Operations Simulator Tools for Analysis and Reporting
Astrometry Analysis for
Opsim3.61

Operations Simulation Team
Large Synoptic Survey Telescope

Release Beta 1.0

The parameters studied here are the proper motion and parallax. In the following we have studied only observations in r, i, z and y filters, as these offer a numerous and relatively homogeneous data set.

Proper Motion

The proper motion is measured from the apparent motion over an interval of time. In order to capture the typical intervals available from a set of visits, the visits have been time-ordered, and the intervals evaluated pair-wise between the first and last visits, the second and next to last, etc. The longer intervals will be of greatest weight in calculating proper motion.

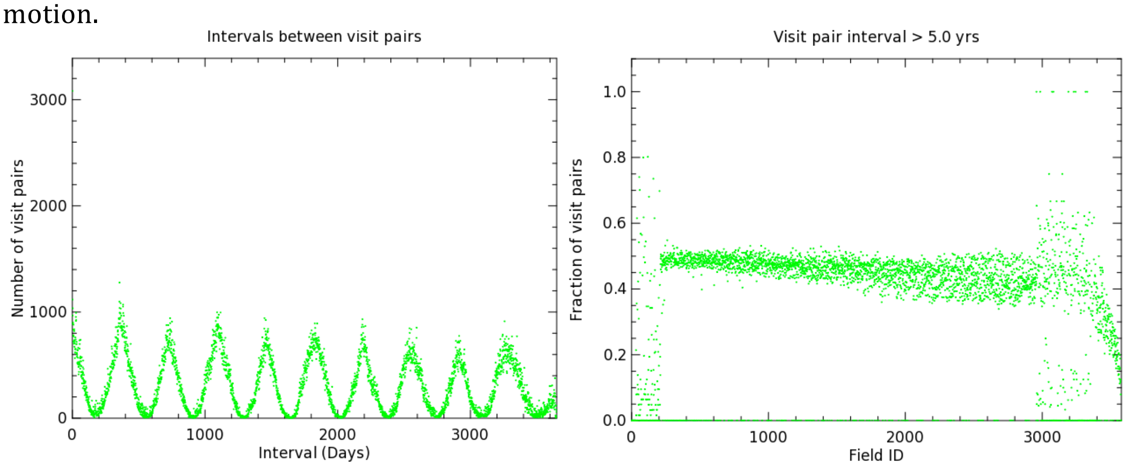


Figure 1. Distribution of visit pairs for the full 10-year survey. (left) The number of visit pairs vs interval, with modulation which is recognized to be due to seasonal availability of fields. (Graph file title: opsim3_61_propermotion_allfields-1.png). (right) The fraction of visit pairs with interval greater than 50% of the simulation length, for each field. (Graph file title: opsim3_61_propermotion_50percent-1.png). The Field ID is an index which approximately, but not exactly, tracks the LSST Field Number.

For a relatively flat distribution of visits with time, the mean visit interval would be approximately 5 years.

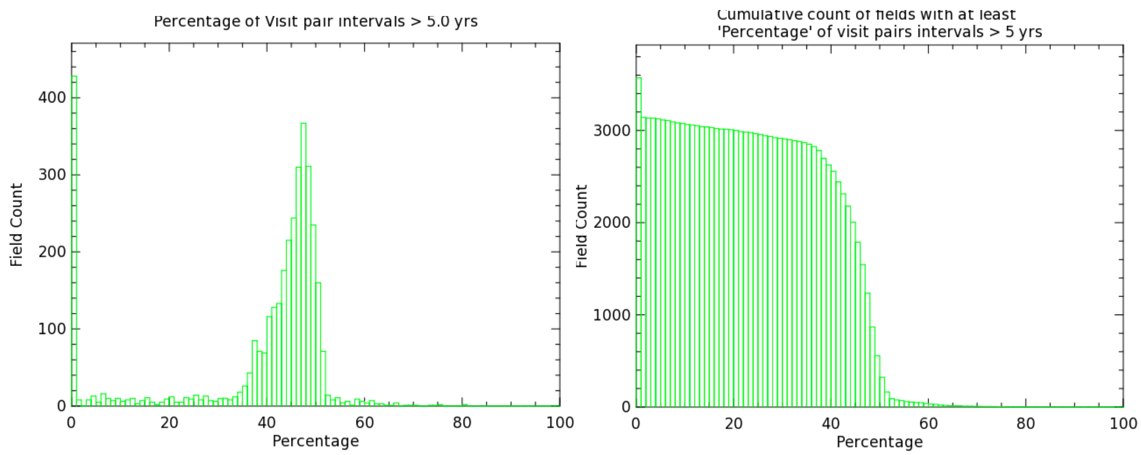


Figure 2. (left) Field count vs. the percentage of visit intervals greater than 50% of the run length. (Graph file title: opsim3_61_propermotion_50percentFields-1.png). (right) A cumulative integral of the Field Count histogram above, starting from large values. (Graph file title: opsim3_61_propermotion_50percentFields_cumulative-1.png).

As a Proper Motion Metric, we adopt the mean of the distribution in Figure 2 (left). A schedule which maximizes this number will be well suited to proper motion analysis.

Parallax Factor Merit

The weight of observations in calculation of parallax is approximately proportional to the offset of the earth from the sun with respect to the line of sight to the target (described by the Parallax Factor). In the following we consider only the RA component of the Parallax Factor, since it dominates the accuracy of the result (the Earth's orbital plane is close to the ecliptic). It can have values from -1 to 1 AU (approximately).

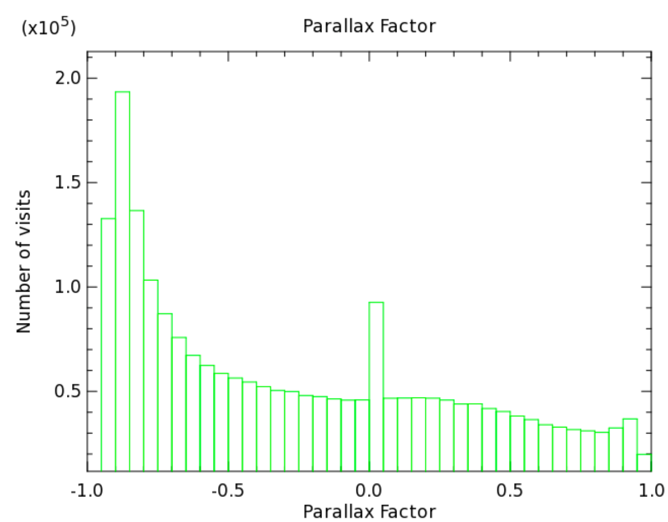


Figure 3. Parallax Factors for all visits to all fields. (Graph file title: opsim3_61_parallax_factor_fields-1.png).

Since parallaxes depend on the difference in parallax factor between visits, we have here paired visits to a field, first ordering the visits by parallax factor, and then pairing the smallest with the largest, then second smallest to second largest, etc. Each pair has a Parallax Factor Difference (PFD), which can range in absolute value from 0 to ~2.

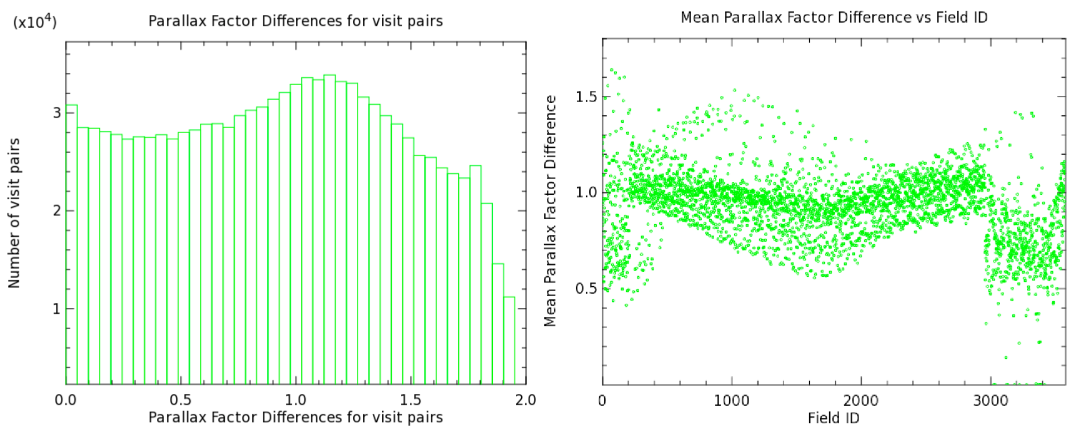


Figure 4. (left) Parallax Factor Differences (PFD) for all visit pairs (paired, as described) to all fields. (Graph file title: opsim3_61_parallax_factor-1.png). (right) Mean PFD for each field. (Graph file title: opsim3_61_parallax_diff_mean-1.png).

For a Parallax Factor Metric, we adopt the mean value of the Mean Parallax Factor Difference for all fields. A large value (greater than or ~ 1) will show that visits are spaced to support parallax measurement, whereas a small value will show the opposite.

Correlation of Parallax Factor with Hour Angle

The evaluation of parallax can be compromised if the visits are obtained so that there is a strong correlation between Parallax Factor and Hour Angle (HA), since the HA-dependent chromatic dispersion can be confused with shift due to Parallax.

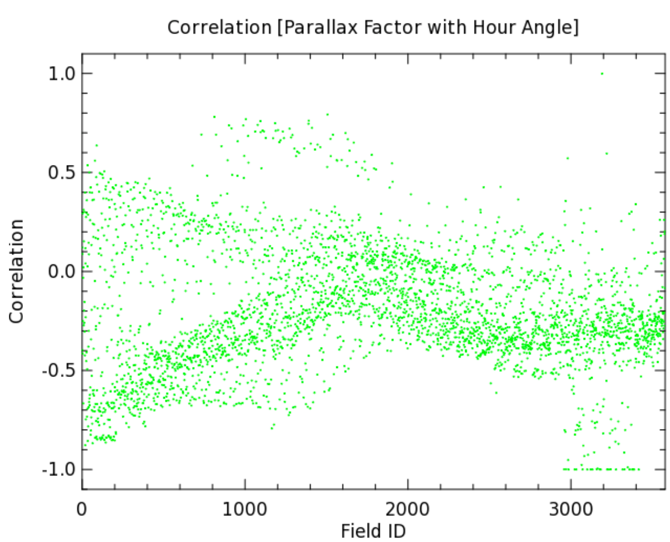


Figure 5. Correlation of Parallax Factor with Hour Angle for all fields. (Graph file title: opsim3_61_correlation-1.png).

For our purposes the absolute value of the correlation is of interest, and Figure 6 shows a histogram of number of fields binned by the absolute value of the correlation and a cumulative distribution for the same data

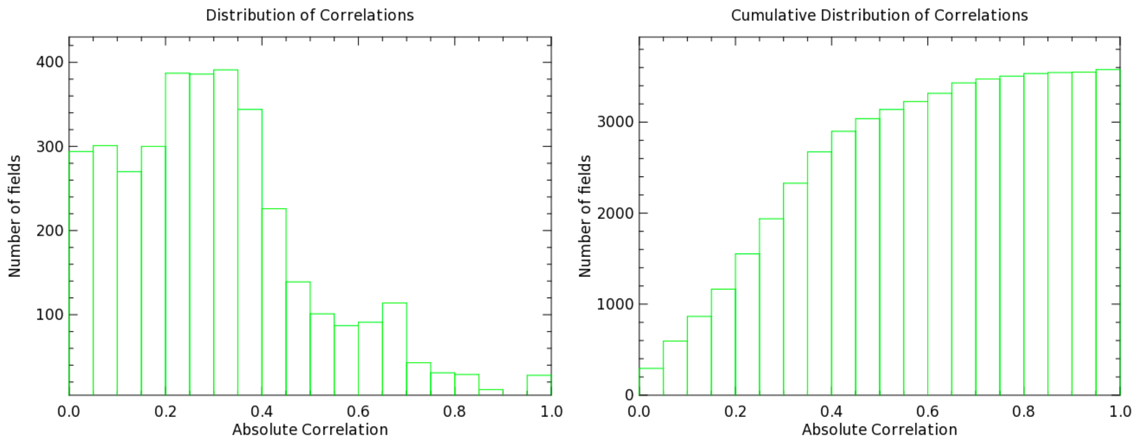


Figure 6. (left) Frequency of occurrence of Parallax Factor correlations. (Graph file title: opsim3_61_correlation_abs_hist-1.png). (right) Cumulative distribution of frequency of occurrence of Parallax Factor correlations. (Graph file title: opsim3_61_correlation_cum_abs_hist-1.png).

