High-fidelity Simulations of the Near-Earth Object Search Performance of the Large Synoptic Survey Telescope

Peter Veres\(^1\) and Steven R. Chesley
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA; peter.veres@cfa.harvard.edu

Received 2017 March 2; revised 2017 May 11; accepted 2017 May 15; published 2017 June 20

Abstract

We perform high-fidelity simulations of a wide-field telescopic survey searching for Near-Earth Objects (NEOs) larger than 140 m, focusing on the observation and detection model, as well as detection efficiency and accuracy. As a test survey, we select the Large Synoptic Survey Telescope (LSST). We use its proposed pointings for a 10-year mission, and model the detection of NEOs in the fields. We discuss individual model parameters for magnitude losses, vignetting, fading, asteroid rotation and colors, fill factor, limiting magnitude, rate of motion, field shape and rotation, and survey patterns. We assess results in terms of the cumulative completeness of the detected population as a function of size and time. Additionally, we examine the sources of modeling uncertainty, and derive the overall NEO population completeness for the baseline LSST survey to be 55 ± 5% for NEOs with absolute magnitude brighter than 22. Including already discovered objects and ongoing surveys, the NEO completeness at the end of the LSST baseline survey should reach ~77%.

Key words: methods: numerical – minor planets, asteroids: general – surveys – telescopes

1. Introduction

The number of currently discovered asteroids is about 730,000, the vast majority of which are found in the main asteroid belt. The size of the asteroid catalog has skyrocketed since the dawn of automated, CCD-based asteroid surveys only two decades ago. The first asteroid discovered, Ceres, was detected in 1801; since 2006, it has been classified as a dwarf planet. In 1900, only 545 asteroids were known. The first Near-Earth Object (NEO), 433 Eros, was discovered two years earlier. In 1992, recognition of NEOs as a potential threat to Earth led the US Congress to mandate that NASA discover 90% of NEOs larger than 1 km within 10 years. Thus, the Spaceguard survey, aimed at the discovery and study of NEOs, was established. The first generation of dedicated asteroid surveys was developed under this initiative, e.g., Spacewatch (McMillan & Spacewatch Team 2006), LINEAR (Stokes et al. 2000), NEAT (Pravdo et al. 1999), and LONEOS (Koehn & Bowell 1999). As a direct result of these efforts, the number of NEOs increased from 649 in 1998 to over 5000 in 2008, and as a byproduct, other small-body populations of the solar system were discovered as well, ranging from main-belt asteroids, to Jupiter Trojans, Centaurs, Kuiper Belt objects, and comets. With new technologies becoming available, and new challenges such as impact hazard mitigation of smaller NEOs, potential commercial activities like asteroid mining, asteroid sample return, and asteroid redirection, as well as crewed mission concepts to an NEO, a new target was established to discover 90% of NEOs larger than 140 m. The next generation of solar system surveys has now emerged, notably, Pan-STARRS (Kaiser et al. 2002; Hodapp et al. 2004) and the Catalina Sky Survey (Larson et al. 2003; Christensen et al. 2012). These search efforts are now dominating NEO discoveries, which reached 15,000 in 2016. Meanwhile, NEOWISE (Wright et al. 2010) is a space-based infrared telescope that is finding many asteroids, and providing diameter estimates for even more. However, the current NEO completeness for 140 m and larger objects is only about 30%, and the currently operating search programs will not able to achieve the 90% goal in the next few decades. Therefore, a number of future projects have been proposed, and are in varying stages of development, such as the Zwicky Transient Factory (Smith et al. 2014), NEOCam (Mainzer et al. 2015), and LSST (Jones et al. 2017).

Survey discovery rates and statistics, along with information on the sky coverage and telescope sensitivity, are widely used for determination of the population counts and statistical distribution of orbital elements. For instance, Bottke et al. (2002), Stuart & Binzel (2004), Mainzer et al. (2011), Harris & D’Abramo (2015), Granvik et al. (2016), and Schunová-Lilly et al. (2017) have utilized discovery statistics and the telescopic biases to derive NEO population properties. This reverse engineering and debiasing led to estimates of the size-frequency distribution of a given population, and is a key source of information about the current state of the solar system inventory—as well as an input for modeling the origin and evolution of planets and minor bodies. These models have uncertainties, mostly originating from errors in determination of the absolute magnitude H of asteroids, as well as poorly understood search and detection efficiencies of individual surveys.

The opposite approach allows prediction of discovery rates for current and future telescopes. This requires knowledge of the key parameters of the telescopes and their detection pipelines. Even though simulations on discovery rates have been performed for solar system surveys, the limiting parameters, errors, or uncertainties are often omitted, and their effects have not been discussed or fully disclosed in the literature. Without a complete description of the input parameters and their effect on the detection efficiency, a useful comparison of survey simulations done by different authors is challenging and often infeasible. Traditionally, “discovery” means not just the first observation of an asteroid, but also its confirming astrometry from the following nights until a provisional orbit is obtained. Future
large-scale, deep, all-sky surveys, like LSST, will not have the luxury of follow-up confirmation and will depend on self-follow-up capabilities. This will remove the difficult-to-model human factor from the process of discovery. Moreover, automated pipelines and processing are now more frequently responsible for object detection and reporting, which allows a more exact description of the input parameters and detection thresholds. Surveys also detect objects already discovered and have to identify them in the pipeline.

Our work is focused on NEO detection and discovery rates, and variations thereof as functions of the selected observational and detection parameters. We studied a broad range of effects, including the magnitude variations due to vignetting, asteroid colors and light curves, the rate of motion of asteroids, limiting magnitudes, the probability of an object being detected when near the faint limit, the shape and rotation of the field, fill factor, the survey search pattern, and the overall sky coverage. As a case study we consider the Large Synoptic Survey Telescope (LSST), which will be commissioned in 2020 and begin its main 10-year mission in 2022. Even though LSST will be mainly focused on understanding and studying dark matter and dark energy, its all-sky coverage, large aperture, and the largest CCD camera in the world make it an effective solar system cataloging tool. It is predicted to increase the number of known Main belt asteroids to 5,000,000, NEOs to 100,000 and Trans-Neptunian Objects to 40,000 (Jones et al. 2016). We used the Moving Object Processing System (MOPS, Denneau et al. 2013) to simulate the detections, as well as to link detections into tracklets. MOPS and its variations have been used to process real data of Pan-STARRS, DECam (Flaugher et al. 2015), and NEOWISE, and will be used by LSST. MOPS computes ephemerides of input synthetic orbits with defined \( H \) for a set of telescope pointings, provides visible detection lists, and submits it to the next stage to create tracklets, which are the single-night detections of a candidate moving object. MOPS is capable of linking inter-night tracks and derived orbits—however, it has never been tested in such a high-density detection and tracklet environment like LSST. Thus, our work assumes that the linking to orbits will work on the available collection of tracks. In a separate paper (Vereš & Chesley 2017), we consider the linking efficiency problem for LSST with MOPS.

The primary survey performance metric of this work is the cumulative completeness of the detected NEO population in detections, tracklets, and available three-night tracks as a function of \( H \), particularly for \( H < 22 \) NEOs (\( G_i < 22 \)), and as a function of time. We also study the effects of using two input NEO populations, as well as the detection efficiency of Potentially Hazardous Asteroids (PHAs). Additionally, we compare our results with previous work.

### 2. LSST Simulation Approach

LSST (Ivezic et al. 2014) is being built atop Cerro Pachón in Chile. It is funded by the National Science Foundation, the Department of Energy, and private contributors. LSST is a next-generation optical and near-infrared all-sky survey telescope, with the mission of sparse sampling of the sky in short exposure times (Table 1). A single 30 s exposure with a 9.6 square degree field of view will achieve 24.5 magnitude depth in the \( r \)-band. LSST will scan 6000 square degrees per night. Because of the unprecedented quantities of data and LSST’s real-time alerting requirements, the detection, processing and data handling will be fully automated.

