

NASA's NEAR-EARTH OBJECT (NEO) OBSERVATIONS PROGRAM: ABBREVIATED HISTORY & UPDATE

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ABSTRACT

In the wake of Comet Shoemaker-Levy 9's (D/1993 F2) collision with Jupiter, NASA's Near-Earth Object (NEO) Observations Program was established more than two decades ago. The NEO Observations Program is responsible for finding, tracking, and characterizing NEOs.¹ Since the Program's inception in 1998, NASA-funded efforts have discovered more than 98% of the more than 30,000 NEOs currently known.

This unique NASA Program supports several NEO surveys that contribute to a sustained and productive campaign to find and track NEOs; collecting data of sufficient precision to allow accurate predictions of the future trajectories of discovered objects. It is a key element of the Planetary Defense Coordination Office (PDCO). The Program also sponsors applied planetary science research conducted at NASA field centers, astronomical observatories, and other locations around the United States.

The PDCO relies on data from projects supported by the NEO Observations Program which, in turn, also coordinates NEO observation efforts conducted at ground-based observatories sponsored by the National Science Foundation (NSF) and the space domain awareness facilities of the United States Space Force (USSF). PDCO's current priority is the NEO Surveyor², launched away from the vicinity of Earth to SEL₁ and working in coordination with large ground-based surveys could complete the NEO survey within a decade following launch. NEOSM's has three primary mission objectives:

- assess the current risk to the Earth of asteroid impact(s);
- examine the origin and ultimate fate of the asteroid population (within our solar system);

- to find suitable, low- Δv targets for future robotic and piloted missions of exploration

Operating at SEL₁, NEO Surveyor will also find NEOs with long synodic periods (i.e., several decades or longer) and unfavorable orbital viewing geometries. The NEO Surveyor will obviate the inherent Earth-based geometric observing handicap.

1 EARLY ASTEROID SURVEYS

While 433 Eros is the first Earth-approaching asteroid (or 'NEO') to be found, the first recognized Earth-crossing asteroid was 1862 Apollo, photographically discovered in 1932 and then effectively 'lost.' 1862 Apollo was recovered in 1973. Further follow-up photometric and radar observations (Đurech *et al.*, 2008 [1]; Ostro *et al.*, 2005[2]) of this asteroid provided the first observational evidence of the Yarkovsky and YORP effects. By the early 1980s photographic survey techniques were, at first, complemented with electronic charged coupled device (CCD) methods. Beginning in the early-1970s a few asteroid survey programs began with the Planet-Crossing Asteroid Survey (PCAS), which utilized the 0.46-m Schmidt telescope on Mt. Palomar (Helin and Shoemaker, 1979 [3]); a second survey program started in 1982 (Shoemaker *et al.*, 1990 [4]) which used the same 0.46-m Schmidt and called the Palomar Asteroid and Comet Survey (PACS); and the Anglo-Australian Near-Earth Asteroid Survey (AANEAS) which operated from 1990 to 1996 utilizing the 1.2-m United Kingdom Schmidt Telescope (UKST) at the Siding Spring Observatory near Coonabarabran, Australia (Steel *et al.*, 1998 [5]). These facilities primarily centered their observing ('surveying') efforts during opposition [on Moonless nights]. In time, photographic techniques would be supplanted by electronic means (i.e., CCDs, automated scanning and pointing, etc.). In some ways, the Near-Earth Asteroid Tracking (NEAT)³ program was representative of the transition from photography to

¹ near-Earth objects (NEOs) include asteroids and comets whose orbits periodically bring them within 1.3 AU of the Sun (or, ~50 million km of Earth's orbit).

² NEOSM was formerly known as NEOCam. While NASA did not select NEOCam in the 2015 Discovery AO, PDCO is directing NEOSM. The mission itself is a single scientific instrument: a cryogenic, 50-cm

diameter telescope optimized in the near-infrared (in two bands: 3–5 μm and 6–10 μm), with a FOV of 11.56° and placed at Sun-Earth Lagrange 1 (SEL₁).

³ NASA, along with the U.S. Air Force, operated NEAT from 1995 to 2007. NEAT utilized the 1-meter GEODSS telescope on Haleakala on Maui, Hawaii.

electronic sensors for NEO survey efforts; however, Spacewatch at the University of Arizona pioneered CCD scanning techniques earlier in the 1980s.

Spacewatch began in 1980 under the leadership of Tom Gehrels (1991 [6]) and Robert McMillan (2009 [7]). Spacewatch's origins, using CCD scanning, was not originally intended for NEOs; rather, it was for a rapid statistical study of comets and asteroids throughout the solar system (Gehrels, 1991 [6]). Spacewatch continues to contribute to the NEO survey effort today and is no longer the only professional electronic discovery program.

