LARGE SYNOPTIC SURVEY TELESCOPE

Large Synoptic Survey Telescope (LSST)
Data Management

LSST Asteroid Discovery Rates

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Abstract

Once operational, the Large Synoptic Survey Telescope (LSST) is bound to become the dominant contributor of Solar System object observations and discoveries. Millions of asteroids are going to be observed on a regular basis leading to a yield of around two billion Solar System Object (SSO) observations after ten years of operations. Internal and external services that ingest and process LSST data on a regular basis, such as the International Astronomical Union (IAU) Minor Planet Center, have a great interest in the predicted data flux directed their way. This DMTN provides updates on LSST SSO observation and discovery rates as well as their uncertainties. Estimates on the number and distribution of SSO observations that can not be linked to known or newly discovered objects and may, thus, trigger unwanted alerts are being provided. Likely data rates for daily submissions of SSO observations to the Minor Planet Center are discussed.

Change Record

Version	Date	Description	Owner name
1	2019-10-17	Unreleased.	Siegfried Eggl

Contents

TABLE 1: Summary of small body populations observed with LSST.

Population	known as of 10/2019	LSST discoveries$^{(1)}$
Near-Earth Objects (NEOs)	21,172	49,000-93,000
Main Belt Asteroids (MBAs)	796,354	5,400,000-225,000,000$^{(*)}$
Jupiter Trojans	7,384	280,000$^{(+)}$
TransNeptunian and Scattered Disk Objects (TNOs and SDOs)	3,800	40,000$^{(+)}$

Notes:
$^{(1)}$: Expected at the end of LSST's ten years of operations. $^{(*)}$: the upper bound is based on an (unlikely) TNO like size-frequency distribution. 100% completeness (as indicated). $^{(+)}$: Not updated from (Jones et al., 2015).

LSST Asteroid Discovery Rates

1 Summary

The LSST is expected to discover millions of Solar System objects (SSOs) as reported in Table 1. Roughly 2bn observations of SSOs can be expected after ten years of the LSST survey with up to 100,000 new discoveries per night. Most objects are going to be discovered during the first years of LSST operations. Main Belt Asteroids (MBAs) are the largest contributors to both, SSO discoveries and operations. The corresponding nightly data volumes to be delivered to the Minor Planet Center are on the order of hundreds of MBs and only rarely exceed a GB. Even with near perfect linking and detection algorithms driving the Solar System Processing (Solar System Processing (SSP)) pipelines, not all SSO observations can be attributed to known sources or new discoveries. The fraction of LSST SSO observations that fall into that category decreases over time, but is unlikely to fall below 2.5% (50M) even in the best case scenario of finding every discoverable asteroid at the first opportunity. Roughly half of those observations belong to objects that are not discoverable at all given the current discovery strategy of "three nighters", i.e. two pairs of observations over three nights in a 15-30 day window. Those may trigger false alerts in a roughly 50deg wide declination band around the ecliptic. A delayed start in processing Solar System observations, caused by a lack of templates in the first year, for instance, would not significantly affect Main Belt Asteroid discovery as long as data is collected and computational resources similar to the yearly data reprocessing can be made available at a later time. In contrast, a delay in SSP would lead to a larger number of unassociated observations potentially affecting LSST alerts. It would also make timely follow-up observations of near-Earth asteroids and interstellar objects impossible.

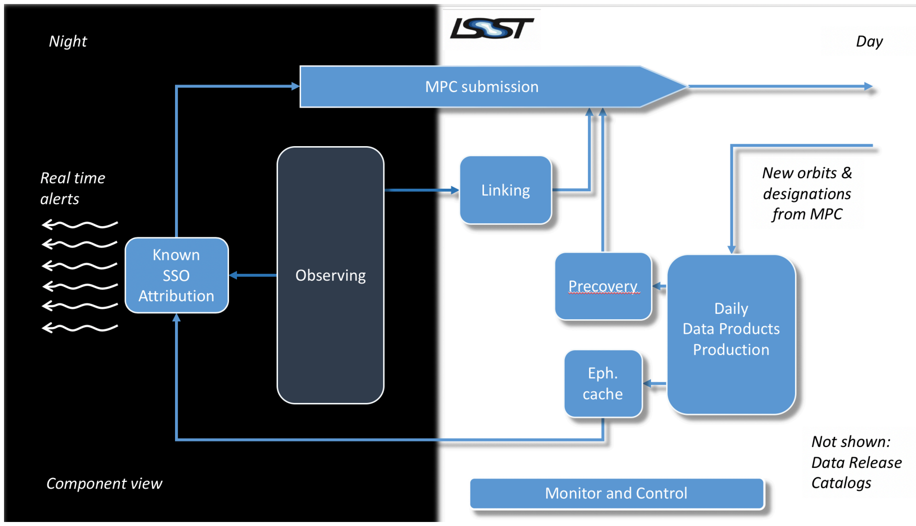

FIGURE 1: Concept of the LSST Solar System Processing cycle.

2 Introduction

The LSST is expected to discover millions of Solar System objects (SSOs) over the course of its ten years of operation (Jones et al., 2015). Past assessments of discovery yields of future surveys see the LSST becoming the dominant contributor of Solar System Object (SSO) related data to the IAU Minor Planet Center (MPC) (LSST Science Collaboration et al., 2009). The currently agreed upon strategy sees LSST deliver astrometric and photometric observations of known SSOs as well as observations that represent potential discoveries after every night of operations. Figure 1 shows a corresponding schematic of the proposed LSST SSO processing pipeline. Apart from Space Situational Awareness (Space Situational Awareness (SSA)) and planetary defense agencies that are mostly concerned with the capabilities of the LSST to discover near-Earth asteroids, services that ingest and process LSST data on a regular basis, such as the MPC, have a great interest in estimates regarding the predicted data flux directed their way. This requires accurate estimates regarding the actual number of predicted SSO observations and discoveries. Early estimates stem from the LSST Science Book (LSST Science Collaboration et al., 2009). As some progress has been made in this respect, both in scientific literature and in the LSST project, it is the aim of this DMTN to summarize and, where necessary, to provide updated LSST SSO observation and discovery rates as well as their uncertainties. This information is intended to inform internal and external services affected by SSO discoveries. The remainder of this DMTN is structured as follows: Section 3 briefly describes the LSST survey and the simulation setup. Section 4 provides a summary of previous work as well as a brief update on near-Earth asteroid discovery with the LSST. Section 5 discusses LSST capabilities to discover Main Belt Asteroids that constitute the main source of LSST SSO observations. In section 6 the impact of delayed LSST operations and Solar System processing on discovery requirements is studied. Section 7 assesses how much noise unattributed SSO observations could contribute to LSST data. As Main Belt Asteroid (MBA) observations dominate SSO observations section 8 discusses likely data rates that LSST has to submit to the IAU Minor Planet Center (MPC) on a nightly basis. Section 9 looks at other SSO populations and section 10 concludes this report.

3 LSST survey simulation

The proposed observation strategy for the LSST survey used in this work is described in baseline2018. Its sky coverage, inter and intra-night gaps as well as the performance in terms of median and maximum five sigma depth is shown in Figure 2.

During the Wide-Fast-Deep (WDF) survey LSST is expected to reach median five signal depths around 23.5 mag with median inter and intra-night gaps of 1.5 days and 20 mins, respectively. Such a cadence facilitates the construction of nightly tracklets, successive observations of moving objects spanning a short arc. Tracklets of individual objects can then be linked over several nights resulting in the discovery of SSOs. Two types of survey simulation software frameworks were used to generate and validate LSST SSO discovery statistics, namely

- LSST Sims_movingObjects (SIMS_MO)
- Open Observation Simulator (OPENOBS)

The former is a high fidelity simulator that includes N-body numerical orbit propagation, the actual LSST camera model, as well as color information of asteroids. SIMS_MO is capable of performing accurate observation simulations for up to several 100k of SSOs. Although that constitutes only a fraction of the true MBA population, information on expected survey completeness statistics can be extracted through sampling of individual orbits over a grid of absolute magnitudes. OPENOBS is capable of performing survey simulations on the entire expected MBA population (around 100M objects) albeit with a lower fidelity. Instead of N-body propagation unperturbed heliocentric Keplerian orbits of SSOs are assumed. The LSST camera footprint is simulated, but the exact geometry including chip gaps has not been taken into