Experience shows that absolute value of the correlation < 0.5 will allow sufficient suppression of chromatic dispersion effects. Metric adopted for the Correlation Factor is the cumulative number of fields which satisfy this criterion.

Summary of Astrometric Metrics

Simulation	3.61
Proper Motion Metric Mean percent of visit intervals > 5 yr	27.3%
Parallax Factor Metric Mean for all fields of Parallax Factor Difference	0.92 AU
Parallax Factor Correlation Metric Fields with Abs(correlation factor) <0.5	3038 fields

Appendix: Algorithms

Proper motion

- For each field set
- For each rizy visit to each field in a set:
  - Compile a list of all N visits, and order them by time.
  - Compute the times (Dt) between visit 1 and N, 2 and N-1, etc.

    - Compute N5, the fraction of Dt times which exceed 50% of the simulation length.
- Prepare a histogram of the fraction N5 vs field index number.
- Find the mean value of N5 for all fields.

Parallax factor

- The calculation
    - sA = sin(RA),
    - cA = cos(RA)
    - sD = sin(Dec),
    - cD = cos(Dec)
    - sE = sin(obliquity of the ecliptic),
    - cE = cos(obliquity of the ecliptic)
    - sS = sin(solar longitude),
    - cS = cos(solar longitude)
    - R = distance to sun in AU = ~1.0
    - Parallax(ra) = +R*(cE*cA*sS - sA*cS)
    - Parallax(dec) = +R*((sE*cD - cE*sA*sD)*sS - cA*sD*cS)
        - The Parallax(dec) factor can be ignored for current purposes.
- The parallax factor for a single observation will be in the range -1 to +1.
- For a pair of visits, the weight for parallax calculation will be ~ proportional to the difference of the parallax factors (range 0.0 to 2.0).
- For each gri visit to each field:
    - Make an ordered list of RA parallax factors, PF
    - Compute the Parallax Factor Differences (PDF) between entries 1 and N, 2 and N-1, etc. This creates a list of PDF values from largest to smallest
- Find the mean value of PDF for all the visits to each field.
- Plot the mean for each field vs field number.
- Compute the mean for all fields

Differential refraction correlation

- For each rizy visit to each field:
    - Make an ordered list of RA parallax factors, PF, with associated hour angle HA
    - Compute the correlation, C, of the PF with the HA.
- Prepare a histogram of the number of fields vs C values.
    - A low value for C is preferred
- Compute the number of fields with C less than 0.5

Operations Simulator Tools for Analysis and Reporting Early Good Image Quality Analysis for Opsim3.61

Operations Simulation Team
Large Synoptic Survey Telescope

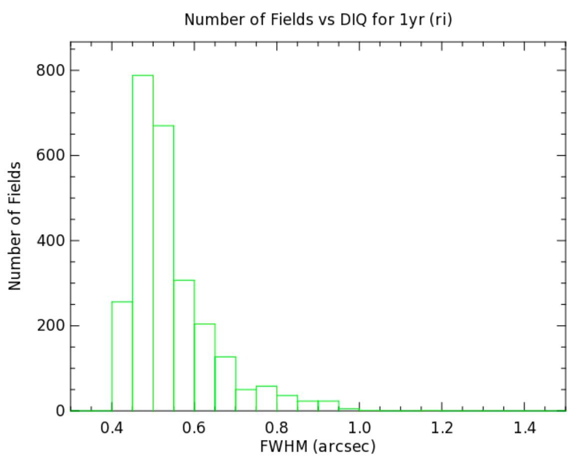
Release Beta 1.0

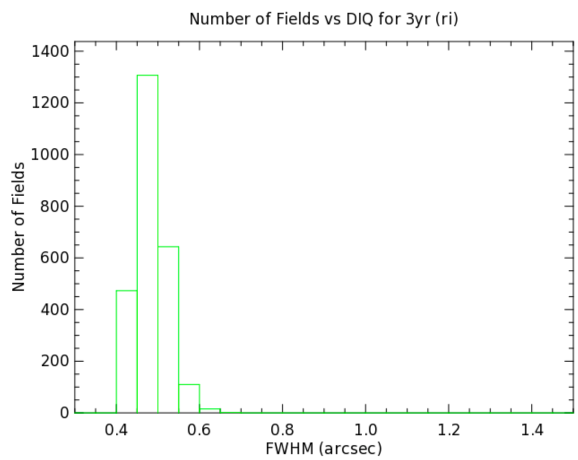
It is valuable to have at least one outstanding quality image of each field early in the survey. These are valuable for developing source catalogs (resolving sources that are blended in poorer images). Also, experience shows that a reference image for detection of transients is most effective if obtained at higher angular resolution than the images that are compared to it.

In order to characterize image quality, we will use the concept of delivered image quality (DIQ) which will be characterized by the FWHM.

Best Images Achieved

Figure 1 shows the distribution of number of fields with the best DIQ visit for all r or i visits to all fields as achieved after 1, 3 or 10 years.





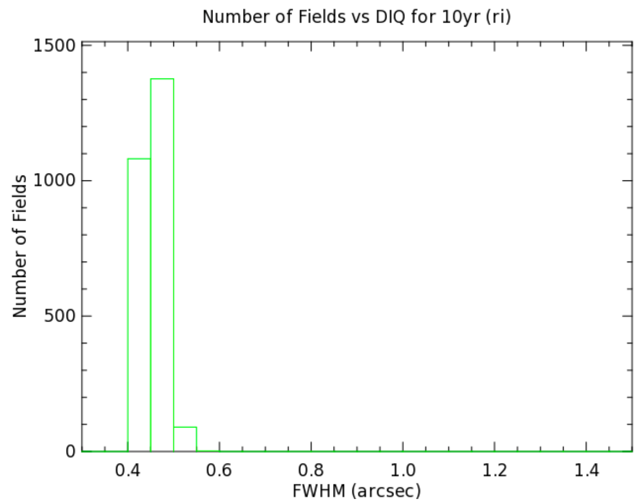


Figure 1. (top left) The number of fields for which the best single image obtained in r or i filters is in the range of the histogram bins, after 1 year. (top right) After 3 years. (bottom) On completion of the full 10 year survey.

As formal metrics, we adopt the median value of the histograms in Figure 1. (The median is robust against moderate skewing due to outliers in a distribution.)

Typical Image Quality Achieved

Another important measure of image quality is the typical DIQ achieved for all images in each field. Again we adopt the median, now on a *per field* basis. Figure 2 shows the distribution of median FWHM for all r and i visits to all fields.

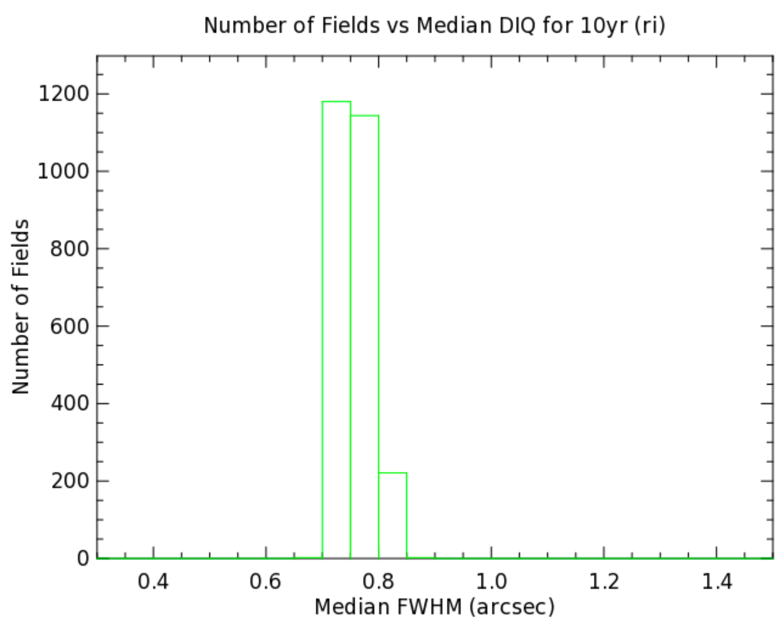


Figure 2. Median FWHM per field for all r and i visits to all fields after 10 years.

As a simple metric to characterize the seeing of all visits to all fields, we adopt the median of the median seeing per field in Figure 2 – hence the median of the medians.

Changes under Consideration

The analysis may be split to treat r and i separately, with graphs and metrics for each, since the image quality will differ for the two wavelengths. Also, the analysis may be repeated for just the wide-fast-deep survey fields , as they are particularly critical for early assessment.

Metrics Summary

Simulation	3.61
Median best FWHM per field after 1 year For all r or i visits to fields	0.52 arcsec
Median best FWHM per field after 3 years For all r or i visits to fields	0.48 arcsec
Median best FWHM per field after 10 years For all r or i visits to fields	0.45 arcsec
Median best FWHM per field after 1 year For all r visits to fields	0.55 arcsec
Median best FWHM per field after 3 years For all r visits to fields	0.50 arcsec
Median best FWHM per field after 10 years For all r visits to fields	0.47 arcsec
Median best FWHM per field after 1 year For all r visits to fields	0.56 arcsec
Median best FWHM per field after 3 years For all i visits to fields	0.50 arcsec
Median best FWHM per field after 10 years For all i visits to fields	0.46 arcsec
Median FWHM for all visits after 10 years For all r and i visits to fields	0.75 arcsec

Appendix: Algorithms

- For each field in the Universal Proposal:
  - Make a time sequence of all ri visits
  - Find the best seeing image in the first 1 yr, 3yr and 10 yr
  - Find the median seeing for 10 years
- Create Best Seeing histograms from 0.3 to 1.5 arcsec by steps of 0.05
  - Make 3 histograms, for 1, 3 and 10 years.

  - For each field, enter a count in the histograms corresponding to the best seeing ri image in 1, 3, 10 yr.
- Create a Median Seeing histogram from 0.3 to 1.5 for 10 years only
  - Enter a count for the median ri seeing of each field
- Plot all histograms on the same figure
  - For metrics, find median values for each histogram

Operations Simulator Tools for Analysis and Reporting
ri Image Quality and Airmass Analysis for
Opsim3.61

Operations Simulation Team
Large Synoptic Survey Telescope

Release Beta 1.0

The simulated values of delivered image quality (DIQ) are based in part on "fixed" factors such as the instrument performance, and in part on uncontrollable factors such as the seeing statistics. One factor that is largely under LSST control is the observing hour angle, as observations at larger zenith distance will be achieve poorer image quality in accordance with the atmospheric model. The focus of this analysis is to determine whether or not the observing sequence is obtaining observations at or near the lowest available airmass (hence with the best DIQ),

In evaluating image quality, the visits in the r and i filters are examined separately, since they are singled out in the SRD for observation under superior seeing conditions. In the discussion below, the DIQ will be described by the FWHM.

