A constellation of CubeSats with synthetic tracking cameras to search for 90% of potentially hazardous near-Earth objects

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ABSTRACT

Congress mandated NASA to find 90% of near-Earth objects (NEO) with sizes over 140 m that are potentially hazardous to the Earth by the year 2020. After an in-depth look at a number of alternative approaches, the National Research Council (NRC) concluded in 2010 that this goal was nearly impossible to reach by 2020. In this paper, we present a new space mission concept that is capable of addressing the challenges of this Congressional mandate. The proposed mission concept relies on two emerging technologies: the technique of synthetic tracking to detect NEOs and the new generation of small and capable interplanetary spacecraft. Synthetic tracking is a technique that destreaks asteroid images by taking multiple fast exposures. With synthetic tracking, a 600 sec observation with a 10 cm telescope, which can fit in a CubeSat, can detect a 20.5 mag moving object without losing sensitivity from streaking. Our primary science objective is to detect, track, catalogue, and characterize 90% of NEAs of H=22 mag (diameter of 140 m) that could impact the Earth. We show that five 9U CubeSats equipped with a 10 cm synthetic tracking camera placed in solar orbit to form a constellation could achieve this objective in \( \sim 3 \) years of observing time. Furthermore, our mission will be able to address the goals of the Congressional mandate at a cost of \( \sim 10\% \) compared to that of the space missions studied in the NRC 2010 report.

Subject headings: astrometry – instrumentation: detectors – minor planets, asteroids: general – techniques: image processing

1. Introduction

The discovery and characterization of near-Earth objects (NEOs) is motivated by several reasons and concerns, including scientific research, planetary protection, and exploration efforts. NEOs are believed to be remnants from the early evolution of the solar system and hence studies of their prevailing dynamics and chemical composition may offer important information about conditions at that early epoch. The possibility that some NEOs could approach and even impact

\[1\] A near-Earth object or NEO is an object that orbits the Sun and approaches or crosses the Earth’s orbit.
the Earth has motivated many observers worldwide to systematically search, catalog, and study the NEO population. Events such as Tunguska, which happened over eastern Siberia in June 1908, and more recently the fireball over the city of Chelyabinsk in Russia in February 2013, emphasize the importance of such efforts. Mining of near-Earth asteroids (NEAs, a subset of the NEOs) has also provided an impetus to private companies to perform a census of these objects to identify the most viable targets. There is also an interest to find NEAs accessible by human spaceflight as targets for an Asteroid Redirect Mission (ARM) which focuses on small NEAs with sizes $\sim 7$–$10$ m in orbits with low relative velocities with respect to the Earth.

Recognizing the threat that NEOs pose to life on Earth, the US Congress has passed the 2005 NASA Authorization Act, according to which NASA was mandated to detect, track, catalogue, and characterize the physical characteristics of at least 90% of NEOs larger than 140 meters in diameter (i.e., with absolute magnitude of $H=22$ mag) that could potentially impact the Earth by the end of year 2020. Responding to the Congressional charge, NASA has funded several NEO surveys to find such potentially hazardous objects (PHOs) However, it has become clear that the current efforts are inefficient, and it is predicted to take over two decades to complete the task. After a detailed look at a number of alternative approaches, in 2010 the National Research Council (NRC) concluded that the goal of finding 90% of $H=22$ mag NEOs by the year 2020 was nearly impossible to achieve (NRC 2010). The NRC committee looked at various ground- and space-based options and found that the most viable approaches with the potential to complete the survey in the period of $\sim 10$ years were the space-based ones. Each of the corresponding missions would rely on a single spacecraft, would require an active decade-long observing campaign, and would cost over $500M. However, even if funded, these expensive missions will not guarantee completion of the survey for 90% of 140 m NEOs by 2020. As a result, even today, the Congressional challenge of 2005 is still unmet.

Since the release of 2010 NRC report we witnessed significant technology progress in several relevant areas that could result in a major paradigm shift in the search for NEOs. One such area is the rapid development, flight heritage, and technology maturation for small and capable spacecraft, namely CubeSats. A single unit (1U) CubeSat is a type of miniaturized satellite that usually has a volume of exactly one liter (based on a $[10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}]$ form-factor), has a mass of no

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2NASA Asteroid Initiative website: [http://www.nasa.gov/mission_pages/asteroids/initiative/index.html](http://www.nasa.gov/mission_pages/asteroids/initiative/index.html)

3The Asteroid Redirect Mission (ARM) is one part of NASA’s Asteroid Initiative, see details at [http://www.nasa.gov/content/what-is-nasa-s-asteroid-redirect-mission/](http://www.nasa.gov/content/what-is-nasa-s-asteroid-redirect-mission/)

4Specifically, the George E. Brown, Jr. Near-Earth Object Survey section of the NASA Authorization Act of 2005 (Public Law 109-155).

5An object is considered a potentially hazardous object (PHO) that is, posing a possible risk to Earth if, among other conditions, its minimum orbit intersection distance (MOID) from the Earth is less than 0.05 AU.

6For information on CubeSats, please visit [http://en.wikipedia.org/wiki/CubeSat](http://en.wikipedia.org/wiki/CubeSat) and [http://cubesat.jpl.nasa.gov/](http://cubesat.jpl.nasa.gov/).
more than 1.33 kg and typically costs $1–2M.

We observe that a CubeSat-based mission architecture presents a viable alternative relative to the missions proposed in the NRC report. Modern CubeSats have benefited from decades of development efforts in miniaturization of many spacecraft technologies. Typically, modern CubeSats use commercial off-the-shelf (COTS) space-qualified hardware that can be purchased at a cost that is dramatically lower relative to that of conventional spacecraft components. The radically lower cost of a CubeSat-based architectures enables one to consider using multiple small spacecraft, each consisting of several CubeSat units, while conventional multi-spacecraft architectures would never be economically viable.

Another technology advancement that enables the proposed small spacecraft mission architecture is the technique of synthetic tracking of NEOs (Shao et al. 2014), which makes it technically feasible to perform NEO searches with small CubeSat-compatible cameras. Synthetic tracking of NEOs is an emerging technology that recently was developed and demonstrated by NASA’s Jet Propulsion Laboratory (JPL) (Shao et al. 2014; Zhai et al. 2014). When used from a ground-based facility, this new tracking technique provides an order of magnitude improvement in the ability to detect and track dim and fast-moving objects. Synthetic tracking implemented on a 10 cm CubeSat telescope in space with 600 sec observations would result in a sensitivity to a 20.5 mag object at SNR=10, making it an ideal candidate technology to use on a CubeSat.

For planetary defense, the ability to accomplish precision orbit determination of NEAs enabled by synthetic tracking is important because discovery is not useful if the orbit, and thus future risk of impacting the Earth is unknown. We note that even if the existing mission concepts, such as those mentioned in the 2010 NRC report were flown, their astrometric precision of ∼0.2″ per observation is inadequate to determine whether it will impact the Earth or not. Synthetic tracking potentially offers an order of magnitude higher astrometric accuracy to address this critical issue.

This paper presents a new mission concept that uses a constellation of 9U CubeSats with a 10 cm synthetic tracking telescope. In addition to a cost that is dramatically lower relative to any of the missions examined by the NRC, this mission would also be capable of surveying over 90% of the population of 140 m NEOs in less than 3 years of observing time. Furthermore, a second generation constellation of synthetic tracking CubeSats could survey 90% of 50 m NEOs in less than 5 years.

This paper is organized as follows: Section 2 provides a short overview of the key findings of the NRC 2010 report. Section 3 summarizes synthetic tracking technique, which leads to high detection sensitivity when implemented with a small 10 cm optics on a CubeSat. Section 4 discusses the CubeSat architecture and presents findings of the recent JPL’s Team Xc study of a CubeSat with a synthetic tracking camera. In Section 5, we present the details of our recent simulation developed to study a search for 140 m NEOs using multiple 9U CubeSats in solar orbit. In Section 6, we discuss several CubeSat-based mission scenarios that could accomplish the Congress-mandated NEO search in ∼3 years of observing time. We also discuss a second generation CubeSat constellation that could
search for 90% of NEOs with sizes down to 50 m in diameter. In Section 7, we address the practical issues related to setting up a constellation of small spacecraft. In Section 8, we summarize and discuss the results.

2. Search for potentially hazardous NEOs

According to the 2005 NASA Authorization Act, NASA is mandated to detect, track, catalogue, and characterize 90% of NEOs larger than 140 m in size that are potentially hazardous to the Earth by the end of year 2020. Due to budgetary constraints and the technical complexities related to implementation of the Congressional mandate, no immediate decision was made at the time of the report. Three years later in 2008, the Consolidated Appropriations Act required NASA to ask the NRC to conduct a study of potentially hazardous NEOs and viable approaches to mitigating identified hazards, which NASA did. The statement of task also required the NRC to include an assessment of the costs of the various alternatives.

In its 2010 report, the NRC presented a study of a number of approaches to address the objectives of the NASA task. The NRC emphasized that a combination of space- and ground-based facilities would be required to find 90% of 140 m NEOs by 2020, and that the task which would require nearly 10 years and cost over half a billion dollars. The committee concluded that the completion of the NEO census, as mandated by the 2005 Act, is not feasible by 2020 without a significant infusion of funds. The report emphasized that a combination of the space-based efforts together with an appropriate ground-based facility could be used to accelerate the survey. Such a combination could complete the survey well before 2030, perhaps as early as 2022. They reported that using a large ground-based telescope alone (such as LSST or PanSTARRS), even if this facility would be fully dedicated to NEO search, could not complete the Congress-mandated survey by the original 2020 deadline. In fact, it would take a decade-long dedicated campaign to complete this effort probably just before 2030. Furthermore, the committee concluded that, despite associated launch risk and a more limited lifetime, a space-based option could be the fastest means to complete the survey.

