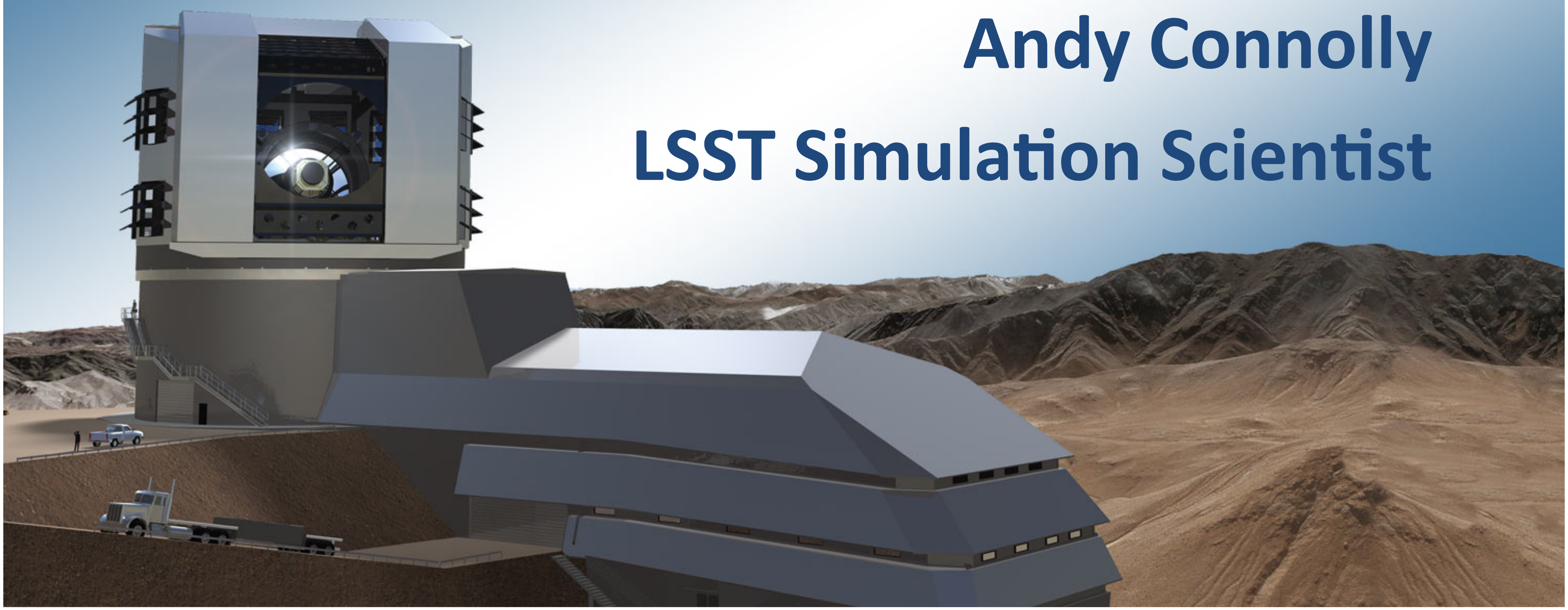
UK LSST ~~Cadence~~ Survey Strategy Workshop

Andy Connolly

LSST Simulation Scientist



Objectives for the workshop

1. To introduce the LSST survey strategy, and the tools and data sets that can be used to evaluate how your science "performs" against that strategy
2. To define quantitative science drivers for the observing strategy of the LSST (e.g. the depth and filters required for early science, the cadence and number of filters required to detect transient and variable sources, the number of filters and cadence required to classify variables and transients)
3. To express these drivers in terms of "metrics" by which the science returns can be quantified
4. 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

Breakout groups

- **Solar System and proper motions**
  – chair: Colin Snodgrass
  – e.g. asteroid populations, parallax and proper motions
- **Static Science**
  – chairs: Victor Debatista, Richard McMahon
  – e.g. weak lensing, photometric redshifts, large scale structure, galactic structure
- **Transients**
  – chairs: Stephen Smartt, Mark Sullivan
  – e.g. SNe, GRBs, orphan GRBs
- **Recovering persistent variables**
  – chairs: Vasily Belokurov, Daniel Mortlock
  – e.g. AGN, stellar variability, strong lensing

People

Peter Yoachim

Phil Marshall

Lynne Jones

Andy Connolly

Does the LSST survey strategy work?

- 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 (can we take all u-band 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 photoz)
  - 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….

How to write your “metric”

- What is your science goal?
  - e.g. a measurement of H_0 from strong lensing
- Qualitatively, how does the survey strategy impact this science?
  - e.g. accurate time delays of days-weeks are needed, and they have to be inferred from long, but noisy, sparsely-sampled light curves
- Quantitatively, how does your science depend on the survey strategy? Are there simple quantities - metrics - that allow you to give approximate answers to this?
  - e.g. the time delay measurement depends on the sampling of the light curve: depth per visit, season length, campaign length and night-to-night cadence are all important properties.

Using iPython notebooks and Github

- We would like all of the discussions to be recorded in iPython notebooks and stored on Github.
- Notebooks support notes on science cases, latex, code or pseudo-code, and descriptions of proposed experiments.

- What should you do?
  - Create a github account (http://www.github.com)
  - git clone https://github.com/lsst-sims/sims_maf_notebooks.git
  - git clone https://github.com/LSST-nonproject/sims_maf_contrib
  - Install the software http://cadence.lsst.org/cadenceWorkshop/
  - If you need help there are people here for you

Agenda

- **Monday 18th May (Ryle):**
  - 1.30 - 3.30pm The LSST System and Observing Strategy
    The Operations Simulator, and Defining an Objective Cadence
    Example: Strong Lens Time Delays
  - 4.00 - 5.30pm The analysis framework for the LSST cadences (tutorial 1)
  - 5.30 - 6.30pm Helpdesk: getting MAF running on your machine

- **Tuesday 19th May (Ryle, Hoyle, Observatory):**
  - 9.00 - 10.30am Building and running your own metrics (tutorial 2)
  - 11.00 – 4.00pm WG hack sessions
    - Group 1: Static Science: (Chairs: Victor Debattista, Richard McMahon)
    - Group 2: Recovering persistent variables (lightcurves) : (Chairs: Daniel Mortlock, Vasily Belokurov)
    - Group 3: Transients (Chairs: Stephen Smartt, Mark Sullivan)
    - Group 4: Solar System and proper motions (Chair:Colin Snodgrass)
  - 4.00 – 5.30pm Multi-Object Spectroscopic Survey facilities for LSST follow-up (Roelof de Jong, Richard McMahon)
  - **6.30pm Dinner at Clare Hall**

- **Wednesday 20th May (Ryle, Hoyle, Observatory)**
  - 9.00 - 10.00am Initial WG presentations (status updates)
  - 10.00 - 1.30pm WG hack sessions
  - 1.30 - 3.30pm Presentation of cadence results - next steps

Why the survey strategy matters?

- The LSST supports a broad range of science objectives
- Many of these science objectives are driven by how we sample the sky (e.g. SN light curves, proper motion accuracy)
- Cadence is set by these competing science proposals, sky brightness, weather, engineering performance, visibility of the survey fields
- Optimization of such a survey is an open and active areas for research and evaluation
- You will be disappointed (probably) so you should get over it and understand what your science will really need.

LSST in a nutshell

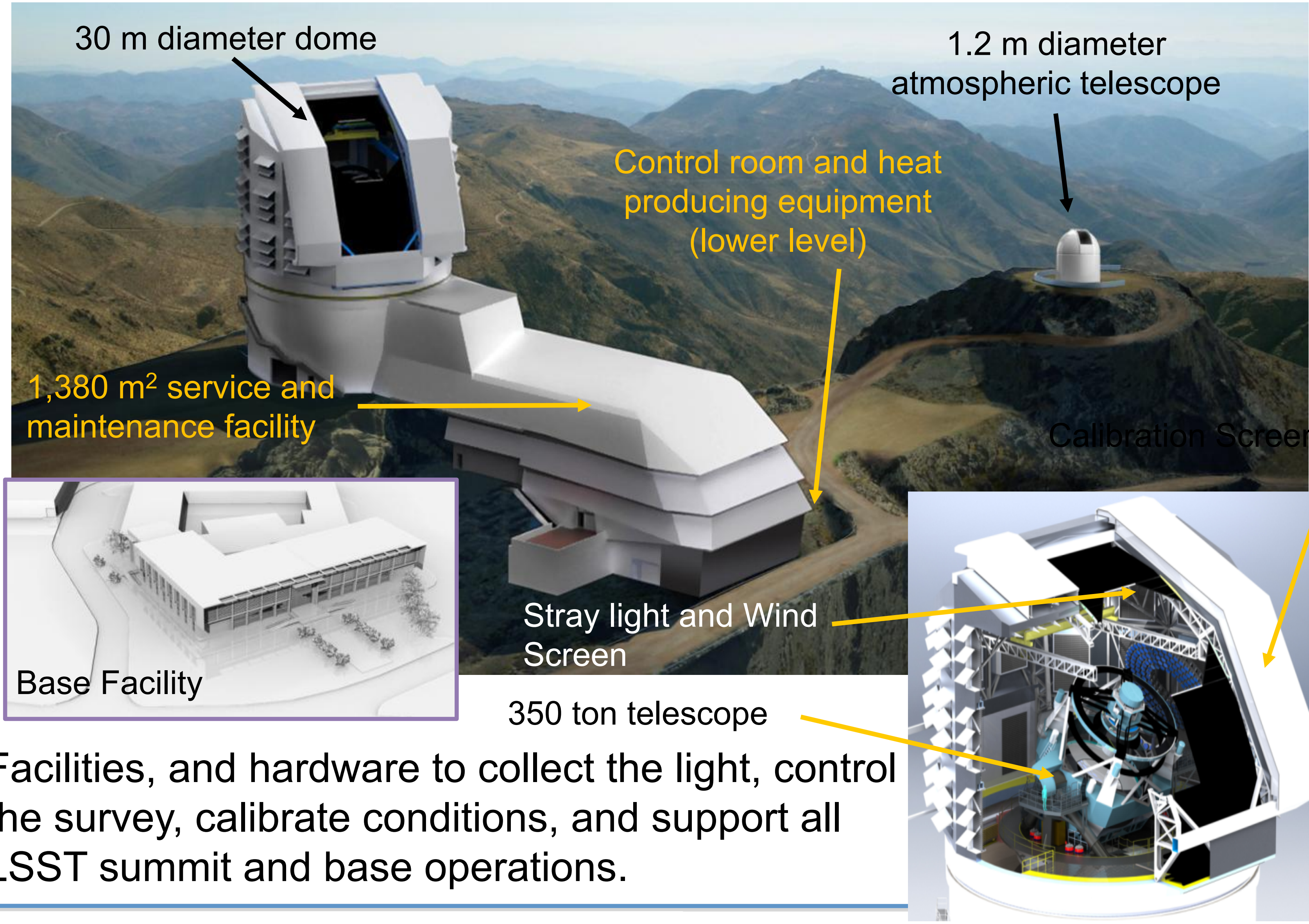
- The LSST will be a large, wide-field, ground-based optical/near-IR survey of half the sky in ugrizy bands to r~27.5 based on 1000 visits over a 10-year period
- Alerts of detected changes on the night sky will be published within 60 sec of the observation as the survey progresses
- LSST will enable a wide variety of complementary scientific investigations: from searches for small bodies in the solar system, to precision astrometry of the Galaxy, to systematic measures of cosmology using gravitational weak lensing.
- Much of the science of the LSST will be systematics limited

