Implementation of the LSST operations simulator for testing observatory design, operations, observing cadences and delivery of LSST science

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Why develop the LSST Operations Simulator

- As we have seen there are distinct science goals for the LSST
  - –Cosmology-- probe dark energy and dark matter
  - –Potentially hazardous asteroids
  - –Inventory of the Solar System
  - –Supernovae for cosmology
  - –The transient universe
  - –Astrometry for proper motions and parallaxes
  - –Milky Way structure and stellar populations
- Opsim: a tool to investigate observing cadences and strategies
  - –Will one, or a few cadences suffice?
  - –Will proposed etendue deliver the science?
  - –Will proposed site allow needed coverage?
  - –Will proposed telescope carry out cadences?

Design Philosophy for Current Simulator

• Simulator developed to explore site suitability, telescope design parameters and science program interactions

• Simple algorithms for ranking potential observations
  – Must input parameters to determine ranking
  – Does not look ahead or explore multiple paths

• Must run 'quickly' to explore a large parameter space for science programs as well as telescope designs

• Coded in python for easy prototyping

• Path finder for scheduler which must schedule ~800 observations/night—there can be no human intervention

Current Operations Simulator

- Modular design
  - –Will accept multiple, distinct, observing programs
  - –Needs more sophisticated inter-program ranking algorithm
  - –Needs 'look ahead' and path optimization
- Reasonable sky model
  - –Sky brightness from Krisciunas and Schaeffer (1991)
  - –Needs better twilight model
  - –Astronomical objects tracked
- Sophisticated telescope model
  - –All motions parametrized
    - •Telescope, dome
    - •Maximum velocities
    - •Accelerations
    - •Optical alignment delays
- ~17,000 lines of python

Site, Telescope and Science Programs controlled by configuration parameters

Large Synoptic Survey Telescope

- Parametrized telescope/instrument model

- Site specific parameters in site configuration files
  - –Site specific weather and seeing
  - –Latitude, longitude, and altitude

- Rather than having simulator parse and interpret science goals, scientists must set parameter values which *may* meet those goals
  - –Sky brightness and seeing rules for filter use
  - –Cadences
  - –Areal coverage

- 100s of parameters in current configuration files

Lots of Configuration Files (3 broad categories)

- System configurations
  - SiteCP.conf
  - AstronomicalSky.conf
  - Filters.conf
  - Instrument.conf
  - schedDown.conf
  - unschedDown.conf
- Scheduler configurations
  - Scheduler.conf
  - SchedulingData.conf
- Survey configurations
  - LSST.conf
  - WItype proposals
    - Universal.conf, …
    - DeepDrilling.conf, …
  - WeakLensing proposals
    - GalaticPlane.conf, …

General parameters

```
######################################################################
########### Configuration for   LSST   ############################
######################################################################

#       Number of years to simulate.
#       Units = year; Format = float; Default = 1 year
nRun = 0.009    # about 3 days
#nRun = 0.08     # 1 lunation
#nRun = 1.0       # 1 year
#nRun = 1.3      # 1+ years

#       Days relative to seeingEpoch from which simulation commences
#       Units = MJD;    Format = float; Default == 0.0
simStartDay = 0.0       # start simulation with first year of Weather data
#simStartDay = 365.0    # start simulation with second year of Weather data

#       Field of View
#           Prepackaged FOV are in range: [3.0 : 4.0] in steps of .1
#           Additional FOV are easily installed on request.
#       Units = degree; Format = float; Default = 3.5
fov=3.5
        #  When using bundled fov, reset Scheduler:reuseRankCount to 1
        #fov = 13.0      # large hexagon simulating 19 hexagons for fov=3.0
```

Sophisticated Telescope Model

- Slew time calculations
  - All movements tracked: mount, dome, optics, rotator, cable wraps, filter change
  - Output can guide telescope engineering
- 50 parameters configure speeds, accelerations (no jerk), delays and limits
- Configurable table to determine sequence of movements for any given slew

Simulator is being used to optimize telescope design

- Vary telescope parameters and determine effect on science
- Tests using survey parameters from fiducial simulation have probed:
  - 4 dome altitude maximum velocity
  - 5 dome altitude acceleration/decelerations
  - 6 telescope altitude acceleration/decelerations
  - 6 telescope azimuth acceleration/decelerations
  - 3 filter change times
  - 3 settle after slew delays
  - 3 camera readout times
  - 4 telescope cable wrap zero points

Proposals implement science programs

• Proposals are the SW objects in charge of offering a list of ranked targets to the observation scheduler at each observing opportunity.

• Several proposals can run simultaneously.

• Each proposal ranks its targets dynamically, according to its own history of granted observations and the current external conditions.

