SPACEWATCH® OBSERVATIONS of HIGH PRIORITY NEAR-EARTH ASTEROIDS. Melissa J. Brucker[1], R. S. McMillan[1], T. H. Bressi[1], J. A. Larsen[2], R. A. Mastaler[1], M. T. Read[1], J. V. Scotti[1], and A. F. Tubbiolo[1]
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Introduction: It is essential to discover and monitor Near-Earth Objects (NEOs) that might hit Earth. We strive to reduce the uncertainty in orbital elements of NEOs and extend their spatial and temporal observation spans. We present details and results from our Target-of-Opportunity program to recover faint Virtual Impactors (VIs) using non-classically scheduled time on larger telescopes.

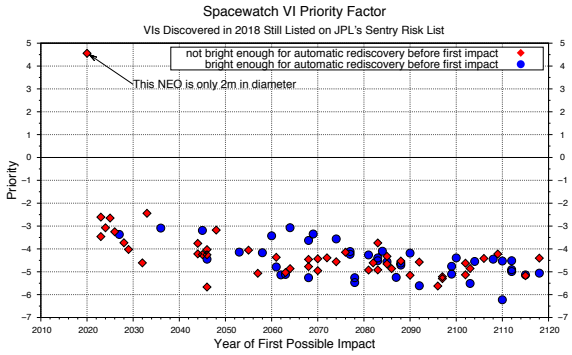
The Spacewatch Project: Spacewatch[1] conducts full-time follow-up astrometry of NEOs primarily with a 1.8-meter and a 0.9-meter telescope on Kitt Peak, Arizona. During bright time, we also utilize the Steward Observatory Bok 2.3m Telescope on Kitt Peak to capitalize on its aperture. We prioritize observing VIs[2], Potentially Hazardous Asteroids (PHAs[3]), objects on the Minor Planet Center's (MPC's) NEO Confirmation Page[4], potential targets of radar[5], NEOs with characterization data (especially targets of the NEOWISE spacecraft[6]), potential destinations of spacecraft[7], and other objects of interest to the small bodies research community. Our first priority, VIs, have uncertainties in their orbital elements such that some possible orbit solutions predict an impact with Earth within the next 100 years. PHAs are NEOs with absolute magnitudes ≤ 22.0 and Earth Minimum Orbit Intersection Distances (EMOID) ≤0.05 au. Spacewatch leads the world community of astrometrists in numbers of observations of PHAs that are fainter than V of 22.5 and in extensions of calendar spans of observations of PHAs. Spacewatch's annual output of astrometry includes ~1,400 NEOs including ~230 PHAs, ~50% of new VIs, ~110 potential radar targets, ~150 NEOs measured by NEOWISE, and ~60 potential rendezvous destinations. We also target candidates for revealing the Yarkovsky effect[8], which like (101955) Bennu[9], may exhibit non-Keplerian orbits due to anisotropic infrared re-radiation of absorbed sunlight.

Target-of-Opportunity Program: In 2018, we began a Target-of-Opportunity (ToO) program to observe faint VIs on larger telescopes in order to rule out (or confirm) predicted impacts, extend the calendar span of observations, and prevent loss due to uncertainty. ToO time is a small amount of competitively awarded time that interrupts the schedule or queue instead of being classically scheduled ahead of time. When a target is selected that requires prompt observations, the ToO is triggered by contacting the observatory. For our ToO program, we focus on VIs since they have a potential to impact the Earth. If VIs accrue large positional uncertainties while they are too faint to be observed using normal NEO follow-up assets, their recovery, once they return and become brighter, can require extensive time and resources and may not be possible. To prevent the need for such extensive effort in the future, we extend the current temporal span of observations longer by days to weeks by using interrupt time on larger telescopes. These telescopes can detect fainter and/or faster-moving VIs than typical NEO astrometric follow-up assets in the one to two meter range. Longer spans of observations lead to lower orbital uncertainties, which in turn lead to more accurate impact predictions. In 2018, 209 new VIs were added to JPL's Sentry risk list and 91 (44%) remain. We want to improve the knowledge of VI orbits in order to eliminate orbit solutions containing high priority impact predictions and reduce the number of VIs.

ToO Target Selection: To select the best targets for our limited number of telescope interrupts, we give higher weight to VIs with first possible impacts that might occur before they become bright enough to be rediscovered. We calculate a "priority" factor using the cumulative impact probability from Sentry, the date of first possible impact (temporal urgency), and the reliability of the impact predictions (related to the observational arc length[10]). Object size and observability are considered separately. In addition to our prioritization scheme, we confer with JPL regarding impact priorities and with other follow-up observing groups. Figure 1 illustrates how a long list of VIs can be narrowed down to those most in need of prompt astrometry. The most urgent VIs lie in the upper part of Figure 1. If a VI has a priority value greater than -2, then it will be given highest consideration over other VIs.

Figure 1. Priority Factor for VIs Discovered in 2018. The set of VIs discovered in 2018 that were still listed by JPL on 2019 August 19 are plotted here. The blue circles are VIs that will become bright enough (V≤22) for serendipitous rediscovery by current all-sky surveys at least one synodic period before their first possible impact. The red diamonds are VIs that will not become bright enough and thus are given precedence. The priority is a logarithmic function of cumulative impact probability, temporal urgency, and reliability of

impact predictions. We did not trigger a ToO for the VI in the upper left of the plot due to its small size. An object with an estimated diameter of 2m will break up in Earth's atmosphere into pieces too small to cause serious damage.



ToO Implementation: Beginning with the 2018A observing semester, we have been awarded ToO time on the Victor Blanco 4-m Telescope and the Southern Astrophysical Research Telescope (SOAR) at Cerro Tololo Inter-American Observatory in Chile, the W. M. Keck Observatory in Hawai'i, the WIYN 3.5-m Observatory at Kitt Peak National Observatory in Arizona, the Large Binocular Telescope Observatory on Mt. Graham in Arizona, and the MMT on Mt. Hopkins in Arizona. We have been conservative about triggering ToOs in order to focus our efforts on objects with high potential hazard. We triggered ToO time in 2018A, 2018B, and 2019A at the Blanco Telescope and in 2018A at the WIYN Telescope. We successfully measured the target VI for each of our observations at the Blanco. Our 2018A observations contributed to the removal of the minor planet 2017 TA6 from the risk list. In 2019A, we observed 2019 GD4 on 2019 April 28. Table 1 shows the improvement in orbital elements as found in JPL's Small-Body Database Browser before and after our observations (2019 April 27 and May 2).

Table 1. Orbital Elements of 2019 GD4.

Element	Value Before	Value After
e	0.46660 ±0.00054	0.46651 ±0.00042
a(AU)	1.7995 ±0.0018	1.7993 ±0.0014
i(deg)	0.38104 ±0.00035	0.38098 ±0.00027
Ω	320.280 ±0.011	320.282 ±0.009
ω	197.813 ±0.011	197.812 ±0.009
M	21.454 ±0.034	21.460 ±0.026

Conclusion: Our ToO program with large telescopes, in conjunction with bright time observations on the Bok Telescope, strives to fill in the faint regime for priority NEO astrometry. The Spacewatch priority factor, by incorporating the arclength of observations as a measure of reliability, provides an analysis of the reliability and urgency of VI predictions which assists in making the best use of limited access to large telescopes.

References:

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