Seeing and Ideal Seeing

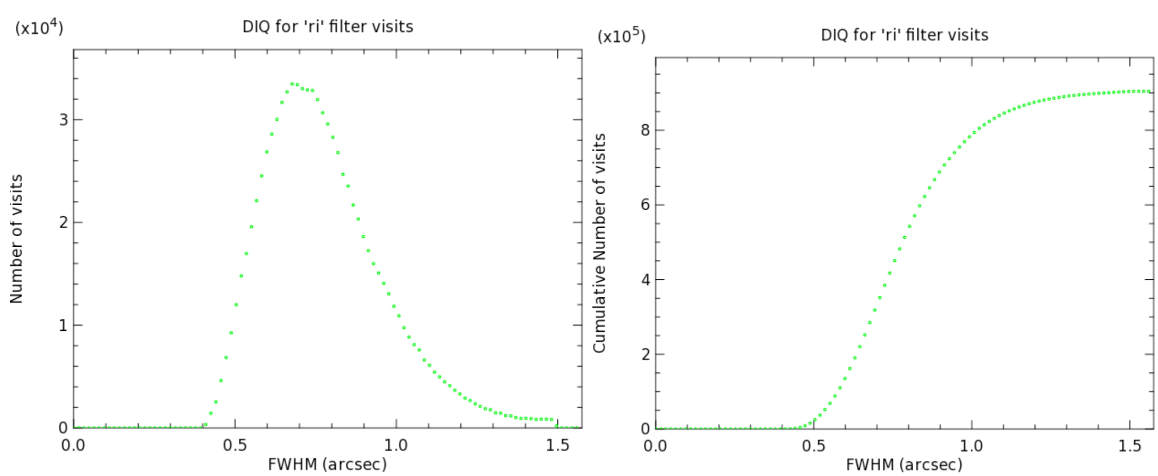
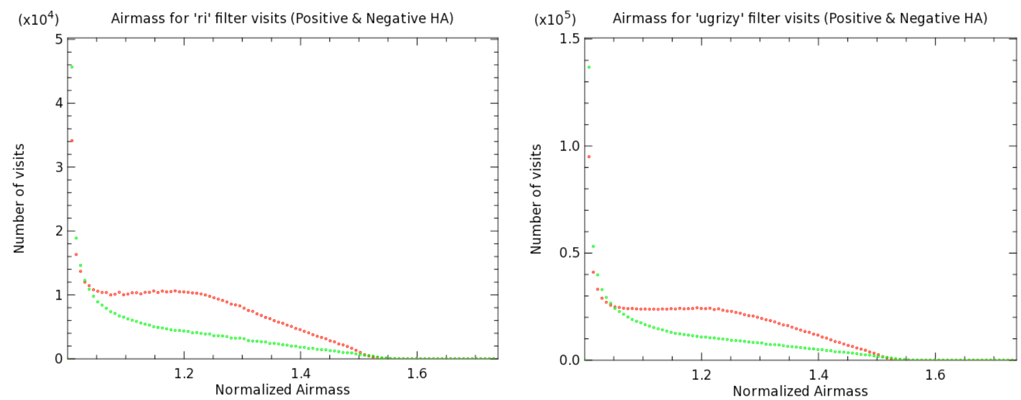


Figure 1. (left) FWHM for all r and i filter visits to all fields that were observed as a part of the wide-fast-deep (WFD) survey. (right) The corresponding cumulative distribution.

We adopt the mean FWHM as a metric. As a benchmark, we adopt the mean "ideal" FWHM width for comparison. The "ideal" is that which would have been realized if the same observation had been made at the altitude of field transit, hence representing performance that might be achieved in a more optimized schedule. The ratio of achieved to ideal FWHM width is a measure of potential gains with different survey optimization.

Airmass and Normalized Airmass

The role of observing hour angle can be seen more directly by looking at the airmass. Of course the observing airmass for targets partially reflects their declination, which is not a free parameter. In order to remove this from the discussion, we have used the concept of normalized airmass, which is the ratio of the observing air mass to the airmass for that target at transit.



Figurre 2. (left) Normalized Airmass for all r and i visits to all Universal Proposal fields but not including visits for NEO search. (right) A similar figure for all visits in all filters to the same fields. Note peaks near 1.0. Red curves correspond to visits west of meridian.

The mean value of the normalized airmass is adopted as a metric.

Summary of Image Quality and Airmass Metrics

Simulation	3.61
Mean achieved FWHM For r and i visits to WFD survey fields	0.77 arcsec
Mean ideal FWHM For r and i visits to WFD survey fields	0.70 arcsec
Mean normalized airmass For r and i visits to WFD survey fields	1.16
Mean normalized airmass For visits in all filters to WFD survey fields	1.15

Appendix: Algorithms

- For all Universal Proposal Fields (excluding NEO sweetspot visits)
  - For all ri visits
    - Prepare a histogram of the incidence of the seeing S.
      - Compute the integral of S starting at 0.0, to give the frequency of occurrence of S less than a given value.
      - Find the 25, 50 and 75% points in the frequency of occurrence.
    - Prepare a histogram of the incidence of the normalized seeing, NS, defined as the ratio of S to the value of S that would be obtained under median conditions at transit (at the wavelength and airmass)
      - Compute the integral starting at 0.0, to give the frequency of occurrence of NS less than a given value.
      - Find the 25, 50 and 75% points in the frequency of occurrence.
  - For just ri visits, and separately for all visits in all filters
    - Prepare histograms of the normalized airmass, NA, defined as the ratio of the visit airmass to the airmass for the field at transit. Values will range from 1.0 and up. Make separate histograms for visits with positive HA and for negative HA.
      - Compute the integral (summing both postive HA and negative HA data) starting at 1.0, to give the frequency of occurrence of NM less than a given value.
      - Find the 25, 50 and 75% points in the frequency of occurrence

Operations Simulator Tools for Analysis and Reporting
Rotator Angle Distribution Analysis for
Opsim3.61

Operations Simulation Team
Large Synoptic Survey Telescope

Release Beta 1.0

Optical aberrations in the telescope or camera can introduce biases that are troublesome for LSST study of gravitational weak lensing. To provide a control on some possible sources of systematic image ellipticity, and to reduce them by randomization, it is wished to observe with a range of camera and telescope angles with respect to the target field and to gravity. Acquisition of observations with a range of angles will also benefit precision calibration of photometry by moving each reference star over different detector regions.

The relevant angles are partially described in the simulations by the rotator sky position (RotSkyPos), and the rotator telescope position, RotTelPos. RotSkyPos is the angle between North in the image and the focal plane "up" reference. The RotSkyPos = RotTelPos – parallactic-angle. RotTelPos is the angle between the telescope and the telescope rotator.

This analysis is applied to fields of the wide-fast-deep survey (WFD), for all visits in either r or i filters.

Distribution of Angles

Figure 1 shows the distribution of RotTelPos. (The angles were incremented by 180 degrees for Figure 1 to show a connected distribution.)

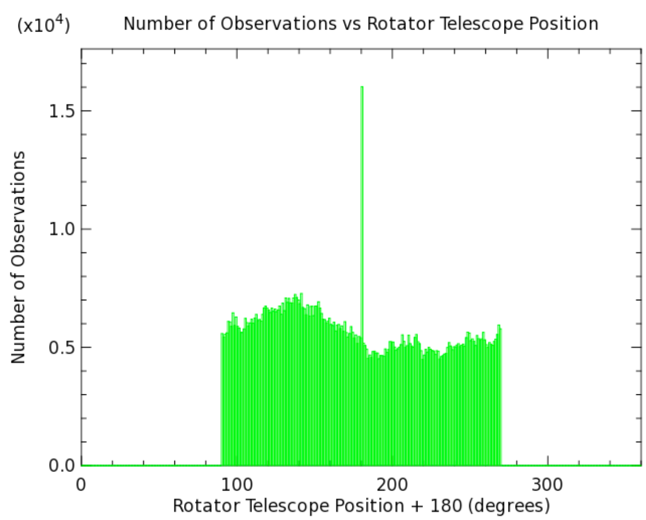


Figure 1. The value of the rotator angle (RotTelPos + 180) which describes the angle of the camera with respect to the telescope, for all r and i visits to WFD fields. (Graph file title: opsim3_61_ rotTel_pos.png).

In operation, the RotTelPos is determined as follows. For each filter change, the rotator is moved to a "zero" position. After that the rotator position is moved only to track while on a target, and thus wanders away from "zero". We find that the "zero" is indeed at zero degrees. The peak at zero is presumably due to a minority of rapid filter changes that enhanced the relative number of observations at this angle.

Figure 2 shows the distribution of RotSkyPos for all visits to all WFD fields.

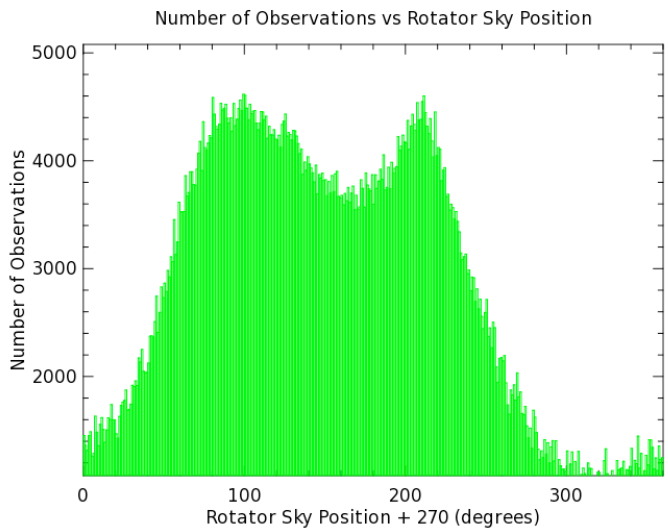


Figure 2. The distribution of RotSkyPos, which is the angle between North in the image and the focal plane "up" reference, for all r and i visits to WFD fields. (Graph file title: opsim3_61_ rotSky_pos.png).

This distribution reflects in part the rotation of the sky with respect to the optical axis of the Alt-Az telescope. If the distribution of observations with hour angle is asymmetric, it will contribute structure to this figure, blurred by the random walk of rotator angle with respect to telescope.

Randomization of Angles

In an analysis of individual image shapes, it will be useful to have a wide distribution of angles for the visits to each field. Figure 3 show frequency of occurrence histograms of the number of fields against the RMS variation of angle as determined on a *per field* basis.

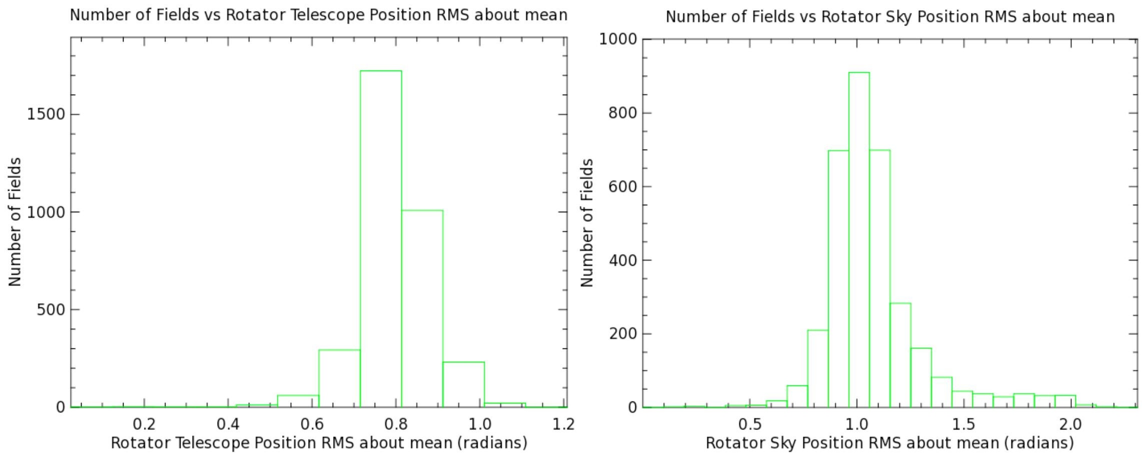


Figure 3. (left) Frequency of occurrence of an RMS RotTelPos per field (angle in radians). (right) Frequency of occurrence of an RMS RotSkyPos per field (angle in radians). (Graph file titles: opsim3_61_rotTel_pos_rms.png, and opsim3_61_rotSky_pos_rms.png)

RMS variations of order 1 radian indicate a good distribution on the half-circle.