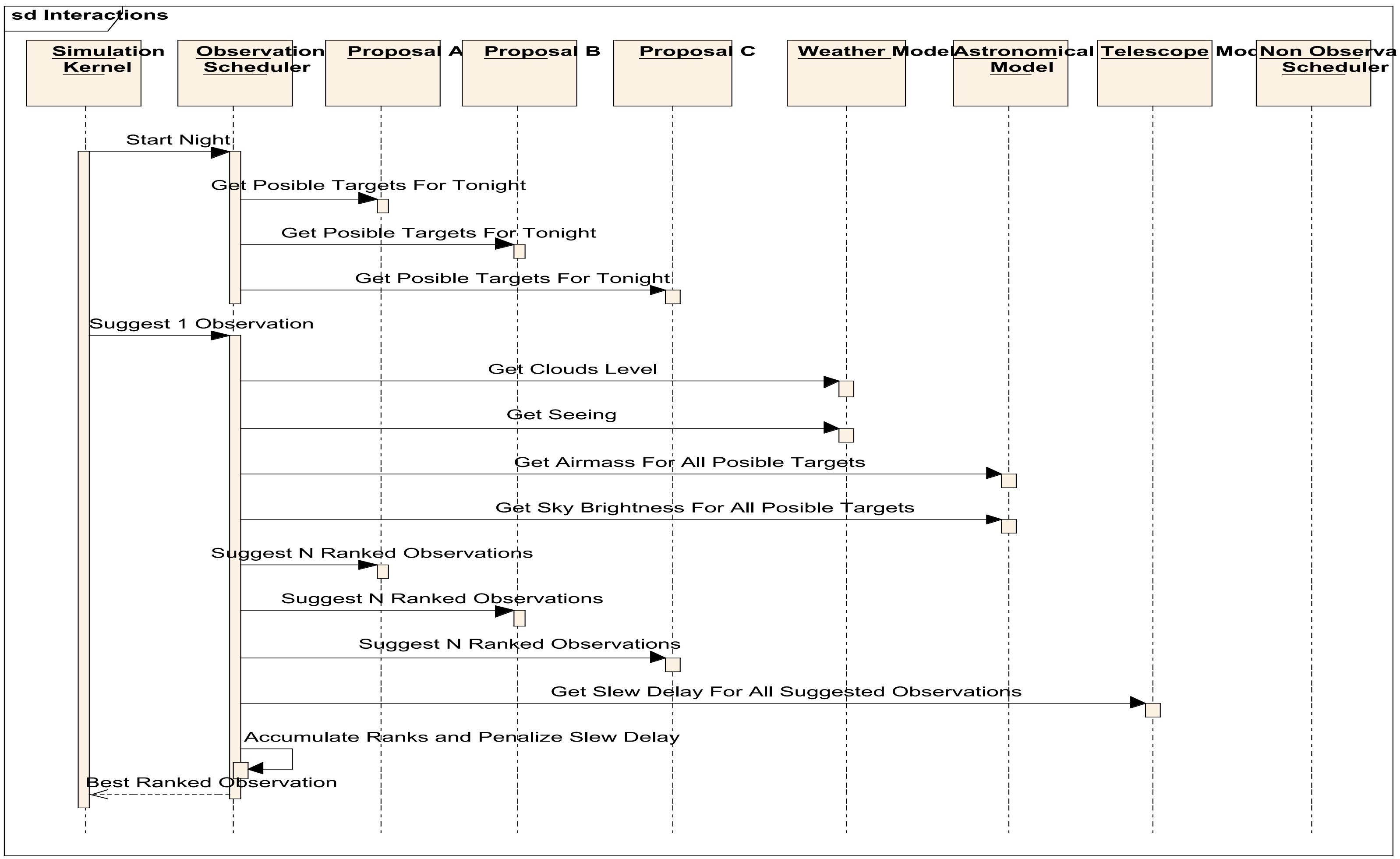
• The rank values follow a unique scale for fair comparison between all the targets among the proposals. 0.0 means no observation required and so none are proposed, 0.1 is an average level, and 1.0 means very important or very urgent.

• Configurable parameters used for building the list of targets and computing the rankings include sky regions, filter requirements, seeing air mass and sky brightness limits, time intervals for repeating fields, etc.

Current Science Programs

- Two classes of science programs implemented
  - Can run one or both, and multiple instances of each
  - Deep Cosmology coverage (WeakLensing)
    - total visits per field/filter combination
  - Time based proposals
    - Simple to complex cadence with simple filter requirements
    - Complex, independent, cadences for multiple filters
    - Multiple sequences with multiple sub-sequences
    - Universal Cadence (special subset of time based proposal)
      - Specified total number of visits collected in 30 minute pairs
- Ranking of fields within a program based upon program parameters
- Ranking of fields between programs currently simplistic
  - Simple priority factor for each program
  - Slew time to field is a significant factor
- Images taken as pairs of 15 seconds exposures termed a ‘visit.’
- Proposals can set limits on airmass, seeing, sky brightness
- Seeing is corrected for wavelength and airmass from V band zenith values.

Scheduling Observations



Simulator produces lots of data

- ~2,500,000 observations in a 10 year run
- 37 relevant parameters stored for each observation in a MySql database table
- Every telescope component activity, dependency and ranking activity is stored in multiple MySql database tables
- Need post processing to understand the science potential-- adds 8 parameters per observation, e.g. proposal information, 5 sigma depth, dither offsets, etc

Simulator operations

- Simulator can be installed on linux and Mac OS–can be installed via LSST eups
- Sky tiling pre-calculated and in database--single set of field centers
- Weather and seeing in database
- All details of simulation saved in database
  - –Configuration parameters
  - –each observation saved in database
- 1 year simulation in about 3-6 hours (disk speed)
  - –Configurable number of fields to nominate from each proposal
  - –Configurable caching of selected nominees

The Operations Simulator attempts to answer whether multiple science goals can be met.

- Primary survey area (18,000 square degrees) sampled with universal cadence to deliver Wide Fast Deep survey for cosmology and Milky Way studies, ~30 minute pairs for Near Earth Objects, temporal sampling for transients, supernovae (currently being optimized via 'rolling cadences')
- Smaller areas devoted to
  - Deep supernovae and Kuiper Belt Objects
  - North ecliptic plane for NEOs
  - Milky Way plane for stellar studies
  - South Celestial cap for transients, stellar pops and Magellanic Clouds