Scheduling of the visited fields is done through the Operations Simulator (OpSim, Delgado et al. 2014). Fields are visited in five “proposals,” each focusing on a different science objective. Most of the time (85%) is spent in the universal proposal that covers the entire Southern Hemisphere; the rest is divided between coverage of the Galactic Plane, Northern Ecliptic Spur, South Celestial Pole, and a few deep drilling (DD) fields (Figure 1). The final survey pattern is not yet selected, but several scenarios have been tested. We used some of the more relevant OpSim runs for our simulations: the old LSST baseline enigma_1189, the new baseline minion_1016, and the NEO-enhanced astro_1016 (which we abbreviate from the full simulation designation astro_lsst_01_1016). Most of the fields are observed twice per night, except for two enigma_1189 variations where three (enigma_1271) and four (enigma_1266) visits per night were targeted (Figure 2). Some of the fields are only observed once per night (singletons). These were removed from our simulation because they cannot aid discovery. Also, the DD proposal covers only a few individual fixed fields, which are visited in an extreme revisit cadence (tens of times per night, one by one), and are not suitable for NEO discovery. Therefore, DD was removed as well. The median revisit time between exposures of the same field in a night is 21 minutes; in 94% of cases, the first and last visit are within 2 hr on a given night (Figure 2). Each field is observed in one of the six filters (Table 2), at a specific limiting magnitude, seeing, simulated atmospheric conditions, and lunar phase.

| Table 1 | LSST in Numbers |
|---------|-----------------|
| Location | Cerro Pachón, Chile |
| Primary mirror | 8.4 m |
| Effective Aperture | 6.67 m |
| Focal Length | 10.3 m |
| Wavelength | 320–1060 nm |
| Filters | \( u, g, r, i, y, z \) |
| Mount | Alt-Az |
| Field diameter | 3.5 deg |
| Camera | 3.2 Gigapixel |
| Pixel size | 0.2 arcsec |
| Exposure time | 30 s |
| Start year | 2022 |

Figure 1. Ten-year sky coverage of the enigma_1189 survey. Note that the DD proposal covers only a few (black) fields. Most of the time is spend in the universal proposal, which covers most of the available sky.
Baseline surveys optimized for two, three, and four visits, and the histogram of time spent on fields visited N-times per night.

Table 2
S/N = 5 Limiting Magnitudes (m<sub>s</sub>) of enigma_1189 OpSim Survey and Time Spent in Individual Filters

| Filter | Average m<sub>s</sub> | Max m<sub>s</sub> | Time Spent (%) |
|--------|-----------------------|-----------------|----------------|
| r      | 24.09 ± 0.33          | 24.91           | 22.00          |
| i      | 23.34 ± 0.37          | 24.33           | 22.00          |
| z      | 22.28 ± 0.41          | 23.71           | 20.00          |
| y      | 21.56 ± 0.23          | 22.21           | 18.00          |
| g      | 24.38 ± 0.35          | 25.24           | 10.00          |
| u      | 23.09 ± 0.33          | 23.99           | 7.00           |

We generated synthetic detections for NEO and MBA population models (see Section 2.1) by propagation of the orbits to the epochs of the OpSim fields. The propagation used JPL’s small body codes with the DE405 planetary ephemerides, where all planets (plus Pluto and our moon) were perturbing bodies. We did not use any asteroids as perturbers. Only detections inside of the fields of view were saved into preliminary detection lists. The limiting magnitude m<sub>s</sub> of the field is defined at a signal-to-noise ratio of S/N = 5. Photometric or astrometric errors associated with the astrometry were neglected because they are not relevant to the study approach, which does not include orbit fitting. The following subsections describe the details of the NEO detection modeling approach.

2.1. Population Models

This work tested two NEO population models. Each model is represented by a set of Keplerian orbits with absolute magnitudes H, defined in Johnson’s V-band following the size-frequency distribution.

The first NEO model that we used is from an earlier work (Bottke et al. 2002; Grav et al. 2011). “Bottke’s” model consists of 268,896 orbits with H < 25. A newer model was published by Granvik et al. (2016) after our work was already underway, which we refer to as “Granvik’s” model. It has 801,959 orbits, again down to H < 25. Even though Granvik’s model has three times as many objects, the number of H < 23 orbits is about the same as in the Bottke’s data set (Figure 3). On the other hand, Granvik’s model lacks objects with H < 17.

For simulations, these objects can be omitted because such bright NEOs are few and mostly discovered. The main difference is in the slope of the distribution for H > 23, where Granvik’s population describes the observational data better than Bottke’s early estimate. Bottke’s orbital element distribution does not depend on H, whereas Granvik’s population does. The slight differences between the distributions of orbital elements are evident in Figure 4. Compared to Granvik, Bottke predicted more objects at low perihelion distances and larger eccentricities, whereas Granvik shows an excess at larger perihelion distance and inclination.

The PHAs are a special subset of the NEOs. They are defined as objects with the minimum orbit intersection distance less than 0.05 au and H < 22, where H = 22 corresponds to the diameter of 140 m when albedo is equal to 0.14. We created a subset of PHAs from both Granvik’s and Bottke’s populations.

2.2. Focal Plane Model

The focal plane of a large-format survey telescope usually differs from a simple square or a circular shape. LSST’s focal plane has a square shape consisting of a 5 x 5 grid of 25 rafts, with the four corner rafts removed (Figure 5). Each raft consists of an array of 9 CCD chips, yielding a total of 189 CCD chips. The detectors are 4096 x 4096 pixel CCDs, and so the total number of active pixels is 3,170,893,824. The design of the mosaic camera includes chip and raft gaps that do not contain pixels. Therefore, a detection hitting the gap is lost. The shape of the field can be modeled easily; in the simulation, we numerically compute the location of each detection with respect to the borders of the camera. Fill factor (the gaps) can be simulated either by exact mapping of the grid to the sky-plane coordinates, or by a statistical approach that randomly removes a fraction of detections. The current LSST camera design expects a 90.8% fill factor.

LSST utilizes an altitude-azimuthal mount, and the camera is able to rotate—thus, the fields are not generally aligned with the local R.A.–decl. frame. In fact, due to desired dithering, each exposure is observed in a randomized field orientation. The change of position angle between two exposures in a night (δ<sub>rot</sub>) is small. The average δ<sub>rot</sub> is 5° and the median δ<sub>rot</sub> is 2°4.
2.3. Detection Fading

In survey simulations, the limiting magnitude is often used as a step function cutoff that strictly determines which detections are visible in the simulated field. However, in real surveys, the detection limit is actually better represented by a function that gradually fades near the limiting magnitude to capture the probability of a given detection. The function can be described as

\[ \epsilon(m) = \frac{F}{1 + e^{-(m - m_5)/w}} \]

where \( \epsilon(m) \) is the probability of the detection, \( F \) is the fill factor, \( m \) is the magnitude of the detection, \( m_5 \) is the limiting magnitude of the field, and \( w = 0.1 \) is the width of the fading function. The fading function is depicted in Figure 6, and its effect on detections counts is shown in Figure 7. Because the limiting magnitude is unique per field, the fading function applies on a per-field basis. The importance of using the fading function lies in the fact that it actually allows detection of asteroids fainter than the \( m_5 \) limit. Given the brightness distribution of moving objects, this tends to increase the number of detections in the field with respect to a scenario where only the \( m_5 \) step function was used to determine detection.

2.4. Trailing and Detection Losses

LSST will observe the sky with a sidereal tracking rate, so the static sources will be detected as point-spread functions (PSFs). Asteroids, however, will move in the images within the exposure time. For instance, in a 30 s single exposure, a typical NEA moving at 0.64 deg day\(^{-1} \) (Figure 8) will move by 0.8 arcsec. The expected mean seeing at the LSST site is 0.85 arcsec (Figure 8). Therefore, instead of a PSF, most NEAs will appear trailed (Figure 9), with the fastest objects being the smallest and closest to the Earth. The detected trail may be described as a convolution of a PSF and a line (Vereš et al. 2012). The flux of the moving source is spread along multiple pixels and the per-pixel signal decreases as a function of its apparent velocity. The longer the trail, the fainter is the peak signal. Also, the S/N decreases due to trailing, as the trailed detection contains the sum of noise from a greater number of pixels.

