LSST Solar System Survey: Cadence and Sky Coverage Requirements

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Solar system goals with LSST include cataloging small Potentially Hazardous Asteroids (PHAs), surveying the main belt asteroid population to extraordinarily small size (where radiation pressure effects may play a dominant role in sculpting orbital distributions and spin states), discovering comets far from the sun where their nuclear properties can be discerned without coma, and surveying the Centaur and Kuiper Belt populations. The present planned observing strategy is to "visit" each field (8 sq. deg. net non-overlapped) with two successive exposures of ~10 sec, reaching to at least V magnitude 24. An intra-night revisit time of not less than ~20 minutes will distinguish stationary transients from even very distant (~70 AU) solar system bodies. The nightly cadence should be two, or possibly 3, visits spaced by about half an hour. In order to link observations and determine orbits, each sky area must be visited on two, or better 3, nights during a month, spaced by about 5 days. Formally, two visits on two nights (2/2) is sufficient for orbit determination, but 2/3, 3/2, or 3/3 cadences would yield detection threshold improvements nearly enough to offset the additional time taken, provide redundancy for missed detections, and result in better orbit determination. We therefore recommend the 2/3 cadence.

We have explored the efficiency of the PHA survey with less than all-sky coverage. It appears that covering a band of the ecliptic ±10° in latitude and ±120° in longitude from the opposition point, less a swath ±20° in galactic latitude through the ecliptic plane, is sufficient to achieve nearly "all-sky" efficiency of surveying, requiring only ~4,000 sq. deg. per month. However, much of this area must be imaged at air mass >1.5, unsuitable for some of the other scientific goals of LSST. It appears that a survey in r band only of <2000 sq. deg. per month that must be reached at higher air mass, combined with coverage in g, r, and i filters done as a part of the astrophysical surveying, can meet the goals of the solar system survey.

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Survey Cadence, object linkage, and orbit determination

The limiting S/N (and limiting magnitude) for the discovery of moving objects depends primarily on the tolerable number of false linkages (association of an image on one frame with an image on another frame) due to statistical noise, and on the loss of real linkages because one or more detections slip below the detection threshold.

A cadence for PHA discovery will define the number and spacing (the integration time is predetermined) of frames within a lunation. The cadence parameters lead directly to the effective limiting magnitude that is attainable in such a search. When the limiting magnitude is known, a figure of merit based on the number of observable PHAs can be calculated, and the best cadence can be selected.

Orbital accuracy considerations led us to the conclusion that observations of a given PHA need cover an arc no longer than 10 days during any given lunation. Linkage of one night's detections with another is best accomplished if the shortest interval between observations does not exceed about five days, although in specific cases there can be considerable latitude in this interval.

Therefore, our modeling effort has concentrated on cadences comprising two and three nights/lunation and spanning 10 days. In the table below, we assume that 50 hours/lunation are available for a PHA search; that each visit to a region comprises two back-to-back 10-s exposures separated by 1 sec readout time; and that visits are separated by 5-s step-and-settle time. Pairs of visits are, somewhat arbitrarily, separated by 1 hour (the results are not sensitive to this interval). The effective rate of sky coverage per hour is 83% of the total sky coverage because of hexagonal tiling of frames on the sky. *B* is the half-width (in latitude) of an ecliptic-centered zone extending $\Delta\lambda$ deg east and west from opposition (assuming a Mercator areal projection. The purpose of this simulation is to determine the relative advantage of various survey cadences, thus we ignore the difficulty or impossibility of actually observing large ecliptic-centered regions from most locations on Earth; we also ignore the fact that the latitude coverage is quantized by the width of LSST's FOV). Detection losses due to PHA image trailing, although negligible, are included. The Figure of Merit is the number of modeled PHAs larger than 200 m diameter that are present in the appropriate search area to the tabulated effective limiting magnitude (which is assumed to be a step function). We assume that the larger the figure of merit, the more successful the cadence. However, we note that the FOM pertains to a "snapshot" of the PHAs present, and may not be a perfect surrogate for the success of an extended search. Our model results pertain to nights of good seeing, when it is expected that pairs of exposures will be taken through *r* and *i* filters. We derived the S/N for each frame from the LSST exposure calculator, and assumed that the *r* – *i* color index for PHAs averages + 0.4 mag. To first order, the limiting magnitude of a PHA search is constrained by the throughput of the *i* filter. The limiting magnitude of all the modeled cadences is *R* = 24.3 mag.

