Review of science-driven cadence optimization to date

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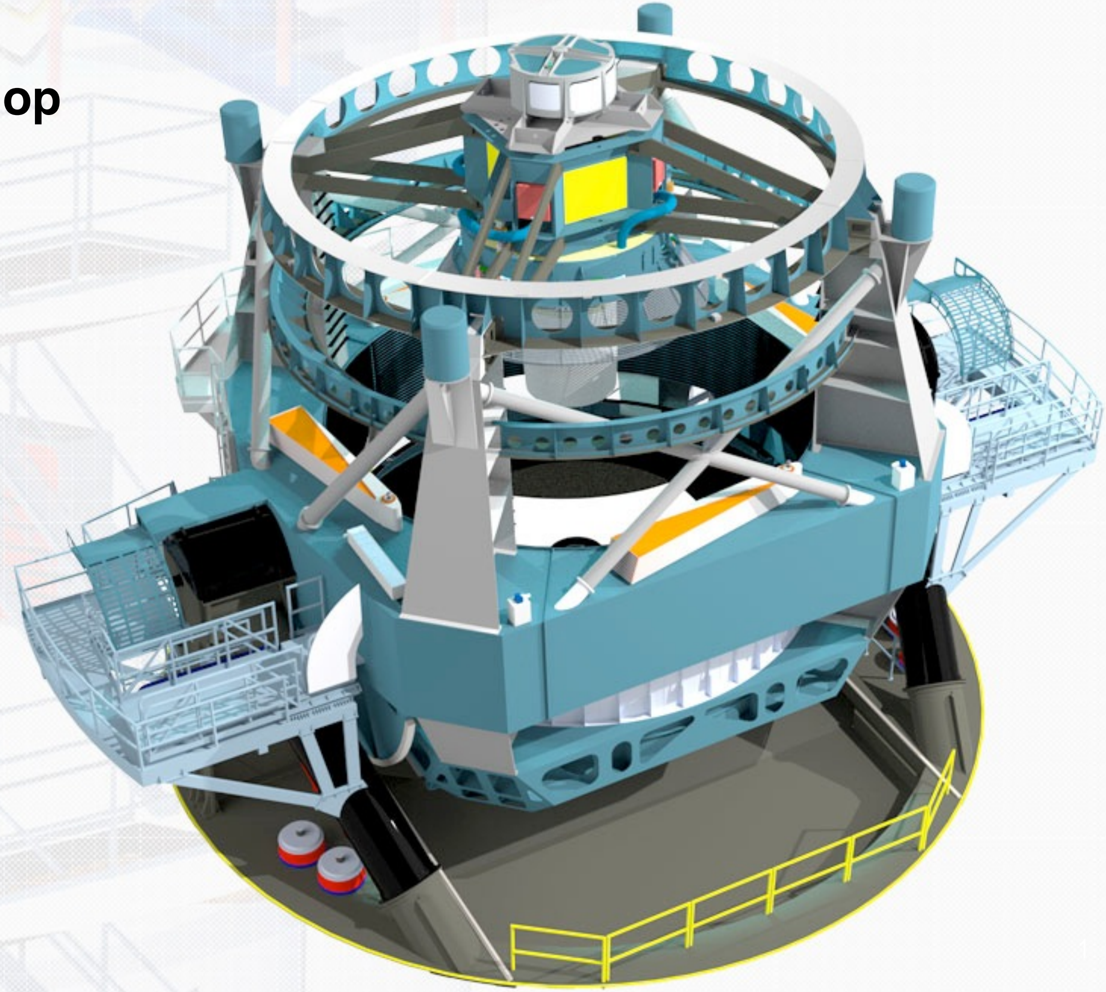
LSST Observing Strategy Workshop
Bremerton, August 20, 2015



Outline

1) Flowdown of science goals to system reqs.
2) SRD specifications for cadence
3) Cadence “conservation laws”
4) Hierarchy of survey complexity
5) **Candidate new baseline cadence**
6) **Cadence exploration and optimization:**
   - how much “reserve” do we have?
   - the impact of special programs
   - the impact of pairs of visits
   - optimization of the visit exposure time
   - optimization of NEO completeness
7) Continuing cadence optimization

1. 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)

Data Properties

Image Depth

Delivered Seeing

Number of images

Distributions with respect to time, bandpass and observing conditions

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)

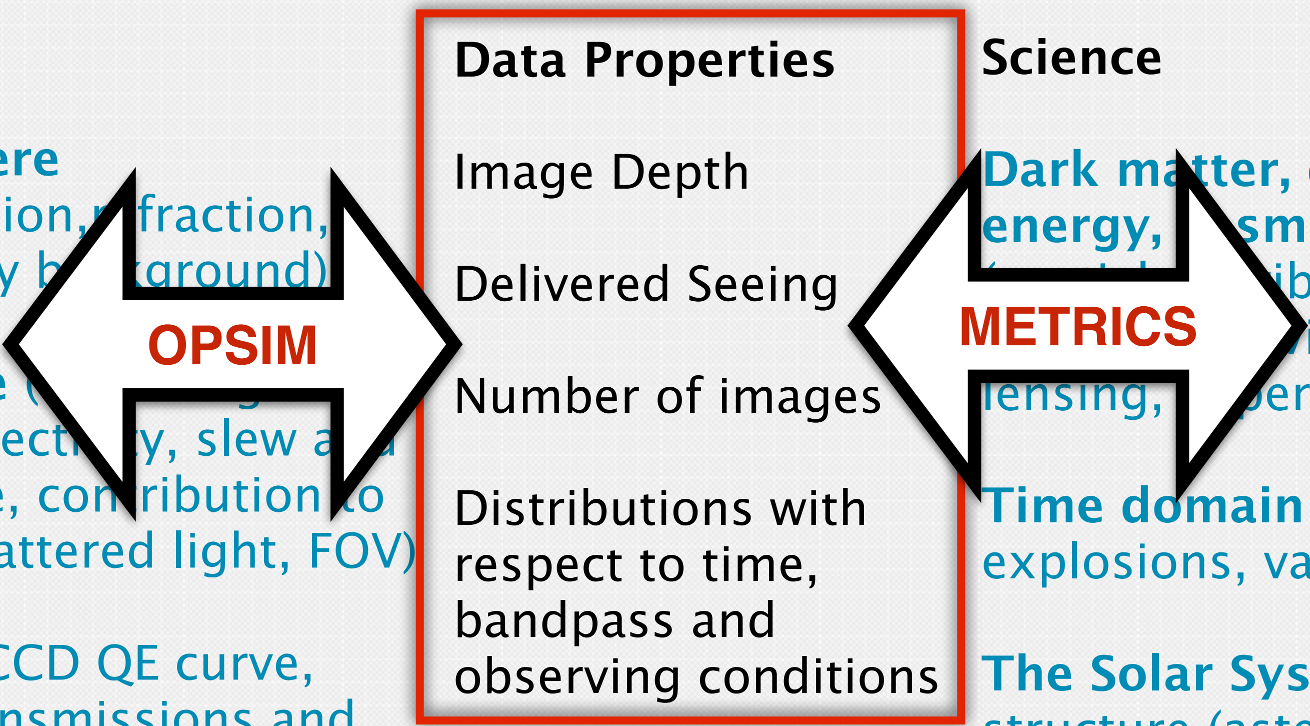
Time domain (cosmic explosions, variable stars)

The Solar System structure (asteroids)

The Milky Way structure (stars, ISM)

SRD specifies data properties needed to achieve science goals

1. Flowdown of Science Goals to System Requirements



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SRD specifies data properties needed to achieve science goals

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, **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.

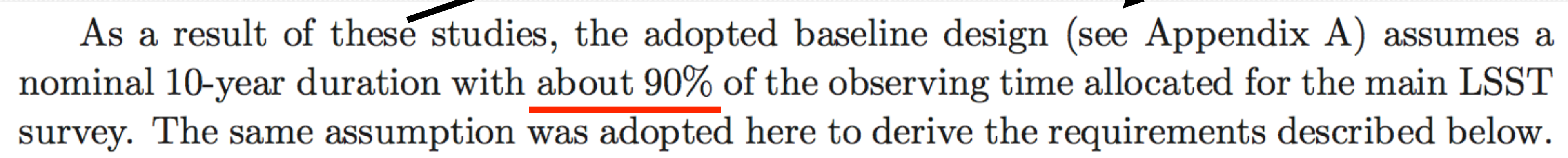
Science Requirements Document (SRD)

At the highest level, LSST objectives are:

1) Obtain ~2.5 million visits, 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:

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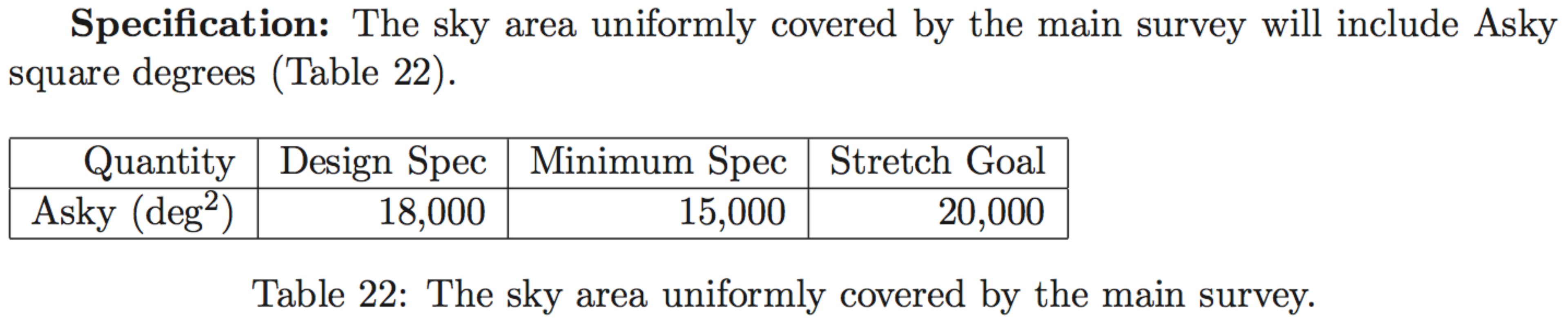
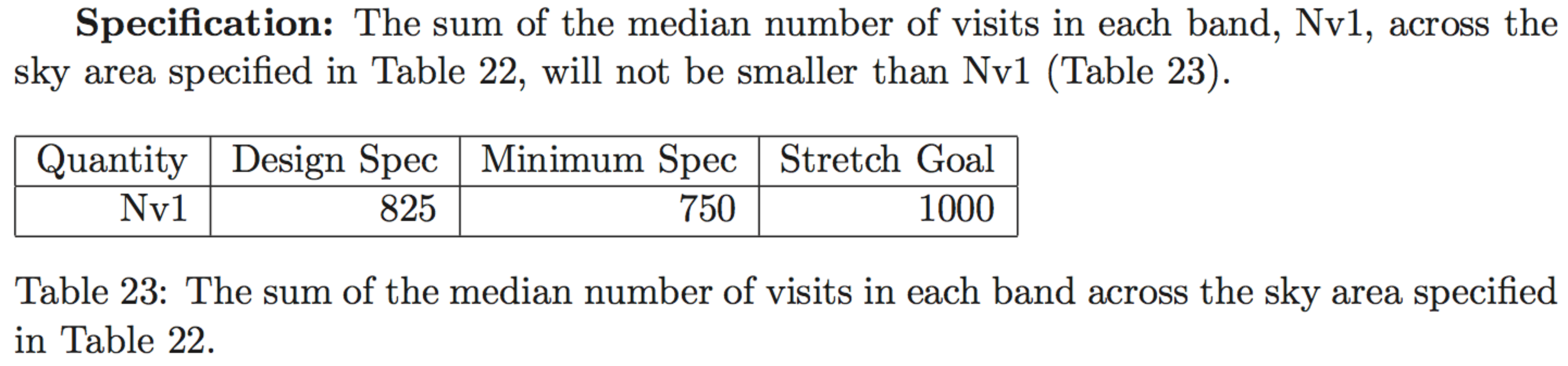


Specification: The sky area uniformly covered by the main survey will include Asky square degrees (Table 22).