As metrics we adopt the mean values of the histograms in Figure 3.

Metric Summary

Simulation	3.61
Mean of RMS RotTelPos per field For all visits to Universal Proposal fields	0.90 radians
Mean of RMS RotSkyPos per field For all visits to Universal Proposal fields	1.22 radians

Appendix: Algorithms

Definitions

- rotTelPos = angle (in radians) between the telescope and the telescope rotator
- rotSkyPos, is the angle (in radians) between North in the image and the focal plane "up" reference
- rotSkyPos = rotTelPos - parallactic-angle

Rotator Metrics

- Process each Universal Proposal field.
- For each field assemble a list of rotSkyPos and rotTelPos angle values for all ri visits.
- Compute the RMS value for rotSkyPos and rotTelPos angle for each field
- Prepare a histogram for each field of rotSkyPos and rotTelPos angle, in bins of 0.1 radians.
- Prepare a histogram for the rms values for all fields in bins of 0.1 radians.
- As metrics
    - Compute the mean of the rms values for rotSkyPos and rotTelPos angle.
    - Count the number of fields that have rotSkyPos less than RMSmin (where RMSmin = 0.4)
    - Count the number of fields that have rotTelPos less than RMSmin (where RMSmin = 0.4)

Operations Simulator Tools for Analysis and Reporting
Solar System Small Body Detection Analysis for Opsim3.61

Operations Simulation Team
Large Synoptic Survey Telescope

Release Beta 1.0

LSST will detect many asteroids. Associating detections will be very difficult owing to large numbers and rapid motions. In order to support linking of detections (tracklets) and merging of tracklets into orbits, it will be important to have sufficiently dense sampling of each target. The Solar System metrics examine a simulation for groupings of detections that support asteroid studies. The sampling characteristics studied include visit pairs and triples in a single night, groupings of nights during a lunation, and availability of multiple groupings during separate lunations.

The Approach

The approach is described here algorithmically to clarify what is studied and how a set of parameters control the planned metrics. The adopted values for the parameters are collected at the end of the document with the results summary.

For each field, we make a list of all visits in any of filters griz. We select Nights that have at least one close Pair of visits with temporal spacing Δt that satisfies search criteria ($T_{min} < \Delta t < T_{max}$). For each such night we note the number of additional visits during that night, since nights with three visits more strongly constrain the tracklets of moving targets.

We then find Groups of Nights. A Group must include at least N_{nights} different qualifying nights within a defined time window (N_{days}). We use a sliding window, so a Night can participate in more than one group.

Since Groups may overlap, it is also valuable to know something about their temporal distribution. This is obtained by counting the number of Lunations that have at least one Group, and by counting the number of fields that have groups in at least 3 successive lunations.

Pairs, Groups, and Lunations

Figur1 1 shows some basic data for total observations, observation pairs, groups, groups with at least one 3-visit night, and lunations with groups.

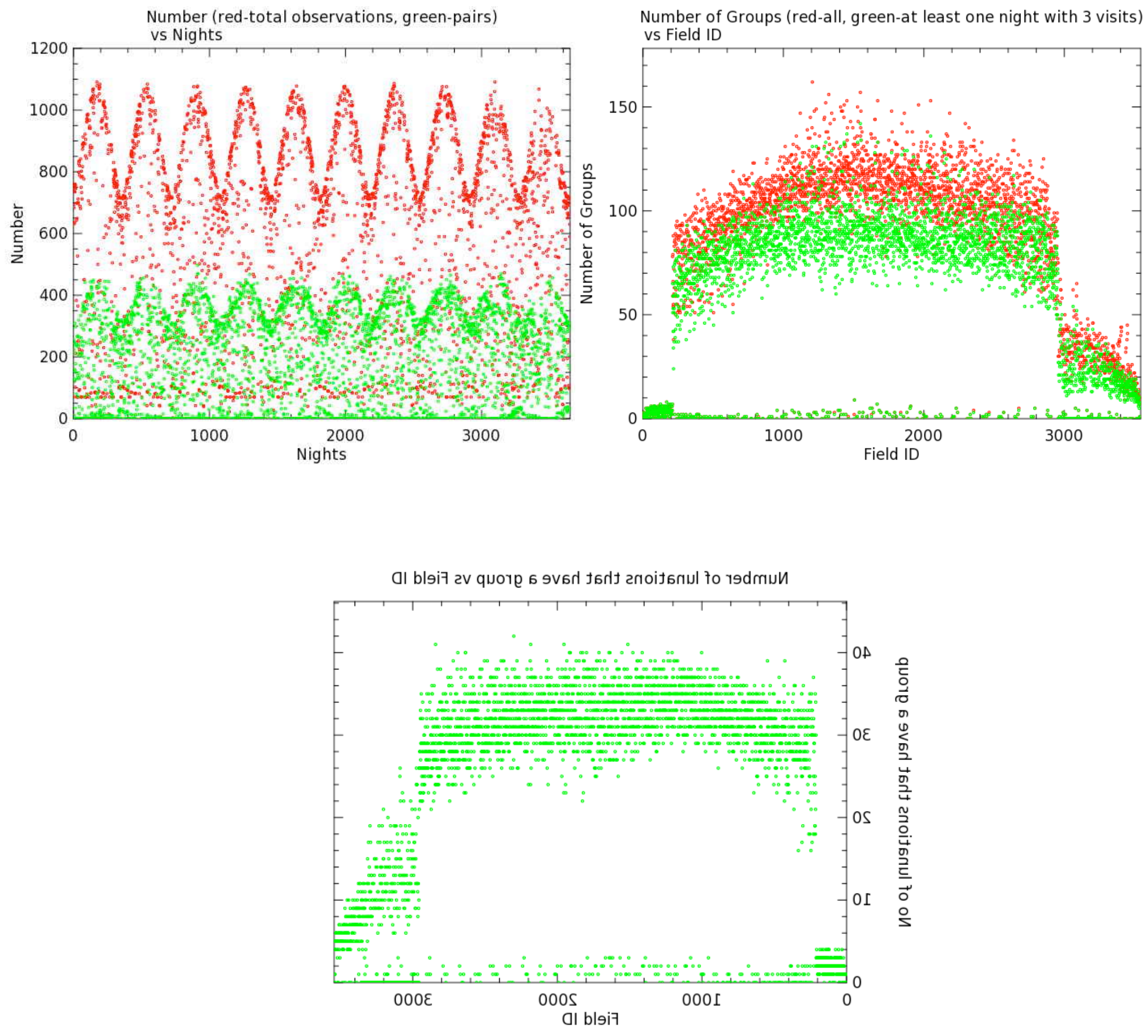


Figure 1. (above left) For each calendar night during the survey, the red data show the total number of visits, and the green data the number of pairs that satisfy the pair criteria. (above right)For each field, the figure shows the number of qualifying Groups obtained (red) and also the number with at least one night having 3 visits (green). (below) The number of separate lunations that have at least one qualifying Group for each field.

Figure 2 shows the distribution of the number of groups per field and the number of groups that include a 3-visit night. In reading Figure 2 (left) it is important to keep in mind that the two distributions are for different measures, and each field will generally fall in a different bin for the two distributions. The condition that groups with a 3-visit night are in a subset of all groups, requires that the former cumulative distribution (Figure 2 right) is always to the left of, or smaller than, the latter. Figure 2 (right) does show that most groups have at least one 3-visit night.

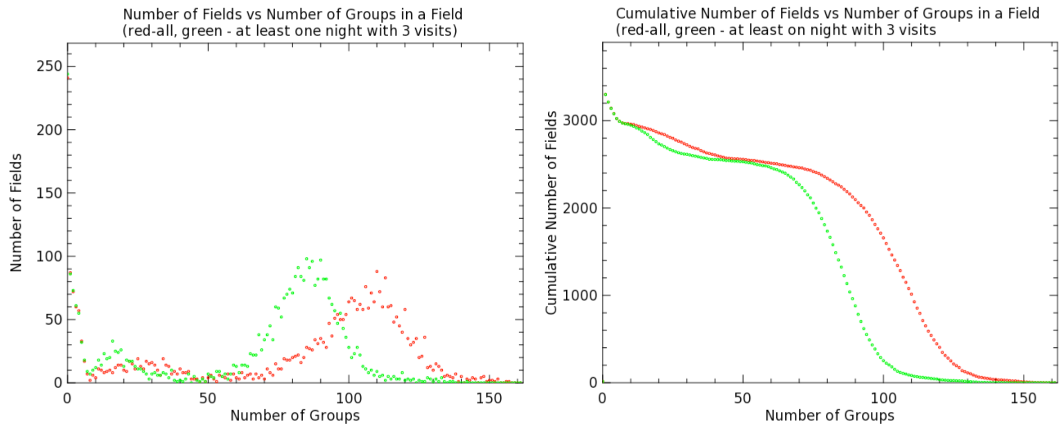


Figure 2. (left) Histogram of the number of fields with different numbers of qualifying Groups. All Groups (red), and Groups with at least one night having 3 visits (Green). (right) Cumulative distribution of the same.

The adopted Metrics for number of Groups is the Group count in Figure 2 (right) achieved by at least half of the fields, separately for all Groups and for Groups with at least one night of three visits.

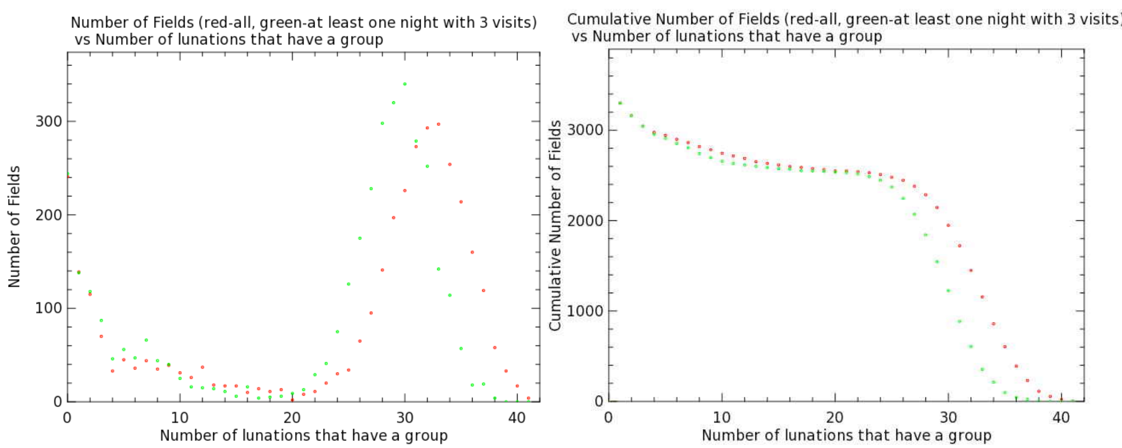


Figure 3. (left) Histogram of the number of fields against the number of lunations that have at least one Group for all Groups (Red) and for Groups with at least one night with 3 visits (Green). (right) Cumulative distribution of the same.