The NRC evaluated several space-based options to survey the NEOs including:

- A 0.5-meter-diameter infrared telescope placed in Earth’s orbit at the Earth-Sun L1/L2 Lagrange points (at a cost of ~$500M). In its 5-year baseline mission, the telescope is estimated...
to discover $\sim 75\%$ of all NEOs larger than 140m; achieving 90\% completeness after 10 years (Chesley and Spahr 2004).

- A 0.5-meter-diameter infrared telescope placed in Venus’ orbit (costing $\sim$\$600M) to allow observations over slightly more than the entire anti-Sun hemisphere. This option would be able to detect over 90\% of all potentially hazardous NEOs larger than 140 m in $\sim$8 years of observing time (Chesley and Spahr 2004).

- A hypothetical 2 m class optical telescope placed either at Earth-Sun L1/L2 or on a Venus-like orbit with a price tag of over $1B. Although, the latter option demonstrated a better performance compared to the two IR options above, it was not supported because of its perceived high cost.

Despite the attractiveness of the concepts presented above, there are challenges with these proposals. The most serious of the challenge is the required longevity of the missions that is needed to complete the surveys. We note that nearly all the concepts discussed in the NRC 2010 report require observations for $\sim$10 or more years to achieve 90\% survey completeness. However, because of the additional redundancy and the need for required testing, space missions that are designed for $\sim$10 year lifetimes are potentially much more expensive than those that last for 5 years or less. The Kepler mission\(^\text{10}\) is an example of a $\sim$\$600M spacecraft that was designed for a 4 year primary mission with consumables to last for $\sim$8–10 years. However, the primary mission was aborted after 2 of the 4 reaction wheels failed after only 4 years of operations. The missions’ longevity is critically important for a NEO search mission in order to achieve 90\% completeness. The resulting cost impact of guaranteeing long-duration missions was not addressed by the NRC report, which is expected to grow the cost estimates significantly.

To date, $\sim$12,300 NEOs had been discovered\(^\text{11}\), 820 of which have a diameter larger than 1 km. From that population, 1,492 objects (12.2\%) are classified as “potentially hazardous” with an MOID less than 0.05 AU. The NRC 2010 report recognized the fact that objects smaller than 140 m in diameter are also capable of causing significant damage to the Earth. The estimates show (Harris 2009, 2011) there are millions of asteroids with sizes ranging from 140 m down to 30 m in diameter that are still undetected, but those objects are large enough to cause major regional damage in the event of an Earth impact. Early analysis of the object that entered the Earth's atmosphere over the Siberian wilderness near Podkamennaya Tunguska in 1908 estimated that its size was $\sim$70 m in diameter. However, recent analyses (Chyba et al. 1993; Boslough and Crawford 1997, 2008) indicate that the object could have been substantially smaller, perhaps 30 to 50 meters in diameter, causing much of the damage by exploding in the atmosphere and resulting in shock waves that devastated more than 2,000 km\(^2\) of forest. Accordingly, NEOs as small as 30–50 m in diameter are capable of causing significant damage to the Earth.

\(^{10}\)The NASA’s Kepler mission: \url{http://kepler.nasa.gov/}

\(^{11}\)The most recent information on the NEOs discovered may be obtained from the IAU’s Minor Planet center at: \url{http://www.minorplanetcenter.net/}
diameter could be highly destructive. Among the recent events, the Chelyabinsk meteor in 2013 had a diameter of only 17 m prior to entering the Earth atmosphere. Therefore, in addition to the efforts of finding objects 140 m and larger, there is a need for detecting as many objects that are 30–50 m (and, perhaps, even smaller) as possible.

There have been two important developments since the 2010 NRC report that could enable a major advancement towards accomplishing the objectives of the NEO 2005 Act. These developments are 1) successful demonstration of the synthetic tracking technique that was developed to detect and track faint fast-moving NEOs (Shao et al. 2014; Zhai et al. 2014) (see Sec. 3 for details), and 2) the rapidly developing field of interplanetary CubeSats (see Sec. 4 for details). When used together, these technologies could lead to a space mission capable of surveying over 90% of 140 m NEOs in less than 3 years of observation at a cost dramatically lower (see Sec. 5 for details) relative to the space missions presented in the NRC report. Furthermore, these technologies make it possible to contemplate a space mission that will be able to conduct the search for even smaller asteroids with sizes down to 30–50 m and still be affordable.

3. Synthetic Tracking Technique

As NEOs are moving against the background stars, their resulting images when using a conventional CCD are streaked, resulting in degradation in sensitivity. The NRC report included a simulation of a hypothetical 2 m space telescope conducting a NEO search. The optimal integration time for this instrument was only 8 sec with 30 sec of slewing between adjacent fields of view (FOV) [S. Chesley of JPL (2015), private communication]. Longer CCD exposures do not improve sensitivity because of image streaking. Synthetic tracking techniques achieve much higher NEO detection sensitivity by taking multiple short exposures and performing a shift/add operation (Shao et al. 2014). This technique makes it possible to achieve a sensitivity down to a ∼20.5 mag object with 10 cm optics in a 600 sec observation, thus offering significant improvements in the sensitivity of detection of NEOs. Below we discuss this technique as it applies for a CubeSat version of a synthetic tracking camera.

3.1. Improving sensitivity, SNR and astrometry with synthetic tracking

It is well-known that traditional approaches to discovering NEOs relies on CCD exposures of ∼30 sec long. Typically, CCDs require ∼10 sec to read-out time at low noise (∼3e−). Although this approach is effective in detecting slowly moving NEOs, results in a streaked image on the CCD and leads to a significant trailing loss of sensitivity. Intuitively, trailing loss results from the fact that the streaked image distributes photons comprising its signal over a larger area on the CCD (compared to those received from a stationary object) yielding a reduced signal per unit area. There have been many studies on trailing losses. Shao et al. (2014) quantify the trailing loss in SNR as
a factor $w/(w+s)$, where $w$ is the width of a seeing-limited point-spread function (PSF) and $s$ is the length of the streak. The longer the exposure leads to a longer streak length and results in a smaller SNR.

![Schematic showing the integration of frames by using synthetic tracking. Frames are displaced according to the velocity of a NEO so that it is at the same location in all the frames during the integration (adopted from Shao et al. 2014).](image)

Fig. 1.— Schematic showing the integration of frames by using synthetic tracking. Frames are displaced according to the velocity of a NEO so that it is at the same location in all the frames during the integration (adopted from Shao et al. 2014).

Compared to the conventional method of a single 30 sec exposure, synthetic tracking uses multiple short exposures: for example, 120 frames at 4 Hz over the same 30 sec interval. For a small object, a single 0.25 sec exposure image is not sufficient to detect the object in one frame; instead, an addition of appropriately shifted image frames is needed to reconstruct the image of the object. Figure 1 illustrates the shift/add technique. We shift each subsequent image by an assumed velocity vector. If that assumed velocity is the actual NEO velocity, all the NEO photons will end up in the same pixels in the stacked image. However, for an unknown NEO with an unknown velocity, several different velocities must be tried to determine the true velocity.

NEOs are found by conducting a 4D velocity $(x, y, v_x, v_y)$ search in our 3D data cube, which are used to solve for the NEO orbits. This effort is computationally intensive (Zhai et al. 2014). For a ground-based facility, the search is done on a graphics-processing unit (GPU) with 2500 cores with a velocity grid of size $100 \times 100$, with velocity grid spacing of $1''$ in 30 sec. This ensures that the maximum velocity error when searching for each NEO is less than $0.5''$ in 30 sec, which means that the images are streaked by less than $0.5''$ along right ascension (RA) or declination (DEC), which is a negligible trailing loss. A typical velocity-searching range covers $\pm 40^\circ$/day in both RA and DEC, which is adequate for most NEO detections. A maximal velocity of $40^\circ$/day is enough to cover over $99.9\%$ of all NEOs. However, even faster-moving objects will be detected but result in streaked NEO images and therefore lower sensitivity.

We have demonstrated the performance of the synthetic tracking technique towards improving the detection SNR by successfully detecting a faint object with an apparent magnitude of 23 (H$\sim$29.5 mag assuming the asteroid velocity is 10 km/s detected at 20 lunar distances) on the Palomar 5 m telescope (Shao et al. 2014). The object was moving at a speed of $\sim 6^\circ$/day, covering $\sim 7''$ during the 30 sec observation time. Figure 2 shows (a) the synthetically tracked images for
tracking at the sidereal rate and (b) the asteroid from integrating more than 500 frames taken at 17 Hz by an EMCCD\textsuperscript{12} with a negligible read noise when used with an EM gain of 200. Image (a) would be the image detected by using the traditional 30 sec exposures. The asteroid image is a 7\arcsec streak with a surface brightness of a 25 mag star, with a sky background of \(\sim 21\) mag/\(\arcsec^2\). We detected this object, shown in (b), with an SNR\(\sim 15\).

The detection above is a good example of using the synthetic tracking technique for detection of a previously unknown, small, fast-moving and otherwise undetectable faint object. It also demonstrates the maturity and functionality of our software that is capable of removing detector artifacts, stars and galaxies, as well as identifying false positives.