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)

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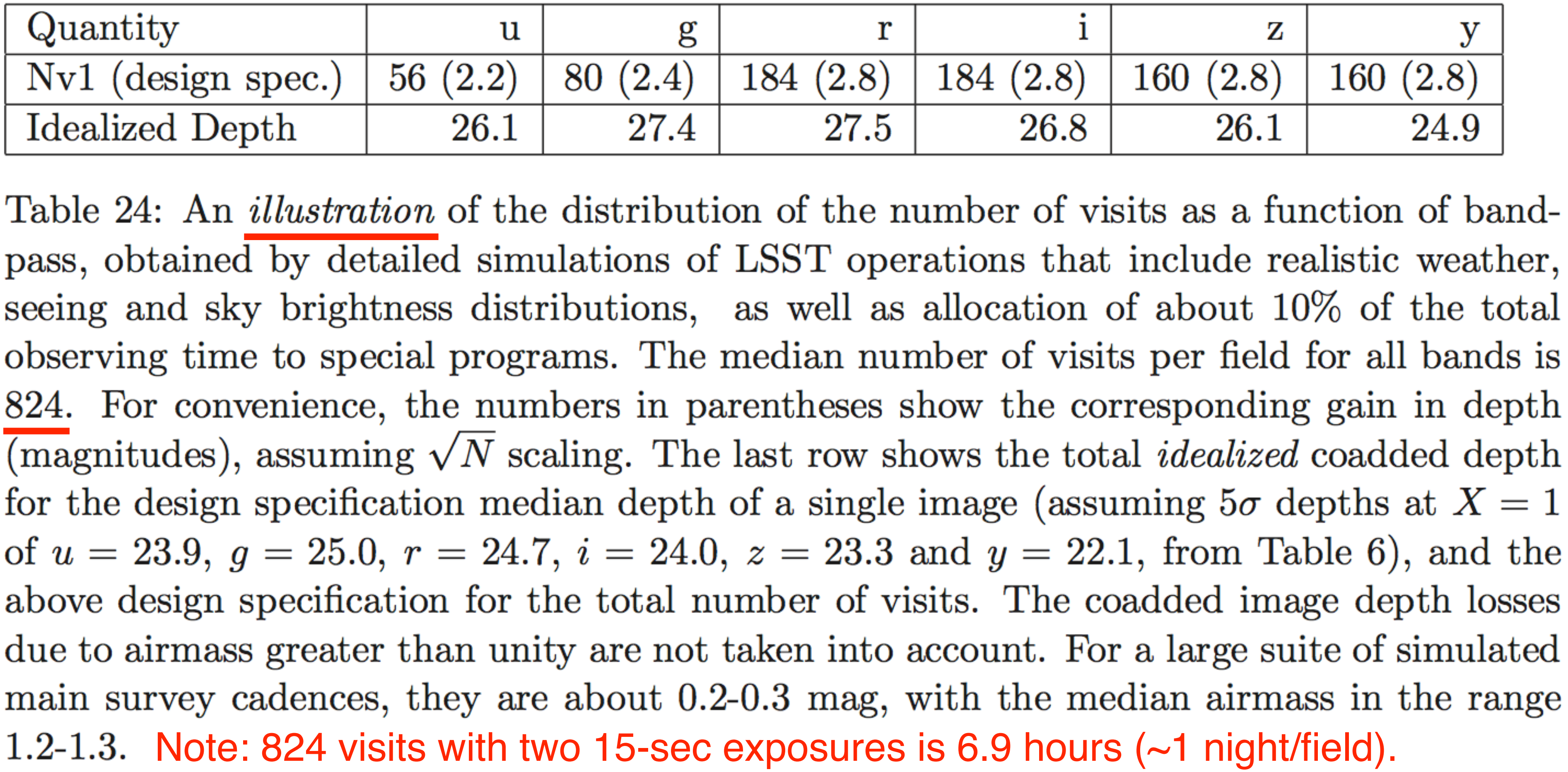

Quantity	u	g	r	i	z	y
Nv1 (design spec.)	56 (2.2)	80 (2.4)	184 (2.8)	184 (2.8)	160 (2.8)	160 (2.8)
Idealized Depth	26.1	27.4	27.5	26.8	26.1	24.9

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).

Science Requirements Document (SRD)

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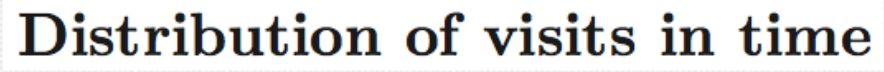
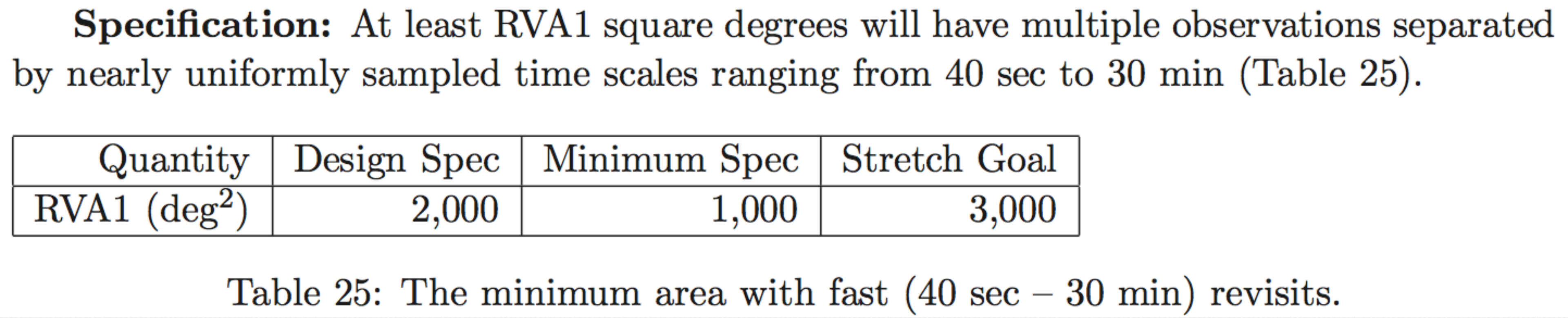


Distribution of visits in time

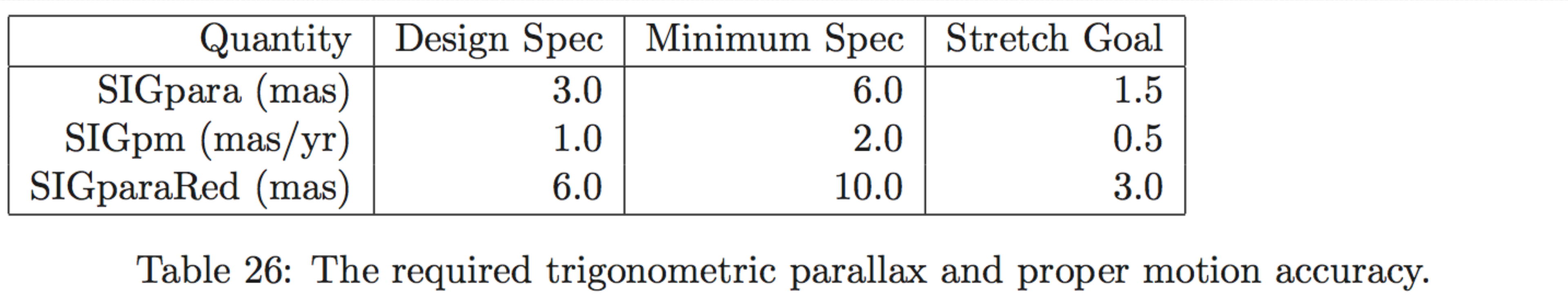
→ intentionally vague!



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

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}?

(assume that the sky area is about 20,000 sq. deg. - we will see why in a few slides)

VISIT: two back-to-back exposures of the same field, separated by a readout (2 seconds); **baseline: 2x15 sec**

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}?

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?

3. Cadence "conservation laws"

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

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

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

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

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

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)

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

3. Cadence “conservation laws”

CONCLUSION:

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**

However, there are reasons to depart from t_{exp} = 15 sec, more later…

4. Hierarchical steps of survey complexity:

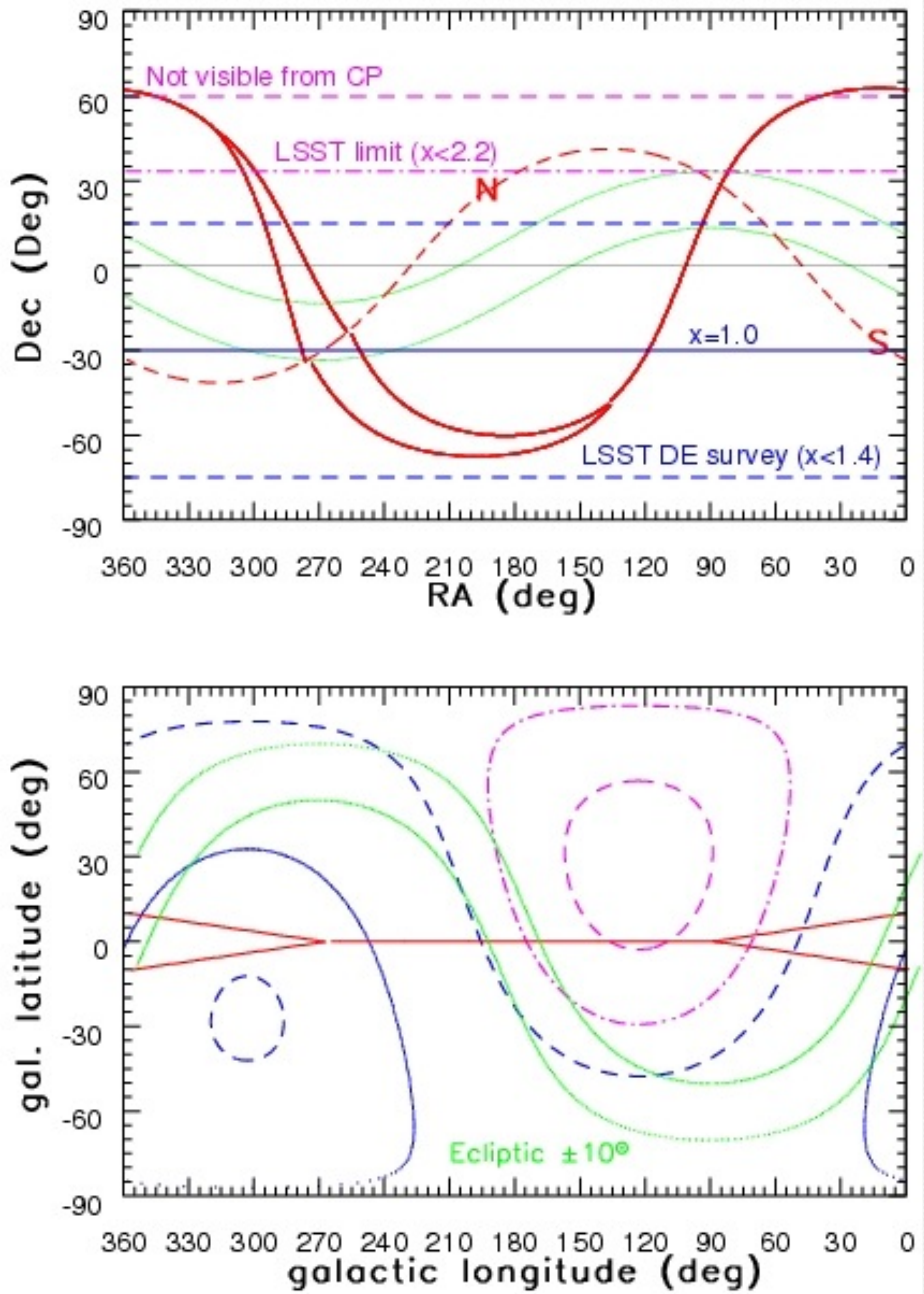
1) single band, single program, static science

Goal: maximize the number of detected sources, e.g. galaxies.

Unless looking at unusual populations (e.g. low-redshift quasars), it is always advantageous to first maximize the sky area and *then* depth.

Detailed optimization takes into account airmass effects and Galactic plane: about 18,000-20,000 sq.deg. of sky

(NB this is about the main survey - deep drilling fields and other "special" regions are "different")



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)

4. Hierarchical steps of survey complexity:

1) single band, single program, static science

2) **...but need multi-bandpass data: ugrizy**

Goal: apportion time per band so that there is no dominant bad band for photometric redshifts of galaxies (it turns out it's ok for stars too)

- **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)

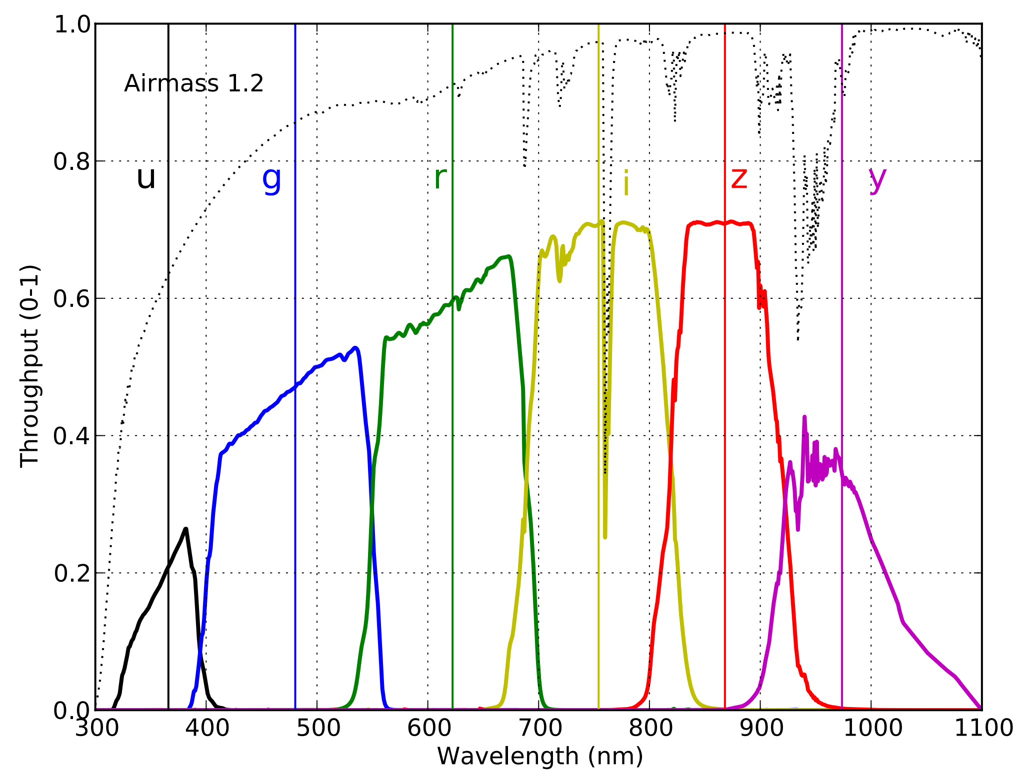


Photo-z requirements correspond to r~27.5 with the following per band time allocations:

u: 8%; g: 10%

r: 22%; i: 22%

z: 19%; y: 19%

Consistent with other science themes (stars)

4. Hierarchical steps of survey complexity:

1) single band, single program, static science
2) need multi-bandpass data: ugrizy

3) **time domain (temporal sampling function)**

Asteroids: (still) believing that two visits per night, about an hour apart, are needed to “connect the dots”.