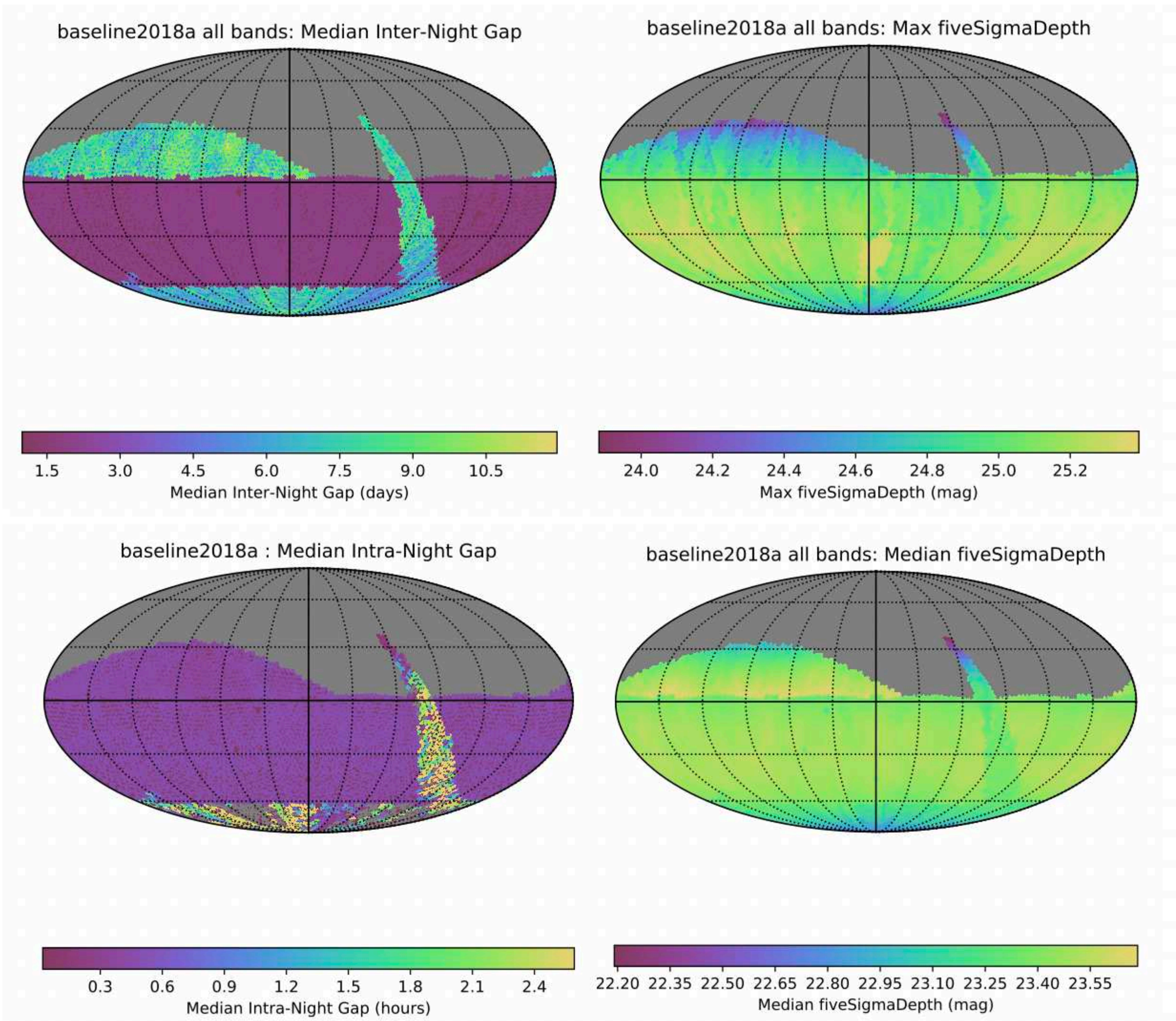

FIGURE 2: LSST survey simulation "baseline2018a". The left column shows intra- (top) and inter-night gaps (bottom) between LSST returns to the same pointing. In the right column maximum (top) and median (bottom) five sigma depths are shown.

account in OPENOBS simulations. Instead, the fill factor of the camera system as calculated in Vereš & Chesley (2017a) was used to statistically filter observations. Spectral energy distributions (SEDs) of asteroids are assumed to be flat in OPENOBS simulations, while S- and C-type asteroid Spectral Energy Distribution (SED)s are used in SIMS_MO (Figure 3). The magnitude cutoff in our simulation was chosen to be H=25mag corresponding to asteroid diameters between 19m-60m depending on object albedo (0.5-0.05).

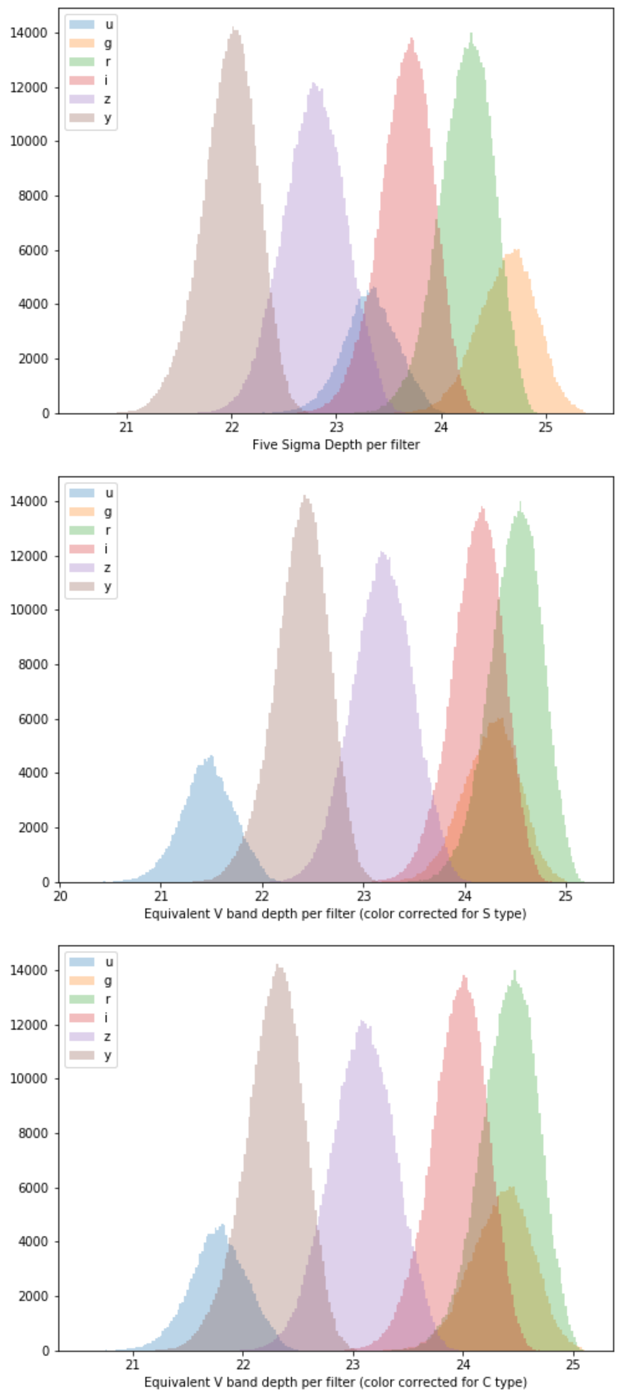

FIGURE 3: A comparison of LSST depths per filter for a flat SED (top), an SED corrected for S-type asteroids (center) and C-type asteroids (bottom), respectively. The units of the x-axis are magnitudes.

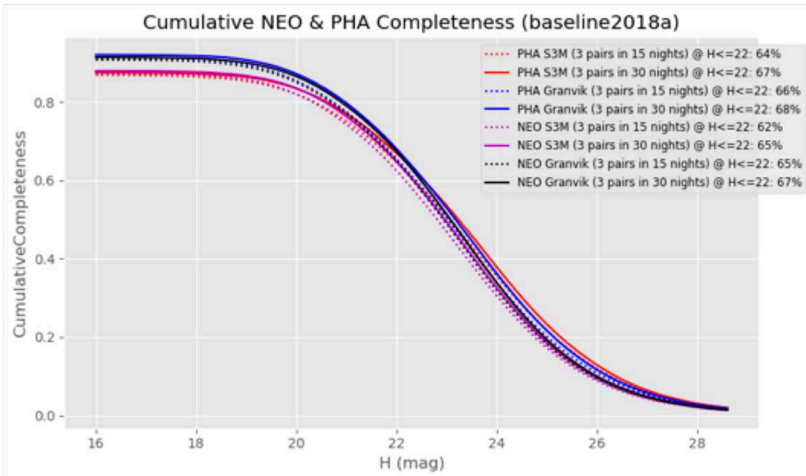

FIGURE 4: Cumulative near-Earth asteroid (NEA) and Potentially Hazardous Asteroid (PHA) completeness at the end of the 10yr LSST survey for different asteroid population models (S3M, Grav et al., 2011) and Granvik et al. (2018). Results for three pairs of observations over 15 nights are compared to similar detection conditions over 30 nights.