Synthetic tracking also improves astrometry of NEOs. It accomplishes this in two ways. First, by mitigating the trailing loss, one achieves more precise measurements due to a higher SNR. Second, it cancels a number of leading error sources that dominate traditional NEO searches, especially those from the ground (Zhai et al.\textsuperscript{14}). Thus, in CCD astrometry of a 2D point source, a template PSF\textsuperscript{13} is fitted to the CCD data. In synthetic tracking astrometry, a moving template is fitted to the 3D data cube. Using the images from the data cube, neither the asteroid nor the background stars are streaked. Therefore, the image motion from the atmosphere and telescope tracking errors are now common between the NEO and background stars and, thus, cancel for relative astrometry.

Observations from space are immune from astrometric errors that are present for ground-based observations. Such an advantage allows for longer integration times yielding higher astrometric precision, which is why deploying synthetic tracking technique on a space telescope is compelling.

\textsuperscript{12}Electron Multiplying Charge Coupled Device (EMCCD), see details at \url{http://www.emccd.com/what_is_emccd/}

\textsuperscript{13}The point spread function (PSF) describes the response of an imaging system to a point source or point object.
3.2. Moderate sensitivity from a very small telescope

In conventional ground-based NEO searches, it does not make sense to take a CCD exposure longer that exceeds $\sim 30$ sec. A NEO at a distance of 0.4 AU moving 10 km/s would appear to move relative to background star by $1''$ in 30 sec. Thus, for a ground-based telescope with $1''$ FOV, 30 sec is close to the optimal exposure time. Longer exposures would not only produce a streak but they would also increase the background noise contribution without increasing the signal. On the other hand, with synthetic tracking, we can observe for a much longer time, $T$, than 30 sec with increased SNR as $\sqrt{T}$.

The sensitivity of a synthetic tracking camera depends on a number of parameters, telescope diameter, the pixel size in arcsec, which determines how much zodi background is captured, and the total observation time, assuming the individual exposures are short enough that the motion of the NEO is less than 1 pixel. Table 1 shows limiting magnitude as a function of telescope diameter and pixel size for SNR=7 in a 300 sec observation.

Table 1: Limiting magnitude for a different telescope diameters and pixel size for SNR=7 in a 300 sec observation.

| Diam. | 3.3 | 3.0 | 2.8 | 2.6 | 2.4 | 2.2 | 2.0 | 1.8 | 1.6 | 1.4 | 1.2 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.10  | 20.58 | 20.68 | 20.76 | 20.84 | 20.93 | 21.02 | 21.12 | 21.24 | 21.37 | 21.51 | 21.68 |
| 0.15  | 21.02 | 21.12 | 21.20 | 21.28 | 21.37 | 21.46 | 21.56 | 21.68 | 21.81 | 21.95 | 22.12 |
| 0.20  | 21.33 | 21.44 | 21.51 | 21.59 | 21.68 | 21.77 | 21.88 | 21.99 | 22.12 | 22.26 | 22.43 |

For a survey of 140 m (H=22 mag) NEOs we looked at a 10 cm telescope with $3.3''$ pixels. This sensitivity is not significantly different from the Asteroid Terrestrial-impact Last Alert System (ATLAS) project.\(^{14}\) When one factors in the slightly lower sky background in space than on the ground, the limiting magnitude of the 10 cm CubeSat synthetic tracking camera at 20.58 mag is consistent with the 50 cm ATLAS's camera five sigma limiting sensitivity of 20.3 mag. For NEOs at 0.4 AU from the telescope, a 10 cm synthetic tracking camera in space has essentially the same sensitivity as a 50 cm ground-based telescope. On the other hand, for smaller NEOs at ranges closer than 0.4 AU, the synthetic tracking camera will have higher sensitivity because there is no loss of sensitivity due to streaked images.

\(^{14}\)For details on the Asteroid Terrestrial-impact Last Alert System (ATLAS) project please visit [http://fallingstar.com/home.php](http://fallingstar.com/home.php)
4. Emerging Capabilities of Interplanetary CubeSats

There is an on-going paradigm shift occurring in the satellite industry that may be compared to events dating back more than three decades to when personal computers disrupted mainframe computing. Small spacecraft, and their most popular sub-classification, CubeSats, hold tremendous utility and potential, not only in the commercial realm, but also by innovating established space programs through the use of CubeSats for research and technology development and demonstration. The low-cost CubeSat components, shorter development cycle, and availability of frequent launch opportunities for smaller satellites make it quicker and less expensive to get the latest capabilities in space. JPL is involved in these efforts with several CubeSat projects both in LEO and for deep space, with several already launched and many more being developed.\textsuperscript{15}

In this Section, we describe a CubeSat-based mission design for NEO search campaign that were derived by a recent JPL Team X\textsuperscript{16} study of a LEO spacecraft. We present an augmented CubeSat design appropriate for interplanetary operation and describe needed changes to the navigation, telecommunication, and propulsion subsystems.

4.1. System design

4.1.1. Science instrument

The synthetic tracking camera is the primary instrument for the NEO search (Fig. 3). The lens would be similar to commercially available camera lenses. The optics and structure would be designed to survive launch loads and will have the necessary thermal insulation to passively cool the instrument to maintain the optics temperature stable to within 5° C of the desired value.

The sensor is a 4K\times 4K class sCMOS\textsuperscript{17} detector. Second generation sCMOS detectors have low \( \sim 1e^- \) read noise and low \( < 0.1e^-/\text{pix/sec} \) dark current. The plate scale of the camera would be \( \sim 3.3''/\text{pix} \), which sets the amount of zodi background per pixel. While conventional large-format CCDs need several seconds to readout at low noise, the SCiMOS sensors can run up to 100 frames/sec with no dead time between frames. The detector would be read-out every \( \sim 10 \) sec. In 300 sec, a data cube would consists of 30 frames.

As discussed previously, synthetic tracking performs a shift/add on multiple velocity vectors,

\textsuperscript{15}For JPL’s effort in the CubeSat area, please visit [http://cubesat.jpl.nasa.gov/](http://cubesat.jpl.nasa.gov/) The NASA efforts in this area are summarized in [http://www.nasa.gov/directorates/spacetech/small_spacecraft](http://www.nasa.gov/directorates/spacetech/small_spacecraft)

\textsuperscript{16}The JPL Team X is a process that engages systems engineers and subject matter experts in series of concurrent design sessions, see details at [http://jplteamx.jpl.nasa.gov/](http://jplteamx.jpl.nasa.gov/) The Team Xc is a Team X effort focused at CubeSats.

\textsuperscript{17}For details on Scientific CMOS (sCMOS) cameras, please visit [http://www.andor.com/scientific-cameras/neo-and-zyla-scmos-cameras](http://www.andor.com/scientific-cameras/neo-and-zyla-scmos-cameras). Larger pixel format sCMOS detectors with 16 Mpix currently under development and are expected to be available by 2017.
where in this application the velocity step size would be 2 pixel/300 sec or 0.53 °/day. We would set the maximum velocity in the velocity search space to ∼ 6 °/day. The velocity search space is ∼520 velocity vectors. Therefore, NEOs moving up to ±6 °/day would not have any reduction in sensitivity from streaked image. Objects moving up to 12 °/day could be detected with a sensitivity lower by a factor of 2. The parallel velocity vector search is the most computationally intensive part of synthetic tracking. The shift/add operation is a “coarse” filter, and potential targets, above ∼ 4σ would be subsequently examined with a 4-parameter least squares fit that refines the position and velocity. After fitting for position and velocity, objects with SNR> 7 would be called detected. The same FOV would be searched ∼1hr later with another 300 sec observation. On the second 300-sec observation, a much smaller volume of velocity space would be searched. Because both velocity and position are determined at each epoch, this quite similar to a 4 image tracklet in CCD based searches. The reason for the 2 hr gap between the two epochs is to provide a more accurate velocity estimate for follow up observations to determine the target’s orbit.

A 300 sec observation at 7σ with 3″ pixels would have a SNR limited astrometric accuracy of ∼0.2″ and two such measurement 2 hr apart would result in a velocity uncertainty of ∼3.5 ″/day.

Synthetic tracking (with 520 velocity vectors) produces 520 images per data cube and at 10σ would have a false positive rate of $1 \times 10^{-13}$ per FOV data cube. Since each FOV takes 610 sec (300 sec plus 5 sec slew performed twice 2 hr apart), we record data on 142 fields per day with a statistical false alarm rate of $1 \times 10^{-8}$ per year.

In the simulations described later, a constellation of 5 9U CubeSats each with a 10 cm camera, would detect over 90% of H = 22 mag NEOs within 3 years. If the CubeSats continuously scanned the sky, the number of times of each NEO is observed depends on a number of details such as the orbit of the NEO and the orbits of the 5 CubeSats. Multiple observation and orbit determination are briefly described in Section 6.

\footnote{Note that vast majority of large 140 m NEOs move slower than ±6 °/day.}
4.2. Spacecraft Design

4.2.1. LEO flight system designed by JPL’s Team Xc

A recent JPL’s TeamXc study, a rapid concurrent design engineering session, developed a detailed design for a Low Earth Orbit (LEO) CubeSat with synthetic tracking [Zarifian et al. 2014]. The LEO flight system design relied on a 6U CubeSat architecture comprised largely of commercial components with flight heritage from previous CubeSat missions that have flown in LEO. Here we describe all major components of the system, except for the telecommunication, navigation, and propulsion systems; these systems were augmented for the interplanetary application due to critical differences for an interplanetary destination and will be discussed in the next Section.