The simplest strategy: roughly uniform coverage, addresses range of time scales, from diurnal to secular changes

However: if the sampling doesn’t meet the science-driven threshold, then it’s better to cover a smaller active sky area more frequently (e.g. supernovae) - "rolling cadence”

4. Hierarchical steps of survey complexity:

1) single band, single program, static science
2) need multi-bandpass data: ugrizy
3) time domain

4) **not all sky regions were created equal!**
Galactic plane
LMC/SMC
northern Ecliptic
south Galactic pole
deep drilling (and other special) fields

It’s likely that these regions will need a modified cadence, but not clear yet how exactly (depends on fast-evolving science drivers and the system performance)

4. Hierarchical steps of survey complexity:

1) single band, single program, static science
2) need multi-bandpass data: ugrizy
3) time domain
4) not all sky regions were created equal!

5) **evolution over time**

- algorithm optimization, evolving science goals, possibly system performance changes

6) **systematics**

- field-of-view position (rotator angle), parallax factor, dithering, etc.

5. Current Baseline Cadence

Maximize the number of objects (area vs. airmass)

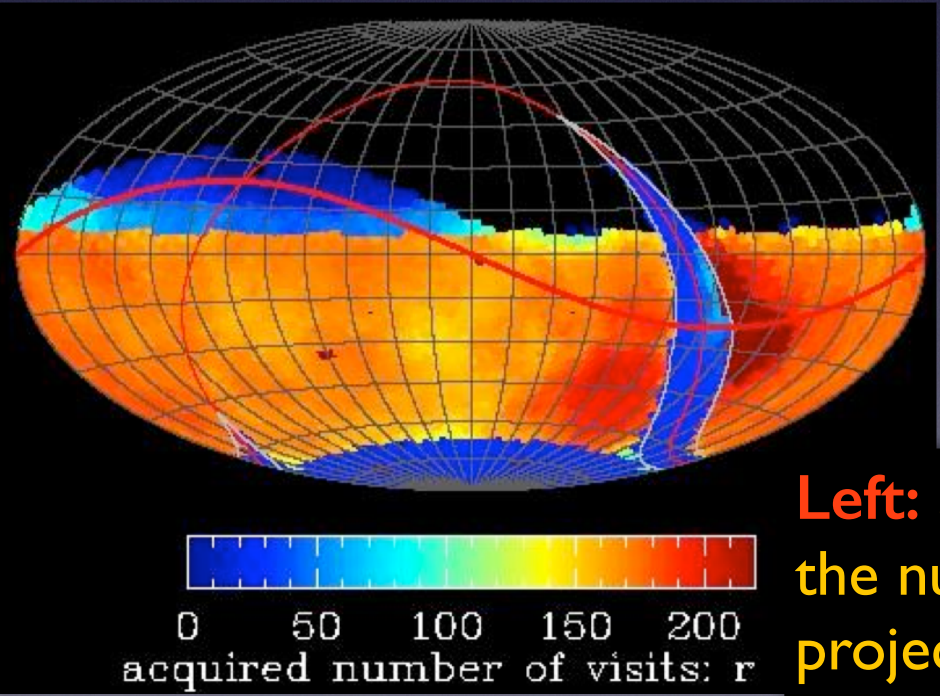
Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.9; g = 25.0; r = 24.7; i = 24.0; z = 23.3; y = 22.1
Photometric calibration	< 2% absolute,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



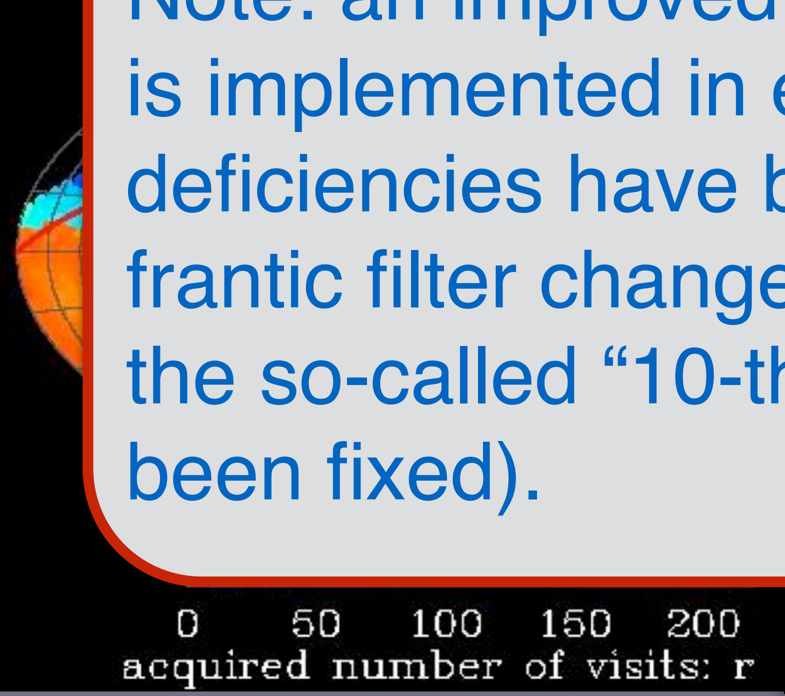
LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 1000 visits over a 10-year period: **deep wide fast.**

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

What is LSST? A uniform sky survey.

The new candidate baseline cadence (enigma_1189) is very similar to the current baseline cadence (opsim3.61): high-level properties remain unchanged!

Note: an improved understanding of the system is implemented in enigma_1189, and numerous deficiencies have been fixed or improved (e.g. frantic filter changes close to the end of survey, the so-called “10-th year panic” problem, has been fixed).



y:
toff
projection of eq. coordinates)

5. Candidate new Baseline (enigma_1189)

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

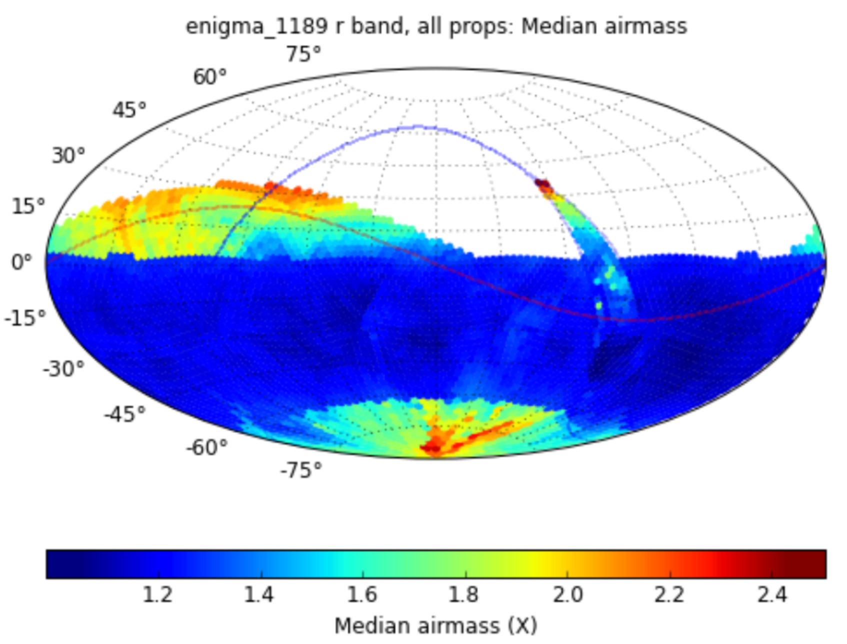
Basic characteristics:

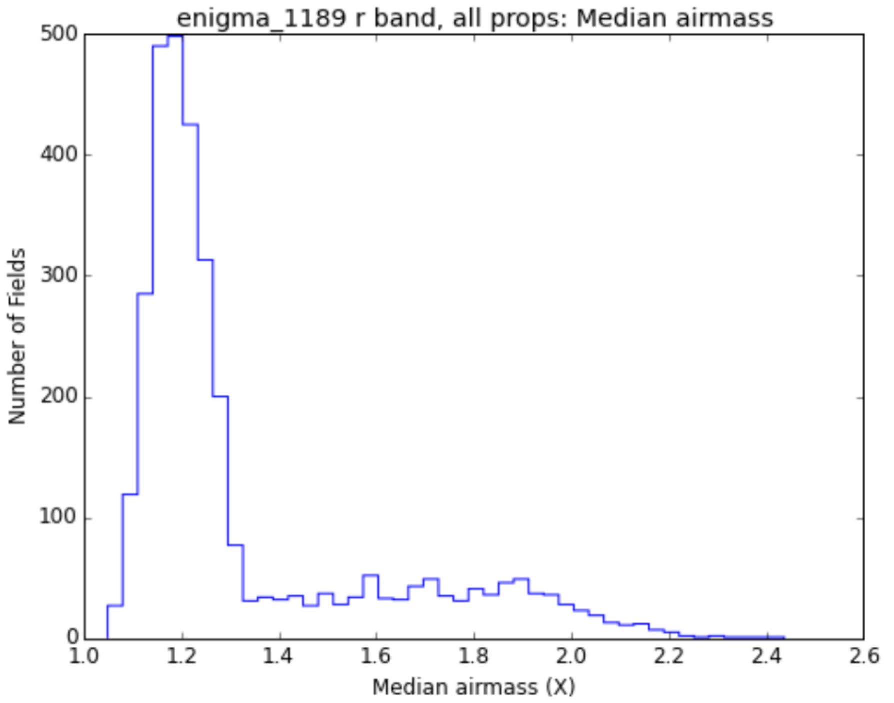
- observing starts/stops at 12 degree twilight
- CTIO 4m weather log as weather model
- telescope model and scheduled downtime for maintenance
- u filter in camera ~ 6 days per lunation
- utilizes 5 science proposals:
  - WideFastDeep: Universal Cadence
  - Galactic plane: collect 30 visits in each passband
  - North ecliptic: Universal Cadence
  - South Pole: collect 30 visits in each filter
  - 5 "deep drilling" fields (a few thousand visits, m~28.5)
- **baseline cadence always uses t_{vis} = 30 seconds!**

5. Candidate new Baseline (enigma_1189)

Basic characteristics:

- the total number of visits is 2.47 million, with 85.4% spent on the Universal proposal (the main deep- wide-fast survey), 6.4% on the North Ecliptic proposal, 1.7% on the Galactic plane proposal, 2.1% on the South Celestial pole proposal, and 4.5% on the Deep Drilling proposal (5 fields)





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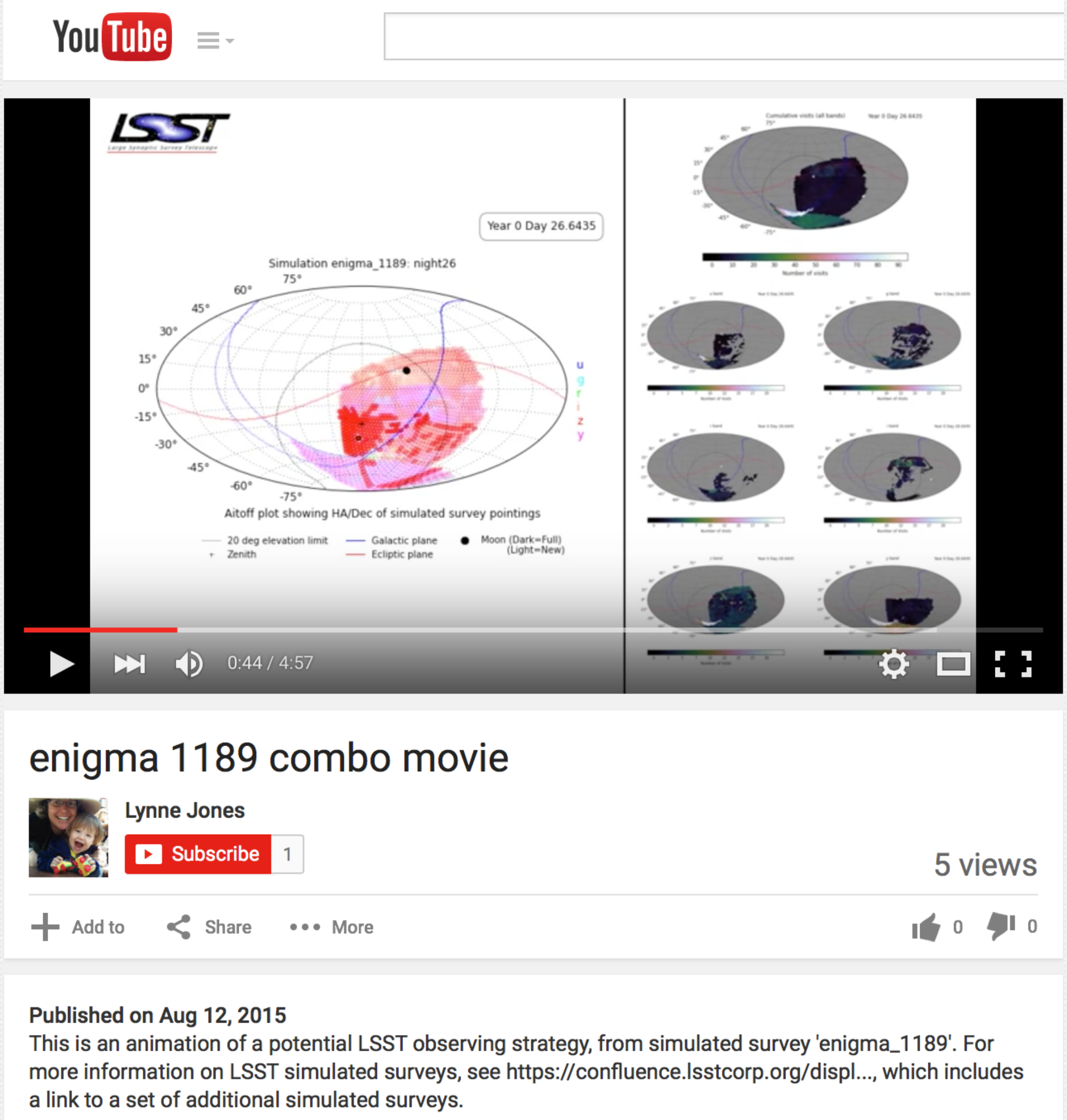


enigma 1189 combo movie

Lynne Jones

Published on Aug 12, 2015
This is an animation of a potential LSST observing strategy, from simulated survey 'enigma_1189'. For more information on LSST simulated surveys, see https://confluence.lsstcorp.org/displ..., which includes a link to a set of additional simulated surveys.

http://ls.st/vl1

First steps towards animation: proving to be extremely useful for understanding resulting scanning patterns!