4 Near-Earth Asteroids

Substantial efforts have been undertaken to assess the potential of the LSST for discovering near-Earth asteroids (e.g. Ivezić et al., 2006; Jones et al., 2015; Grav et al., 2016; Vereš & Chesley, 2017b,a; Jones et al., 2018; Ivezić et al., 2019). The current consensus is that LSST is capable of achieving around 60% integral completeness NEOs with absolute magnitude brighter than 22, roughly 140m in size and larger. Together with other existing NEO surveys that number can be increased to 73% with the current LSST survey strategy. The prospects for discovering Potentially Hazardous Asteroids (PHAs) are even better, with a predicted 81% completeness at the end of the nominal LSST survey (Ivezić et al., 2019). The completeness fraction is largely independent of NEO population models such as (S3M, Grav et al., 2011) and Granvik et al. (2018), see Figure 4. In contrast, the actual number of discovered objects varies considerably as shown in Figure 5. LSST discoveries for asteroids brighter than H=25mag range from 50k to 100k over the 10yrs of the LSST survey, which corresponds to 2.5 to 5 times the number of currently known NEOs (Figure 6). Uncertainties in the NEO population model are the most significant contributors to the uncertainty in the number of NEO discoveries. All NEO simulations have been performed with SIMS_MO.

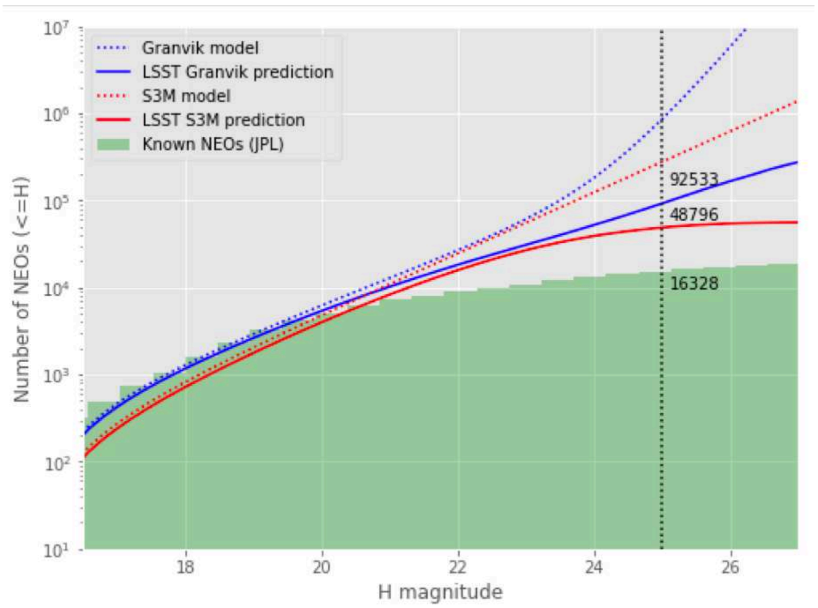

FIGURE 5: Number of NEOs discovered with the LSST for different population models (S3M, Grav et al., 2011) and Granvik et al. (2018). The prediction curves represent the cumulative number of discovered NEOs as a function of their absolute magnitude H, while the model curves show the number of expected objects in the population.

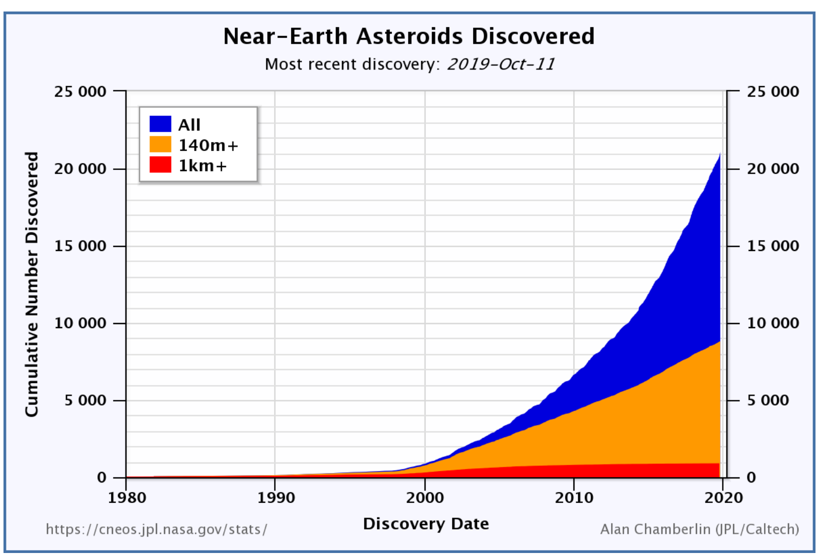

FIGURE 6: Number of known NEOs as a function of time. Source: NASA JPL/Caltech

5 Main Belt Asteroids

The vast majority of SSOs accessible to the LSST populate the Main-Belt (MB) between Mars and Jupiter (LSST Science Collaboration et al., 2009). Estimates on SSO discovery and observation statistics presented in this document are, therefore, based on simulations of Main-Belt asteroid (MBA) observations with the LSST. In order to quantify the number of potential LSST discoveries, we adopt a simple model for the size-frequency and orbit distribution of MBAs of the form

$$N(\mathrm{H}) = \beta \; 10^{\,\alpha \mathrm{H}} \tag{1}$$

where N is the number of MBAs, H the absolute magnitude, and α and β determine the slope and the anchor value of the log-linear fit, respectively. The parameters in equation (1) were derived from the current MBA population using actual data of the main belt supplied by the MPC. Assuming the bright main belt population is essentially complete up to H=14.5mag, we can fit lower and upper bounds on the size-frequency distribution that we extrapolate to fainter objects. The corresponding results are presented in Figure 7 as well as in Table 2. In order to guarantee that the slope and anchor parameters for the MBA population are not influenced by the specific choice of the bin-size in H we derived the underlying distribution n(H) using kernel density estimation where

$$n\,(\mathrm{H}) = \frac{1}{I\,b} \sum_{i=1}^{I} K\left(\frac{\mathrm{H} - \mathrm{H}_i}{b}\right), \tag{2}$$

where K is the (Gaussian) kernel and b a smoothing parameter, respectively. The resulting slopes are compatible with Jedicke et al. (2002) who find local slopes between $0.24 < \alpha < 0.58$ for MBAs with H> 10mag, as well as with size-frequency distributions from Trans-Neptunian Objects (TNOs), where $\alpha \approx 0.66$ (Bernstein et al., 2004). Orbital elements of synthetic MBAs are sampled from the joint distribution of orbital elements of the current main belt. We assume that the size-frequency and orbital element distribution are essentially uncorrelated. While, strictly speaking, this is not the case for asteroids that belong to families, a similar approach was used to create the S3M (Grav et al., 2011), a synthetic Solar System model for Pan-STARRS. In contrast to the ”bracketing” approach adopted in this work via estimating upper and lower bounds to the size-frequency distribution in the main belt, the MBA population in the S3M is based on work by Jedicke et al. (2002). A comparison between the here adopted model and Jedicke et al. (2002) used in S3M can be seen in Figure 7. The current strategy of the LSST Solar System Processing is to send only those observations of SSOs to the MPC that have a high likelihood of being either associated to know objects or new discoveries. In order to

model	α	β	N_{tot}(H ≤ 25mag)
A	0.3	2.29	104 $\times 10^6$
B	0.56	4.43 $\times 10^{-4}$	34.5$\times 10^9$

TABLE 2: Main Belt Asteroid (MBA) population models used in this work. The parameters α and β are input to equation (1). N_{tot} is the estimate for the total asteroid population with $H \le 25$mag.

