The Near-Earth Object Human Space Flight Accessible Targets Study: An Ongoing Effort to Identify Near-Earth Asteroid Destinations for Human Explorers

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Abstract

NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) began in September of 2010 under the auspices of the NASA Headquarters Planetary Science Mission Directorate in cooperation with the Advanced Exploration Systems Division of the Human Exploration and Operations Mission Directorate. The purpose of the NHATS is to identify known near-Earth objects (NEOs), particularly near-Earth asteroids (NEAs), that may be accessible for future human space flight missions. In this paper we provide an overview of the NHATS methodology and process, summarize current NHATS results and data statistics, discuss NHATS-compliant NEA properties in relation to the overall NEA population, and present some details for particular human space flight mission opportunities identified by the NHATS.

Keywords: Human space flight, mission design, asteroid rendezvous, near-Earth asteroids, trajectory design

1. Introduction

NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) (pron.: /næts/) began in September of 2010 under the auspices of the NASA Headquarters Planetary Science Mission Directorate in cooperation with the Advanced Exploration Systems Division of the Human Exploration and Operations Mission Directorate. The purpose of the NHATS is to identify known near-Earth objects (NEOs), particularly near-Earth asteroids (NEAs), that may be accessible for future human space flight missions.

This research is largely motivated by the growing interest in the human exploration of NEAs. In 2009, the Augustine Commission identified NEAs as high value destinations for human exploration missions beyond the

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Earth-Moon system, and in 2010 the current U.S. presidential administration directed NASA to include NEAs as destinations for future human exploration with the goal of sending astronauts to a NEA in the mid to late 2020s. This directive became part of the official U.S. National Space Policy as of June 28, 2010.[10] Planning such deep space missions and identifying potential NEAs as targets for human spaceflight requires selecting objects from the large and ever growing list of known NEAs, hence the development and implementation of the NHATS.

The NHATS uses astrodynamics-based trajectory analysis to determine which NEAs meet a purposely inclusive set of mission design constraints; NEAs with mission opportunities that satisfy those constraints are classified as NHATS-compliant. To be classified as NHATS-compliant, a NEA must offer at least one round-trip trajectory that satisfies specified requirements for Earth departure date, round-trip mission duration, total mission change in velocity (Δv), stay time at the NEA, and atmospheric entry speed at Earth return. The total mission Δv includes an Earth departure maneuver from a notional circular parking orbit, a maneuver to match the NEA's velocity upon arrival, a maneuver to depart the NEA for Earth return, and, when necessary, a maneuver to reduce the atmospheric entry speed during Earth return. This sequence of maneuvers is shown in the context of the overall mission sequence in Figure 1.
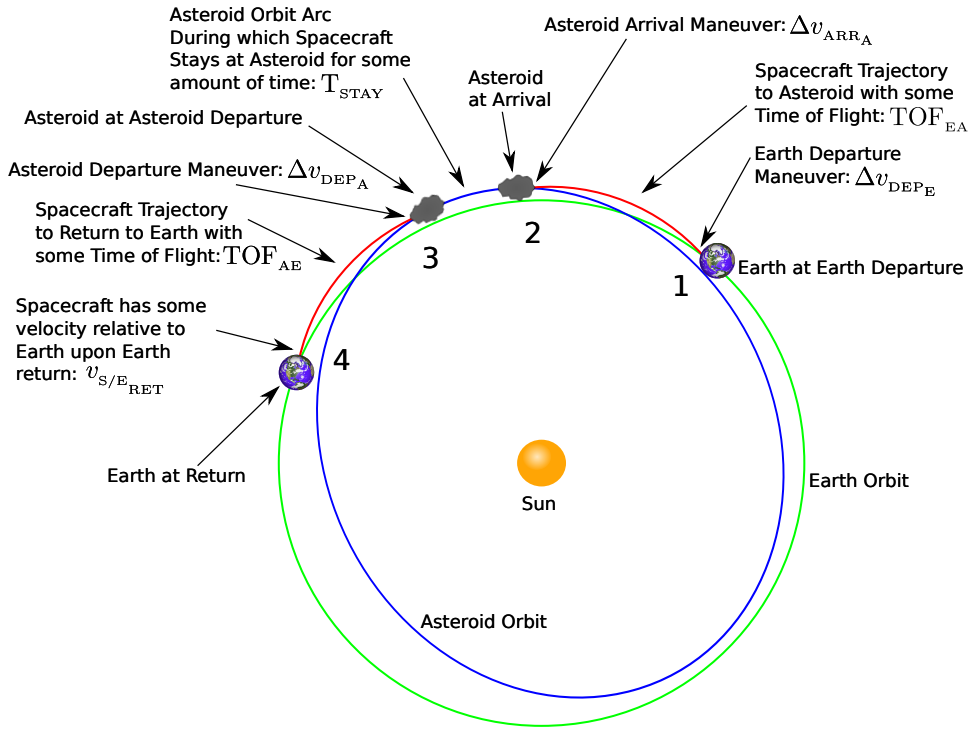

Figure 1: High-level depiction of mission sequence for a human mission to a NEA.

The automated NHATS system performs a daily update of the list of NHATS-compliant NEAs as additional NEAs are discovered and as our knowledge of known NEA orbits improves. The current list of NHATS-compliant NEAs identified as potentially viable for future human exploration under the NHATS criteria is available to the international community via a website maintained by NASA's NEO Program Office. Interested users may also subscribe to an email list for daily NHATS updates. In addition to mission opportunities and trajectory data, the website also provides predicted optical and radar observing opportunities for each NHATS-compliant NEA to facilitate timely acquisition of follow-up observations.

This promising list of NEAs will be useful for analyzing robotic mission targets, identifying optimal round-trip trajectories for human spaceflight missions, and highlighting potentially attractive objects of interest that require future observations for further characterization and/or orbit refinement. In this paper we provide an overview of the NHATS methodology and process, summarize current NHATS results and data statistics, discuss NHATS-compliant NEA properties in relation to the overall NEA population, and present some details for particular human space flight mission opportunities identified by the NHATS.

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[10]http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf, accessed on 2013-03-18

2. NHATS Background and Overview

Phase I of the NHATS was conducted during September–October 2010 and Phase II was conducted February–March 2011. In early 2011, an effort was also initiated to automate the NHATS algorithms such that the NEA trajectory processing is automatically performed on a daily basis to keep pace with new NEA discoveries and update the results when NEA orbit knowledge changes. This automation was completed in early 2012, and a NHATS web-site was released to the public on March 20th, 2012. The NHATS data products are hosted on NASA's Near-Earth Object Program web-site at `http://neo.jpl.nasa.gov/nhats/` within a filterable and sort-able table interface, shown in Figure 2.[11] Any interested individual may also subscribe to the NHATS mailing list at `https://lists.nasa.gov/mailman/listinfo/nhats`, to which the automated NHATS system automatically transmits a processing results summary email each day.

Figure 2: Screen capture of the NHATS web-site table.

The data published on the NHATS web-site include

- The complete listing of NHATS-compliant NEAs, identified by their provisional designations and numbers/names for numbered/named NEAs.

- The JPL orbit solution ID number, absolute magnitude (H), estimated diameter (using assumed geometric albedos of 0.6 and 0.03 for the minimum and maximum estimated diameters, respectively), and Orbit Condition Code (OCC) for each NHATS-compliant NEA.[12]

- The minimum total Δv and minimum mission duration solutions for each NHATS-compliant NEA, within the limits on Δv, duration, stay time at the NEA, and Earth departure date span specified in the web-site's user interface.

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[11]Accessed on 2013-03-16 at `http://neo.jpl.nasa.gov/cgi-bin/nhats`.

[12]OCC is a measure of how well a NEA's orbit is known. It is a 0 to 9 integer scale, where 0 represents the best orbit knowledge and 9 represents the poorest orbit knowledge. NEAs with OCC > 5 are generally considered "lost" for the purposes of locating them again in the sky at future apparitions. OCC is another name for the Minor Planet Center (MPC) "U" parameter, for which more technical details are provided at `http://www.minorplanetcenter.net/iau/info/UValue.html`, accessed on 2013-03-22.

- The number of viable trajectory solutions for each NHATS-compliant NEA. This metric serves as a proxy for relative accessibility amongst the NHATS-compliant NEAs, i.e., NEAs with larger numbers of viable trajectory solutions tend to be more accessible (offering lower Δv/duration mission opportunities over a wider range of Earth departure dates) in comparison to other NHATS-compliant NEAs.[13]

- The next optical observing opportunity and next Arecibo and Goldstone radar observing opportunities for each NHATS-compliant NEA. Future observing opportunities are not always available or certain for each NEA, and this is indicated explicitly in each case.

Furthermore, a web-page is dynamically generated for each NHATS-compliant NEA that provides a Pork Chop Contour (PCC) plot showing the total Δv required for all mission opportunities to the NEA as a function of Earth departure date and mission duration. Examples of these PCC plots are shown later (see Figure 17). A data table is also shown that provides the following details for the NEA's minimum Δv and minimum duration trajectory solutions:

- Outbound flight time, stay time at the NEA, and inbound flight time.

- Earth departure characteristic energy, C_3, and corresponding hyperbolic excess velocity, v_∞.

- Δv_{DEP_E} to depart Earth from an assumed circular Earth parking orbit.

- Δv_{ARR_A} (to arrive at the NEA) and Δv_{DEP_A} (to depart the NEA).

- The atmospheric entry speed at Earth return and the maneuver, Δv_{RET}, if any, required to reduce it.

- The declination angles for the Earth departure and Earth return asymptotes.

- The NHATS trajectory solution ID number.

The end-to-end NHATS processing is illustrated in Figure 3.

2.1. NHATS Round-Trip Trajectory Analysis

The NHATS uses astrodynamics-based trajectory analysis to determine which NEAs offer mission opportunities that meet a purposely inclusive set of mission design constraints; such NEAs are classified as NHATS-compliant. The NHATS system performs a truly comprehensive analysis by applying the method of embedded trajectory grids [1, 2], depicted in Figure 4, to compute round-trip trajectories to each known NEA for all combinations of Earth departure date, outbound flight time, stay time at the NEA, and inbound flight time, all at 8-day intervals. The trajectory calculations are performed using patched conics with Lambert solutions for the spacecraft and with full precision high-fidelity ephemerides for the Earth and NEAs obtained from JPL's Horizons system. The specifics of the NHATS trajectory analysis are expressed by the particular constraints applied to the calculations, which are [1]

1. Earth departure date between 2015-01-01 and 2040-12-31.
2. Earth departure $C_3 \leq 60$ km^2/s^2.
3. Total mission $\Delta v \leq 12$ km/s. The total mission Δv includes the Earth departure maneuver from a 400 km altitude circular parking orbit, the maneuver to match the NEA's velocity at arrival, the maneuver to depart the NEA, and, when necessary, a maneuver to meet the following Earth atmospheric entry speed constraint (item 6).
4. Total round-trip mission duration ≤ 450 days.
5. Stay time at the NEA ≥ 8 days.
6. Earth atmospheric entry speed ≤ 12 km/s at an altitude of 125 km.

In order to be classified as NHATS-compliant, a NEA must offer at least one round-trip trajectory solution that meets all those constraints.