The adopted Metrics for number of lunations is the lunation count in Figure 3 (right) achieved by at least half of the fields, separately for all Groups and for Groups with at least one night of three visits.

Analysis Parameters

T_{min}:	15 min
T_{max}:	60 min
N_{days}:	14
N_{nights}:	3

Metric Summary

Simulation	3.61
Minimum number of Groups for 50% of fields For all griz visits to all fields	97
Minimum number of Groups for 50% of fields For all griz visits to all fields With at least 3 visits on at least 1 night	79
Minimum number of Lunations for 50% of fields For all griz visits to all fields	30
Minimum number of Lunations for 50% of fields For all griz visits to all fields With at least 3 visits on at least 1 night	28

Appendix: Algorithms

Visit Groups for Solar System Object Detection

- For every field, scan the visits and look for groupings that are suitable for moving object detection.
- The approach:
  - Make a list of all visits.
  - Select only Nights that have at least one close Pair of visits (interval Tmin < t < Tmax)
  - For each such Night, note the number of additional visits during that Night
  - Find Groups of Nights within a defined time window (Ndays) – each Night may be "tested" in several possible groups, but may only count in one Group.
- Make histograms:
  - The number of Optimum Groups for each field, overplotted with the number of Groups for which at least one Night has three visits.
  - The number of fields with Optimum Groups in each 30 day time interval, overplotted with the same for which at least one Night had three visits.
- Metrics – characterize each histogram (4 of them) with the 25, 50 and 75% points.

Parameters and Initial Values

- Fi – field numbers – initially all fields
- Wi – filters accepted – initially g, r, i, and z
  - Nights consist of visits in the same filter
  - Groups may include Nights with different filters

- Xi – required limiting magnitude in filter i
  - Initially Xg=23.92, Xr = 23.5, Xi=24.72, Xz=24.72
    - Based on Xr=23.5 and typical colors from Piironen et al, A&Asuppl 128, 525 (1998); Ivezic et al, AJ 124, 2943 (2002).
- Tmin – minimum interval between visits in a Pair – initially 15 minutes
- Tmax – maximum interval between visits in a Pair – initially 60 minutes
- Ndays – Duration of a Group – initially 14 days
- Nnghts – number of Nights required in a Group (ie Nights with Visit Pairs that satisfy the requirements) – initially 3

Definition of Night Number

- Compute Integer(expMJD-0.3) to compensate for the time difference between Greenwich and Chile.
- This gives a count of observing nights, defined to start after midday
- The observing nights thus defined starts at noon or noon + 1 hour local time, depending on savings time.

Algorithm 1

- For each field Fi:
  - Make a sequential list of all visits with any listed filter Wi, and limiting magnitude better than Xi
    - List contains:
      - expMJD-1, filter
  - Make a sequential list of all Nights with at least one visit Pair satisfying Tmin < t < Tmax – all visits in a Night must be in the same filter
    - List contains:
      - expMJD-1, filter, NgtVisits, expMJD-2,…, expMJD-NgtVisits
      - NgtVisits = number of visits during the Night, >= 2

Algorithm 2

- Search the list of Nights
  - For Night i = 1, 2,….
    - Count the number of Nights within a following interval = Nmax days
    - If the number of Nights is < Nnghts, skip Night i and advance to Night i + 1
    - If the number is >= 3, add an entry to the Group list which contains:
      - » expMJD-1, GrpVisits
      - » GrpVisits is the total number of visits = sum of NgtVisits in the Group
    - Start the next Group at Night i + Ndays – that is, each Night can only count in one Group. (This does not give the optimum groups, which would require a more complex search with additional criteria to score the value of different Groups.)

Algorithm 3

- Make histograms:

    - The number of Groups for each field, overplotted with the number of Groups for which at least one Night has three visits (the ratio GrpVisits/GrpNights > 2.00).
    - The number of fields with at least one Group in each 30 day time interval, overplotted with the same for which at least one Night has three visits (the ratio GrpVisits/GrpNights > 2.00).
- Metrics – characterize each histogram (4 of them) with the 25, 50 and 75% points.

Operations Simulator Tools for Analysis and Reporting
Uniformity and Distribution for
Opsim3.61

Operations Simulation Team
Large Synoptic Survey Telescope

Release Beta 1.0

While some science objectives require particular visit cadences, or benefit from non-uniform visit distributions, others are best served by a uniform pattern of visits. This metric group describes some of these.

Standard Deviation of time sampling

For each field and each filter, all visits are arranged in time order. Two measures of non-uniformity are computed. One is the difference between the mean (or median) of all visit times and the mid-point time of the survey. This measures the relative excess of early or late visits. The second is the StDev of the visit times relative to the mean(or median) of the times for that dataset (field and filter), or for the RMS about the midpoint of the survey. Each field is represented by a single point in a StDev vs Difference plot. Figure 1 shows an example.

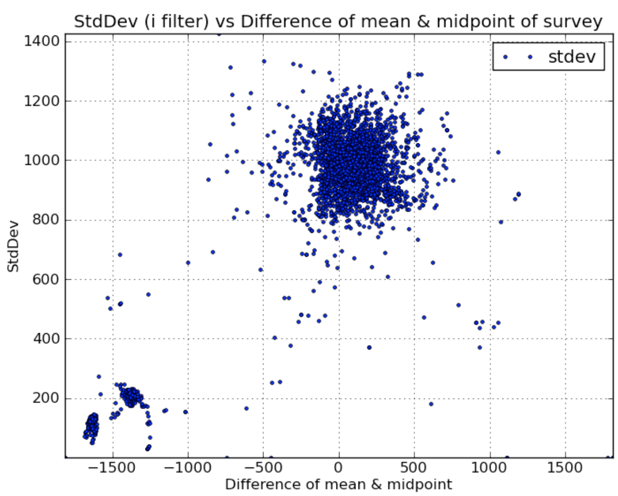


Figure 1a. The StDev of the visit time about the mean visit date, vs the difference between the mean visit date and the survey midpoint, with each filed represented by a point. (Graph file title: opsim3_61_i_stdev_ab_mean_vs_median_midpoint.png).

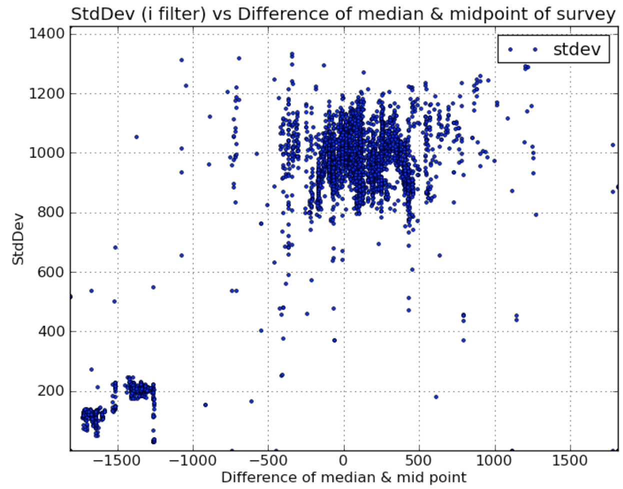


Figure 1b. The StDev of the visit time about the median visit date, vs the difference between the median visit date and the survey midpoint, with each filed represented by a point. (Graph file title: opsim3_61_i_stdev_diff_medians_midpoint.png).

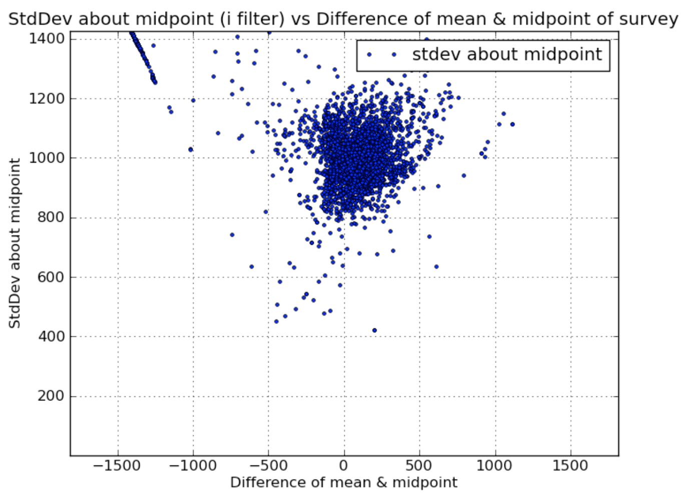


Figure 1c. The RMS of the visit time about the mean visit date, vs the difference between the mean visit date and the survey midpoint, with each filed represented by a point. (Graph file title: opsim3 _61_i_stdev_midpoint_diff_means_midpoint.png).

For a uniform sampling, the difference between mean or median and the midpoint would be zero, and the standard deviation would be 1053.4. The metric adopted is the number of fields which fall within the bounds +-400 in difference, and +-250 of 1053.4 in standard deviation or RMS.

Zeljko Kolmogorov-Smirnov test

This metric computes a quantity F that measures departures from the uniform sampling expectation, and is akin to the KS test – that is, it examines the difference between the actual distribution and the desired distribution (uniform). It ranges from 0 (perfectly uniform) to +-0.5 (all data taken on the first or last night). Figure 2 shows an example.

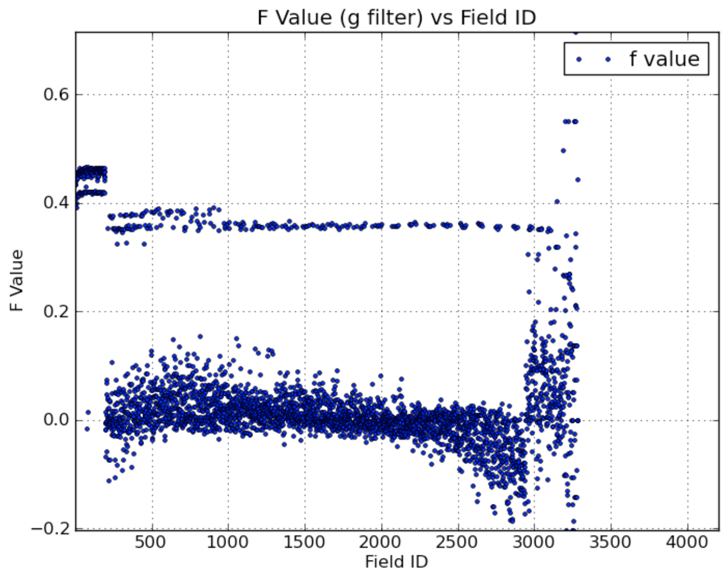


Figure 2. The value of the F function for each field, for the g filter. (Graph file name: opsim3_61_g_fvalue.png). The Field ID is an index which approximately, but not exactly, tracks the LSST Field Number.

Multi-color Visits

For a transient of an anonymous target, there will initially be little or no information available for characterization beyond the LSST data itself. The principle opportunity for rapid characterization with LSST is in repeat visits. A repeat visit in the same filter offers additional time variability information, while a repeat visit in another filter offers color information. The former is covered with metrics of the Solar System group.

Figure 3a shows the distribution of inter-visit times for visit pairs in different filters, as a simple total in each bin without regard to the field identity. The metrics associated to this figure give the total number of fields for which the mean of the 10 (30, 100) shortest inter-visit times is less than 1 hour or more than 100 hours, where for the former a large value is good, and for the latter a small value is good.

