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Introduction: The population of near-Earth asteroids (NEAs) that may be accessible for human space flight missions is defined by the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS). The NHATS is an automated system designed to monitor the accessibility of, and particular mission opportunities offered by, the NEA population. This is analogous to systems that automatically monitor the impact risk posed to Earth by the NEA population. The NHATS system identifies NEAs that are potentially accessible for future round-trip human space flight missions and provides rapid notification to asteroid observers so that crucial follow-up observations can be obtained following discovery of accessible NEAs. The NHATS was developed in 2010 [1, 2] and was automated by early 2012. NHATS data are provided via an interactive web-site[1], and daily NHATS notification emails are transmitted to a mailing list[2]; both resources are available to the public.

Automation of the NHATS processing was motivated by the fact that NEAs are often discovered when they are near the Earth, and they may only be detectable for several days or weeks surrounding their discovery epochs because of their faintness in the night sky and tendency to depart Earth's vicinity relatively quickly after approaching the Earth. The brief window of time surrounding discovery is, therefore, a crucial time during which to obtain follow-up observations that provide information about a NEA's physical characteristics and improve our estimates of its orbit. Accurate physical characterization data and orbit ephemerides are both prerequisites for deploying missions to NEAs, and so it is important to collect observations during the window of opportunity surrounding NEA discovery. The automated NHATS system supports those efforts by rapidly identifying particularly accessible NEAs and notifying observers. [3]

NHATS Criteria: A NEA is classified as NHATS-compliant if there exists at least one round-trip trajectory solution to the NEA that satisfies NHATS trajectory analysis constraints. These constraints are: The total propulsive change in velocity (Δv) required for the round-trip mission must be $\leq$12 km/s; the Earth departure C_3 energy must be $\leq$60 km^2/s^2; the total round-trip mission duration must be$\leq$450 days; the stay time at the NEA must be $\geq$8 days; the atmospheric entry speed at Earth return must be $\leq$12 km/s; and Earth departure must occur sometime during the years 2015 through 2040. The total mission Δv is the sum of the following Δv maneuvers: (1) Departure from a circular 400 km altitude Low Earth Orbit (LEO), (2) NEA arrival (matching NEA's heliocentric velocity at the time of arrival), (3) NEA departure, and (4) reduction of Earth atmospheric entry speed if necessary (some trajectories will naturally have Earth atmospheric entry speed $\leq$12 km/s). The total round-trip mission duration is the sum of: (1) the time of flight required to reach the NEA from Earth, (2) the stay time at the NEA, and (3) the time of flight required to return to Earth from the NEA. The trajectories to/from the NEAs are computed by solving Lambert's problem with precise ephemeris files for the Earth and NEAs obtained from the JPL HORIZONS system. The Lambert trajectory solutions omit mid-course maneuvers and gravity assists, but those trajectory design techniques are unlikely to be useful when total round-trip mission duration is limited to no more than 450 days. Additionally, the Lambert solutions have been found to be quite accurate when compared to precision trajectory solutions obtained via differential corrections and high-fidelity force models for the spacecraft.

Summary of Current Results: As of April 1st, 2015 the number of known NEAs is 12,380, and the current rate of NEA discovery is approximately 1,000–1,500 per year. Over the past four and a half years, the rate of NHATS-compliant NEA discoveries has exceeded the overall NEA discovery rate. When NHATS assessments began in September of 2010, just over 7,000 NEAs were known and 666 of those were identified as NHATS-compliant. Today the number of known NEAs is just over 12,000—an increase of about 70%. The percentage increase in the number of accessible asteroids in the catalog has been even greater: On January 18, 2015—a little over four years since the NHATS assessments began—the 1332nd NHATS-compliant NEA was identified, doubling the number of known accessi-

[1]http://neo.jpl.nasa.gov/nhats/
[2]https://lists.nasa.gov/mailman/listinfo/nhats

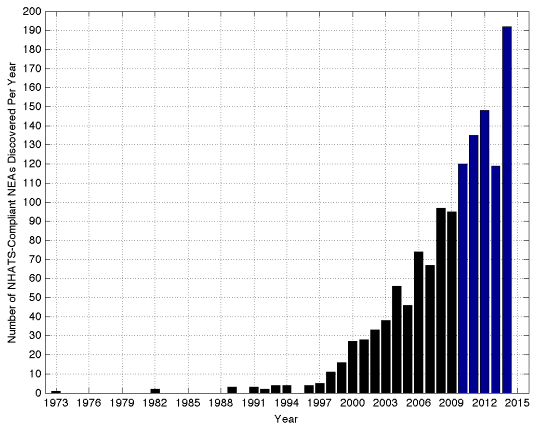

Figure 1: The number of accessible (NHATS-compliant) NEAs discovered each year since the first one (Anteros) was discovered in 1973.

ble NEAs since September 2010[3]. Figure 1 shows the number of accessible (NHATS-compliant) NEAs discovered each year since the first one (Anteros) was discovered in 1973. Until the NHATS system was established in 2010, we did not have a good measure of just how accessible some NEAs could be. The discoveries tabulated in black in Figure 1 represent those NEAs that were recognized as accessible when the system started up in 2010. The discoveries shown in blue are of the NEAs that were recognized as accessible as soon as they were discovered, due to the automated NHATS monitoring.