The avionics of the spacecraft will include the radiation-tolerant LEON processor and algorithms to perform data analysis, command, and control. The computational requirements are dominated by multi-vector shift/add processing, which is required for the synthetic tracking algorithms. A top-level conceptual design of the computation architecture was studied using flight-qualified FPGAs (discussed below). The number of arithmetic operations are \((1.6 \times 10^8 \text{ pix}) \times (30 \text{ images}) \times (520 \text{ velocity vectors}) \sim 2.6 \times 10^{11}\) operations per data cube. We allocate 600 sec to perform this computation, which results in the required processor performance of \(\sim 0.43 \text{ Gflops}\). The computation could be done by programming 24 computational units into a single flight-qualified FPGA. In addition to the FPGA, approximately 6 GB of RAM would also be needed to store the data for a subsequent on-board processing. About 35% of processing capabilities of a VIRTX-6 FPGA would be used for computation. The FPGA power consumption is anticipated to be \(\sim 6–7\) W.

The attitude control system will be based on the Blue Canyon Technologies XACT unit, which consists of a star tracker, reaction wheels, and an inertial measurement unit (IMU), to achieve the pointing stability and agility requirements of the mission. Based on the specifications, the XACT unit achieves pointing control of \(10.8''\) (1-sigma), knowledge of \(6''\) (1-\(\sigma\)) and stability of \(10.8''\) over 4 sec. The NEO CubeSat requires a pointing control at \(2''\) which is easily met by XCAT. However, the pointing stability requirement for NEO CubeSat is \(6''\) over 4 sec, which is at the limit for the current XACT unit. Thus, a minor modification may be required to meet the pointing stability requirements once improved thermal/structural designs are available and an end-to-end simulation can be done. Such a modification may lead to additional isolation for jitter mitigation, which can be achieved by adding a fourth reaction wheel or other stabilization methods.

The power system consists of i) deployed solar arrays that generate \(\sim 40\) W at the beginning of the mission, ii) a solar array drive assembly to point the arrays at the Sun, iii) the on-board

\[19\text{For details on LEON processors, please consult }\url{http://www.gaisler.com/}\]

\[20\text{For details on the Blue Canyon Technologies XACT unit, please consult }\url{http://bluecanyontech.com/product/xact/}. \text{ Also, for XACT, High Performance Attitude Control for Cube-Sats, see }\url{http://bluecanyontech.com/wp-content/uploads/2012/07/BCT-XACT-datasheet-1.5.pdf}\]
battery to support high-powered events, and iv) power management system. A standard Aluminum CubeSat structure will protect components from radiation in the LEO environment. In addition, a standard deployment system will house and deploy the spacecraft.

The total current best estimate for a “dry” mass of the LEO system was estimated to be 8.2 kg, without margin (Zarifian et al. 2014). The cost, including mission and science operations, was found to be $\sim 9M, including 20% margin.

4.2.2. Computing architecture

In developing the required computing architecture, we account for the fact that an average H=22 mag NEO can be detected by 10 cm synthetic camera at a distance $\sim 0.4$ AU, when the observatory is at $\sim 0.7$–0.8 AU from the Sun. If the NEO moves with velocity of 10 km/s relative to the observatory, its angular motion is 0.034 $''$/sec. Since the pixel is 3.3 $''$, we have to record images faster than one per 100 sec for the streak related loss in sensitivity to be small, for the total 600 sec of observation. We have chosen 10 sec exposures to capture i) NEOs with the highest velocity and ii) smaller NEOs that can only be detected at ranges much closer than 0.4 AU. A 300 sec observation (which is followed 2 hrs later by a 2nd 300 sec observation) would have 30 images. When we shift/add these images, we should shift and add with a velocity vector range of velocities that includes the highest velocities a NEO can have and the spacing between velocity vectors should result a velocity mismatch of less than 2 pixel/300 sec data cube. We take a maximum velocity as approximately 30 km/s at 0.4 AU (i.e., 0.1 $''$/sec) and 1 pixel per 300 sec is 0.01 $''$/sec. The velocity search space for synthetic tracking is $\sim 520$ different velocities. NEOs moving faster the 12 $^\circ$/day can still be detected, but at lower SNR. A velocity of 24 $^\circ$/day would result in a 2X lower SNR.

At a high level, the onboard data processing computer performs four core functions: data reduction and star removal, integer shift-and-add, candidate selection, and postage-stamp image generation for downlink. The shift-and-add operation provides all driving requirements, as it applies two orders of magnitude more arithmetic operations than data reduction and star removal, and the final two steps operate on significantly smaller datasets. The proposed operational scenario is summarized as follows: 10-second integration per frame, 30 frame per data cube, 520 velocity vectors, 16 Mpix images, <600 seconds to perform processing. Based on these specifications, derived requirements for per-data-cube data volume $D$, memory bandwidth $BW$, and computational capability $C$ on the data processing computer are: $D = (4 \text{ bytes/pix}) \times (16 \text{ Mpix/frame}) \times (30 \text{ frames}) = 2.0 \text{ GB}$, $BW = D \times (520 \text{ vectors/cube}) / 600 \text{ sec} = 1.7 \text{ GBps}$, and $C = BW / (4 \text{ bytes/pix}) = 436 \text{ MFlops}$.

Figure 4 outlines our proposed FPGA-based computational architecture. We have baselined a Xilinx Virtex-6 device, which is currently slated to fly as the core processor for the Iris v2 radio
onboard the Lunar Flashlight\textsuperscript{21} and NEA Scout CubeSat\textsuperscript{22} missions. Camera data stream into the FPGA and are offloaded into one of the two separate external memory banks, which operate in as a ping-pong buffer pair. Once an entire datacube is collected, data collection immediately resumes and targets the second memory bank. Data processing is performed as described in the previous section, with candidate objects reported to an onboard soft core microprocessor. The processor runs software to identify unique objects among the candidates and coordinates postage stamp collection and downlink to Earth.

For this initial design, we have chosen 3 GB of 64-bit DDR3 at 200 MHz per external memory bank, which supports a data rate of 12.8 GBps. By utilizing a parallel NEO detection algorithm with twelve separate streams running at 200 MHz and 1 operation per cycle, the system provides 2,400 MFlops. These capabilities exceed the requirements described above.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fpga.png}
\caption{Proposed FPGA-based computational architecture.}
\end{figure}

A prototype implementation including memory controllers, shift-and-add logic, softcore microprocessor, and onboard memory has been built and run through FPGA design tools. Targeting a Virtex-6 LX130, the resource utilization is around 52\%. This design was also analyzed with Xilinx’s power estimation tool, with a resultant power draw of approximately 6.5 W split equally among configuration logic, device I/Os, and design logic.

\textsuperscript{21}For information on the Lunar Flashlight mission, please visit \url{http://sservi.nasa.gov/articles/lunar-flashlight/}

\textsuperscript{22}For information on NEO CubeSat mission, please consult \url{http://www.lpi.usra.edu/sbag/meetings/jul2014/presentations/0930_Thu_Castillo_NEAScout.pdf}
4.2.3. Required changes from the LEO to interplanetary NEO CubeSat design

The interplanetary application of the NEO CubeSat requires changes to the LEO design discussed above. The required changes to the hardware may be inherited from many common spacecraft elements developed for interplanetary CubeSat missions that have been or are currently being developed at JPL. These missions include INSPIRE\textsuperscript{23}, LunarFlashlight, NEAScout, and MarCO\textsuperscript{24}, which are expected to fly before this NEO CubSat, providing additional maturity and flight heritage to our design. The major changes for the interplanetary CubeSat design will affect several subsystems including navigation, communication, and propulsion, as summarized in Table 2.

To enable navigation and telecommunication in deep space, the interplanetary NEO CubeSat will include the Iris transponder\textsuperscript{25} (Duncan et al. 2014) and a High Gain Antenna (HGA), such as the one used on the NEAScout mission\textsuperscript{26}. With the Iris transponder and HGA with direct to Earth transmission to the NASA’s Deep Space Network (DSN), data rates of approximately 1 kbps will be achievable at the closest expected distance of 0.3 AU (once the constellation is established), data rates of ∼90 bps are achievable at distances of 1 AU, and less than 30 bps at the maximum distance of 2 AU. Throughout the mission, the data rates will be adjusted according to the spacecraft distances from Earth. To return the total of approximately 128 MBytes of data throughout the 4 year mission with 5 CubeSats, each spacecraft will download for 0.1% or 16.4 mins/week (at 0.3 AU) and 7% or 12.2 hrs/week (at 2 AU) of the mission time, which is accounted for in the engineering time allocation. Future studies we will also investigate the option of sending data through inter-satellite relays to return the data to Earth to achieve higher throughput.

To send the CubeSat into a solar orbit at heliocentric ranges of less than 1 AU, a dedicated propulsion system is required. Compared to the ground-based observations or a LEO version, the solar orbit would provide the mission with a better observing geometry and a faster orbit to conduct NEO search. The CubeSat would share a ride to GEO and then it would use an electric propulsion motor to enter solar orbit. A suitable propulsion option would be provided by a cluster of the Busek Electrospray thrusters\textsuperscript{27}. The module is based on an electrospray thruster providing a specific impulse ($I_{sp}$) of 1,300 sec, to deliver a thrust of 1 mN per thruster; it occupies less than 0.5 U of a CubeSat-class volume. This thruster cluster has a mass of 1.1 kg and requires less than 9 W of power. There are other propulsion options based on the systems that are currently being developed. These new systems satisfy the size, power, thermal, and launch constraints of a small spacecraft and should be considered in an end-to-end system optimization (Mueller et al. 2010; Mueller et al. 2010; Mueller et al. 2010).