Please send us your movies!

5. Candidate new Baseline (enigma_1189)

Basic characteristics:

- for all 2,293 fields (somewhat overlapping) from the Universal Cadence area, the minimum number of visits per field **exceeds** the design specification from the SRD: (56, 80, 184, 184, 160, 160) in ugrizy.
- **the mean number of visits** over the Universal Cadence area, summed over all bands, **is 920** (SRD design spec: 825). The minimum is 898.
- the median total open shutter time (per night) as a fraction of the observing time (the ratio of the open shutter time and the sum of the open shutter time, readout time and slew time) is **73%** (mean slew time: 6.9 sec; min=4.5 sec)
- the 25%-75% quartiles for the number of filter changes per night are 2 and 7, with the mean of 4.6. **The total number of filter changes is 15,364.**

5. Candidate new Baseline (enigma_1189)

Constraints on filter exchanges:

- the system is designed to undergo 100,000 changes over 15 years (including the daily in-dome calibrations during the daytime)

- it takes **2 minutes to change a filter in the camera** (5 out of 6)

- we won't know details about thermal performance degradation or other effects until we are further down the road; at this time, we think the following are reasonable assumptions:

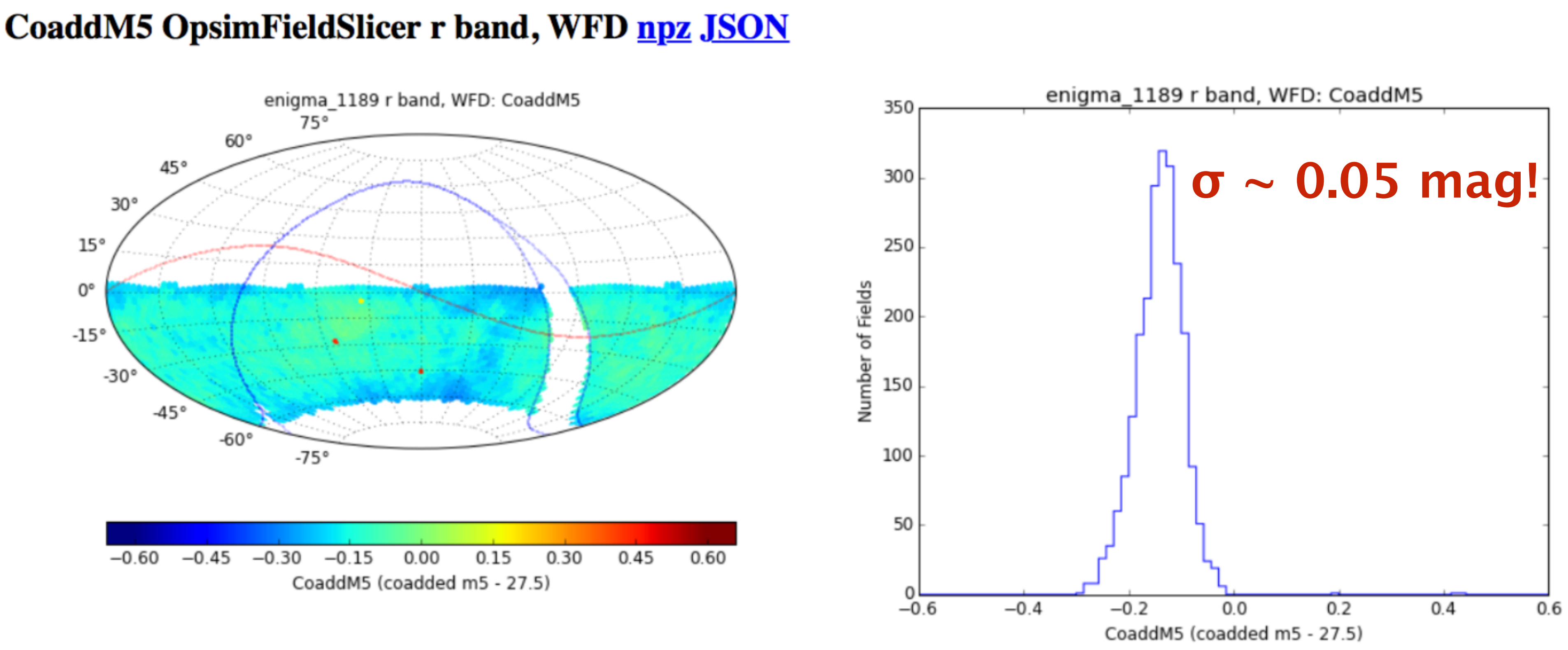
  - o **6 consecutive exchanges every 3 minutes will be fine**
  - o **a (rare) night with exchanges every 10 minutes will be fine**
  - o **steady-state implies the main survey will have fewer than about 10 exchanges per night** (enigma_1189: mean = ~5)

5. Candidate new Baseline (enigma_1189)

Basic characteristics:

- the distribution of coadded depth across the sky is fairly **uniform** (26.1, 27.3, 27.4, 26.7, 25.4, 24.4 in ugrizy)

r band coadded depth (dithered):



CoaddM5 OpsimFieldSlicer r band, WFD npz JSON

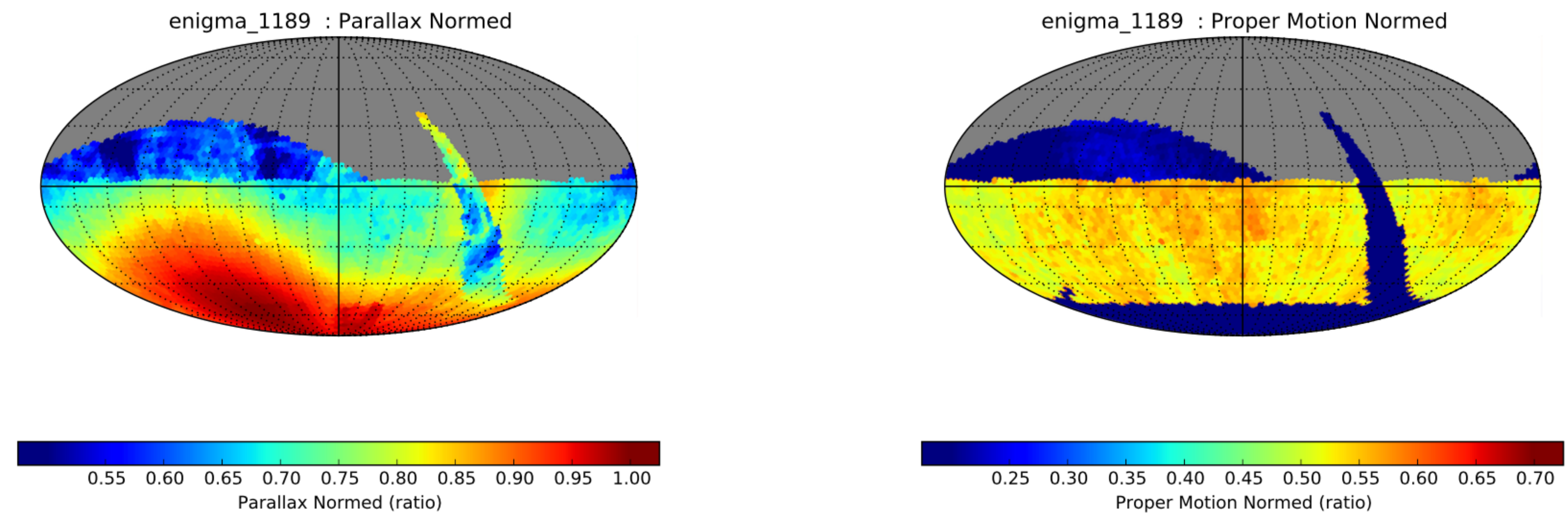
σ ~ 0.05 mag!

5. Candidate new Baseline (enigma_1189)

Trigonometric parallax and proper motion uncertainties

- the median trigonometric parallax and proper motion errors are 0.57 mas and 0.16mas/yr, for bright sources, and 5.5 mas and 1.6 mas/yr for points sources with r = 24

errors normalized by the values for idealized perfectly optimized cadences:

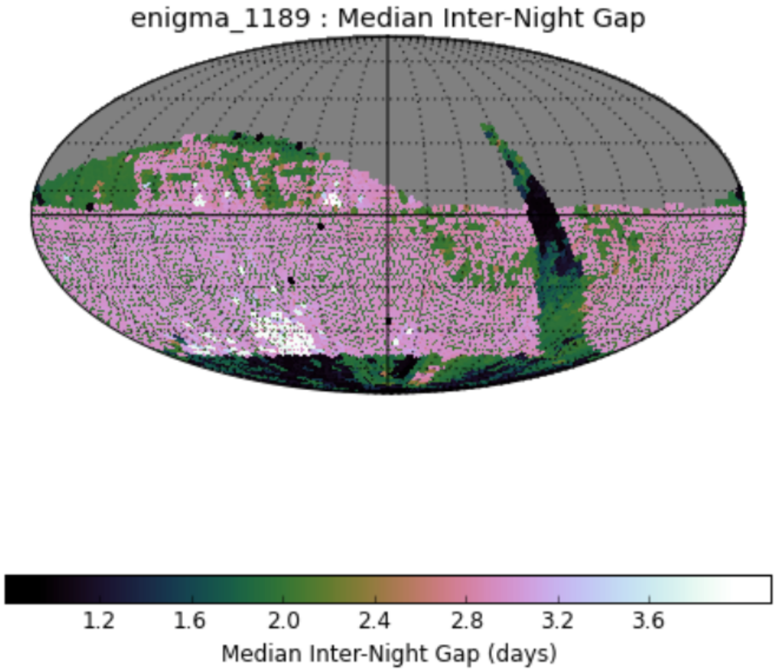


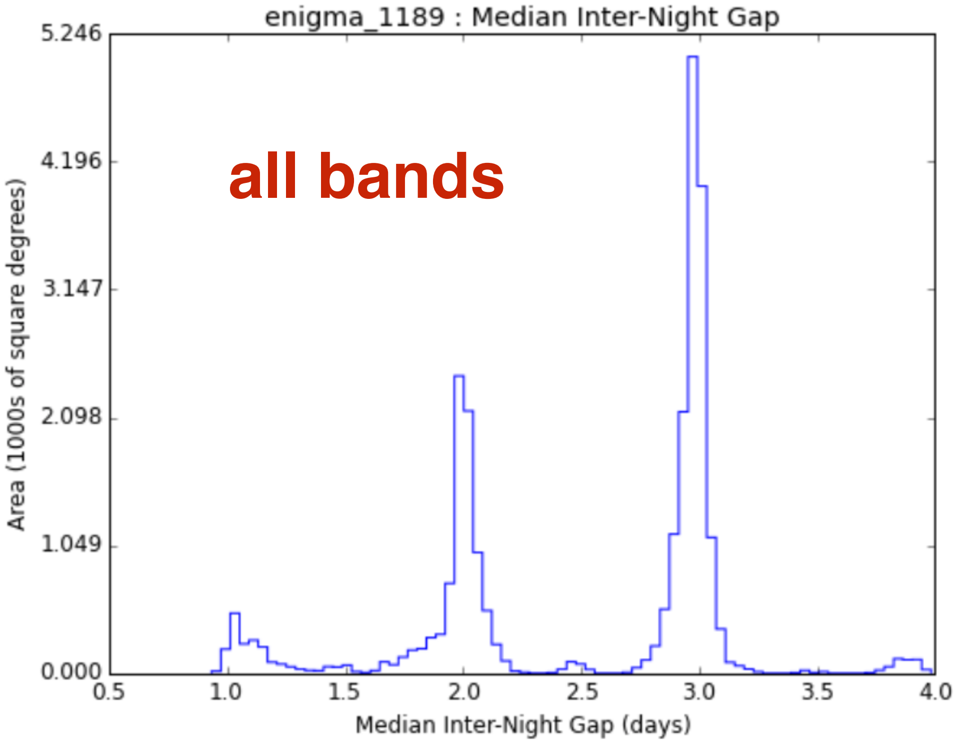
5. Candidate new Baseline (enigma_1189)