Figure 4. Comparison of orbital element distribution between Botke’s and Granvik’s NEO populations. These density plots reflect the ratio of the normalized density between the respective models.
Therefore, if the model function is traditionally modeled according to static and well-defined sources like unsaturated stars (Jones et al. 2017). Therefore, if the model finds a trail, it only captures a fraction of the flux in it (Figure 9). We call this magnitude loss the “detection” loss (Ivezić et al. 2009). It is described by the function

\[
\Delta m_{\text{Trail}} = 1.25 \log_{10}(1 + cx^2),
\]

where \(c = 0.42\) and \(x = (v\tau_{\text{exp}})/\Theta\) is the trail length in units of FWHM seeing disks \(\Theta\). Here, \(v\) is the rate of motion, and \(\tau_{\text{exp}}\) is the exposure time.

After LSST detects a source, it calculates the \(S/N\) with a number of algorithms, including the use of a trail-fitting kernel, which leads to our second type of trailing magnitude loss. Here, the \(S/N\) of the trail is calculated from the source flux and the noise of the background from the entire trail. The greater the area of the source, the larger the amount of background noise that decreases the overall \(S/N\) of the detection. The magnitude loss due to the \(S/N\) trailing penalty (Ivezić et al. 2009) can be described by the function

\[
\Delta m_{S/N} = 1.25 \log_{10} \left( \frac{1 + ax^2}{1 + bx} \right),
\]

where \(a = 0.76\), \(b = 1.16\), and \(x\) is again the normalized trailing factor (Jones et al. 2017). As shown in Figure 10, the detection losses are a factor of two worse than the \(S/N\) losses, which immediately implies that significantly trailed detections found by LSST will have \(S/N \gg 5\).

2.5. Asteroid Colors

Absolute magnitudes of asteroids are published in the Johnson \(V\)-band and used to calculate the apparent magnitudes. However, LSST will observe in five distinct filters covering the visible and near-infrared (\(u\), \(g\), \(r\), \(i\), \(z\), \(y\)). The transformation to the \(V\)-band depends on the spectral characteristics of the asteroid. Even though distributions of asteroid colors in the main belt are relatively well understood to \(H < 18\) (DeMeo & Carry 2014), sampling of the NEA population is rather sparse. For instance, the SDSS database (Carvano et al. 2010) contains only 174 NEAs, and the Asteroids Lightcurve Database (Warner et al. 2009) currently contains 1115 NEAs with identified spectral type. That is only a small fraction of the NEAs currently known (15,000, as of 2016 November). Bottke’s and Granvik’s NEA populations, which we used in this work, do not include albedo, diameter, or spectral type. We generated the distribution of spectral classes of NEA by the debiased distribution derived by Stuart & Binzel (2004), shown in Table 3. For simplification of the magnitude transformation from LSST filters to Johnson \(V\)-band, we divide these classes into two groups: \(S\) (Q-type, S-type, and high-albedo X-types) and \(C\) (C-types, D-types, and low-albedo X-types). With this scheme, the numbers of \(C\) and \(S\) type asteroids are similar. Also, the generated colors do not depend on \(H\) or orbital elements. The magnitude transformation model used in the study is presented in Table 4. The tabulated color indices are based on the LSST filter bandpasses, with mean reflectance spectra from DeMeo et al. (2009) and the Chance & Kurucz (2010) model for the solar spectrum.

2.6. Light Curve Variation

The apparent magnitudes of asteroids derived from the MOPS ephemerides do not reflect the amplitude variation due to asteroid shapes, rotation, and spin axis orientation. This effect could be significant when the sky is observed in a sparse temporal resolution, e.g., a few times per night. If the asteroid has an apparent brightness close to the limiting magnitude, a change in the brightness due to rotation in the time interval between two LSST exposures can cause the asteroid to be visible in only one of the images. Therefore, the tracklet will not be created and the asteroid would be lost on that particular
night. On the other hand, some asteroids can be brighter than the ephemeris magnitude just because they were observed near the maximum of the light curve, leading to the possibility of finding objects nominally below the detection limit.

In this work, we have generated amplitudes and periods for the model populations based on the debiased model by Masiero et al. (2009). We have extended this model so that it depends on the absolute magnitude $H$ by the method described in Vereš et al. (2015). The simplified light-curve corrections are represented by a sine wave defined by the generated amplitudes and periods at the epochs of the time of observation. This approach does not reflect the real shape of asteroids nor an amplitude that depends on the phase angle or the spin axis orientation. Despite the simplification, the generated magnitudes should reflect reality because they follow the debiased, rather than the observed distribution. The main drawback lies in the fact that Masiero et al. (2009) observed MBAs near opposition at very low phase angles, but NEA phase angles vary widely. At large phase angles and differing geometry, the resulting light curve is altered and the resulting amplitudes may be smaller.

2.7. Vignetting

Optical and mechanical pathways with lenses and mirrors cause vignetting, which decreases brightness, especially at great distance from the optical axis of the system. Large focal planes and wide fields are especially prone to vignetting, even though specialized optical elements and optimized wide-field systems like LSST can reduce the effect significantly (Xin et al. 2015). The LSST vignetting model depends only on the distance from the center of the field (Araujo-Hauck et al. 2016). Figure 11 shows the effect of vignetting-induced magnitude loss in the LSST focal plane. Only 7% of the collecting area has a sensitivity penalty due to vignetting that is greater than 0.1 mag. The magnitude loss is significant only far from the field center, and will only affect the most distant corners of the detector. Therefore, vignetting should not be expected to cause a large completeness loss.

3. Simulation Results

MOPS—our simulation framework—provides NEO detections in LSST fields based on selected parameters and constraints. A list of detections for a given night is submitted to MOPS in the second stage to create tracklets. A tracklet is generated for a detection in the first image of a given field, if a second detection near the first is present in a subsequent image. The area of the search circle is determined by lower and upper velocity limits, set as 0.05 deg day$^{-1}$ and 2.0 deg day$^{-1}$ in this work. If there are more possible connections in the circle, in addition to a clean tracklet consisting of the same object, a tracklet consisting of two objects is created as well. Increasing the upper velocity limit increases the number of false tracklets rapidly. Therefore, for velocities of 1.2–2.0 deg day$^{-1}$, we used the information on the trail length of the detection for making tracklets. At 1.2 deg day$^{-1}$, the detection will have a non-PSF shape and its length will be 1.8 times the PSF at the average 0.86 arcsec seeing, so its length and orientation can be determined. Thus, instead of a large, circular search area around detections that are trailed, only smaller regions that are consistent with the anticipated velocity and direction of the

Figure 6. Probability of a target to be detected, with a fixed fill factor of 90% and variable width (left), and fixed width of $w = 0.1$ and variable fill factor (right). The $m_5$ limiting magnitude is equal to a 50% probability detection, neglecting fill factor.

Figure 7. Histogram of NEOs present in the field in one night of the LSST survey (light bars) and detected NEOs with fading, $m_5$, and fill factor applied (dark bars). The cumulative number of NEO detections with fading is slightly greater than with the $m_5$ step function scenario.
trails need to be searched. Potential matches must also agree in the rate of motion.

Having detection and tracklet lists is enough to predict tracks, neglecting linkage inefficiencies. Moreover, to perform quick studies of the 10-year survey detection and tracklet efficiency, we decreased the number of NEOs to 3000 and created detection and tracklet lists with only limiting magnitude, field shape, and rotation parameters. The absolute magnitude for all 3000 objects was set to $H = 0$. The advantage of this approach is that allows us to adjust individual model parameters in post-processing and measure their effects on overall performance. The per-bin detection efficiency is then derived from the list of simulated detections or tracklets by adding a bin-by-bin $\delta H$ correction, according to the anticipated size-frequency distribution, and then accumulating the found objects to obtain integral completeness. This low-density approach is $>100\times$ faster than a full-density NEO-only simulation. Ephemerides of 3000 representative NEO orbits were computed for all OpSim fields, providing a detection list.

