Big Science in Small Packages: a Constellation of Cubesats to Search for Near Earth Asteroids

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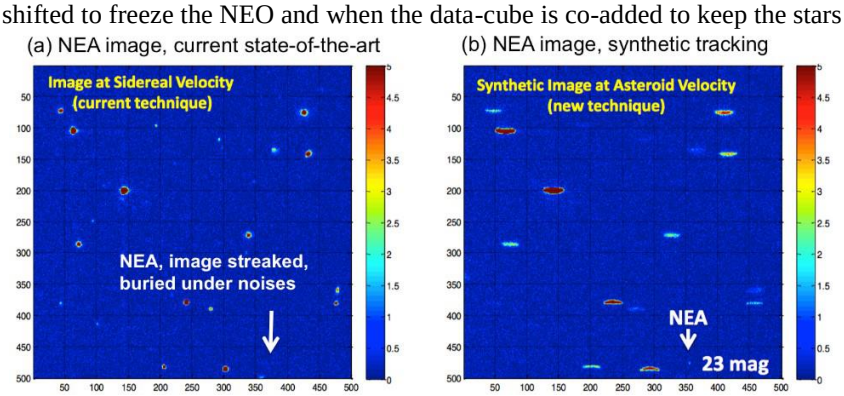
Abstract: Astronomers for many decades have been searching for Near Earth Asteroids (NEA) that could potentially impact the Earth in the future. Large Synoptic Survey Telescope (LSST), when completed, would be by far the most powerful tool for a ground-based search for NEAs. In space, IR telescopes are undergoing detailed design studies. These facilities are projected to find 90% of potentially hazardous NEAs in about a dozen years. We introduce a different approach to search for these objects by using multiple micro- and nano-spacecraft distributed in orbit around the Sun. Their ability to faint moving objects with small telescopes is based on a new generation of low noise, fast-frame cameras combined with processors that can execute 100's of gigaflops in a low power space environment.

1. Introduction to Synthetic Tracking

To image a moving dim object on a CCD, one typically relies on a long exposure needed to integrate the signal. During this time, the object produces a streak that spreads the signal photons across many pixels, leading to reduced signal-to-noise ratio (SNR) relative a stationary object (i.e., a star). The optimal exposure times is roughly the time it takes to move across one PSF. Thus, a need for higher sensitivity nominally translates to larger telescopes. Synthetic tracking [1–2], takes multiple images where each exposure has minimal motion and performs a shift and add operation over the data-cube. Because the object, in general, is not detectable in a single exposure, one does not know how much to shift each successive image and/or in which direction. We perform the shift/add operation in ~10^3–10^4 different velocity vector directions – a computational operation that is done on fast computers that can perform the multi-vector shift/add in real-time. In addition, what makes this approach to work, is the availability of the sCMOS detectors that have a very low read-noise (typically ~1.2e). Because of these detectors, we are dominated by photon fluctuations in the zodi background. Of course, a telescope in space also has lower sky background, it does not lose the sensitivity even in the daytime or when the moon is up. The figure below shows a 23mag NEO when a ~450 image data cube is shifted to freeze the NEO and when the data-cube is co-added to keep the stars unstreaked [1].



Diffferent asteroids move at different angular velocities across the sky. With a single CCD exposure, some NEAs will move too fast and will be streaked, for others, moving slower, a longer exposure could improve sensitivity. Ground-based telescopes have typical exposure times between ~15–30 sec. A telescope with synthetic tracking with ~600s integration time and lower sky-background can have the same sensitivity as a ground-based telescope ~5–10 times larger in diameter. A synthetic tracking camera with a 10cm telescope would have a limiting magnitude of ~20.9mag (3" pixels), while a 20cm telescope (1.4" pixels) would have a limiting magnitude of 22.3mag.

2. A Constellation of micro/nanoSatellites

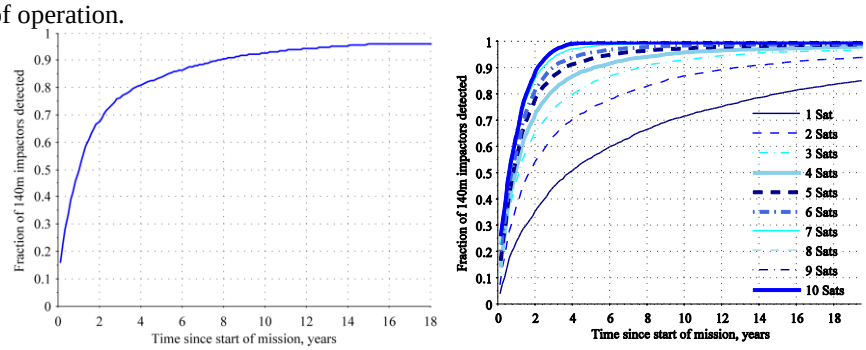
Cubesats and the relevant cubesat technology has grown explosively in the last few years. While a satellite with a 20cm telescope is probably too big to be called a Cubesat, many of cost savings features of cubesat would apply. In the not too distanct past, cubesats were expected to only last a few months in space. JPL recently finished two iden-

