SENTINEL MISSION PERFORMANCE FOR SURVEYING THE NEAR-EARTH OBJECT POPULATION.

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Introduction: The search for and dynamical characterization of the Near-Earth population of Objects (NEOs) has been a busy topic for surveys for many years. Most of the work thus far has been from ground-based optical surveys such as the Catalina Sky Survey and LINEAR. These surveys have found over 90% objects down to a 1 km diameter and have shown all known objects do not pose any significant impact threat. Smaller objects are correspondingly smaller threats but there are more of them and fewer of them have so far been discovered. The next generation of surveys will extend their reach down to much smaller sizes. From an impact risk perspective, those objects as small as 30-40m are still of interest (similar in size to the Tunguska bolide). Smaller objects than this are largely of interest from a space resource or in situ analysis efforts.

A recent mission concept promoted by the B612 Foundation and Ball Aerospace calls for an infrared survey telescope in a Venus-like orbit, known as the Sentinel Mission[4]. This wide-field facility has been designed to complete the inventory down to a 140 m diameter while also providing substantial constraints on the NEO population down to a Tunguska-sized object. We have recently developed a suite of tools to provide survey modeling for this class of survey telescope. The purpose of the tool is to uncover hidden complexities that govern mission design and operation while also working to quantitatively understand the orbit quality provided on its catalog of objects without additional followup assets.

Baseline Mission: The baseline mission design calls for a 6.5 year survey lifetime and is modeled here at 100% of the time used for surveying. The heliocentric orbital elements for the spacecraft are a=0.66AU, e=0.091, i=0.27°, Ω=162°, ω=90°, M=12°, Epoch=2018-07-15 5:00 TDB. The angular elements were arbitrary choices. This orbit is achieved using a Venus gravity assist that lowers the aphelion distance.

The telescope can be pointed at any location in the sky where the angle to the Sun is greater than 80°. The camera has a field-of-view of 11 square degrees with a filling factor of 96%. The image scale is 2.15 arcsec/pixel. The detectors are sensitive from 5 to 10.2 micrometers. The integration time per pointing is 180 seconds. With this camera, it takes 7 days to cover the available sky.

The survey reference design calls for 4 distinct pointings to each location in the sky during a single pass through the available sky. The 4 observations for a given location will be spread over 48 hours. Each object could thus be seen every 28 days with this cadence. This sequence of four observations is continuously repleated for the available sky.

Survey Model: This survey model is a statistically based tool for establishing completeness as a function of object size and survey duration. Effects modeled include the ability to adjust the field-of-regard (includes all pointing restrictions), field-of-view, focal plane array fill factor, and the observatory orbit. Consequences tracked include time-tagged detection times from which orbit quality can be derived and efficiency by dynamical class. The dominant noise term in the simulations comes from the noise in the background flux caused by thermal emission from zodiacal dust. The model used is sufficient for the study of reasonably low-inclination spacecraft orbits such as are being considered. Results to date are based on the 2002 Bottke NEA orbit distribution model[1] and a recent size distribution[2]. The system can work with any orbit distribution model and with any size-frequency distribution. This tool also serves to quantify the amount of data that will also be collected on main-belt objects by simply testing against the known catalog of bodies.

The model uses a simple estimation of the thermal flux that mimics an average over all possible rotation pole positions. Effects of solar phase angle are included. A uniform albedo of 10% was used. The source flux is thus only a function of geometry and target size. The source flux is further reduced if the target is moving rapidly. The detection process requires a 5-sigma excess in signal in a 2-pixel diameter detection kernel. Objects moving slower than 0.57 degrees/day will no incur any trailing losses. An object moving twice this rate will appear to be half as bright in the detection kernel.

The dominant noise source is background signal from the zodiacal dust. A simplified dust distribution was used with line-of-sight integration of the thermal emission from the dust where the dust is assumed to be in thermal equilibrium at each point. The detector noise is included but is unimportant in comparison.