The list of potential mission targets identified by the NHATS algorithms should not be interpreted as a complete list of viable NEAs for an actual human exploration mission. In part, this is because as the NEA orbits are updated, the viable mission targets and their mission parameters will change. This ever-changing state of NEA

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[13]However, recall that NHATS only considers Earth departure dates between 2015 and 2040. There will generally be some NEAs, particularly those with long synodic periods, that offer NHATS-compliant trajectory solutions during a different Earth departure interval and are therefore not classified as NHATS-compliant even though they would be if their viable Earth departure seasons were within the 2015-2040 interval.
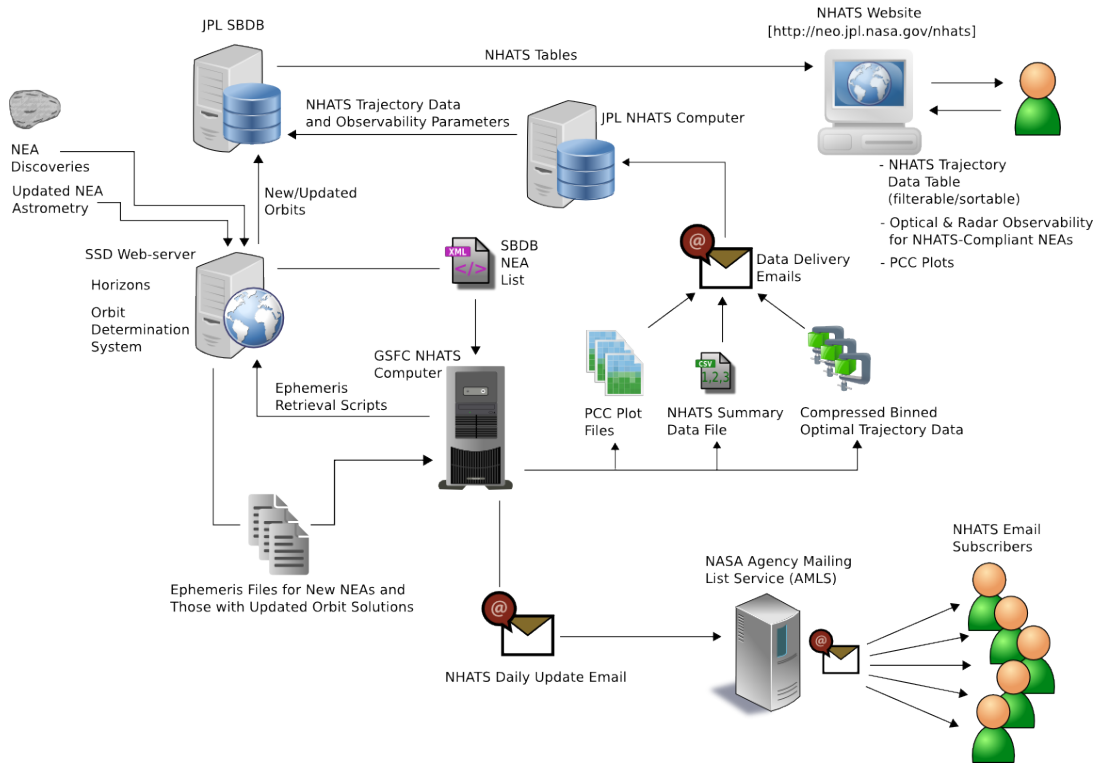
Figure 3: NHATS process flowchart.
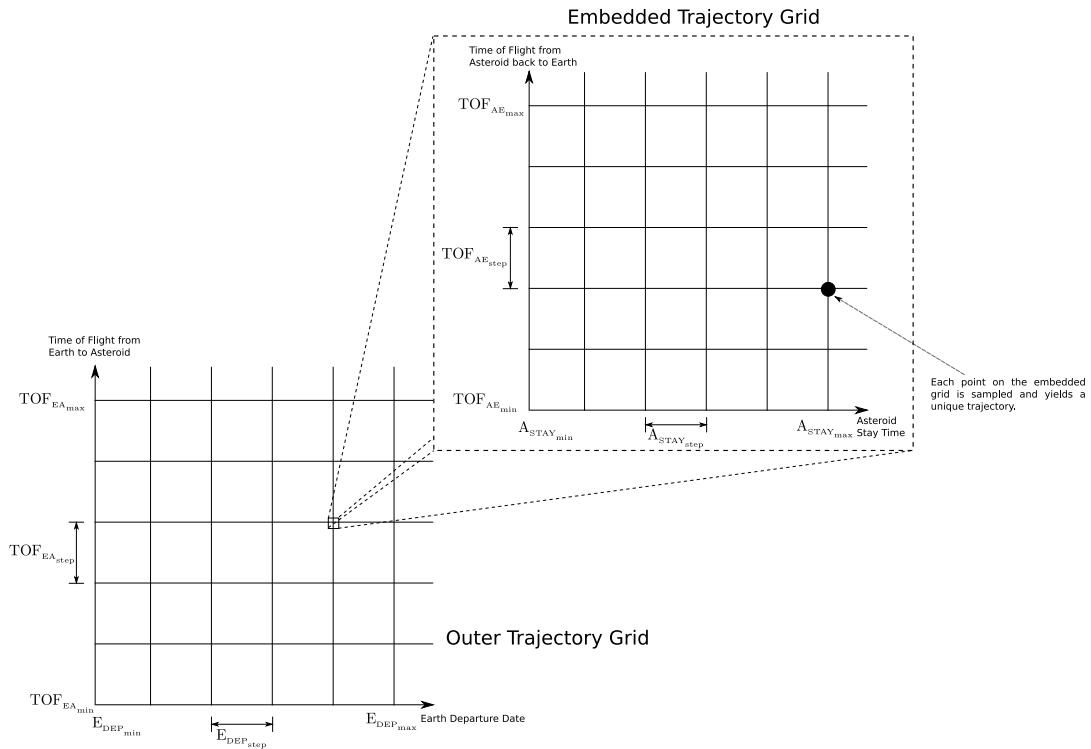
Figure 4: Graphical representation of the method of embedded trajectory grids for comprehensive analysis and optimization of round-trip mission trajectories.

knowledge is addressed by having the NHATS system run automatically on a daily basis to keep the results current. To select an actual NEA destination and mission scenario, additional non-trajectory constraints must be applied including astronaut health and safety considerations, performance and readiness of human space flight architecture

elements, the physical nature of the target NEA, and mission schedule constraints. Application of those constraints must generally be done on a case-by-case basis for various reasons. One such reason is that human space flight architecture elements for deep space missions have yet to be constructed and their performances and readiness dates are therefore unknown at this time. Another reason is that physical characterization data are not available for most NEAs.

Finally, as described previously, the NHATS trajectory analysis utilizes conic Lambert solution trajectory arcs for the spacecraft and does not consider Deep Space Maneuvers (DSMs) or gravity assists, both of which can reduce the overall Δv required for a mission, though often at the cost of increased mission duration. Thus the decision to omit those trajectory design features was made in part because the relatively short durations of the NHATS trajectory arcs generally do not afford the necessary time or space for such trajectory design techniques to deliver the benefits that they can during longer duration trajectories. Additionally, continuous thrust options (e.g., solar electric propulsion) were omitted for reasons of calculation complexity/cost. As such, there are generally additional mission options for the NHATS-compliant NEAs that are not within the scope of the NHATS itself; that is, most of the additional options are likely to be better suited to robotic missions than human missions.

A good example of the sort of trade-offs required for robotic mission optimization is provided by the trajectory design for the Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx). OSIRIS-REx is a NASA asteroid sample return mission scheduled to launch in 2016 and return a sample in 2023 from the Potentially Hazardous Asteroid (PHA) designated 101955 (1999 RQ_{36}). The round-trip trajectories for this mission utilize optimally located DSMs, an Earth gravity assist, and multiple revolutions about the Sun [3]. Applying the NHATS constraints of departure from a 400 km altitude circular LEO and a maximum atmospheric entry speed of 12 km/s to the optimal trajectory data for OSIRIS-REx presented in [3] reveals that the overall minimum total Δv trajectory solution requires a total Δv of 5.930 km/s and has a round-trip mission duration of 2192 days. By contrast, the overall minimum Δv NHATS mission solution for 101955 (1999 RQ_{36}) requires a total Δv of 6.965 km/s and has a round-trip mission duration of 362 days.[14] In this case the combination of optimally located DSMs, an Earth gravity assist, and multiple revolutions about the Sun is able to reduce the total mission Δv by 15% compared to the NHATS result, but at the expense of increasing the mission duration by 500%.

2.2. Determination of Optical and Radar Observing Opportunities for NHATS-compliant NEAs

As indicated in Figure 3, the observability of each NEA is analyzed. This is done by generating its geocentric ephemeris through to the year 2040 and then using that ephemeris to assess observability by applying several constraints. For optical observation opportunities, the variation in optical observing constraints between different observatories must be accounted for, and the constraints chosen for the NHATS data were purposely selected to represent observing programs with access to large-aperture telescopes. This allows even the difficult observational opportunities to be included. The optical observational constraints used for the NHATS are

1. The apparent visual magnitude must reach 24.0 or brighter.
2. The geocentric angular distance from the Sun (solar elongation) has to exceed 60°.
3. The 3σ plane-of-sky uncertainty must be less than 1.5° over a 3-day period.
4. The object must be at least 5° away from the galactic equator.
5. Observations are excluded for the 4-day period around each full moon.

The NHATS website displays the peak apparent visual magnitude (V_p) during the observational opportunity as a guide to observers. Examples of these are shown in the NHATS web-site table screen capture presented in Figure 2.

Many asteroids with poorly-determined orbits violate the plane-of-sky uncertainty constraint soon after discovery; these objects are considered *lost*. A secondary filter is then applied to simulate a serendipitous re-discovery of such an object by two generic asteroid survey programs. The survey programs are simulated by removing the plane-of-sky uncertainty constraint and imposing the following survey constraints

1. To simulate current programs, a limiting magnitude of 21.5 and minimum solar elongation of 70° are used.
2. To simulate the proposed Large Synoptic Survey Telescope (LSST) survey, a limiting V_p of 24.0 is used, starting in the year 2021, and sky coordinates must be within the LSST survey region.

The dates of possible survey recoveries are shown in the NHATS web-site table with leading and trailing "?" characters to indicate that these are far from certain. For an example of such an entry in the table, see the data for NEA 2012 HK_{31} in Figure 2.

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[14]See `http://neo.jpl.nasa.gov/cgi-bin/nhats?sstr=101955&dv=12&dur=450&stay=8&launch=2015-2040`, accessed on 2013-03-22.

In addition to optical observation opportunities, radar tracking opportunities for Arecibo and Goldstone are determined by calculating the daily signal-to-noise ratio (SNR) values using the best known physical parameters for the asteroid (primarily size and rotation period), as well as the actual parameters for these antennas. The radar constraints are

1. The SNR must be at least 10.
2. Either the 3σ plane-of-sky uncertainty must be $< 0.75'$, or
3. There must be an optical observing opportunity shortly before, with magnitude brighter than 21.5 and plane-of-sky uncertainty less than $3°$, 3σ. This is meant to simulate the optical astrometry often requested to lower the pointing uncertainty and make the radar experiment possible.

