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RESEARCH

SPACEWATCH Astrometry of Near-Earth Asteroids for Planetary Defense

Robert S. McMillan[1,2] · **Melissa J. Brucker**[1] · **Cassandra Lejoly**[1] · **Jeffrey A. Larsen**[1,3]

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Abstract
The SPACEWATCH® project at the University of Arizona makes astrometric and photometric observations of asteroids and comets to improve orbital knowledge for the purpose of planetary defense. We are ready to follow up asteroids detected by the upcoming Legacy Survey in Space and Time (LSST) and the Near-Earth Object Surveyor Mission (NEOSM). SPACEWATCH®'s highest priority targets are asteroids categorized as Virtual Impactors (VIs), recently discovered Near-Earth Objects (NEOs), the subset of Potentially Hazardous Asteroids (PHAs) capable of making close approaches to Earth in the next few decades, NEO candidates for detecting the Yarkovsky Effect, and asteroids of otherwise declared scientific interest. SPACEWATCH® leads the USA's NEO community in astrometric observations of the following priority objects while they are fainter than a V magnitude of 22.5: VIs while distant, asteroids being studied for the Yarkovsky effect, PHAs that will make close approaches to Earth, NEAs measured in the infrared by the WISE/NEOWISE spacecraft mission, and small NEOs that will make close approaches to Earth. By detecting such moving objects while they are faint (and therefore distant), we can increase the accuracy of the orbital elements more. On the dates of the observations, eighty percent of SPACEWATCH®'s NEO observations were not duplicated by other surveys. In addition to astrometry, SPACEWATCH® collects high signal-to-noise photometry of NEOs to create lightcurves and provide rotation periods and rough shape information through their amplitudes of modulation. SPACEWATCH®'s target selections for lightcurve observations are set by the needs of radar observers and by the above priorities.

Keywords Follow-up · Ground-based telescope · NEOs · Virtual impactors

Extended author information available on the last page of the article

1 Purpose

The main objective of the SPACEWATCH® project (subsequently referred to as Spacewatch), is to reduce the uncertainty in the orbital elements of Near-Earth Objects (NEOs; asteroids or comets) for the purpose of planetary defense. Fully funded by NASA's Planetary Defense Coordination Office (PDCO), we conduct astrometric and photometric observations of NEOs in order to reduce the uncertainty of their on-sky positions, leading to improved orbital elements. This provides better predictions of their locations in the future and allows determination of whether they have a small but non-zero probability of impacting Earth within the next 100 years. Spacewatch's highest priority targets are potential impactors and NEOs larger than the George E. Brown Congressional mandate of 140-m; however, after the atmospheric impact of the 20-m asteroid near Chelyabinsk, Russia in 2013, we also prioritize smaller NEOs that may approach close to Earth or cause future damage.

2 Equipment History

We use three telescopes at the Steward Observatory site on Kitt Peak in the Tohono O'Odham Nation, Arizona, USA. They are the Steward Observatory 0.9-m (Minor Planet Center (MPC) observatory code 691), the Lunar and Planetary Laboratory (LPL) Spacewatch II 1.8-m (MPC observatory code 291), and the Steward Observatory Bok 2.3-m telescope with the Spacewatch Cassegrain Camera (SCC) (MPC site program codes `695 and D695). Separately, we collaborate with Catalina Sky Survey to use the Steward Observatory Bok 2.3-m telescope with the 90Prime camera (MPC program code V00), as discussed in Sect. 6.4. The Bok 2.3-m telescope is a Steward Observatory facility for which time is proposed and allocated by their telescope allocation committee. Currently, our use of the SCC and 90Prime combined is about 15 nights per lunation.

We began observing in 1984 [1–3] with only the 0.9-m. Throughout the years, Spacewatch-operated telescopes have undergone a number of upgrades, as documented in Tables 1 and 2, and in [4–24]. The present configuration parameters date from September 27, 2015 (available in Table 3). The analyses hereafter refer to observations made from that date onward, unless otherwise specified.

The 0.9-m telescope has a mosaic of four thinned, back-illuminated, antireflection-coated CCDs at corrected prime focus. The 1.8-m telescope has a thinned, back-illuminated 2kx2k CCD at folded and corrected prime focus. Both the 0.9-m and the 1.8-m have a Schott OG-515 filter that only passes wavelengths longer than 500 nm, thus reducing the effect of moonlight and minimizing the effects of atmospheric refractive dispersion on point sources. The SCC is a 2kx2k thinned, back-illuminated CCD at the Cassegrain focus of the 2.3-m telescope and is used specifically during lunar bright time with its fine pixel scale that samples well the sometimes sub-arcsecond seeing at that telescope. A new camera, the SCC-2, with twice the field width is nearing commissioning. Our observations at the Bok telescope were unfiltered from 2015 September 27 through 2019 June 11 and after June 11 were made through

Table 1 History of the equipment setup for the Spacewatch 0.9-meter telescope. From the beginning of observations until Nov. 3rd 1997, the telescope drives were created and maintained by Jack E. Frecker. Subsequently, they were taken over by Terrence H. Bressi. Imaging from 1984 through 2002 April 22 were drift scans. Imaging from 2002 October 22 through current are typically sidereal tracking

