**NEO SURVEYS AND GROUND-BASED FOLLOW-UP:
A WHITE PAPER FOR THE 2023-2032 PLANETARY DECADAL SURVEY**

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1 Executive Summary

The white paper “The Future of Planetary Defense in the Era of Advanced Surveys” (Mainzer, et. al. 2020) discusses motivations and details of next-generation surveys for Near Earth Objects (NEOs). This companion paper’s goal is to discuss how NEO surveys and follow-up telescopes work together and how they will build on successful community collaborations into the future.

1. **More and larger telescopes investing time on solar system observations are required to respond to the accelerating NEO discovery rate.** The Vera Rubin Observatory (Legacy Survey of Space and Time, LSST) and the NEO Surveyor Mission (NEOSM) are in advanced planning and construction. Other telescopes will need to increase NEO observations or be constructed to fully capitalize on the new discoveries and data.
2. **Current and future surveys complement each other** in survey strategy, field of regard, and other figures of merit. Current facilities are sensitive to rapid close approachers to Earth while future surveys will search for more distant NEOs, moving more slowly.
3. **Infrared and optical observations are complementary.** Thermal IR data provide a measure of diameter, and of albedo when combined with optical data.
4. **A robust NEO community exists** (surveys, follow-up telescopes, archive and orbit computation centers) in the United States and internationally. However, the community must identify a sustainable path to grow and evolve to prepare for more extensive and larger aperture telescope support for next decade’s surveys.
5. **NEO follow-up time is sparsely distributed, and many telescopes used by the NEO community are overcommitted,** especially during dark and gray times of the lunar month. NEO discoveries have been accelerating for more than two decades¹, challenging follow-up facilities to keep up with NEO confirmations, arc extensions, and characterization. Discoveries from NEO surveys can be lost to insufficient follow-up (Vereš 2018).

NEOSM and LSST will increase by orders of magnitude the number of NEOs that can be targeted with small and medium aperture telescopes, thus increasing the observing load on current follow-up facilities. Current facilities can prioritize brighter targets but new dedicated large-aperture follow-up facilities and/or significant access to existing large-aperture telescopes will be required to complement the surveys’ self-follow-up plans.

The NASA Authorization Act of 2005, also known as the George E. Brown, Jr. Near-Earth Object Survey Act², established a Congressional mandate for NASA to “detect, track, catalogue, and characterize” 90% of NEOs ≥ 140 -m by 2020. Since 2014, surveys have discovered on average 500 discoveries per year in this size range. The estimated population of ≥ 140 -m NEOs is $\sim 25,000$, 63% of which remain undiscovered as of June 2020. To be confirmed, each discovery requires a sequence of observations, usually contributed by multiple telescopes. While NEOSM and LSST plan on self follow-up, there will always be a need for coordinated community astrometric follow-up of priority targets and corresponding characterization.

NEOSM and LSST, working together with current NEO surveys, should be able to reach the 90% discovery completion of ≥ 140 -m NEOs within in a decade after the new surveys begin. This will require an average $\sim 1,300$ discoveries per year in that size range. Efficient strategies will be required to find edge case NEOs (e.g., asteroids that approach Earth from the direction of the Sun or quadrature) instead of solely emphasizing those from opposition. A large network of interdependent telescopes and data centers will be needed to accomplish the 90% goal.

¹ In 2019, 2,436 NEOs were discovered, $>10\%$ of the catalog of 23,000 known NEOs beginning in 1898.

² <https://www.congress.gov/109/plaws/publ155/PLAW-109publ155.pdf>

2 Operating Multiple Surveys in Space and on the Ground

Near Earth Objects (NEOs) are asteroids and comets that approach closer than 1.3 au to the Sun. This population is of interest both for planetary defense and scientifically. It contains small, easily accessible bodies for study of monolith and rubble pile asteroids, binary asteroids, surface composition, the Yarkovsky Effect, and the evolution of the solar system, among other topics. Building, maintaining, and growing the NEO catalog to manage impact risks inherently provides targets for scientific study.