Summary of high level requirements

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

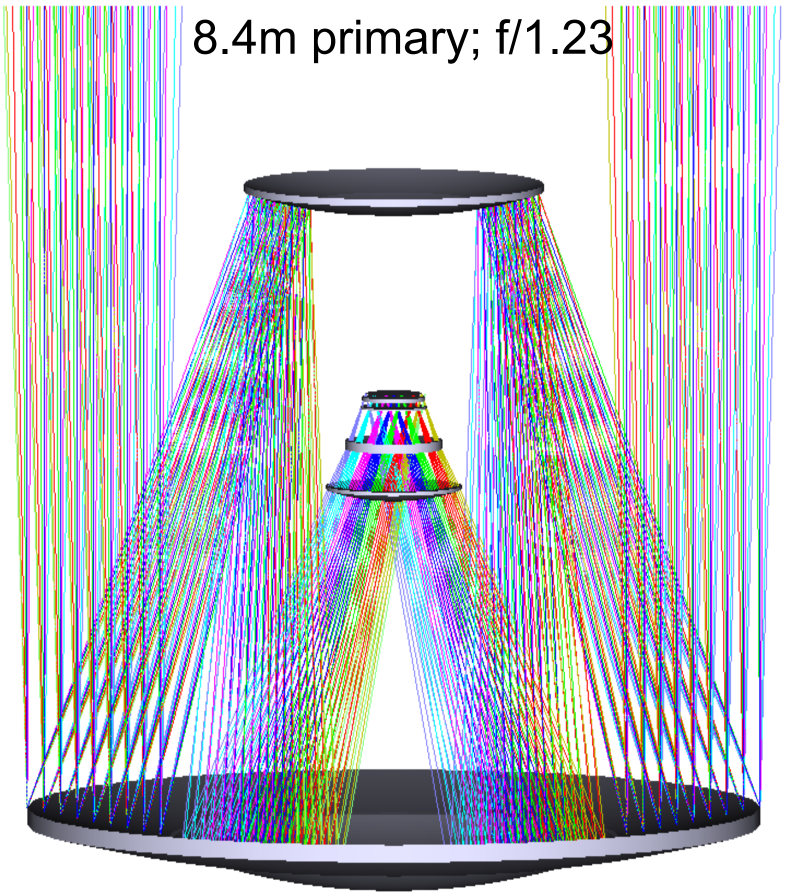
The LSST Site and Base Facilities

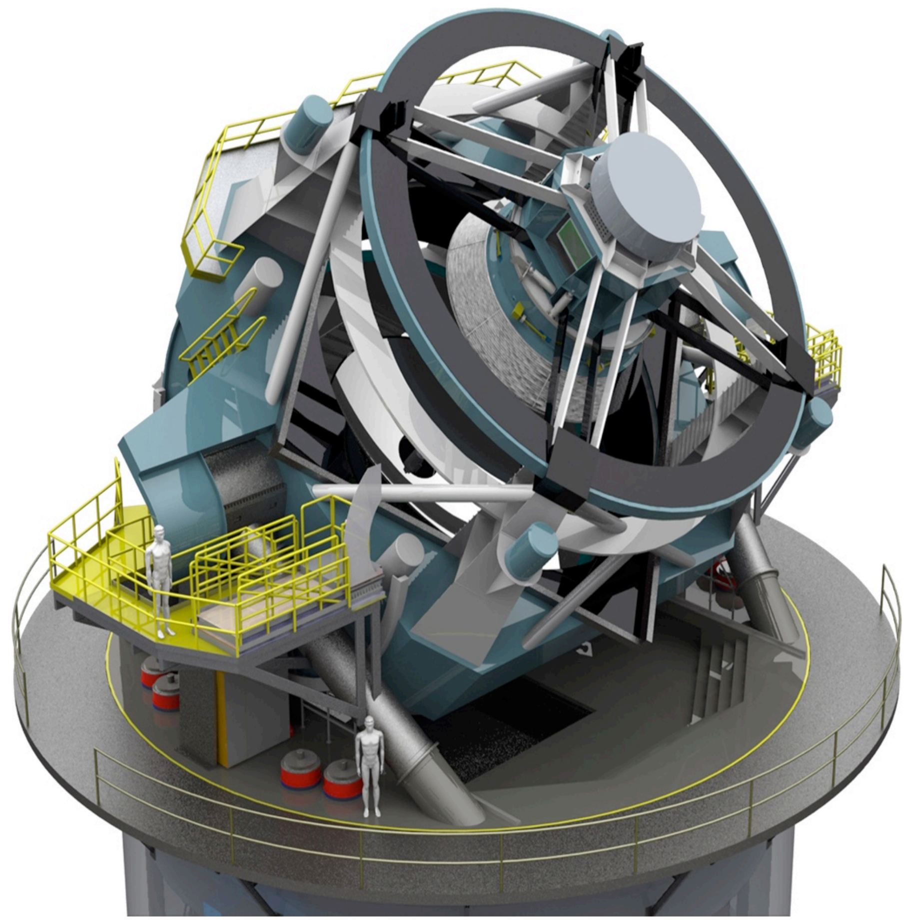
8.4m survey and 1.2m atmospheric telescope



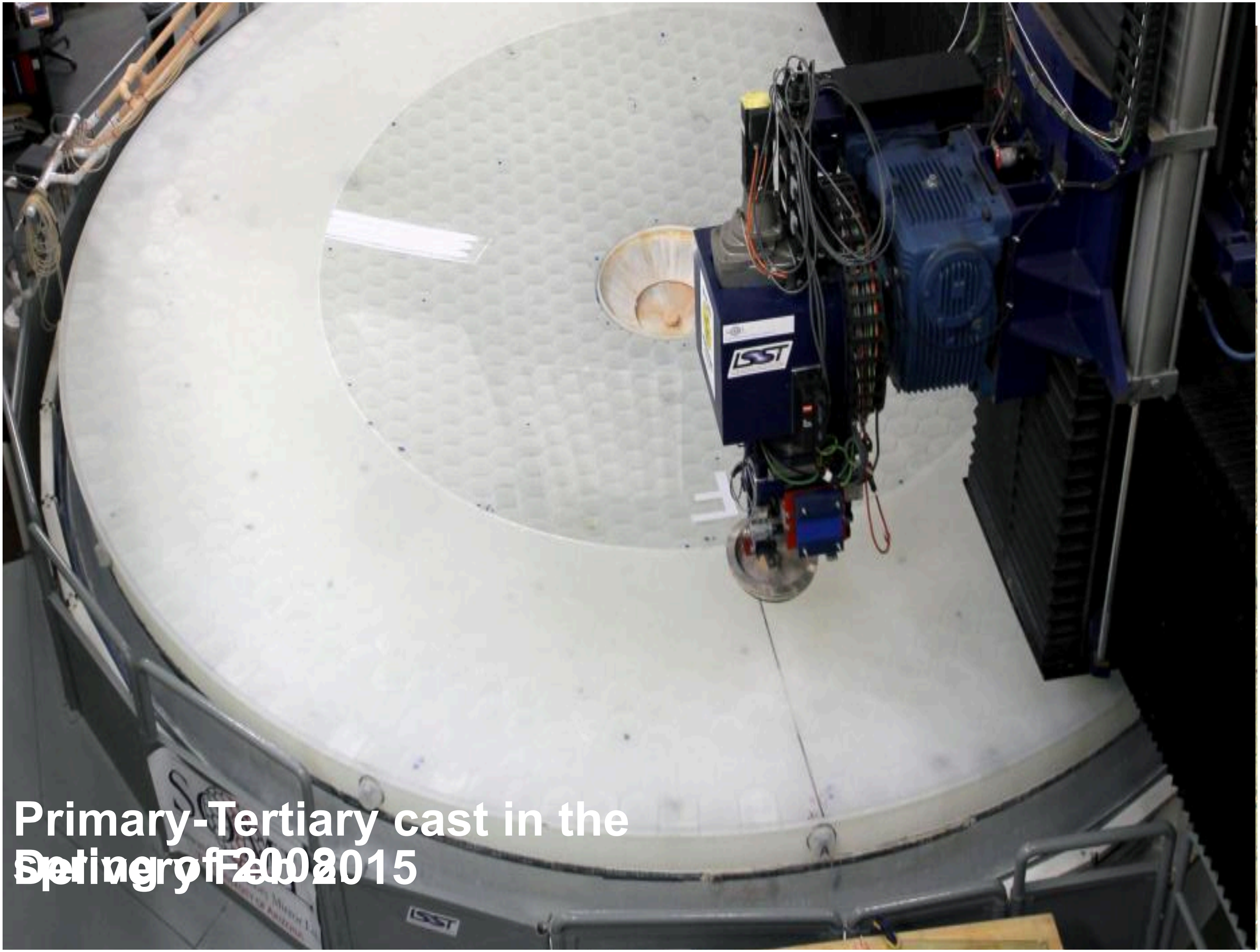
Facilities, and hardware to collect the light, control the survey, calibrate conditions, and support all LSST summit and base operations.