CCD	Optics	Dates	Limiting Magnitude[a]	Pixel Scale[b]
Thin 320 × 512[c]	f/5 prime uncorrected unfiltered	1984 Apr 22 - 1984 Jun 22	19.6	1.345
Thin 320 × 512	f/3.87 xfer lens; unfiltered	1984 Sep 19 - 1988 Apr 19	19.6	1.733
Thick 2K × 2K[d]	f/5 prime uncorrected unfiltered	1989 Apr 04 - 1992 Sep 18	20.5	1.211
Thin 2K × 2K[e]	f/5 prime uncorrected unfiltered	1992 Sep 19 - 1995 Jun 20	20.9	1.076
Thin 2K × 2K	f/5 coma corr. lens & OG-515[f]	1995 Jun 21 - 1999 Sep 28	21.5	1.051
Thin 2K × 2K	f/5 coma corr. lens & OG-515	1999 Sep 29 - 2002 Apr 22	21.8	1.051
Thin 4CCD Mosaic[g]	f/3 + lens & OG-515	2002 Oct 22 - current	22.2	1.00

[a]Limiting V magnitude

[b]Arcseconds per pixel

[c] RCA SID 53612 CCD 320 × 512, 30 micron pixels, thinned and backside-illuminated

[d]Tektronix 2048-SP 2048 × 2048, 27 micron pixels, thick and front illuminated

[e] Tektronix TK2048EB-1 2048 × 2048, 24 micron pixels, thinned and backside-illuminated

[f] Schott OG-515 filter transmitting wavelengths from 515 nm to the long wavelength cutoff of the CCD

[g] Four E2V Technologies, Model CCD42-90-I-941; 4608 × 2048 pixels each, thinned and backside illuminated

Table 2 History of the equipment setup for the Spacewatch 1.8-meter telescope. The telescope drives were created by Larry D. Barr, Marcus L. Perry, and T. H. Bressi. They are presently maintained by T. H. Bressi. Imaging from 2002 through 2011 October 01 were drift scans. Imaging from 2011 October 01 through current are typically sidereal tracking

CCD	Optics	Dates	Limiting Magnitude[a]	Pixel Scale[b]
Thin 2K × 2K	f/2.7 + lens & OG-515	2002 Oct 22 - 2011 Oct 01	22	1.00
Thin FLI2k[c]	f/2.7 + lens & OG-515	2011 Oct 02 - present	23[a]	0.6[a]

[a]Limiting V magnitude

[b]Arcseconds per pixel

[c]2048 × 2048, 15 micron pixels, thinned and backside illuminated

Table 3 Current telescope configuration parameters for Spacewatch operations

Telescope	MPC	V^{a}	FOV^{b}	Image Scale	Pixel Size	Filter
1.7	Obs. Code	1.7	1.7	(”/pixel)	(μm)	
0.9-m (f/3)	691	22.4	1.7° × 1.7°	1.00	13.5	Schott OG515
1.8-m (f/2.7)	291	23.0	20’ × 20’	0.62	15	Schott OG515
Bok 2.3m/SCC^{c} (f/9)	ˆ695, D695	24.2	5’ × 5’	0.26	15	Open/Tiffen Wratten #12[4]

[a]Limiting V magnitude,

[b]FOV is the field-of-view,

[c]Spacewatch Cassegrain Camera - FLI instrument with 2048x2048 pixels

[d]The filter was added in mid-2019

a Tiffen (Wratten) Yellow #12 filter with a bandpass similar to that of the Schott OG-515.

3 Method

We perform full-time NEO astrometric follow-up observations for planetary defense with the 1.8-m and the 0.9-m for approximately 24 dark/grey nights per lunation, weather permitting. In addition, we perform NEO astrometric follow-up at the Bok 2.3-m with the SCC using competitively allocated time from the Steward Observatory Telescope Allocation Committee (TAC). We routinely have been awarded 6 nights per lunation with the SCC, explicitly scheduled during the brightest part of each lunation – a time when most other stations with smaller telescopes cannot reach faint priority targets. We also make Target-of-Opportunity (ToO) interruption observations as needed with competitively allocated time on large telescopes to observe priority virtual impactors[1] (VIs) before they become too faint to be recovered during their current apparitions.

For detection of moving objects, we usually take exposures between 10 and 120 s in duration. For the 1.8-m, a typical single exposure time is 60 s. Exposure times for the 0.9-m are a function of the object’s rate of motion (among other quantities). The exposure time is chosen to minimize elongation of the target NEO in the image while driving the telescope at the sidereal rate. To detect faint objects, many such short exposures are shifted at the object’s expected rate of motion and stacked to build up sufficient signal. We usually create three such stacks to form a “tracklet” to reveal the target’s motion; but, two images or stacks can be used for our astrometric measurements if necessary to achieve a sufficient signal. Table 4 and Figs. 1 and 2 represent examples of some of the fainter observations accomplished with the 1.8-m, the 0.9-m, and the Bok 2.3-m with the SCC.

[1] NEOs identified as having a low but non-zero probability of impacting Earth within 100 years.

