Near-Earth Asteroids: The Next Destination for Human Explorers

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1 Introduction

Near-Earth objects (NEOs) are asteroids and comets with perihelion distance < 1.3 AU, permitting many of them to closely approach or cross Earth's orbit. The vast majority of NEOs are asteroids, classified as near-Earth asteroids (NEAs). Figure 1 presents the various NEA groups according to orbit type. These objects are largely unchanged since the early days of our solar system and may have even deposited the seeds of life on the young Earth; the study of NEOs therefore provides vital scientific knowledge about the formation and evolution of the solar system, our planet, and ourselves. There is also evidence of many past impacts on Earth by these objects, some of which were sufficiently energetic to destroy life on a planetary scale. NEOs therefore bear careful monitoring for the possibility of future impacts that we may be able to prevent if proper preparations are made. The close proximity of some NEOs' orbits to Earth's orbit and the fact that some of them contain usable resources, such as water, raises the possibility of sending human explorers to visit them. Human missions to NEAs would be the most ambitious and exciting journeys of human discovery since the Apollo missions and would therefore serve to reinvigorate our space program and renew public passion for space exploration. Those missions would also provide much-needed experience in true interplanetary travel prior to larger, longer-duration expeditions to more distant destinations, such as Mars.

In 2009, the Augustine Commission identified NEAs as high value destinations for human exploration missions beyond the 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 National Space Policy of the United States of America on June 28, 2010.[1] Planning such deep space missions and identifying potential NEAs as destinations for human spaceflight requires selecting objects from the large and ever growing list of known NEAs. At the time of this writing $9,910$ NEAs have been discovered[2] and more are being discovered on a continual basis. Statistical models of the total NEO population allow us to estimate how many NEOs remain to be discovered, and recent data from the NEOWISE mission has yielded an updated estimate of the size of the NEO population. The estimated population of NEOs ≥ 1 km in diameter is nearly $1,000$; just over 90% of these have been discovered and determined to not pose a threat to Earth. However, there are an estimated $16,300$ NEOs with diameters between 100 and $1,000$ m yet to be discovered. Thus far approximately $3,500$ NEOs with diameters < 100 m have been discovered and there may be hundreds of thousands, if not millions, of NEOs in this size category yet to be discovered.

In order to monitor the growing population of known NEAs for human space flight accessibility, NASA began the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) (pron.: /næts/) in

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[1] `http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf`, accessed on 2013-06-21

[2] `http://neo.jpl.nasa.gov/stats/`, accessed on 2013-06-23.

September of 2010. The purpose of the NHATS is to identify known NEOs, particularly NEAs, that may be accessible for future human space flight missions.[1, 2] Additional background and the NHATS data itself, updated daily, are available at `http://neo.jpl.nasa.gov/nhats/`.

2 Motivations for Human Exploration of NEAs

There are many compelling reasons to study NEAs and send humans to visit them. They are vital targets for fundamental solar system science and the impact threat they pose to life on Earth makes it even more imperative that we understand the details of their physical characteristics so that we may be prepared to act when we discover a NEA on a collision course with Earth. The close proximity of NEA orbits to Earth's orbit also raises the possibility of deploying relatively short duration round-trip human missions to visit them and perhaps one day utilize their natural resources.

2.1 Science

Asteroids and comets are largely unchanged in composition since the early days of our solar system, and studying them provides vital insight into our origins. For instance, the Stardust mission to the comet Wild 2 returned samples of cometary material that proved the existence of large-scale circulation patterns in the solar nebula, which completely revised our views of nebular dynamics and chemistry [3]. Additionally, it is possible that asteroids and comets may have delivered vast quantities of water to the young Earth and may have also have carried the seeds of life itself.