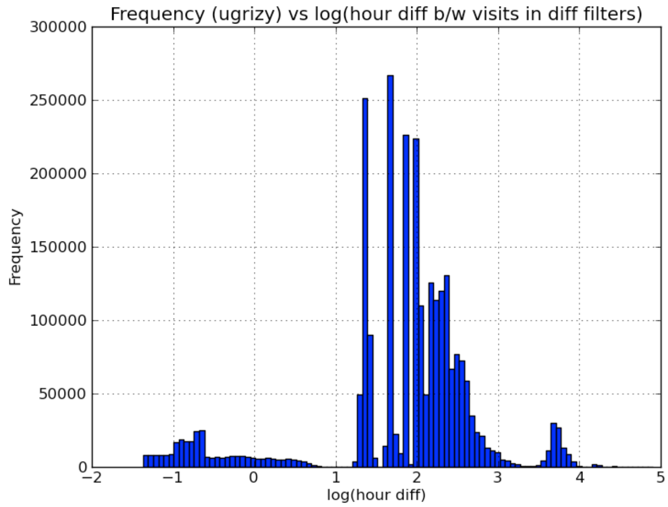


Figure 3a. The number of visit pairs with different filters vs the spacing in time between the visits. The plot shows the total number of such pairs for all fields and for any 2 filters of the ugrizy set. (Graph file name: opsim3_61_ugrizy_all_hour_diff.png)

A cumulative distribution for Figure 3a is shown in Figure 3b. A metric formed from this view of the information is the cumulative total number of visits with time interval less than 1 hour and less than 10 hours.

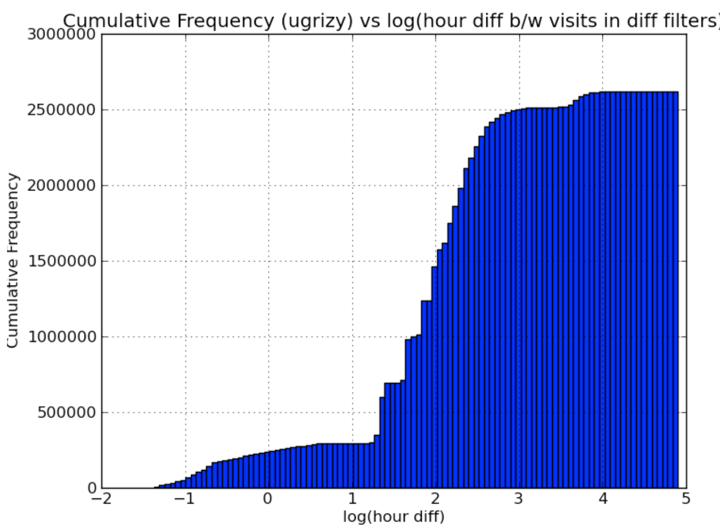


Figure 3b. The number of visit pairs with different filters vs the spacing in time between the visits. The plot shows the total number of such pairs for all fields and for any 2 filters of the ugrizy set. This is the cumulative version of Figure 3a. (Graph file name: opsim3_61_ugrizy_all_hour_diff_cum.png).

Uniformity of Sky Coverage

In order to optimize the photometric calibration, it is important to have a minimum amount of high quality data for most contiguous fields, since gaps on the sky interfere with closing the calibration by benefitting from field overlap and multiple paths.

For this metric, we look at the sky coverage for each filter after 1 year, 2 years and NYear years. In order to be counted in this metric, a visit must be qualified – ie, obtained under seeing, sky brightness and airmass satisfying specified requirements.

Figure 4a shows the number of qualifying visits in each field in the u filter during the first 2 years.

The metric is the number of fields for which at least 3 qualified visits have been obtained in a filter within the specified period of time at the beginning of the survey.

Figure 4b shows an Aitoff plot for all filters for the first year of the survey.

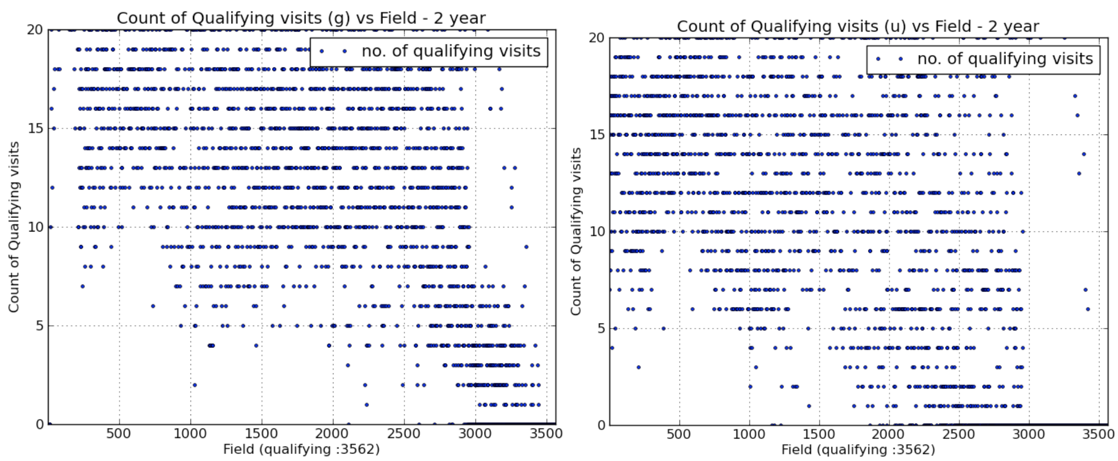


Figure 4a. The number of qualifying visits in the g and u filter obtained in each field during the first 2 years of the survey. (Graph filenames: opsim3_61_g_skycoverage_0_2_years.png and opsim3_61_u_skycoverage_0_2_years.png).

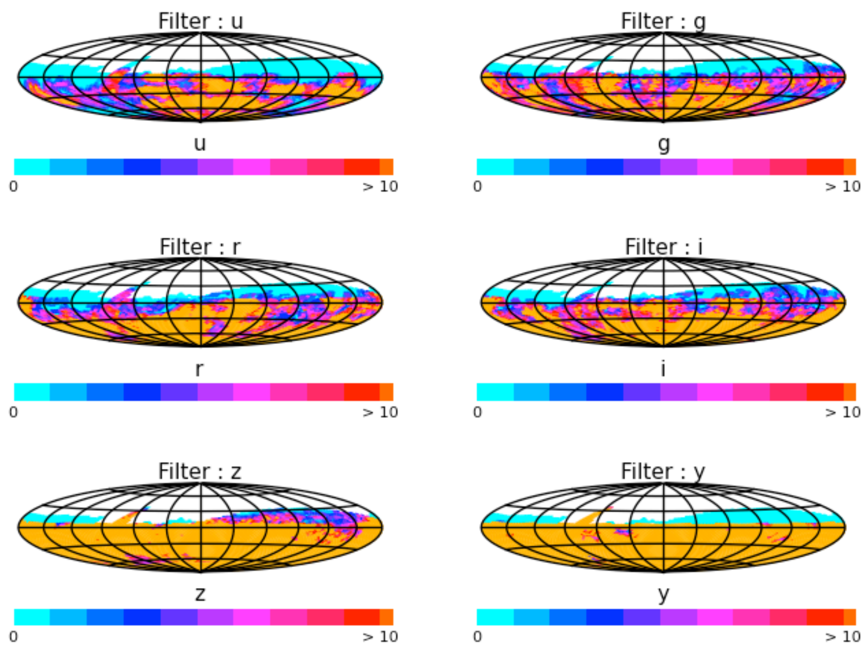


Figure 4b. Projection plot on the sky showing the number of qualifying visits obtained in each field during the first year of the survey. (Graph file name: opsim3_61_ugrizy_skycoverage_aitoff_0_1_years.png).

Analysis Parameters

D:	400 days
SD	250 days
NYear	3 years
SEEmax	1.5 arcsec
SKYmax	0.0
Xmax	0.0
Nvis	

Metric Summary

Simulation 3.61

StDev - Number of fields well distributed in time according to standard deviation or RMS about midpoint, and difference between mean or median date and survey midpoint

Filter	Median	Mean
u	560	620
g	1367	1940
r	1180	1705
i	1426	1772

z	795	1176
y	1105	1411

Kolmogorov-Smirnov test (number of fields satisfying criterion)

Filter	Fields
u	2025
g	2744
r	2880
i	2859
z	3062
y	2636

Multi-color – visit pairs in any two different filters within a short interval

Number of fields for which the mean of the 10 shortest intervals between two filters is:

Less than 1 hour	Greater than 100 hours
2570	208

Number of fields for which the mean of the 30 shortest intervals between two filters is:

Less than 1 hour	Greater than 100 hours
2175	308

Number of fields for which the mean of the 100 shortest intervals between two filters is:

Less than 1 hour	Greater than 100 hours
210	513

Cumulative Frequency

Cumulative number of visit pairs in different filters to all fields

Interval < 1 hour	Interval < 10 hours
244494	296495

Uniformity of sky coverage

Number of fields with fewer than Nvis visits (ugrizy) after:

1 year	1362	844	875	713	275	576
2 years	974	513	402	450	158	572
NYear years	823	421	350	334	158	572

Number of main survey fields with fewer than Nvis visits (ugrizy) after:

1 year	703	703	250	344	187	1	4
2 years	389	389	21	19	42	0	0
NYear years	238	0	0	1	0	0

Appendix: Algorithms

StDev of temporal distribution

- For each field and filter, analyze the sequence of visit times.

- Find the mean (median) visit times and difference from the time of the midpoint of the survey. This measures displacement early or late in the survey.
- Find the RMS of the visit dates about the mean (median). This is an indicator of the compactness of the distribution.
- Count the fields for which:
  - -D < Difference < D, where D=400, and,
  - (1053.4 - SD) < StdDev < (1053.4 + SD), where SD = 250

KS uniformity metric – Zeljko's description

- First extract the starting and ending time of simulation, tmin and tmax. Then loop over all fields and filters and for each combination extract the vector of observing times, t_i, i=1,...,Nobs. Given t_i vector, then
- make a cumulative distribution of t_i, normalized to 1 (i.e. divide the cumulative counts by Nobs), call it c_i. Actually, I didn't use real t_i, but evaluated cumulative counts on a regular grid from tmin to tmax, with a step of 14 days (it shouldn't make much difference).
- 2) make a model distribution expected for the uniform sampling, m_i = (t_i-tmin)/(tmax-tmin)(m_i is a straight line starting at 0 for tmin, and ending at 1 for tmax)
- 3) then compute the following two quantities f1 = 1/Nobs * sum(|c_i-m_i|)where the sum is over all data points, and || means absolute value, and similarly f2 = 1/Nobs * sum((c_i-m_i)/|c_i-m_i|)
- f1 measures departures from the uniform sampling expectation, andis akin to KS test. It ranges from 0 (perfect sampling) to 0.5 (all data taken on the first or last night).
- f2 simply measures whether the sampling is "front-loaded"(the first half of the survey) with 0<f2<1, or "back-loaded" with -1 < f2 <0)
- Then define FOM=f1*f2
  - which varies from -0.5 to 0.5. It's amplitude is driven by f1 and signby f2. For perfectly uniformly sampled data, FOM=0, for front-loaded FOM=0.5 and for "oh my gosh the survey finishes tomorrow and we haven't observed this field yet - let's do it tonight" we have FOM=-0.5.It has better properties than for simply looking at the mean (or median)and standard deviation of the observation times (for similar reasons that make KS such a powerful statistical test).