Table 4 Examples of three faint objects recovered for each of the main Spacewatch telescopes with the mean and median of the percent difference reduction in uncertainty of the six orbital elements (eccentricity, semimajor-axis, inclination, argument of perihelion, longitude of ascending node, and mean anomaly) and the on-sky uncertainty as calculated before our measurement was made and after, along with the average of the R magnitudes measured for each object

Object	MPC Observatory Code	% difference in uncertainty of orbital elements		On-sky Uncertainty (arcseconds)		Date observed (UTC)	R-mag
		Mean	Median	Pre-obs	Post-obs		
2025 UE5[a]	291	47.92	52.06	1.49	0.108	2025-11-11	22.8
2025 RZ5[a]	691	156.77	163.35	4.98	0.181	2025-10-24	22.6
2013 TM4[a]	D695	3.69	0.20	0.037	0.029	2025-08-31	23.0

[a]These observations were all the last time the object was reported as of 2025-11-18

Astrometric solutions of images and measurements of targets are made with either an in-house wrapper to Astromatic[2] or with Astrometrica.[3] Astromatic is the main data processing software for the 1.8-m and the 0.9-m, Astrometrica is used with the 1.8-m if there an issue with measuring the target in stacked images in denser star fields. The main difference between Astromatic and Astrometrica is that the point they stack upon and centroid are slightly different, allowing for two options when star trails become an issue. The SCC utilizes only Astrometrica because of the type of hardware available at a shared-facility telescope. We are working with Steward Observatory to get space in which to store a local copy of Gaia. We use the online Gaia DR2 catalog as a reference star catalog[4] with a local copy of USNO-B1.0[5] as a backup in case we cannot connect to Gaia DR2 remotely. In the past year, for example, we have used the Gaia DR2 exclusively for the 0.9-m, and over 99% of the time for the 1.8-m. Due to connection issues at the Bok 2.3-m with the SCC, Gaia DR2 was used about 51% of the time at that telescope. Since 2024 November 22, our astrometry has been reported to the MPC in their preferred Astrometry Data Exchange Standard (ADES) format. Referencing the MPC's "residual blocks" in their Minor Planet Electronic Circulars (MPECs), our average astrometric residual standard deviations ($\Delta x, \Delta y$) are (0.3, 0.3) arcsec *including* the very few observations that were rejected by the MPC.

Figure 3 shows astrometric residuals published in MPEC "residual blocks" for the Bok 2.3-m with the SCC, quadratically-averaged by lunation, versus time. Our transition from the use of the USNO-B1.0 star catalog to the Gaia-DR2 catalog was on 2020 Oct 31 immediately following the gap imposed by the shutdown of Kitt Peak during the COVID-19 pandemic. We note that our residuals did not improve much upon adoption of the Gaia DR2 catalog due to the small FOV. Regarding the lack of improvement at 695, we note that our astrometry tends to be limited by local random errors such as the signal-to-noise ratio of the images, small FOV, and less-than-perfect seeing. We acknowledge that the MPC had been applying corrections to our astrometry made with USNO-B1.0 according to the known systematic errors of that

[2] https://www.astromatic.net/software/

[3] www.astrometrica.at/ version 4.11.1.442 as of 2025 June.