			$\Delta\lambda$ = 120°		$\Delta\lambda$ = 90°	
Visits/Night	Nights/Lunation	Effective Sky Coverage (sq. deg./hour)	*B* (deg)	Figure of Merit (FOM)	*B* (deg)	Figure of Merit (FOM)
2	2	277	28.8	1420	38.4	869
2	3	184	19.2	1215	25.6	750
3	2	184	19.2	1208	25.6	745
3	3	123	12.8	977	17.1	616

We comment as follows:

Two visits on 2 nights/lunation (2/2) produces the highest FOM because of the large areal coverage. 2/3 and 3/2 cadences are very similar to each other, as expected.

We recommend using a 3-night/lunation cadence, both for accurate orbit computation within a lunation and to improve detection because of lightcurve variations. The 2/3 cadence is best.

Comparing $\Delta\lambda$ = 120 deg with $\Delta\lambda$ = 90 deg, we see a decrease in FOM in the latter case. This is consistent with our survey models (right), which clearly show that an ecliptic-centered survey is superior.

Our cadence results are insensitive to other variables. For example, changing the intervals between internight visits, but keeping the total interval constant at 10 days, led to a change of only 0.1 mag in limiting magnitude. Also, computed FOMs for PHAs larger that D = 100 m and larger than D = 400 m indicated no change in the best cadence.

In summary, we advocate two pairs of observations per night on three nights per lunation in good seeing during gray or dark time for an effective PHA search. Observations through z or Y filters are likely to contribute little to the effectiveness of a PHA search.