A 'Fiducial' run: opsim3.61

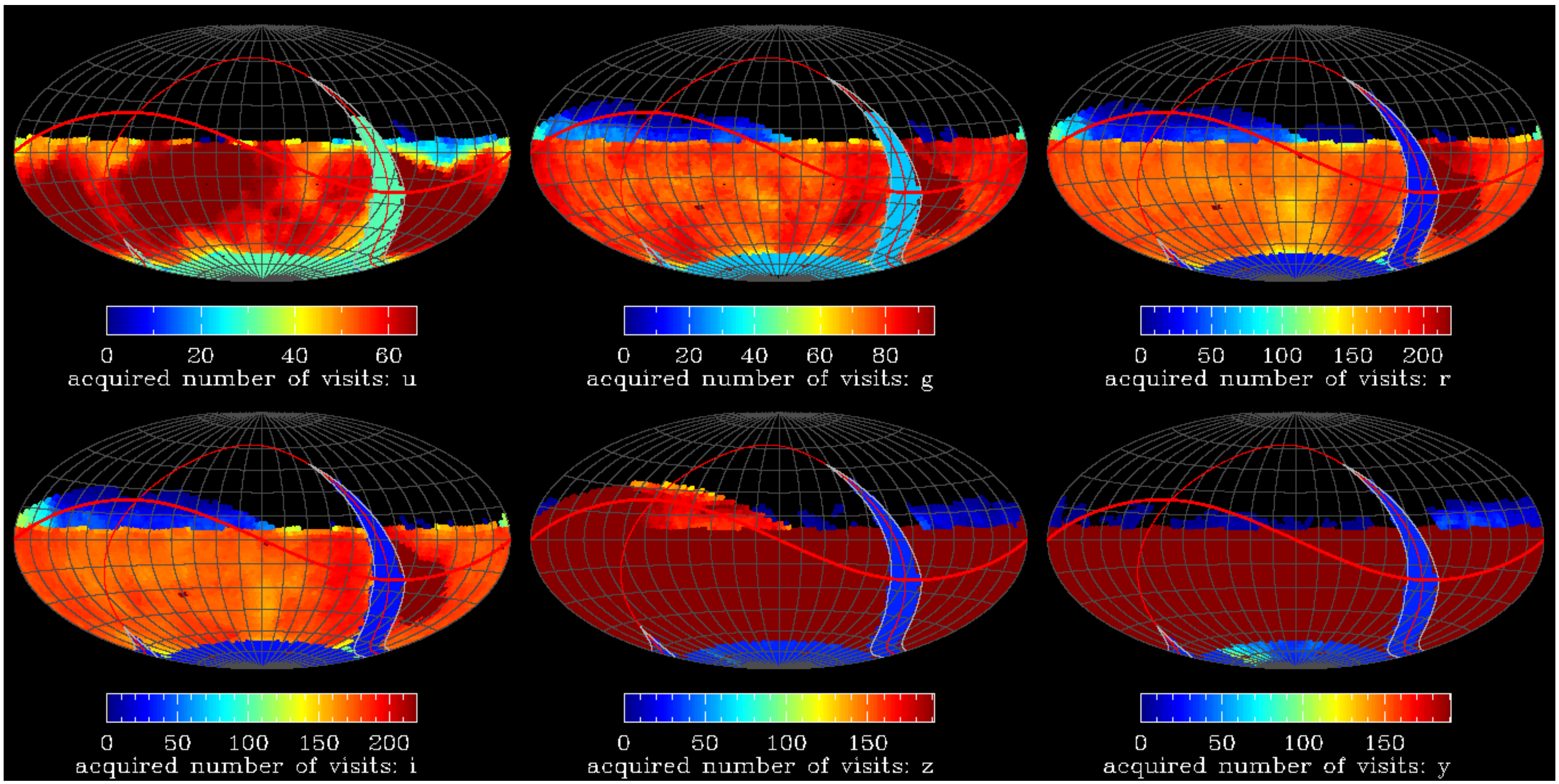
- 10 year simulation
- Observing starts/stops at 12 degree twilight
- CTIO 4-m weather log, octants clear
- Observe when more than 3/8ths clear
- Scheduled downtime for maintenance
- u filter in camera ~ 6 days per lunation
- Five science proposals
  - WideFastDeep (WFD): collect needed number of exposures for deep cosmology etc, but in pairs of visits separated by ~ 30 min.
  - Univeral 'north:' collecting pairs along northern ecliptic
  - Galactic: collect 30 visits in each filter
  - South Pole: collect 30 visits in each filter
  - 6 fields of 'deep' supernova sampling
    - 100 day sequence
    - Every 5 days
    - 5 filters 5,10,10,10,10 minutes in grizy

Summary of telescope activity for opsim 3.61

- number of nights: 3650
- number of exposures: 2651588
- exposures/night: 726.5
- average exposure time: 34.00s
- average slew time: 6.40s
- number of stopped initial telescope positions: 3421
- statistics for angle TelAlt: min= 17.5d max= 86.5d avg= 54.3d std= 12.0d
- statistics for angle TelAz: min=-270.0d max= 270.0d avg= -29.2d std=118.1d
- statistics for angle RotPos: min= -90.0d max= 90.0d avg= -5.2d std= 50.3d
- DomAlt: active= 93.3% of slews, active avg= 3.01s, total avg= 2.81s, max= 37.89s, in critical path= 1.7% with avg= 8.77s
- DomAz: active= 14.6% of slews, active avg= 7.23s, total avg= 1.06s, max=119.50s, in critical path= 4.0% with avg= 16.44s
- TelAlt: active= 93.3% of slews, active avg= 1.51s, total avg= 1.41s, max= 18.95s, in critical path= 39.3% with avg= 1.75s
- TelAz: active= 93.3% of slews, active avg= 1.71s, total avg= 1.60s, max= 52.17s, in critical path= 47.7% with avg= 1.72s
- Rotator: active= 0.9% of slews, active avg= 13.30s, total avg= 0.12s, max= 29.21s, in critical path= 0.0% with avg= 0.00s
- Filter: active= 0.9% of slews, active avg=120.00s, total avg= 1.02s, max=120.00s, in critical path= 0.9% with avg=120.00s
- TelOpticsOL: active= 93.3% of slews, active avg= 0.65s, total avg= 0.61s, max= 17.95s, in critical path= 0.0% with avg= 4.58s
- Readout: active= 99.9% of slews, active avg= 2.00s, total avg= 2.00s, max= 2.00s, in critical path= 6.3% with avg= 2.00s
- Settle: active= 93.3% of slews, active avg= 3.00s, total avg= 2.80s, max= 3.00s, in critical path= 87.0% with avg= 3.00s
- TelOpticsCL: active= 1.6% of slews, active avg= 20.00s, total avg= 0.32s, max= 20.00s, in critical path= 1.6% with avg= 20.00s
- slew maximum speed for DomAlt: avg=1.14d/s, max=1.75d/s in 8.8% of slews
- slew maximum speed for DomAz: avg=0.16d/s, max=1.50d/s in 7.1% of slews
- slew maximum speed for TelAlt: avg=2.28d/s, max=3.50d/s in 8.8% of slews
- slew maximum speed for TelAz: avg=4.89d/s, max=7.00d/s in 12.3% of slews
- slew maximum speed for Rot: avg=0.03d/s, max=3.50d/s in 0.7% of slews