[4] https://www.cosmos.esa.int/web/gaia/dr2

[5] http://tdc-www.harvard.edu/catalogs/ub1.html

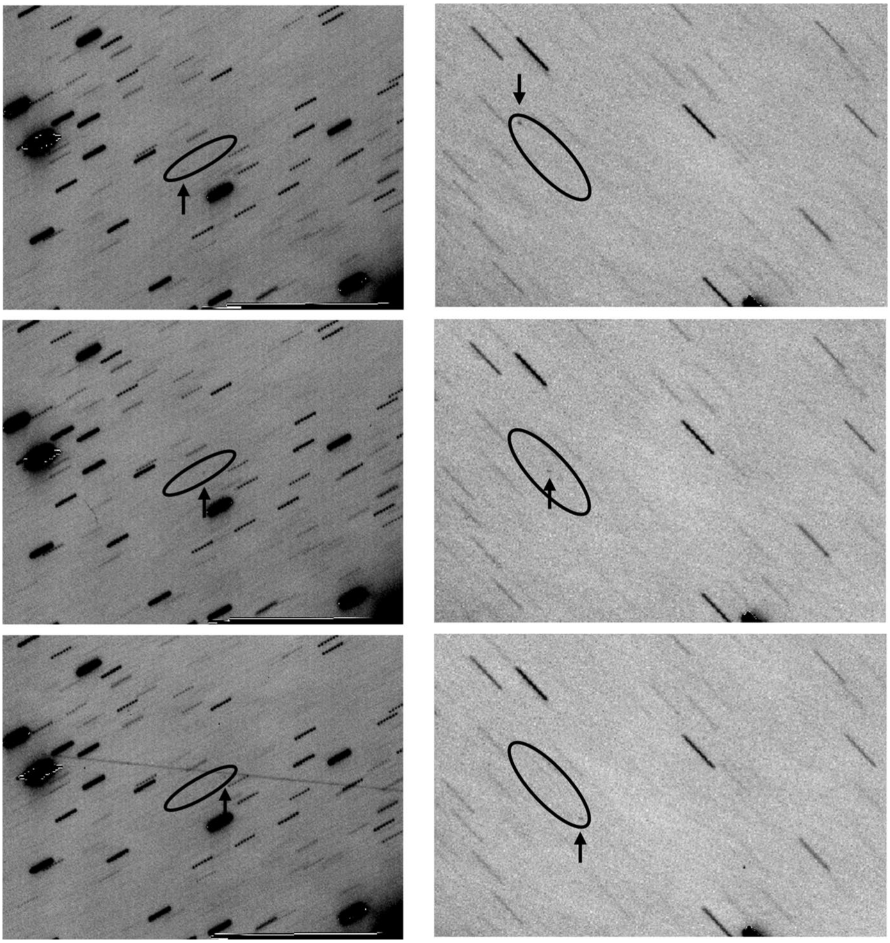

Fig. 1 Left: NEODyS target 2025 RZ5 observed on 2025-10-24 UT from the 0.9-m telescope (691). Each image stack cut-out contains 7 132-s sidereal exposures stacked at the object's ephemeris rate of motion. The measured R magnitudes were 22.5, 22.7, 22.5 with corresponding signal-to-noise ratios (SNRs) 7, 6, and 7. Each image stack cut-out is approximately 29.4" by 5'12" Right: NHATS target (also discovered by V00) 2025 UE5 observed on 2025-11-11 UT from the 1.8-m telescope (291). Each image stack cut-out contains 20 60-s sidereal exposures, stacked at the object's ephemeris rate of motion. The measured R magnitudes were 22.4, 23.0 and 22.9 with corresponding SNRs 11, 7, and 9. Each image in the tracklets contains an oval circumscribing the path of the target with an arrow pointing to the faint target's location

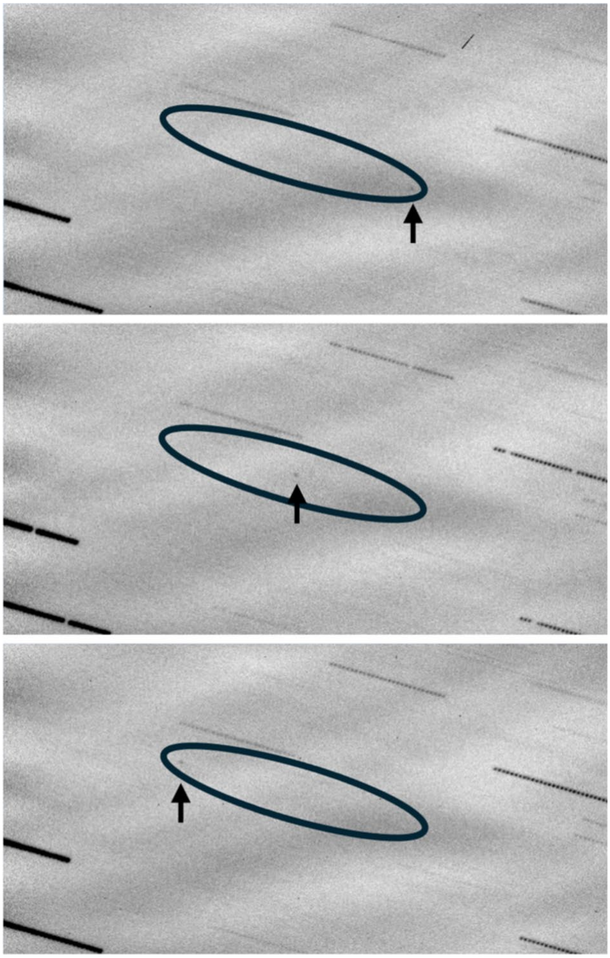

Fig. 2 Candidate for the detection of the Yarkovsky Effect 2013 TM4 observed on 2025-08-31 UT from the Bok 2.3-m telescope with the SCC (D695). Each image stack cut-out contains 28 34-s sidereal exposures stacked at the object's ephemeris rate of motion. The measured R magnitudes were 23.0, 23.1, and 22.9 with corresponding SNRs 9, 9.4, and 9.3. Each image cut-out is approximately 14" by 1'45" and contains an oval circumscribing the path of 2013 TM4 and an arrow pointing to its location

catalog ([25] and G. Williams private communication), so no significant improvement from Gaia DR2 would necessarily be evident from our sites.

4 Targets for Astrometry

For our main operations (observatory program codes 291, 691, and D695), we prioritize our NEO astrometric follow-up target selections for planetary defense from highest to lowest priority as listed below, while also considering the uncertainty of

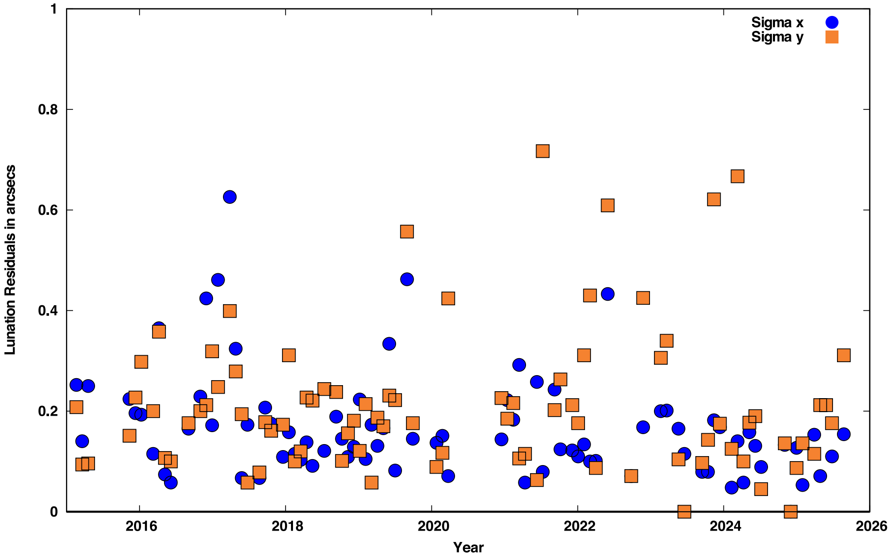

Fig. 3 Astrometric residuals obtained from the published MPECs for the Bok 2.3-m with the SCC. These measurements were quadratically-averaged by lunation and plotted versus time

position, time since last observation, and NEOfixer[6] ranking, and NEOfixer activity page such that we do not duplicate observations with other follow-up resources.