2.3. Benefits and Utility

Relatively little was known regarding the accessibility of NEAs for future human space flight missions prior to the commissioning of the NHATS. While some example mission scenarios had been constructed to a limited set of candidate targets and some notional accessibility criteria had been formulated [4, 5], no comprehensive survey of the entire NEA population for round-trip mission accessibility had been performed. The NHATS has radically altered that state of affairs by providing, for the first time, a comprehensive and detailed accessibility assessment for the entire known NEA population using well-defined, concrete, astrodynamics-based accessibility criteria. This information is crucial for efforts to ascertain future NEA mission opportunities and investigate options for the first deep space human exploration missions. The NHATS has thus greatly increased our understanding of the options presented by the NEA population for round-trip human space flight missions.

The automation of the NHATS processing and the creation of NASA's NHATS web-site has made this vast database of round-trip NEA trajectory data readily accessible via the internet. NASA engineers and decision-makers, members of industry and academia, and the general public can all easily access these data. Furthermore, the fact that the NHATS process automatically executes daily ensures that all the trajectory data remain up to date and that newly discovered NEAs can be promptly identified as promising mission targets under NHATS accessibility criteria.

The fact that the next available optical and radar observation opportunities for each NHATS-compliant NEA are automatically computed and published on the NHATS web-site, along with the fact that the NHATS system identifies particularly accessible NEAs as soon as they are discovered, means that the NHATS system is a valuable aid in the prioritization of NEAs for vital follow-up observations during the crucial time period immediately following discovery. For particularly accessible NEAs whose next observing opportunities do not manifest for some number of months or years, observing campaigns can be planned well in advance.

Over the past year since the NHATS web-site and mailing list were released to the public there has been significant engagement with observers. Follow-up optical and radar observations have been made for a number of NHATS-compliant NEAs, and those observations have led to improved orbit knowledge and even some physical characterization. One notable example is 2001 QJ_{142}, one of the more sizable of the relatively accessible NHATS-compliant NEAs with mission opportunities in the mid-2020s, whose OCC was reduced from 6 to 0. Additionally, several NHATS-compliant NEAs, including 2012 EC, 2012 LA, 2012 PB_{20}, 2010 JK_1, 2012 XB_{112}, 2013 BS_{45}, and 2012 UW_{68}, had their OCC values reduced to 4 or less. Rotation periods were also measured for several NHATS-compliant NEAs, including 2012 XB_{112} (2.59998 minutes)[15] and 2012 UX_{136} (2.2866 minutes $\pm$ 30%).[16] In the case of 2012 XB_{112}, its diameter was also measured (2.5 $\pm$ 0.5 m) using a combination of radar data from Goldstone and the lightcurves from which its rotational period was derived. A total of 51 NHATS-compliant NEAs have been observed by radar thus far[17] and those radar observations were enabled to a significant extent by timely assistance from the professional and amateur astronomy communities. Those observers responded to requests made through the Minor Planet Mailing List and reported astrometry that shrank the plane-of-sky pointing uncertainties sufficiently to accurately point the telescopes. The subsequent radar observations would have been quite difficult if not impossible otherwise.

The automated NHATS system compliments JPL's automated Sentry system because while Sentry continually monitors the *threat* posed by NEAs (and near-Earth comets (NECs)) that may collide with the Earth, the NHATS system continually monitors the *opportunity* presented by NEAs that may be accessible destinations for the next generation of astronauts. Just as the automated monitoring of NEA impact risk has defined a distinct NEA sub-population of interest to observers—the Potentially Hazardous Asteroids (PHAs)—so too has the automated monitoring of NEA accessibility by the NHATS system defined a distinct NEA sub-population that is also of interest to observers: the NHATS-compliant NEAs.

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[15]`http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=2012XB112`, accessed on 2013-03-26.

[16]`http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=2012UX136`, accessed on 2013-03-26.

[17]See `http://echo.jpl.nasa.gov/~lance/radar_detected_neas_summary/nea.radar.aei.html` and `http://echo.jpl.nasa.gov/asteroids/PDS.asteroid.radar.history.html`, both accessed on 2013-03-26.

2.4. Comparing Astrodynamics-Based Accessibility Criteria for Various Destinations

To provide context for the aforementioned NHATS accessibility criteria (Δv, mission duration, etc.), consider that a round-trip to a low altitude circular lunar orbit requires approximately 5 km/s of total mission Δv (starting from a circular LEO), and a round-trip to the lunar surface requires approximately 9 km/s of total mission Δv. The total mission duration for either of those cases is on the order of at least 6 to 12 days, depending on the mission profile (as demonstrated during the Apollo missions) [6]. Round-trip missions to the Earth-Moon Lagrangian points have similar total Δv requirements to round-trip missions to lunar orbit ($\sim$ 5 km/s), and similar mission duration requirements ($\sim$ one week to one month, depending on mission operations). Round-trip missions to 433 of the currently known NHATS-compliant NEAs require less total mission Δv (i.e., < 9 km/s) than a round-trip mission to the lunar surface, and there are currently 37 NHATS-compliant NEAs with round-trip Δv requirements less than that of lunar orbit (i.e., < 5 km/s). The aforementioned values for the numbers of NHATS-compliant NEAs available at various levels of Δv result from applying the least restrictive constraints on OCC, H, minimum stay time, and Earth departure date. When more restrictive values of those constraints are applied, the numbers of available NEAs at particular total mission Δv levels are reduced.

It is also instructive to compare the accessibility of NHATS-compliant NEAs to the accessibility of the martian surface for round-trip human space flight missions. The Addendum to NASA's Mars Design Reference Architecture (DRA) 5.0 report [7] documents round-trip conjunction class Mars missions available across a range of Earth departure dates during the years 2031 through 2046.[18] Depending on Earth departure date, these missions require between 6.290 and 7.402 km/s of Δv for Earth departure, arrival in a 250 × 33,793 km altitude Mars orbit, and Mars orbit departure (not including any plane changes that may be required at Earth or Mars), and the mission durations range between 877 and 923 days, which is roughly twice as long as the maximum NHATS mission duration of 450 days. Each of these Mars missions also requires a Δv of 0.615 km/s for entry, descent, and landing at Mars, along with a Δv of 5.625 km/s for ascent from the martian surface after the stay on Mars is completed. Thus, the best case total Δv for a round-trip mission to the martian surface is 12.530 km/s, which exceeds the NHATS limit of 12 km/s for total mission Δv. The Mars mission designs described here also allow an atmospheric entry speed at Earth return of up to 13 km/s, which exceeds the NHATS atmospheric entry speed limit of 12 km/s. Enforcing the NHATS entry speed limit for these Mars missions would require additional Δv and/or mission duration in some cases. Consideration of the accessibility of the martian surface in the context of NHATS naturally gives rise to consideration of the accessibility of Mars orbit, which removes the Δv costs of entry, descent, landing, and ascent. Recent research[19] shows that every $\sim$ 15 years there are opportunities for opposition class round-trip missions to a highly eccentric 590 × 44,655 km altitude Mars orbit (with a $\sim$ one week stay in that orbit) within the NHATS maximum mission duration constraint of 450 days, but with best-case total mission Δv requirements of approximately 13 to 14 km/s, which is greater than the NHATS limit of 12 km/s. Thus, round-trip missions to Mars cannot be made NHATS-compliant even if landing on the martian surface is forgone. These data make it clear that all of the 1052 currently known NHATS-compliant NEAs are more accessible for round-trip missions than Mars orbit or the martian surface.

3. Current NHATS Results

As of March 16th, 2013, a total of 1052 NEAs have been classified as NHATS-compliant. That is about 11% of the currently known 9700 NEAs[20]. On March 3rd, 2013, several sets of summary data were collected from the NHATS website for analysis and discussion herein. On that date a total of 1042 NEAs were classified as NHATS-compliant and the numbers of those NEAs that offer at least one mission opportunity within various combinations of mission Δv and duration thresholds are shown in Table 1. An empty cell indicates that none of the known NEAs offers a mission opportunity that satisfies the Δv and duration constraint associated with that cell.

The data in Table 1 would seem to indicate that an appreciable number of NEAs offering attractive mission opportunities are already known. However, the data in Table 1 correspond to Earth departure date between 2015 and 2040, no limit on H (as a proxy for NEA size), and no limit on OCC. Applying limits of Earth departure date between 2025 and 2030, $H \leq 22.0$, and OCC ≤ 5 yields the results shown in Table 2. Cells shaded gray in Table 2 indicate that NEAs would be available in those cells (as per Table 1) if the aforementioned restrictions on Earth departure date, H, and OCC were not applied. Table 2 shows that no NEAs are available with those constraints for less than 6 km/s of Δv, and only one NEA, 99942 Apophis (2004 MN$_4$), is available for missions requiring 6 to 7 km/s and 330 to 450 days of round-trip mission duration.

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[18]The DRA 5.0 Addendum is available at `http://www.nasa.gov/pdf/373667main_NASA-SP-2009-566-ADD.pdf`, accessed on 2013-03-25.

[19]Performed by B. W. Barbee, not yet published.

[20]NHATS-compliant NEAs have been found to comprise approximately 10% of the total number of NEAs known at the time since the beginning of the NHATS in September of 2010.

Table 1: Number of NHATS-compliant NEAs known on 2013-03-03 within all combinations of compliant mission Δv and duration thresholds.

Total Δv (km/s)	Round-Trip Mission Duration (days)														
	≤ 30	≤ 60	≤ 90	≤ 120	≤ 150	≤ 180	≤ 210	≤ 240	≤ 270	≤ 300	≤ 330	≤ 360	≤ 390	≤ 420	≤ 450
Δv ≤ 4											1	1	2	2	3
Δv ≤ 5					1	5	6	7	9	12	16	26	31	34	37
Δv ≤ 6			3	4	6	14	18	23	32	38	52	76	87	91	93
Δv ≤ 7		1	4	6	18	32	55	69	79	96	123	155	172	174	176
Δv ≤ 8		3	10	19	38	84	111	122	142	164	199	253	274	280	280
Δv ≤ 9		9	24	45	86	139	178	197	225	253	314	385	412	425	431
Δv ≤ 10	1	17	46	80	149	209	265	295	321	357	442	527	571	583	594
Δv ≤ 11	1	30	93	136	218	311	374	406	453	504	606	700	760	785	799
Δv ≤ 12	3	49	130	192	309	420	504	550	597	667	782	914	997	1023	1042

Table 2: Number of NHATS-compliant NEAs known on 2013-03-03 within all combinations of compliant mission Δv and duration thresholds with Earth departure date between 2025 and 2030, H ≤ 22.0, and OCC ≤ 5.