minimize false positives in potential asteroid discoveries, observations of new objects are only submitted, if they are detected at least twice per night on three distinct nights (so-called ”three nighters”). The three nights do not have to be consecutive. Detections can be spread over a window of 15-30 nights. Assuming a linking efficiency close to 100%, such ”three-nighters” can be turned into preliminary orbits that have a high likelihood of belonging to newly discovered objects. The expected completeness as a function of absolute magnitude (a proxy for the size of objects) for MBAs is shown in Figure 8 after 6 months, 1 year, 2 years and after 10 years of LSST operations. The graph shows that after two years of survey more than 90% of kilometer sized MBAs will have been discovered. By the nominal end of the LSST survey we know essentially all MBAs with diameters of half a kilometer and larger. The total number of discovered MBAs as a function of absolute magnitude is presented in Figure 9. Results for the two size-frequency distributions probed are shown for both software packages, SIMS_MO

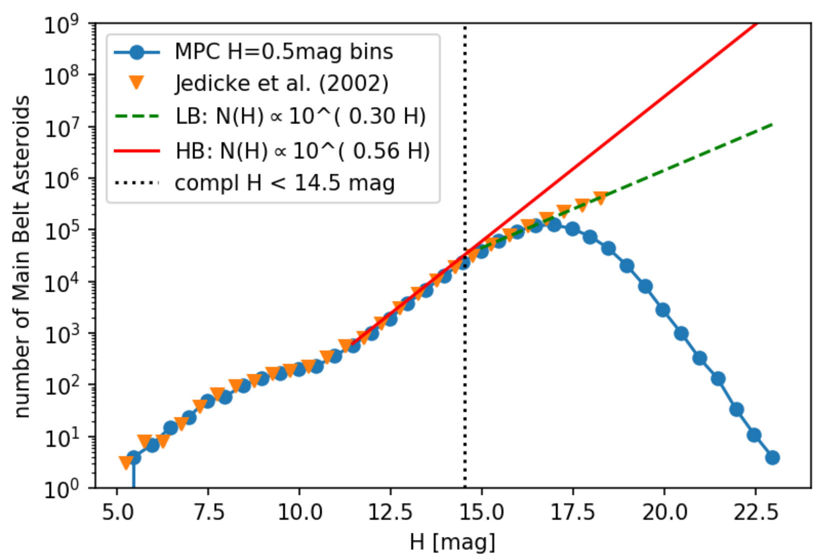

FIGURE 7: MBA population extrapolation using a continuous (red, green) and broken H(N) power law (orange), respectively.

and OPENOBS. Formal errors for SIMS_MO discoveries are based on the sample size selected from the assumed size frequency distribution. A comparison of Figures 8 and 9 shows that results for SIMS_MO and OPENOBS are very similar where LSST is expected to be essentially complete (H≈ 19mag). For smaller and fainter objects discovery rates differ slightly leading to a discrepancy of roughly 10%, which is negligible compared to the uncertainties in the expected number of MBAs. Figure 10 shows the expected number of LSST MBA discoveries per night as predicted by OPENOBS simulations. The number of discovered objects ranges from a few per night to 100,000 discoveries depending on the momentary cadence and ecliptic latitude. Figure 10 provides statistical information on how many nights are expected to yield a certain number of discoveries. The conservative size-frequency distribution sees an average of 2000 discoveries per night[1] during the ten year survey for more than 200 nights. Nights with more objects are rare but do occur. Discovery maxima of roughly 100,000 discoveries per night can occur. A steeper size-frequency distribution of MBAs (population model B) would see nights with more than 10 million discoveries.

Figure 11 shows the number of expected MBA discoveries for each of the ten years of LSST operations. If Solar System Processing (SSP) starts right away, the majority of objects will be discovered during the first years of the LSST survey. Figures 8 and 11 demonstrate the power of the LSST to quickly distinguish between various hypothesis on the size-frequency distribution in the main belt.

[1] not observed night

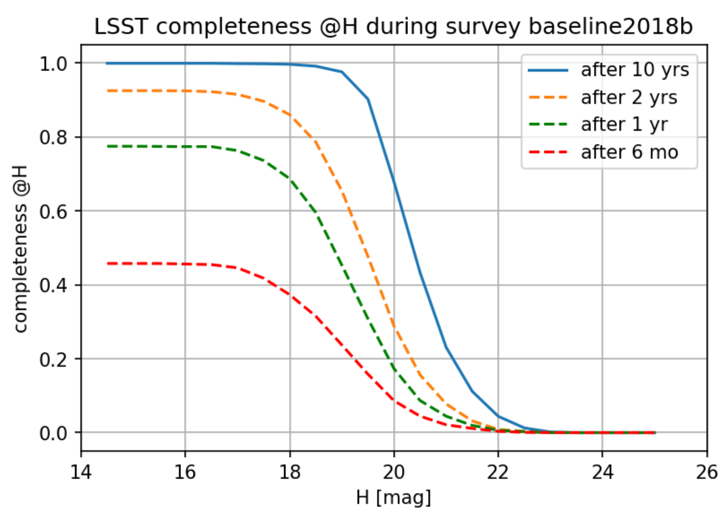

FIGURE 8: Survey completeness for MBAs at a given absolute magnitude (H) as a function of time.

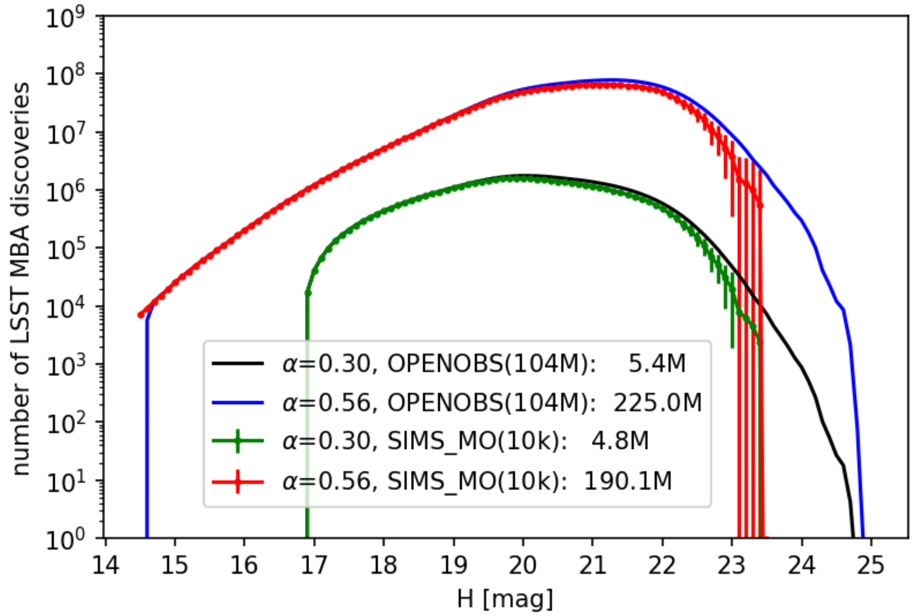

FIGURE 9: LSST Main Belt asteroid discoveries as a function of absolute magnitude for two different size-frequency distributions (population model A and B) and simulation software packages OPENOBS and SIMS_MO. See text for details.

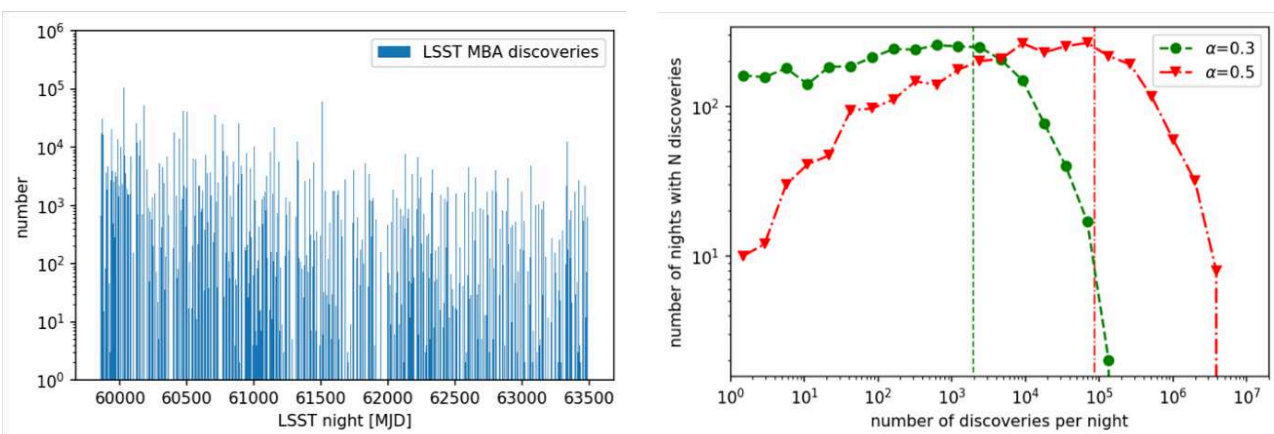

FIGURE 10: Left: LSST Main Belt Asteroid (MBA) discoveries per observed night for population model A. Right: Number of nights with a certain discovery yield versus number of discoveries per night for two different MBA size-frequency distributions.