### Table 3

NEA Spectral Classes by Stuart & Binzel (2004)

| Type | Fraction |
|------|----------|
| C Group X low albedo | 0.17 |
| D | 0.18 |
| C | 0.10 |
| S Group X high albedo | 0.17 |
| Q | 0.14 |
| S | 0.23 |

**Note.** The X-class consist of two distinct subpopulations based on albedo.

### Table 4

Magnitude Transformation from Johnson’s V-band to LSST Filter System

| Asteroid color | $V-u$ | $V-g$ | $V-r$ | $V-i$ | $V-z$ | $V-y$ |
|---------------|------|------|------|------|------|------|
| C Group       | $-1.614$ | $-0.302$ | $0.172$ | $0.291$ | $0.298$ | $0.303$ |
| S Group       | $-1.927$ | $-0.395$ | $0.255$ | $0.455$ | $0.401$ | $0.406$ |

Figure 8. Left: normalized histogram of rate of motion of main belt and near-Earth asteroids detected by LSST in one lunation of enigma 1189. Right: normalized histogram of seeing in three simulated surveys.

Figure 9. The profile of the trail and the PSF kernel.

Figure 10. $S/N$ and detection loss as a function of rate of motion for a 30 s exposure and average seeing of 0.86 arcsec (solid curves). The magnitude loss strongly depends on seeing. The dotted lines represent a substandard seeing (1.0 arcsec), dashed lines are a superb seeing (0.6 arcsec).
Post-processing readily creates tracks because all detections and tracklets are identified with the associated object by MOPS. We studied two potential scenarios: 12- and 20-day tracks. The minimum number of distinct nights for a track is three, and so the minimum time span between the first and last tracklet is about two days. The output of this quick sim is an integral completeness that agrees well with the full-density sim (Figure 12), and so we rely primarily on the low-density approach in this paper. The output of the low-density simulation is an integral completeness for detections, tracklets and tracks as a function of absolute magnitude or time (Figure 13).

3.1. System Performance and Model Dependencies

The key output of our simulation is the 10-year integral completeness for detections, tracklets, and tracks as a function of absolute magnitude or time. Figure 13 reveals that over 80% of NEOs with $H < 22$ are detected at least once in the 10-year enigma$_{1189}$ survey. That number drops to 76% for at least one tracklet in 10 years, and 67% for three tracklets in ten years, irrespective of their timing. To actually consider an object discovered and cataloged in this study, we require three tracklets on distinct nights over no more than 20 days or 12 days, which leads to 61% or 58% completeness, respectively, in Figure 13. The time history of completeness reveals that, after 10 years, the rate of cataloging is still increasing at about 2% per year in $C_{H<22}$.

We tested the importance to $C_{H<22}$ of a number of our modeling assumptions as discussed in the following list. The relevance of each item for $C_{H<22}$ is tabulated in Table 5 and depicted in Figures 14 and 15.

1. To compare the population models, we performed two low-density simulations with 3000 NEOs on enigma$_{1189}$ fields for Bottke’s and Granvik’s NEO models. Granvik’s population led to a slightly greater completeness $C_{H<22}$, but the efficiency is significantly greater for Bottke’s population at $H < 25$ (Figure 14), primarily because most of Granvik’s NEO are smaller.

Figure 11. Contour plot showing magnitude loss due to vignetting (Araujo-Hauck et al. 2016) in the LSST focal plane, depicted by a thick black line. Dashed lines represent individual rafts.

Figure 12. Comparison of completeness for a full-density NEO model (solid) and a 3000 object random sample (dashed). Upper curves represent objects detected in at least one detection in 10 years, and the lower curves require a track of three tracklets within 20 days to be present. A 92% fill factor is assumed, with fading and trailing losses.

Figure 13. Detection, tracklet, and track efficiency (NEO completeness) in a low-density simulation as a function of time for $H < 22$ (top) and absolute magnitude after 10 years (bottom) in the enigma$_{1189}$ baseline survey.
and therefore much harder to detect. Table 5 shows the percentage difference between the two models for detections, tracklets, and tracks.

2. Fill factor is one of the key effects that drives detection efficiency down. The low-density simulation focused on altering statistical fill factor by one percentage point. Dropping fill factor by one and two percentage points from 0.90 led to almost no loss for detections and small losses (0.5%–0.9%) for 12- and 20-day tracks. (Figure 14, Table 5).

3. Trailing losses represent a major effect for NEOs; however, they are negligible for distant asteroids like MBAs. NEO completeness is reduced by one percentage point for single detections, and up to two percentage points for 12- and 20-day tracks. Even though detection losses cause much larger magnitude loss per a single detection, in a 10-year, low-density simulation, detection losses are similar to S/N losses in completeness. (Figure 14, Table 5).

4. Because of Malmquist bias, the fading model leads to more detections than a hard step-function faint limit. However, for tracks, fading actually decreased the completeness. This counterintuitive effect arises because, at the faint limit, the fading model behaves as a very low (50%) fill factor. So, even though fading provided more detections, these originated from the faint end, below the \( m_5 \) threshold, where the probability of a single detection is below 0.5. In the case of a tracklet, this is less than 0.5\(^2\), and in the case of tracks, which require three tracklets and a minimum of six detections, the probability is only 0.5\(^5\) of getting cataloged. (Figure 14, Table 5).

5. We tested three scenarios, with NEOs being only S type, C type, or a 50–50 mixture of S and C types, independent of orbital elements or \( H \). The default class of NEO used in this work is S type. Switching to C types led to a net decrease of detection efficiency. Nevertheless, the loss was rather small. Switching from S to a mixture of C and S types led to a relative loss of 0.5% at \( H < 22 \) for 12- and 20-day tracks. If all asteroids were C types, then the completeness loss will be slightly larger, at 1.2%. (Figure 15, Table 5).

6. Like fading, the light curve variation provided somewhat more detections, and yet fewer linkable tracks. For detections and tracklets, the completeness increased by 0.3% and 0.1% at \( H < 22 \). However, 12- and 20-day tracks showed that the light curve variability caused a decrease in completeness by 0.3% and 0.2%. This effect is similar to the detection gain due to fading and related combinatorics. The results showed that light curve variation has a negligible effect in completeness. (Figure 15, Table 5).

7. As expected, vignetting plays only a minor role in the completeness of the survey. The NEO completeness penalty at \( H < 22 \) is only about 0.3% for the tracks. (Figure 15, Table 5).

8. So far, we have discussed several nominal modeling aspects of the baseline LSST survey. However, we wish to also consider off-nominal performance of the LSST system. For instance, the limiting magnitude and seeing