Total Δv (km/s)	Round-Trip Mission Duration (days)														
	≤ 30	≤ 60	≤ 90	≤ 120	≤ 150	≤ 180	≤ 210	≤ 240	≤ 270	≤ 300	≤ 330	≤ 360	≤ 390	≤ 420	≤ 450
Δv ≤ 4															
Δv ≤ 5															
Δv ≤ 6															
Δv ≤ 7											1	1	1	1	1
Δv ≤ 8										1	1	2	4	4	4
Δv ≤ 9						2	2	3	4	4	8	13	13	16	18
Δv ≤ 10				1	2	4	6	6	8	9	18	22	29	30	34
Δv ≤ 11			1	1	2	9	11	12	13	19	30	40	49	58	61
Δv ≤ 12		1	1	1	9	15	19	20	25	36	49	68	91	94	96

The overall reduction in the total number of available NEAs is rather striking: Table 1 shows the total of 1042 NHATS-compliant NEAs known as of March 3rd, 2013, and Table 2 shows that this number is reduced to a mere 96 NEAs simply by applying the constraints of Earth departure date between 2025 and 2030, H ≤ 22.0, and OCC ≤ 5. Examining the effects of those constraints applied individually is enlightening. If only the Earth departure date constraint is applied, 644 NEAs are still available. If only the OCC constraint is applied, 413 NEAs are still available. If both the Earth departure date and OCC constraint are applied, 258 NEAs are still available. However, if *just* the H ≤ 22.0 constraint is applied, only 171 NEAs are still available. This is indicative of a particular phenomenon revealed by the NHATS, which is that the majority of the more accessible NEAs tend to be rather small in size (where size is usually based on H with assumed geometric albedos, for lack of actual measurements of size or albedo). Further research into dynamical modeling of the NEA population's evolution may shed light on the nature of this phenomenon, e.g., whether it is more likely to be a perception caused by observational biases or an actual phenomenon caused by aspects of the orbital environment in which the orbits of NEAs evolve over time.

Table 3: Number of NHATS-compliant NEAs known on 2013-03-03 within all combinations of compliant mission Δv and duration thresholds with Earth departure date between 2025 and 2030, H ≤ 23.0, and OCC ≤ 5.

Total Δv (km/s)	Round-Trip Mission Duration (days)														
	≤ 30	≤ 60	≤ 90	≤ 120	≤ 150	≤ 180	≤ 210	≤ 240	≤ 270	≤ 300	≤ 330	≤ 360	≤ 390	≤ 420	≤ 450
Δv ≤ 4															
Δv ≤ 5															
Δv ≤ 6													1	1	1
Δv ≤ 7											3	4	4	4	4
Δv ≤ 8										2	4	6	8	9	9
Δv ≤ 9						2	3	4	5	8	14	20	22	26	28
Δv ≤ 10				1	3	6	8	9	13	16	26	32	44	45	51
Δv ≤ 11			1	2	5	13	17	18	23	30	43	59	70	82	87
Δv ≤ 12		1	2	3	13	20	28	30	39	51	66	89	119	125	128

The fact that the more accessible NEAs tend to have larger H values is also demonstrated in Table 3, for which the constraint of H ≤ 23.0 is applied while keeping the Earth departure date and OCC constraints as they are for

Table 2. An additional 32 NEAs are available in Table 3 (as compared to Table 2), and, more importantly, a NEA, 2011 AA$_{37}$, is now accessible for Δv between 5 and 6 km/s. Also, a total of four NEAs are now accessible for Δv between 6 and 7 km/s, whereas in Table 2 there is only one such NEA. The two additional NEAs (besides 99942 Apophis (2004 MN$_4$) and 2011 AA$_{37}$) are 2001 CQ$_{36}$ and 2007 UP$_6$. General increases in the number of available NEA destinations (as compared to Table 2) are seen at all Δv levels in Table 3.

4. Characteristics of the NHATS-compliant NEA Population

The NHATS-compliant NEAs constitute a unique subset of the overall NEA population in that they are particularly accessible for round-trip missions compared to all other NEAs. Here we present an analysis of how the NHATS-compliant NEAs relate to the various NEA orbit groups, including the Atiras, Atens, Apollos, Amors, and Potentially Hazardous Asteroids (PHAs). We also present trends in the NHATS-compliant NEA population for estimated size and synodic period with respect to Earth.

4.1. NHATS-compliant NEAs By Orbit Group

The number of NHATS-compliant NEAs within each of the NEA orbit groups (Atira, Aten, Apollo, Amor), defined in Figure 5, are summarized in Table 4 and displayed graphically in Figures 6 and 7. The plots in those figures show the semi-major axes, eccentricities, and inclinations of the NHATS-compliant NEA orbits, classified by orbit type. Figure 5 does not contain any information about inclination, while Figure 7 endeavors to combine semi-major axis (a), eccentricity (e), and inclination (i), information in a single figure by plotting i versus the semi-latus rectum, p, where $p = a\left(1 - e^2\right)$.
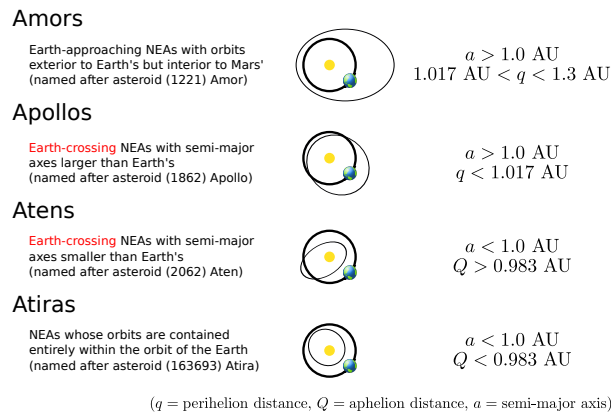

Figure 5: NEA groups according to orbit type.

Table 4: NHATS-compliant NEAs by orbit group.

NEA Orbit Group	All NEAs	NHATS-Compliant NEAs	Portion of Group	Portion of NHATS-compliant NEAs
Atiras	12	0	0.00%	0.00%
Atens	759	247	32.54%	23.48%
Apollos	5259	633	12.04%	60.17%
Amors	3670	172	4.69%	16.35%

Table 4 shows that the majority of NHATS-compliant NEAs (60.17%) are Apollos while the NEA orbit group that contains the highest percentage within that group of NHATS-compliant NEAs (32.54%) is the Atens. Another notable fact is that none of the very few known Atiras are NHATS-compliant. These facts suggest that an increase in the rate of discovery of Atens may yield a more rapid increase in the number of known NHATS-compliant NEAs. However, discoveries of Atens are hindered by the fact that NEAs in that orbit group tend to spend more time interior to Earth's orbit and are therefore more difficult to observe with ground-based assets. This is an even more significant issue for Atiras, whose orbits are completely interior to Earth's.
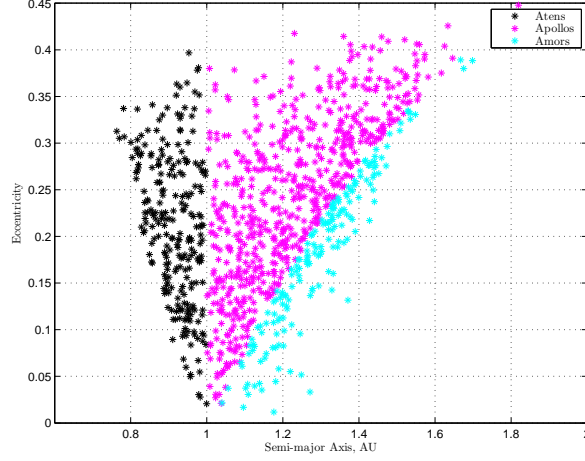
Figure 6: Semi-major axis versus eccentricity for the NHATS-compliant NEAs according to orbit group.
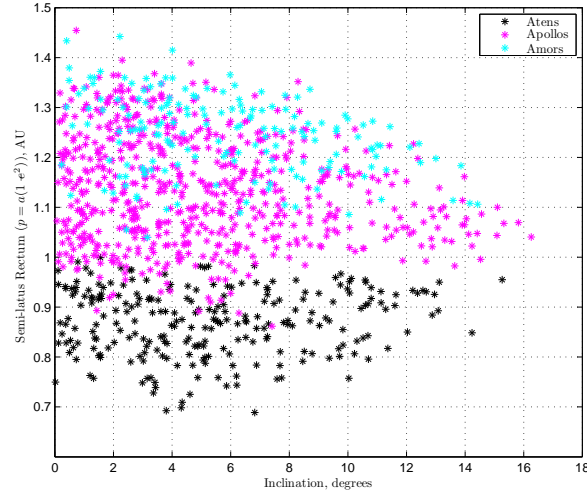

Figure 7: Inclination versus semi-latus rectum for the NHATS-compliant NEAs according to orbit group.

4.2. NHATS-compliant Potentially Hazardous Asteroids (PHAs)

Potentially Hazardous Asteroids (PHAs) are another NEA orbit group formally defined as having a Minimum Orbit Intersection Distance (MOID) with Earth ≤ 0.05 AU and $H \leq 22.0$, where $H \leq 22.0$ with geometric albedo of 0.13 corresponds to NEA diameter ≥ 150 m.[21] As of March 16th, 2013 there were 1384 known PHAs, of which 106 were NHATS-compliant (7.7% of PHAs, 10% of NHATS-compliant NEAs). Given that the PHA definition is meant to identify NEAs that could pose a threat to life and/or property on Earth's surface, a more inclusive PHA definition might replace the $H \leq 22.0$ criterion with $H \leq 24.34$, which corresponds to NEA diameter ≥ 50 m (with an assumed geometric albedo of 0.13). In that case the number of known PHAs on March 16th was 2373, of which 284 were NHATS-compliant (12% of PHAs, 27% of NHATS-compliant NEAs). Further investigation reveals that the primary limiting factor on how many NHATS-compliant NEAs are also PHAs is H (rather than MOID). Consider that only 167 NHATS-compliant NEAs had $H \leq 22.0$ while 409 NHATS-compliant NEAs had $H \leq 24.34$. However, with no constraint on H we find that 877 NHATS-compliant NEAs (83% of NHATS-compliant NEAs) had MOID ≤ 0.05 AU. These facts imply that mission-accessible NEAs will tend to make relatively close approaches to Earth and that the majority of the NHATS-compliant NEAs tend to be physically small relative to the overall NEA population (5570 of 9700 NEAs had $H \leq 22.0$ while only 167 of 1052 NHATS-compliant NEAs had $H \leq 22.0$).

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[21]See http://neo.jpl.nasa.gov/neo/groups.html, accessed 2013-03-16.

4.3. NHATS-compliant NEA Properties Relative to the Overall NEA Population

Statistics for the semi-major axes, eccentricities, and inclinations of the NHATS-compliant NEA orbits are summarized in Table 5. Note that these statistics are not correlated to one another. Gaining an understanding of the correlations between orbital elements for the NHATS-compliant NEAs, both as a group and with respect to the overall NEA population, is accomplished most readily by plotting the data. Figure 8 compares the relationship

Table 5: Uncorrelated statistics for the semi-major axis, eccentricity, and inclination of NHATS-compliant NEA orbits.