1. Virtual impactors (VIs) as defined by the Jet Propulsion Laboratory's (JPL) Sentry[7] or the Near Earth Objects – Dynamic Site's (NEODyS-2) risk list[8]; and candidates on the MPC NEO confirmation page[9] that were discovered by the Bok NEO Survey (observatory code V00).
2. Other NEO candidates posted on the MPC NEO Confirmation Page.
3. Candidates for detection of the Yarkovsky Effect [26], communicated to the NEO follow-up community by JPL.
4. Potentially Hazardous Asteroids (PHAs) coming closer to Earth than 0.03 au within 40 years.
5. Near-Earth asteroids (NEAs) listed as priorities on the NEODyS-2 webpages.[10]
6. Potential targets for the Goldstone Solar System Radar.
7. Objects observed by the Wide-field Infrared Survey Explorer (WISE) or NEOWISE [27].

[6] https://neofixer.arizona.edu/activity/500

[7] https://cneos.jpl.nasa.gov/sentry/

[8] https://newton.spacedys.com/neodys/index.php?pc=4.1

[9] https://www.minorplanetcenter.net/iau/NEO/toconfirm_tabular.html

[10] https://newton.spacedys.com/neodys/index.php?pc=10.0 and https://newton.spacedys.com/neodys/index.php?pc=10.1

8. Objects listed on the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS)[11] webpage and objects for which NASA requested observations via the small-bodies-observations mailing list.
9. Small NEAs coming closer to Earth than 0.03 au within 40 years.

Internally, we keep a running VI target list that only includes objects targetable from our telescopes on Kitt Peak or through our ToO program. To create the other lists enumerated above, we filter by the objects' uncertainty now and in two weeks to exclude objects with uncertainties $< 6''$, the arc of observations in days, the MPC's and JPL's orbit condition codes,[12] and the last observed date. Successful recovery of a target depends on the weather, the seeing, the lunar elongation and phase, the predicted uncertainty of Right Ascension and Declination in the NEO's ephemeris, and the difference between the predicted and actual apparent NEO magnitude.

5 Effectiveness of Spacewatch Follow-up Observations

According to the PDS Small Bodies Node's MPEC Watch,[13] the 1.8-m (observatory code 291) is the fifth top contributor between 1993 September 19 to 2025 June 16 to MPECs in general and the sixth for MPEC'd follow-up observations since 1993. Site 291 is seventh in performing the first follow-up observation for an MPEC in last 12 months and third since 1993. The 0.9-m (observatory code 691) is seventh in discovery MPECs and eighth in MPEC'd precoveries since 1993.

Based on the MPC's listing of our accepted and published observations between 2015 September 27 and 2025 May 15, for our sites combined (291+691+695), we made 80,298 observations[14] of 11,364 distinct NEOs, including 1269 distinct PHAs. Most of the time, we submit tracklets of three measurements and occasionally of two measurements. Therefore, a rough estimate of the number of tracklets submitted would be about 26,000.

For PHAs, although Spacewatch only prioritizes PHAs that will get close to Earth within the next 40 years, the 1260 distinct PHAs observed were still 57.5% of all the PHAs observed by anyone during that interval. This is a significant fraction, considering that we concentrate on the subset of PHAs that will make close approaches to Earth in the next few decades. The MPC's definition of "PHA" only requires that the *orbit* of the object and the *orbit* of the Earth come into proximity, not that the Earth and the object itself would be present at that point at the same time. We thus refine our targeting to those PHAs that will approach Earth closer than 0.03 au that also are in need of astrometric measurement update, and PHAs that are faint. Our subset of faint PHA observations included 1122 measurements fainter than magnitude 22.5 which represent more than twice the number of faint PHA observations made by the next

[11] https://cneos.jpl.nasa.gov/nhats/

[12] https://www.minorplanetcenter.net/iau/info/UValue.html

[13] https://sbnmpc.astro.umd.edu/mpecwatch/index.html

[14] Of 80-character formatted text lines of astrometry.

most active USA follow-up program (482 faint PHA observations by Astronomical Research Institute; ARI).

We can compare follow-up stations by looking at NEOs that were observed while faint. Figure 4 illustrates our standing within the USA NEO community with respect to observations of priority objects while they are faint between 2015 September 27 and 2025 May 15.

Another way of representing the value of our follow-up observations of NEOs is whether the NEO tracklets we report are unique for the given objects on the nights they were collected. We analyzed Spacewatch tracklets over the shorter, more recent interval of 2019 November 15 through 2023 February 15 to determine the number of our submitted tracklets that were unique. In that time interval, there were ∼5900 unique tracklets by site codes 291, 691, and 695 combined, representing 88% of our total observations during that time period. Although a very small number of MPECs include links to old data which may only appear to be unique within the new MPEC, few other programs observe the same objects on the same nights that we do.

We provided the last tracklet listed in 1764 MPECs, which is about 25% of all the MPECs in which we appear. The average absolute magnitude we observed is H=23.0, or an effective diameter ∼85 m, thus encompassing the full range of USA Congressionally-mandated sizes [28–30]. In addition, the faintest asteroid measurement made by Spacewatch was magnitude 23.7[15] in MPEC 2018-C48.