KS uniformity metric – Implementation

- Apply to every field-filter vector of visits
- Tmin and Tmax are the times of first and last visits in the survey (same for all fields). Define DT as Tmax – Tmin.
- Nobs is the number of visits for the field-filter
- Tn is the time of visit n for the field-filter
- T1 is the time of the first visit
- Tnobs is the time of the last visit
-

F = (1/DT)*[

-(0.5*(T1 + Tmin) – Tmin)/DT))*(T1 – Tmin)
+SUM(n=1 to Nobs-1) [
((n/Nobs) – (0.5*(Tn + Tn+1) – Tmin)/DT) * (Tn+1 – Tn)

+(1 – (0.5*(TNobs + Tmax) – Tmin)/DT)*(Tmax – Tnobs)]
]

Multi-color visits

- For all fields
  - Collect all visits in all filters in a time-ordered list (typically 2000 visits)
  - For each visit, find the time intervals in hours until the next visit in a different filter (now we have ~2000 numbers)
  - Sort the list of intervals into order, small to large
  - Find the mean of the smallest 10 (30, 100) entries
  - Plot the mean vs field number
  - For metrics, find the mean for all fields of the means for each field for smallest 10 (30, 100)
- Create a single binned plot of the combined interval lists
- Create a cumulative plot (small to large values of time)
  - For metrics, find the values at 1 hour and 10 hours.

Uniformity of sky coverage

- For year 1, years 1-2, and years 1-Nyear (initially Nyear = 3)
- For each field
  - Count the number of visits in each filter (6 counts for each field) which satisfy quality criteria
  - seeing < SEEmax(filter) (initially SEEmax = 1.5)
  - filtsky > SKYmax(filter) (initially SKYmax = a small number)
  - xparency <= Xmax (initially Xmax = 0.0)
- For each field and each filter
  - Determine which fields have at least Nvis qualifying visits (initially Nvis=3)
    - Make an Aitoff plot
- Metrics
  - For each field (if possible, separately for main survey and "other")
    - Count the fields with fewer than Nvis visits

Operations Simulator Tools for Analysis and Reporting
Variables and Transients
Opsim3.61

Operations Simulation Team
Large Synoptic Survey Telescope

Release Beta 1.0

These metrics describe aspects of the observing cadence and timing of visits to fields, with respect to the time scale of variability of transient and variable sources. The characteristics described are the timing of visit pairs, the time scales of well-sampled sequences, the number of sequences acquired suitable for study of supernovae, and the complete phase coverage achieved for periodic variables.

Visit Pairs

Visit pairs can detect variation of a source with a characteristic time similar to the interval between the pairs. Figure 1 shows the number of visit pairs to any field vs the time interval between visits (dt). All filters are considered, but pairs must consist of visits in the same filter. The behavior of the function for large intervals (log(dt) > 4) are not very sensitive to the details of the survey. The average value of the bins between log(dt) = 0 and 2 is adopted as a metric for visit pairs. Additional metrics are the numbers of visit pairs in any filter (both visits in the same filter) in 12 hour bins from 12 to 72 hours.

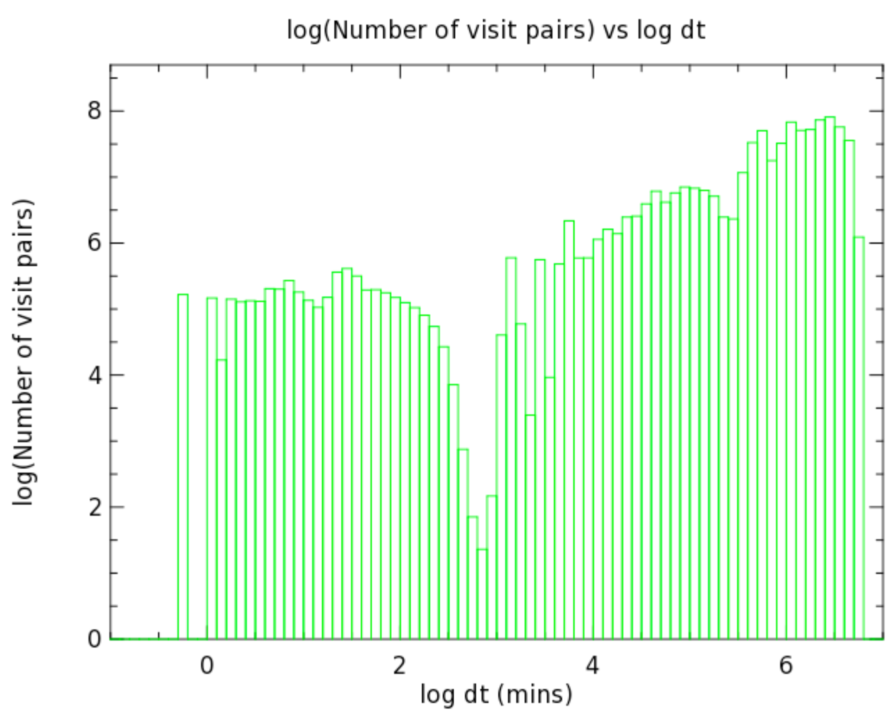


Figure 1. The log(number of visit pairs) to fields per bin in log(dt), where dt is the time between visits. (Graph file title: opsim3_61_logvisitpairs_logdt.png).

Sampled Sequences

In order to characterize a transient of arbitrary flux-time profile, it is naturally preferred to have a sequence of consecutive measurements which are properly sampled (in the Shannon sense) with respect to the characteristic time – which initially is of course not known. As a surrogate for such an ideal time series, Figure 2 shows the log(number of sequences) vs the longest interval between any pair of visits in the sequence, for several values of sequence length (6, 8 and 10). All visits must be in the same filter. Overlapping sequences in the same bin are rejected, but are counted if they fall in different bins.

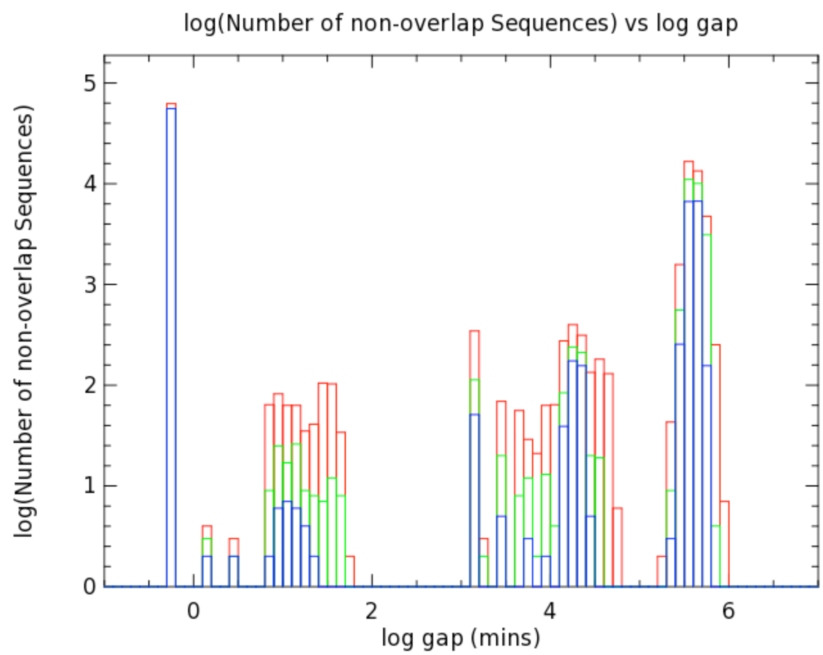


Figure 2. The log(number of sequences) to fields per bin in log(gap), where gap is the longest interval between any two visits in the sequence, for several values of the number of visits in the sequence. The plot shows results for sequence lengths of 6, 8 and 10 visits (red, green and blue respectively). (Graph file title: opsim3_61_lognoofsequences_loggap.png).

Gaps in Long Time Series

For study of slowly and irregularly varying sources, it is desirable to have long time series without large gaps. For r and i filters (separately) the time series of visits to each field was examined to determine the maximum gap, and also the average of the 10 longest gaps (assumed to represent the expected seasonal gaps). The number of fields with such gap values is shown in Figure 3. The number of fields with an average seasonal gap less than 100 days is adopted as a metric for long time series.

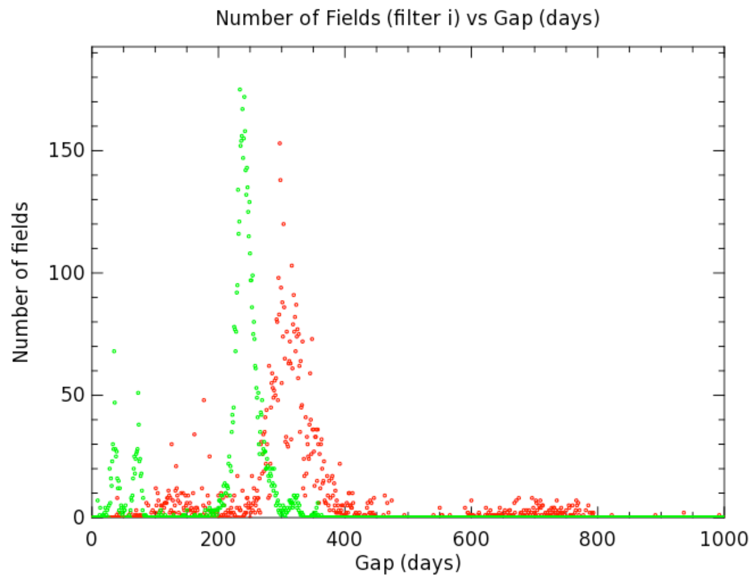


Figure 3. The number of fields which have time series with maximum (red) and typical (green) gap lengths of Gap days.

Time Series for Supernova Studies

The LSST Science Book chapter on supernova studies with the main survey defines a precise minimum requirement for time series required. The minimum number of visits required for such a time series is 7, and the minimum number of filters is 2. The number of days on which a supernova reaching maximum brightness in a field would be properly sampled by visits before and after is an appropriate count. In Figure 4, the number of such supernova "field-days" is shown for 7, 14, 21 and 28 total visits and at least 4 filters in the visit sequence. The adopted metric is the total number of field-days for 14 visits in 4 filters (ie the sum of the green histogram in Figure 4.).

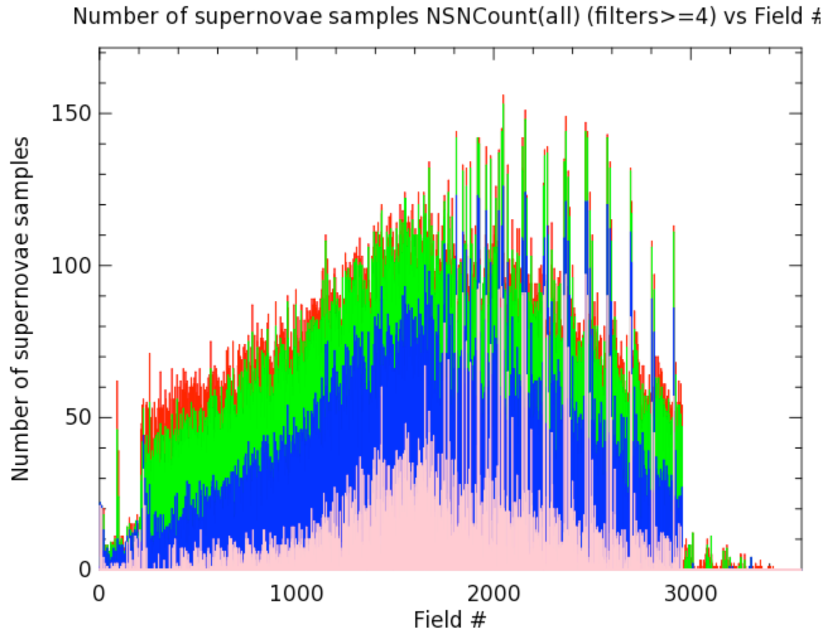


Figure 4. The number of days for each field for which supernovae at max would have good sampling, with at least 7, 14, 21 or 28 visits total during the specified interval (red, green, blue, pink respectively) and at least one visit in each of 4 filters. The peaks on the right are clumps associated with the deep drilling fields.