---

### Table 5

| Parameter                  | Penalty          | Detection % | Tracklet % | 3 Tracklets % | 12-day Track % | 20-day Track % |
|----------------------------|------------------|-------------|------------|---------------|----------------|----------------|
| Population penalty         | Bottke’s NEOs    | 0           | 0          | 0             | 0              | 0              |
|                            | Granvik’s NEOs   | +0.7        | +1.0       | +1.4          | +1.7           | +1.6           |
| Fill Factor                | On               | +0.9        | +0.2       | −0.4          | −0.8           | −0.6           |
|                            | Off              | 0           | 0          | 0             | 0              | 0              |
| Colors                     | S class          | 0           | 0          | 0             | 0              | 0              |
|                            | C+S class        | −0.3        | −0.3       | −0.4          | −0.5           | −0.5           |
|                            | C class          | −0.6        | −0.7       | −0.9          | −1.2           | −1.2           |
| Light curve                | Off              | 0           | 0          | 0             | 0              | 0              |
|                            | On               | +0.3        | +0.1       | −0.1          | −0.3           | −0.2           |
| Vignetting                 | Off              | 0           | 0          | 0             | 0              | 0              |
|                            | On               | −0.2        | −0.2       | −0.3          | −0.3           | −0.3           |
| Limiting magnitude         | \( m_5 \)        | 0           | 0          | 0             | 0              | 0              |
|                            | \( m_5 - 0.2 \) mag | −1.7       | −2.1       | −2.7          | −3.2           | −3.1           |
|                            | \( m_5 - 0.5 \) mag | −4.5       | −5.7       | −7.3          | −8.2           | −7.9           |
| Rate cutoff                | 0.5 deg day\(^{-1}\) | −9.5       | −9.6       | −12.3         | −13.6          | −13.3          |
|                            | 1.0 deg day\(^{-1}\) | −2.0       | −1.1       | −1.6          | −1.9           | −1.7           |
|                            | 2.0 deg day\(^{-1}\) | 0          | 0          | 0             | 0              | 0              |
|                            | 5.0 deg day\(^{-1}\) | +0.5       | +1.1       | +1.6          | +0.9           | +1.1           |
for fields is theoretical, despite being based on long-term observations from Cerro Pachón. Systematic offsets in limiting magnitude could cause a drastic drop in completeness, possibly more than all previously mentioned parameters. For instance, if the limiting magnitude is only 0.2 mag shallower, the NEO ($H < 22$) completeness penalty is $\sim 3\%$ for 12- and 20-day tracks, and the corresponding penalty is $\sim 8\%$ for a 0.5 mag loss. (Figure 15, Table 5).

9. This study enforced a tracklet velocity limit of 2.0 deg day$^{-1}$, and a subset of that velocity range (1.2–2.0 deg day$^{-1}$) used a special treatment when creating tracklets, using the length and orientation of the elongated detections. Figure 8 depicts the rates of motion of NEOs and MBAs. Linking complexity is reduced for lower limiting velocities because pairs of detections are more separated at higher velocities. This comes at the cost of reduced completeness, because some fast-moving asteroids would not be discovered due to the velocity limit. So selecting the velocity threshold is a trade-off between computational loads and the objective of discovering small, fast-moving NEOs. Figure 16 and Table 5 show how different velocity cutoffs for tracklets affect the NEO completeness. Decreasing the upper velocity limit to 0.5 deg day$^{-1}$ would dramatically decrease $C_{H<22}$, by more than 13% for tracks. On the other hand, increasing the upper bound from 2.0 to 5.0 deg day$^{-1}$ only had a slight benefit of about 1% in completeness for tracks. When making use of the trail velocity information for fast detections, increasing the upper velocity threshold is not likely to significantly increase the false tracklet rate, and comes at a modest benefit.

3.2. Overall LSST Performance and Uncertainties

Throughout this work, we have tested and analyzed an array of different survey models, including various OpSim runs, NEO population models, and detection models. Here, we collect and summarize the various modeling details discussed above and characterize the uncertainty of the overall performance estimate.

For what we consider our final result, we select the most current LSST baseline survey, minion_1016, and the latest...
An unbiased NEO population estimate, namely Granvik’s NEO model. This “new” approach can be compared with the “original” alternative of Enigma_1189 with Bottke’s NEO model. Table 6 makes this comparison in an incremental fashion by cumulatively adding various model details. Examining the Enigma_1189 column of Table 6, we see that, for 12-day tracks, $C_{H<22} = 65.9\%$ when using the most rudimentary and optimistic detection model. The completeness drops by 6.8\%, to 59.0\%, when fill factor, fading, trailing losses, vignetting, NEO colors, and light curves are applied. Accounting for the linking losses and bright source masking assumed by Vereš & Chesley (2017), we lose another 4.4\%, arriving at a final $C_{H<22}$ estimate of 54.6\%.

Comparing the Enigma_1189 results with those from the Minion_1016 column, we see that there is very little difference for $C_{H<22}$ performance. Minion_1016 is only slightly better, by about 1.5\% in $C_{H<22}$, after 10 years (Figure 17). This agreement is because of the compensating factors of Granvik’s steeper size distribution, which provide a ~2\% increase in $C_{H<22}$ (Table 5) for the Minion_1016 simulation, and a ~0.25 mag reduction in
The completeness derived from our simulations has numerous error sources. The easiest to define are those associated with sampling. Other contributions from the various individual modeling details were derived step-by-step, and we discuss them below and summarize them in Table 6. The modeling details and our ad hoc approach for understanding their potential effect on $C_{H<22}$ are as follows:

1. By using low-density simulations, the statistical sampling error is about 0.6%.
2. Using Granvik’s NEO population instead of Bottke’s leads to a 2% increase in $C_{H<22}$, and we take this as proxy for the uncertainty due to uncertainties in the NEO size distribution.
3. Changing the fill factor by $+0.0/-2.0\%$ leads to a shift of $+0.0/-0.8\%$ in $C_{H<22}$.
4. The assumed width for detection fading was a constant value of $w = 0.1$. If this value is altered by 32%, then the completeness error from this source is 0.2%.
5. Trailing losses are described by a detection loss function that is theoretical and not operationally validated. If the detection loss penalty varies by 32%, it leads to a 0.7% error in completeness.
6. For vignetting, we take a 32% variation in the magnitude loss to obtain a 0.1% variation in completeness.
7. We allow the color indices taken from SDSS and assumed in the study to vary by $1\sigma$ of their values, which affects completeness by 0.1%.
8. We allow a 32% variation in light curve amplitude, which leads to a 0.2% effect on completeness.
9. Bright sources lead to a large number of false detections in difference images, which could make linking inefficient. Jones et al. (2017) found that masking areas around bright sources—about 1% of the focal plane area—dramatically reduces the false detection rate. Thus, we reduce the fill factor by 1%. If this value varies by $-0.5(+1.0\%)$, then the completeness error from this source is $0.2/-0.4\%$.
10. Linking efficiency is discussed at length by Vereš & Chesley (2017). Here, we assume a value of 93.6$_{-5}^{+2}\%$. These uncertainties cause $C_{H<22}$ to vary by $+3.3/-0.6\%$.

We note that many of the foregoing stated uncertainties are more akin to sensitivity exercises than uncertainty estimates. In many cases, we have no good statistical footing from which to infer the uncertainty in the inputs, and so the corresponding uncertainty estimate relies heavily on judgement. Nonetheless, taken altogether, these modeling effects lead to a ±5% uncertainty in the predicted value of $C_{H<22}$. In light of this uncertainty, the difference between the old (enigma_1189/Bottke) and new (minion_1016/Granvik) simulations is negligible. Therefore, we report our final LSST performance result as $C_{H<22} = 55 \pm 5\%$ after linking losses. Here, we emphasize that the stated uncertainty is not a Gaussian one-sigma error bar, but rather reflects the possibility of modeling systematics that could compromise the result by up to 5%.

### 3.3. Alternatives to Nightly Pairs

Historically, the Minor Planet Center accepts only high-reliability tracklets from observers, and its internal linking processes assume that the false tracklet rate is low. This has been a reasonable assumption for past and current major surveys, which follow a cadence that naturally returns 3–5 detections per tracklet by repeatedly returning to the same field within a span of an hour or so. This survey approach is robust against false positives because the 3–5 detections in a tracklet must all be consistent with a common linear (or nearly linear)
motion, effectively eliminating the possibility that one or more false detections could contaminate a tracklet.

LSST, on the other hand, is baselined to return only two detections per tracklet, which eliminates the possibility of checking for internal consistency among the elements of a tracklet. The result is a high rate of false tracklets that is not suitable for submission to the MPC. LSST will work past this obstacle by submitting only high-reliability three-night tracks to the MPC.

The LSST approach of obtaining nightly pairs is certainly more fragile for linking than a cadence that returns nightly triples or quads, but the fragility comes with the marked benefit of significantly increased sky coverage per night, and hence a shorter return period. This leads to more tracklets per observing cycle, which restores some measure of robustness, and certainly leads to increased discovery rates—so long as the linking problem can be managed. If, for whatever reason (however unlikely), LSST cannot successfully link two-detection tracklets, then it could conceivably be forced to observe triples or quads to meet survey objectives.