Time domain: the median intra-night gap: 20-30 min

Time domain: the median inter-night gap (revisit time)

On average, fields in the main survey are revisited every 3 days (all bands together):

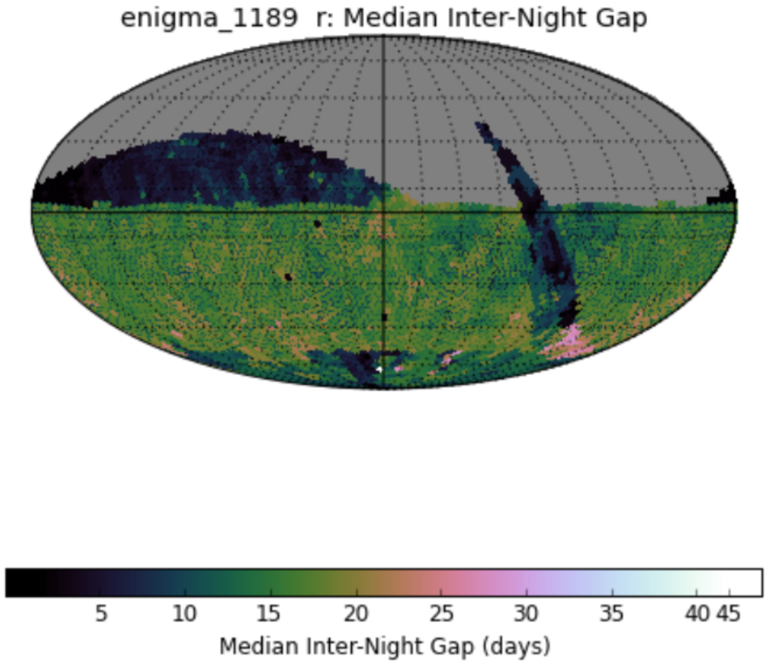


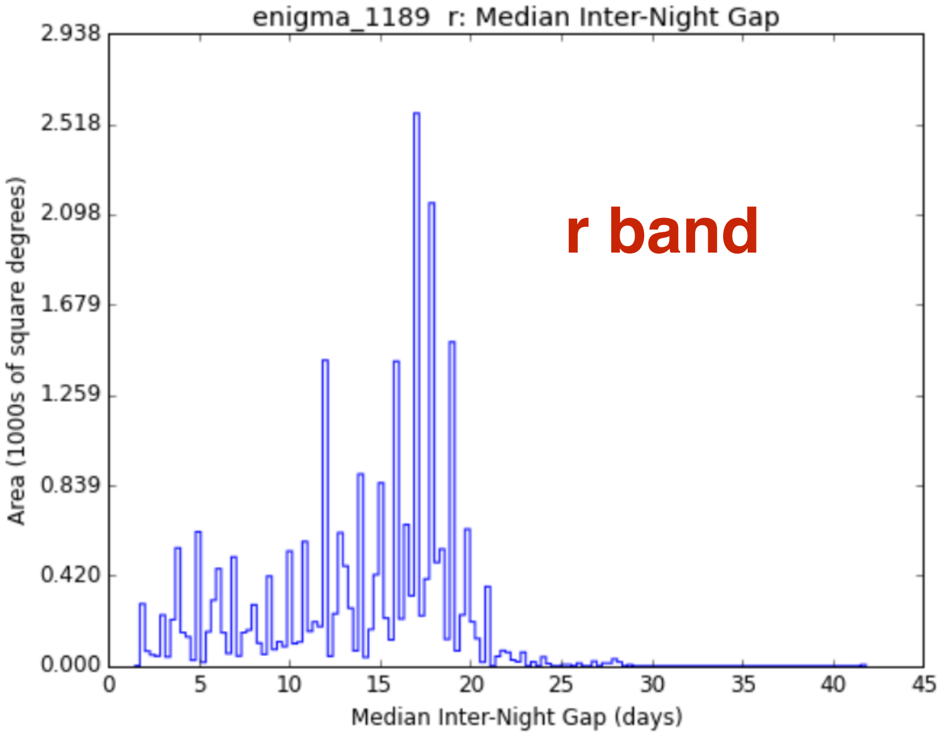


5. Candidate new Baseline (enigma_1189)

Time domain: the median inter-night gap (revisit time)

On average, fields in the main survey are revisited every 15 days in r band (most other bands similar, 30 days for u band)



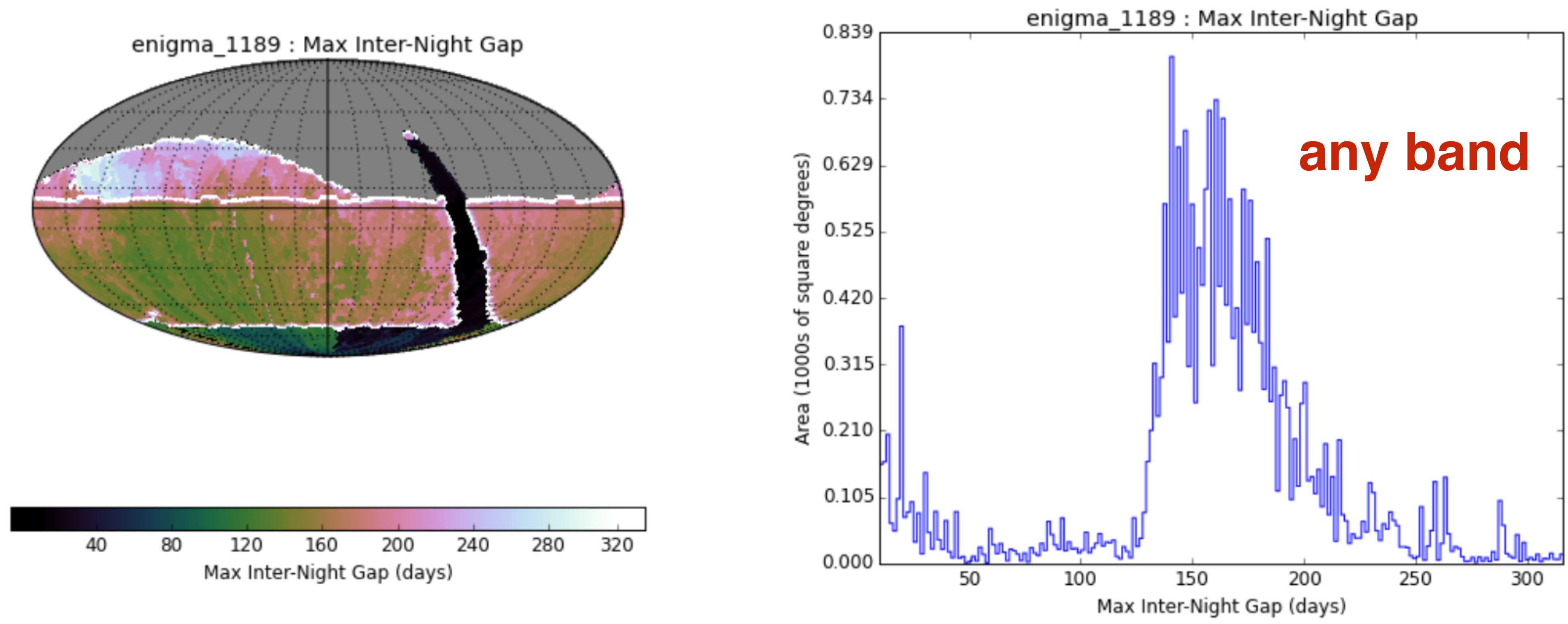


r band

5. Candidate new Baseline (enigma_1189)

Time domain: the longest gap (inter-season)

On average, the longest gap without data (all proposals, any band) is about 5-6 months:



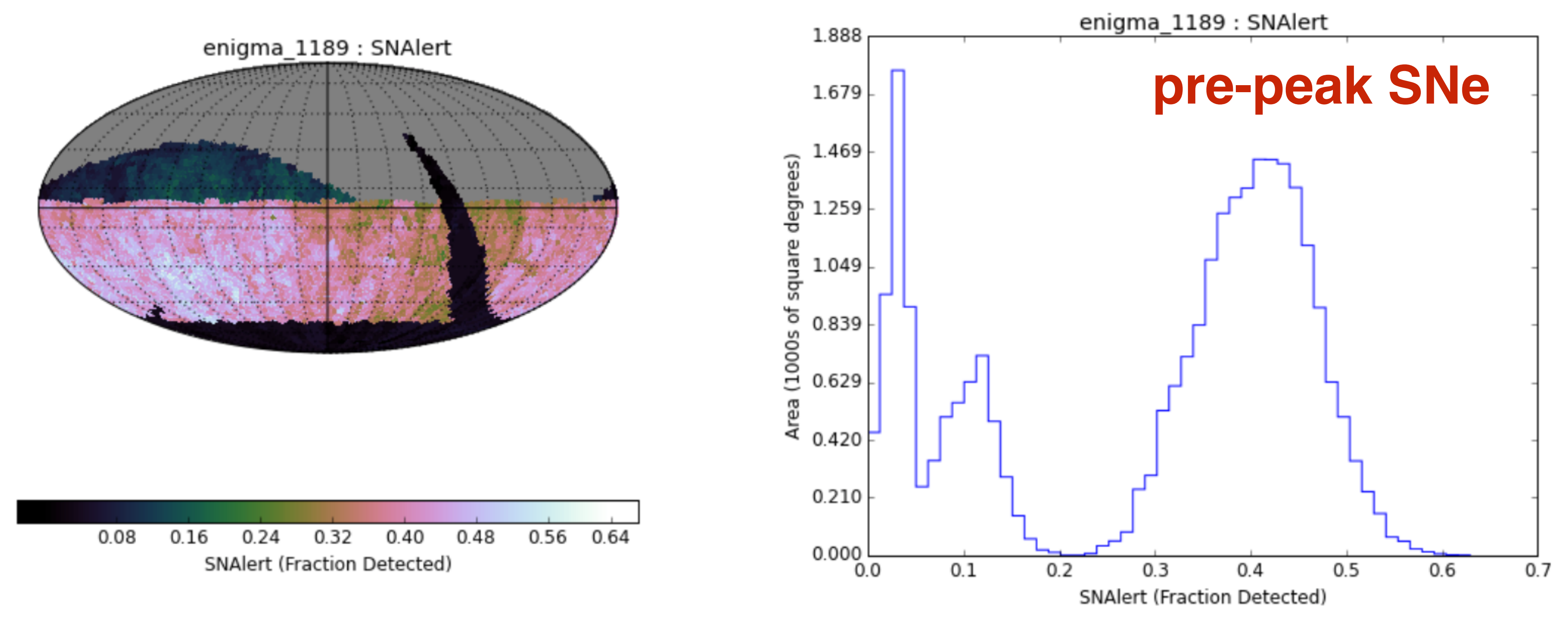
any band

5. Candidate new Baseline (enigma_1189)

Time domain: SNe recovery

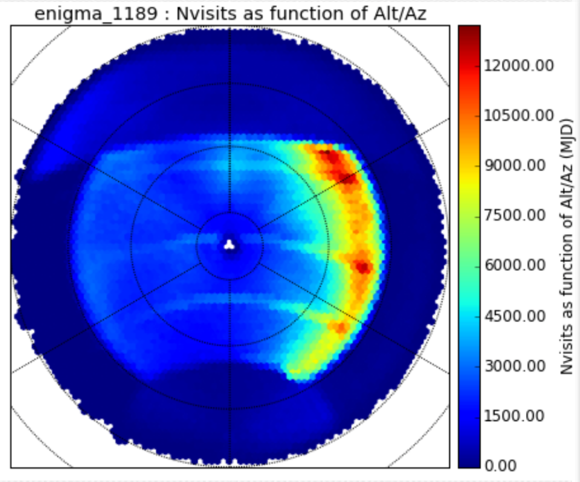
numerous metrics: here “pre-peak discovery”

On average, about 40% of SNe in the main survey will have data before the maximum brightness:

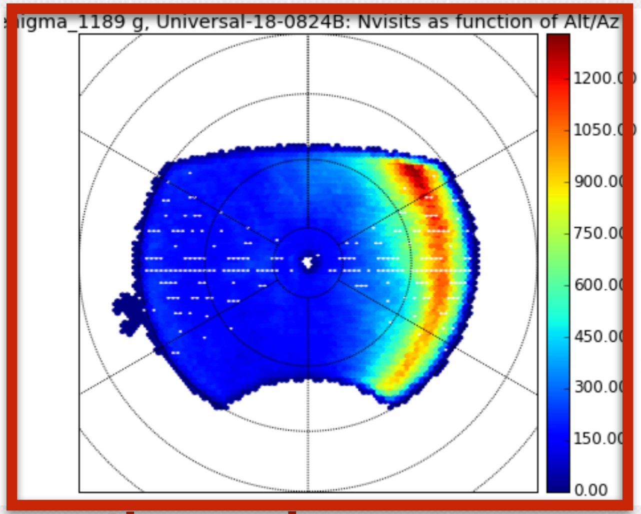


5. Candidate new Baseline (enigma_1189)

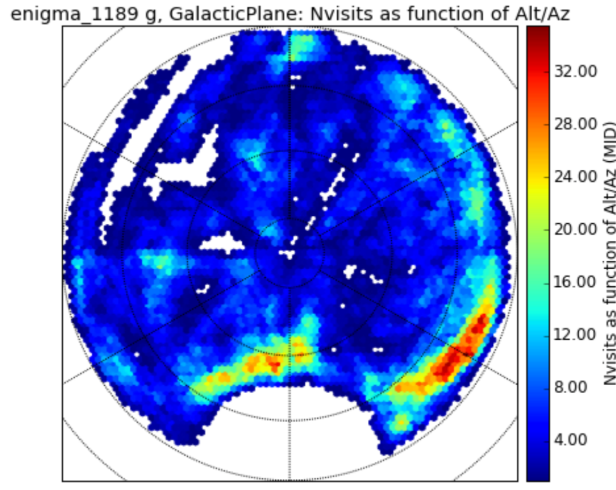
The main current problem: “the western bias”, Alt-Az


enigma_1189 : Nvisits as function of Alt/Az

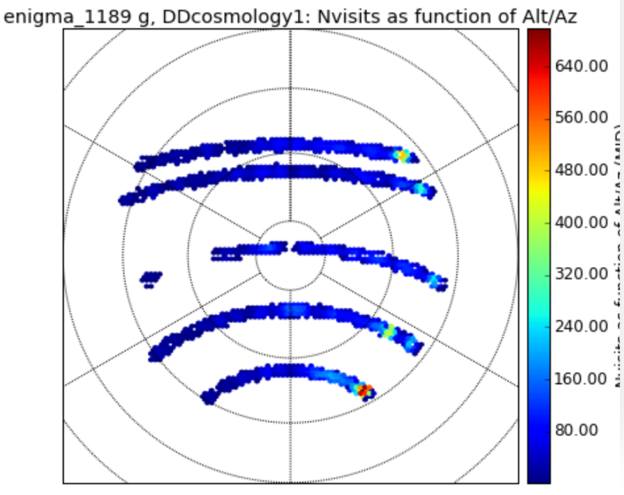
All data, g band


igma_1189 g, Universal-18-0824B: Nvisits as function of Alt/Az

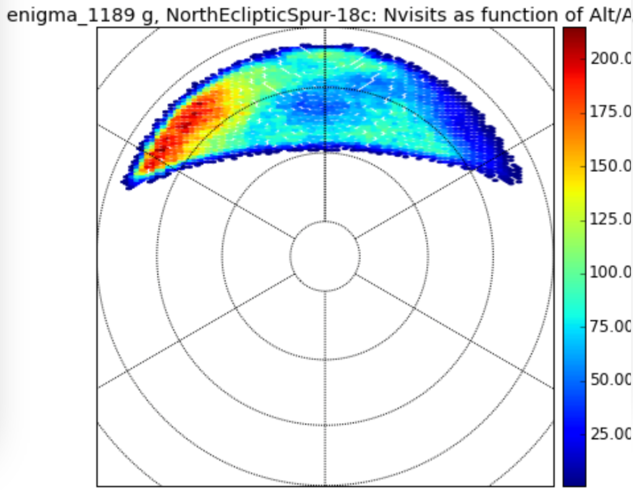
the main survey


enigma_1189 g, GalacticPlane: Nvisits as function of Alt/Az

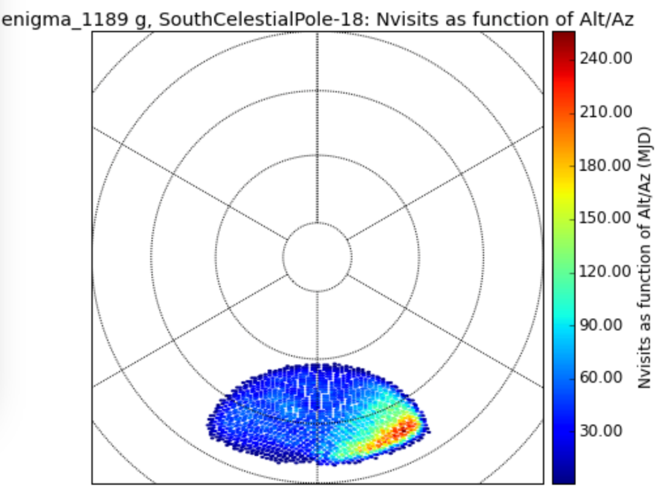
Galactic Plane


enigma_1189 g, DDcosmology1: Nvisits as function of Alt/Az

Deep drilling


enigma_1189 g, NorthEclipticSpur-18c: Nvisits as function of Alt/A

North Ecliptic


enigma_1189 g, SouthCelestialPole-18: Nvisits as function of Alt/Az

South Cel. Pole

6. Cadence exploration and optimization

- how much “reserve” do we have?
- the impact of special programs
- the impact of pairs of visits
- optimization of the visit exposure time
- optimization of NEO completeness

6. Cadence exploration and optimization

how much "reserve" do we have?

What would be the effect on the number of visits of ignoring special programs and spending all of the observing time on the main Universal Cadence fields?

ops2_1098, using only fields from the uniform cadence proposal, delivered 99.2% of the total number of visits obtained by Baseline Cadence (for all proposals).

With dithering, the effective number of visits is increased by 43%, **relative to the SRD design** specification of 825 visits over 18,000 sq.deg.

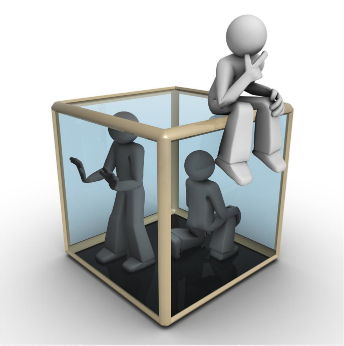
6. Cadence exploration and optimization

how much “reserve” do we have?

What would be the effect on the sky coverage of ignoring special programs and applying the main Universal Cadence strategy everywhere?

ops2_1092, also known as “Pan-STARRS” cadence, shows that the survey area could be increased by about 40% (to 25,000 sq.deg.), while still delivering the mean number of fields at the level of 98% of that in Baseline Cadence (or 92% of the SRD design value).

Should we drastically simplify observing strategy and just deploy this idea?



6. Cadence exploration and optimization

how much “reserve” do we have?

We have about 40% reserve, which could be spent on:

i) increase the no. of visits per field for the WFD area

ii) increase the surveyed area while keeping the number of visits per field statistically unchanged

iii) increase both area and the number of visits

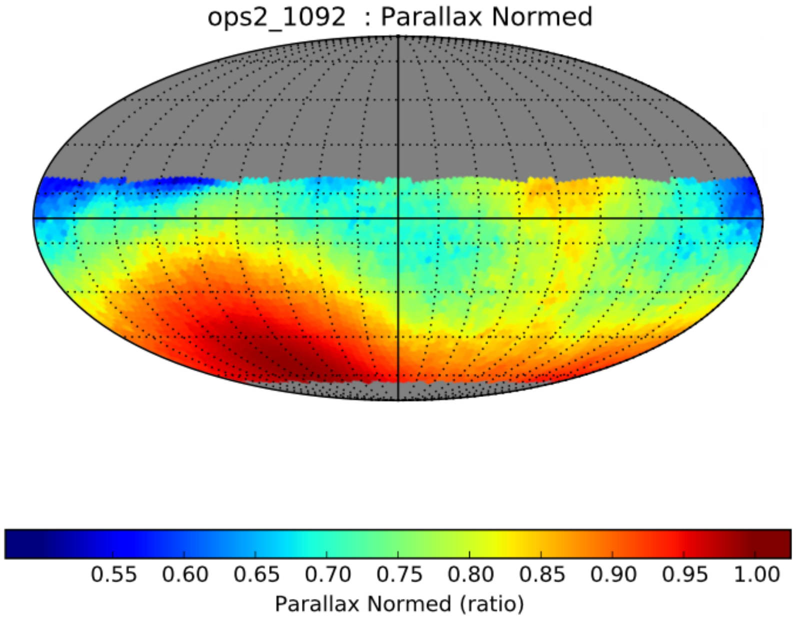
iv) execute additional programs (the current baseline).

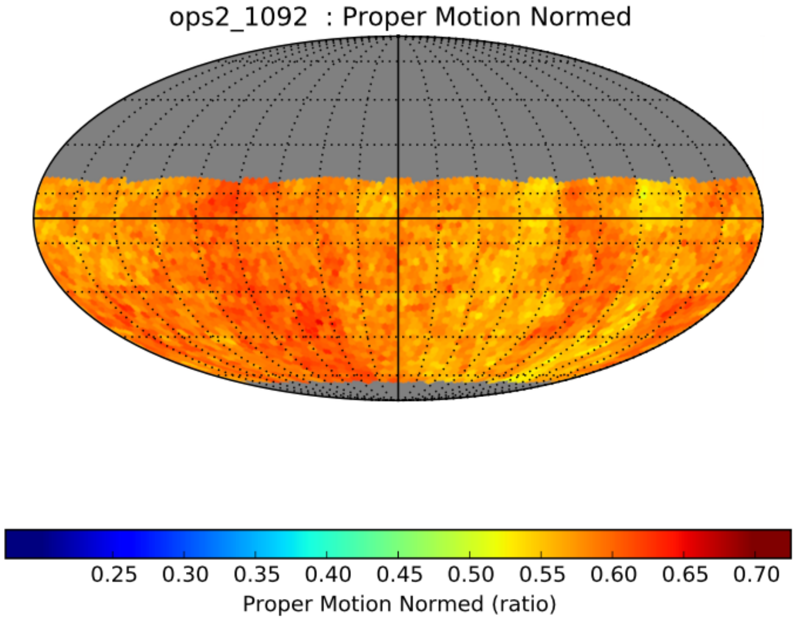
(or to mitigate performance losses, e.g. in SNR)

6. Cadence exploration and optimization

Should we simply apply Universal Cadence everywhere?

If you are interested in trigonometric parallax and proper motions, it certainly looks nice! Note, though, that the Galactic Plane may not be that good due to crowding issues. (also good: self-calibration, legacy,...)

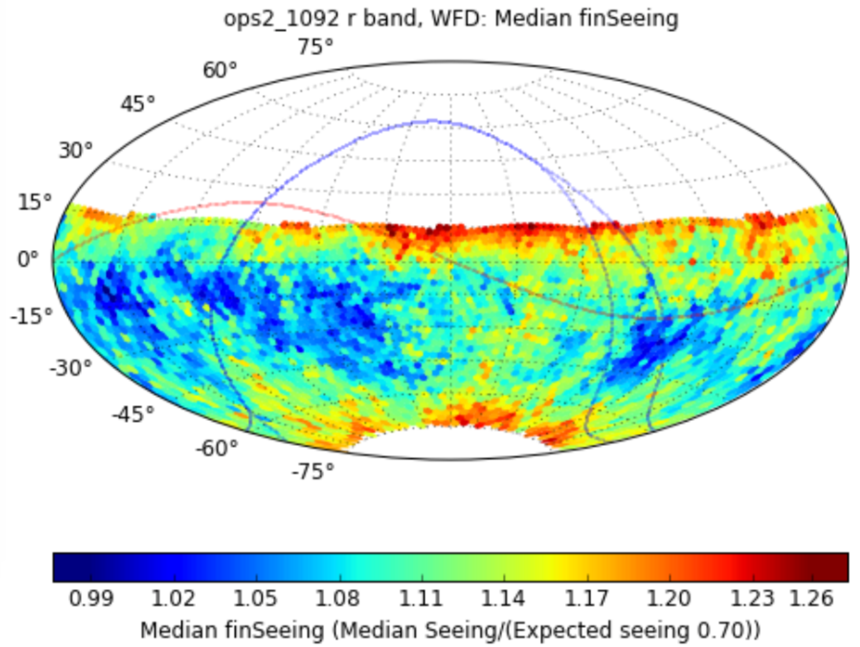


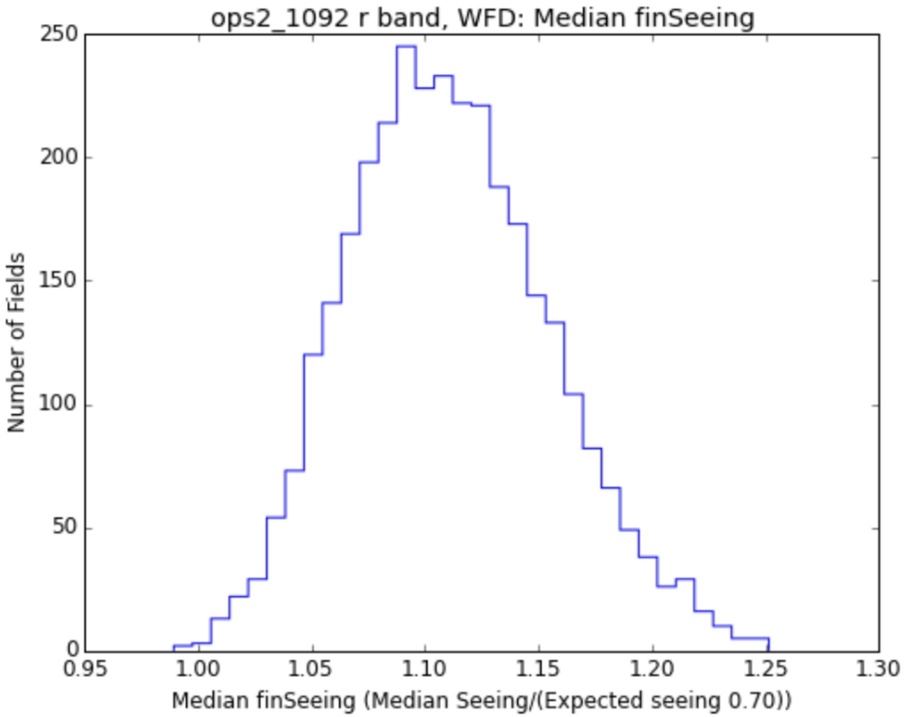


6. Cadence exploration and optimization

Should we simply apply Universal Cadence everywhere?