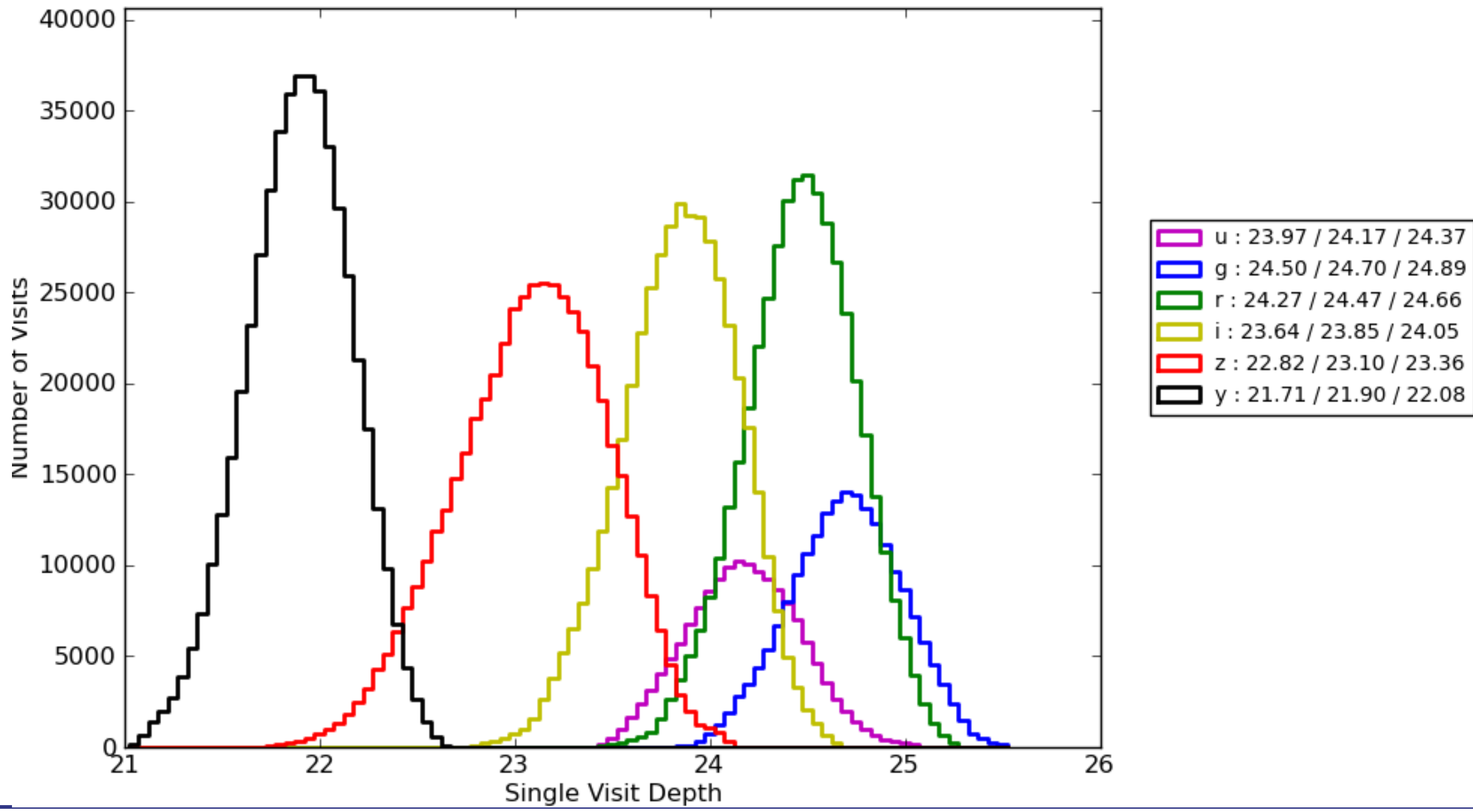
Opsim 3.61 visit distribution on the sky

- The number of visits acquired for each field is plotted in Aitoff projection for each fiter. All visits acquired by all observing modes are included in this plot.