\textsuperscript{23}For information in INSPIRE Mission, please visit: http://cubesat.jpl.nasa.gov/projects/inspire/overview.html

\textsuperscript{24}For information on MarCO mission please consult http://space.skyrocket.de/doc_sdat/marco.htm

\textsuperscript{25}http://mstl.atl.calpoly.edu/bklofas/Presentations/DevelopersWorkshop2014/Duncan_Iris_Deep_Space_Transponder.pdf

\textsuperscript{26}For details on the NEA-Scout (Near Earth Asteroid Scout) is a CubeSat mission, please visit http://space.skyrocket.de/doc_sdat/nea-scout.htm

\textsuperscript{27}For details on the Busek Electrospray Thruster system, please visit http://busek.com/technologies_espray.htm
Table 2: The changes to LEO design needed for the interplanetary version of NEO CubeSat.

| Change                                                                 | Function                                                                 | Cost, $M |
|-----------------------------------------------------------------------|--------------------------------------------------------------------------|----------|
| Replacement of UHF radio with Iris deep-space Transponder             | To enable interplanetary communication and navigation                    | 0.4      |
| Addition of propulsion system                                         | Busek Thrusters (4x)                                                     | 1.0      |
| Additions to ACS, power, structure, thermal subsystems                | Increased spacecraft size, mass, and design work expected                 | 0.5      |
| Operations                                                            | Trajectory planning and ground systems                                   | 1.0      |
| Total LEO CubeSat (before margins)                                   |                                                                          | 7.5      |
| Total change                                                          |                                                                          | 2.9      |
| Total Interplanetary NEO CubeSat (before margins)                     |                                                                          | 10.4     |
| Total Interplanetary NEO CubeSat (including 20% margin)               |                                                                          | 12.5     |

We also expect changes to the power, thermal, structural, and attitude control systems. These changes will result in the increases in mass, volume, power, and cost estimates for the NEO CubeSat, as reflected in Table 2. The highest power for the interplanetary CubeSat is expected to be about 47 W during the download mode. To accommodate these changes we would have to resize the solar panels and/or batteries. Trajectory planning and ground operations are also expected to result in additional cost increases. Although pointing requirements are similar to the LEO version, we expect using larger reaction wheels assemblies (RWA) which may result in larger torques on the spacecraft during RWA de-saturation and motivate changes to the algorithms and thrusters controls during RWA de-saturation periods. Additional spacecraft structural thickness will be implemented surrounding the radiation-sensitive components such as components of the attitude control system (ACS) (i.e., the stellar reference unit (SRU), RWA driver) and the electrical power subsystem (EPS). For example, 7 mm of (1.92 mils) Aluminum shielding will yield only 10 krad over a 3 year mission at the expected orbit (0.7 AU from the Sun), which CubeSat components can survive. There are other safety and mission assurance strategies the small spacecraft community is developing to mitigate these concerns for interplanetary missions (Fazio et al. 2014).

The resulting spacecraft will be a 9U CubeSat bus. The cost estimate for the interplanetary NEO CubeSat was estimated to be $12.5M, including 20% margin, as shown in Table 2. We start with a cost estimate for the LEO CubeSat provided by the JPL Team Xc and add our estimates for the cost changes for each of the affected subsystem.
4.3. Spacecraft mass, power budgets

The CubeSat is expected to have a dry mass of approximately 13.2 kg, including payload and all major subsystems: power, propulsion, command and data handling, attitude determination and control, thermal, and structure. Table 3 shows the current best estimate (CBE) for the masses of each subsystem. The required propellant mass will depend on the orbit chosen for the spacecraft, and is expected to be ∼9 kg (to boost to an orbit of 0.7 AU). Therefore, the total expected wet mass is about 20 kg before margins.

Table 3: The current best estimates (CBE) for the mass of the interplanetary NEO CubeSat.

| Subsystem                  | Components                                      | Mass, kg |
|----------------------------|-------------------------------------------------|----------|
| Science instrument         | Synthetic tracking camera                        | 2.8      |
| Navigation, communication  | Iris transponder; high gain antenna              | 1.0      |
| Command, data handling     | LEON processor and board                         | 0.25     |
| Attitude control system    | BCT XACT with sized-up wheels                    | 0.85     |
| Propulsion                 | Busek thrustes (4x)                              | 4.8      |
| Thermal                    | Radiator                                        | 1.0      |
| Power                      | Solar panels, batteries, EPS                     | 0.86     |
| Mechanical                 | Structure                                        | 2.0      |
|                            | **Total Dry**                                    | **13.2** |
|                            | **Total Wet (20% margin)**                      | **15.8** |

4.4. Spacecraft Lifetimes and Constellation Architectures

The ability to achieve the mission’s science objectives of detecting 90% of all the NEOs is directly related to the mission lifetime; therefore, we are concerned about CubeSat failures. We have studied historical data on CubeSat failures, available for missions developed and launched by universities, government, and industry. Figure 5 shows the statistics for typical lifetimes of over 200 CubeSats (including 1U, 2U, 3U) launched since 2003, where the full data set is described in Ref. [Fazio et al., 2014]. We closely examined the data and filtered out failures due to launch or deployment, and those due to causes that are expected to be preventable like communication or power problems due to poor designs, or latch-up due to potential radiation exposure. We also filtered out CubeSats that de-orbited, where they did not fail due to technical reasons, and those that were only recently launched and have not yet failed. Most of this historical data is based on university-built CubeSats, so using this data to inform expected lifetimes is conservative as the proposed CubeSats will be developed by professional engineers using high-heritage components. Furthermore, there is no available statistical information about planetary CubeSats because they have not yet been launched, so this is the only data that we can use to extrapolate performance.
Assuming a Gaussian distribution, the lifetime is approximately $(2.09 \pm 0.12)$ yrs. Based on our statistics, approximately 45% of CubeSats have lifetimes exceeding 3.5 years, as shown in Figure 5. This indicates the trend in technological maturity and growth of the lifetimes of the CubeSats.

The low cost of an interplanetary CubeSat presents the opportunity of a mission architecture consisting of launching multiple spacecraft in solar orbit. With low anticipated cost, this option is not only feasible, it also a highly attractive one. In fact, a mission relying on multiple spacecraft allows for added mission redundancy, effective sky coverage, it enables shorter period to complete the NEO search and provides chances for frequent technology upgrades. With preliminary cost estimates for an interplanetary CubeSat are being so low, a further cost reduction will come from the fact that additional CubeSats will cost only a fraction of the original cost (50% or less due to recurring engineering costs). Therefore, the cost of launching 5 to 10 interplanetary CubeSats is still expected to be an order of magnitude lower than that for the missions examined in the 2010 NRC report.

In the next Section, we explore the NEO search with a constellation of interplanetary CubeSats.

5. Simulation of a survey to find 90% of NEOs

Although the 2010 NRC report examined combinations of a spacecraft and a dedicated ground-based NEO search facility [NRC 2010], the idea of putting multiple spacecraft into a solar orbit was not examined, likely because of a prohibitively large cost of launching multiple ~0.5-1.0 billion dollar spacecraft. Furthermore, low-cost small spacecraft were not studied, likely because they were perceived as incapable of accomplishing this mission.

Our approach to a simulation of the NEO search is different relative to the others presented...
in the NRC report because we set out to explore the use of multiple small spacecraft to accomplish this mission. To examine the advantages of using multiple spacecraft, we developed a simulation that takes into account the current model for distribution of the NEOs, expected performance of the synthetic tracking camera on a CubeSat, and the 9U NEO CubeSat operational characteristics, etc.

We simulated a number of NEO observing scenarios using multiple spacecraft in solar orbits. The methodology of our simulation was designed to mimic the survey simulations discussed in the NRC 2010 report, with the exception of using mission architectures consisting of multiple spacecraft.

We used the published debiased orbital and absolute magnitude distribution of NEOs (Bottke et al. 2002; Morbidelli et al. 2002; Greenstreet et al. 2012). In the NEO population model, we simulated ~200,000 NEOs that had a distribution in semi-major axis, eccentricity and orbital inclination published in the literature. Figure 6 shows the resulted synthetic parent distribution of the ~200,000 NEOs. Orbital parameters of the NEOs other than semi-major axis, eccentricity and inclination were chosen randomly, with a uniform distribution over $2\pi$ or $\pi$ as appropriate. As the literature does not describe any correlation between distributions in different orbital parameters, our simulations also assumed that they were independent.

To simplify the calculation of the minimum orbit intersection distance (MOID), the Earth was assumed to be in a circular orbit. Using this assumption, we calculated the MOIDs of the 200,000 NEOs from the parent NEO distribution with a circular 1 AU orbit representing the Earth. Any NEO that would came to within 0.002 AU from the Earth’s orbit was considered a potential “impactor”. The value of 0.002 AU (i.e., ~23.5 Earth’s diameters) was somewhat arbitrary. Since all of the telescopes/cameras we examined could detect an H= 22 mag NEO at a distance of ~0.4–0.6AU, the choice of 0.002 AU (as opposed to 1 Earth radius) should not bias our results. Approximately 5,000 of our 200,000 NEOs were found to be “impactors”. The distribution of impactors in semi-major axis and eccentricity is shown in Figure 7. The simulation then searched the sky for these ~5,000 impactors.