2.2 The Impact Hazard

NEOs pose a threat to life and property on Earth because they can collide with our planet, sometimes to devastating effect. Potentially Hazardous Asteroids (PHAs) are defined[3] as having a Minimum Orbit Intersection Distance (MOID) with Earth ≤ 0.05 AU and estimated diameter ≥ 150 m. There are currently $1,411$ known PHAs. Given that the PHA definition is meant to identify NEAs that could pose a significant threat to life and/or property on Earth's surface, a more inclusive PHA estimated diameter criterion might be ≥ 50 m. $2,435$ of the currently known PHAs meet that criterion. At least once per year, Earth is struck by very small NEAs that explode at extremely high altitudes, and NEAs pass within the Moon's orbit radius every few weeks. Our planet bears the scars of past NEO impacts, though they are largely obscured by natural processes. At the time of this writing the number of confirmed impact structures discovered on Earth[4], is 184 and counting. One of the most famous is the Chicxulub crater in the Yucatan peninsula, formed approximately 65 million years ago by an impact that caused the Cretaceous-Paleogene (K-Pg) extinction event[5], during which the dinosaurs and most other species alive at the time were made extinct [4]. More recently, on February 15th, 2013, a 17 to 20 m diameter NEO released 440 kt of energy[6] when it exploded approximately 23 km above the Russian city of Chelyabinsk, injuring $1,500$ people and damaging some $7,200$ buildings.

2.3 Resource Utilization

NEAs contain a variety of raw materials that could be harvested, including useful substances such as iron, rock, water, carbon, nitrogen, semiconductor and platinum group metals, and trapped gasses such as carbon

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[3] `http://neo.jpl.nasa.gov/neo/groups.html`, accessed 2013-06-21.

[4] `http://www.passc.net/EarthImpactDatabase/index.html`, accessed on 2013-06-23.

[5] In the past this event was commonly referred to as the Cretaceous/Tertiary (K/T) boundary extinction event.

[6] This is approximately 20–30 times more energy than was released by the nuclear explosive detonated at Hiroshima.

dioxide and ammonia. These resources can be utilized for a variety of purposes, including the manufacture of radiation shielding and spacecraft propellant, without needing to expend the tremendous energy required to launch the raw materials into space from Earth or another gravity well (such as the Moon or Mars). Harnessing these resources will require extensive infrastructure development, however the first steps are to identify available resources and develop utilization capabilities. That will require scientific study, the ability to have humans operate effectively and safely in the vicinities of NEAs and on their surfaces for extended periods of time, and the capability to modify NEA orbits. NEA resource utilization is clearly synergistic with solar system science, planetary defense, and human exploration.

3 The Accessibility of NEAs for Human Exploration

The aforementioned NHATS uses a comprehensive astrodynamics-based trajectory analysis to determine which NEAs offer mission opportunities that satisfy the following mission design constraints: Earth departure date between 2015-01-01 and 2040-12-31; Earth departure $C_3 \leq 60$ km^2/s^2; Earth atmospheric entry speed ≤ 12 km/s at an altitude of 125 km; 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 Earth atmospheric entry speed constraint); Total round-trip mission duration ≤ 450 days; and stay time at the NEA ≥ 8 days. A diagram depicting the mission sequence is shown in Figure 2. At the time of this writing, $1,071$ of the currently known NEAs offer at least one trajectory solution meeting the NHATS constraints; such NEAs are classified as NHATS-compliant. A summary of the currently known NHATS-compliant NEAs is presented in Table 1.

To provide context for the NHATS accessibility criteria (Δv, mission duration, etc.), consider that a round-trip mission 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 mission 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) [5]. Round-trip missions to Earth-Moon Lagrangian point orbits have requirements similar to those of lunar orbit missions.

It is also instructive to compare the accessibility of NHATS-compliant NEAs to the accessibility of the martian surface for human space flight missions. The Addendum to NASA's Mars Design Reference Architecture (DRA) 5.0 report [6] documents round-trip conjunction class Mars missions with Earth departure dates between the years 2031 and 2046. The required mission durations range between 877 and 923 days, roughly twice as long as the maximum NHATS mission duration of 450 days, and the best case total Δv for a round-trip mission to the martian surface is at least 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 12 km/s atmospheric entry speed limit enforced in the NHATS.[7] 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[8] shows that every ~ 15 years there are opportunities for opposition class round-trip missions to a highly eccentric 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 exceeds 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.

Considering the NHATS data presented in Table 1 in light of the aforementioned lunar and martian mission requirements shows that, in terms of total mission Δv,:

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[7] Enforcing the NHATS entry speed limit for these Mars missions would require additional Δv and/or mission duration in some cases.

[8] Performed by B. W. Barbee and colleagues, not yet published.

- All $1,071$ currently known NHATS-compliant NEAs are more accessible for round-trip missions than Mars orbit or the martian surface;
- 441 of the currently known NHATS-compliant NEAs are more accessible for round-trip missions than the lunar surface;
- 38 of the currently known NHATS-compliant NEAs are more accessible for round-trip missions than low lunar orbit or Earth-Moon Lagrangian point orbits.