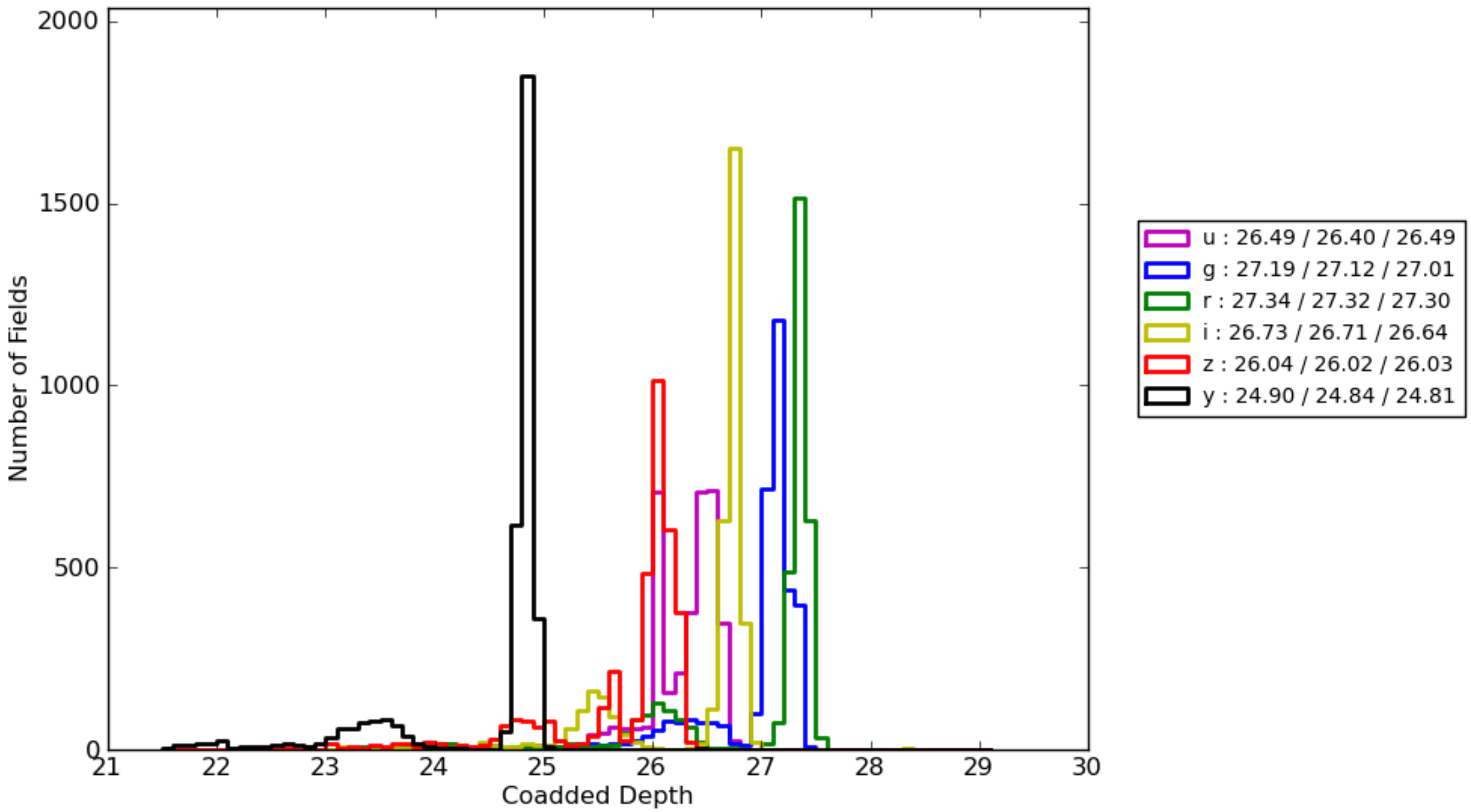
Single visit 5 sigma limiting magnitude

- The side box contains the values of the 25th, 50th (median), and 75th percentiles for each curve. The Simulator has limits for sky brightness and seeing conditions for each filter in each observing cadence. These limits result in the relatively tight distributions of limiting magnitudes for each filter .



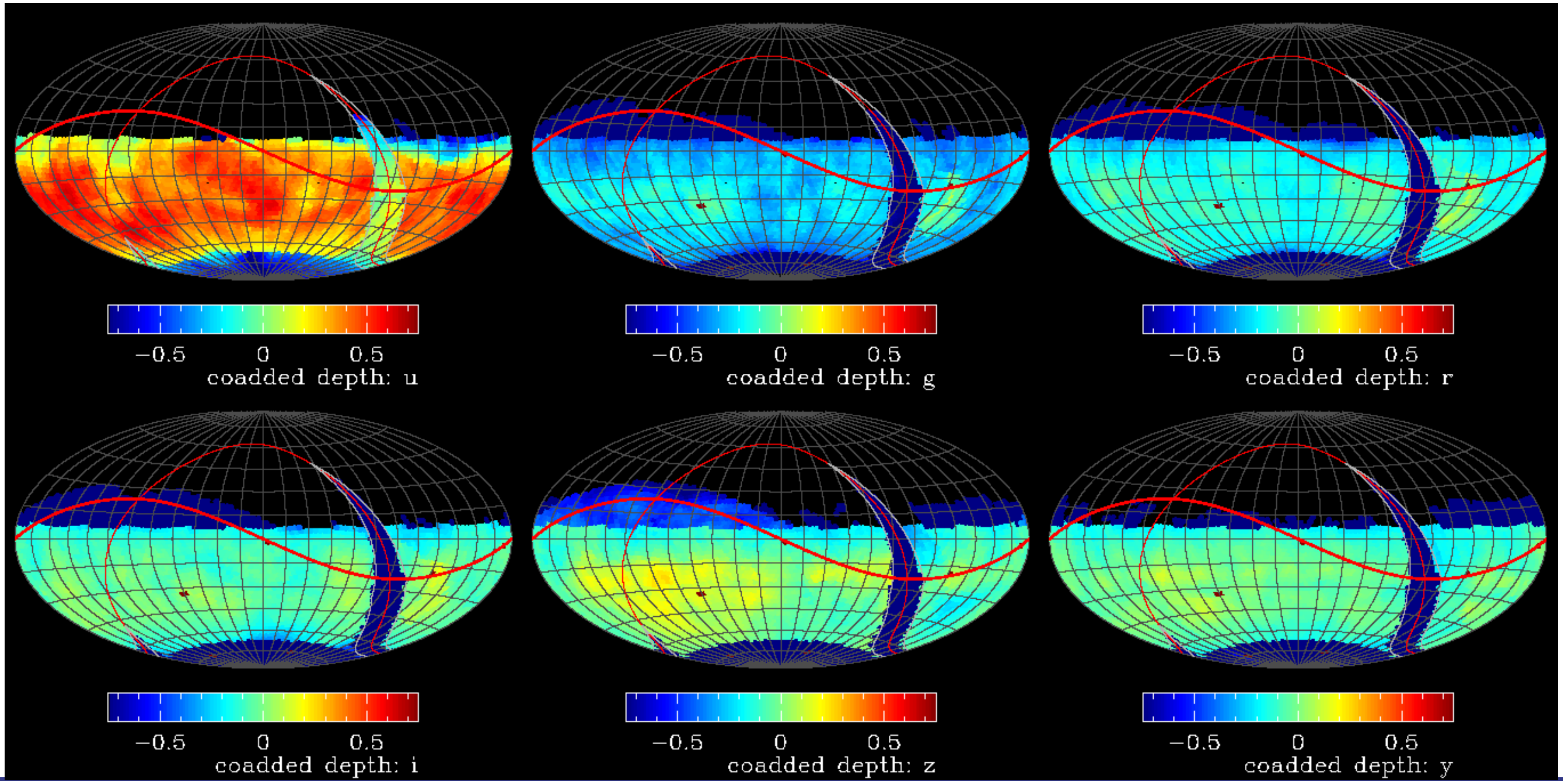
Coadded depth for the WideFastDeep fields