The orbits of the CubeSats were then calculated. While the constellation of $N$ CubeSats could have arbitrary orbits, we first examined CubeSat constellations where all the spacecraft had the same semi-major axis and inclination, but were uniformly distributed around the Sun. The simulation then stepped through $N$ to simulate observations, typically lasting for the period of 20 years. The time step for the simulation was variable. In the high fidelity simulation, the time step was ~300 sec (integration time at one FOV). The time step was selected to represent the combination of the integration time and the time needed to slew the telescope to an adjacent FOV.

At each time step, the telescope would point at a particular part of the sky. Every NEO was checked to see if it was within the FOV of the camera. If it was, the apparent magnitude of the NEO was calculated, given its H magnitude, distance from the Sun and distance from the CubeSat and the phase angle (angle from telescope to NEO to Sun.). The telescopes scanned the sky in an “orange peel” pattern and avoided pointing closer than 45° to the Sun. We also had a
"coarse" simulation where the time step was every 5 days and we assumed the telescope could scan 40,000 (°)² every 5 days. Currently, we do not simulate the loss of sensitivity when the NEO image would be streaked. With synthetic tracking, this was not an issue because our 300-sec integrations came from 30 of 10-sec short exposures. Without synthetic tracking for H=22 mag 140 m NEOs this would not be a significant effect with ∼200 sec integrations and 3″ pixels. However, loss of sensitivity due to streaking would be a significant issue for smaller, e.g. 50 m NEOs or for cameras with smaller pixels, when synthetic tracking is not used.

For a search of H = 22 mag NEOs we look at a 10 cm aperture camera with a limit magnitude of 20.58 mag similar to many existing and near future ground-based observatories (CSS,28 and ATLAS, PTF,29) not as sensitive as NEO surveys with larger telescopes (i.e., PanSTARRS, LSST). This camera is also less sensitive than all of the space missions mentioned in the NRC report. With a 4K sensor and 3.3″ pixels the FOV∼14 (°)² is similar to the IR space telescopes in NRC 2010.

28 The Catalina Sky Survey (CSS), http://www.lpl.arizona.edu/css/
29 The Palomar Transient Factory, http://www.ptf.caltech.edu/iptf
6. Case Studies

In running our simulations, we first validated our modeling approach and assumptions by re-producing the results for the IR telescope in Venus-trailing orbit from the 2010 NRC report (i.e., Section 5.1 in NRC (2010)). We then investigated the trade-offs between telescope FOV, sky coverage rates, and survey time to verify the choice of the proposed aperture design for the CubeSat and scanning strategy. We also explored different constellation sizes and choice of heliocentric orbits to identify optimal constellation parameters that could minimize survey time and cost. Finally, we investigate the ability of a CubeSat constellation to detect 90% of smaller NEOs with sizes down to 50 m in diameter. Below we present all these special cases and discuss results obtained.

6.1. Case 1: Comparison to the proposed Venus orbit IR telescope

To verify our simulation approach, we first aim to replicate the results for the NRC-proposed IR telescope in a Venus-like orbit. Our objective was to verify that our simulation was consistent with those conducted for the 2010 NRC study. The information for this mission was obtained from publicly available resources and email correspondence [H. Reisma, private communication (2014)]. The IR telescope on a Venus-like orbit is sufficiently sensitive to detect a 140 m NEO from a distance of 0.6 AU. For a telescope at a distance of 0.7 AU from the Sun, such a sensitivity yields a limiting magnitude of 21.5 mag or ~1 mag more sensitivity than the telescope on our proposed CubeSat mission. The IR telescope would integrate for a total of 180 sec over six 30 sec exposures followed by a 60 sec slew/settle period. These 6 exposures will be used to remove cosmic rays events before co-adding the frames. The scanning strategy consists of revisiting areas of the sky

30 See information on the Sentinel mission: http://sentinelmission.org/
about 1 hour apart to confirm the detection of moving objects. We assumed the FOV of 11 ($^\circ$)$^2$ (similar to that of the Sentinel mission\textsuperscript{31}); thus, we modeled each observation as two observations 240 sec including slew times separated by 1 hr. When observing a NEO that is 90$^\circ$ from the Sun, only half of the surface is in sunlight. In the visible band, the apparent brightness of a NEO at 90$^\circ$ phase angle is $\sim$1/3 of its brightness at opposition. This phase angle effect was turned off in our simulation of the IR telescope.

We found that using our simulation approach, the Venus IR mission required $\sim$7.8 years to find 90% of H=22 mag (140 m) NEOs as in Figure 8 which is within 10–20% of the 7.5 years in the NRC report. A small discrepancy is expected because there may be differences in the modeling assumptions relative to the NRC report. However, overall these results confirm our major assumptions and provide confidence that our general simulation approach is correct.

6.2. Case 2: Survey time vs sky cover/camera FOV

We next studied the importance of the synthetic tracking camera FOV size in its effectiveness to detect 90% of 140 m NEOs. The motivation for this was the desire to identify the most optimal size of the FOV and to understand where our CubeSat scanning strategy with 1,980 ($^\circ$)$^2$/day falls relative to these trades.

The conventional wisdom for ground-based NEO searches suggests that that the larger the FOV the better. The expectation is that selection of a larger FOV would result in a larger number

\textsuperscript{31}http://sentinelmission.org/sentinel-mission/sentinel-data-sheet/
of objects detected per night, which is a common performance metric. Ground-based NEO searches typically use a 30 sec CCD exposure, which is near optimal both from the perspective of the time to perform the scan of the sky and to minimize the image streaking (for a typical NEO moving at 10 km/s at 0.4 AU, the motion is 1" in 30 sec for a pixel size of 3""). Streaking is the known problem for conventional CCD-based NEO searches where exposure times exceeding 30 sec compromise the NEO detection sensitivity because the objects move during the exposure. With a fixed integration time, the limiting magnitude is constrained by the size of the telescope. In fact, a particular choice of the telescope size, integration time, and pixel scale fixes the limiting magnitude.

Unlike conventional CCD-based exposures (that cannot trade integration time and sensitivity), with synthetic tracking we have the flexibility to trade the limiting magnitude for the sky coverage. Doubling the integration time results in the SNR improving by $2^{1/2}$, the detection distance increasing by $2^{1/4}$, and the volume of space covered increasing by $2^{3/4}$, however, the sky coverage rate (in square degrees/day) drops by a factor of 2. For synthetic tracking, shorter integration times are preferred because they enable covering the sky faster, despite the reduction in SNR and sky volume coverage. It takes a finite amount of time to slew the telescope, so that the FOV focuses on the next area on the sky. For a given slew time it is relatively easy to calculate the optimum exposure time, which is $\sim 3$ times the slew time when the goal is to maximize the numbers of objects viewed per hour. However, when searching for NEOs, maximizing the coverage per hour is not an appropriate objective. This is because the population of available objects changes slowly, on the time scales of approximately 3 months. Therefore, there is a trade-off between the sensitivity (which improved with a smaller sky FOV) and the frequency of scanning the sky (which improved with a larger sky FOV).

To evaluate the impact of the FOV, we choose the constellation with 5 CubeSats at 0.7 AU and simulated a range of FOVs between $0.25 - 50.0 \, (\text{c})^2$ (i.e., $425 - 14,000 \, (\text{c})^2$ in 24 hours), as shown in Figure 9 (assuming all had a 20.5 magnitude limit). We note that for FOVs $< 3 \, (\text{c})^2$ the time to complete the survey exceeded 20 years, but the exact time was not solved; thus, these results are not shown in Figure 9. The point where there are diminishing returns with increasing the FOV (or the knee in these plots) is around $10 \, (\text{c})^2$ (i.e., $1,400 \, (\text{c})^2$/day), where for greater FOVs the time to detect 90% of NEOs was not affected significantly, but for smaller FOVs the detection time grows exponentially. However, as the FOV decreases below $25 \, (\text{c})^2$, there is also a small increase in the time needed to detect 90% of NEOs.

Figure 9 depicts the effectiveness of a NEO search campaigns as a function of the FOV of a telescope. It shows that for a search for 90% of 140 m NEOs with facility that has a limiting magnitude of 20.6 mag, scanning rate of more than $1,400 \, (\text{c})^2$/24 hrs is counterproductive. The PanSTARRs telescope operating 10 hrs per night would survey $1,400 \, (\text{c})^2$ each observing night. Increasing the sky coverage from $1,400 \, (\text{c})^2$ to $20,000 \, (\text{c})^2$ per night with more ground-based observatories would not significantly reduce the time to find 90% of 140 m NEOs. A space mission in an Earth orbit duplicates the search volume of the ground-based observatories. The major advantage of a space observatory is that one can observe even when the Moon is up, which reduces the observing time.
Fig. 9.— Time to find 90% of 140 m NEOs detected as a function of FOV size and daily sky coverage for ideal constellation with 5 CubeSats at 0.7 AU with variable FOVs, 600 sec integration, 10 sec slews, with a magnitude limit of 20.5, with slewing model active.

These results confirm that our choice of telescope and camera parameters that result in 20.58 mag limit and 1,400 \(^{(\circ)}^2\) in 24 hr sky coverage are close to the optimal combination that allows one to minimize the time needed find 90% of 140 m NEOs.

6.3. Case 3: Design of Interplanetary CubeSat Constellation

Next, we investigate CubeSat constellation architectures. The simulation environment described above was used to study different number of spacecraft in the constellation at various heliocentric ranges. For the multi-spacecraft architectures, we assumed that the spacecraft were phased with equal angles in solar orbit. The telescope magnitude limit was assumed to be 20.5 mag with FOV=14 \((\circ)^2\) (see Section 4). The telescope performs 600 sec integration time and 10 sec (i.e., 300 sec observation and 5 sec slew time repeated once) slews between different pointings, while covering \(~1,980\ (\circ)^2/24\ hrs. This is beyond the knee in the curve noted in Figure 9, which is expected to provide good results.