Figure 1 – Annual survey footprints, approx. to scale. Ground-based survey areas are ultimately limited by declination, while NEOSM will survey ± 42 degrees from the inclined ecliptic plane. The sky is divided into five areas, with northern NEO surveys covering the region near the north ecliptic pole (NEP), and LSST covering the south ecliptic pole (SEP) region.

2.1 Surveying the entire sky leads to more NEO discoveries

Figure 1 shows the NEO survey coverage³ anticipated by the middle of the next decade. The NEO Surveillance Mission (NEOSM), successor to NEOWISE, will survey the broad swath in between the red lines on either side of the ecliptic (though the mission is designed with the capability of surveying from pole to pole if needed; the latitude limits were chosen to maximize discovery of the most hazardous NEOs). Its infrared discoveries will be enriched by optical follow-up from the ground. LSST in Chile will survey south of the blue line, and optical discoveries will similarly benefit from infrared follow-up. The ongoing northern hemisphere surveys, Catalina Sky Survey (CSS, Larson, et al. 1998) in Arizona and Pan-STARRS (Hodapp et al. 2004) in Hawaii, with important contributions from others including ATLAS (Tonry, et al. 2018) in Hawaii and the Zwicky Transient Factory (ZTF) (Bellm et al. 2019) in California, survey north of the green line. Continuing current strategies, NEO community assets will observe the entire the sky from pole-to-pole before LSST and NEOSM are fully deployed. Most NEO surveys and major follow-up projects operate multiple telescopes to maximize discoveries and to secure orbits of known catalog objects. For example, ATLAS is commissioning two new 0.5-m very wide field telescopes in South Africa and Chile.

NEOSM and LSST will serve as excellent serendipitous follow-up engines in addition to their numerous anticipated solar system discoveries. This flexibility of survey and follow-up operations shared among an evolving network of observational assets has defined the planetary defense community since its earliest days. Different groups have different strategies tuned to be sensitive to different limiting magnitudes, rates of motion, and objects sizes. Objects sometimes pass

³ The main LSST survey will cover 18,000 sq. deg with 40-50 pairs per year, and the LSST North Ecliptic Spur (NES) is 7,000 sq. deg at 5-10 pairs/year. The NEOSM footprint will be 27,500 sq. deg at ~ 25 quads/year. As of 2020, the northern surveys are collectively covering 36,000 sq. deg with 50+ quads per year.

undiscovered through survey volumes, no matter how close the picket lines, and a united approach is not only the best way to tile the entire sky, it increases completeness significantly.

Satisfying the Congressional goal will require contributions from multiple surveys. Estimating survey completeness for NEOs is challenging because each survey has a different observing strategy. Completeness is estimated relative to a derived population (Granvik, et al. 2018). Different instrumentation, pipeline software, and strategies make each survey sensitive to different classes of targets. No single survey can be tuned to optimize discoveries of all types. In addition to these systematic effects, each survey’s point source limiting magnitude is only indirectly tied to the 50% limiting magnitude of moving object detections from multiple exposures. CSS, for example, detects 50% of known catalog objects with predicted magnitudes within a bin up to ~ 1.25 mags brighter than the detected background stars in V. Due to source confusion, detector gaps, image artifacts, etc., no magnitude bin for any survey reaches 100% completion against the catalog. Detection efficiency limits will also apply to LSST and NEOSM.

2.2 NEO discoveries benefit from coordinated operations

Because asteroids’ sky positions and magnitudes quickly change as they approach and recede from Earth, there is a limited time in which follow-up observations can be made. LSST has stated that it will engage in “self-follow-up” for solar system use cases. The necessary community follow-up will need to target fainter objects than currently targeting, requiring larger telescope apertures. Other surveys engage in self-follow-up on a more limited scale, whether in survey mode or targeted follow-up. LSST will differ in scale, magnitude range, and by linking candidate tracklets composed of observation pairs rather than linking tracklets composed of quads or triplets. NEOSM also employs a “self-follow-up” cadence, albeit with four detections (quads) within a survey set to maximize reliability (Mainzer et al. 2015). During the short duration of a NEO’s discovery epoch, overlapping and complementary observing capabilities are important to ensure ephemeris reliability and to extend the observational arc. The magnitudes in the set of observations may indicate the presence of a rotational light curve. There will always be cases in which follow-up astrometric observations are required to learn more about an object than what discovery images provide; e.g. to pinpoint impact corridors, and to reduce ephemeris uncertainties in order to get precise pointing for spectroscopic and radar observations.