Optical design of the LSST





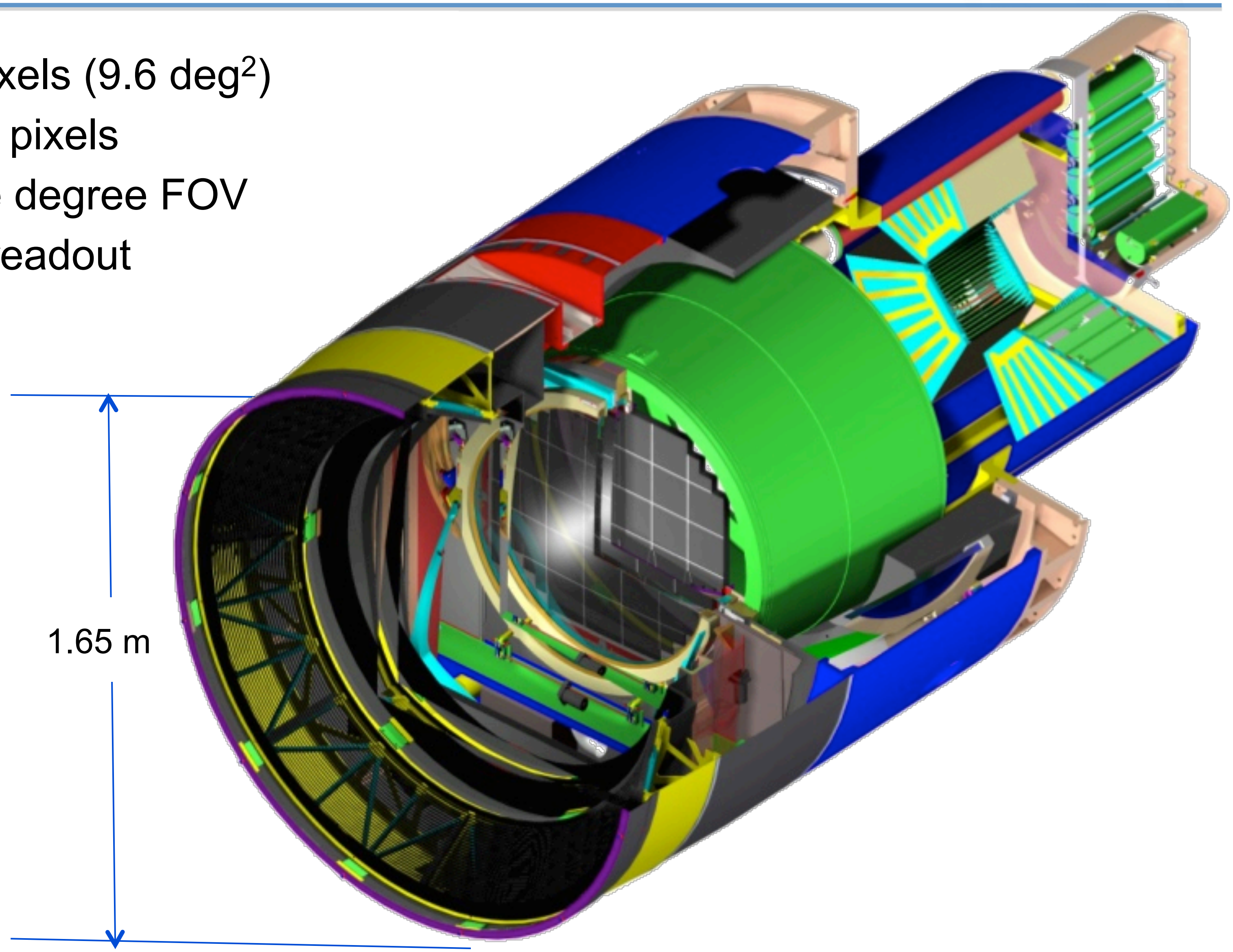
350 tons (60 tons optical system).Three-mirror design (modified Paul-Baker system) delivering 0.35 arcsec or better from the optical system and an etendue of 319 m^2 deg^2



Primary-Tertiary cast in the
Spring of 2008
Delivery Feb 2015

LSST camera: A 3.2 Gigapixel camera

- 3.2 Gigapixels (9.6 deg^2)
- 0.2 arcsec pixels
- 9.6 square degree FOV
- 2 second readout
- 6 filters



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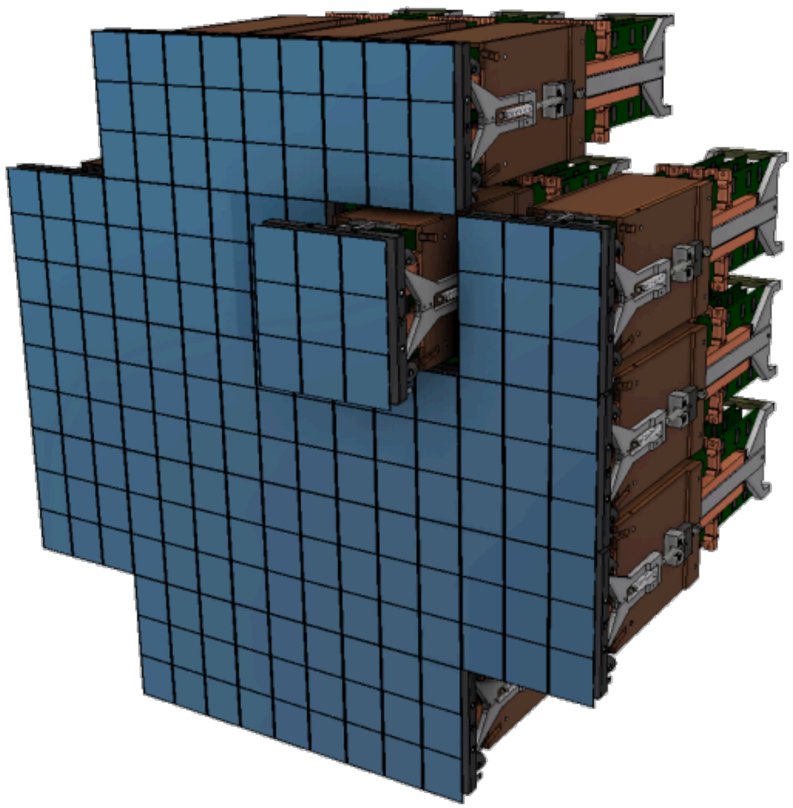
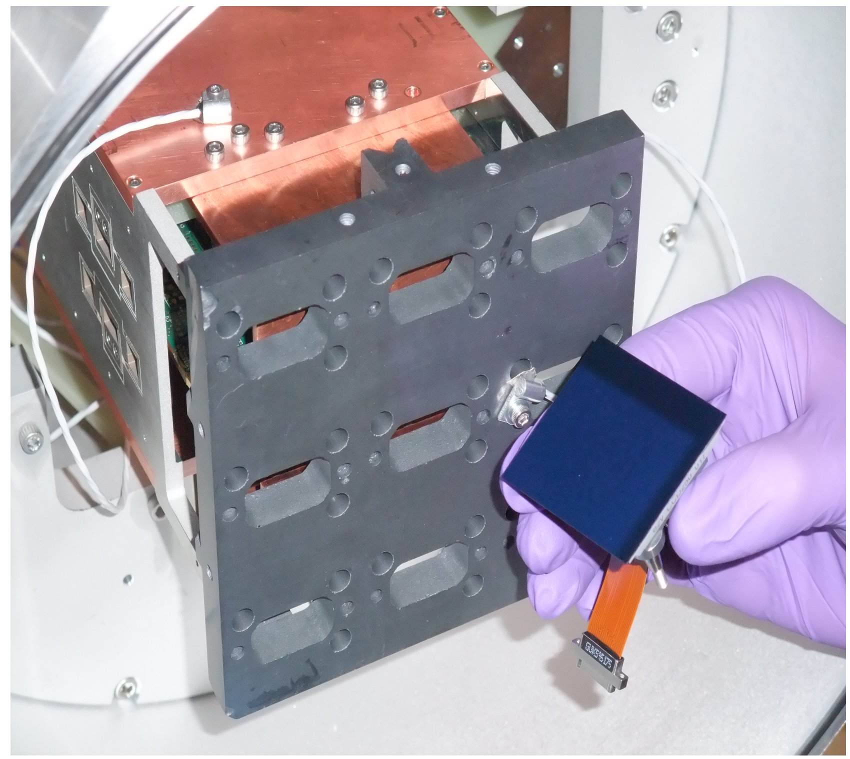
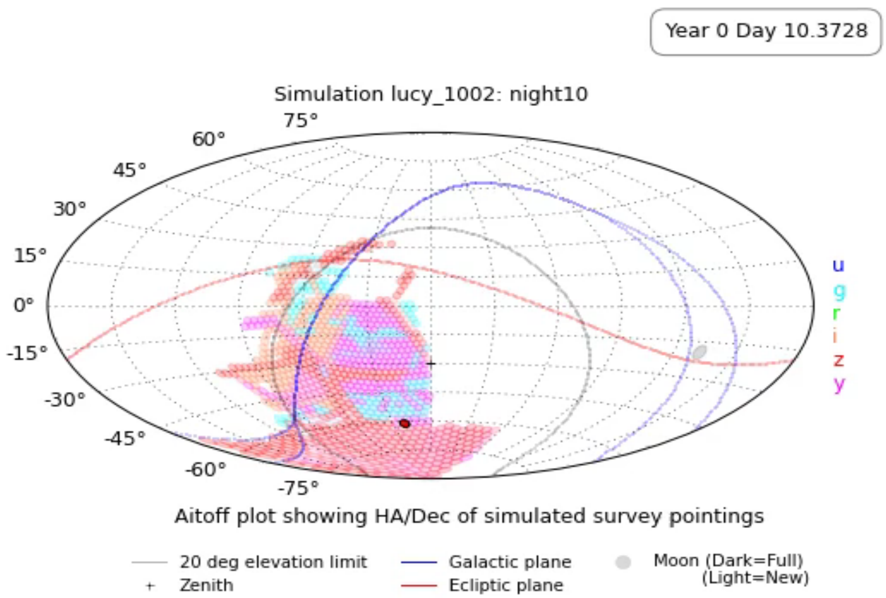
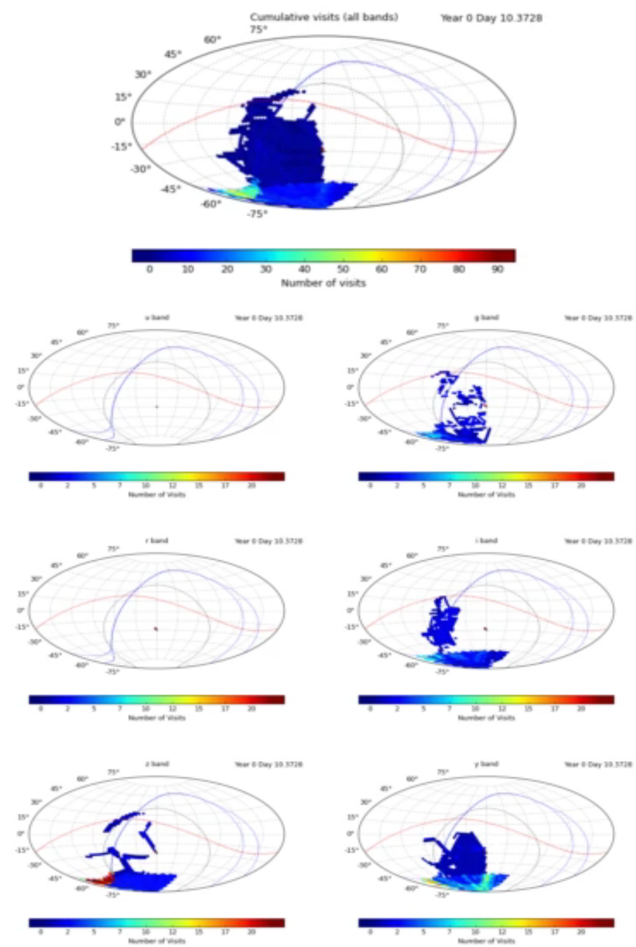