However, it is important to note that those numbers of NHATS-compliant NEAs offering mission opportunities at various levels of Δv result from applying the least restrictive constraints on Orbit Condition Code (OCC)[9], absolute magnitude (H)[10], 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, as 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. The data in Table 2 show that the currently known NEA population is lacking in sizable members with accurately determined orbits offering low Δv, short duration mission opportunities during the mid to late 2020s. This has led the technical community concerned with NEOs to recommend the deployment of a space-based NEO survey telescope that would avoid the geometrical constraints associated with observing solely from Earth and thus provide a very comprehensive NEO population survey within only a few years of deployment [7]. Such a survey would simultaneously benefit the scientific, human space flight, and planetary defense communities.

On the other hand, Table 2 also indicates that there are several known NEAs that are sizable, have accurately determined orbits, and offer some 6 to 12 month round-trip mission opportunities during the mid to late 2020s that require much less Δv than missions to the lunar surface, Mars orbit, or the martian surface. Specific mission opportunity data for some of these NEAs, obtained from the NHATS web-site, are presented in Table 3, while Table 4 displays the associated minimum and maximum distances to the Sun (relevant to thermal protection and solar power, respectively) and maximum distance from Earth (relevant to communications and human psychology) for selected NEA mission trajectories. For reference, Figures 3–6 display heliocentric and geocentric views of the round-trip mission trajectories to visit two of the NEAs that appear in Table 3.

4 Conclusion

NEAs are among the most exciting and intriguing destinations in our solar system for human explorers. While there are only eight planets, there are many thousands of NEAs, each a fascinating and unique world unto itself whose secrets contain the clues to our primordial past and the keys to our future aspirations. We are therefore quite fortunate that round-trip missions to any of the $1,071$ currently known NHATS-compliant NEAs require less Δv than round-trip missions to Mars, and round-trip missions to hundreds of those NEAs require less Δv than a round-trip mission to the lunar surface. There are even several dozen of those NEAs for which round-trip missions require less Δv than a round-trip mission to lunar orbit or an Earth-Moon Lagrangian point orbit—and we discover more NEAs on a continual basis.

However, 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. Fortunately, the same enhancements to NEA observing capabilities that are crucial to finding hazardous NEAs well in advance of Earth impacts

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[9] 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 2013-06-23.

[10] Absolute magnitude is indicative of NEO diameter, with decreasing absolute magnitude corresponding to increasing diameter. For the definition of absolute magnitude, see `http://neo.jpl.nasa.gov/glossary/h.html`, accessed 2013-06-23.

will also serve to discover larger numbers of attractive NHATS-compliant NEAs well in advance of their programmatically desirable Earth departure seasons.

NEAs are a unique and powerful intersection of planetary defense interests, fundamental science, and pioneering human exploration beyond the Earth-Moon system, and are therefore among the most potent threats and richest opportunities found in nature. This profound duality makes them all the more compelling and worthy of our attention. Visiting and 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 live 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 human 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. For all of these reasons, and more, NEAs should be the next destination for human explorers.

Disclaimer

The views and opinions expressed herein are those of the author and do not necessarily state or reflect those of NASA or the United States Government, nor do they represent the official position of NASA.

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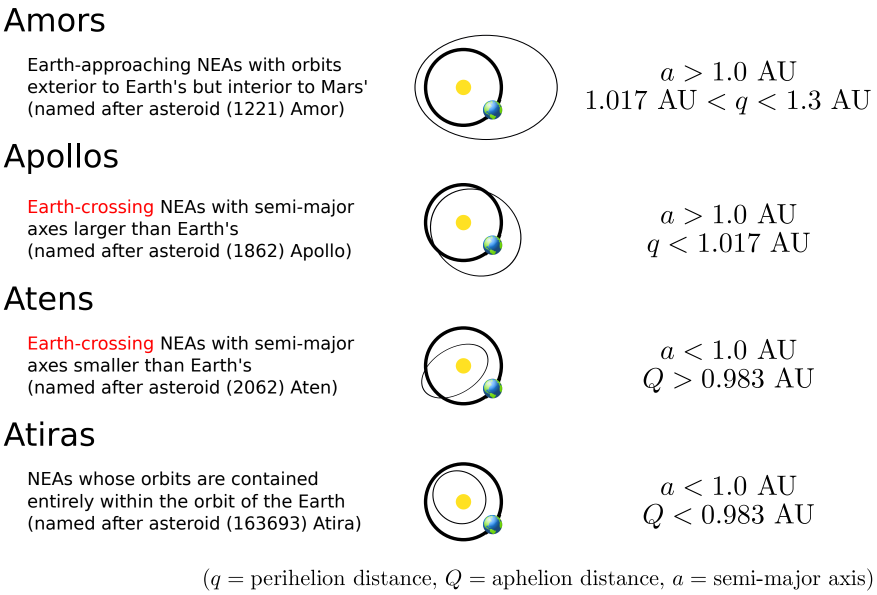