Here, we compare the performance of the pair-wise enigma_1189 baseline survey with enigma_1271 and enigma_1266, which are tuned to provide three- and four-visit cadences, respectively. For the two-visit baseline survey, we required at least two detections for tracklet creation. In the three-visit baseline, at least three detections are required per tracklet (“triples”), and the four-visit cadence requires at least four detections per tracklet (“quads”).

We emphasize that the benefit of a cadence that produces triples or quads is that it eases the linkage challenge. It does not produce better orbits. Tracklets formed from three or more detections have far higher confidence than those obtained from pairs because, with only two positions, there is no independent corroboration of linear motion. Thus, for pairs, the idea that a tracklet’s detections are associated with a single moving object is a hypothesis to be tested by the linking engine, whereas with three or more detections, the tracklet has a high likelihood of being real. Linking is challenging for pairs because of the high false tracklet rate, but easy for triples or quads because there is no hypothesis testing involved.

In terms of orbit quality, there is no appreciable difference between orbits derived from pairs, triples, or quads. Each tracklet provides a position and rate of motion on the plane of sky, with no information on plane of sky acceleration (except for very close objects, which are rare enough to be ignored in this context). The orbit quality depends primarily on how many distinct nights the object has been observed and the time interval between the first and last night.

Table 7 shows that visiting the same field more often per night predictably decreases the effective areal search coverage by a significant margin, even though the alternate surveys have a similar number of fields observed in 10 years, with similar limiting magnitudes, and inter-night survey patterns. Figure 2 shows that all three surveys also contain some fields that are visited fewer or more than the target number of visits per night.

| OpSim Desig. | No. visits | No. fields | Used fields | Mean $m_V$ in V-band | Effective sky coverage (deg$^2$) |
|--------------|------------|------------|-------------|----------------------|---------------------------------|
| enigma_1189  | 2          | 2,469,307  | 1,943,901   | 23.63                | 805,128                         |
| enigma_1271  | 3          | 2,438,990  | 1,932,391   | 23.65                | 463,636                         |
| enigma_1266  | 4          | 2,417,999  | 1,928,921   | 23.65                | 309,154                         |
As mentioned earlier, singleton and DD fields are not used in our simulations. Figure 18 and Table 8 show the direct impact of the three- and four-visit cadence approaches on NEO completeness. The completeness penalty is not as dramatic on the single tracklet level; however, due to reduced sky coverage, the tracks are dramatically affected. Three and four-visit cadences could decrease the number of false tracklets significantly, but at the cost of a steep reduction in $C_{H<22}$. The figure shows that three- and four-visit cadences have a severe impact on NEO completeness in all stages, from detections to tracklets to tracks. At $H < 22$, the completeness for 12-day tracks falls from 38.6% for nightly pairs to 36.9% at a three-visit cadence to 19.0% at a four-visit cadence. The four-visit cadence could be improved by accepting tracklets with detections on three out of the four visits, which would provide a performance somewhere in between that tabulated (and plotted) for the three- and four-visit cadences.

We note that triples or quads should dramatically reduce the false tracklet rate, such that reliable tracks could likely be assembled from tracklets on only two nights. This approach would lead to increased completeness; however, such two-night tracks would inevitably lead to weak orbits that are not likely to meet survey objectives. In particular, two-night orbits are generally uncertain enough that MBAs and NEOs cannot generally be distinguished. As discussed by Vereš & Chesley (2017), this is already an issue for some three-night orbits, but it is the norm for two-night orbits. Table 9 indicates the level of NEO completeness that would be obtained for the four-visit enigma_1266 survey, assuming that a minimum of either 3 or 4 detections per tracklet are available for each tracklet. We did not analyze the orbit quality of two-night tracks, but the challenge here is that the shortest arcs (e.g., three days) may be readily linked, but the orbits are likely to be highly uncertain, whereas for the longer arcs (e.g., 12 days), the orbit may still be unacceptably weak but the linkage problem may be difficult. The numbers in Table 9 should be compared with the 12-day, three-night tracks completeness for enigma_1266 in Table 8, which is 19.1%. Even the most optimistic scenario in Table 9

![Figure 18](image_url) Integral completeness for two-, three-, and four-visit optimized baseline surveys as a function of absolute magnitude. NEO was detected at least once in a single tracklet (left), and in at least one 12-day, three-night track (right). Parameters applied: fading, fill factor $= 0.89$, trailing loss, vignetting, colors, and light curves.

**Table 8**
NEO Completeness in Percentages for Two-, Three-, and Four-visit Optimized Surveys, based on the enigma_1189 Baseline, with Fading, Fill Factor Equal to 0.90, Trailing Losses, Vignetting, S+C NEO Colors, Light Curves, and Bright Source Removal Represented by a 1% Penalty in Fill Factor

| OpSim Desig. | No. visits | Detection | Tracklet | 3 Tracklets | 12-day Track | 20-day Track |
|--------------|------------|-----------|----------|-------------|--------------|--------------|
| enigma_1189  | 2          | 81.6      | 75.7     | 67.9        | 58.0         | 61.0         |
| enigma_1271  | 3          | 81.3      | 69.9     | 57.1        | 37.0         | 43.1         |
| enigma_1266  | 4          | 80.6      | 62.6     | 45.2        | 19.1         | 25.7         |

**Table 9**
NEO Completeness $C_{H<22}$ in Percentages for Two-night Tracks based on the Four-visit enigma_1266 Survey, for a Range of Arc Length Requirements, and for a Requirement of either $\geq 3$ or $\geq 4$ Detections per Tracklet

| Detections per tracklet | Arc Length |
|-------------------------|------------|
|                         | 3 days     | 6 days    | 9 days    | 12 days    |
| $\geq 3$                | 23.3       | 38.3      | 46.1      | 49.9       |
| $\geq 4$                | 11.2       | 22.3      | 29.9      | 35.5       |
significantly underperforms, compared to the baseline enigma_1189.

### 3.4. Including Prior and Ongoing Surveys

In all of the analyses presented so far, we have implicitly assumed that no NEOs have been discovered prior to the LSST survey. However, based on current NEO discovery statistics and published population models (e.g., Bottke et al. 2002; Harris & D’Abramo 2015; Granvik et al. 2016), the population of NEOs with \( H < 22 \) is currently already complete to a level of approximately 30%. It is expected that this number will continue to increase until LSST becomes operational in 2022, and that at least some current or future NEO survey assets will continue to operate during the LSST mission. Therefore, some fraction of potential LSST NEO discoveries will have already been discovered by other surveys. Similarly, some fraction of objects missed by LSST will also have already been discovered.

To make an estimate of what the completeness will be after the 10-year LSST survey, we must account for the contributions of other surveys.

Spacewatch (McMillan & Spacewatch Team 2006) was the first CCD-based NEO search program, but the era of dedicated wide-field NEA surveys began approximately 18 years ago when LINEAR (Stokes et al. 2000) became operational. Since then, improvements in instrumentation and techniques allowed fielding of other advanced ground based surveys like NEAT (Pravdo et al. 1999), LONEOS (Koehn & Bowell 1999), the Catalina Sky Survey and the Mt. Lemmon Survey (Larson et al. 2003; Christensen et al. 2012), and Pan-STARRS (Hodapp et al. 2004; Kaiser et al. 2010). The space-based NEOWISE program (Wright et al. 2010) has also made contributions to cataloging NEOs.

We simulated past, current, and presumed future NEO surveys, starting 15 years in the past and proceeding to 15 years in the future (2002–2032). In the simulation, LSST begins operation in 2022, about five years from this writing. Ephemerides of all objects where calculated once per day, and an object was considered discoverable when all of the following criteria were met:

1. Apparent magnitude brighter than the detection limit \( V_{\text{lim}} \).
2. Ecliptic latitude between \( \pm 60^\circ \).
3. Geocentric opposition-centered ecliptic longitude between \( \pm 90^\circ \).
4. Declination from \( -30^\circ \) to \( +75^\circ \).
5. Lunar elongation \( >90^\circ \).