The on-sky distribution of observations of discoverable MBAs is shown in Figure 12. The darker spots showing an increased number of observations per square degree correspond to the LSST deep drilling fields from small to high Right Ascension values: ELAIS S1, XMM-LSS,

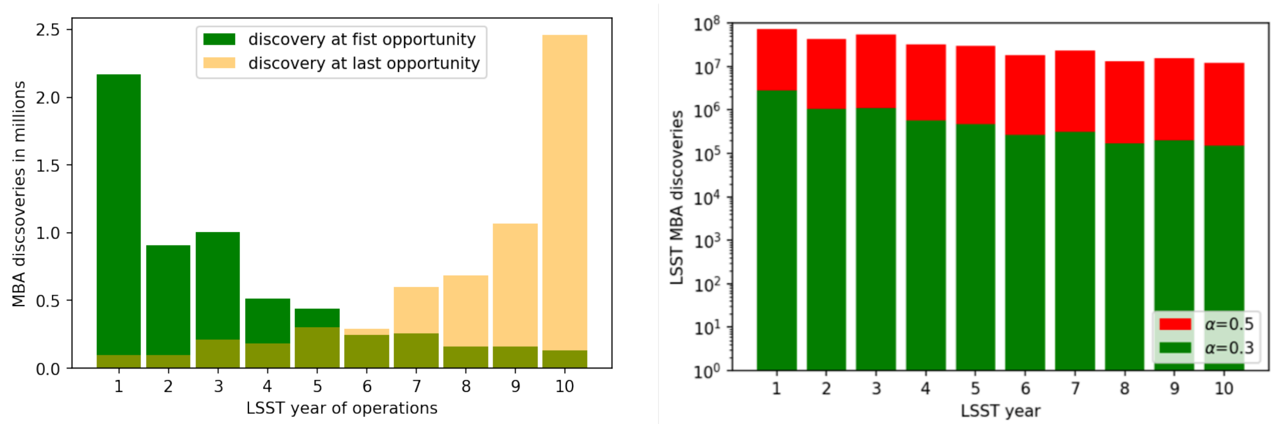

FIGURE 11: LSST Main Belt Asteroid (MBA) discoveries per year on a linear (left) and logarithmic scale (right) assuming 100% linking efficiency. The left panel compares yields for early and late discovery scenarios. The right panel shows discovery yields for population models A (green) and B (red) in an early discovery scenario.

Extended Chandra, Deep Field-South and COSMOS. Many asteroids are observed frequently

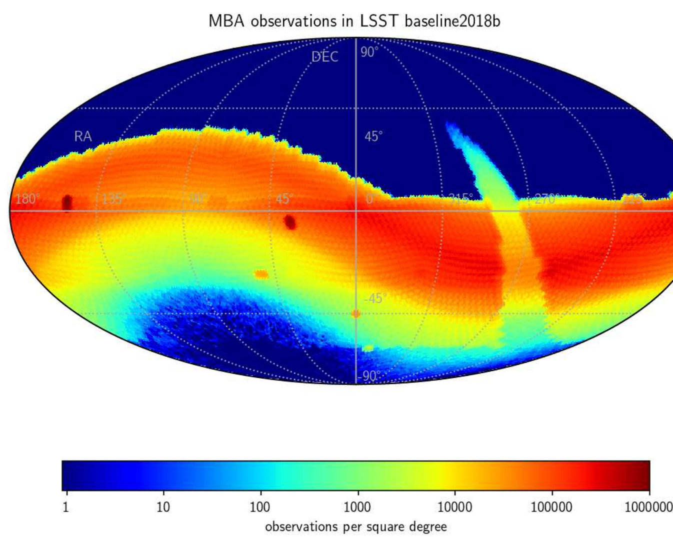

FIGURE 12: On-sky (ICRF) distribution of observations per square degree of MBAs (population model A, 14.5 ≤ H [mag] ≤ 25) discoverable with the LSST. The dark spots suggesting a locally larger number of observations correspond to the LSST deep drilling fields from right to left: ELAIS S1, XMM-LSS, Extended Chandra, Deep Field-South and COSMOS.

enough so that they can be discovered later on, if initial discovery opportunities were missed (Figure 13). Missed discovery opportunities may result from a failure to identify and/or link possible tracklets in the Solar System Processing pipeline, or a hardware/software malfunc-

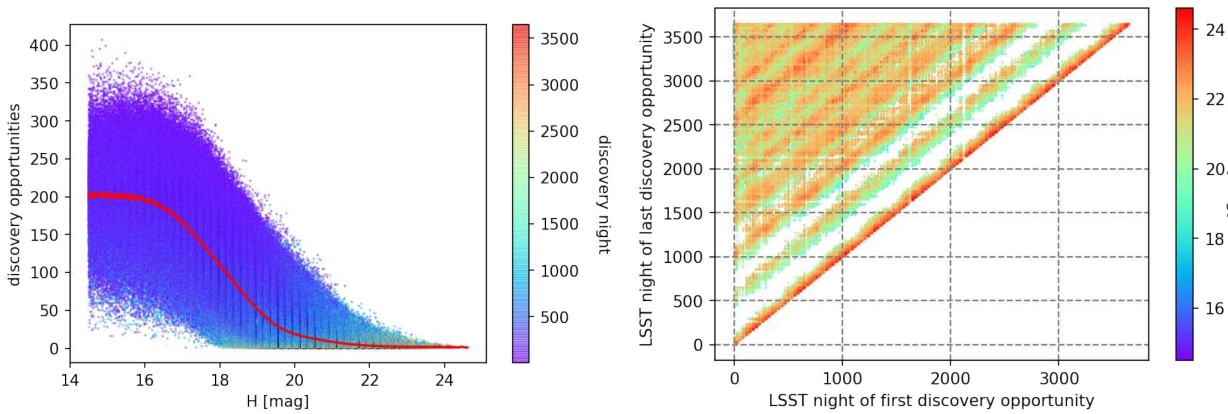

FIGURE 13: Left: Discovery opportunities for MBAs as a function of their absolute magnitude (H). The red line indicates the median for each H bin. Right: First vs. last discovery opportunity for MBAs. The color coding indicates the LSST night in which the object could be first discovered.

tion in the telescope itself, for instance. Bright objects have on average 200 discovery opportunities. This number drops fast for fainter objects, however. Discovery opportunities for MBAs generally reoccur after a synodic period between the Earth and the Main belt (≈ 500days) as can be seen from Figure 13. Most of the very faint objects have one discovery opportunity only. They populate the main diagonal in the right panel of Figure 13.

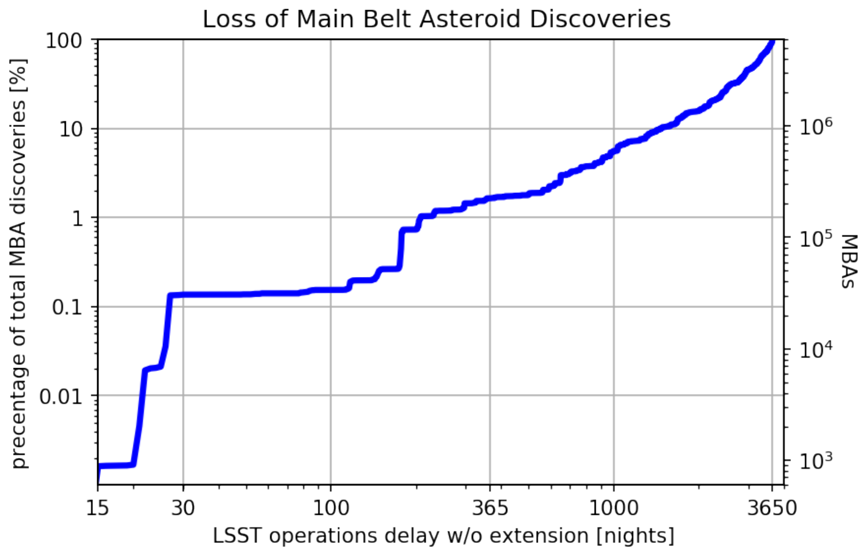

FIGURE 14: Losses in MBA discoveries due to delayed operations of the LSST (assuming no extension) for population model A.