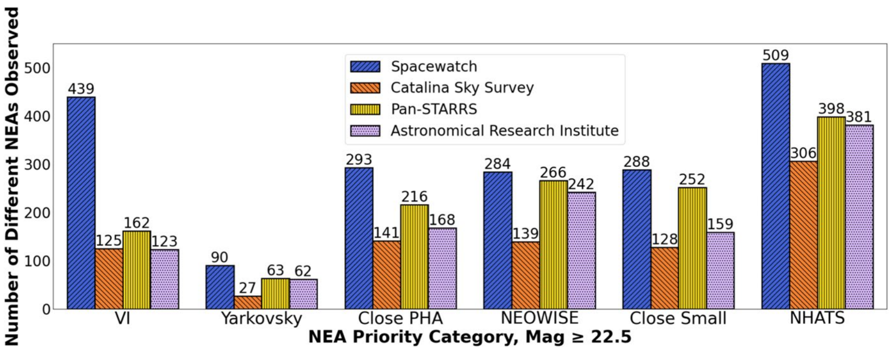

Fig. 4 Number of unique priority Near-Earth Objects observed while they are faint in apparent magnitude by selected principal observing projects. NEOs may be in more than one category. The categories are as follows: "VI" = Virtual Impactors, "Yarkovsky" = Candidates to detect the Yarkovsky Effect, "Close PHA" = Potentially Hazardous Asteroids that will come within 0.03 au of Earth in the next 40 years, "NEOWISE" = asteroids whose infrared flux was measured by the WISE or NEOWISE spacecraft missions, "Close Small" = asteroids of absolute magnitudes fainter than 22 expected to approach within 0.03 au to Earth within the next 40 years, and "NHATS" = asteroids of interest for potential spacecraft visits

[15] 23.7 was the V-magnitude in the ephemeris at the time.

6 Additional Programs

In addition to our astrometric follow-up with the 0.9-m, 1.8-m, and the 2.3-m telescopes, we also execute additional programs to advance planetary defense objectives.

6.1 Target of Opportunity (ToO) Program

We use ToO options to observe urgent VIs. Through 2024 and 2025 we obtained time on Gemini North, Gemini South, Keck, MMT, and CTIO Blanco. Our recent ToO triggers include 2024 VK2, which was successfully recovered with DECam at the Blanco 4-m (site program code }W84) on 2024 Dec 2 and accepted by the MPC [31]. ToOs are very valuable in recovering faint objects that are typically not accessible to smaller 1-2 m class telescopes due to their faint magnitudes. Table 5 shows the benefit of ToO observations as most of our observations reduced the uncertainty in the orbital elements by close to 20% in almost all cases. We recovered the notable VI 2024 YR4 on 2025 February 26 with the Low Resolution Imaging Spectrometer (LRIS) on the Keck I telescope. Figure 5 contains stacked image cut-outs from our ToO recoveries of 2024 YR4 and 2024 VK2. By their nature, ToO observations are faint and catch the object when it is distant, sampling the asteroid's orbit on a very different place from where most of the observations were taken. Table 5 shows that the lever arm of our added observations often causes a significant improvement in the uncertainties in the orbital parameters and that ToOs are often the last observations of these objects for their current apparition. Sometimes, however, as with 2024 YR4, the parameters do not show a significant change, though even this is hardly a wasted observation. It is merely a solid confirmation that would not have existed otherwise that the orbit of this potential impacting object can be trusted.

Table 5 Sample of a few ToOs recovered with larger telescopes with the mean and median of the percent difference reduction in uncertainty of the six orbital elements (eccentricity, semimajor-axis, inclination, argument of perihelion, longitude of ascending node, and mean anomaly) and the on-sky uncertainty as calculated before our measurement was made and after, along with the MPC observatory code and the V magnitude of each object at the stated time of observation

Object	MPC Observatory Code	% difference in uncertainty of orbital elements		On-sky Uncertainty		Date observed (UTC)	V-mag
		Mean	Median	Pre-obs	Post-obs		
2021 EU[a]	W84	26.3	26.8	0.244	0.141	2021-03-17	23.4
2021 GV2[a]	696	19.2	18.7	0.153	0.144	2021-05-10	23.6
2021 TB4[a]	W84	19.8	19.6	0.126	0.104	2021-10-30	23.6
2022 LX[a]	T16	48.2	46.5	0.312	0.164	2022-07-28	23.7
2024 VK2[a]	W84	2.56	3.54	0.2	0.123	2024-12-02	23.6
2024 YR4	T16	0.24	0.00	0.018	0.014	2028-02-26	24.5
2024 YR4[b] [2]	T16	0.68	0.78	0.018	0.014	2028-02-26	24.5

[a]These observations were all the last time the object was reported as of 2025-08-29.

[b]These calculations omitted the observations directly preceding ours made from H01,to represent our improvement if one other follow-up facility were incapacitated.