The Minor Planet Center⁴ (MPC) of the International Astronomical Union is responsible for collecting, verifying, and disseminating astrometry, identifying objects, and determining orbits for NEOs as well as all other minor planets and irregular satellites. This includes operating the NEO “confirmation page” (NEOCP) as a real-time resource in support of community observing. NEOCP operations link verified observation tracklets of an object from all observers into orbital arcs. The instantaneous field of regard of the future surveys will only sometimes overlap each other, see Figure 2, but strictly contemporaneous follow-up observations are not required, and indeed building an orbital arc requires time to pass. For linkages between tracklets from NEOSM at the L-1 point and tracklets from the ground-based surveys in both hemispheres significant time will usually have to pass as NEOSM’s eastern field leads solar opposition by 1-3 months and the western field trails by a similar amount.

The sky-motions, elongations, and changing apparent brightness on relatively short timescales of NEOs make it challenging to implement a cohesive single community strategy for discovery and follow-up. As objects traverse the sky, some will travel north or south and become accessible

⁴ <https://www.minorplanetcenter.net>

to additional follow-up and survey telescopes. NEOs also change brightness by many magnitudes as they approach and recede from Earth during a single apparition. Some new NEOs will be discovered by LSST and become bright enough for northern surveys to extend their arcs. Some new NEOs will be identified by northern surveys before LSST multi-night linking creates a full track, simplifying the LSST detection process. For ground-based operations weather, the phase of the moon, and the density of star fields in the Milky Way will impact different telescopes at different times as to whether or not observations and linkages can be made.

Figure 2 – Approximate instantaneous fields of regard for LSST, NEOSM, and current northern surveys. Survey target pointings over short periods (hours) are selected from these fields, generally not overlapping. The NEOSM field of regard alternates between western and eastern regions about weekly, and nods north and south in declination seasonally. Targets for follow-up may cover all locations in the sky.

A myriad of pointing strategies are implemented to cover the variety of orbits that NEOs occupy. Not all NEOs pass through opposition, i.e., those in Earth-like orbits including Earth Trojans, Atens, some Apollos, and Atiras (also known as Interior Earth Objects). Thus, some surveys include low elongation observations. For ground-based telescopes, these obviously occur shortly after sunset or shortly before sunrise. Space-based NEOSM will not have those limitations. The NEOSM survey strategy embraces fields at small solar elongations and is anticipated to make numerous discoveries of non-opposition NEOs.

One additional challenge to contemporaneous infrared observations from NEOSM and optical observations from LSST or other ground-based surveys is the advent of “mega-constellations” of Low Earth Orbit artificial satellites. Detailed simulations show a disproportionate impact on ground-based astronomical observations made in the early evening or late morning hours, especially near the horizon. Techniques to dynamically shutter exposures or to reorder telescope queues are being investigated.

3 Telescopes and Telescope Networks for Astrometric Follow-up

Near-Earth asteroids (NEAs) are diverse in size, distance, and albedo. As they and Earth revolve in separate orbits, follow-up occurs at a wide range of solar elongations, declinations, phases of the moon, and sometimes against dense background star fields. When near Earth, they traverse the sky rapidly. Observations can be made sidereally or non-sidereally, tracking with the moving object. Each targeted observation must be tailored to the circumstances.