Amors

Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid (1221) Amor)

$a > 1.0$ AU
$1.017 \text{ AU} < q < 1.3$ AU

Apollos

Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid (1862) Apollo)

$a > 1.0$ AU
$q < 1.017$ AU

Atens

Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid (2062) Aten)

$a < 1.0$ AU
$Q > 0.983$ AU

Atiras

NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid (163693) Atira)

$a < 1.0$ AU
$Q < 0.983$ AU

(q = perihelion distance, Q = aphelion distance, a = semi-major axis)

Figure 1: NEA groups according to orbit type.

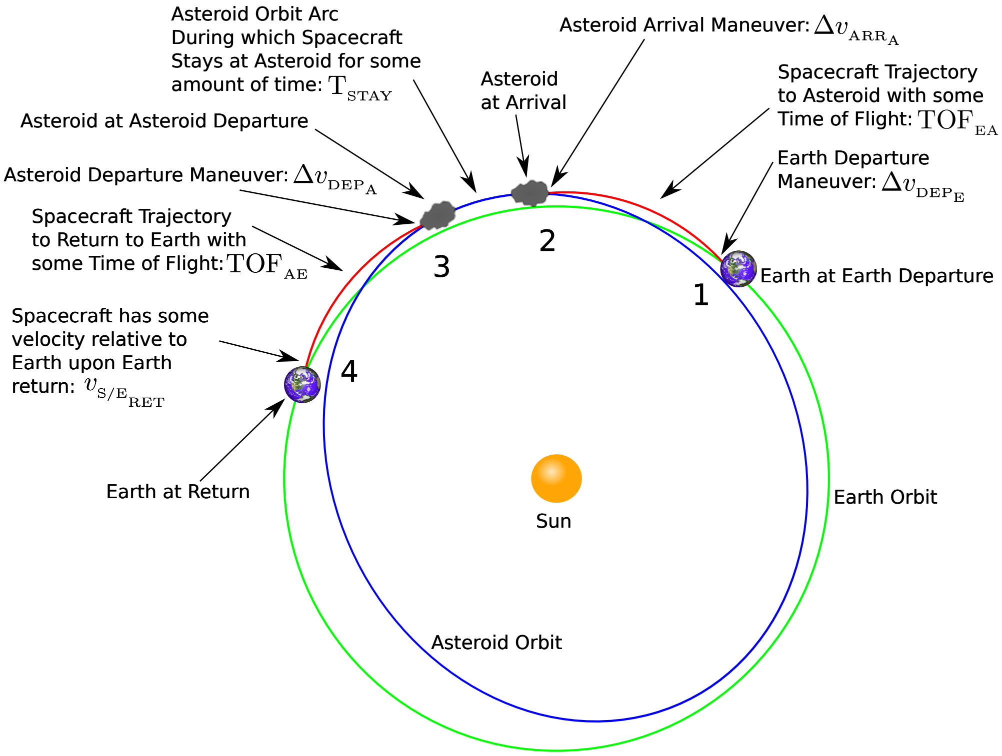

Figure 2: High-level depiction of the mission sequence for a human mission to a NEA.