2 ESTABLISHMENT OF NASA'S NEO OBSERVATIONS PROGRAM

At the request of the U.S. Congress in the early 1990s, NASA conducted a preliminary study to define a program in order to dramatically increase the detection rate of NEOs. As a result, NASA proposed that an 'International Spaceguard Survey'⁴ be established to detect and perform follow-up observations of the most hazardous NEOs for the foreseeable future. The NASA report called for six 2.5-meter class wide-field telescopes located at existing facilities. The costs were anticipated to be ~\$50 million for the hardware [in 1990 U.S. dollars] with an additional ~\$10 to \$15 million/year in operations support. While the Spaceguard Survey as envisaged within the NASA report did not materialize, other dedicated NEO surveys later that decade emerged (i.e., LINEAR, Catalina Sky Survey, Pan-STARRS, ATLAS, etc.).

The impact of Comet P/Shoemaker-Levy 9 (D/1993 F2) in July 1994 into Jupiter⁵ provided significant impetus that eventually led to NASA's initial formulation of the NEO Observations Program. The U.S. Congress established two directives [for NASA] in the search for NEOs. The first, the so-called Spaceguard Survey was in 1998 and directed NASA to discovered 90% of all NEOs with a diameter of 1 kilometer and larger within 10 years. An object this size, if it were to strike the Earth, would have global catastrophic consequences. That goal of finding 90% of large NEOs was achieved at the end of 2010. The original 1998 NASA NEO Observations Program did not have the resources to build a network of telescopes optimized to detect NEOs, so existing, but little-used telescopes were modified for this task. Since 1998, fifteen different ground-based telescopes have been surveying the sky for various durations. Most were

older telescopes requiring refurbishing and upgrades to be effective for this purpose.

The second Congressional directive, set in the NASA Authorization Act of 2005, provided more detailed direction for NASA to plan, develop, and implement an NEO survey program to detect, track, catalogue, and characterize the physical characteristics of NEOs equal to or greater than 140 meters in diameter in order to assess the threat of such bodies to the Earth. The [then-] newly updated objective of the NEO Observation Program is to discover 90% and more of all NEOs larger than 140 meters in size by 2020.

3 LOWELL OBSERVATORY NEAR-EARTH OBJECT SEARCH (LONEOS)

Originally begun in 1993, the LONEOS system utilized a 0.6-m f/1.8 Schmidt telescope in Flagstaff, Arizona to survey asteroids and comets. The telescope was acquired from Ohio Wesleyan University in 1990. Two years later, NASA funding enabled the team to equip the focal plane with 4K x 4K CCD detector to cover a field of view of 2.9° x 2.9°, the telescope is designed to make four scans per region over the entire visible sky each month down to a limiting visual magnitude (V_{lim}) of ~19. LONEOS finally saw first light in 1998 (Bowell *et al.*, 2012 [8]). A regular observing cadence was developed to avoid the Full Moon and the typical standard exposure was 45 seconds. The LONEOS program concluded in late-February 2008.

4 LINCOLN NEAR-EARTH ASTEROID RESEARCH (LINEAR)

From 1998 to 2013, the Massachusetts Institute of Technology (MIT) Lincoln Laboratory operated two 1-meter telescopes located at the Experimental Test Site (ETS) in Socorro, New Mexico. In 2014, the Lincoln Near-Earth Asteroid Research (LINEAR) survey transitioned from these smaller 1-m telescopes to the 3.5-m Space Surveillance Telescope (SST) which was then located at Atom Site on the White Sands Missile Range (Stokes *et al.*, 1998 [9]; Ruprecht *et al.*, 2014 [10]).

The SST was developed by MIT Lincoln Laboratory for the Defense Advanced Research Projects Agency (DARPA) to detect and track satellites and orbital debris in geosynchronous orbit. The initial asteroid search efforts with the SST were modeled after the legacy 1-

⁴ Since the publication of NASA's report in 1992, the term 'Spaceguard' has come to loosely refer to all of the efforts to detect and characterize NEOs. Spaceguard was first coined in 1972 by Arthur C. Clarke in his science fiction novel *Rendezvous with Rama*.