Detailed simulations of survey completeness by Mainzer et al. (2015), Grav et al. (2016), Jones et al. (2018), and Chesley and Vereš (2017) result in similar conclusions. It is generally agreed that for NEOs of absolute magnitudes $H \leq 23$ (a proxy for sizes ≥ 140 -m, Wright et al. 2016), that the “*completeness achieved by the entire system is significantly higher than what LSST alone can deliver*” and “*asteroids discovered by the LSST will add ~10 percentage points to what the system would have discovered*” (Jones et al. 2018). Statements like these should inform operational

requirements for the evolution of the network of telescopes and data centers. Surveys should be at least loosely coordinated to maximize both discoveries and arc length, based on the characteristics of the surveys and a model population. Such a plan will have both long-term and near-real-time operational implications.

To facilitate coordination and coverage, useful software systems are being implemented such as NEO alert brokers for new discoveries, and flexible queue scheduling for targeted and survey observations. The Target Observation Manager (TOM) framework of Las Cumbres Observatory (Street et al. 2018) addresses both of these functions for telescopes that can be relatively tightly networked as an effective member of LCO’s own network. But the NEO community is diverse, with hundreds of professional and amateur sites contributing astrometry each year. Telescopes that may never be connected to a network can still benefit from the NEOfixer⁵ broker currently being prototyped by Catalina Sky Survey as part of a broader LSST alert broker discussion. NEOfixer generates a single ranked score for every item in the entire catalog of NEOs and NEO candidates based on estimates of 1) each object’s importance, 2) the benefit to its orbit of making an observation from a particular telescope at a particular time, 3) the urgency of making the measurement before it becomes unobservable, and 4) the cost of the observation with the particular instrument and telescope. Targets’ priorities are adjusted as other telescopes schedule observations and submit astrometry.

3.1 Maintenance of the NEO catalog requires long-term monitoring

More than two-thirds of NEAs are single opposition objects whose ephemeris uncertainties can be larger than the field of view of many telescopes. Extending orbital arcs and confirming existence requires continuing observations, ideally from multiple telescopes to build confidence. Much of this catalog maintenance is accomplished by incidental observations during normal operations, with specifically targeted observations from follow-up telescopes for various classes of high priority objects. Queries against the MPC catalog⁶ compared to the modeled NEO population (Granvik, et al. 2018) show that currently operating surveys detect and extend the arcs for about the same number of known $H \leq 22$ NEOs as are discovered each year and about three times as many known $H \leq 20$ NEOs as are discovered.

Operationally, NEO surveys pursue two different types of quarry: large asteroids that pose large risks infrequently, and small asteroids that pose frequent small risks. While one telescope can discover all sizes of asteroid, it won’t discover them at the same distances. One implication is that small possible Earth impactors are generally discovered as they make their final approach and that the larger, more dangerous asteroids can be found many years in advance. Potentially Hazardous Asteroids (PHAs) are ≥ 140 -m NEOs that approach within 0.05 au of Earth’s orbit. During a recent two-year period, for the major NASA-funded NEO surveys in Arizona and Hawaii, about half of the accessible PHAs were detected by only a single survey observatory, demonstrating the value of operating overlapping surveys.

Another resource for long-term NEO monitoring are archived images. They can be searched for precoveries (NEOs not initially detected in images collected before the object was officially discovered). The number of images submitted to NASA archives is growing, extending sky coverage over more than a quarter of a century. Precovery efforts often provide critical NEO astrometry and characterization over extended temporal baselines (cf. Ye et al. 2020; Masiero et al. 2018).

⁵ <https://cpb-us-e1.wpmucdn.com/sites.northwestern.edu/dist/a/2770/files/2019/08/seaman.pdf>

