Spacewatch Observing Status

Summary:
To support NASA's mandate to discover and track near-Earth Objects (NEOs), we observe the positions and motions of priority NEOs, securing their orbits and thereby refining the measures of their hazards. We report our observations promptly to the Minor Planet Center (MPC; https://www.minorplanetcenter.net/iau/mpc.html), which publishes the measurements and the correspondingly updated orbital elements.

Scientific Justification:

An impact with the Earth by a near-Earth object (NEO) is one of the few predictable natural disasters that can be prevented if the object is discovered and its orbit is determined with adequate warning time. But prediction and mitigation can only occur if we know where the NEO is going with sufficient accuracy. However, some NEOs can slip away before sufficient observations are made during their discovery apparitions. Those tend to be the ones with the more closely approaching, short-lived apparitions, including some with dangerous orbits. Below we give examples of some of the types of NEOs that we prioritize.

Potential Impactors: Virtual Impactors (VIs) are NEOs whose heliocentric orbits may include an impact with the Earth within 100 years. Thus VIs are our highest priority targets. Our observations increase the spatial arcs and temporal spans of observations, reduce the uncertainty in the orbital parameters, and help to rule predicted impacts in or out. VI lists are maintained at JPL (https://cneos.jpl.nasa.gov/) and NEODyS (https://newton.spacedys.com/neodys/index.php?pc=0). As more astrometric data are collected, asteroids either remain listed as VIs or are removed, depending on whether they still show potentially dangerous close encounters with Earth within 100 years. VIs that are still listed may be "lost" or "recoverable". An asteroid is considered "lost" if its positional uncertainty is so large that it is more likely to be rediscovered by chance than recovered by observations targeted to its ephemeris (Milani 1999). In 2021, 391 new VIs were listed by JPL. As of March 15, 2022, 164 (42%) were removed after previously predicted potential impacts became inconsistent with later observations. 227 (58%) of the VIs discovered in 2021 remained potential impactors. For 133 of the 227, the date of their first possible impact will occur before they become bright enough again to be rediscovered by the current all-sky surveys. Our observations have contributed to the retirement of many virtual impactors.

Potentially Hazardous Asteroids: PHAs are defined by the IAU as NEOs with absolute magnitudes equal to or brighter than 22 (a proxy quantity for diameters ≥140-m) and with orbits that approach within 0.05 AU of the orbit of Earth. We further narrow that category for our priority targeting to those PHAs that will themselves make close approaches to Earth itself within the next 40 years.

Radar Targets are NEOs observable with the Goldstone Solar System Radar (https://gssr.jpl.nasa.gov/), provided their positions will be known in advance to within 20 arcsec. Our astrometric updates to orbital elements can help ensure accurate ephemerides to facilitate radar observations.

NEOs Observed by Spacecraft: The relationships between the mineralogical properties and orbits of asteroids are clues to their origins and subsequent processing, but albedos are generally difficult to determine from visible light. The NEOWISE spacecraft is making an all-sky thermal infrared survey of minor planets including hundreds of NEOs. NEOWISE constrains their diameters and albedos (Wright *et al.* 2010; Mainzer *et al.* 2011a,b, 2012a,b; Nugent *et al.* 2015). After such hard-won physical parameters are determined, it is important that such objects be recoverable in future apparitions for further study. We observe NEOs detected by spacecraft that are in need of more accurate orbits.

Yarkovsky Objects are asteroids (not necessarily NEOs) whose orbits are being monitored for long-term drift induced by asymmetrical thermal re-radiation of incident sunlight (Nugent *et al.* 2012; https://svs.gsfc.nasa.gov/11964). In the cases of VIs like (101955) Bennu, knowledge of the amplitude and direction of the Yarkovsky drift can make the difference between an impact and a miss of the Earth. We observe candidates for the Yarkovsky Effect from monthly lists provided by an orbital dynamics specialist at JPL (D. Farnocchia private communications).

Small NEOs: Asteroids that are "small" enough may be bare rock without an overlying layer of regolith. At what size this transition occurs has not been established, but accurate orbital elements will allow further studies of them. The distribution of their rotation periods and what fraction of them are tumbling with multiple periods can reveal the dynamical history of the population. Observations of taxonomic colors and spin states, such as are made by Moskovitz *et al.* (2015) and Thirouin *et al.* (2018), require accurate knowledge of position.