⁵ The impact of Comet Shoemaker-Levy 9 into Jupiter perhaps created a greater perception for the importance of detecting NEOs. Since that

series of impacts, 10 more asteroid-like bodies have been observed to collide with Jupiter (as well as a likely fireball observed during the *Voyager 1* flyby on 5 March 1979). It is due to the gravitational influence primarily of Jupiter and Mars that lead to collisions in the inner part of the Main Belt. This process is the reservoir for these bodies that dynamically evolve into NEOs..

meter strategy.⁶ In 2014, LINEAR had 4 to 6 nights per month dedicated to asteroid search operations with SST. The following year, in 2015, SST allocation increased to ~8 nights per month for the asteroid search (Ruprecht *et al.*, 2015 [11]).

In October 2016, DARPA formally transferred the operations of the SST to the U.S. Air Force Space Command. The SST is currently being disassembled and will be shipped to the Holt Naval Communication Station in Western Australia and be reassembled. The SST [re]achieved initial operational capability in 2022; providing southern hemisphere coverage of the sky. LINEAR is currently processing asteroid data. SST is expected to achieve final operational capability next year.

5 CATALINA SKY SURVEY (CSS)

Located in the Catalina Mountains, northeast of Tucson, Arizona, the Catalina Sky Survey (CSS) began operations in April 1998 and currently consists of three telescopes: 0.7-meter Schmidt ($f/1.8$); the 1.5-meter reflector ($f/2.0$) Mt. Lemmon narrow-field survey telescope; and the 1-meter ($f/2.6$) narrow-field Cassegrain telescope for follow-up. The CSS is dedicated to addressing the NEO survey, observing 24 nights per lunation (Christiansen *et al.*, 2014 [12]).

The 0.7-m Schmidt has an 8.2 square degree field-of-view (FOV), can cover the entire sky (with a bias towards the ecliptic) and limiting visual magnitude (V_{lim}) of ~19.7. The 1.5-m reflector has a 1.2 square degree FOV; surveys $\pm 5^\circ$ from the ecliptic with a bias towards opposition and V_{lim} of ~21.3.

As important as the telescopes are for initial detection and discovery, follow-up is key; in fact, it is an integral part

of discovery. Dedicated follow-up assets exist throughout the world and even for V_{lim} of ~20, amateurs often assist in this effort. In late-2014, a 1-meter reflector ($f/2.6$) was incorporated into the CSS for follow-up. This 1-meter is operated remotely and can conduct same night (and subsequent night(s)) follow-up of NEO discoveries from the CSS and other surveys such as Pan-STARRS as well as arc extensions of important newly-designated and returning NEOs.

6 PANORAMIC SURVEY TELESCOPE & RAPID RESPONSE SYSTEM (Pan-STARRS)

The two Pan-STARRS telescopes have a 1.8-m ($f/4.4$) aperture Ritchey–Chrétien design, both located atop Haleakalā on Maui, Hawaii. Equipped with a gigapixel camera, it has a 7° FOV, and a V_{lim} of ~24 (Wainscoat *et al.*, 2014 [13]; 2016 [14]).

The first of these telescopes, Pan-STARRS1 (PS1) became operational in 2010. From 2010 until March 2014, PS1 performed a general purpose, multi-color survey of the sky north of -30° declination and included observations related to brown dwarfs, Milky Way, supernovae, other transient phenomenon, and cosmology. In April 2014, Pan-STARRS began to use 100% of its observing time searching for NEOs.

Pan-STARRS executes four (4) 45-s exposures separated by 20 min in the opposition direction or 7-minute exposures in the low solar elongation ‘sweet spot’ directions. As with the discoveries from other surveys, the NEO candidates that Pan-STARRS finds are submitted to the Minor Planet Center (MPC). However, Pan-STARRS generally does not perform its own follow-up and is largely dependent on other surveys and efforts to verify the discoveries.

⁶ This strategy focused on a wide-area search of sky covering nearly 9000 square degrees during each lunation; divided into two different search areas. The cadence allowed each region to be revisited five times each night with 15 min between revisits. Simulations were

performed modelling SST performance using this legacy LINEAR observing strategy against a simulated population of large (> 140 m) NEAs and simulation results were used to select a 2-s integration time for SST in asteroid search mode

7 ASTEROID TERRESTRIAL-IMPACT LAST ALERT SYSTEM (ATLAS)

NASA has funded the development of the ATLAS system. It currently comprises four 0.5-meter telescopes, and developed and operated by the University of Hawaii Institute for Astronomy (IfA). The two sites in Hawaii are on Haleakalā and Mauna Loa (beginning operations in 2014 and 2017, respectively). The other two ATLAS telescopes became operational in 2022; are located in the Southern Hemisphere: at the South African Astronomical Observatory (SAAO) near Sutherland and the other at El Sauce Observatory near Rio Hurtado, Chile. ATLAS automatically scans the sky several times every night. Its rapid cadence (~ 1 hour between visits) can capture asteroids relatively close to the Earth. ATLAS complements the surveys described above.

