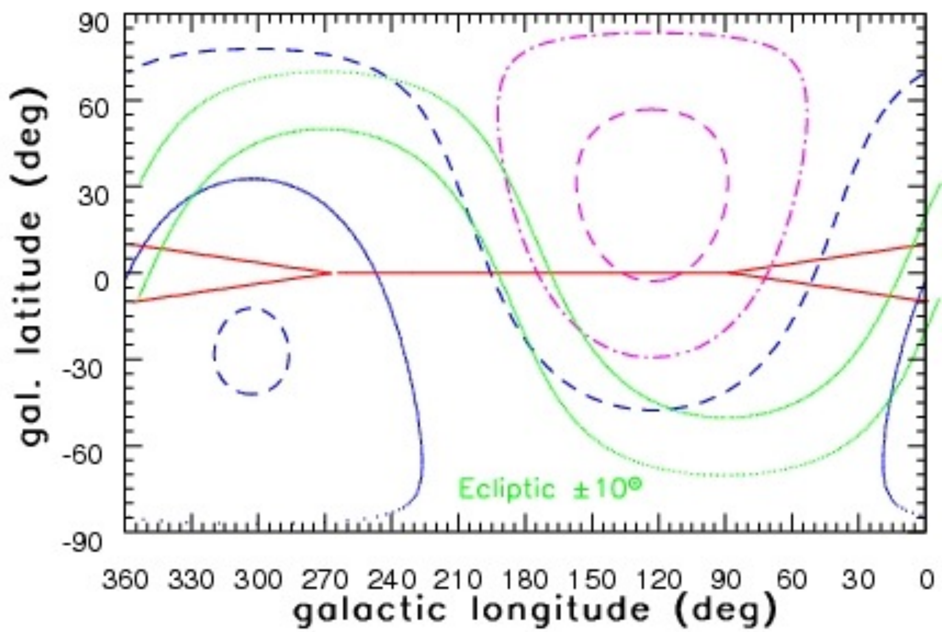
However, there may be reasons to depart from t_{exp} = 15 sec.

What is the shortest **sustainable** exposure time?

1) 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).
2) 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.

The main message: if you have ideas for scientifically compelling programs that would require faster frame rates, you should bring them to the Project's attention.





Sky coverage:

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

X<1.4 corresponds to

−75° < Dec < +15°

(25,262 sq. deg.)

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

I.4 Current Baseline Cadence

Maximize the number of objects (area vs. airmass)

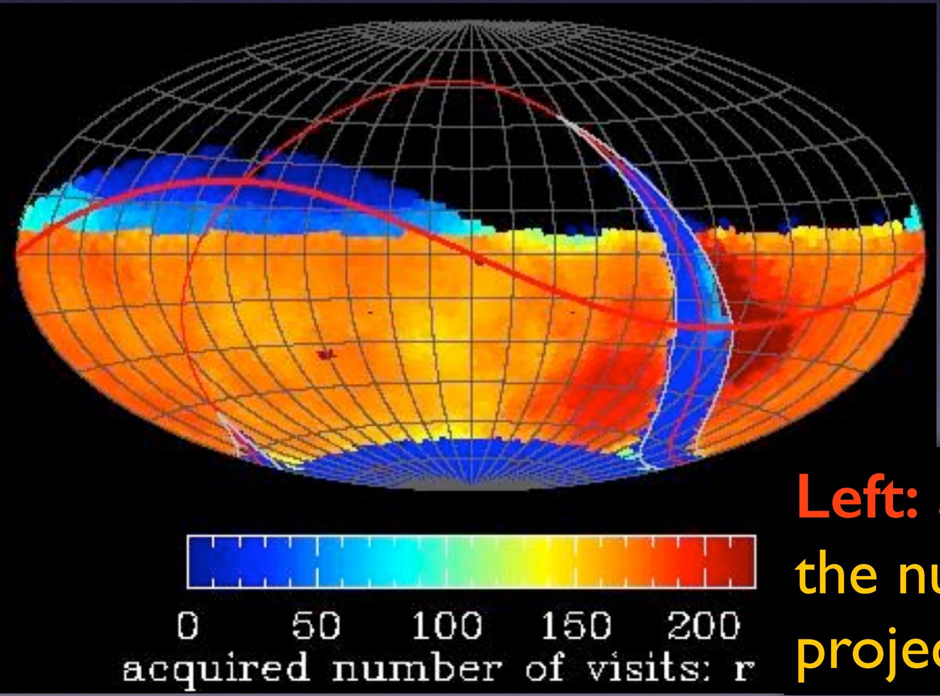
Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.9; g = 25.0; r = 24.7; i = 24.0; z = 23.3; y = 22.1
Photometric calibration	< 2% absolute, < 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