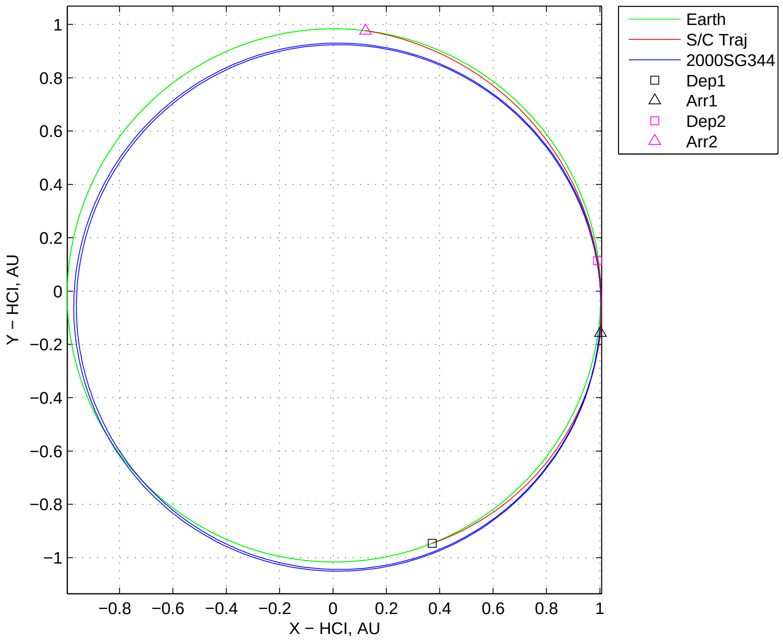

Figure 3: Heliocentric inertial frame view (ecliptic plane projection) of 154 day round-trip trajectory to 2000 SG$_{344}$.

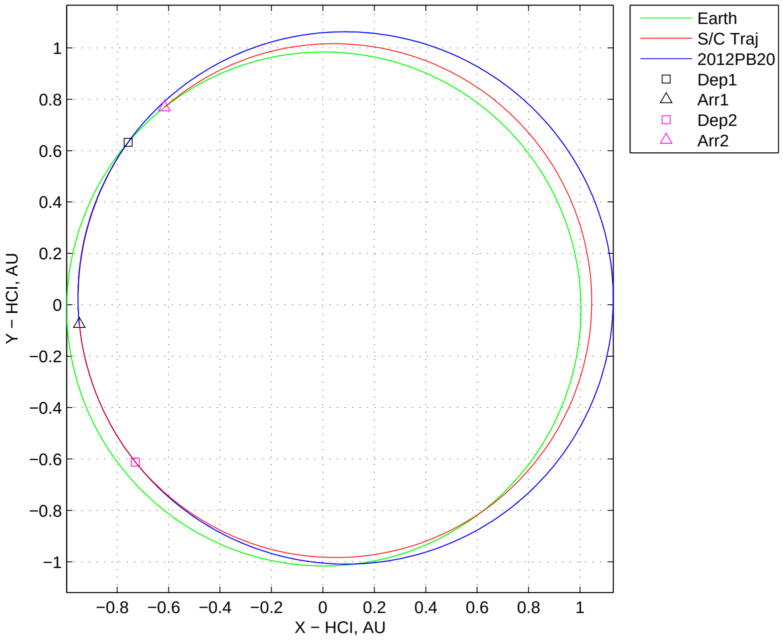

Figure 4: Heliocentric inertial frame view (ecliptic plane projection) of 354 day round-trip trajectory to 2012 PB$_{20}$.

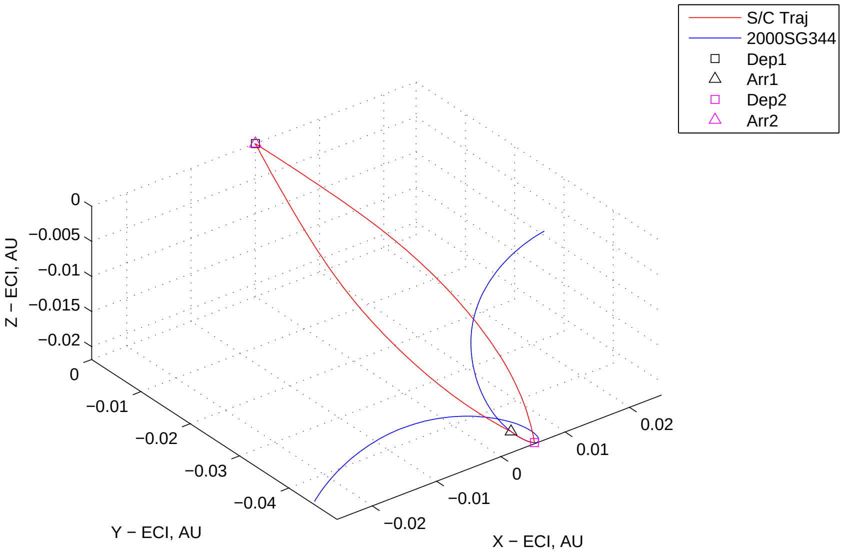

Figure 5: Geocentric inertial view (three-dimensional view) of 154 day round-trip trajectory to 2000 SG$_{344}$.