ATLAS couples a 0.5-m ($f/2$ Wright-Schmidt system) aperture with a 110-megapixel CCD camera. The field of view is 7.4° ; exposure times are 30 seconds (plus 5 seconds of readout) and can reach V_{lim} of 20 (Tonry, 2011 [15]).

8 WISE & NEOWISE

The Wide-field Infrared Survey Explorer (WISE) was launched into a Sun-synchronous orbit about the Earth on 14 December 2009. Optimized as an astrophysics survey, during its prime mission, WISE surveyed the entire sky in four infrared wavelengths: 3.4, 4.6, 12 and 22 μm . It operated in this mode through September 2010 (when its frozen hydrogen cryogen was depleted). The spacecraft was then placed into hibernation in February 2011. Its aperture is 40-cm, with a FOV of 47 arc-minutes.

The solar system science portion of the mission at the time was known as NEOWISE. During the prime mission, the NEOWISE project identified ~ 700 NEOs - of which 135 were new discoveries; and 160 comets - of which 21 were new discoveries (Mainzer *et al.*, 2014 [16, 17]).

NEOWISE was brought out of hibernation in late-2013, resuming its search for minor planets on 23 December 2013 and currently surveys the sky in 'warm' mode at 3.4 and 4.6 μm . As an infrared survey, NEOWISE detects asteroids based on their thermal emission and is equally sensitive to high- and low-albedo objects; consequently, NEOWISE-discovered NEOs tend to be large and dark. The spacecraft is expected to continue its mission to discover and characterize NEOs and Main Belt asteroids well into 2023.

9 NASA INFRARED TELESCOPE FACILITY (IRTF)

The IRTF is a 3.0-meter infrared telescope located at an altitude of $\sim 13,600$ feet (~ 4125 meters), near the summit of Mauna Kea on the island of Hawaii. Near the time of

the *Voyager 1* and 2 encounters with Jupiter in 1979, the IRTF was established to obtain infrared (IR) observations of interest to NASA; namely, to support a variety of planetary exploration missions. Designed for maximum performance in the infrared portion of the spectrum, it takes advantage of the high transmission, excellent seeing, minimal water vapor, and low thermal background that characterize the atmosphere above Mauna Kea. Approximately 50% of available time is dedicated to mission support and planetary observations. The remaining observing time is assigned to non-solar system science.

The IRTF has flexible set of facility instruments that are of great utility for planetary science observing programs. Generally, the instrument of choice for NEO efforts is the SpeX instrument. SpeX is a medium-resolution near-IR spectrograph and imager covering the 0.8–5.3 μm wavelength range. In its higher-resolution cross-dispersed mode, SpeX is used in studies of planetary atmospheres and comets. SpeX also provides a low-resolution prism mode ($R \sim 100$) that can record the wavelength range from 0.8 to 2.5 μm as a single spectrum, ideal for compositional studies of NEOs, main-belt and Trojan asteroids, and the brightest Centaurs and KBOs. SpeX provides a unique combination of capabilities not equaled anywhere. The high observing efficiency of SpeX makes the IRTF competitive with 8- to 10-m class telescopes in terms of clock time to achieve a given signal-to-noise and wavelength coverage.

10 PLANETARY RADAR

The rapid development of radar during the Second World War led to other uses of the [then, ‘new’] technology to better comprehend our solar system by detecting radar echoes from planets as well as small celestial bodies. As applied to planetary astronomy, it is an observing technique that reflects microwaves off of the target body (i.e., large planetary bodies such as Mercury, Venus, Mars, the Moon – as well as asteroids) and then analyzes/deconvolves those reflections. The strength of the radar return signal is proportional to the inverse fourth power (i.e., $1/r^4$) of the distance to the body. It is a powerful tool to better understand the basic physical properties of small bodies (e.g., shape, morphology, near-surface bulk density, spin state, etc.). Additionally, delay-Doppler measurements can precisely determine the orbits of asteroids and comets, dramatically reducing the ephemerical uncertainty compared to only the optical observations (Banner *et al.*, 2015 [18]).

The two primary radar facilities utilized for planetary radar observations have been the Goldstone Solar System Radar (GSSR) and the Arecibo Observatory. Currently, the GSSR is currently the only operating planetary radar facility. Following two cable breaks (in August and November 2020) and the remaining support cable failures on 1 December 2020, the support structure, antenna, etc. collapsed into the primary dish, effectively destroying the telescope. The National Science Foundation (NSF) and NASA have recently commenced a feasibility study to examine a logical successor facility to Arecibo.