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)

Baseline cadence (OpSim3.61)

A 10 year simulation: “existence proof” for an LSST survey

Basic characteristics:

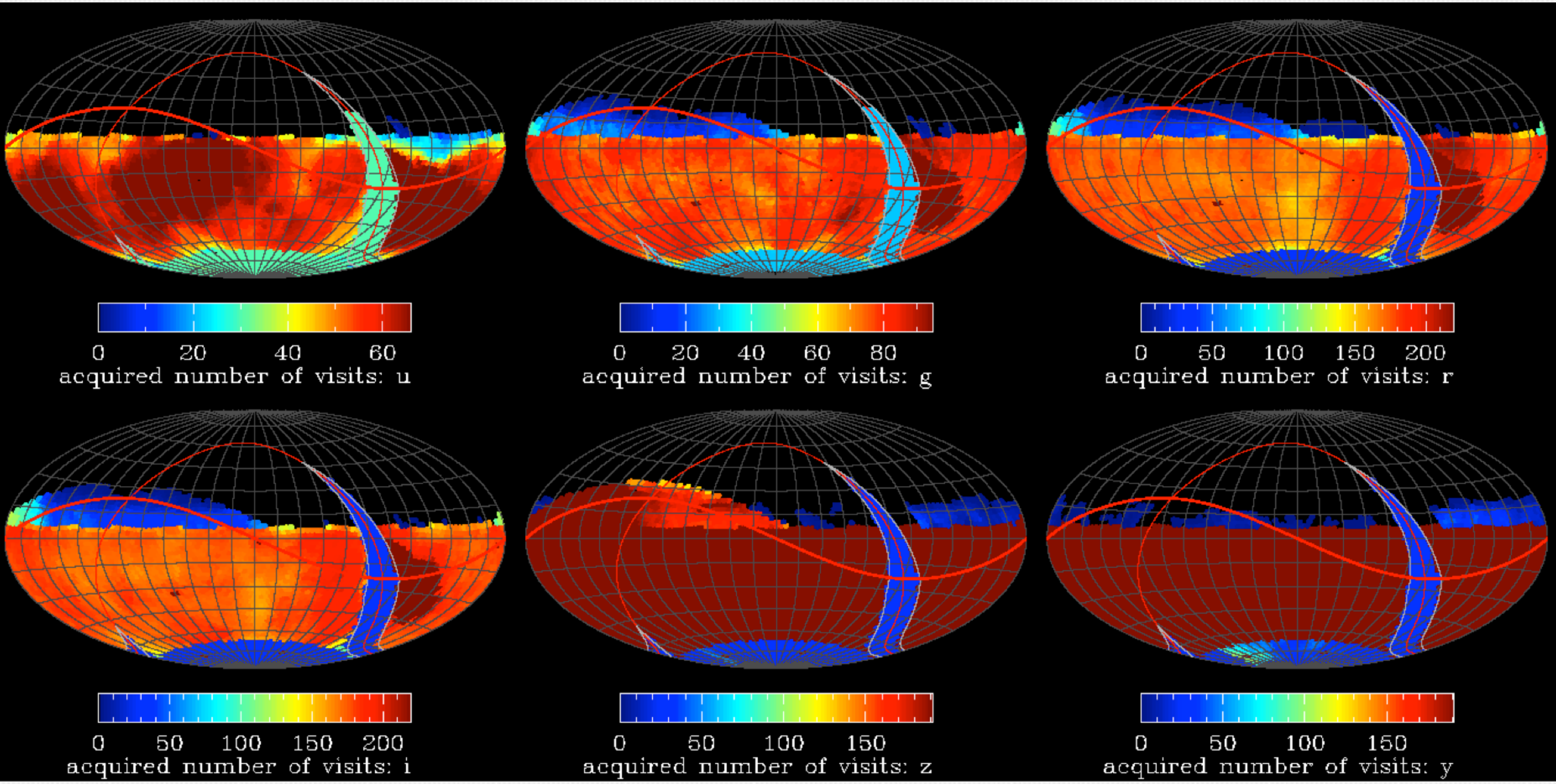
- observing starts/stops at 12 degree twilight
- CTIO 4m weather log as weather model
- telescope model and scheduled downtime for maintenance
- u filter in camera ~ 6 days per lunation
- utilizes 5 science proposals:
  - WideFastDeep: Universal Cadence
  - Galactic plane: collect 30 visits in each passband
  - 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)