The majority of the currently known NHATS-compliant NEAs (60%) are Apollos, yet only 12% of the currently known Apollos are NHATS-compliant. Furthermore, 33% of Atens are NHATS-compliant, yet Atens are currently a minority among NEAs at ∼8% of the known NEA population. This phenomenon and may lead to an improved understanding of where the most accessible NEAs tend to reside in orbital element space [4]. While the NHATS-compliant NEAs have more Earth-like orbits than other NEAs, as expected, the extent to which NHATS-compliant NEA orbits can deviate from being Earth-like is notable. Table 1 summarizes the uncorrelated minimum, mean, and maximum values for NHATS-compliant NEA orbit semi-major axes, eccentricities, and inclinations.

The mean value of absolute magnitude, H, is 21.823 for all NEAs and 24.796 for NHATS-compliant NEAs. Thus, the NHATS-compliant NEAs tend to be less intrinsically bright (in the visible spectrum) than the overall NEA population. If the NHATS-compliant NEAs

[3]http://neo.jpl.nasa.gov/news/news189.html

Table 1: Uncorrelated statistics for NHATS-compliant NEA orbital elements.

Orbital Element	Min.	Mean	Max.
a (AU)	0.764	1.163	1.819
e	0.012	0.224	0.447
i	0.021°	5.180°	16.253°

have a distribution of geometric albedo similar to that of the overall NEA population, then the aforementioned statistics for H imply that NHATS-compliant NEAs tend to be physically smaller, on average, than other NEAs. For reference, with a geometric albedo of 0.14 (considered representative for the average NEA), H of 21.823 corresponds to a diameter of 153 m and H of 24.796 corresponds to a diameter of 39 m. However, our ability to draw conclusions about the characteristics of the total NHATS-compliant NEA population (including objects not yet discovered) from the currently available data is limited because the data are likely influenced by observational bias; accessible NEAs will tend to closely approach Earth, and smaller (less bright) NEAs are often only detectable when near Earth.

The tendency of NHATS-compliant NEAs to closely approach Earth is further illustrated by comparing the NHATS-compliant NEAs to the Potentially Hazardous Asteroids (PHAs). A NEA is classified as a PHA if its Minimum Orbit Intersection Distance (MOID) with Earth's orbit is $\leq$0.05 AU and its H is $\leq$22. 1034 NHATS-compliant NEAs (83%) have Earth MOID $\leq$0.05 AU and comprise 21% of all NEAs with Earth MOID $\leq$0.05 AU. However, only 178 NHATS-compliant NEAs (14%) have H $\leq$22. The number of NHATS-compliant NEAs that are classified as PHAs (both Earth MOID $\leq$0.05 AU and H $\leq$22) is 115. Thus, only 9% of the currently known NHATS-compliant NEAs are also classified as PHAs, but this is largely because of their H values rather than their Earth MOID values.

Accessibility Considerations: The NHATS criteria are defined such that any NHATS-compliant NEA is more dynamically accessible than Mars (and, therefore, the martian moons Phobos and Deimos)[4]. No possible Mars mission opportunity of any kind can be performed for both round-trip Δv $\leq$12 km/s *and* round-trip duration $\leq$450 days. Furthermore, the most aggressive Mars mission options are only sparsely available during particular Earth departure years and entail close approaches to the Sun (Venus orbit distance or less). Thus, all 1382

[4]http://www.lpi.usra.edu/sbag/science/NHATS_Accessible_NEAs_Summary.png

(and counting) NHATS-compliant NEAs are more astrodynamically accessible than is Mars or its moons.

Round-trip missions to a low altitude circular lunar orbit or the lunar surface require a total mission Δv of $\sim$5 or $\sim$9 km/s, respectively, and one to several weeks of mission duration. Some of the NHATS mission solutions have durations that approach lunar mission duration, and a substantial number of NHATS mission solutions require less Δv than a lunar mission. Specifically, 580 NHATS-compliant NEAs can be visited round-trip for less total Δv than a round-trip mission to the lunar surface, and 49 NHATS-compliant NEAs can be visited round-trip for less total Δv than a round-trip mission to a low altitude circular lunar orbit.