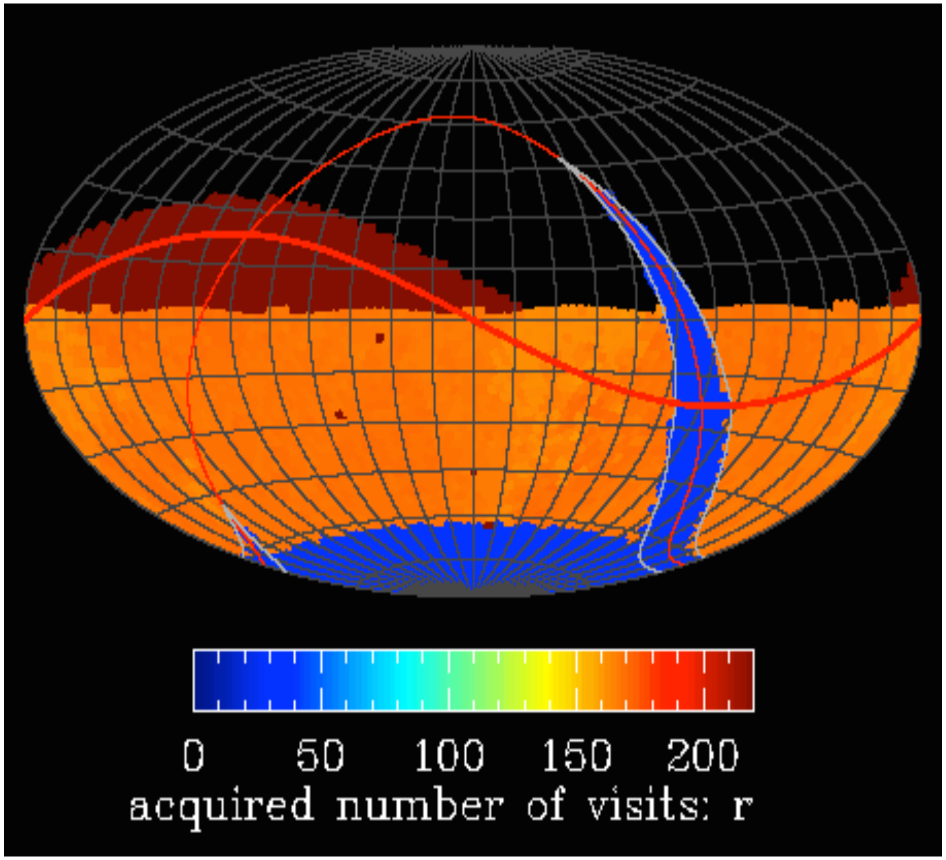
Modular design: 3200 Megapix = 189 x16 Megapix CCD
9 CCDs share electronics: raft (21=camera)
100 μm deep depletion devices (10 μm pixels)

Observing the sky





LSST footprint (825 visits per field)



Total Visits per unit area and Visits per filter (Main survey)

	u	g	r	i	z	y
Nb Visit	56	80	184	184	160	160
1 visit mag	23.9	25.0	24.7	24.0	23.3	22.1
10 year	26.1	27.4	27.5	26.8	26.1	24.9

90% of survey is 18,000 sq degree main survey
10% of survey is NES, SCP, Galactic plane, ***deep drilling fields***, others

LSST data volume and scientific yields

Raw Data

- Two 6.4-gigabyte images (one visit) every 39 seconds (15TB per night)
- ~1000 visits each night, ~300 nights a year
- Up to 450 calibration exposures per day

Level 1

- Can detect >10 million real time events per night, for 10 years
- Changes detected, transmitted, within 60 seconds of the observation

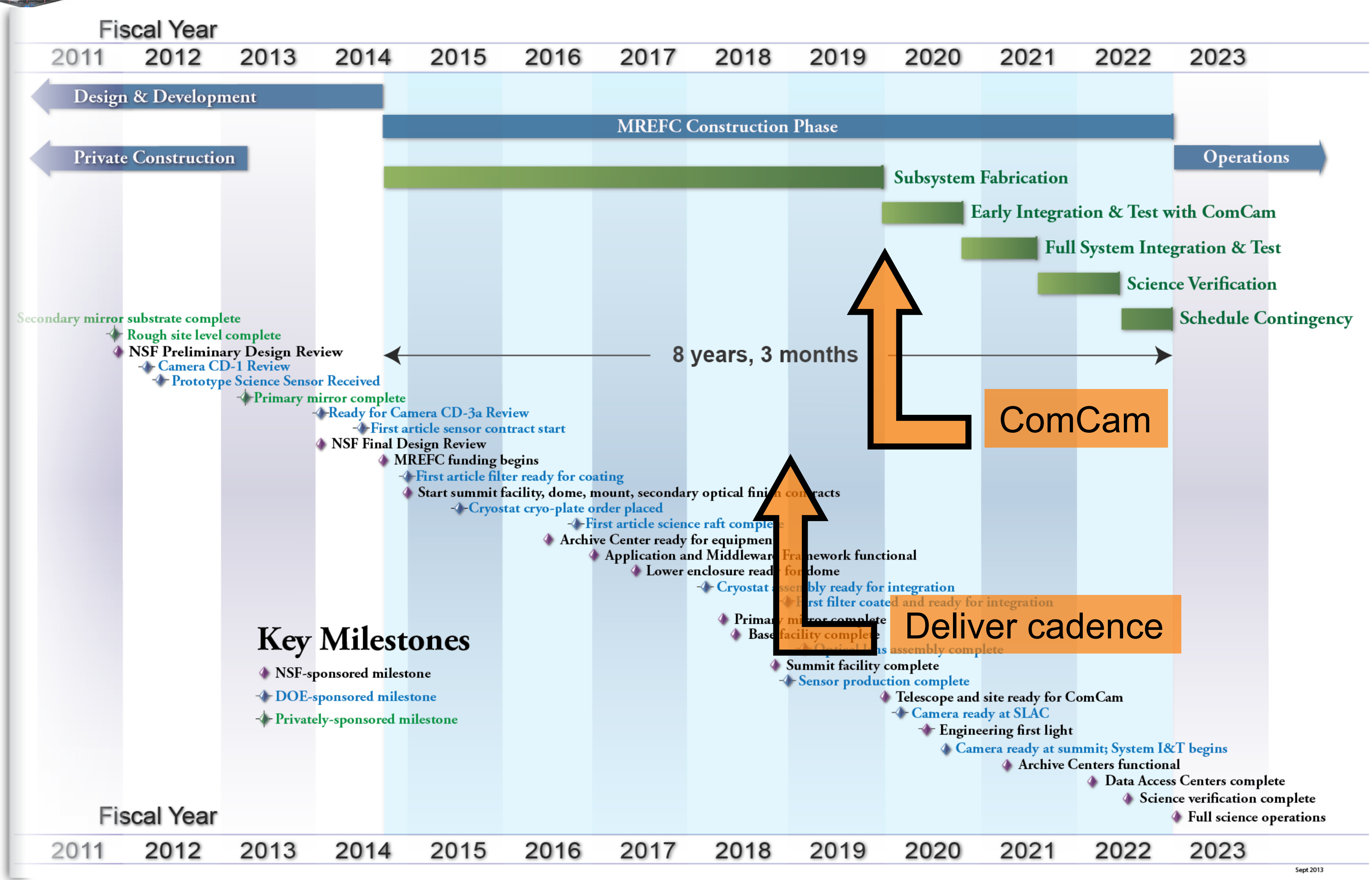
Level 2

- Observe ~38 billion objects (24B galaxies, 14B stars)
- Collect ~5 trillion observations ("sources") and ~32 trillion measurements ("forced sources") in a 20 PB catalog