Magnitude loss with increasing zenith distance

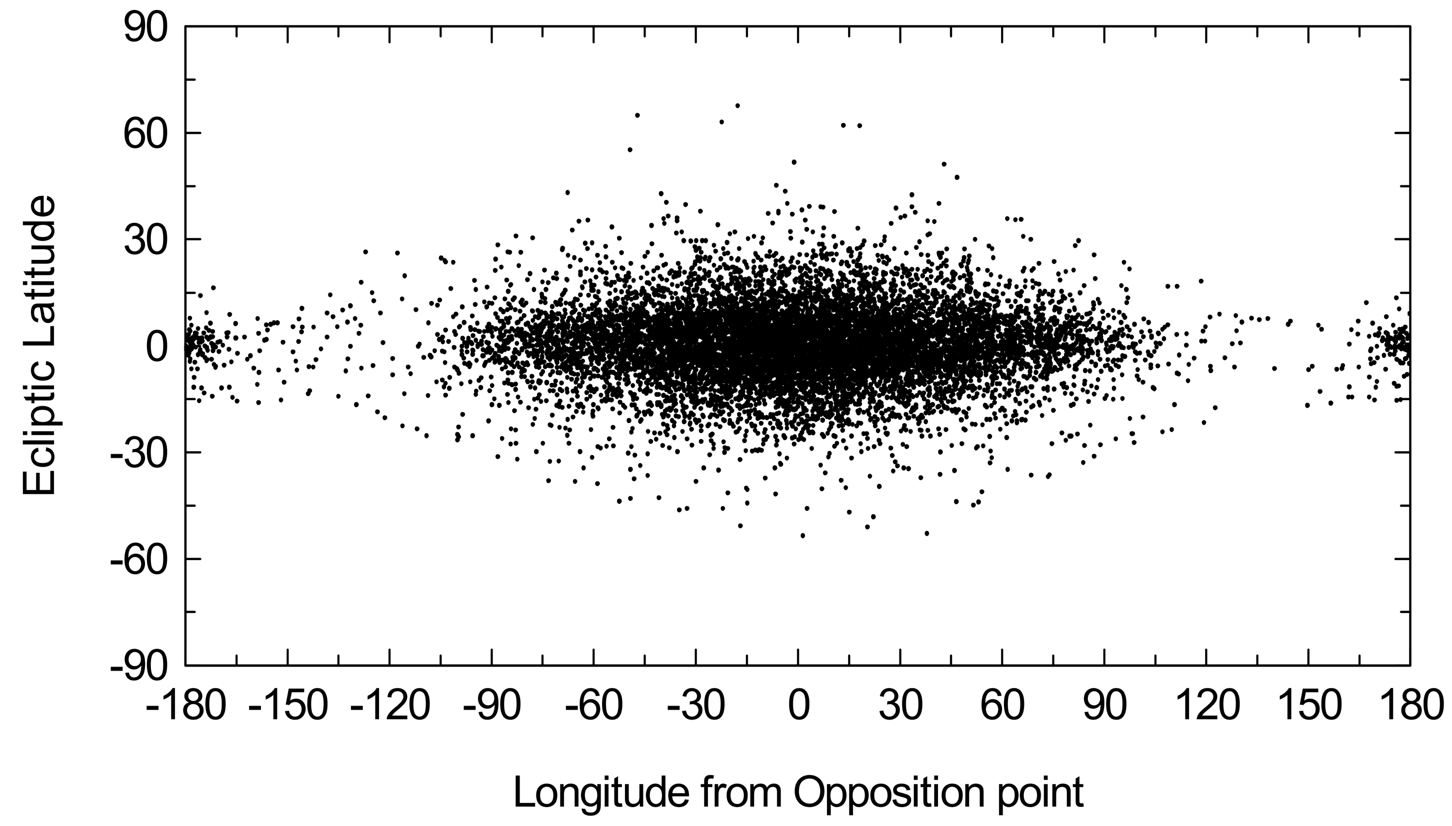
Limiting magnitude degrades with increasing zenith distance due to three effects:

- Atmospheric extinction reduces the signal received
- Degradation in seeing leads to more background light (noise) underlying the signal.
- Sky background generally increases with zenith distance, e.g. increasing path length of air glow, light pollution.