- The distribution of fields with coadded depth in each filter. Only visits acquired by observing modes designed to meet the WFD number of visits are included. The inset box contains the values of the 25th , 50th (median), and 75th percentiles for each curve.

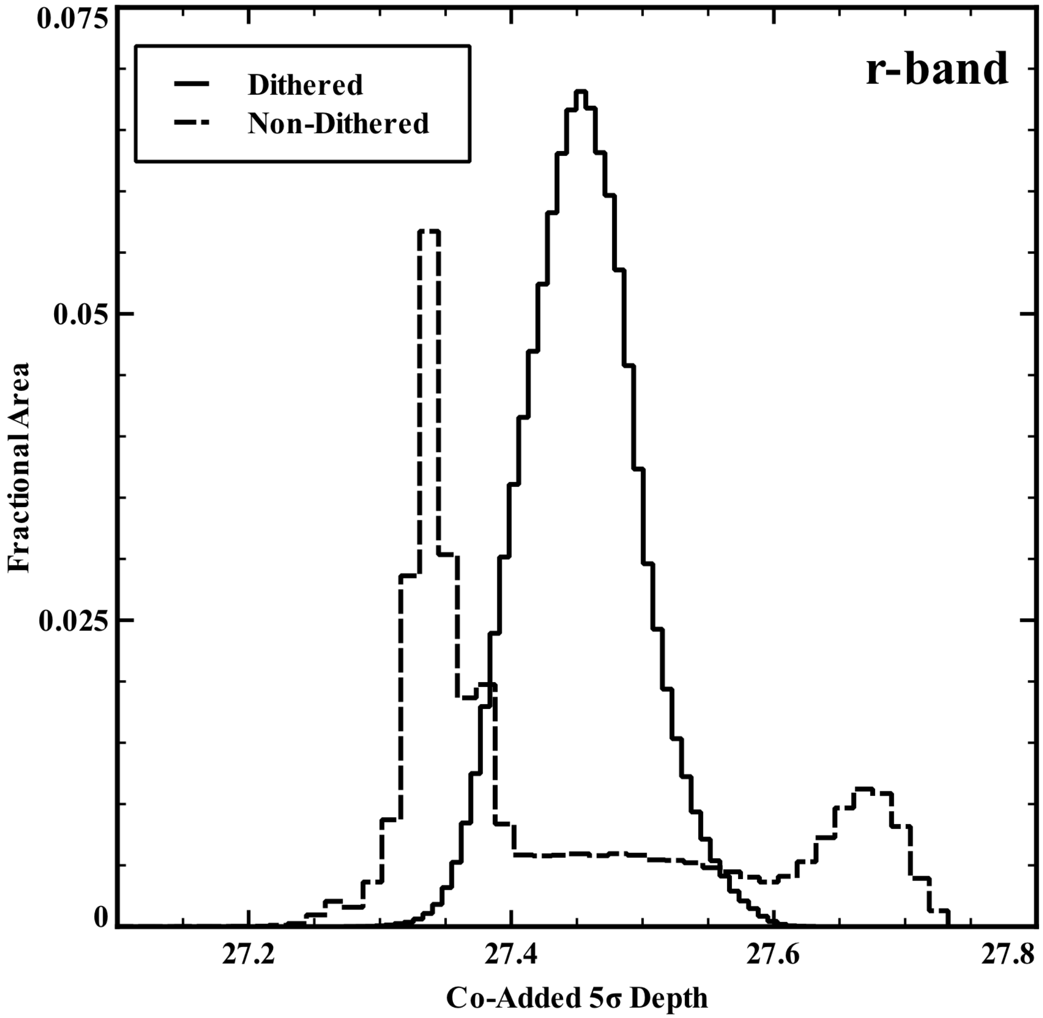


Full survey coadded depth

- The WFD design spec is used as a fiducial and the difference between it and the coadded depth for each field is plotted in Aitoff projection for each filter. Fields with positive values have a coadded depth deeper than the WFD zenith value. Visits acquired by all observing modes are included in this plot and are not limited only to observing designed to meet the WFD number of visits.