Experimental Design & Technical Description:

Contribution to Goals: Our goal is to improve knowledge of orbital elements of near-Earth asteroids and comets by means of astrometry. Astrometry (https://www.sciencedirect.com/topics/earth-and-planetary-sciences/astrometry) is the measurement of the positions and motions of celestial objects. For solar system objects of interest, astrometry must span sufficiently wide arcs of orbits such that the accuracy of the orbital elements will allow recovery of the objects on their subsequent apparitions. As an example, a target with a listed ephemeris uncertainty of 50 arcsec that is observed by us with our typical astrometric accuracy of 0.5 arcsec would receive an improvement of a factor of 100 in ephemeris accuracy. Sufficiency of time span and accuracy of astrometry are evaluated by, and orbits are updated by dynamicists at the Minor Planet Center (MPC), JPL/CNEOS, and NEODyS in Pisa, Italy.

Spacewatch Astrometry: We conduct a full-time intensive program of follow-up astrometry of faint NEAs and comets as the sole users and maintainers of the Steward Observatory 0.9-m Telescope and the LPL Spacewatch II 1.8-m Telescope on Kitt Peak (Brucker *et al.* 2020; McMillan *et al.* 2016). We measure more PHAs of V≥22 than most other astrometry groups. The 0.9-m telescope can detect asteroids as faint as V=22.2 and the 1.8-m telescope can reach V=23 with low SNR when conditions permit.

Method: Spacewatch observing has been described by Brucker *et al.* (2017, 2018, 2019a&b, 2020) and McMillan *et al.* (2007, 2014, 2016a,b). We take a series of exposures of the sky at a NEO's predicted position. At least three images (or stacks of images) of the NEO are required to show its positions and make two measurements of its tangential velocity with respect to the background stars. Identification of the NEO is verified by blinking the images. Pixel coordinates are mapped to a celestial reference frame using a stellar astrometric catalog. Coordinates of the NEO at the standard epoch are thus derived.

Precision and Required Signal: Astrometry of close approachers to subarcsecond accuracy after the most recent previous observation usually makes a vast improvement to the knowledge of an orbit. The astrometric precision depends on the seeing. We require an astrometric precision of 0.3 arcseconds. If the seeing is 1.2 arcsec, we calculate the required Signal-to-Noise Ratio (SNR) as 9.6. With seeing of 1.8 arcseconds, we need the SNR to be greater than 14 for each of three images or stacks of images. Because the targets are moving, we take a series of exposures of a few minutes' duration each, short enough to avoid significant trailing. Our targeting software reviews the conditions from the previous target when computing the total exposure time predicted to acquire the necessary SNR for a newly selected target.

Photometry: R magnitude zero points are determined from untrailed images of known stars in our scientific target fields. This makes our photometry less sensitive to thin clouds, changes of transparency, and uncertainty of the extinction coefficient. The MPC publishes photometry rounded off to tenths of a magnitude, so SNR=14 satisfies their requirement.

Number of Targets and Number of Nights: During each lunation, about 388 new NEO candidates are posted on the NEO Confirmation Page. An average of 22 new objects will show virtual impact solutions sometime in the next century. Of those, about 10% will probably remain unconfirmed on a second night despite lingering on the page for several days or weeks.

Use of Larger Telescopes:

Astrometry with the Spacewatch Cassegrain Camera (SCC) on the Bok Telescope: We have used the 2.3-m Bok Telescope (https://www.as.arizona.edu/bok-23m-telescope) of the Steward Observatory since the 2010A semester for astrometry of NEOs. In semesters 2019A through 2022A we have been awarded an average of 6 nights per lunation for NEO astrometry. In 2021, we made 959 measurements of 291 unique NEOs, including 123 larger than 140-m, 63 of which are Potentially Hazardous Asteroids (PHAs). This corresponds to a monthly average of 24 unique NEOs, 10 larger than 140-m, and 5 PHAs with the Bok. Astrometric data are reduced, submitted to the Minor Planet Center (https://www.minorplanetcenter.net/iau/mpc.html), and published in their Minor Planet Electronic Circulars (MPECs), Daily Orbit Updates (DOUs), or Minor Planet Supplements (MPS).

Survey for NEOs and Earth Trojans with 90Prime: In 2019, Spacewatch®, the Catalina Sky Survey (https://catalina.lpl.arizona.edu/), and the University of Minnesota (https://experts.umn.edu/en/persons/chick-e-woodward) began a collaboration using the wide-field prime focus camera 90Prime (https://lavinia.as.arizona.edu/~tscopewiki/doku.php?id=public:kitt_peak:bok_90:bok_90_telescope#prime) on the Bok to discover faint asteroids, especially Earth Trojan candidates and larger NEOs. Surveying for discoveries uses a different pointing strategy than the follow-up astrometry addressed by our other proposals. We were awarded about 122 nights for the 2019B - 2022A semesters. At least 232 new NEOs were discovered, including the PHA 2020 DB5. The Bok NEO Survey is the #4 site in Discovery MPECs 2021 Apr 1 through 2022 Mar 31, and #9 over the past 5 years. It is also #9 in precovery measurement MPECs 2021 Apr 1 through 2022 Mar 31.