We performed simulations for different constellation sizes at various heliocentric ranges from 0.6 to 0.9 AU, as shown in Figure 10. The results showing the time to detect 90% of 140 m NEOs for an idealized constellation with no scanning strategy implemented is in Figure 11. We assumed the entire sky is covered every five days, thus covering 8,251 \((\circ)^2\) in 24 hours (with the
Fig. 10.— Representative CubeSat constellation with spacecraft equally distributed in a solar orbit at 0.7 AU in 1 month after initial uniform spacecraft formation was established.

Fig. 11.— Time to detect 90% of 140 m NEOs assuming the entire sky is covered every 20 days (covering $\approx 1,980 \left(^\circ\right)^2$ in 24 hours). The scanning strategy is inactive with variable ranges from the Sun (0.6–0.9 AU) for different sizes of constellations, where the CubeSats are distributed equally.

We observe that addition of a new CubeSat to the constellation of $N$ spacecraft generally reduces the total time needed to complete the survey, where this reduction is most significant for small numbers of CubeSats and an improvement of a factor of two from one to two CubeSats. However, each time we add a spacecraft, we reduce the search performance gain of the resulted constellation, with almost no practical gain after $N = 5$.

We also note that beyond $N = 5$ it takes at least 2 years to achieve the mission objective.
Fig. 12.— Orbital properties of NEOs that were not found after 1.2 years (left) and 3.0 years (right) with a representative CubeSat constellations in Figure 6.

regardless of constellation size. This is due to the fact that with 5 uniformly-distributed spacecraft in solar orbit it takes nearly 2 years to find almost 96% of all the NEOs with magnitude less than H=22. The remaining “undiscovered” NEOs have semi-major axis ranging from 2–3 AU, spending most of their orbits beyond the accessibility of the CubeSats placed on solar orbit with semi-major of 0.7–0.9 AU, as in Figure 12. Capturing these NEOs is simply a waiting game until the NEOs approach their periapsis and are close enough to a spacecraft to be detected.

Placing the CubeSats in a heliocentric orbit with semi-major axes less than 1.0 AU provides significantly shorter times to accomplish the mission objectives (90% of 140 m NEOs). Note that the results for 1.0 AU were slightly worse than 0.9 AU. Orbits closer to the Sun have shorter periods (i.e., a 0.6 AU orbit is nearly twice shorter compared to that of a 0.9 AU orbit). Therefore, the spacecraft placed on these orbits would cover the sky faster and would have improved access to the NEOs when these come closer to the Sun near their perigees. On the other hand, given the limiting range for a 10 cm telescope on a CubeSat of 0.4 AU, shorter heliocentric distances are not as effective in providing access to NEOs that are far out away from the Sun. In this trade off, the shorter heliocentric ranges hold the advantage until the point where there are least 5 CubeSats in the constellation. Beyond that point, the returns are diminished.

The prior simulation was performed assuming the telescope could scan the whole sky every 5 days. It was only used to assess the relative performance of constellations of N CubeSats in various orbits around the Sun. A higher fidelity simulation implemented an orange peel scanning pattern where the 14 (°)² FOV of the CubeSat camera was properly taken into account.

Figure 13 shows that with a higher-fidelity sky-scanning approach the constellation takes slightly longer to accomplish the mission objectives. This figure shows cumulative NEOs detection performance for an ideal constellation placed at 0.7 AU from the Sun with slewing model on. The telescope has the nominal FOV= 14 (°)² and performs two observations 600 sec with 10 sec slews,
Fig. 13.— Fraction of 140 m NEOs detected for a constellation at 0.7 AU with FOV = 14 (°)², 600 sec integration, 10 sec slews, covering 1,983 (°)²/24 hours, with slewing model on.

covering 1,983 (°)²/24 hours. For example, a 5 CubeSat constellation requires 2.6 to 2.75 years to detect 90% of 140 m NEOs. However, in contrast to the non-scan ning cases above, addition of a new CubeSat beyond \( N = 5 \) improves the mission performance which approaches the 2-year result of the non-scan ning cases (see Figure 11). This increase is due to the time losses associated with scanning the sky.

6.4. Case 4: Detection of Smaller NEOs

The 2010 NRC report concluded that a survey to find 90% of 140 m NEOs would require a space mission with a lifetime of \( \sim 8-10 \) years. In addition to surveying for large NEOs, the report also emphasized the need to look for smaller NEOs, with sizes down to 30 m, for planetary protection purposes. Figure 14 is from the NRC report showing the effectiveness of a NEO search campaigns with a combined IR telescope in a Venus-like orbit and a dedicated LSST. If completely dedicated to NEO search, LSST would be a very powerful facility. If we ignore the loss of sensitivity from streaked images, LSST would be able to detect 25 mag objects. However, the combination of these two facilities represent a rather large investment, and even then, detection of 90% of 50 m NEOs would take \( \sim 14 \) years. The NRC report ended by saying that detection of these smaller NEOs is extremely challenging and expensive.

We re-examined this conclusion with a constellation of CubeSats with synthetic tracking cameras. Specifically, given the higher sensitivity enabled by synthetic tracking and high sky coverage rates at affordable costs provide by CubeSat platforms, we were interested in the potential for the proposed architecture to detect 50 m NEOs in less than 10 years.

The 50 m NEOs are almost a factor of 10 dimmer than the 140 m NEOs, with \( H = 24.24 \) mag. If
Fig. 14.— Years to completion for 0.5 m IR telescope in a Venus-like orbit and a dedicated Large Synthetic Survey Telescope (LSST) [Fig. 3.10 from NRC (2010)].

the observatory is at 0.7 AU, a 140 m NEO (H=22 mag) could be detected at ranges up to 0.45 AU away, if the detection magnitude limit was 20.5 mag. However, a NEO with H=24.24 mag (with diameter of 50 m) would have to be at a range of no greater than 0.20 AU from the telescope and at opposition to be detected. At any one time, the volume of the search space is 8 times smaller. We look at three alternative CubeSat constellations that could find 90% of 50 m (H=24.23 mag) NEOs in less than 10 years. One is an extension of our basic concept using 10 cm telescopes, while the others will use 15 cm telescopes.

Table 4 gives the parameters of three examples of CubeSat constellations that could conduct a search for 50 m NEOs. There are two major changes to the instrument, we now assume that an 8K×8K detector is available and, instead of 5 of 9U CubeSats, we now place 8 and 15 of 9U CubeSats into 0.8 to 0.85 AU orbits. The pixels are now much smaller (1.2″ to 1.6″) to reduce the zodi background per pixel.

Table 4: Parameters of CubeSat constellations that could be used to search for 50 m NEOs.

| Parameters               | Case 1 | Case 2 | Case 3 |
|--------------------------|--------|--------|--------|
| Number of CubeSats       | 15     | 8      | 8      |
| Semi-major axis          | 0.85 AU| 0.85 AU| 0.8 AU |
| Telescope Diameter       | 10 cm  | 15 cm  | 15 cm  |
| Magnitude Limit          | 21.68 mag | 21.81 mag | 21.95 mag |
| Detector                 | 8K×8K pix | 8K×8K pix | 8K×8K pix |
| Camera FOV               | 7.5 (°)^2 | 13.3 (°)^2 | 10.1 (°)^2 |
| Pixel scale              | 1.2″   | 1.6″   | 1.4″   |
| Time to find 90% of NEOs | 5.0 years | 5.7 years | 4.2 years |
In solar orbits at 0.8 AU, the constellations of 8 CubeSats with 10 cm apertures (Case 1) and 15 CubeSats with 15 cm apertures (Case 2) would both achieve the same result and detect 90% of 50 m NEOs in approximately 5.5 years, as shown in Figure [15]. In Case 3, the constellation of 8 CubeSats with 15 cm apertures in solar orbits at 0.8 AU would detect 90% of 50 m NEOs in only 4 years, as shown in Figure [15].

These examples illustrate the potential for a constellation of CubeSats to conduct a 90% complete search for 50 m NEO that, according to NRC report, would otherwise take a long time at a prohibitively high cost. These examples are not yet optimized to identify the configuration with minimal detection time or cost. Nevertheless, they are shown to demonstrate that in addition to the search for 140 m NEOs, synthetic tracking with CubeSats may become preferred architecture as we aim to detect NEOs smaller than 140 m.

The results above demonstrate the advantages of the proposed approach based on a constellation of CubeSats with synthetic tracking to search for NEOs with various sizes. Such a constellation could conduct a 90% complete survey in significantly less time and lower cost relative to what was indicated in the NRC report. A more detailed and thorough examination of CubeSat constellations aiming at detecting 90% of $\sim$35–100 m NEOs would be the topic of a future paper.

7. Setting up a Constellation of CubeSats

In the previous Section, we studied CubeSat constellations with spacecraft uniformly distributed in a solar orbit. Although establishing such a constellation technically is not a difficult task, the objective of keeping the low cost paradigm consistent with CubeSat payloads may present
challenges. Unlike conventional spacecraft that are launched on a dedicated launch vehicle, Cube-Sats are generally launched as secondary payloads. Commercial companies have started to offer CubeSat launch services relying on various secondary launch opportunities to GEO, GTO, and even Earth-escape trajectories at affordable costs (e.g., Spaceflight Services Inc.). Currently, NASA offers no-cost launch opportunities through the CubeSat Launch Initiative (CSLI), which could take CubeSats to LEO. In the near future NASA plans to provide launch opportunities for CubeSats as secondary payloads through the Space Launch System (SLS). Benefiting from these developments, our mission design approach relies on novel propulsion systems capable of transferring small spacecraft from initial GEO, GTO, or Earth-escape orbits to a 0.7 AU solar orbit.