Orbital Element	Minimum	Mean	Maximum
Semi-major Axis (AU)	0.763	1.163	1.819
Eccentricity	0.012	0.226	0.448
Inclination	0.021°	5.150°	16.256°

between semi-major axis and eccentricity for the NHATS-compliant NEAs to that relationship for the overall NEA population. Note that three NEAs with semi-major axis > 5 AU (1999 XS_{35}, 2010 CA_{55}, and 2011 AF_3) are excluded from Figure 8 because their inclusion would could cause unfavorable scaling of the plot; none of those NEAs are NHATS-compliant. Figure 9 displays the inclination versus semi-latus rectum for the NHATS-compliant NEAs and the general NEA population. Note that two NEAs with inclination > 80° (2009 HC_{82} and 2007 VA_{85}, neither of which are NHATS-compliant) are excluded from Figure 9 to avoid unfavorable plot scaling. Earth is essentially at coordinates (1,0) in Figure 8 and at coordinates (0,1) in Figure 9.
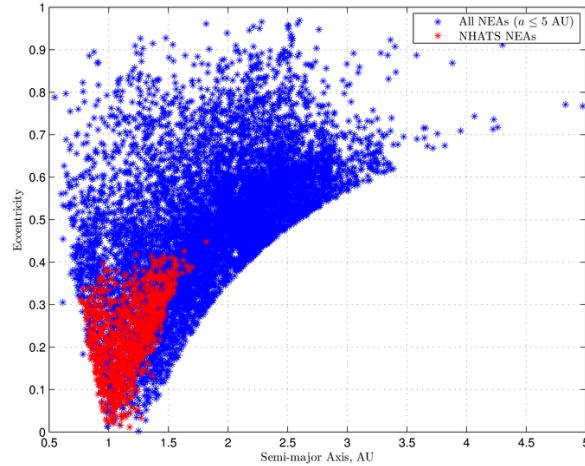

Figure 8: Semi-major axis versus eccentricity for the overall known NEA population and the currently known NHATS-compliant NEAs.

The distributions of osculating orbital elements for the NHATS-compliant NEAs and all NEAs are are shown in Figures 10(a)–10(e), and the distribution of H is shown for the NHATS-compliant NEAs and all NEAs in Figure 10(f). These data, along with the data in Table 5 and Figures 8 and 9, clearly show that the NHATS-compliant NEAs tend to have semi-major axes near 1 AU, low eccentricity, and low inclination. However, the distributions of longitude of the ascending node and argument of perihelion for the NHATS-compliant NEAs are very similar to those distributions for the general NEA population and there appear to be no particular trends for those two orbital elements. That is an intuitively satisfying result because Earth's orbit has essentially zero inclination and very small eccentricity.

The distributions of H for the NHATS-compliant NEAs and all NEAs shown in Figure 10(f) are noteworthy and corroborate data presented previously for current NHATS results. In the data shown previously we indicate that the NHATS-compliant NEAs tend to be smaller than average for the NEA population, and Figure 10(f) shows this directly. The mean H for the NHATS-compliant NEAs is 24.657 while the mean H for all NEAs is 21.595. Another noteworthy trend is that the more accessible NHATS-compliant NEAs (in terms of required total mission Δv) tend to be smaller in size than the less accessible NHATS-compliant NEAs. Consider Figure 11, which presents a plot of minimum required total mission Δv versus H for the NHATS-compliant NEAs. The Pareto front
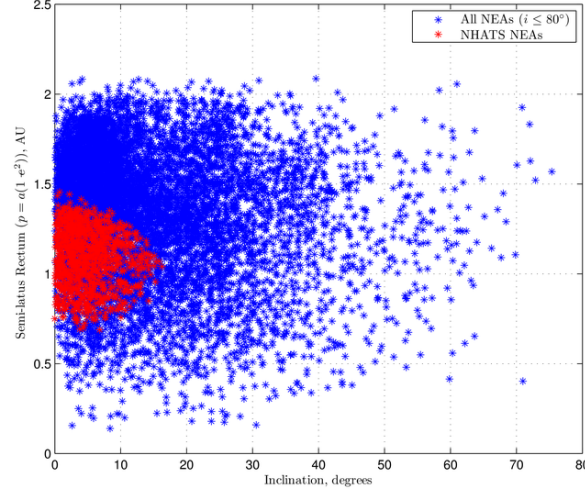
Figure 9: Inclination versus semi-latus rectum for the overall known NEA population and the currently known NHATS-compliant NEAs.

in Figure 11 clearly shows that the minimum available H increases steadily with decreasing minimum mission Δv.

From the perspective of identifying the most accessible NEAs for round-trip human space flight missions, it is important to understand the impact of NEA orbit parameters on the Δv required to fly round-trip missions to those NEAs. Figure 12 once again shows semi-major axis versus eccentricity for the NHATS-compliant NEAs, but with the data markers color-coded to indicate the Δv of the minimum Δv round-trip trajectory to that NEA. Figure 13 shows the same thing, but for inclination versus semi-latus rectum. There are clear gradients in both of these plots showing that the lower Δv solutions are for NEAs whose orbit parameters are closer to those of Earth; the lower Δv solutions cluster near (1,0) in Figure 12 and near (0,1) in Figure 13.

However, there are clearly some higher Δv values amidst the lower ones in those low Δv regions of the plots. In the case of Figure 12 this is because some of those low eccentricity NEA orbits with semi-major axis near 1 AU also have higher inclinations. This is shown directly in Figure 14, which color-codes the Figure 12 data markers according to inclination rather than Δv; there are clearly a number of higher inclination NEAs present amidst those with semi-major axis near 1 AU and low eccentricity. In the case of Figure 13 the few higher Δv solutions near (0,1) are due to some of the low inclination NEA orbits happening to have combinations of semi-major axis and eccentricity that are not entirely Earth-like but still conspire to produce a p value near 1 AU.

4.4. NEA Synodic Period

The synodic period between objects on different orbits is the time that must elapse before a given relative position between the objects will repeat. This concept has important implications for discovering accessible NEAs sufficiently far in advance of their optimal human space flight mission opportunity windows to allow for appropriate characterization of the NEA and preparation of the human space flight systems for launch, assembly, and Earth departure. When considering only the individual heliocentric motions of the NEA and Earth, the synodic period is dominated by the difference between the semi-major axis of the NEA's orbit and the semi-major axis of Earth's orbit.[22] As a NEA's semi-major axis approaches 1 AU, the synodic period quickly becomes very large (technically infinite for a NEA with a semi-major axis identical to that of Earth). This can clearly be problematic as we have already noted that the most accessible NEAs tend to have relatively Earth-like orbits, which includes having a semi-major axis near 1 AU and hence a relatively long synodic period. The problem arises when a particularly accessible NEA is discovered during a close approach to Earth and will not return to the Earth's vicinity again for a long time, thereby interfering with plans to deploy a human space flight mission within several years to a decade of the NEA's discovery (the opportunity windows for short duration, low Δv round-trip missions require that the NEA be relatively near the Earth).

In Figure 15 we see that there are a number of NHATS-compliant NEAs with synodic periods of several centuries (nearly 1100 years in one case), and these very long synodic periods are associated with many different Δv requirements. As discussed previously, this is because while a NEA may have semi-major axis near 1 AU, it's

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[22]In this discussion we are considering synodic period based on osculating orbital elements, however these can change dramatically if the NEA encounters a planet (such as Earth).

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(a) Semi-major axis, a.

(b) Eccentricity, e.

(c) Inclination, i.

(d) Longitude of the ascending node, Ω.

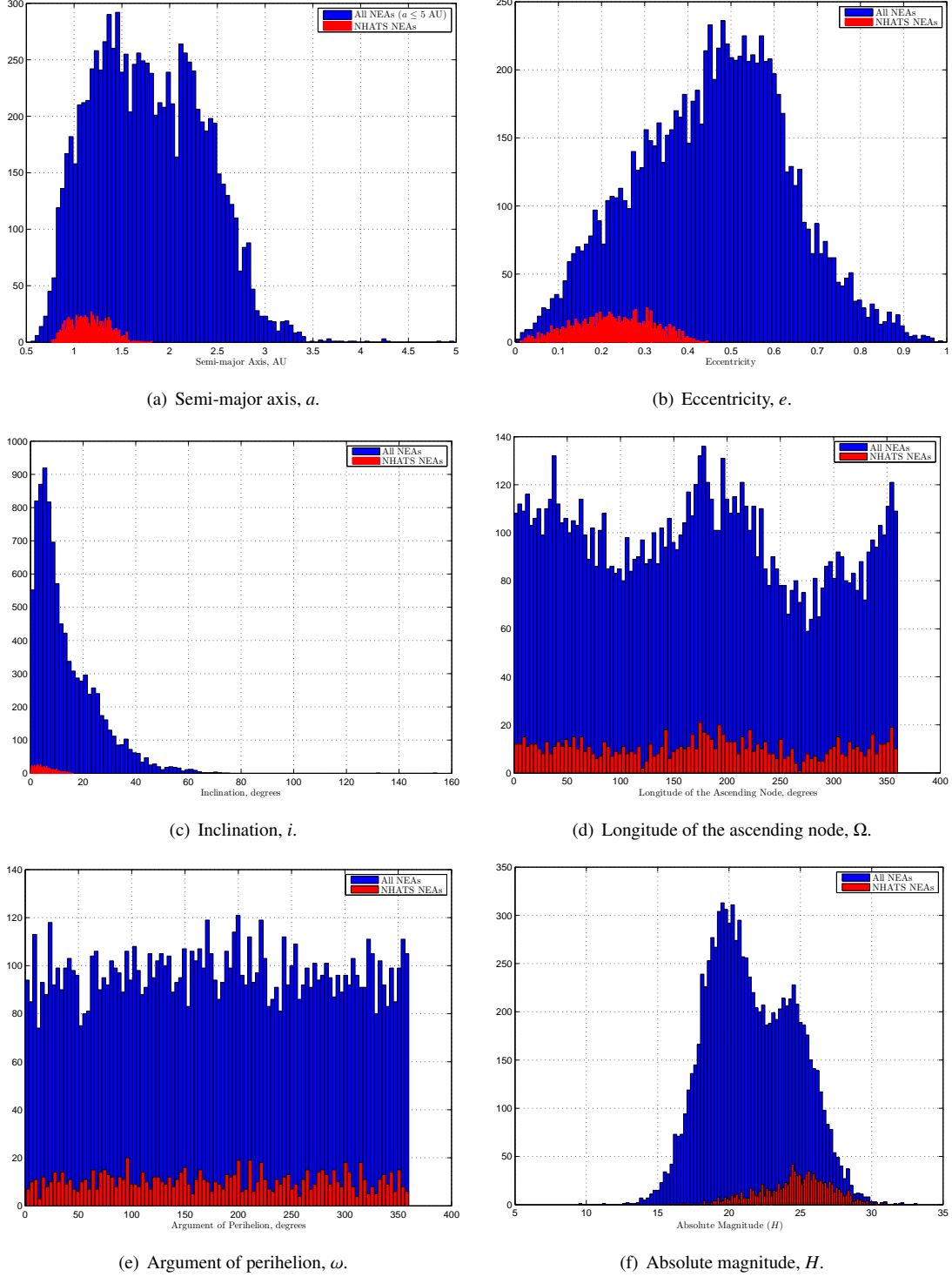(e) Argument of perihelion, ω.

(f) Absolute magnitude, H.