Ground-based surveys are limited by weather and cannot cover the entire sky per night; therefore, only a fraction \( F_{\text{disc}} \) of the objects that were discoverable according to the above criteria were added to the catalog.

Surveys have improved over time, so we slowly improve the detection model in five-year steps:

I. A LINEAR-like era from 15 to 10 years ago with limiting magnitude \( V_{\text{lim}} = 19.5 \) and \( F_{\text{disc}} = 0.5 \)
II. A Catalina era with limiting magnitude of \( V_{\text{lim}} = 21.0 \) the next 5 years and \( F_{\text{disc}} = 0.6 \)
III. For the past five years, Pan-STARRS1 and the Mt. Lemmon Survey have operated at the limiting magnitude of \( V_{\text{lim}} = 21.5 \) and \( F_{\text{disc}} = 0.7 \)
IV. For the next five years from the present, we expect the limiting magnitude to be \( V_{\text{lim}} = 22.0 \) and \( F_{\text{disc}} = 0.8 \)

![Figure 19. Estimate of integral NEO completeness (H < 22) for past, existing, and future NEO survey assets combined. The dotted curve represents the real-world NEO discovery rate, the black curve the modeled assets, the dashed curve the LSST performance as if no NEO are known at the beginning of LSST survey, and the thick black curve represents the combined performance with LSST. The present date is at zero on the time axis, and LSST starts to operate in year 5. The LSST simulations are for enigma_1189 with the Bottke NEO model, 90.8% fill factor, fading, trailing, 50/50 C and S type asteroids, and vignetting. Linking losses (bright source masking and linking efficiency) are neglected.](image)

V. Starting five years from the present, we augment the previous search interval with the LSST survey and increase \( F_{\text{disc}} = 0.9 \) to account for continuing improvements in the other surveys.

Figure 19 shows the outcome of the rudimentary simulation, which is deliberately tuned to match the current estimated completeness at the current time. Our simple model predicts that 42% of NEOs with \( H < 22 \) will be discovered before LSST becomes operational, and that without LSST the current NEO surveys alone could achieve \( C_{H<22} = 61\% \) by 2032, when the LSST survey is planned to conclude. We have shown above that LSST acting alone will achieve completeness of about 58% by itself (neglecting linking efficiency here), but when combined with past and other expected NEO search efforts, \( C_{H<22} \) rises to 77%. This is not a high-fidelity analysis, but it shows that the combination of LSST with other ground-based search activity will increase \( C_{H<22} \) by about 20%, compared with the naive assumption of LSST starting with an empty catalog. Put another way, we project that LSST will provide a 16% increase in \( C_{H<22} \) over the anticipated efforts of the existing NEO search programs.

### 3.5. Comparison with Previous Work

Predictions of NEOs and PHAs discovery and detection rates for LSST have been done for a decade. Ivetic et al. (2007) used 1000 synthetic NEO orbits based on a large population \( (D > 1 \text{ km}) \), with assumed LSST sky coverage and revisit rate, and only a rough estimate of cadence or limiting magnitudes. Ivetic et al. (2007) predicted that LSST will detect 90% of PHAs larger than 250 m and 75% of PHAs larger
than 140 m, with the optimistic estimate of 90% completion if the cadence and survey is NEO-optimized. Ivezić et al. (2014) used a list of LSST pointings and a higher-fidelity model for the survey, using diameter-limited PHA population of 800. This analysis found 82% PHA completeness ($D > 140$ m), which could be improved to 90% with the same cadence if stretched to 12 years.

Grav et al. (2016) simulated the NEO and PHA performance of LSST for the baseline enigma_1189 and four-visit enigma_1266 surveys. Additionally, they discussed the discovery performance of LSST combined with existing surveys and the proposed NEOCAM space-based survey. They used the same fields as this study (except that they did not remove singletons and DD fields), the same limiting magnitudes and a 95% fill factor, which is higher than the currently anticipated 90.8%. The synthetic population was different, consisting of 20,000 NEOs down to a size threshold of 100 m. Also, Grav et al. (2016) allowed creation of tracklets in a velocity range between 0.011 and 48 deg day$^{-1}$, which is significantly broader than our range (0.05–2.0 deg day$^{-1}$). The spectral distribution of synthetic objects had an equal balance between C and S types; however, the color transformation to the V-band was derived by slightly outdated specifications from SDSS (Ivezić et al. 2001). Their simulation process was similar to ours, where detections and tracklets were assembled into lists and built into assumed tracks through post-processing. A track was created when three tracklets were detected within 12 days, with a maximum separation of six days from two of them. However, for the four-visit case, enigma_1266, Grav et al. (2016) required only two four-detection tracklets within 12 days to build a track. This is a significant difference from our metric of three tracklets on three distinct nights over at most 12- or 20-day tracks. Although Grav et al. (2016) were skeptical of the two-visit cadence, given that it has never been tested operationally on a comparable survey, their four-visit alternative only required two tracklets for a track. They also did not include trailing losses, vignetting, fading, light curve variation, and they assumed the linking efficiency to be 100%. Grav et al. (2016) derived that, for the two-visit cadence, LSST will have a 63% completion of NEOs larger than 140 m and for PHAs they find $C_{D>140m} = 62\%$. In the four-visit cadence, they reported $C_{D>140m} = 59\%$ for NEOs and 58% for PHAs. The completeness was presented with $\pm1\%$ uncertainty.

To make a robust comparison with this work, we ran a simulation with a Grav et al. (2016) population of NEOs (19,597) and PHAs (2,346). Our model included fading, trailing losses, vignetting, and 90% fill factor. Table 10 and Figure 20 present the comparison. Our results are substantially consistent with Grav et al. (2016); however, we note that our

| Table 10 | 140 m Integral Completeness of NEAs and PHAs, According to Grav et al. (2016) and the Present Study |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| NEO | PHA | NEO | PHA |
| Two det. | Two det. | Two det. w/ others | Four det. | Four det. w/ others |
| 62.6% | 63% | 67% | 59% | 67% |
| 63.8% | 62% | 73% | 58% | 71% |

**Note.** The columns marked “w/others” incorporated discoveries from other (past and future) survey activity in the completeness estimate.
drive their estimated completeness down. Also, Jones et al. (2017) used a more sophisticated model for chip and raft gaps, masking the exact locations in the focal plane, whereas our work used only a random number as a fill factor to assign a detection probability to every detection. Collectively, these model variations readily explain the slightly different NEO completeness estimates reported by Jones et al. (2017).

4. Conclusions

We have demonstrated the importance of the observational constraints and input parameters on the detection of NEOs by an automated survey such as LSST. Among the numerous modeling details that we investigated, few result in a significant effect on survey performance if reasonable care is taken in developing the nominal survey model. A 2% reduction in fill factor or a major increase in trailing losses could lead to nearly a 1% reduction in \( C_{H<22} \) for NEOs. We found a 2% difference in \( C_{H<22} \) between the Bottke and Granvik NEO models, suggesting some dependence on the population size distribution. However, the Granvik model is based on a data set vastly superior to the 15 year old Bottke model. One should not expect that future population models will lead to such large swings in the size distribution, and thus \( C_{H<22} \) should be more stable in this regard. The effective, operational limiting magnitude of the LSST survey is a crucial parameter. We find that \( C_{H<22} \) degrades by \( \sim 1.8\% \) for every 0.1 mag loss in sensitivity, making this the single largest source of model uncertainty in our completeness estimates.

We find that \( C_{H<22} \approx 55 \pm 5\% \) for the baseline \textit{enigma}_1016 survey operating alone, with the linking working at 93.6\% efficiency (Vereš & Chesley 2017). This result assumes 12-day, three-night tracks, and accounts for all of the other modeling features and sources of error, including linking losses. The 12-day track linking is very conservative; \( C_{H<22} \) increases by \( 2\%\text{–}3\% \) if the linking uses 20-day tracks in the baseline LSST cadence.