6 Impact of delayed LSST operations and Solar System Processing

Even in a worst case scenario where LSST operations are significantly delayed, the majority of asteroids could still be discovered during the last years of the nominal period of operations (Figures 11 and 14).[2] A delay in LSST operations for a month would result in roughly 0.1% of asteroids lost. Shortening operations for a a year would result in the loss of 2% of main belt asteroid discoveries, roughly 200k objects. A delay in Solar System Processing alone would have less dramatic consequences, if LSST operations proceed nominally and data of SSOs is still collected. The computational resources to reprocess the collected data do have to be accounted for, however. As can be gathered from Figure 6, an SSP delay of a month requires the reprocessing of almost half a million objects with 20 million attributable observations. If SSP were to be delayed for a year, for instance, in order to have high quality templates available, around two million objects with 100 million observations would need to be processed on top of the daily data releases. Although this constitutes a non-negligible computational effort, the planned, yearly LSST data releases would be of similar magnitude. Hence, we do not anticipate a change in the computational requirements at this point, even if the SSP were to be delayed. That being said, timely Solar System Processing offers numerous advantages:

[2]Note, that this is not necessarily true for near-Earth asteroids, since their discovery function is not as simple a function of the synodic period as it is for MBAs.

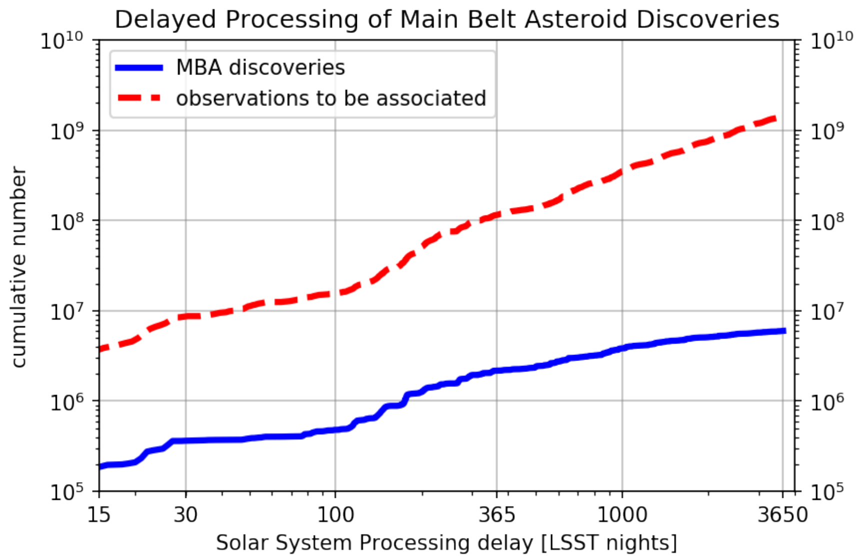

FIGURE 15: Cumulative number of MBAs (blue) and observations (red) that require reprocessing if SSP is delayed.

- The success of follow up observations hinges on a timely identification and publication of objects of interest.
- A continuous rather than a blocked reduction of LSST SSO data can help avoid computational bottlenecks later in the survey.
- Identifying detections belonging to SSOs can help decrease the number of “false alerts”.

A quantitative assessment of the latter point is presented in the next section.

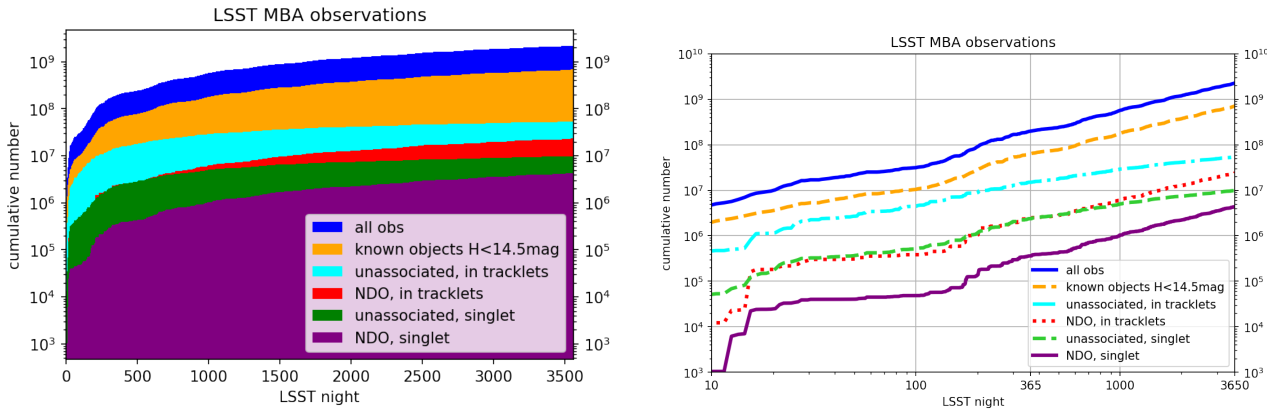

FIGURE 16: Cumulative number of LSST observations of MBAs over time. The left panels shows all LSST observations (blue), observations of bright, already known objects (orange), unassociated observations in tracklets (cyan) and singlets (green) and non-discoverable objects in trackelts (red) and singlets (purple). The left panel is log linear, while the right panel contains a log-log plot. The corresponding numbers are presented in Table 4.

7 Solar System Objects as a Source of Noise

Not all new SSOs detected by the LSST accumulate enough observations to count as "discovered". The current discovery policy for SSOs requires repeated recurrence (three-nighters). An object must have at least two observations per night over three nights in a 15-30 night window to be considered a candidate object that can be sent to and validated by the MPC. Detections that can neither be linked to known objects nor grouped to form a new discovery are bound to contribute to the overall "noise" that may trigger false alerts, for instance. In order to estimate how many observations of SSOs may fall into the latter category we used the baseline2018b cadence together with the more likely size-frequency distribution for asteroids in the main belt (model A) and simulated observations via OPENOBS. The resulting observations, roughly 2 billion, were then analyzed in order to understand how many observations could be linked to known and newly discovered sources and how many would remain unassociated. The outcome is presented in Figures 16 as well as in Table 4. We distinguish between observations of

- bright objects that are known today accounting for approximately 30% of LSST SSO observations,
- observations of non-discoverable objects (NDOs), SSOs that cannot be grouped into "three nighters",

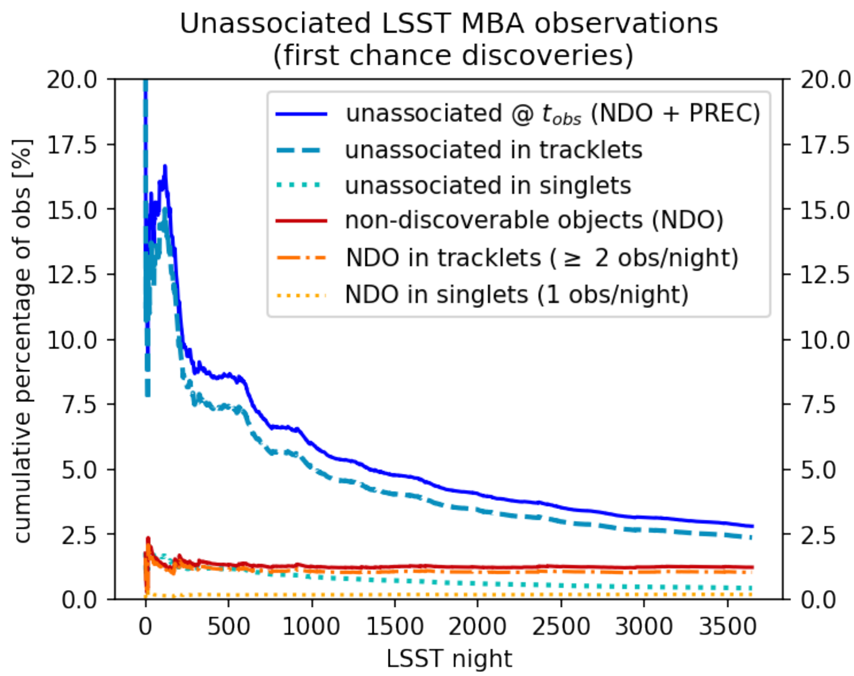

FIGURE 17: Fraction of unassociated and non-discoverable object observations of MBAs assuming all asteroids have been discovered at the first opportunity.

- and unassociated observations, i.e. observations of NDOs and objects that have not been discovered at the epoch of observation.