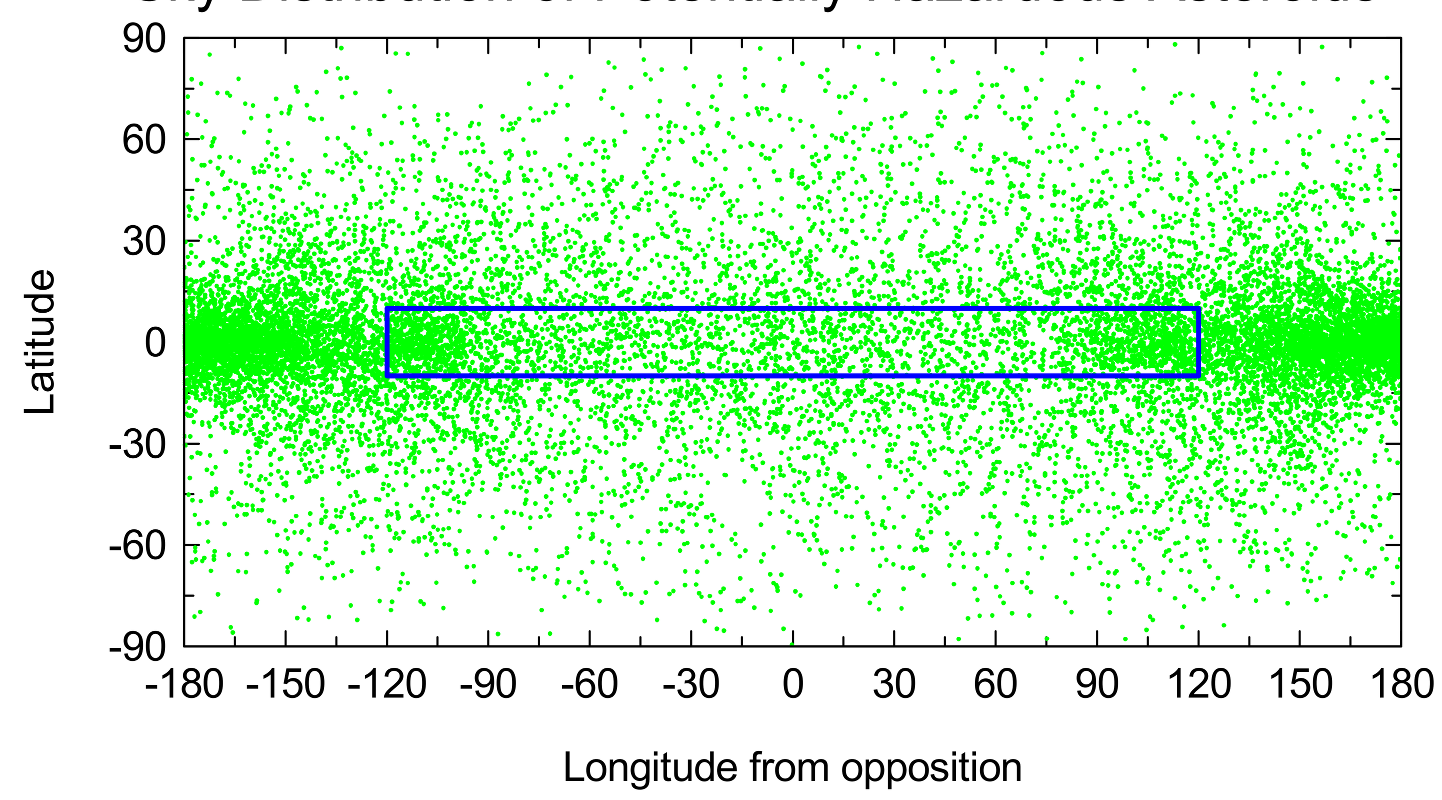
The combination of these effects can be well represented as a log function of air mass, $dm_{lim} = -A\log X$. For various reasonable models of extinction, seeing degradation, and sky background, we find values of *A* in the range from 1.7 to 3.1. In the survey models presented here, we adopt a value of 2.0.

To simulate a survey, we generate a set of 1000 synthetic orbital elements that match the distribution of discovered objects in the large size range where present surveys are essentially complete. We compute positions and magnitudes in the sky at five day intervals for ten years. This file is saved and then in a second program, we "filter" the file according to assumed sky coverage and cadence pattern, limiting magnitude of survey instrument, visibility constraints, and magnitude loss according to observing conditions. All objects are taken to be the same "size", and the observation file is "filtered" repeatedly for different assumed values of absolute magnitude H, each time tabulating how many of the 1000 objects are "discovered".