- 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)

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)

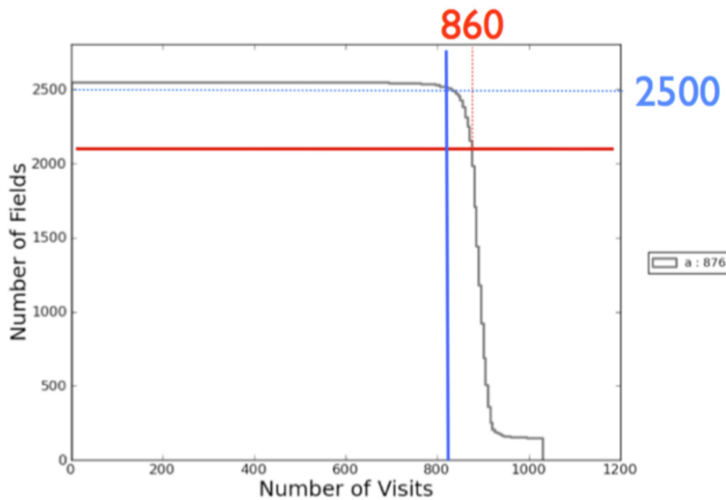


Figure 6: *(opsim3_61_cvisits_allfilters_all.png)* The cumulative distribution of Figure 4 showing the number of fields having visits $\geq x$. Only visits acquired by modes designed to meet the WFD number of visits are included. The inset box contains the values of the 25^{th}, 50^{th} (median), and 75^{th} 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 $\sim$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 $\sim$ 2500 fields.

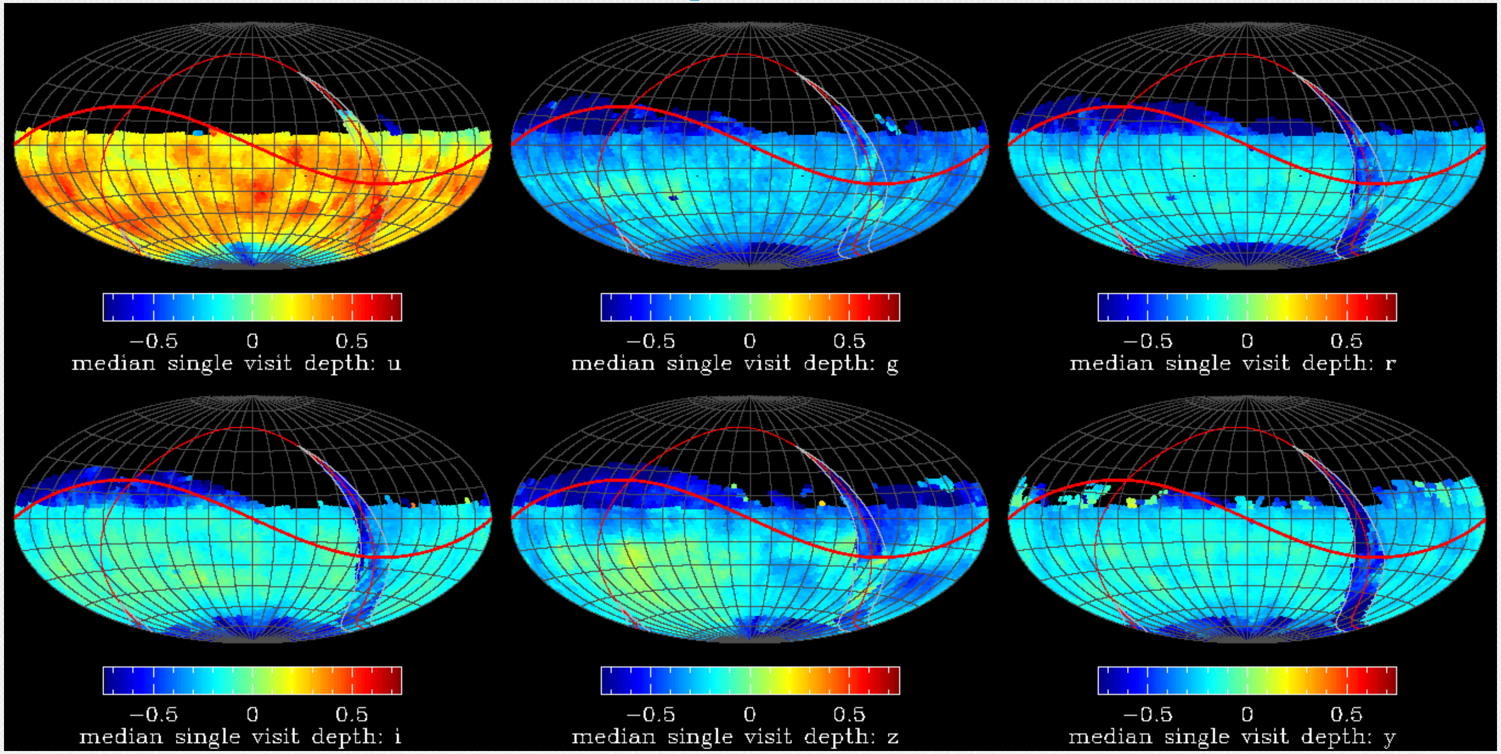
OpSim3.61 produced 2.65 million visits.