The Green Bank Telescope (GBT) has occasionally been utilized to observe asteroids but, cannot transmit. The GSSR can operate in two different modes. In monostatic mode, the GSSR both transmits and receives the reflected signal. In bistatic mode, GSSR transmits and while GBT receives. This, in turn, utilizes interferometry to extract more details from the returned signal. The measurements of the distribution of echo power in time delay (range) and Doppler frequency (radial velocity), especially if used in bistatic mode between two radar sites, can provide spatial resolution better than 4 meters, depending on the strength of the radar echo.

11 ESTABLISHING PDCO

In January 2016, NASA formally established the Planetary Defense Coordination Office (PDCO). It is managed in the Planetary Science Division of the Science Mission Directorate at NASA Headquarters in Washington, D.C.

The PDCO is responsible for:

- Ensuring the early detection of potentially hazardous objects (PHOs) - asteroids and comets whose orbits are predicted to bring

them within 0.05 AU of Earth's orbit; and of a size large enough to reach Earth's surface - that is, greater than approximately 30–50 meters;

- Tracking and characterizing PHOs and issuing warnings about potential impacts;
- Providing timely and accurate communications about PHOs; and
- Leading the coordination of U.S. Government planning for response to an actual impact threat.

The PDCO relies on data from projects supported by NASA's Near-Earth Object Observations Program which coordinates NEO observation efforts conducted at ground-based observatories sponsored by the National Science Foundation (NSF) and space situational awareness facilities of the United States Space Force (USSF). In addition to finding, tracking, and characterizing PHOs, NASA's planetary defense goals include developing techniques for deflecting or redirecting PHOs, if possible, that are determined to be on an impact course with Earth. In the event that deflection or redirection is not possible, the PDCO is responsible for providing expert input to the Federal Emergency Management Agency (FEMA) for emergency response operations should a PHO be on a trajectory that actually impacts the Earth.

12 NEO SURVEYOR MISSION

The Near-Earth Object Surveyor mission, formerly known as NEOCam, has transitioned from a science-driven concept to a planetary defense driven mission. It is designed to discover and characterize most of the potentially hazardous asteroids that are near the Earth. The NEO Surveyor consists of an infrared telescope and a wide-field camera operating at thermal infrared wavelengths. It is currently in Phase C, slated for launch in 2027. NEO Surveyor has three (3) primary objectives:

- assess the current risk to the Earth of an NEO impact;
- examine the origin and ultimate fate of the asteroid population; and,
- find suitable, low- Δv targets for future robotic and human exploration

PDCO is directing the development efforts. The mission itself is a single scientific instrument: a cryogenic, 50-cm diameter telescope optimized in the near-infrared (in two bands: 3–5 μm and 6–10 μm), with a FOV of 11.56° and placed at Sun-Earth Lagrange 1 - SEL₁ (Mainzer *et al.*, 2014)

After more than two decades of continuing the NEO survey, roughly more than 60% of the 140 meters and larger population NEO population remains undiscovered.

NEO Surveyor is specifically designed to discover more than 90% of that NEA population within a decade if coupled with large ground-based assets similar to the capability of the Rubin Large Synoptic Survey Telescope (LSST).

13 CONCLUSION

While there is currently no known object on a collision course with the Earth, the key to understanding the impact hazard and the overall NEO population is to complete the NEO survey first. NEO Surveyor has undergone a transition from being a science-driven mission to a **planetary defense**-driven mission. The essential key and first step in planetary defense is to complete the survey. Away from the vicinity of the Earth at SEL₁ and working in coordination with large ground-based surveys, that survey (for objects down to ~140m in size) could be completed within a decade after launching NEO Surveyor. Due to the long synodic periods (several decades or longer) and unfavorable orbital geometries of some NEOs, ground-based assets alone have great difficulty overcoming their inherent geometric observing handicap of being located on Earth's surface.

There are other side benefits to planetary defense and completing the survey. Low Δv targets will be discovered and completing a catalog of candidate NEOs could then be transformed into a matrix of opportunities for robotic and even piloted missions for the next several decades. This matrix would include critical mission parameters (e.g., required Δv , mission durations, departure opportunities, etc.) and shared with the international community. This matrix would not necessarily drive architectures or schedules, but would illustrate windows of opportunity that could be exploited by the respective space agencies based on their respective capabilities and budgets. The overall return to the NEO community in terms of planetary defense mitigation missions, science, flight techniques, *in situ* resource utilization, and technology/instrument demonstration would be increased by this collaboration more than the contribution of any single agency and could pave the way for a true spacefaring civilization.

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