If asteroids are discovered early in the survey, e.g. with the first discovery opportunity, practically all LSST observations of asteroids can be associated with SSOs after ten years of operations. Figure 17 as well as the data displayed in Table 4 underline this fact. However, the fraction of unassociated observations remains non-negligible throughout the survey. Figure 17 shows that that fraction is around 15% at the beginning of the LSST survey compared to merely 2.5% near the end. This is not surprising as the fraction of discovered to undiscovered objects increases over time. Precovery algorithms can reduce the number of unassociated observations by roughly 50%, but only a posteriori. At the time of observation, unassociated observations may still trigger unwanted LSST alerts. Figure 18 suggests that most nights tend to have a relatively low number of unassociated observations, typically between 1k-10k (Table 3). Similarly, one can expect between 100 and 10k observations from non-discoverable objects per night. Only a hand-full of nights may prove to be "noisier". Figure 19 shows the absolute magnitude distribution of detected, discovered and non-discovered objects for the

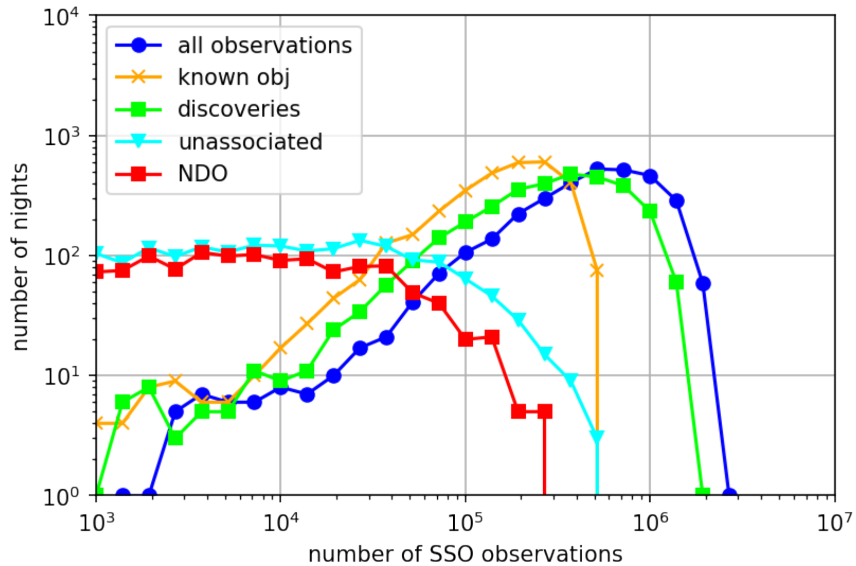

FIGURE 18: Frequency of nights with a given number of observations.

LSST Observations of MBAs

per night	all obs.	discoveries	known obj.	UNO	NDO
median	528,022	312,077	177,172	626	72
mean	621,084	402,334	193,570	17,490	7,688
std. dev.	511,835	363,013	145,676	47,643	24,491
maximum	2,976,668	2,134,030	683,392	656,687	356,857

TABLE 3: Nightly statistics for all LSST MBA observations, currently known object observations, unassociated observations and observations of non-discoverable objects.

MBA population model A. One can see that the LSST MBA survey is bound to discover practically all objects down to absolute magnitude $H = 19.5$mag. The 50% completeness mark is $H = 21.5$mag. Absolute magnitudes for non-discoverable objects range from H=19mag to H=25mag. The on-sky distribution of observations of non-discoverable objects is shown in Figure 20. The distribution broadly resembles the one in Figure 20. Over ten years of operations, one would expect fewer than 4000 observations per square degree from non-discoverable MBAs near the ecliptic with an all-sky median value of 76 per night (3).

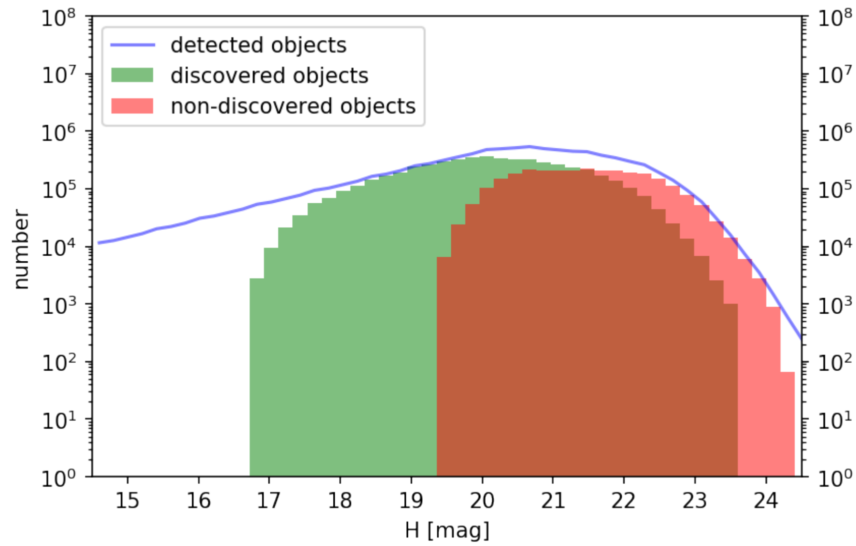

FIGURE 19: Number of detected, discovered and non-discovered MBAs as a function of their absolute magnitude H.

LSST Observations of MBAs

Discovery at	Total	$H < 14.5$mag	UNO TR	UNO SNGL	NDO TR	NDO SNGL
first chance	2.27e+09	7.06e+08	5.39e+07	9.86e+06	2.37e+07	4.36e+06
percentage	100%	31.2%	2.4%	0.4%	1.1%	0.2%

TABLE 4: Main Belt Asteroid (MBA) observations at the end of the LSST survey. Observations of bright, already known objects are in the column $H < 14.5$mag. Unassociated observations (UNO) can partly be linked to discovered objects via precovery. NDOs are observations of non-discoverable objects. The number of observations that are part of tracklets (TR) is contrasted with single observations per night (SNGL). Dashes indicate the first and last chance observations are the same.

8 Expected MPC Data Rates

Based on observation statistics presented in the previous section we can estimate nightly data rates for submitting SSO observations to the MPC. The new Astrometry Data Exchange Standard (Astrometry Data Exchange Standard (ADES)) submission format[3] that will be adopted by the time LSST goes on line permits a more detailed description of optical observations of SSOs. Observation covariance information can be provided, for instance. As such, each observation should have an equivalent size of roughly 500bytes when submitted to the MPC. Figure 21 shows the corresponding, expected nightly data volumes. Submissions will typi-

[3] https://www.minorplanetcenter.net/iau/info/ADES.html

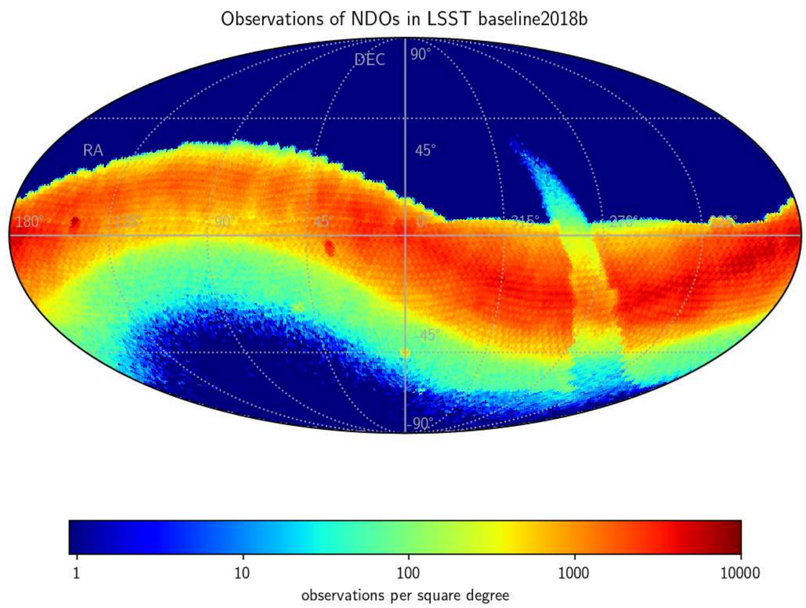

FIGURE 20: On-sky distribution of observations per square degree of non-discoverable objects (NDOs).

cally be on the order of several hundred MBs per night. GB sized submissions are fairly rare occurring on roughly 50 nights during the ten years of LSST operations. Given the fairly steep size-frequency distribution in population model A that has been used in this assessment, observations of new discoveries will dominate MPC submissions despite the fact that known objects are brighter and tend to have more observations per object. Table 5 contains the corresponding statistics. It is currently not planned to submit all observations to the MPC. Only observations that can be linked to known objects and those that can be confidently attributed to new discoveries are to be delivered.