Dithering will smooth coadded depth



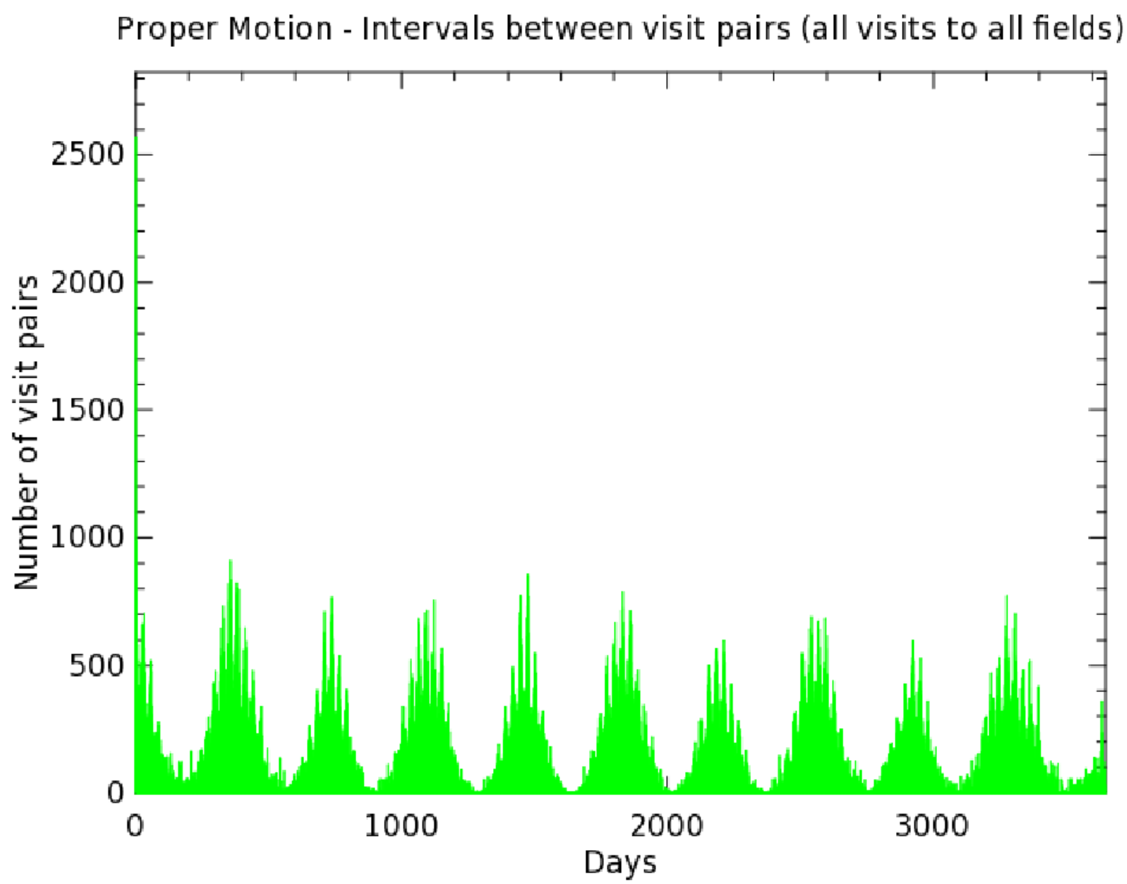
The current Operations Simulator assumes each visit is taken with the field centers placed onto a fixed grid of an optimally packed tessellation. This strategy gives a variation of the effective depth across the sky, as shown in the dashed line in the figure. Using a simple dithering pattern based on a triangular tessellation of the inscribed hexagon, we have shown that the co-added 5 sigma depth is significantly increased relative to the non-dithered cadence. The distribution of depth values is also much smoother, and well behaved in the dithered case.

WFD cadence recovers periods well

A light curve is constructed from an average Delta Scuti light curve's Fourier coefficients with an arbitrary mean and amplitude. The measurement errors are drawn from a Gaussian distribution with a mean of amplitude/Signal to Noise of 7 and a phase from a flat distribution of phases. The curve is sampled using r-band observations from fields in the wide, fast, deep cadence in the baseline survey, and analyzed with the cleanest algorithm. Periods range from 0.1 to 1000 days. The period is considered recovered if found within the listed tolerance. The cadence does well except for a 1 day alias.

Period	%Recovered	Period Tolerance
0.1 day	100%	$< 1\times10^{-5}$
1.0 day	50%	2×10^{-5}
10 day	100%	2×10^{-4}
100 day	100%	2×10^{-3}
1000 day	70%	2×10^{-2}

Opsim 3.61 delivers good astrometric sampling



The sampling delivers multiple long baselines for proper motion determination.
The sampling also delivers good parallax factors for most fields.

Opsim 3.61 summary

- SSTAR uses LSST ETC to estimate depths from number of visits.
- 2,651,588 total visits,
- 20,000 square degrees: 75% in Universal (DeepWideFast)
  - u 24.2, g 24.7, r 24.5, i 23.9, z 23.1, y 21.9
  - 656,687 pairs of griz with 15-60 minute separation
  - ~ 6 pairs per field per lunation
- 4,000 square degrees of northern ecliptic (12%)
  - 41,774 pairs of griz with 15-60 minute separation
  - ~ 2 pair per field per lunation
- 1,900 square degrees of Galactic Bulge/Plane (7%)
  - 30 visits in ugrizy each
- 1,300 square degrees of south celestial pole (6%)
  - 30 visits in ugrizy each
- 23 perfect deep 100 day supernova sequences, 170 incomplete
- Excellent period recovery for periodic variables

We need a new baseline cadence

We need a replacement for the current baseline cadence (opsim3.61) produced with the new (v3.0+) version of OpSim code