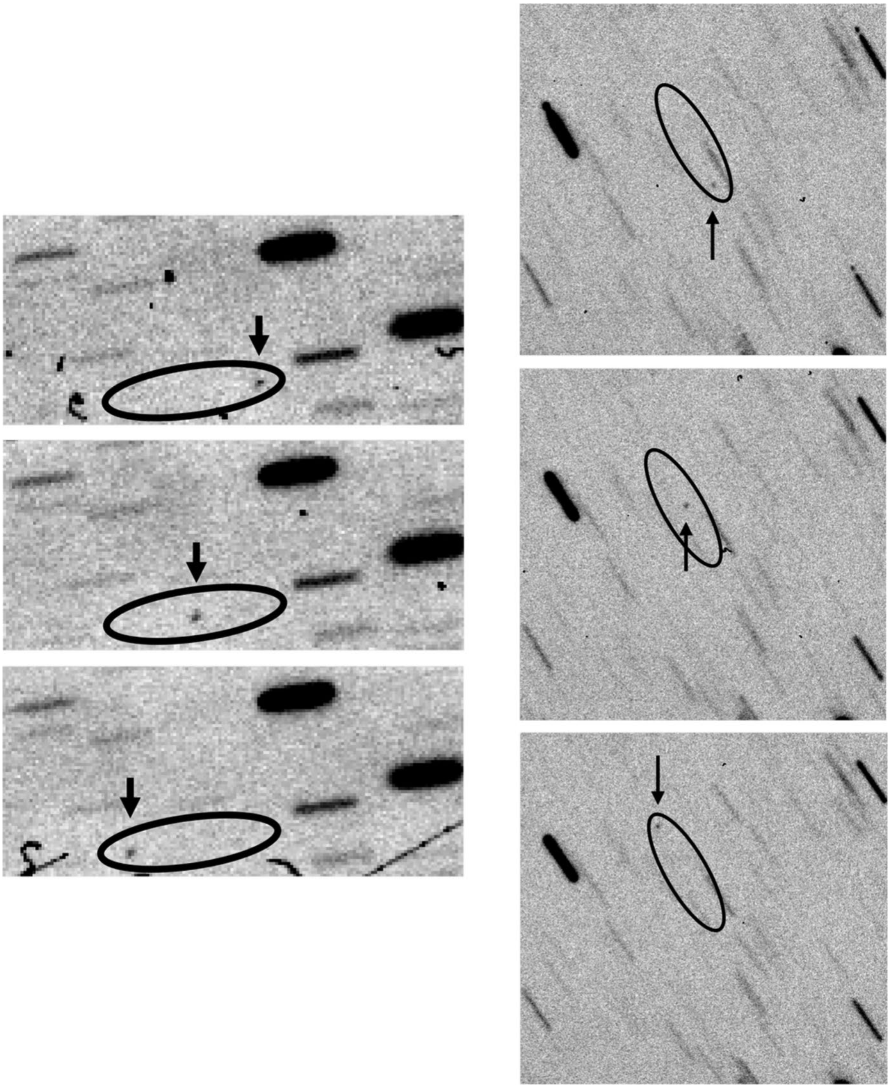

Fig. 5 Sample target-of-opportunity observations with large telescopes. Left: VI 2024 YR4 observed on 2025-02-26 UT with LRIS on Keck 1 (T16). Each image stack cut-out contains 11 60-s sidereal exposures stacked at the object's ephemeris rate of motion. The measured G magnitudes were 24.6, 24.4, and 24.5. Each image stack cut-out is approximately 40" by 18". Right: VI 2024 VK2 observed on 2024-12-02 UT with DECam on the Victor M. Blanco 4-m Telescope (W84). Each image stack cut-out contains 30 30-s sidereal exposures, stacked at the object's ephemeris rate of motion. The measured G magnitudes were 24.0, 23.3 and 23.4. Each image stack cut-out is approximately 2' by 2'. Each image in the tracklets contains an oval circumscribing the path of the target with an arrow pointing to the faint target's location

6.2 Precovery searches

We search our data archives for serendipitous precovery observations[16] of newly discovered VIs, newly announced candidates on the MPC's Near-Earth Object Confirmation Page, and PHAs [10, 22, 32]. FITS-format data from the old (1990–2002) configurations of the 0.9-m telescope cover a sky area of ∼33,000 deg^2 with three passes per sitting. Images from the current epoch of the 0.9-m CCD mosaic cover an area equivalent to >192,000 deg^2 three times. Data from the 1.8-m telescope cover >30,000 deg^2, likewise three times. Precoveries can extend a short observation arc to one that has a much longer time span, even up to years. We regularly search our archive between 2003 and the present for VIs that are listed on JPL's Sentry website, as well as current PHAs. This endeavor requires a significant amount of time for our internal code to run the VIs and PHAs through all our database. We then manually review the potential precoveries, to submit them to the MPC. Additionally, we search our recently acquired data on a nightly basis for objects posted on JPL's Scout[17] as these objects need the most rapid follow-up. This daily Scout NEOCP precovery search is performed once per night, near the end of the night by the current observer. This requires little effort from the observer, and only requires review and submission of data if a precovery was found. For the VIs and Scout NEOCP objects, we precover about 2 per year, while for the PHAs we precover about 10 per year. We also submit measurements of other objects that have been recently detected and that would increase the observed arc of their orbits.

6.3 Lightcurves

Our photometric lightcurves of asteroids, examples being [33, 34], are made on asteroids designated by the scientific community to help interpret radar observations and for other investigations that would benefit from knowledge of rotation periods and photometric amplitudes. Although not a main Spacewatch priority, we obtain about 5 lightcurves of NEOs per year. Our lightcurve work is supported by the Brinson Foundation.

6.4 Survey Collaboration

We have been collaborating with the Catalina Sky Survey (CSS) [35] and the University of Minnesota since 2019, working together as the Bok NEO Survey (MPC site code V00) during dark time to discover new NEOs and search for Earth Trojans with the 90Prime camera on the Steward Observatory Bok 2.3-m Telescope. We were allocated about 370 nights from 2019B through 2025A. All the data were reduced and analyzed, and astrometric measurements were submitted promptly to the MPC. From March 1, 2023 through February 28, 2025, the Bok NEO Survey observed 1517 different NEOs including discovering 476 new NEOs. New discoveries include

[16] Objects in older data that were not initially detected.