⁶ https://www.minorplanetcenter.net/db_search

3.2 The value of follow-up with large-aperture telescopes

Astronomical surveys, including for NEOs, are a trade-off between how much of the sky can be covered (field-of-view) and how deeply (aperture). Survey operations will evaluate this trade-off differently than follow-up operations. In order to reach deeper, large aperture telescopes in both hemispheres are needed to follow-up and characterize faint discoveries from LSST and NEOSM. If such telescopes also have a medium to large field-of-view they will most efficiently tie down discoveries that might otherwise become ‘lost’ due to large ephemeris uncertainties resulting from short arcs. Historically, most NEO telescopes have been located in the northern hemisphere. In the south, LSST will contribute a larger aperture, effectively 6.4-m, with a slight increase in field-of-view relative to current surveys. The northern sky will be covered more frequently, and the southern sky will be covered deeper. Additional large aperture, moderate field-of-view NEO-optimized telescopes (large pixels to limit trailing losses, fast slew and readout) for both follow-up and survey would complement LSST and NEOSM (Kingsley et al. 2018). If one was added in the northern hemisphere, its incidental survey observations would provide optical measurements for NEOSM discoveries as well as increasing the overall survey coverage.

Together, **NEOSM and LSST may conservatively increase follow-up demand near $V=22$ by an order of magnitude.** The bright tail of the discoveries from the advanced surveys will rival and likely dominate the operating regime of targets generated by the currently operating surveys. Deeper follow-up (larger aperture telescopes) will certainly be needed closer to the operating range (larger numbers of discoveries and fainter magnitudes) of LSST and NEOSM, but the current portfolio of small to medium aperture follow-up facilities will also see a dramatic increase in available targets.

Follow-up observations tend to occur in a sequence of steps. Candidate NEO discoveries first require follow-up observations to be confirmed both as real objects and as having perihelion distances that make them NEOs. Then, observations to improve astrometry and lengthen arcs support the improvement of the NEO orbital catalog. In turn, this reduces ephemeris uncertainties enough for precision radar targeting, light curves, and spectroscopy. Spectra can constrain taxonomic classification and surface mineralogy and help make associations between asteroids and well-studied meteorites. Extremely accurate ephemerides also allow study of other science use cases such as the detection and characterization of the Yarkovsky and YORP Effects.

Follow-up observations often require larger telescopes than were used to discover an object in the first place. NEAs generally fade after discovery. Currently, they become an average of 0.75 magnitudes fainter before they are even confirmed as actual NEOs. Further, NEAs tend to be discovered during atypically bright orbital configurations and thus return in future apparitions with fainter magnitudes. Between apparitions, the uncertainty of position for NEOs can grow large without sufficient follow-up observations. They can become “lost”, likelier for blind survey recovery than targeted recovery (Milani et al. 1999). For example, it was difficult to recover the virtual impactor 2012 TC4 because it had insufficient follow-up during its discovery apparition (Reddy et al. 2019). The use of large aperture follow-up before the end of the discovery apparition would permit observations at significantly fainter magnitudes and significantly extended orbital arcs, thus a later recovery campaign will hopefully not be needed (Galache et al. 2015). For small close approachers, large-aperture telescopes would enable observations after the departing asteroids have passed beyond Earth's Hill sphere and Earth's gravity is no longer torquing their orbits, again aiding in future recovery efforts for objects known to have very small Minimum Orbit

Intersection Distances (MOIDs) with the Earth. (Dozens of NEOs are known to have passed within the Earth's Geosynchronous satellite belt.)

4 Conclusion

NEO follow-up telescopes for both astrometry and characterization have had to keep pace with the year-after-year growth of the NEO surveys over the past couple of decades. Indeed, even 8-m class telescopes (and Hubble in space) have been called upon for occasional observations of high priority targets like the interstellar object 'Oumuamua. The faint end of workhorse NEO follow-up occurs in the 2 to 4-meter class facilities like Spacewatch (McMillan, et al. 2007), Magdalena Ridge Observatory, McDonald Observatory, and various telescopes on Maunakea. A few 1.0 to 1.5-meter facilities also work past 22nd magnitude, including telescopes of the Astronomical Research Institute and Catalina Sky Survey. Our community proposes regularly for access to larger competitively scheduled facilities in both hemispheres, but time allocations can amount to hours per semester making these a precious commodity. The highly trained solar system observers of **these facilities could already make good use of access to additional larger aperture telescopes.** This will become a critical need when LSST and NEOSM begin relentlessly supplying NEO and other solar system targets. The heightened demand will extend from V-band equivalence significantly below magnitude 22 to well above magnitude 25.

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