Candidate NEAs for NASA's proposed Asteroid Redirect Mission (ARM), which seeks to capture a boulder from a NEA and place it in a lunar Distant Retrograde Orbit (DRO) for human visitation, also tend to be NHATS-compliant. Thus, although the NHATS analysis system was designed and implemented prior to the conception of ARM, the mission accessibility of NEAs classified as NHATS-compliant is sufficiently general that candidate ARM targets also tend to be NHATS-compliant. Figure 2 illustrates the concepts described above by comparing the round-trip mission accessibility of selected NHATS-compliant NEAs to the accessibility of an object placed into a lunar DRO. For reference, the Δv and round-trip duration requirements for visiting the DRO are approximately 4.5 km/s and 25 days, respectively, where 5 of the 25 days are spent at the DRO. The data in Figure 2 illustrates the concepts described above and shows that the most accessible of the NHATS-compliant NEAs have mission accessibility approaching that of an object in lunar DRO. However, this comparison can be extended and tied to the discussion of NEA accessibility during discovery epochs by applying the NHATS algorithm to selected NHATS-compliant NEAs during the timeframes surrounding their discovery epochs. That analysis was performed for 2006 RH_{120} and 2009 BD, the former of which was discovered when it was temporarily captured by Earth from about September 2006 through June 2007.

The results show that 2006 RH_{120} could have been visited for a total Δv of 4.451 km/s and a round-trip mission duration of 58 days in mid-January of 2007, while 2009 BD could have been visited for a total Δv of 5.998 km/s and a round-trip mission duration of 50 days in mid-April of 2011. Thus, both 2006 RH_{120} and 2009 BD were at their most accessible near the times when they were discovered, and their accessibilities during those times, especially that of 2006 RH_{120}, rivals that of an object in lunar DRO. Note that the mid-April 2011 launch for 2009 BD would have come about 2 years after its discovery and so a sufficiently long observation arc would have been obtained to characterize its orbit and ascertain that it isn't an artificial object. However, 2006 RH_{120} did not even receive its minor planet designation until February 2008, so January 2007 would have been much too early for deploying a mission to the NEA. These results serve to emphasize (1) how accessible NEAs can be in their natural orbits, and (2) that a space-based telescope stationed away from the Earth has the potential to discover and characterize NEAs sufficiently far in advance of their peak mission accessibility seasons to enable missions for which we would otherwise not have enough advance notice.

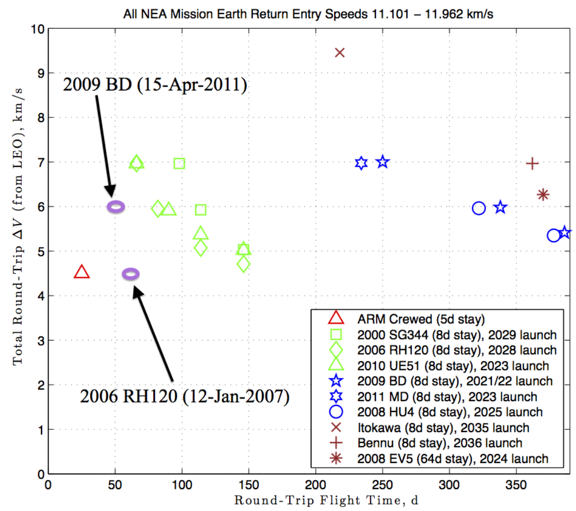

Figure 2: Comparison of round-trip mission accessibility for selected NHATS-compliant NEAs and an object in lunar DRO.

Conclusion: The NHATS automated NEA accessibility monitoring system provides rapid identification of accessible NEAs as they are discovered, which facilitates timely notification of NEA observers. This enables crucial follow-up observations of NEAs of interest shortly after they are discovered. Those observations can improve our knowledge of the accessible NEA orbits, preventing those NEAs from becoming "lost" (unable to be located in the sky during future apparitions). Furthermore, follow-up observations can, in some cases, provide information about a NEA's physical characteristics including size, rotation period, and spectra.

Since mid-2013, specific observation requests for approximately 40 NHATS-compliant NEAs were transmitted to observers by NASA, and in many cases this resulted in measurements of spectra, rotation periods, and sizes using a combination of visible, near-infrared (NIR), and infrared (IR) wavelength observations, as well as radar observations by both Goldstone and Arecibo. Future work includes efforts to streamline the processes for disseminating specific observer alerts and organizing the resulting obervational data.

In summary, many accessible NEAs have been discovered and identified to date, and more such NEAs are being discovered at an increasing rate. It is likely that many more accessible NEAs are waiting to be found in the population of undiscovered NEAs, which could include on the order of a billion objects (considering objects down to approximately 3 m in size). In future work we may apply the NHATS algorithms to simulated NEAs drawn from modern NEO population models to learn what the population models predict in terms of the accessibility of the NEAs that have not yet been discovered.

Finally, current survey capabilities tend to discover NEAs very close to the times of their optimal mission opportunities. A space-based NEA survey telescope is needed to discover NEAs with implementable mission opportunities (i.e., discover the NEOs far enough in advance of their mission opportunities. Such an asset would simultaneously benefit human exploration, planetary defense, and science.

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