[17] JPL's SCOUT at https://cneos.jpl.nasa.gov/scout/#/

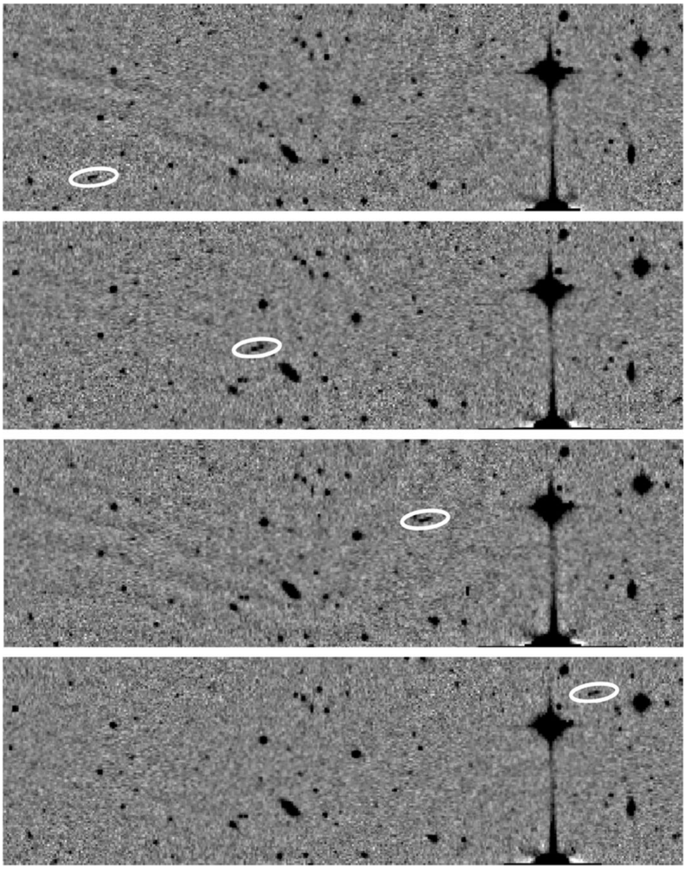

Fig. 6 Discovery images of the imminent impactor 2024 XA1 discovered by Vivian Carvajal of the Catalina Sky Survey on December 3, 2024 UT as part of the Bok NEO Survey collaboration, observatory code V00. Each sidereal exposure was 30-s. V00 uses the 90Prime camera with 2x2 binning and a pixel scale of 0.9065"/pix. A white oval surrounds the location of 2024 XA1 in each image

the imminent impactor 2024 XA1[18] (see Fig. 6 for the discovery images) which broke up in the atmosphere over Siberia and the hyperbolic comet C/2025 D1 (Gröller). Of top MPEC-ed Discoverers,[19] the Bok NEO Survey is currently fourth over the last year and over the last 5 years, and sixth since 1993.

[18] We did not attempt to observe 2024 XA1 with the 1.8-m or 0.9-m because we coordinate splitting up the follow-up magnitude ranges of the new discoveries between the Spacewatch and CSS telescopes with CSS observers handling the brighter targets.

[19] as of June 30th, 2025 at https://sbnmpc.astro.umd.edu/mpecwatch/index.html

7 The Future Value of Spacewatch

Because we have access to three telescopes (at two of which we are the sole users) and we are not constrained to observe using survey patterns or fixed queues, Spacewatch will be able to follow urgently flagged asteroids or comets discovered by the Vera C. Rubin Observatory with the Legacy Survey in Space and Time (LSST) [36] and the Near-Earth Object Surveyor Mission (NEOSM) [37]. LSST currently plans to collect pairs of observations on three separate nights within an interval of 15 to 30 days [38]. A collection of tracklets covering that length of time would usually have a secure enough orbit to qualify to be MPEC'd rather than being posted to the NEOCP. In addition, 15 to 30 days after initial discovery, the NEOs will likely be too faint for typical ground-based follow up.

NEOSM will be reporting a visual magnitude estimate with an uncertainty of ± 2 [39], which is too uncertain for much of the characterization that needs to be done by the planetary defense community. Obtaining the visual magnitude with a much smaller uncertainty is something we will be able to quickly and relatively easily provide for important targets as part of our follow-up observing. We have a long history regarding follow-up observations for the WISE and NEOWISE missions and have attended meetings regarding preparing for NEOSM operations. We plan on relying on NEOfixer more heavily during the NEOSM era when there may be many more targets. We will support NEOSM and continue astrometric observational follow-up of priority NEOs as long as it is valuable and feasible.

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Data Availability The data products of our research are the lines of astrometry submitted to the Minor Planet Center https://minorplanetcenter.net, which are freely and publicly available.

Declarations

Conflict of interest The authors declare no conflict of interest.

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Authors and Affiliations

Robert S. McMillan[1,2] · Melissa J. Brucker[1] · Cassandra Lejoly[1] · Jeffrey A. Larsen[1,3]

✉ Robert S. McMillan
rmcmilla@arizona.edu

Melissa J. Brucker
mbrucker@arizona.edu

Cassandra Lejoly
lejoly@arizona.edu

Jeffrey A. Larsen
larsen@usna.edu

1 Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

2 Steward Observatory, University of Arizona, Tucson, AZ 85721, USA

3 United States Naval Academy, Annapolis, MD 21402, USA