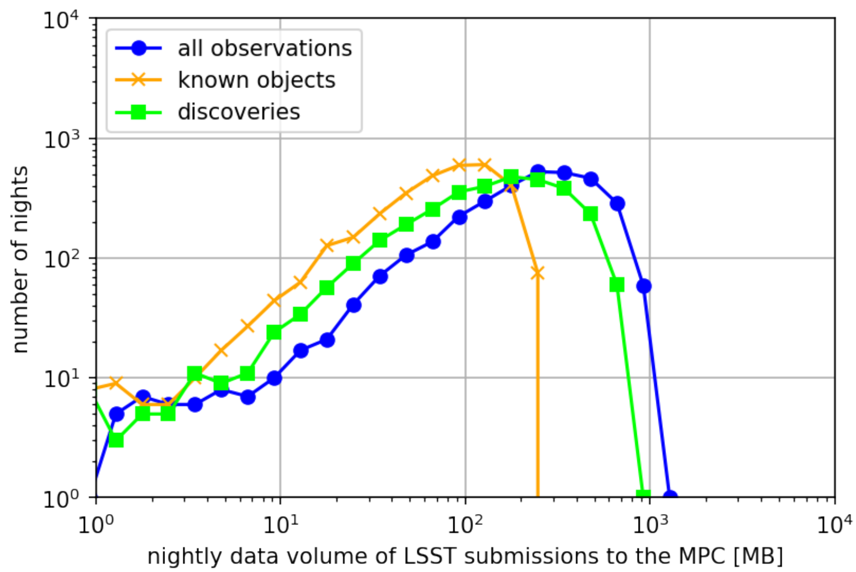

FIGURE 21: Predicted nightly data volumes for submissions of LSST observations to the Minor Planet Center.

LSST data volumes for MPC submission in ADES format [MB]			
per night	all obs.	discoveries	known obj.
median	252	149	84
mean	296	192	92
std. dev.	244	173	69
maximum	1,419	1,018	326

TABLE 5: Nightly data volumes for the submission of LSST MBA observations, discoveries and currently known object observations to the Minor Planet Center in MegaBytes.

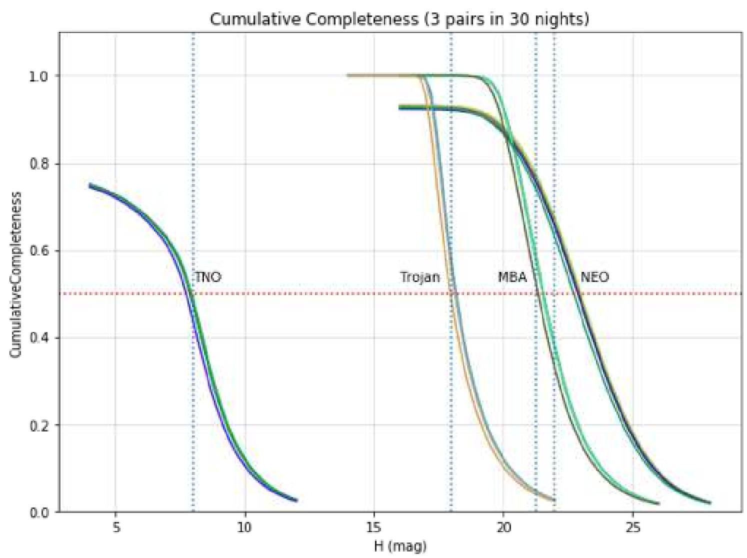

FIGURE 22: Cumulative completeness for various solar system populations with the Feature Based Scheduler 1.2 baseline. The two lines show results with visit pairs in the same filter vs. pairs in different filters (TNOs with C colors)

9 Other Solar System Object populations

Similar to the inner Solar System, size frequency distributions for SSOs in the outer solar system are not well understood. For Trojans and Trans-Neptunian Objects (TNOs) only cumulative completeness estimates are available at this point. Those are presented in Figure 22. Until updated figures become available we suggest to use the previous predictions of 40k Trojan and 280k TNO discoveries from Jones et al. (2015). Interstellar objects and comets have not yet been investigated in detail.

10 Conclusions

LSST is going to be the largest contributor of Solar System object observations and discoveries to be processed by the IAU Minor Planet Center. The study at hand shows that

- LSST is bound to discover between 49k-93k near-Earth asteroids (NEOs) depending on the actual size-frequency distribution.
- Observations and discoveries of Main belt asteroids (MBAs) are bound to dominate LSST SSO data submitted to the IAU Minor Planet Center.
- The number of MBAs discovered over 10 years of LSST likely ranges between 4.8M and 5.4M and is unlikely to be higher than 220M.
- The majority of discoveries are going to be made within the first 2 to 3 years of the LSST survey.
- The number of MBA discoveries per night can be up to 100 000 with an average of 2000 for the most likely size-frequency distribution (population model A). Even in the unlikely case of a TNO-like size-frequency distribution in the Main Belt we expect no more than 3 million discoveries per night on a handful of nights during the survey.
- The vast majority of asteroids observed with LSST have two and more observations per night.
- The "three nighter" paradigm for detecting SSOs leads to a non-negligible fraction of unattributable observations, since not all observations that can be connected into tracklets occur on three separate nights.
- After ten years of LSST operations observations of non-discoverable objects are likely to be on the order of several thousands per square degree concentrated in a band around the ecliptic. This excludes TNOs that are too slow to be identified as moving objects.
- Nightly data volumes delivered to the Minor Planet Center are generally on the order of several hundred MBs and only rarely exceed a GB.

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A Glossary

ADES Astrometry Data Exchange Standard.

B Byte (8 bit).

camera An imaging device mounted at a telescope focal plane, composed of optics, a shutter, a set of filters, and one or more sensors arranged in a focal plane array.

Center An entity managed by AURA that is responsible for execution of a federally funded project.

declination Often abbreviated Dec, it is a part of an equatorial coordinate pair that expresses the angular distance (usually expressed in degrees) from the Celestial Equator, measured along great circles that intersect the Equatorial poles. Positions south of the equator are given negative sign.

DMTN DM Technical Note.

epoch Sky coordinate reference frame, e.g., J2000. Alternatively refers to a single observation (usually photometric, can be multi-band) of a variable source.

flux Shorthand for radiative flux, it is a measure of the transport of radiant energy per unit area per unit time. In astronomy this is usually expressed in cgs units: erg/cm2/s.

footprint See 'source footprint', 'instrumental footprint', or 'survey footprint', 'Footprint' is a Python class representing a source footprint.

GB Gigabyte.

IAU International Astronomical Union.

JPL Jet Propulsion Laboratory (DE ephemerides).

LSST Large Synoptic Survey Telescope.

MB MegaByte.

MBA Main Belt Asteroid.

MPC IAU Minor Planet Center.

NASA National Aeronautics and Space Administration.

NDO non-discoverable object.

NEO Near-Earth Object.

Object In LSST nomenclature this refers to an astronomical object, such as a star, galaxy, or other physical entity. E.g., comets, asteroids are also Objects but typically called a Moving Object or a Solar System Object (SSObject). One of the DRP data products is a table of Objects detected by LSST which can be static, or change brightness or position with time.

Pan-STARRS Panoramic Survey Telescope and Rapid Response System.

PHA Potentially Hazardous Asteroid.

pipeline A configured sequence of software tasks (Stages) to process data and generate data products. Example: Association Pipeline.

precovery The process of finding, or putting upper limits on, detections of a newly discovered DIAObject in previously obtained images, typically using forced photometry. Alert Packets will contain precovery data derived from the past 30 days of images that include the location of a new DIAObject.

SED Spectral Energy Distribution.

Source A single detection of an astrophysical object in an image, the characteristics for which are stored in the Source Catalog of the DRP database. The association of Sources that are non-moving lead to Objects; the association of moving Sources leads to Solar System Objects. (Note that in non-LSST usage ”source” is often used for what LSST calls an Object.).

Spectral Energy Distribution the radiated energy of an astrophysical object as a function of energy (or wavelength) across the entire spectrum of light.

SSA Space Situational Awareness.

SSO Solar System Object.

SSP Solar System Processing.

TNO Trans-Neptunian Object.

UNO Unassociated object.

Wide-Fast-Deep The main survey of the LSST to cover at least 18000 square degrees of the southern sky.

XMM X-ray Multi-mirror Mission (ESA; officially known as XMM-Newton).