First try: opsimblitz2.1035

-2.47 million visits (2.65 in opsim3.61); OK

-mean slew time: 7.0 sec; OK

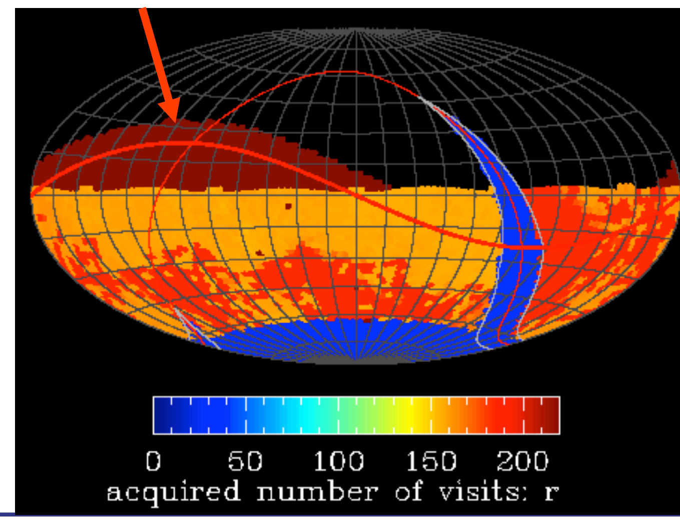
-For WFD: the mean number of visits is 95% of the SRD design value

-satisfactory airmass distribution

-problem: as much as 16% of time spent on North Ecliptic Spur (NES)

-1035 has design area and design visits

-3.61 has stretch area and stretch visits



It is unlikely that opsimblitz2.1035 will replace opsim3.61. We are continuing to vary parameters and have ~6 good candidates without rolling cadences.

Rolling Cadences

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

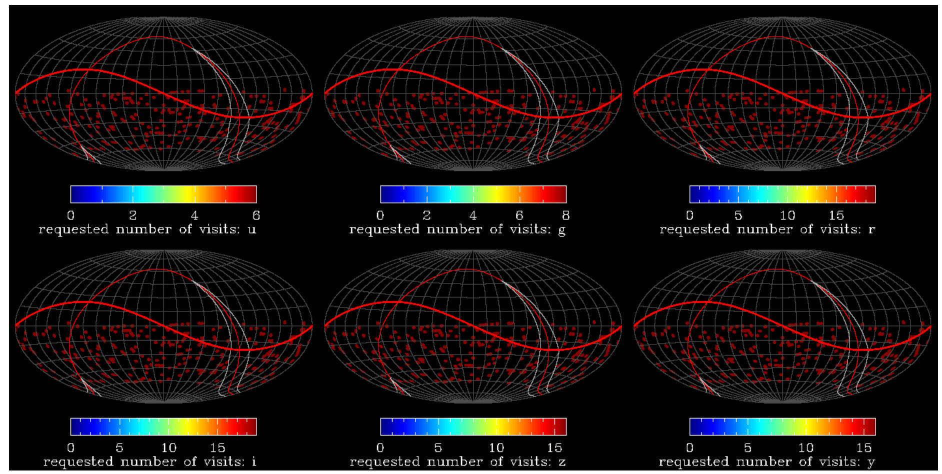
- The seemingly straightforward rolling cadence of defining RA and Dec limits for a more densely sampled survey over some portion of the total survey, yielded 3 subtle bugs in the operation simulator. All of these have been fixed as of late last week.

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

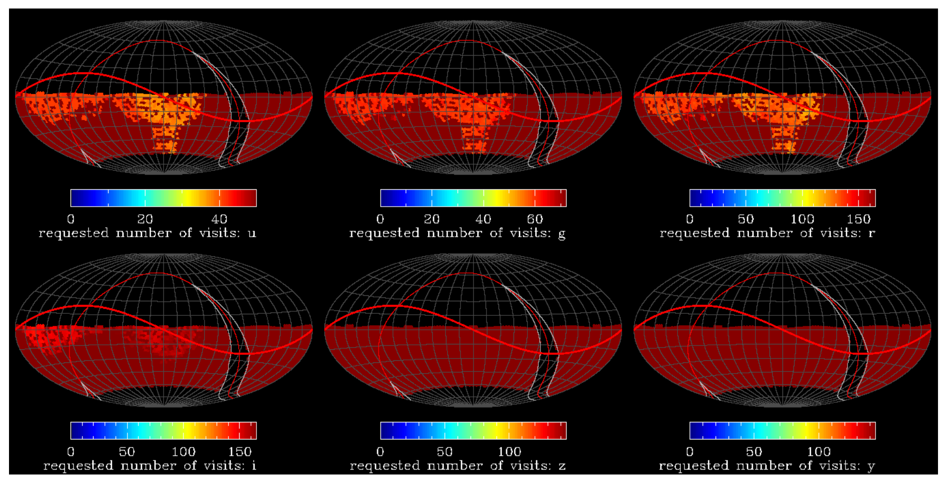
- Mixed cadences with different cadences in rolling areas have yet to be investigated, but are similar to some Deep Drilling proposals

Rolling Cadence—'Swiss Cheese'

- 'Random 1/10th of WFD fields whose proposal is active for 1 year with an arbitrary cadence (say optimized for 60 day light curves). There are 10 of these.



- WFD proposal with 90% of SRD visits requested running for all ten years.



Operations Simulator Status

- The current simulator includes parametric input of key science specifications from the Science Requirements Document, and the analysis compares to these values as the merits of success.
- The current simulator does not optimize its path across the sky beyond weighting slew time heavily. It does not look ahead. Deterministic look ahead development is underway.
- Effort is now underway developing figures of merit (metrics analysis framework, MAF) to measure survey completeness, temporal uniformity and to enable results that are more generic and support other science programs.
- As LSST approaches operational status, interest in enabling other science will grow and thus more metrics will be needed.