Figure 10: Distributions of osculating orbital elements and absolute magnitude for the currently known (blue) and NHATS-compliant (red) NEAs.

eccentricity and inclination are not necessarily low. Figure 16 restricts the range of the data to only show synodic periods of 30 years or less so that more detail can be seen. Here we see a Pareto front whereby the minimum available synodic period increases with decreasing Δv, which is the expected trend.
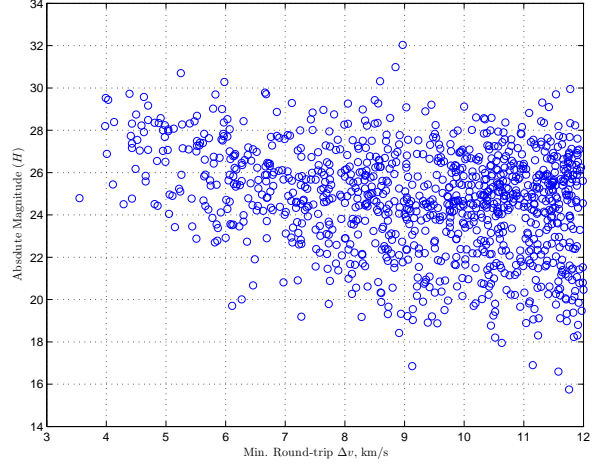
Figure 11: Minimum mission Δv versus absolute magnitude, H, for the NHATS-compliant NEAs.
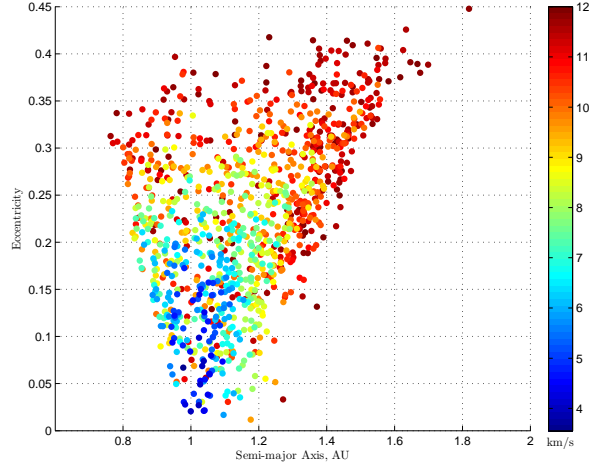
Figure 12: Minimum mission Δv for the NHATS-compliant NEAs as a function of a and e.
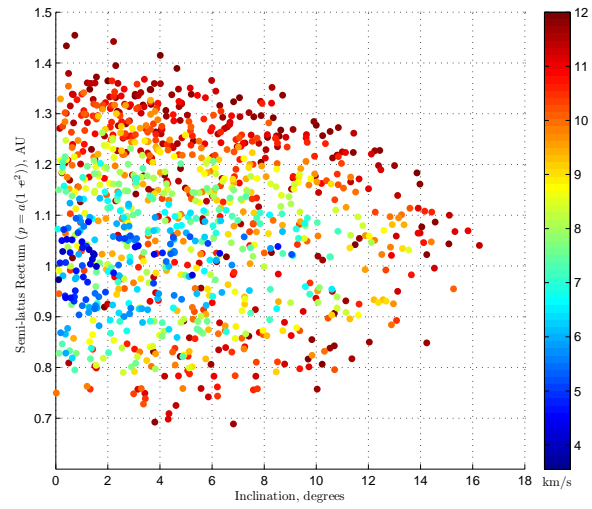
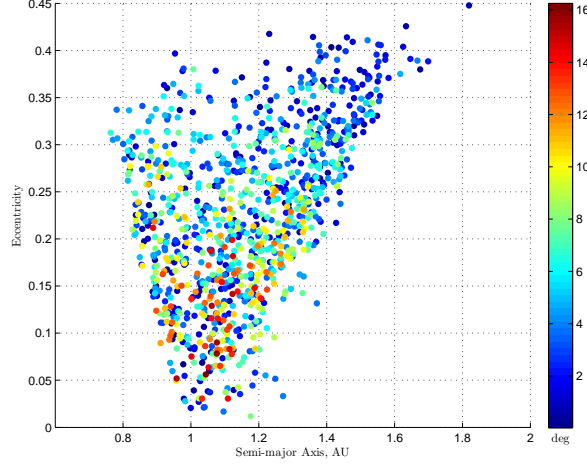Figure 13: Minimum mission Δv for the NHATS-compliant NEAs as a function of i and p.
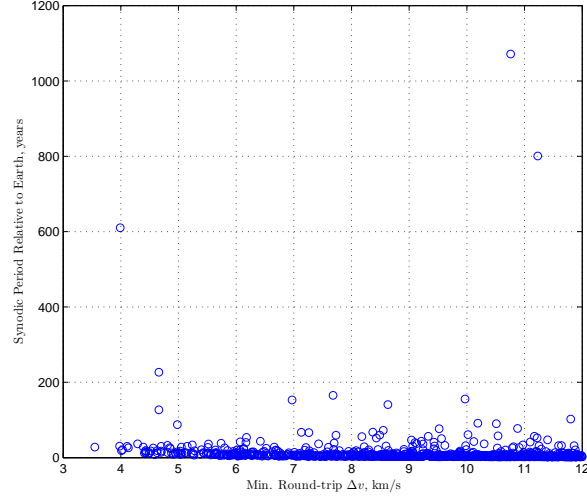
Figure 14: NEA inclination as a function of *a* and *e*.

Figure 15: Minimum round-trip Δv for the NHATS-compliant NEAs versus their synodic periods relative to Earth.

5. Example Round-Trip Trajectory Solutions for Selected NHATS-compliant NEAs

To provide examples of representative round-trip trajectory solutions under NHATS criteria, the NHATS web-site was queried to identify some NEAs with OCC < 5 offering mission opportunities departing Earth between 2024 and 2029 with total mission durations less than one year, at least two weeks spent at the NEA, and total mission Δv < 7 km/s. Six of the NEAs that meet those criteria were selected for discussion herein, but their selection for this discussion should not be interpreted as an endorsement of them as feasible destinations for future human space flight missions. Minimum Δv trajectory solutions for these NEAs from the NHATS web-site are presented in Table 6.

2000 SG_{344} is currently the most accessible NEA known in terms of the large number of low Δv, low duration round-trip trajectory opportunities it offers. Table 6 shows two trajectory solutions for 2000 SG_{344}, one requiring 346 days with very low Δv and another requiring 154 days with a Δv requirement approximately equal to that for a round-trip mission to low lunar orbit ($\sim$ 5 km/s). 341843 (2008 EV_5) is a relatively large NEA that has been characterized by ground-based radar observations and offers some reasonable mission opportunities. 2001 QJ_{142} has a well-known orbit and is estimated to be somewhat larger in size than 2000 SG_{344}. However, one thing that 2001 QJ_{142} has in common with 2000 SG_{344} is that the round-trip mission duration to visit it can be cut in half with a relatively modest increase in the required Δv. 2011 DV is one of the larger NHATS-compliant NEAs discovered within the past two years and while it's Δv requirement is somewhat high compared to the other selected NEAs, it is still interesting to examine if only for comparison. 2012 PB_{20} is a relatively recently discovered NEA, estimated to be similar in size to 2000 SG_{344}. Its Δv requirement is higher than that of 2000 SG_{344} but is still relatively low
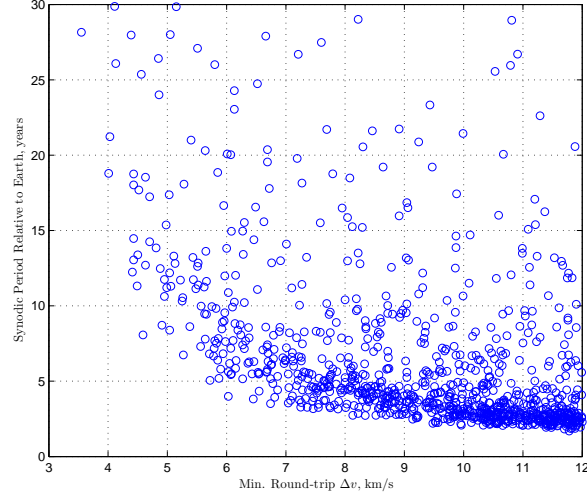
16

Figure 16: Minimum round-trip Δv for the NHATS-compliant NEAs versus their synodic periods relative to Earth with the vertical plot axis limited to 30 years.

Table 6: Round-trip mission opportunities departing Earth between 2024 and 2029 for selected NHATS-compliant NEAs.

	2000 SG$_{344}$		341843 (2008 EV$_5$)	2001 QJ$_{142}$		2011 DV	2012 PB$_{20}$	99942 Apophis
Estimated Diameter (m)	19–86		450	35–159		128–573	18–81	325
OCC	2		0	0		2	4	0
Total Δv (km/s)	**3.601**	**4.989**	**6.654**	**6.440**	**6.915**	**6.875**	**5.443**	**6.155**
Total Mission Duration (days)	**346**	**154**	**354**	**354**	**178**	**354**	**354**	**354**
Outbound Flight Time (days)	137	65	121	73	73	193	41	49
Stay Time (days)	32	16	64	16	16	32	32	16
Inbound Flight Time (days)	177	73	169	265	89	129	281	289
Earth Departure Date	2028-04-22	2029-07-14	2024-06-30	2024-03-18	2024-04-19	2024-10-28	2025-02-09	2029-04-09
Earth Departure C_3 (km^2/s^2)	1.737	1.990	25.051	2.897	5.818	28.035	17.053	26.201
Earth Departure Δv (km/s)	3.256	3.268	4.276	3.309	3.441	4.400	3.936	4.324
Earth Departure Declination	−8.723°	−22.498°	−20.430°	74.941°	27.574°	65.776°	−37.266°	16.894°
NEA Arrival Δv (km/s)	0.128	0.754	1.227	1.912	1.287	0.779	0.437	0.522
NEA Departure Δv (km/s)	0.217	0.968	1.152	1.219	2.186	1.696	1.069	1.310
Earth Return Δv (km/s)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Atmospheric Entry Speed (km/s)	11.141	11.157	11.692	11.244	11.396	11.996	11.592	11.734

compared to the other NEAs. The PCC plots for 2000 SG$_{344}$ and 2012 PB$_{20}$ from the NHATS web-site are shown in Figures 17 and 18, respectively, for comparison. Finally, 99942 Apophis is a very well-known, perhaps even infamous, NEA that has relatively low Δv requirements and is relatively large in size.

Note that several of the mission opportunities presented in Table 6 require large Earth departure declinations, e.g., 74.941°, 65.776°, and −37.266° for 2001 QJ$_{142}$, 2011 DV, and 2012 PB$_{20}$, respectively. Those cases will entail degraded mass-to-orbit performance for every launch during the assembly phase prior to Earth departure, which will generally increase launch costs for those missions compared to otherwise equivalent missions with departure declinations in the ± 28.5° range.