Level 3

- User databases and workspaces ("mydb")
- Making the LSST software available to end-users
- Feeding the data back to the community

Construction and commissioning of LSST



Designing a Survey

- The main goal: to review important cadence constraints set by the Science Requirements Document, and to introduce and illustrate a few optimization goals and current "baseline survey"
  - Flow down of LSST science goals to LSST system requirements
  - SRD specifications for cadence
  - Cadence "conservation laws"
  - Hierarchy of survey complexity
  - Current baseline cadence
  - Progress towards survey goals
  - 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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Any given system parameter can have impact on numerous science programs

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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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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 properites

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

Science Requirements Document (SRD) Specifications for Cadence

- At the highest level, LSST objectives are:
  - 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)
  - Calibrate these images (and provide other metadata), with characteristics as specified in the SRD
  - Produce catalogs ("model parameters") of detected objects (37 billion), with characteristics as specified in the SRD
  - 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).

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.

Cadence "conservation laws"

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

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exposure time per visit, t_{vis}, single-visit depth, m_5, the mean revisit time, $t_{revisit}$, 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):

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

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

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

How to allocate the total observing time per position of ~7 hours to ugrizy, and how do we split allocations into individual visits?

Cadence "conservation laws"

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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)

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)!

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 main survey $\boxed{t_{vis} = 30 \text{ sec as default}}$

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

Hierarchical steps of survey complexity

1. **single band, single program, static science**

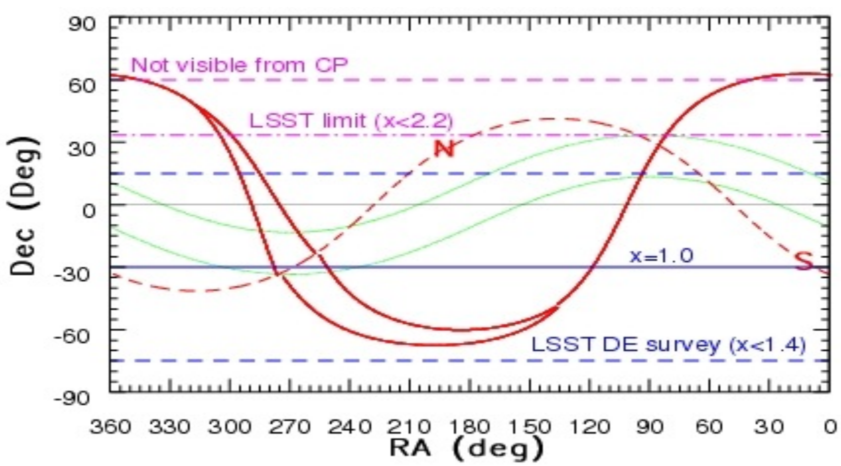
Goal: maximize the number of detected sources, e.g. galaxies.

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

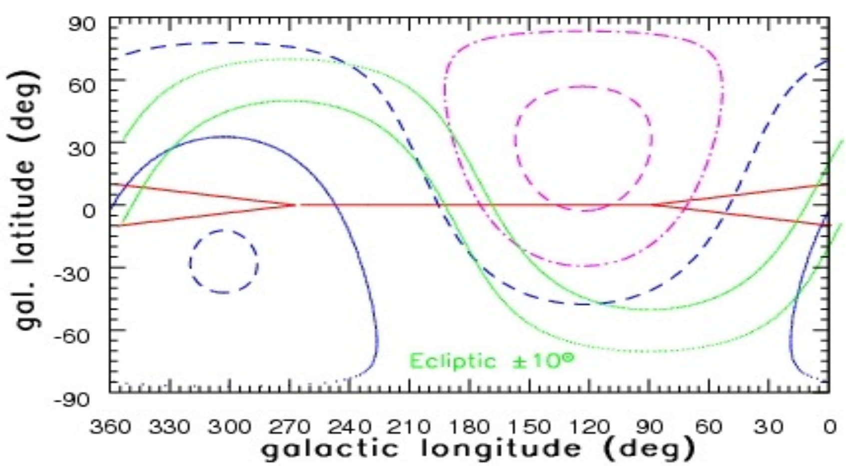
Detailed optimization takes into account airmass effects and Galactic plane: about 18,000-20,000 sq.deg. of sky

Hierarchical steps of survey complexity

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°

Note telescope can reach Dec = +40° (X=2.9)

Hierarchical steps of survey complexity

1. **single band, single program, static science**

...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)

Science drivers

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)

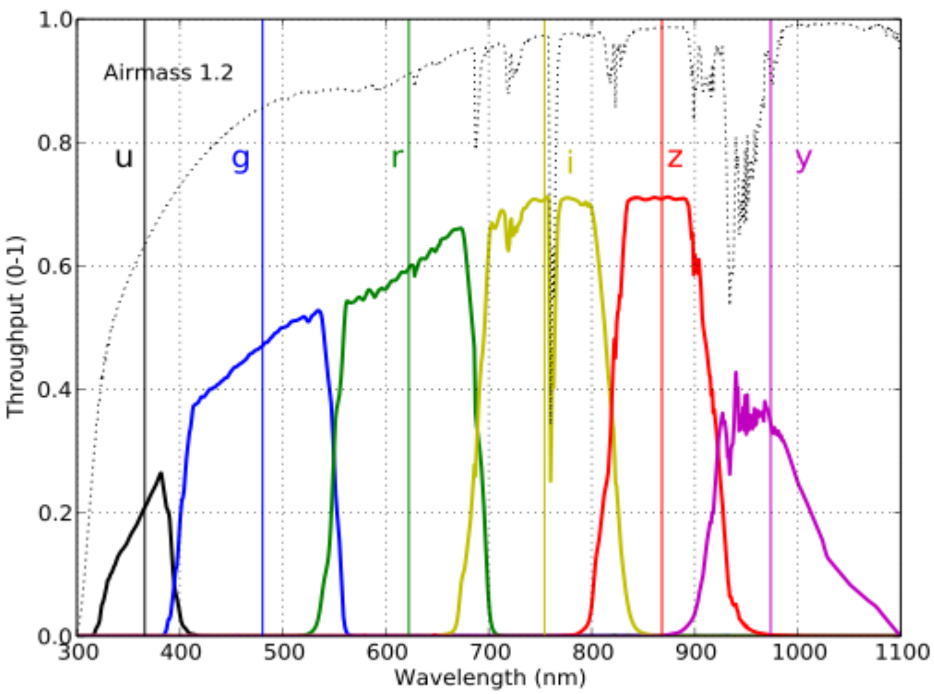


Photo-z requirements correspond to r~27.5 with the following per band time allocations:

u: 8%; g: 10%

r: 22%; i: 22%

z: 19%; y: 19%

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

Hierarchical steps of survey complexity

1. **single band, single program, static science**
2. **multi-bandpass data: ugrizy**

…. but 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”

Hierarchical steps of survey complexity

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

… 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)

Hierarchical steps of survey complexity

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

evolution over time

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

systematics

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

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

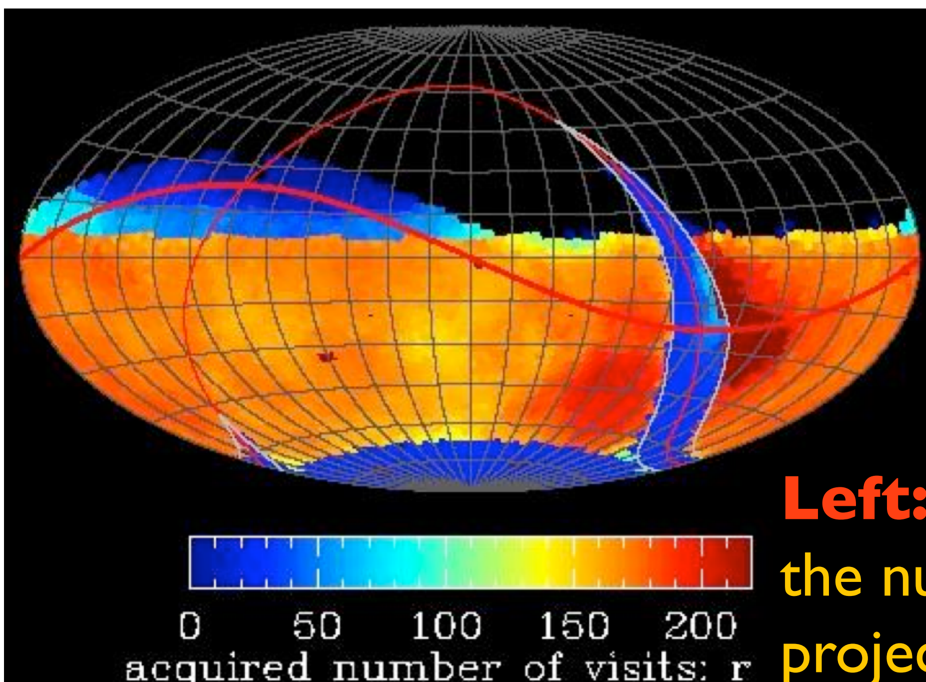
Valid for baseline cadence: t_{vis}=30 s

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:

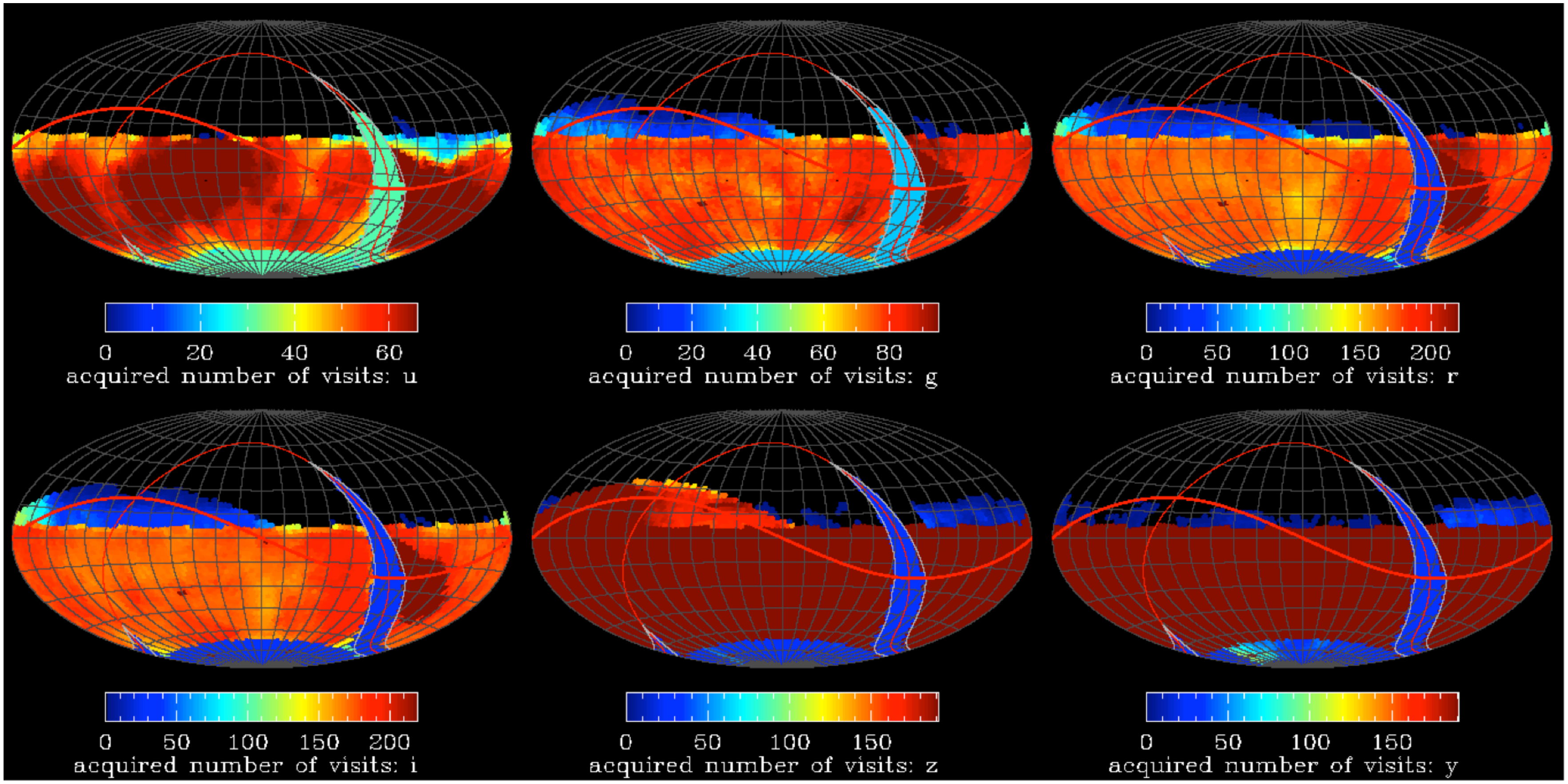
- observing starts/stops at 12 degree twilight
- CTIO 4m weather log as weather model
- telescope model and scheduled downtime for maintenance
- u filter in camera ~ 6 days per lunation
- utilizes 5 science proposals:
  - WideFastDeep: Universal Cadence
  - Galactic plane: collect 30 visits in each passband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



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)

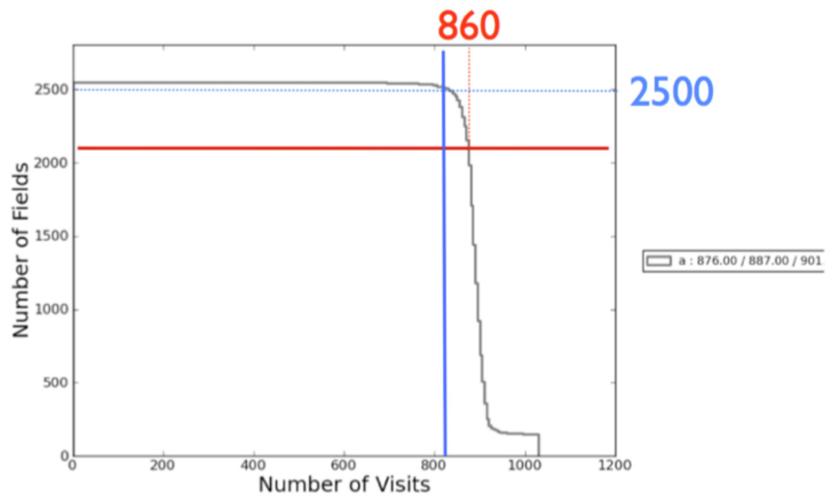


Figure 6: *(opsim3_61_cvisits_allfilters_all.png)* The cumulative distribution of Figure 4 showing the number of fields having visits $\geq x$. Only visits acquired by modes designed to meet the WFD number of visits are included. The inset box contains the values of the 25^{th}, 50^{th} (median), and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

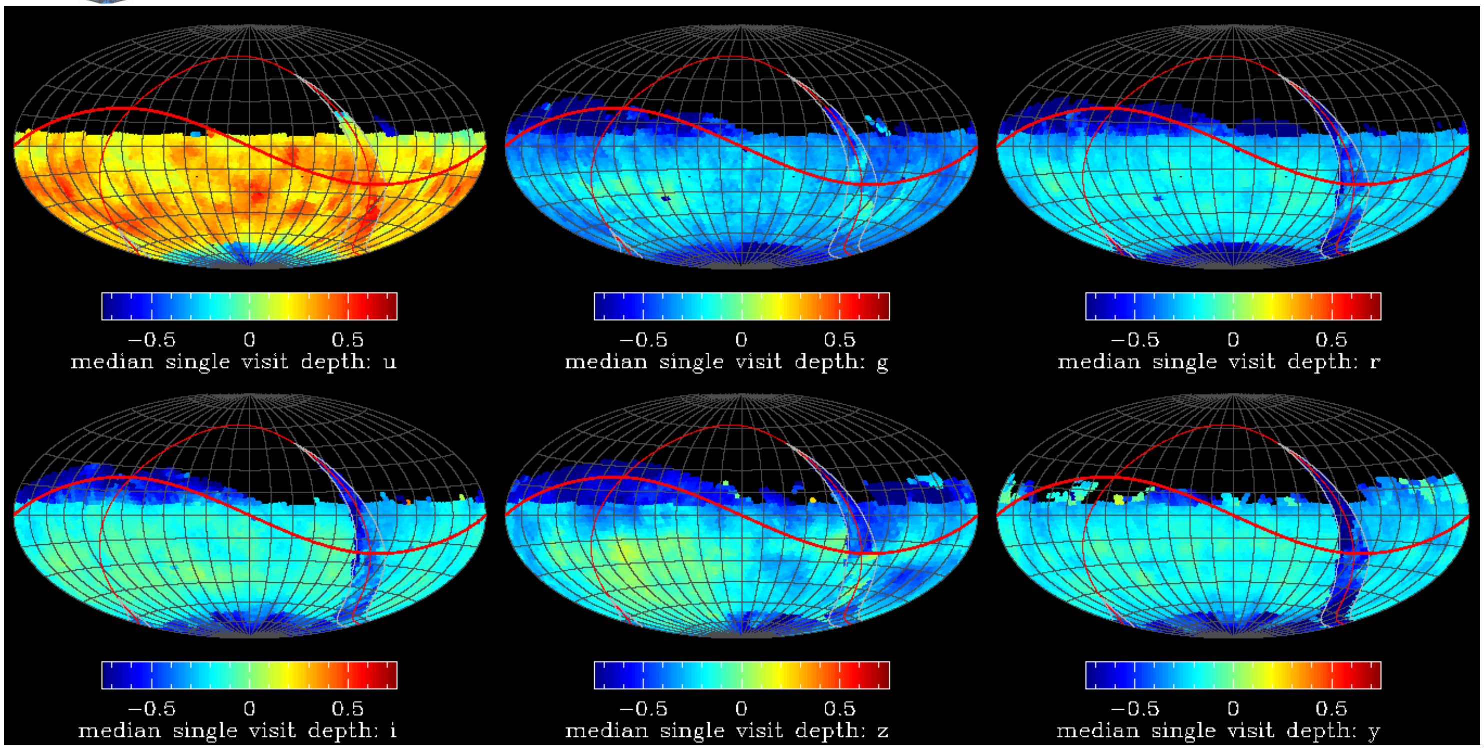
OpSim3.61 produced 2.65 million visits.

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

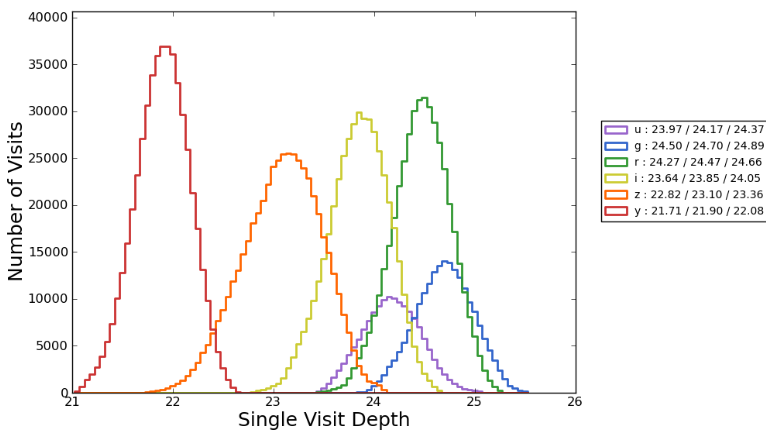
With the current baseline cadence, we have **a margin of ~18%.**

(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)

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.