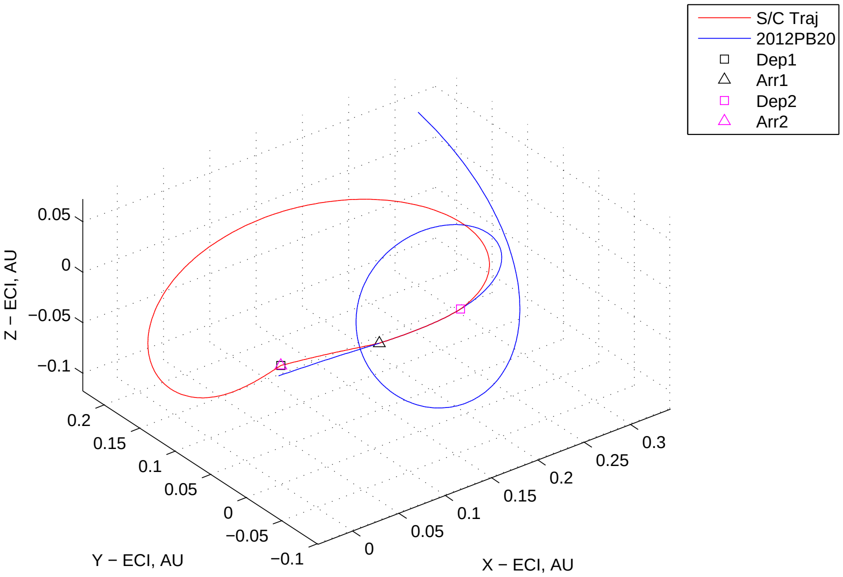

Figure 6: Geocentric inertial view (three-dimensional view) of 354 day round-trip trajectory to 2012 PB$_{20}$.

Table 1: Number of NHATS-compliant NEAs known on 2013-05-27 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
$\Delta v \leq 4$											1	1	2	2	3
$\Delta v \leq 5$					1	5	6	7	9	12	16	27	32	35	38
$\Delta v \leq 6$			3	4	7	15	19	24	33	39	54	79	90	94	96
$\Delta v \leq 7$		1	4	7	19	34	58	72	82	98	125	158	175	177	179
$\Delta v \leq 8$		3	11	20	39	85	112	124	144	166	204	259	280	286	286
$\Delta v \leq 9$		10	25	45	87	142	182	201	229	257	323	394	422	435	441
$\Delta v \leq 10$	1	18	47	80	150	212	270	301	328	366	452	538	582	594	605
$\Delta v \leq 11$	1	31	92	138	221	317	382	414	462	515	619	716	778	804	818
$\Delta v \leq 12$	3	50	131	194	315	429	516	563	613	688	807	942	1025	1052	1071

Table 2: Number of NHATS-compliant NEAs known on 2013-05-27 within all combinations of compliant mission Δv and duration thresholds with Earth departure date between 2025 and 2030, $H \leq 23.0$, 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
$\Delta v \leq 4$											▨	▨	▨	▨	▨
$\Delta v \leq 5$					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
$\Delta v \leq 6$			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	1	1	1
$\Delta v \leq 7$		▨	▨	▨	▨	▨	▨	▨	▨	▨	3	4	4	4	4
$\Delta v \leq 8$		▨	▨	▨	▨	▨	▨	▨	▨	2	4	6	8	9	9
$\Delta v \leq 9$		▨	▨	▨	▨	2	3	4	5	8	14	20	22	26	28
$\Delta v \leq 10$	▨	▨	▨	1	2	6	8	9	13	16	26	32	44	45	51
$\Delta v \leq 11$	▨	▨	1	2	5	13	17	18	23	30	44	60	71	84	89
$\Delta v \leq 12$	▨	1	2	3	13	20	29	31	40	53	68	91	122	128	131

Table 3: 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

Table 4: Distances from Sun and Earth for selected round-trip NEA mission trajectories from Table 3.

	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