Target-of-Opportunity (ToO) Time on Even Larger Telescopes: Spacewatch was awarded ToO time on the MMT (https://www.as.arizona.edu/mmt-65m-telescope) for 2019B - 2022A and on the LBT for the 2019A - 2021A semesters to recover very faint high priority Virtual Impactors (VIs). We triggered the 2021A MMT observations. Spacewatch also was awarded 1 hour of ToO time on Keck I (https://www2.keck.hawaii.edu/inst/index.php) in each of the 2018A through 2022B semesters for the highest priority targets in our VI program. In addition, we have been awarded ToO time for the VI project on the following telescopes: the Victor Blanco 4-m Telescope (https://noirlab.edu/science/programs/ctio/telescopes/victor-blanco-4m-telescope) in 2018A through 2022A; the 4.1-m Southern Astrophysical Research Telescope (SOAR) in 2018A, and 2019A through 2021A; NOIRLab's Gemini N and Gemini S in 2020B through 2022A; and the WIYN 3.5-m Observatory in 2018A.

Overall Output: In 2021, from the 1.8m, 0.9m, SCC follow-up, and Bok NEO Survey combined, we submitted 405,681 astrometric measurements, including 9,809 NEO measurements representing 1641 unique NEOs including 222 unique PHAs. That's equivalent to a monthly average of 817 NEO measurements, observing 137 different NEOs, including ~19 different PHAs per month. In 2021 with 1.8m, 0.9m, and SCC, we also targeted objects on the MPC's NEO Confirmation Page 1666 times. Our astrometry submissions generated 783 MPEC and DOU publications in 2021. Spacewatch has contributed observations on about two-thirds of NEOs that have ever been on JPL's VI impact risk list.

Other Information:

Congressional Mandates: Our proposed observations have direct relevance to NASA's mandates and goals. The NASA Authorization Act of 2005 increased the scope of NASA's objectives by amending the National Aeronautics and Space Act of 1958 ("NASA Charter") to add: *"The Congress declares that the general welfare and security of the United States require that the unique competence of [NASA] be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth."* This made NEO detection, tracking, and research one of seven explicitly stated purposes of NASA. Congress provided additional direction to *"...plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue within 15 years"*. That 15-year deadline corresponded to the year 2020. The ground-based facilities dedicated to this search are working more and more efficiently every year, but a purpose-built spacecraft telescope is needed to find the rest of that population in an acceptable time.

International Collaboration: We are part of a world-wide campaign to discover, monitor, and study asteroids that might hit the Earth, as well as the populations of asteroids from which they are derived. We work with Spaceguard (https://spaceguardcentre.com/), the NASA Planetary Defense Coordination Office (https://www.nasa.gov/planetarydefense/overview), JPL's Center for Near Earth Object Studies (https://cneos.jpl.nasa.gov/), the Minor Planet Center (https://www.minorplanetcenter.net/iau/mpc.html), the United Nation's International Asteroid Warning Network (IAWN; https://iawn.net/), NEOWISE (https://neowise.ipac.caltech.edu/), the Catalina Sky Survey (https://catalina.lpl.arizona.edu/), Pan-STARRS (https://panstarrs.ifa.hawaii.edu/pswww/), the Las

Cumbres Observatory NEO Follow-up Network (https://lco.global/science/projects/asteroids/), ATLAS (https://atlas.fallingstar.com/home.php), NASA's Goldstone Solar System Radar (https://gssr.jpl.nasa.gov/), and the European Southern Observatory (https://www.eso.org/public/). We have participated in 4 recent campaigns to test planetary defense readiness: the recovery of 2012 TC4 (Reddy *et al.* 2019), the IAWN characterization of binary asteroid (66391) Moshup 1999 KW4 (Reddy *et al.* 2022a, Scheirich *et al.* 2021), the IAWN "recovery" and "characterization" of Apophis (Reddy *et al.* 2022b), and the IAWN astrometric timing analysis with 2019 XS (Farnocchia *et al.* 2022, in prep).

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[Links to references may be found at **https://ui.adsabs.harvard.edu/ .]**

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