If you are interested in maximizing the counts of "effectively resolved" galaxies (for WL), the total count of galaxies is similar as in Baseline Cadence:





6. Cadence exploration and optimization

Should we simply apply Universal Cadence everywhere?

If you are interested in maximizing the counts of "effectively resolved" galaxies (for WL), the total count of galaxies is similar as in Baseline Cadence:

1) the counts of galaxies per unit area down to a fixed SNR would decrease by about 15-20% (about 0.15 mag shallower data due to larger median airmass)
2) due to larger area, the total count increased by 10%
3) due to larger seeing (airmass again): down by 5%
4) due to increased dust extinction: down by ~5%

Conclusion: we need to very carefully quantify the scientific value of **both** main survey & special programs!

6. Cadence exploration and optimization

the impact of special programs

ops2_1098, using only uniform cadence proposal, delivered 99.2% of the number of visits over the WFD area obtained by Baseline Cadence.

Therefore, the “filler" aspect of other proposals does not have a major impact on the surveying efficiency.

6. Cadence exploration and optimization

the impact of pairs of visits

ops2_1093, using only uniform cadence proposal, showed that requiring pairs of visits (in a given observing night) does not result in an appreciable loss of surveying efficiency.

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

A few more details when discussing NEOs later.

6. Cadence exploration and optimization

optimization of the visit exposure time

The optimal exposure time per visit for the main survey, in the limit of a single value for all bands and at all times, is in the range of about 20-60 seconds.

Design shortest exposure: 1 sec (goal 0.1 sec)

Expectations:

Shorter exposure time: shallower single-visit data, more visits, but lower surveying efficiency

Longer exposure time: deeper single-visit data, fewer visits, but with higher surveying efficiency

Simulations ops1_1163 (20 sec) and ops1_1164 (60 sec) show that the effect of varying exposure time can be easily understood using simple efficiency estimates. 30 sec visit exp. time is close to optimal!

6. Cadence exploration and optimization

optimization of the visit exposure time: u band

The read-out noise in the u band is not negligible compared to the background noise as in other bands, due to darker u band sky. The **coadded** depth in the u band could be improved by 0.24 mag by increasing the exposure time per visit from 30 seconds to 60 seconds (but with factor of 2 fewer visits).

Two simulations with 60 sec visit exposure time in u:
- cut the requested number of visits to 1/2
- keep the requested number of visits unchanged: it effectively doubles the allocation of observing time to the u band from 5% to 10%.

6. Cadence exploration and optimization

optimization of the visit exposure time: u band

Two simulations with 60 sec visit exposure time in u:

ops1_1162: 1/2 visits; confirms expectations: gain 0.24 mag in the coadded depth, with the number of visits decreased by about a factor of two (with a negative impact on time-domain science).

ops1_1161: keep the requested number of visits unchanged; it effectively doubles the allocation of observing time to the u band from 5% to 10%.
It shows that we could improve the u-band depth by 0.6 mag (both single-epoch and coadded) at the expense of decreasing the number of visits in other bands by ~5% (and coadded depth by ~3%).

6. Cadence exploration and optimization

optimization of NEO completeness

The baseline cadence implements a requirement that two visits to a field be obtained per night, separated in time by a fraction of an hour. Two detections are combined in a “tracklet”, and three such tracklets obtained within 15 days are combined in a “track”. Orbital determination software (MOPS) fits orbits to tracks.

Detailed simulations of the performance of image differencing software and MOPS indicate that two visits per night are likely to be sufficient. Nevertheless, a quantitative analysis of other strategies is clearly within the purview of the cadence optimization program.

6. Cadence exploration and optimization

optimization of NEO completeness

1. No requirements for pairs of visits: ops2_1094
2. Pairs of visits: Baseline Cadence (enigma_1189)
3. Triples of visits: enigma_1258
4. Quads of visits: enigma_1259

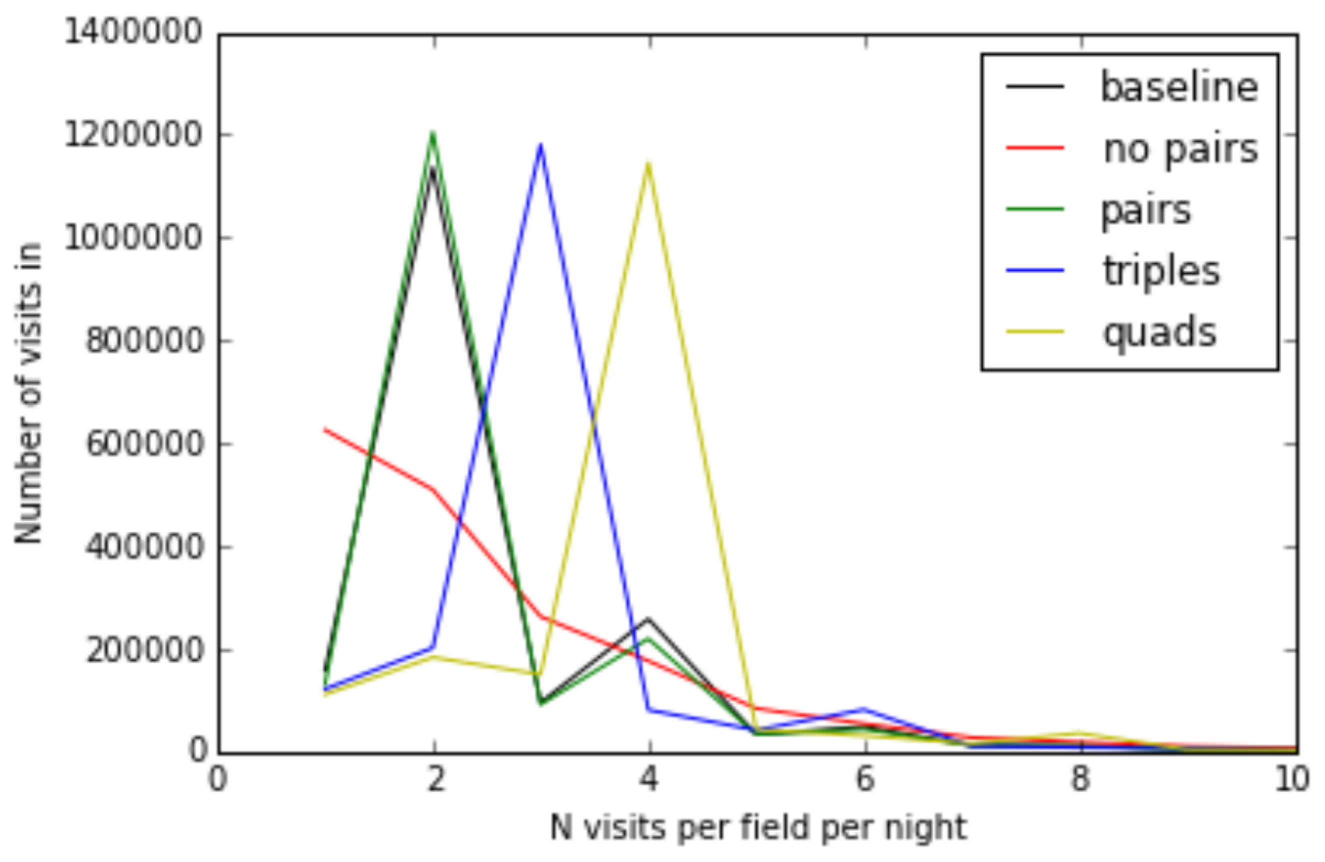
Motivation for a simulation that does not ask for pairs of visits is to gauge the impact on the survey efficiency and other performance parameters.

Motivation for simulations with more than two visits to a given field per night is to investigate the feasibility of a more robust approach to linking individual detections into a plausible object track.

6. Cadence exploration and optimization

optimization of NEO completeness

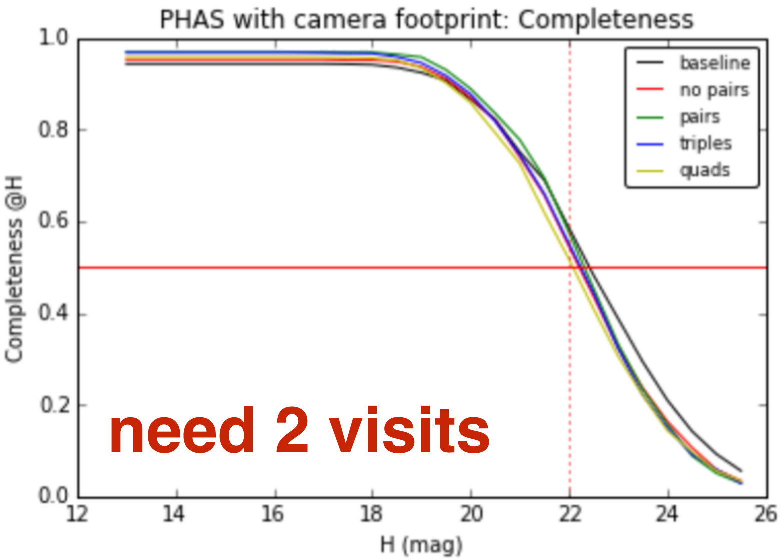
The distribution of the number of visits used for nightly sequences:



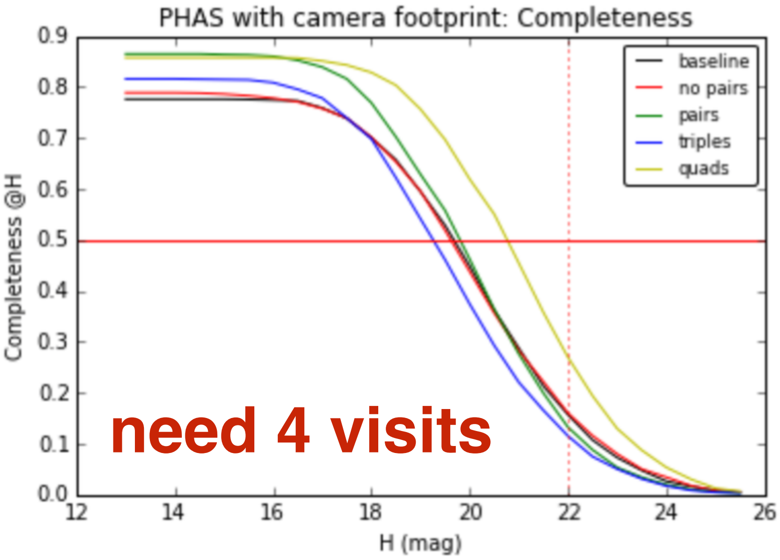
The OpSim doesn’t yet have nightly “look behind”

6. Cadence exploration and optimization

optimization of NEO completeness



need 2 visits



need 4 visits

We have a tool!

First results: going from pairs of visits to triples (both for cadence requirement and for NEO detection) reduces completeness for PHAs with H≤22 by about 15-20%, and by about 30% for quads (from ~70%).

7. Continuing 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)
- improved time-domain programs
- improved special programs

7. Continuing 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)

7. Continuing cadence optimization

Existing to-do list (more to hopefully come from *you*):

1. Further exploration of the main survey (e.g., exposure time in general, and u band exposure time in particular; fixing western bias; exploring airmass limit and sky coverage; investigations of variable, perhaps SNR-driven, exposure time).

2. Exploration of temporal sampling function in general, and of Rolling Cadence in particular.

3. NEO completeness studies: what would it take for LSST to reach 90% completeness for 140m and larger NEOs? Based on previous analysis, directions to explore are deeper visits along the Ecliptic and longer survey duration (about 12 yrs).

7. Continuing cadence optimization

4. Exploration of Galactic plane and Bulge science programs (e.g. should we extend the main survey to the Galactic plane per A.Gould's proposal, arXiv:1304.3455)

5. Optimization of LMC/SMC coverage (and somewhat less importantly, the South Celestial Pole coverage).

6. Deep drilling exploration (detailed analysis of existing proposals; investigation of gains from going to a larger observing time allocation, e.g. 20%).

7. Twilight short-exposure time observing (per internal Stubbs proposal).

7. Continuing cadence optimization

8. Planning commissioning observations (e.g. the tension between going wide to enable self-calibration, and dense temporal sampling to obtain various light curve templates and fine tune image differencing and multi-epoch data processing and data analysis software tools).

9. Dynamic cadence explorations (the main goal at this time is to answer: are our tools good enough to act and react swiftly and robustly in operations?).

7. Continuing cadence optimization

Objectives for this workshop (and white paper):

1. To define quantitative science drivers for the observing strategy of the LSST (e.g. the depth and filters required for early science; the sky region, cadence and number of filters required to "measure something")

2. To express these drivers in terms of "metrics" by which the science returns (simulated surveys) can be quantified

3. To define the experiments needed to develop and test these metrics so that we can determine how much science is gained or lost as a function of the current survey strategy or future strategies

- **Examples of questions you might want to address:**
  - the amount of sky coverage (as a function of season)
  - the sampling of the Galactic plane including number of bands and over what timescale (e.g. can we take all u-band data in one year?)
  - how many bands must be observed to start getting out science
  - what signal-to-noise is required within each band for your science (e.g. photometric depth for photo-z)
  - for transient science, what measurements are needed to determine how well you can discover a transient (e.g. time sampling of observations - pairs, triplets, n-tuples)
  - for transients and variability what metric would be used to define how well you can characterize/classify a source (e.g. number of colors over what period)
  - and so on….

Summary

The LSST baseline cadence, and various implemented assumptions, are NOT sacrosanct! But there are some “conservation laws” set by the integrated etendue.