Orbit Estimation: In addition to studying the detection characteristics of the survey, we analyzed synthetic astrometry for NEOs to assess the quality of the orbit that can be expected. These results clearly show the benefit of a self-followup survey such as Sentinel. Most objects discovered will be seen in multiple observing epochs and the resulting orbits will preclude losing track of them for many decades to come. All of the ephemeris calculations, including investigation of orbit determination quality, are done with the OpenOrb software package[5].

To illustrate the orbit quality versus number of observations, consider a representative object. At any given point in the survey one can take the given observations and estimate the error on some future position. The error at the time of the next observation can give some insight on the challenge of linking to the new observations. Within a single observing cycle there is a need to connect two pairs that will be 2 days apart. The first pair has an arc-length of 1 hour that can be used to estimate its future position. At 2 days, the positional error is 3-4 arc-minutes. Using motion vector and orbital motion constraints this is an easy linkage to make. Given the first set one now has a 2-day arc and can then predict the position 26 days later for the next opportunity. At this linkage step, the positional error is the largest in the process and is 2-3 degrees. However, it is still a reasonable linkage problem if all constraints are used. At this point, with two observing cycles linked the object is considered to be found. An object in this category will be easy to find again even though the orbital elements are somewhat uncertain. This is a good enough determination that the error ellipse nearly collapses down to a line-of-variations and has a 10 arc-minute uncertainty after 1 year.

Getting just one more observing cycle makes a huge difference in the determined orbit quality. The worst case is if the only other recovery is in the next cycle and you have a 58 day arc. In this case, the positional uncertainty is well under an arc-minute after 10 years. Based on these results, the survey discovery results were tabulated on the basis of the number of cycles observed. Three categories were kept, 1-cycle, 2-cycle, and 3 or more cycles. The official completeness values used for the mission design are based on 2-cycle observations.

Results: The bottom line result of the survey output for the baseline mission as applied to NEOs, is that Sentinel will reach 74% completion for D>140m objects in 6.5 years and will provide high-quality orbits for all of these. The total number of objects that are predicted to be seen is about 31,000. The size at which 90% completion is seen is for D>240m. The completion level is a few points higher if the sample of objects is restricted to PHOs (potentially hazardous objects). If the sample is restricted to virtual impactors[3] the completion level rises to 89% in the same time frame.

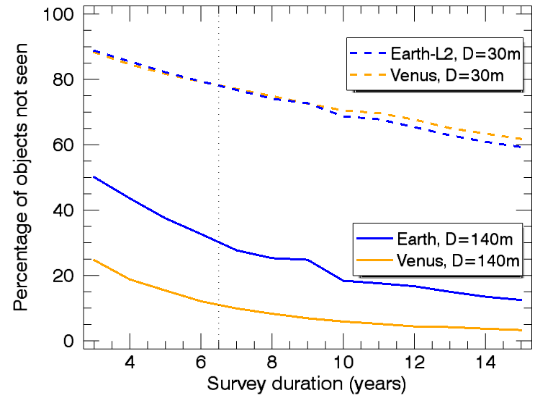

Figure 1: Percentage of population not seen as a function of survey length. The bottom (solid) curves are for D=140m objects. The top (dashed) curves are for D=30m objects. The blue curves are for a Venus-like spacecraft orbit and the orange curves are for a Earth-like (L1 or L2) orbit. The objects simulated are the virtual impactors[3].

We ran comparison tests for alternate spacecraft orbits that include a near-Earth orbit (like L1 or L2) or another with perihelion near Venus and aphelion near the Earth. A summary graph for two representative target sizes is shown in Fig. 1. For NEOs and PHOs (not shown), the survey results are similar but there is a distinct advantage to the Venus-like orbit for virtual impactors at the D=140m. An Earth-Sun L1/L2 orbit with the same mission design only gets a 70% completion rate on D=140m impactors. This is due to the impactors having, in general, much longer synodic periods relative to the Earth and thus making it harder to get the same completeness in the same time. The advantage disappears at smaller sizes because the detections require the targets to be much closer to the observatory. At this smaller, more incompletely surveyed size (D=30m), the objects detected are largely uncorrelated between the two locations indicating that a combined survey would be nearly a factor of two more effective.

References:

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