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

Progress towards survey goals

Main performance metrics as functions of time (t):

Co-added survey depth:

$$m5(t) = m5Final + 1.25*\log(t\ /\ 10\ yr)$$

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 (FOMFinal ~750):

$$FOM(t) = FOMFinal * (t\ /\ 10\ yr)$$

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

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

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

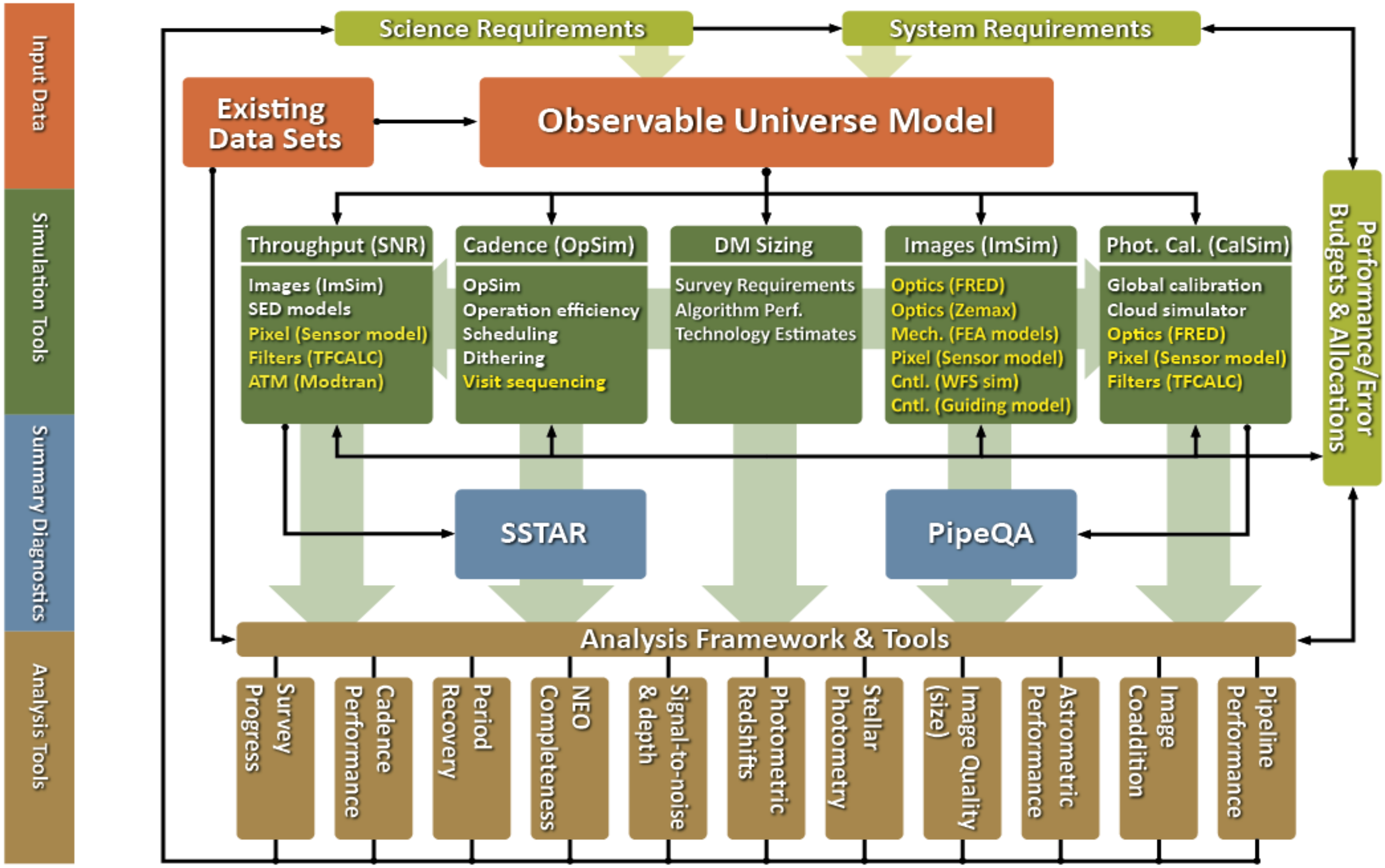
VARIOUS SCIENCE METRICS AS FUNCTIONS OF SURVEY DURATION.

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.