The most important conclusion of the preliminary cadence explorations 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 sec, and thus only slightly larger than the design specifications for the system slew and settle time of 4.5 sec. **But 6% of LSST is a lot!**

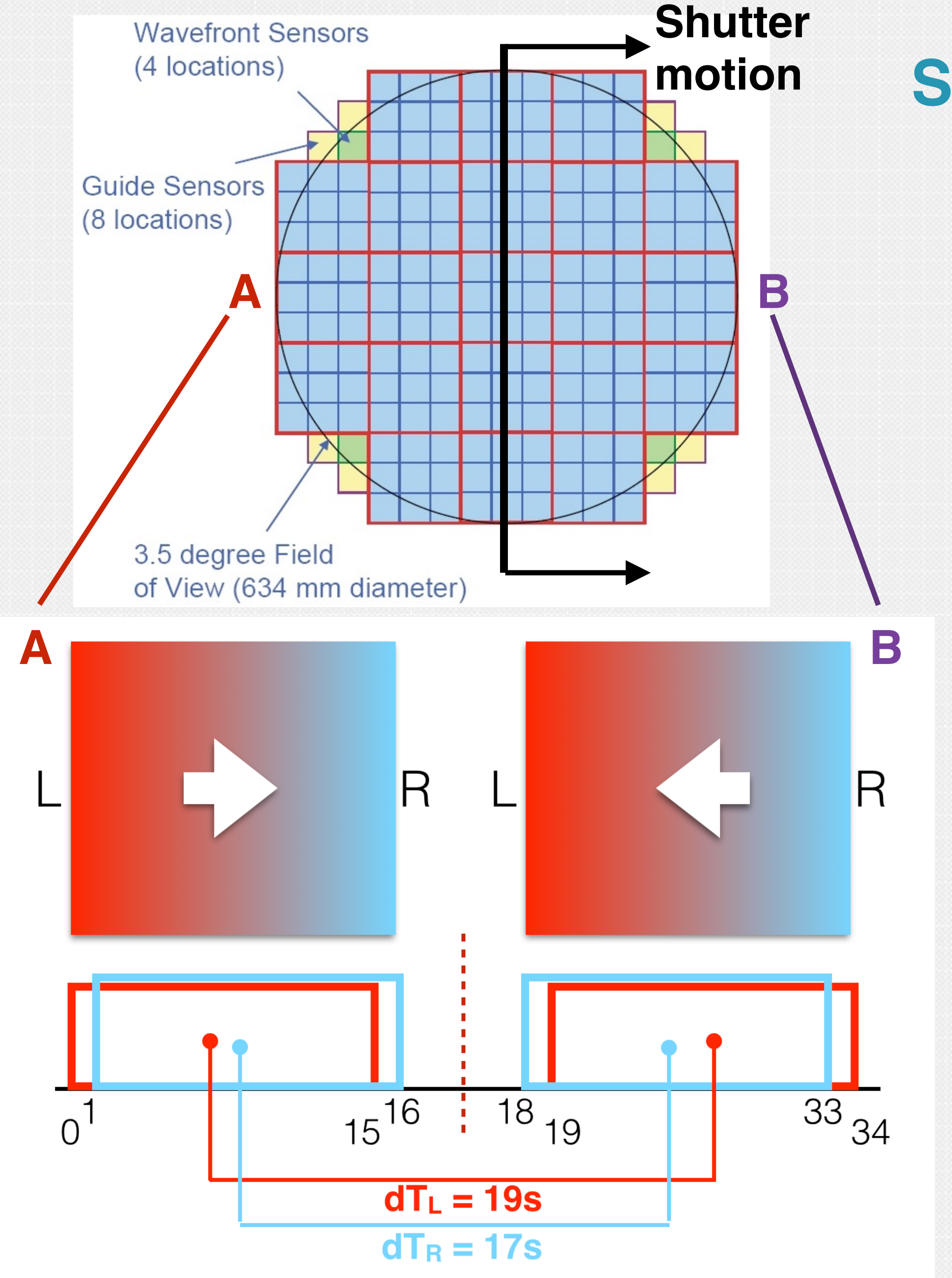
Nevertheless, it is likely that **the performance for time-domain science can be significantly improved** (e.g. rolling cadence for SNe survey).

Key questions:

1) what exactly do we want to do? **The main question for this workshop!**
2) can the existing scheduler algorithms support it?

Backup Slides

Snaps time delays



VISIT: two back-to-back exposures of the same field, separated by a readout (2 seconds); **baseline: 2x15 sec**

It takes 1 second for the shutter blade to move across the focal plane: the end of the first snap and the start of the second snap are separated by 2 (B) to 4 (A) seconds.

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)

6. 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):

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

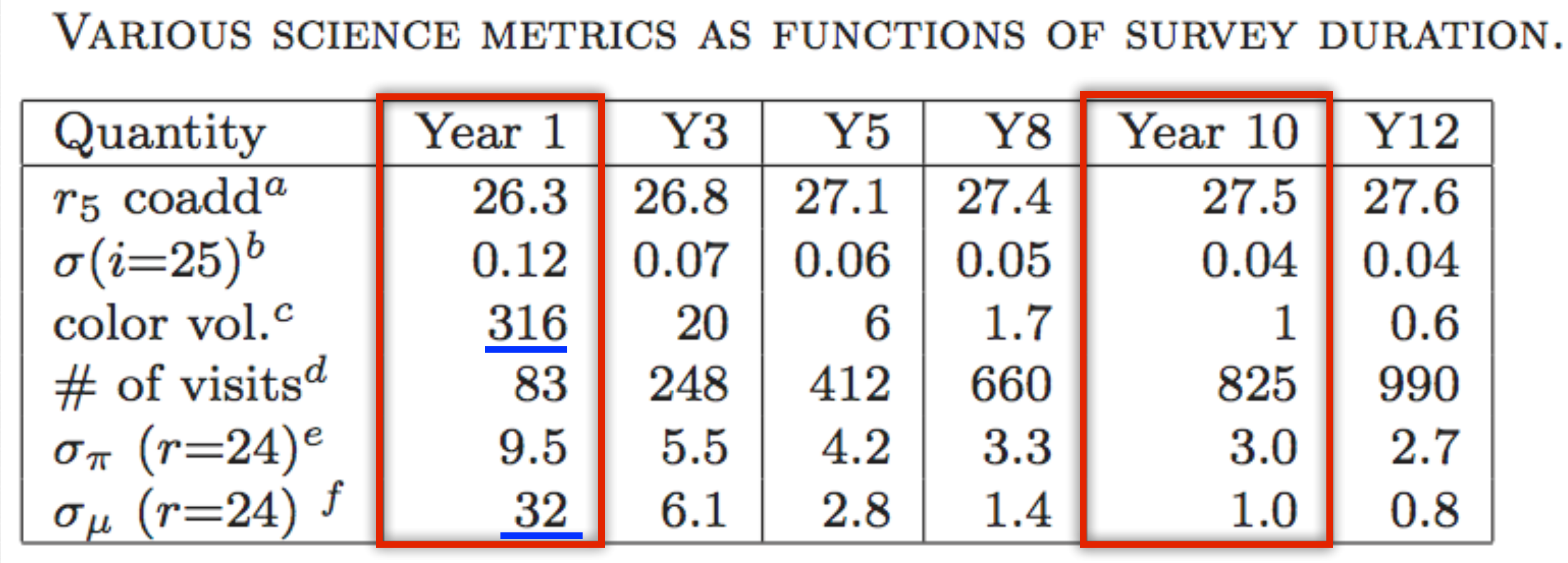
NEO (140m) completeness (t_{NEO}~4 yrs; C_{NEO}~93%):

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

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.

Ways to start discussions about LSST cadence

LSST Science Advisory Council (SAC)

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

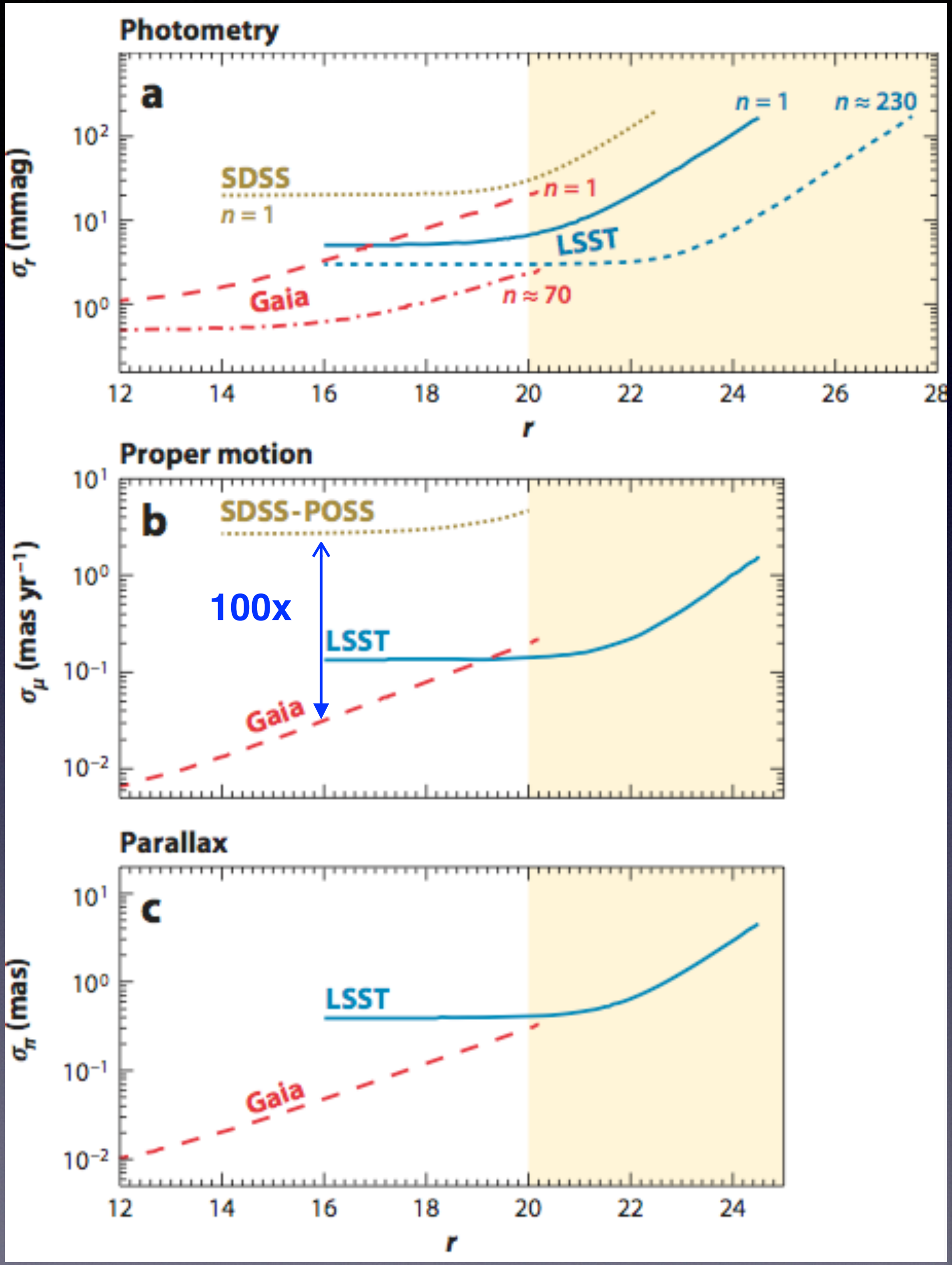
LSST Project Science Team (PST)

- an operational unit, within the Project, that includes key scientists (Angeli, Claver, Connolly, Ivezić, Jurić, Kahn, Lupton, Ritz, Strauss, Stubbs, Thomas, Tyson, Willman). 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.

Gaia vs. LSST comparison



Ivezić, Beers, Jurić 2012, ARA&A, 50, 251

- **Gaia:** excellent astrometry (and photometry), but only to r < 20
- **LSST:** photometry to r < 27.5 and time resolved measurements to r < 24.5
- Complementarity of the two surveys: photometric, proper motion and trigonometric parallax errors are similar around r=20

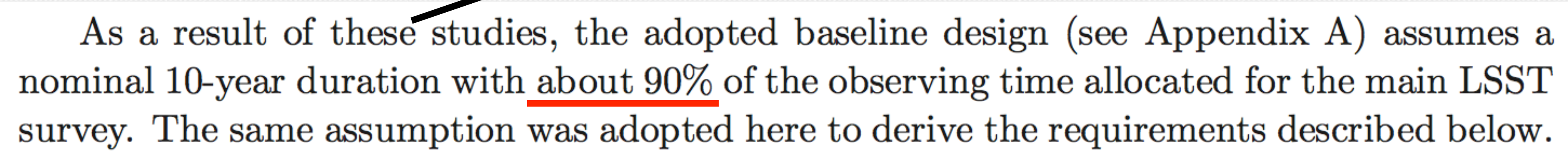
The Milky Way disk "belongs" to Gaia, and the halo to LSST (plus very faint and/or very red sources, such as white dwarfs and LT(Y) dwarfs).

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:**

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.

A quote from the Jefferson Memorial

(originated in a letter to Samuel Kercheval from July 12, 1816)

I am not an advocate for frequent changes in laws and constitutions, but laws and institutions must go hand in hand with the progress of the human mind. As that becomes more developed, more enlightened, as new discoveries are made, new truths discovered and manners and opinions change, with the change of circumstances, institutions must advance also to keep pace with the times.