Table 7 presents the osculating heliocentric orbital elements for NEAs cited in Table 6 and shows that most of them have relatively Earth-like orbits.[23] Three notable exceptions are 341843 (2008 EV$_5$), 2011 DV, and 2012 PB$_{20}$, which have relatively high inclinations compared to the other three NEAs. Another interesting aspect of this set of NEAs is that 4 of the 6 are Atens and 3 of the 6 are PHAs.[24]

Four of the trajectory solutions in Table 6 are subjected to further analysis by simulating the associated round-trip spacecraft trajectories, and the Earth and Sun distances observed during those simulations are summarized in Table 8. The variability in distance from the Sun (important for solar electric power and thermal control reasons) is generally less than ± 10% of 1 AU, but the variability in the maximum distance from Earth is larger. The relatively

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[23]Retrieved from the JPL Small-Body Database Browser web-site at `http://ssd.jpl.nasa.gov/sbdb.cgi` on 2013-03-17.

[24]Note that 99942 Apophis is an Aten on the Table 6 launch date in early April 2029. However, the April 13, 2029 close approach of Apophis to Earth transforms the orbit of Apophis such that is re-classified as an Apollo. Thus, Apophis is a Aten when the spacecraft launches towards it, but it has become an Apollo by the time the spacecraft arrives.
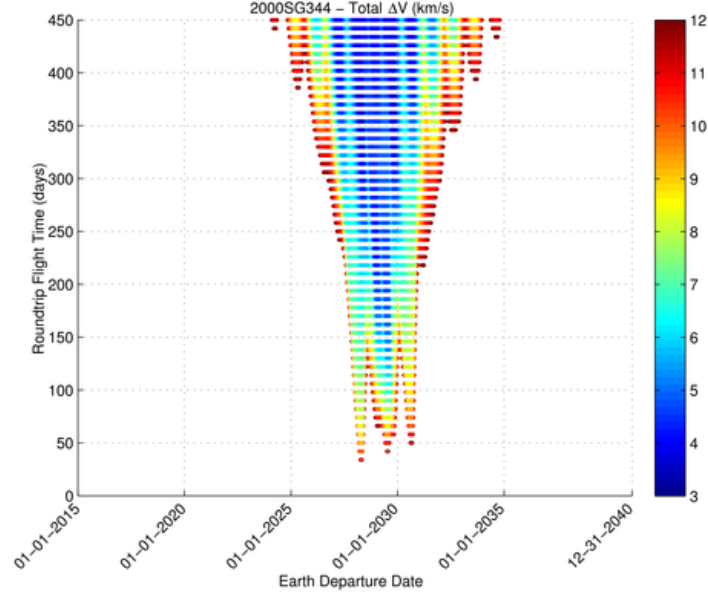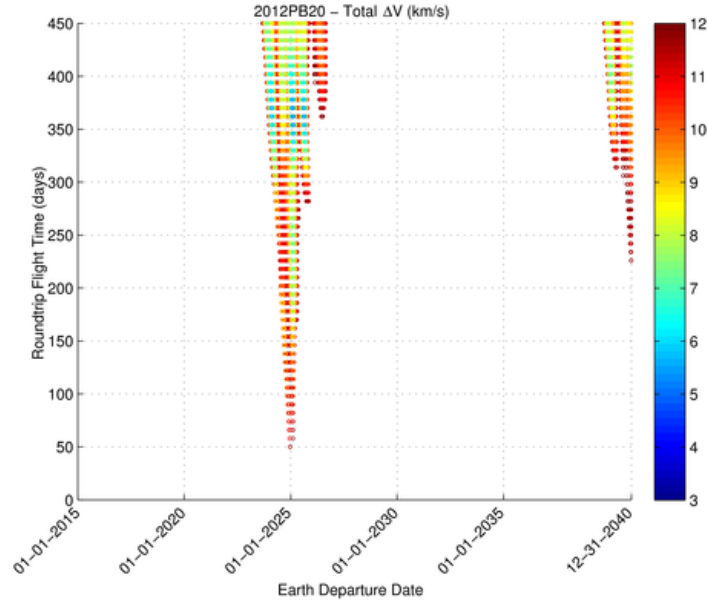
Figure 17: NHATS PCC plot for 2000 SG$_{344}$.

Figure 18: NHATS PCC plot for 2012 PB$_{20}$.

Table 7: Osculating orbital elements at epoch 2013-04-18.0 TDB and orbit group classifications for the NHATS-compliant NEAs in Table 6.

	2000 SG$_{344}$	341843 (2008 EV$_5$)	2001 QJ$_{142}$	2011 DV	2012 PB$_{20}$	99942 Apophis
Semi-major Axis (AU)	0.9775	0.9582	1.0618	0.9567	1.0541	0.9223
Eccentricity	0.0669	0.0835	0.0861	0.0496	0.0948	0.1910
Inclination	0.1112°	7.4370°	3.1031°	10.594°	5.8384°	3.3319°
Classification	Aten	Aten, PHA	Apollo	Aten, PHA	Apollo	Aten, PHA

short 154 day mission to 2000 SG$_{344}$ takes the spacecraft only 21 Lunar Distances (LD) from Earth, whereas the longer 354 day trajectories take the spacecraft much farther from Earth. However, there is still variability amongst

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Table 8: Distances from Sun and Earth for selected round-trip NEA mission trajectories from Table 6.

	2000 SG$_{344}$ (154 day)	2008 EV$_5$	2012 PB$_{20}$	99942 Apophis
Minimum Distance to Sun (AU)	0.976	0.912	0.951	0.893
Maximum Distance from Sun (AU)	1.027	1.074	1.052	1.109
Maximum Distance from Earth (AU)	0.055	0.343	0.224	0.499
Maximum Distance from Earth (LD)	21.226	133.325	86.987	194.211

the 354 day trajectories; the mission to 2012 PB$_{20}$ only travels 87 LD from Earth whereas the missions of equal duration to 2008 EV$_5$ and 99942 Apophis reach 133 and 194 LD from Earth, respectively. For comparison, the ecliptic plane projections of the heliocentric inertial frame trajectory plots for the 2000 SG$_{344}$ and 2012 PB$_{20}$ missions are presented in Figures 19 and 20, respectively, while geocentric views of these trajectories are shown in Figures 21 through 24.
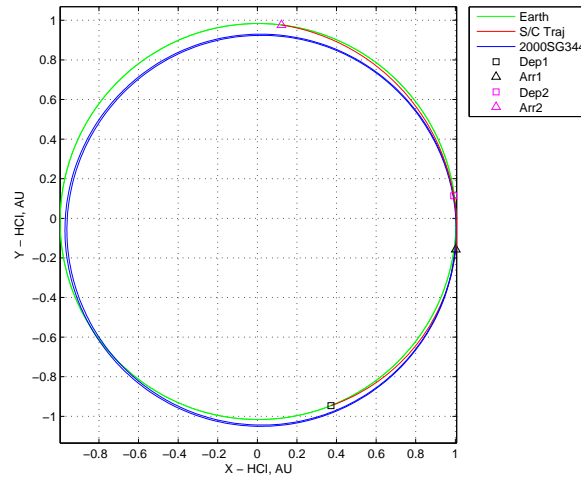
Figure 19: Heliocentric inertial frame view (ecliptic plane projection) of 154 day round-trip trajectory to 2000 SG$_{344}$.
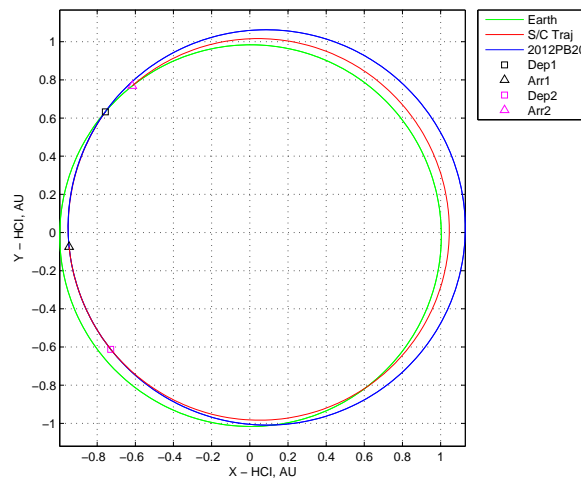
Figure 20: Heliocentric inertial frame view (ecliptic plane projection) of 354 day round-trip trajectory to 2012 PB$_{20}$.
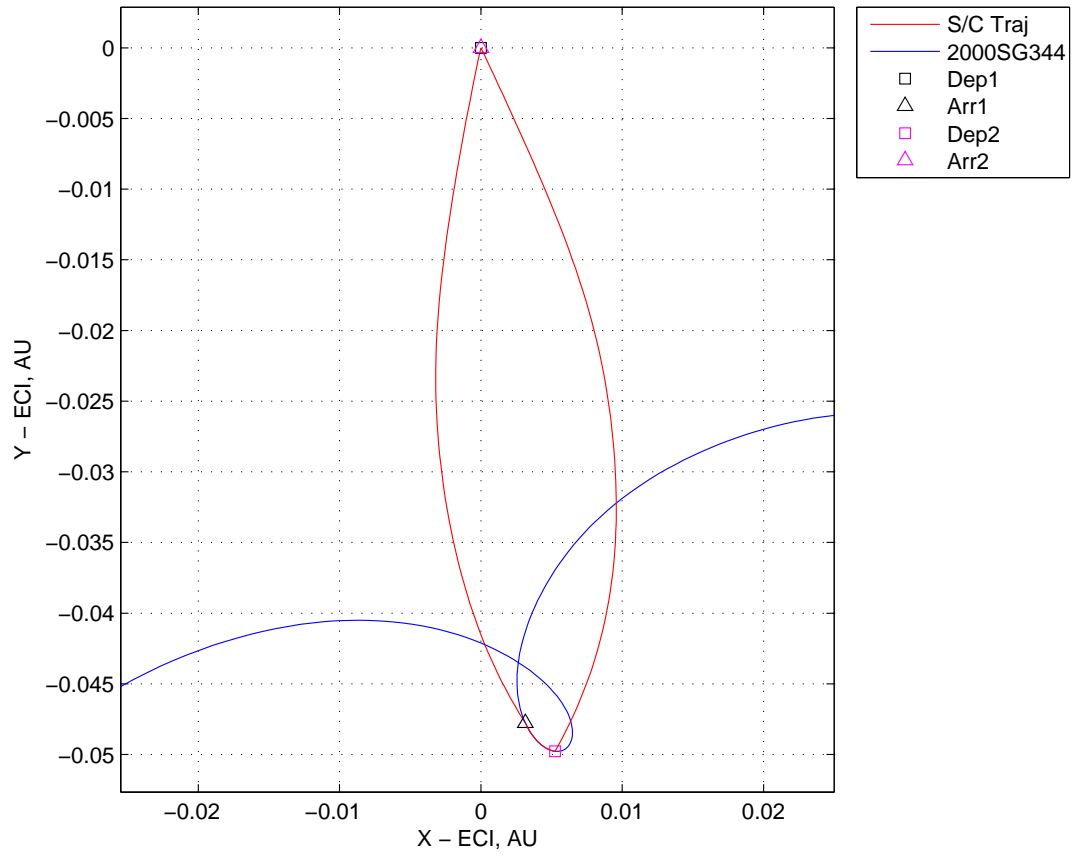
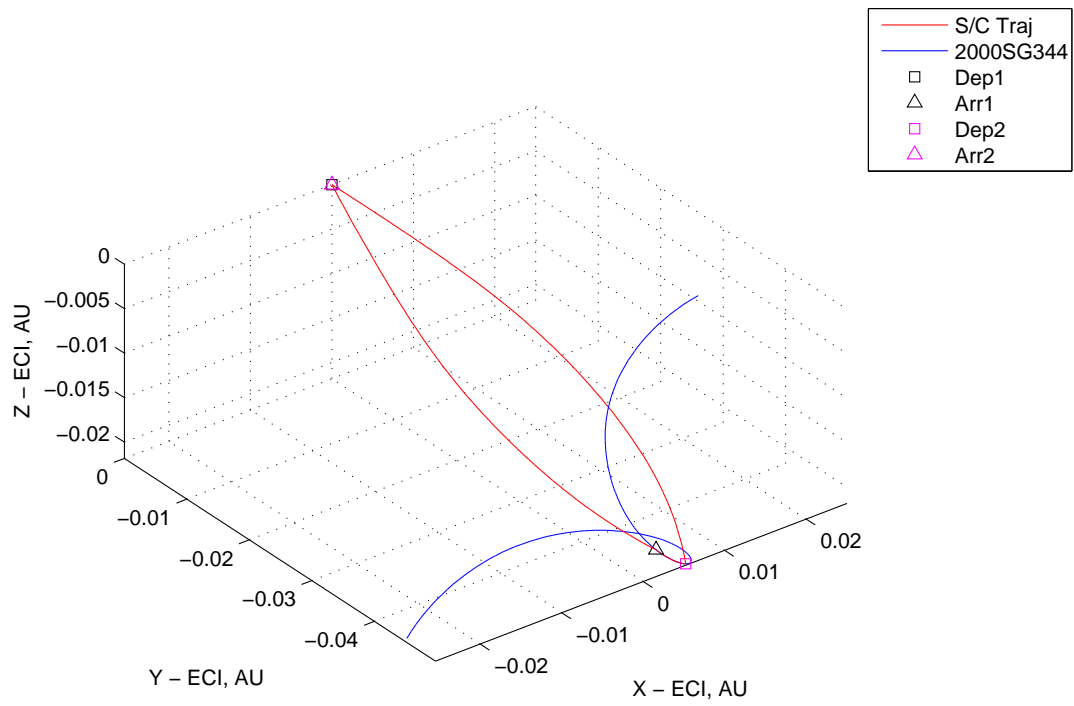Figure 21: Geocentric inertial view (equatorial plane projection) of 154 day round-trip trajectory to 2000 SG$_{344}$.