tical interplanetary cubesats, called Mars Cube One (MarCO) http://www.jpl.nasa.gov/cubesat/missions/marco.php, at a cost ~$13M. What is indicative of the new cost paradigm is the fact that the cost of the 2nd duplicate spacecraft was only ~10% of the cost of the first one. This offers a very intriguing possibilities for cubesat constellations.

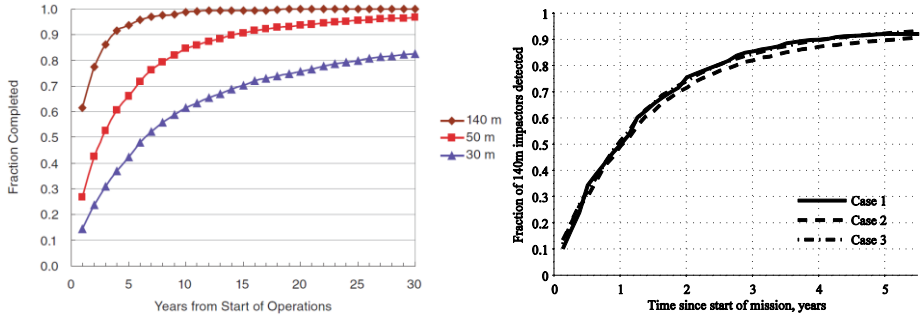
Because of synthetic tracking techniques small telescopes would have the sensitivity similar to that of their much larger telescopes that rely on single CCD exposure [3]. If using only one telescope, long integration time results in that fact that it takes longer to cover the entire sky. However, sky coverage can be made up with a number of duplicate cubesats, whose cost of duplication is very low. But while multiple cubesast with small telescopes in Earth orbit can equal to that of a much larger single telescope in Earth orbit, there are also significant advantages to placing the satellites distributed around the solar system. At a brightness of 21 mag, the NEOs with diameter of 140m can be detected at a distance of ~0.6AU from the camera. Clearly in the case of for one telescope, NEOs on the other side of the Sun cannot be detected. A distributed constellation of satellites lets each satellites survey a non-overlapping volume of space, completing the survey much faster.

3. Simulations of Constellation Searches, discovery versus orbits

We conducted a large series of simulations of how a constellation of synthetic tracking cubesats would perform [3] similar to the simulations conducted in the 2010 NRC report [4]. The plots show the fraction of 140m NEOs detected after N years of operation.



Left: Validation of our model by reproduction of Venus IR results [4]. The spacecraft is on a circular orbit at 0.7 AU from the Sun. The camera's FOV = 11 deg^2, 420 sec integration time, 60 sec slew time (covering 1,980 deg^2 /24 hours) threshold magnitude = 21.5. Right: Fraction of 140 m NEOs detected for constellations of CubeSats with FOV = 14 deg^2, 600 sec integration, 10 sec slews, covering 1,983 deg^2/24 hours, with slewing model active. The figure shows sensitivity to number of CubeSats for constellations 0.85 AU from the Sun.



Left: 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 [4]). Right: Time to detect 90% of 50~m NEOs with several CubeSat constellations.

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4. References

[1] M. Shao, B. Nemati, C. Zhai, S.G. Turyshev, J. Sandhu, G.W. Hallinan, L.K. Harding, "Finding Very Small Near-Earth Asteroids using Synthetic Tracking," The Astrophysical Journal **782**:1 (10pp), (2014), arXiv:1309.3248 [astro-ph.IM].

[2] C. Zhai, M. Shao, B. Nemati, T.A. Werne, H. Zhou, S.G. Turyshev, J. Sandhu, G.W. Hallinan, L.K. Harding, "Detection of a faint fast-moving near-Earth asteroid using synthetic tracking technique," The Astrophysical J. **792**, 60 (14pp) (2014), arXiv:1403.4353 [astro-ph.IM]

[3] M. Shao, S.G. Turyshev, S. Spangelo, T. Werne, and C. Zhai "A constellation of CubeSats with synthetic tracking cameras to search for 90% of potentially hazardous near-Earth objects," AJ, submitted, (2015), arXiv:1503.07944 [astro-ph.IM].

[4] National Research Council, 2010, "Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies," The National Academies Pres, Washington, D.C.