A detailed mission analysis that optimizes the mass, time of setting up a NEO CubeSat constellation, and associated cost is beyond the scope of this paper. Here we take a simplified approach to describe a sequential transfer of several CubeSats from an Earth’s orbit to a Venus-like one. We start with the first spacecraft. If after leaving the Earth’s orbit the first spacecraft is placed on an Earth-Venus transfer orbit (with a semi-major axis of 0.85 AU), it would arrive at 0.7 AU in \( \sim 0.39 \) years. With a thruster burn, the spacecraft could circularize its orbit and settle on a Venus-like orbit with 0.7 AU semi-major axis. If the second CubeSat leaves the Earth’s orbit \( \sim 100 \) days later after the first departure, being placed on the same transfer trajectory, it would arrive to the 0.7 AU orbit being \( \sim 1/5 \) of a Venus’ year behind the first one. Repeating the same transfer approach for the remaining three CubeSats would result in the configuration where the five CubeSats are uniformly distributed in a Venus-like orbit – the constellation that was simulated in Section 6. The total time of setting up this constellation is about 1.5 years after the launch of the first spacecraft.

Since the CubeSats can observe as they transit to a Venus-like orbit, the transfer time could, in principle, only lengthen the mission lifetime by \( \sim 1.5/2 = 0.75 \) years. The simulation of 5 9U CubeSat in Section 6 showed that \( \sim 2.75 \) yrs of observation could detect 90\% of \( H = 22 \) mag NEOs, so, at least in theory, the survey could be conducted in \( \sim 3.5-4.0 \) years after initial launch. Our preliminary analysis has shown that the Congressionally mandated NEO survey goals may be accomplished in less than 4 years by a constellation that is approximately 10\% of the costs of the missions studied in the NRC report and in less than 2.5 years (including set-up time) by a constellation, that is approximately 20\% of those costs. This is a unique advantage of a CubeSat-based mission architecture that enables to trade the survey completion time, risk, and cost. We plan to optimize the overall mission architecture in more details. Results will be reported elsewhere.

32 The cost of getting into a GEO (or GTO) orbit is often quoted as \( \sim \$100K \) per 1 kg from commercial vendors.
33 Spaceflight Services Inc., for details see \( \text{http://spaceflightservices.com/} \)
34 NASA’s CubeSat Launch initiative (CSLI) provides opportunities for CubeSats to fly as auxiliary payloads on previously planned missions; see details at \( \text{http://www.nasa.gov/directorates/heo/home/CubeSats_initiative.html} \)
35 For information on NASA’s Space Launch System (SLS) visit \( \text{https://www.nasa.gov/exploration/systems/sls/} \)
The NRC (2010) report concluded that it would take close to 10 years for a single spacecraft with a 50 cm telescope to conduct a search for 90% of H=22 mag NEOs. As we mentioned earlier, designing a spacecraft with the redundancy and required testing to ensure survival for 10 years can significantly increase the mission cost. With a constellation of 5 CubeSats, a failure of a single spacecraft is not catastrophic; in fact, the constellation’s performance degrades gracefully with respect to losing a node. Fig. 11 shows the sensitivity in search time to constellation size. Given the low cost of an additional CubeSat, one may consider placing more than 5 spacecraft at the desired solar orbit to form a redundant constellation. Such a redundancy would not only reduce the time to conduct the 90% NEO survey, it would also reduce the risk of the NEO search to potential spacecraft failures identified in the NRC report.

Significant improvements are expected from optimizing the constellation design, scanning strategies, FOVs, and anticipated CubeSat lifetimes. A rigorous analysis of the optimal number of spacecraft to mitigate risks and ensure a high probability of mission success in the desired time for an acceptable cost is beyond the scope of this paper; it will be presented elsewhere.

8. Discussion and summary

The length of time required to detect 90% of 140 m NEOs depends on a number of factors, including limiting magnitude sensitivity, size of the FOV, and number and configuration of spacecraft. Our 10 cm CubeSat camera and ground-based telescopes like ZTF, CSS, ATLAS have a limiting magnitude of ∼20.5 mag. Larger telescopes, like PanSTARRs and LSST with smaller pixels (″/pixel), are more sensitive. Space-based 50 cm IR telescopes are also more sensitive (∼21.5 mag) relative to similar ground-based visible cameras. Simulations conducted for the 2010 NRC report showed the importance of the distribution of the observatories. For ground-based observatories, a distribution in geographic latitude helps with sky coverage. The NRC report also hinted at the importance of distributing observatories around the solar system. The most capable combination of observatories examined in the NRC report was LSST and an IR telescope in a Venus orbit. A Venus-like orbit is advantageous relative to one on Earth or in an Earth orbit because this type of telescope would essentially duplicate much of what LSST would detect.

Our survey simulations in Sec. 6.2 showed that sky coverage beyond ∼1,400 (°)²/24 hours would not decrease the time needed to find 90% of 140 m NEOs. It should be noted that PanSTARRs with its 7 (°)² FOV and spending 4 × (30 sec + 15 sec) per FOV would cover ∼1,400 (°)² in 10 hrs. Adding more ground-based telescopes without increasing sensitivity would not shorten the time to conduct a 90% complete survey.

The major result of the simulations in Section 6 is that distribution of multiple observatories

36The Zwicky Transient Facility (ZTF) is a new time-domain survey that will have first light at Palomar Observatory in 2017. For details, please visit: [http://www.ptf.caltech.edu/ztf](http://www.ptf.caltech.edu/ztf)
around the solar system can dramatically lower the survey time needed to find 90% of 140 m NEOs. Even though the 10 cm telescopes only had a sensitivity of 20.58 mag, 5 of them in orbit could detect 90% of 140 m NEOs in approximately one third the time of a ∼50 cm IR telescope.

We described in the introduction that reaching high astrometric precision is as important as detecting the NEOs. For planetary protection purposes, the goal finding 90% of 140 m NEOs is not sufficient if we do not have the data to determine if a newly discovered asteroid will impact the Earth or not. If the astrometric accuracy is 0.2″, and the NEO is observed a half dozen times on its first pass, the orbit derived from those measurements is rather poor. In fact, it is so poor that if the NEO were to revisit ∼4–5 years later, we would not know where to point the telescope within ≈10° (Zhai et al. 2014).

Currently the only way to obtain accurate orbits of NEOs is with radar observations. However, at the current discovery rate is over 1,000 NEOs per year, because of the limited availability radar can observe only less than 100 of these objects per year. Therefore, accurate astrometric observations of NEOs conducted from space must be able to reach orbital precision much better than 0.2″. Otherwise, these objects will be lost. To confidently determine if a NEO will hit the Earth within the next ∼5–10 years, the astrometric accuracy has to be even better. Astrometry of objects that produce streaked images is dramatically worse than astrometry of objects that do not move relative to reference stars. Synthetic tracking offers a robust solution to both the accuracy of astrometric measurements as well as the large volume of needed astrometric measurements. As a result, astrometric follow-up of NEOs discovered by space observatories may now be possible with ground-based instruments. Thus, the NEOs would have to be observed by a dedicated constellations of space-based telescopes. A more detailed examination of this issue will be described in a subsequent paper.

In this paper, we leveraged the combination of two new technologies to drastically reduce both the cost and the time needed to conduct a 90% complete survey of 140 m (H=22 mag) NEOs. Synthetic tracking enables reasonable sensitivity (20.5 mag) using very small (10 cm) telescopes that can fit in a CubeSat. The mass-produced space-qualified hardware used in small satellites dramatically reduce the cost of a space constellation.

Although CubeSats have mostly been used in Earth orbit, existing and emerging CubeSat propulsion units can enable a CubeSat to get into a solar orbit after getting a piggyback ride to GEO, GTO, or an Earth-escape trajectory. The space technology is evolving rapidly for small spacecraft and we expect steady improvements in many relevant capabilities over the next several years and deep-space flight heritage for many of the components we plan to fly. In addition to drastically lowering cost, the use of multiple small spacecraft also minimizes risks by allowing us to launch more low cost CubeSats than are required to complete the mission, which yields graceful performance degradation. A large constellation of CubeSats results in total mission costs that are significantly lower relative to competing mission architectures.

The mass-produced space-qualified hardware used in small satellites dramatically reduces the
cost of a space observatory making a constellation of these telescope not only just affordable, but also significantly lower cost relative to conventional medium-sized space telescope such as those in the NRC report. Furthermore, NEOs much smaller than 140 m can still cause major damage when the impact the Earth. We emphasize that the only affordable way to survey 90% of 70 m or 50 m NEOs would be with the synthetic tracking multiple CubeSat architecture. We will investigate the relevant mission design and architecture in a subsequent publication.

The key conclusion is that by combining synthetic tracking and CubeSat technologies, compared to all survey architectures and methods proposed previously, we are fundamentally “playing in a different ball park”. This new paradigm is both drastically less expensive and significantly more capable of finding not just 140 m NEOs in much less time, but also able to address the more difficult challenges of finding 90% of smaller NEOs with sizes down to 100 m, 70 m, and 50 m. Clearly, the potential of a constellation-based architecture presented here will be explored further.

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