Figure 22: Geocentric inertial view (three-dimensional view) of 154 day round-trip trajectory to 2000 SG$_{344}$.
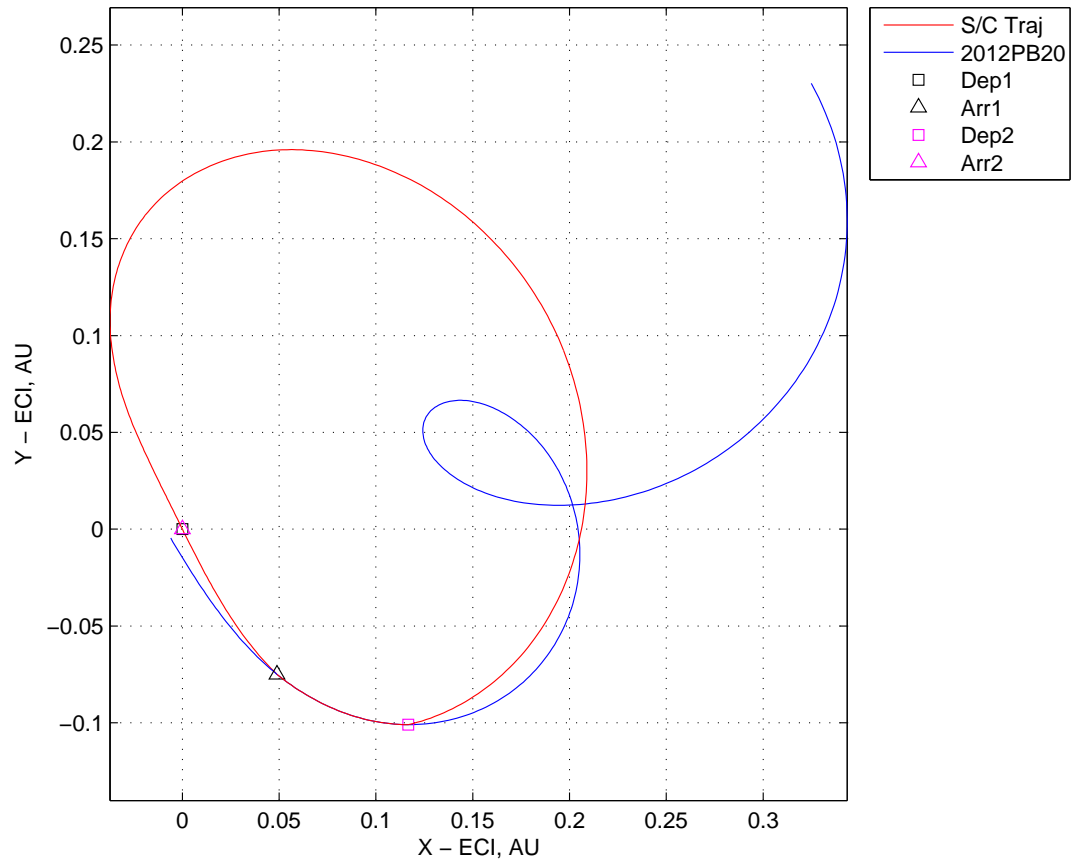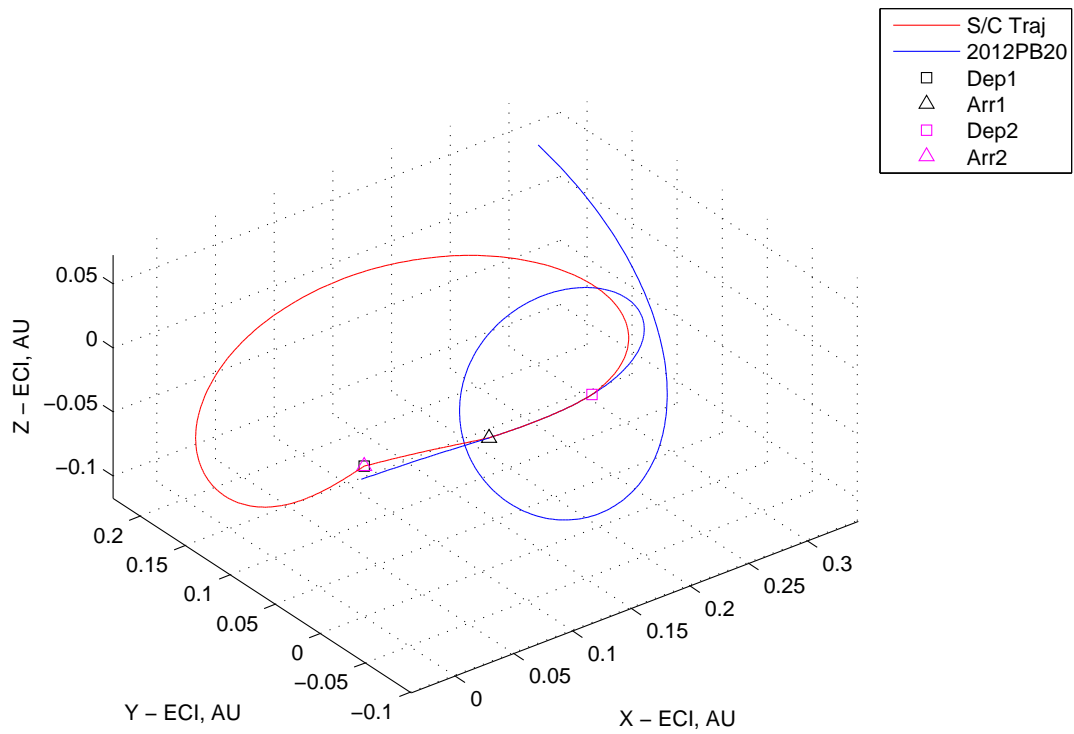
20

Figure 23: Geocentric inertial view (equatorial plane projection) of 354 day round-trip trajectory to 2012 PB_{20}.

Figure 24: Geocentric inertial view (three-dimensional view) of 354 day round-trip trajectory to 2012 PB_{20}.

6. Conclusions

Since its inception during the fourth quarter of 2010, the NHATS has provided an unprecedented comprehensive view of the NEA accessibility landscape for future exploration missions. In this paper we have described the development of the NHATS processing system that keeps the NHATS data current with respect to new NEA discoveries and updated NEA orbit knowledge, as well as the NHATS web-site that makes the large database of round-trip NEA trajectory data publicly available and provides timely notification of opportunities to observe these objects to obtain critical follow-up observations to secure our knowledge of their orbits and collect physical characterization data.

The NHATS has defined a unique sub-population of NEAs, the NHATS-compliant NEAs, that are unusually accessible relative to the NEA population as a whole. NHATS-compliant NEAs currently comprise approximately 11% of known NEAs, and approximately 8 to 12% of the NHATS-compliant NEAs are also classified as Potentially Hazardous Asteroids (PHAs), depending on PHA size definition. Round-trip missions to any of the NHATS-compliant NEAs require less Δv than round-trip missions to Mars, while round-trip missions to hundreds of the NHATS-compliant NEAs require less Δv than round-trip mission to the lunar surface. There are even several dozen NHATS-compliant NEAs for which round-trip missions require less Δv than a round-trip mission to lunar orbit or an Earth-Moon Lagrangian point orbit.

Analysis of the NHATS data reveals that the most accessible NHATS-compliant NEAs tend to have relatively Earth-like orbits, although there are some interesting exceptions to this precept. Furthermore, the NHATS-compliant NEAs are smaller than most of the general NEA population currently known, and the most accessible NHATS-compliant NEAs tend to be smaller still. These interesting trends may be studied further in the context of both observation bias and the dynamical evolution of the NEA population.

Relatively few NEA mission opportunities with very low Δv and mission duration are available for sizable NEAs with Earth departure during the mid to late 2020s, and the same enhancements to NEA observing capabilities that are crucial to finding hazardous NEAs well in advance of Earth impacts will also serve to discover larger numbers of attractive NHATS-compliant NEAs well in advance of their programmatically desirable Earth departure seasons. NEAs represent a unique and powerful intersection of planetary defense interests, fundamental solar system science, and pioneering human exploration beyond the Earth-Moon system.

NEAs are among the most potent threats and richest opportunities found in nature, and this duality makes them all the more intriguing and worthy of our attention. Studying them prepares us to defend ourselves against any would-be Earth impactors, while simultaneously greatly expanding our understanding of both the very early solar system and the natural environment in which we find ourselves today. Their proximity to Earth and Earth-like orbits, both of which create the possibility of Earth collisions, also make them the most dynamically accessible deep space destinations for future human and robotic explorers. Furthermore, their high accessibility, compositions, and lack of strong gravitational fields make them prime targets for the development and application of in-situ resource utilization techniques that may prove vital to future expansion of human presence in our solar system and perhaps, someday, beyond.

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