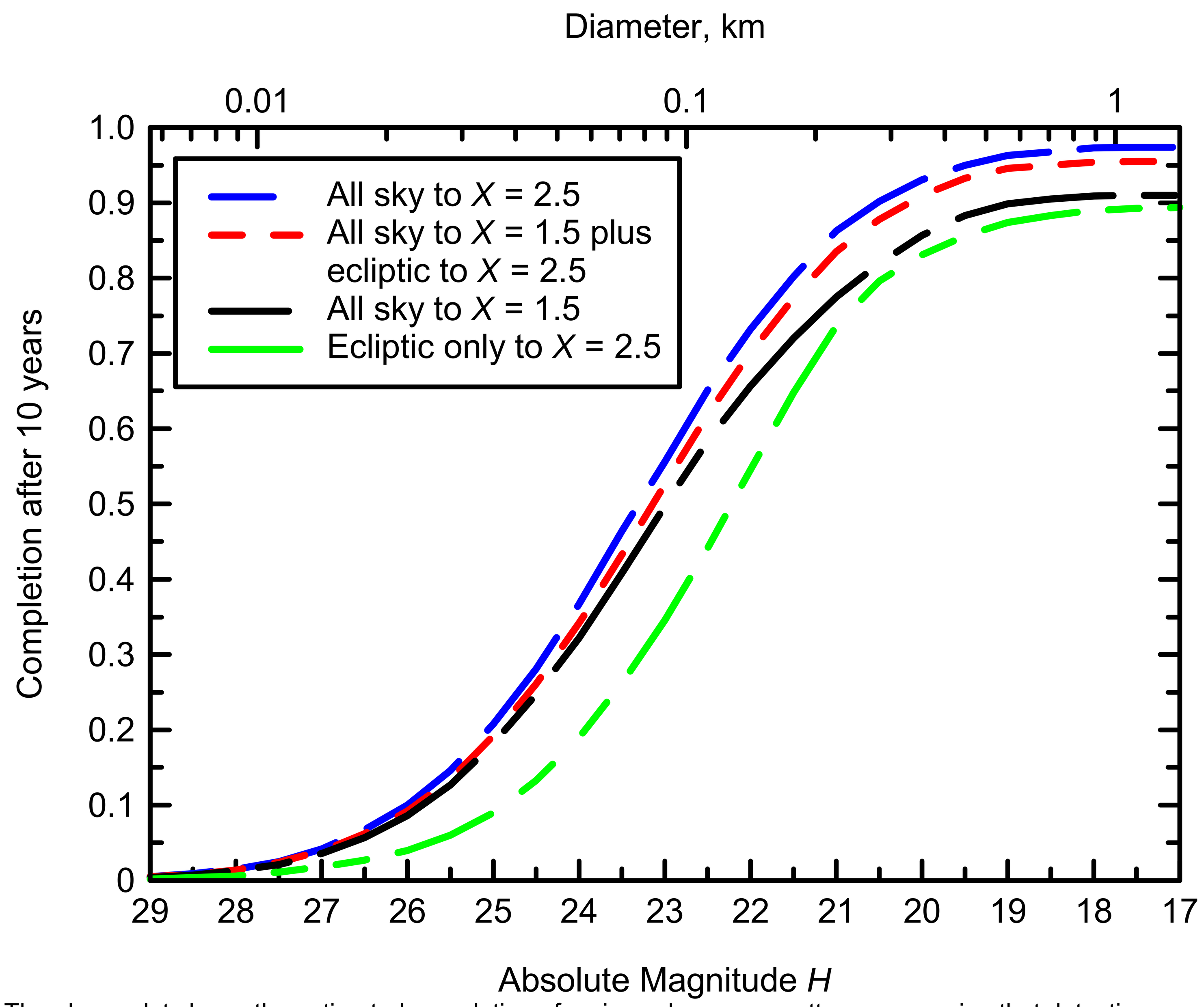
Sky Distribution of Main-Belt Asteroids



Sky Distribution of Potentially Hazardous Asteroids



It is clear from the above plots that it is essential to cover the ecliptic band to as great an elongation as possible. We find a band extending ±10° in latitude and ±120° in longitude from the opposition point (blue box in figure above) yields good efficiency in surveying for PHAs. This is true because even objects in highly inclined orbits must pass through the ecliptic sometime. Nevertheless, adding coverage of the rest of the sky that can be reached at low air mass (X < 1.5) significantly improves the survey efficiency.



The above plot shows the estimated completion of various sky survey patterns, assuming that detections on two days out of three days observed in a month suffices for orbit determination. A moderate magnitude loss with air mass of $dm_{lim} = -2.0\log X$ was applied. Clearly neither the all sky to X = 1.5 nor the ecliptic only to X = 2.5 perform well compared to all sky to X = 2.5, but the combination of all sky to X = 1.5 plus the ecliptic band to X = 2.5 is nearly as good as covering all sky to X = 2.5. This pattern can achieve a survey completion in ten years of about 90% of objects larger than ~350 m diameter.