The minimum number of visits, with a nominal FOV fill-f=0.86, to satisfy the SRD (including 10% for DD) is 2.25 million.

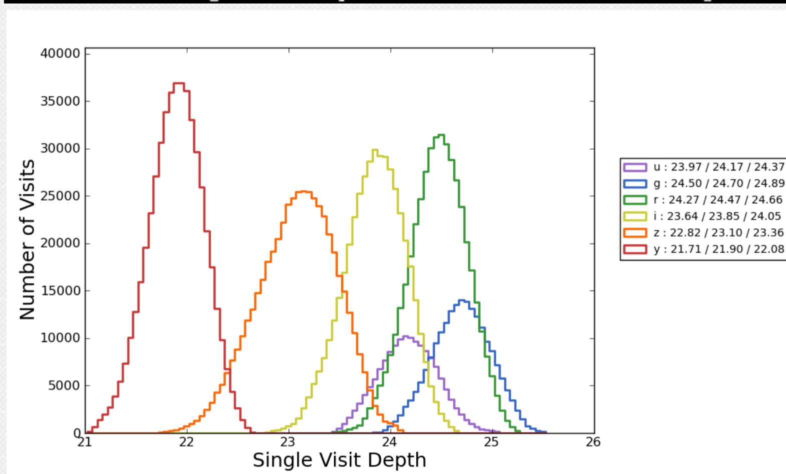
With the current baseline cadence, we have **a margin of ~18%.**

(not including margins from expected depths)

Baseline cadence (OpSim3.61)



Median 5-sigma depth (for all visits)



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

The nominal value is given as input to OpSim (best Cm estimates)

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:

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

- 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.
- given the difference between C_m and its nominal value, and all other parameters at their nominal values, then an "effective open-shutter time" metric is

  $\log(f2) = 0.8*(m5 - m5nominal)$
- excellent high-level metric for engineering and science tradeoffs

- caveat: C_m for the u band depends a bit on t_{vis} (readout noise)

I.5 Progress towards survey goals

Main performance metrics as functions of time (t):

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):

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

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?

I.6 Continuing Baseline cadence optimization

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)

I.6 Continuing Baseline cadence optimization

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)

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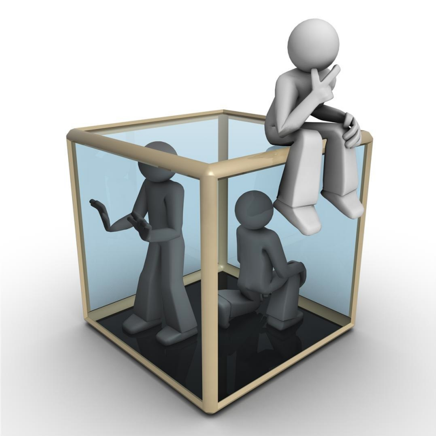
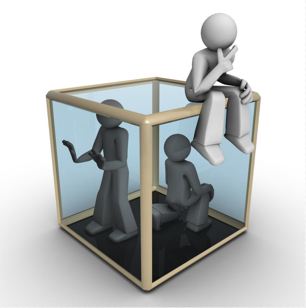


The Project aims to empower the community with tools to explore all of these possibilities. Out-of-the-box thinking is strongly encouraged, but at the same time we need to have a process and tools to communicate and test new ideas. Hence this workshop, and other to follow…

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 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).