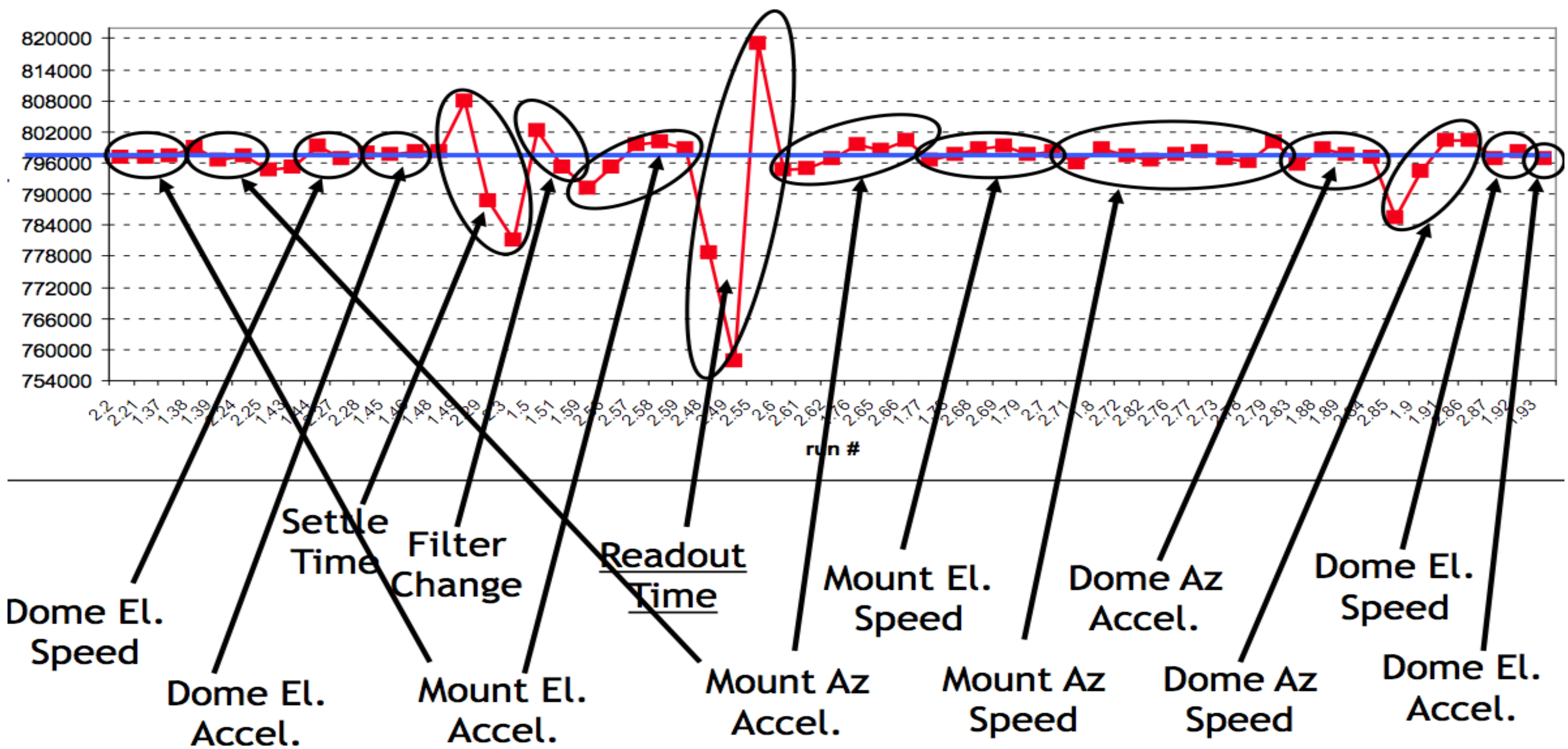
Tools for Simulations



Software is open source

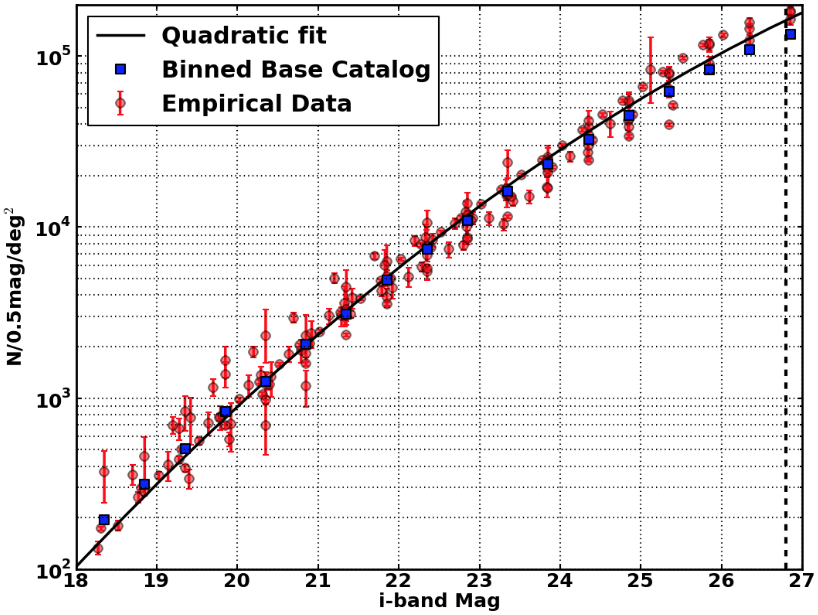
Engineering and science are integrated

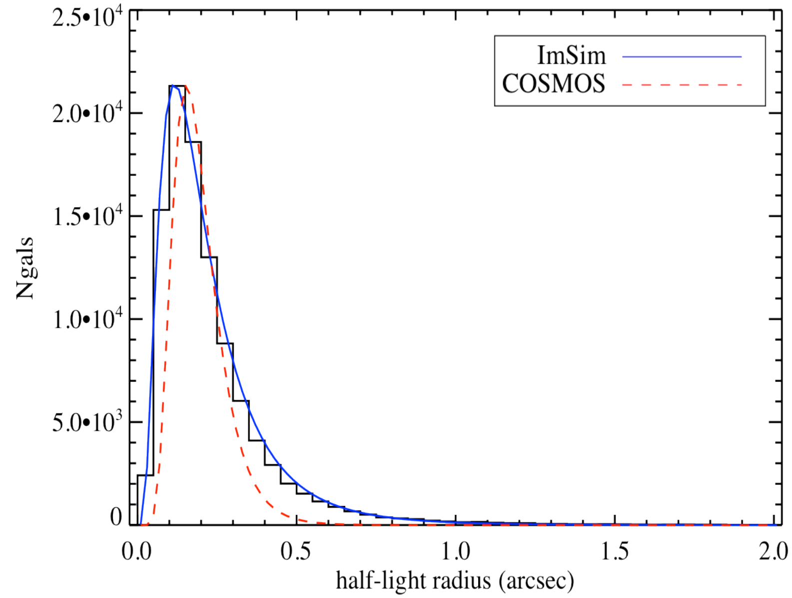
Run of the Cadence Simulator



The number of visits as a function of engineering properties

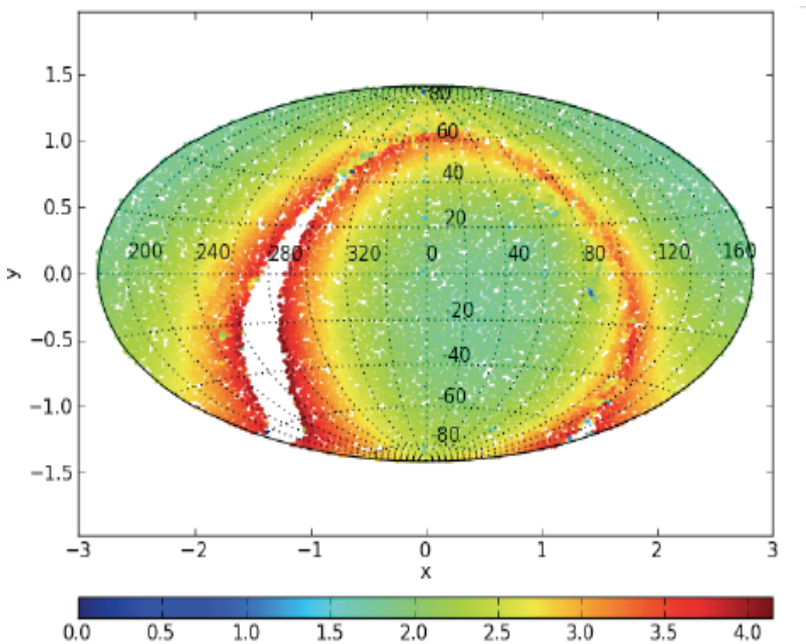
The LSST universe model (CatSim)

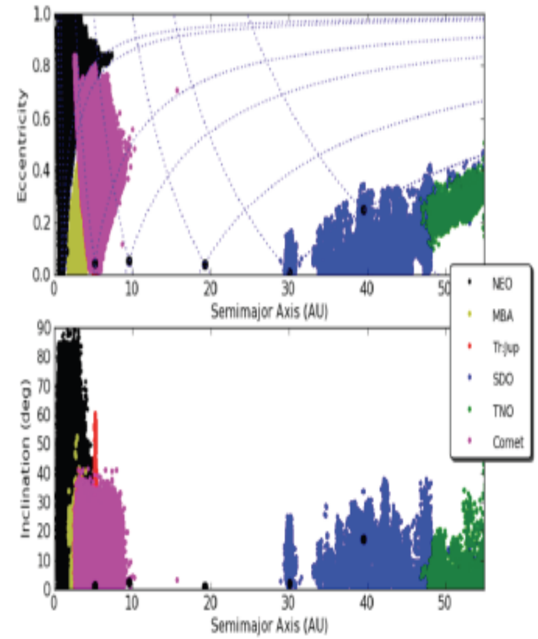




Source counts are based on simulations of the universe matched to observed densities and color of sources (reproduce the observed number counts, size distributions, and redshifts).

Galactic and Solar System





Galactic structure model

Main sequence, giants, dwarfs, Cepheids, micro-lensing…

Proper motion, parallax…

Juric et al (2008)

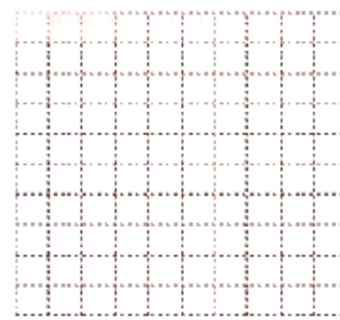
Solar system model

10 million main belt

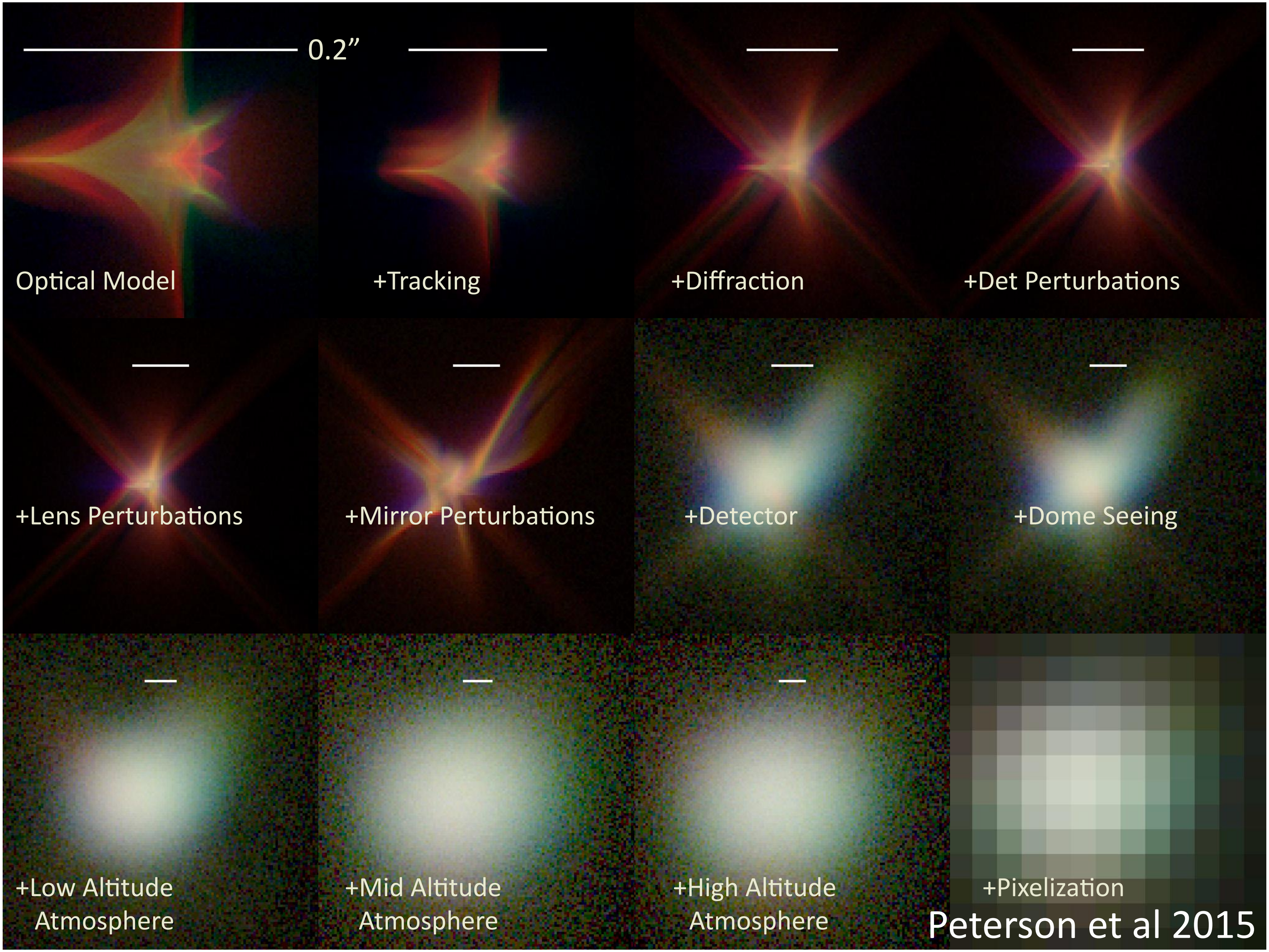
KBO, TNO, Trojans….

Grav et al (2007)

Following the photon flow to generate images



John Peterson 2010


0.2”
Optical Model
+Tracking
+Diffraction
+Det Perturbations
+Lens Perturbations
+Mirror Perturbations
+Detector
+Dome Seeing
+Low Altitude Atmosphere
+Mid Altitude Atmosphere
+High Altitude Atmosphere
+Pixelization
Peterson et al 2015

−4°54′48.0″
55′00.0″
12.0″
24.0″
36.0″
Dec (J2000)
49.00^s
48.00^s
47.00^s
0^{h}05^{m}46.00^s
RA (J2000)

3.2 Gigapixels

9.6 sq. degrees

20 million sources

10^{10} photons

12.8 Gbytes

1000 CPU hours