Sampling of Periodic Variables

This merit function is oriented toward strictly periodic variables, in which measurements from different cycles can be combined according to phase to make a single composite variability function. For each field, all visits are considered. All possible periods between log(P) = -1 and 3.5, at increments of 0.01 in log(P), where P is in days. The visits are then ordered by phase for each value of log(P) and the largest phase gap is noted.

Figure 5 shows the median largest phase gap for all fields for each period bin. The peaks are of course associated with the expected poor sampling for 1.0 sidereal days and 1 year. Since this effect is well known and expected, we adopt as a metric the median value over the range log(P) = 1.1 to 2.4, thus representing the phase coverage for the majority of periods of interest.

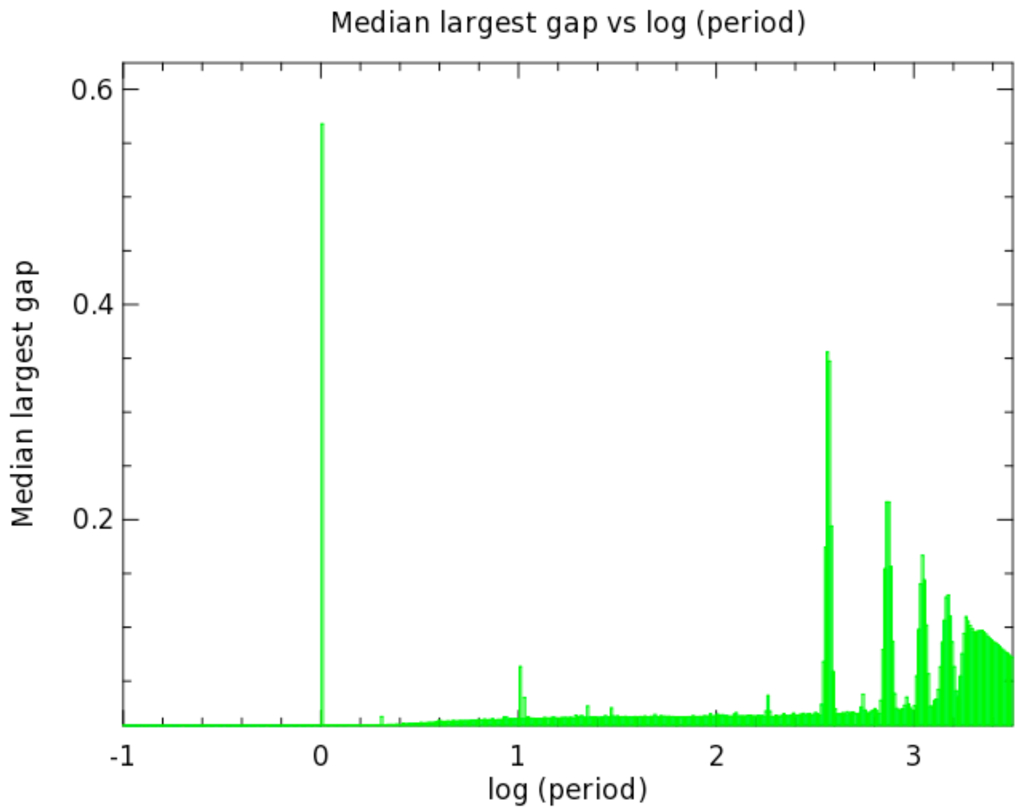


Figure 5. The median of the largest phase gap is shown for all fields for each value of log(P), where P is period in days.

Summary of Transient and Variables Metrics

Simulation	3.61
Visit Pairs Metric	10^5.21
Short interval mean value	
Sampled Sequences Metric	
Number of sequences with at least 8 visits	
dt = 3 min - 12 hours	123
dt = 1 – 70 days	748
Long Sequences Metric (r, i)	(424, 859)
Number of fields with no gaps > 100 days	
Supernova Sequences Metric	
Number of field-days with useful sequences (14 visits, 4 filters)	157092
Number of field-days with excellent sequences (28 visits, 6 filters)	8163

Periodic Variables Metric (all filters)

Median phase gap for log(P) = 1.1 to 2.4 0.0169

Appendix: Algorithms

Input

- Stephen Bailey on gap analysis – Jan 3, 2010 and Oct 1, 2010 email
- Andy Becker and Abi Saha on sampling of variables – March 9, 2010 email
- Abi Saha–Oct1, 2010 email
- Zeljko Ivezic on revisit interval – Mar 12, 2010 email
- Chris Fassnacht – Jan 4, 2010email
- Phil Marshall – Dec 22, 2009; Jan 1, 2010 emails
- Neil Brandt – Dec 18, 2009 email
- LSST Science Book – page 384 on SN sampling

Long time Series Gap Analysis

- For each field, look at ri images only
    - Make a list of gaps between visits
        - Include an initial gap between the start of observations and the first visit, and a final gap between the last visit and the end of observations.
    - Arrange the gaps in *decreasing* order
    - Make a plot vs Field number of
        - The largest gap
        - The average of the 10 largest gaps
    - Make a histogram of the number of fields vs largest gap and another vs the average of the 10 largest gaps
- Compute the 25, 50 and 75% points of each histogram as metrics

Supernova Sampling

- Assume that SNe will occur in every field on every day.
- For each field and each day, determine whether or not the associated sampling satisfies the requirements of LSST Science book page 384
    - One visit at $T < -5$ and one at $T > +30$
    - At least 7 nights with visits ($-20 < T < 60$)
    - No gap greater than 15 days in the range (-5 to 30)
    - Multiple filters (Nfilt) needed in order to determine colors
- Count the number of field-days for which suitable observations are acquired, for different numbers of Nfilt.
- Parameters
    - FirstNt - first night studied (initially = SurveyStart + 5)
    - LastNt – last night studied (initially = SurveyEnd – 35)

Supernova Algorithm

- For each field, collect all visits in time order

- (Nights are designated by sequential integers)
- Test the data set for suitable coverage for a possible SNe with restframe max on each night, Nt, in the range FirstNt to LastNt (to allow time for required preceding and following visits)
- Find which nights satisfy the SN requirements
  - At least one visit at <=Nt– 5 and one at >= Nt+30
  - At least 7 nights with visits in the range Nt-20 to Nt+60 (count the number of visits, NSNcount
  - No gap greater than 15 days in the range (Nt-5 to Nt+30)
  - Count the number of filters observed in the range Nt-5 to Nt+30, Nfilt
- Prepare a histogram with the number of accepted qualifying nights, SNnights, for each field, by field number, with separate curves overplotted for Nfilt =1, 2, 3, and 4 or more
- Prepare a histogram of number of nights SNnights, summed over all fields, vs number of visits NSNcount, with separate curves overplotted for 1, 2, 3, 4 or more filters.
- As metrics, find the 25, 50 and 75% points of the integrated probability of each SNnights histogram.

Periodic Variable Algorithm

- For each field, select all visits in the list FilterList and arrange them in time-order
  - Loop through periods LogPmin to LogPmax by steps of DeltaLogP
  - For each value of P, step through the list of visits and compute the phase of the visit with respect to the first visit, and create a list of phases for this field and this period
    - Phase = mod(MJD – MJD0, P)/P
  - Sort the list of phases from smallest to largest. Scan the list and find the largest gap in phase.
  - Create an array of largest gaps, with one entry for each period tested. (For DeltaP = 0.01, this array will hold about 500 entries.) There will be such an array of gap vs period for each field.
- Average all the arrays of gap vs period to get one array of average gap vs period and plot it.
- Plot the largest gap for any period vs Field number.
- Stop here.
- *Create a histogram for each Period Group, including data for all fields. Integrate from small to large values. Characterize with the 25, 50 and 75%, and largest values at each P.*
- *Plot the 25, 50 and 75% and largest values vs logP*
- *As metrics compute the median of the 50% and largest values.*

Periodic Variable Parameters, Flags and Initial Values

- FilterList – list of filters accepted for merit function, initial value = All Filters
- LogPmin - log of the minimum period studied, P in days, initial value = -1
- LogPmax - log of the maximum period studied, P in days, initial value = 3.5
- DeltaLogP – step in log(P) to be used in exploring periods, initial value = 0.01
- *Period Groups (initially):*
  - *0.5-0.95 days*
  - *1.05-10 days*
  - *10-100 days*
  - *0.95 – 1.05 years*

- *1.2-5 years*

Visit Pairs Algorithm

- For each field, step through the visits.
- For each visit, find all future visits to that field in the same filter, note the time difference (DT), and save the DT value.
- For each field, find the number of DT pairs in the time ranges DT1-DT2, DT3-DT4, DT5-DT6, and plot these superimposed on a histogram vs field number (these intervals are poorly covered by LSST).
- Prepare a histogram of the total number of visit pairs vs the time difference. For the histogram use N vs log(DT), with DT in minutes. Prepare the histogram for log(DT) in the range Logdtmin to Logdtmax, with bin size of DtBin.
- Parameters:
  - Logdtmin = minimum DT in minutes (initially = 0)
  - Logdtmax = maximum DT in minutes (initially = 5)
  - DtBin = bin size in log(DT) (initially 0.1)
  - Initial values of DT1-6: 12, 24, 36, 48, 60, 72 hours

Sampled Sequences Algorithm

- For each field, prepare a sequential list of visits.
- For each visit, find the interval GAP until the next visit to the same field in the same filter.
- Find each successive visit and each previous visit to the same field in the same filter. As long as the interval between successive visits and previous visits is no greater than GAP, continue adding visits to the sequence. Stop adding visits at the first previous interval > GAP and the first following visit interval > GAP.
- The start of the sequence is designated MJDfirst and the end MJDlast.
- Find the number of intervals spanned by the sequence, Nint = (MJDlast – MJDfirst)/GAP.
- If Nint >= Nmin, then save the sequence. Nmin is the minimum number of acceptable samples in a sequence.
- Save the following information:
  - Field, filter, MJDfirst, MJDlast, GAP, Nint, Nvis, Nother
  - Nvis is the total number of visits to the field in the primary filter between MJDfirst and MJDlast.
  - Nother is the total number of visits to the field in all other filters between MJDfirst and MJDlast.
- Sort the list of sequences by Nint from largest to smallest (longer sequences are more valuable)
- Determine what bin of GAP the first (longest) sequence falls in. Then delete from the list all subsequent sequences that:
  - Are in the same bin of GAP, and;
  - Have any visit in common with the first sequence.
    - This avoids counting a sub-sequence twice in the merit function
- Repeat for all sequences from longest to shortest, deleting according to this rule.
- We now have a list of qualifying sequences for the field which satisfy the criteria, ordered from longest to shortest. Each sequence has several parameters that describe it.
- Repeat for all other fields.
  - This algorithm may be slow – might want to try for a subset of fields first.

- In preparing the histograms (below) add together all qualifying sequences for all filters and all fields.
- Plot a histogram of the number of sequences (all fields, all filters) for bins in Log(GAP).
    - Make the histograms vs log(GAP), with GAP in minutes. Prepare the histogram for log(GAP) = LogGAPmin to LogGAPmax, with bin size of GAPBin.
    - Parameters:
        - Nmin = minimum sequence length in samples (initially = 10)
        - LogGAPmin = minimum log(GAP) in minutes (initially = 0)
        - LogGAPmax = maximum log(GAP) in minutes (initially = 5)
        - GAPBin = bin size in log(GAP) (initially 0.1)
- Plot the median values of Nint, Nvis, and Nother, computed for the sequences in each bin, against Log(GAP)

Metrics are TBD after we see the results

For each field, consider each gap between adjacent visits as the possible largest gap in a sequence in its filter. In this example, examine visit V(i) and V(i+1) as a candidate starting point for a sequence. All visits below are in the same filter.