We find that \( C_{H<22} \) for PHAs is generally \( 3\text{–}4\% \) greater than for NEOs. Jones et al. (2016) reported simulations for \textit{enigma}_1189 that suggest the PHA completeness is actually lower by \( 1\% \). In contrast, Jones et al. (2017) report shows a good agreement in \( C_{H<22} \) for NEOs and PHAs in \textit{enigma}_1016 simulation. For \textit{astro}_1016, the Jones et al. results exhibit slightly larger \( C_{H<22} \) by \( \approx 3\% \) with respect to our results.

The old and new LSST baselines (\textit{enigma}_1189 and \textit{enigma}_1016, respectively) and the NEO-enhanced scenario (\textit{astro}_1016) all provide similar NEO detection efficiencies, to within \( 1\% \), for a 10-year survey. Surveying for longer than 10 years increases \( C_{H<22} \) by about \( 2\% \text{ per year} \) (1\% per year if other surveys are taken into consideration). The three- and four-visit optimized LSST cadences that we tested had a dramatically reduced NEO completeness relative to that obtained for the two-visit baseline cadences. This result relies on the modeling hypotheses assumed throughout this study, and assumes that tracklets in three distinct nights within 12 days are required for cataloging. The performance loss associated with these alternate cadences could be significantly eased if the cataloging requirement was for tracklets on only two nights, rather than three, but it is doubtful that such two-nighters would have high enough orbit quality to meet cataloging objectives.

When LSST becomes operational in 2022, about \( 42\% \) of NEOs with \( H < 22 \) should have been discovered with current assets. Without LSST, current assets could discover \( 61\% \) of the catalog during the LSST era. With LSST and other surveys combined, \( C_{H<22} \) should reach \( 77\% \) by the end of its 10-year mission in 2032, assuming 12-day tracks with \textit{enigma}_1189.

Assembling the foregoing completeness results, including the contribution of other surveys, the post-LSST \( C_{H<22} \) should reach \( 80\% \) for PHAs in ten years, and slightly more if 20-day tracks are linked. In our judgement, the \( H < 22 \) PHA catalog is likely to approach \( \sim 85\% \) completeness, but probably not 90\%, after 12 years of LSST operation.

The Moving Object Processing System was crucial to the successful completion of this work. This tool is the product of a massive development effort involving many contributors, whom we do not list here but may be found in the author list of Denneau et al. (2013). We thank Larry Denneau (IFA, University of Hawaii) for his tremendous support in installing and running the MOPS software.

This study benefited from extensive interactions with Željko Ivezic, Lynne Jones, and Mario Juric, all from the University of Washington. As members of the LSST project, they provided vital guidance in understanding the performance and operation of LSST. They also provided important insight into the expected interpretation and reliability of LSST data. They ensured that some of the OpSim runs required to fulfill study objectives were generated by LSST.

Mikael Granvik (Univ. Helsinki) kindly provided an early version of the Granvik et al. (2016) NEO population model, which was used extensively in this work.

Tom Statler (NASA HQ) provided valuable guidance in the development and documentation of this study.

Tommy Grav (PSI) provided an instantiation of the Grav et al. (2016) NEO population model, which allowed us to conduct a direct comparison with their results.

This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.

References

Araujo-Hauck, C., Sebag, J., Liang, M., et al. 2016, Proc. SPIE, 9906, 99060L

Bottke, W. F., Morbidelli, A., Jedicke, R., et al. 2002, Icar, 156, 399

Carvano, J. M., Hasselmann, P. H., Lazzaro, D., & Mothé-Diniz, T. 2010, \textit{A&A}, 510, A43

Chance, K., & Kurucz, R. L. 2010, \textit{JQSRT}, 111, 1289

Christensen, E., Larson, S., Bootini, A., et al. 2012, in AAS/Division for Planetary Sciences Meeting 44 Abstracts, 210.13

Delgado, F., Saha, A., Chandrasekharan, S., et al. 2014, Proc. SPIE, 9150, 915015

DeMeo, F., Binzel, R. P., Slivan, S. M., & Bus, S. J. 2009, PDSS, EAR-A-VARGBDET-5-BUSDEMOETAX-V1.0, 114

DeMeo, F. E., & Carry, B. 2014, \textit{Natur}, 505, 629

DeMeo, F. E., & Carry, B. 2014, \textit{Natur}, 505, 629

Denneau, L., Jedicke, R., Grav, T., et al. 2013, \textit{PASP}, 125, 357

Flaughter, B., Diehl, H. T., Hounsfield, K., et al. 2015, \textit{AJ}, 150, 150

Granvik, M., Morbidelli, A., Jedicke, R., et al. 2016, \textit{Natur}, 530, 303

Grav, T., Jedicke, R., Denneau, L., et al., 2011, \textit{PASP}, 123, 423

Grav, T., Mainzer, A. K., & Spahr, T. 2016, \textit{AJ}, 151, 172

Harris, A. W., & D’Abramo, G. 2015, Icar, 257, 302

Hodapp, K. W., Steigmann, W. A., Kaiser, N., et al. 2004, Proc. SPIE, 5489, 667

Ivezic, Ž., Tabachnik, S., Rafikov, R., et al. 2001, \textit{AJ}, 122, 2749

Ivezic, Ž., Tyson, J. A., Abel, B., et al. 2014, \textit{arXiv}0805.2366

Ivezic, Ž., Tyson, J. A., Axelrod, T., et al. 2009, \textit{BAAS}, 41, 460.03

Ivezic, Ž., Tyson, J. A., Juric, M., et al. 2007, in \textit{IAU} Symp. 236, Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, ed. G. B. Valsecchi, D. Vokrouhlický, & A. Milani (Cambridge: Cambridge Univ. Press), 553
Jones, R. L., Jurić, M., & Ivezić, Ž. 2016, in IAU Symp. 318, Asteroids: New Observations, New Models (Cambridge: Cambridge Univ. Press), 282
Jones, R. L., Slater, C., Moeyens, J., et al. 2017, Icar, submitted
Kaiser, N., Aussel, H., Burke, B. E., et al. 2002, Proc. SPIE, 4836, 154
Kaiser, N., Burgett, W., Chambers, K., et al. 2010, Proc. SPIE, 7733, 77330E
Koehn, B. W., & Bowell, E. 1999, BAAS, 31, 12.02
Larson, S., Beshore, E., Hill, R., et al. 2003, BAAS, 35, 36.04
Mainzer, A., Grav, T., Bauer, J., et al. 2011, ApJ, 743, 156
Mainzer, A. K., Wright, E. L., Bauer, J., et al. 2015, in AAS/Division for Planetary Sciences Meeting 47 Abstract, 308.01
Masiero, J., Jedicke, R., Ďurech, J., et al. 2009, Icar, 204, 145
McMillan, R. S. & Spacewatch Team 2006, BAAS, 38, 58.07
Pravdo, S. H., Rabinowitz, D. L., Helin, E. F., et al. 1999, AJ, 117, 1616
Schunová-Lilly, E., Jedicke, R., Vereš, P., Denneau, L., & Wainscoat, R. J. 2017, Icar, 284, 114
Smith, R. M., Dekany, R. G., Bebek, C., et al. 2014, Proc. SPIE, 9147, 914779
Stokes, G. H., Evans, J. B., Viggh, H. E. M., Shelly, F. C., & Pearce, E. C. 2000, Icar, 148, 21
Stuart, J. S., & Binzel, R. P. 2004, Icar, 170, 295
Vereš, P., & Chesley, S. R. 2017, AJ, 154, 13
Vereš, P., Jedicke, R., Denneau, L., et al. 2012, PASP, 124, 1197
Vereš, P., Jedicke, R., Fitzsimmons, A., et al. 2015, Icar, 261, 34
Warner, B. D., Harris, A. W., & Pravec, P. 2009, Icar, 202, 134
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Xin, B., Claver, C., Liang, M., et al. 2015, ApOpt, 54, 9045