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

Presented to the 2013 IAA Planetary Defense Conference

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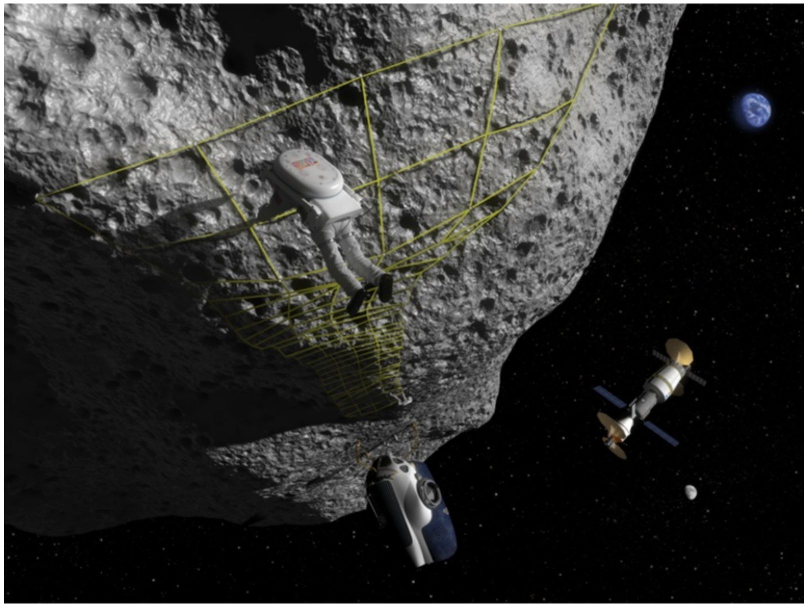
April 16th, 2013

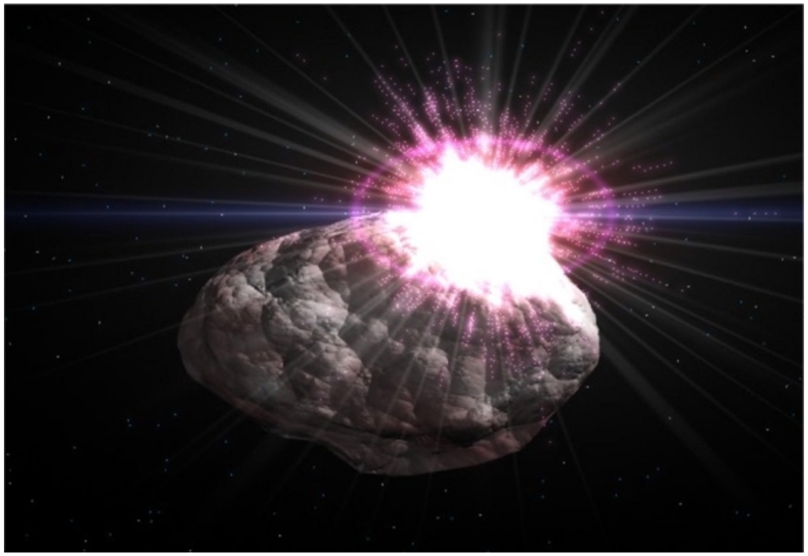
Introduction

- **Near-Earth Objects (NEOs)** are asteroids and comets with perihelion distance < 1.3 AU
    - Small, usually rocky bodies (occasionally metallic)
    - Sizes range from a few meters to ≈ 35 kilometers
- **Near-Earth Asteroids (NEAs)** are currently candidate destinations for human space flight missions in the mid-2020s
- **As of April 4th, 2013, a total of 9736 NEAs have been discovered, and more are being discovered on a continual basis**



Motivations for NEA Exploration

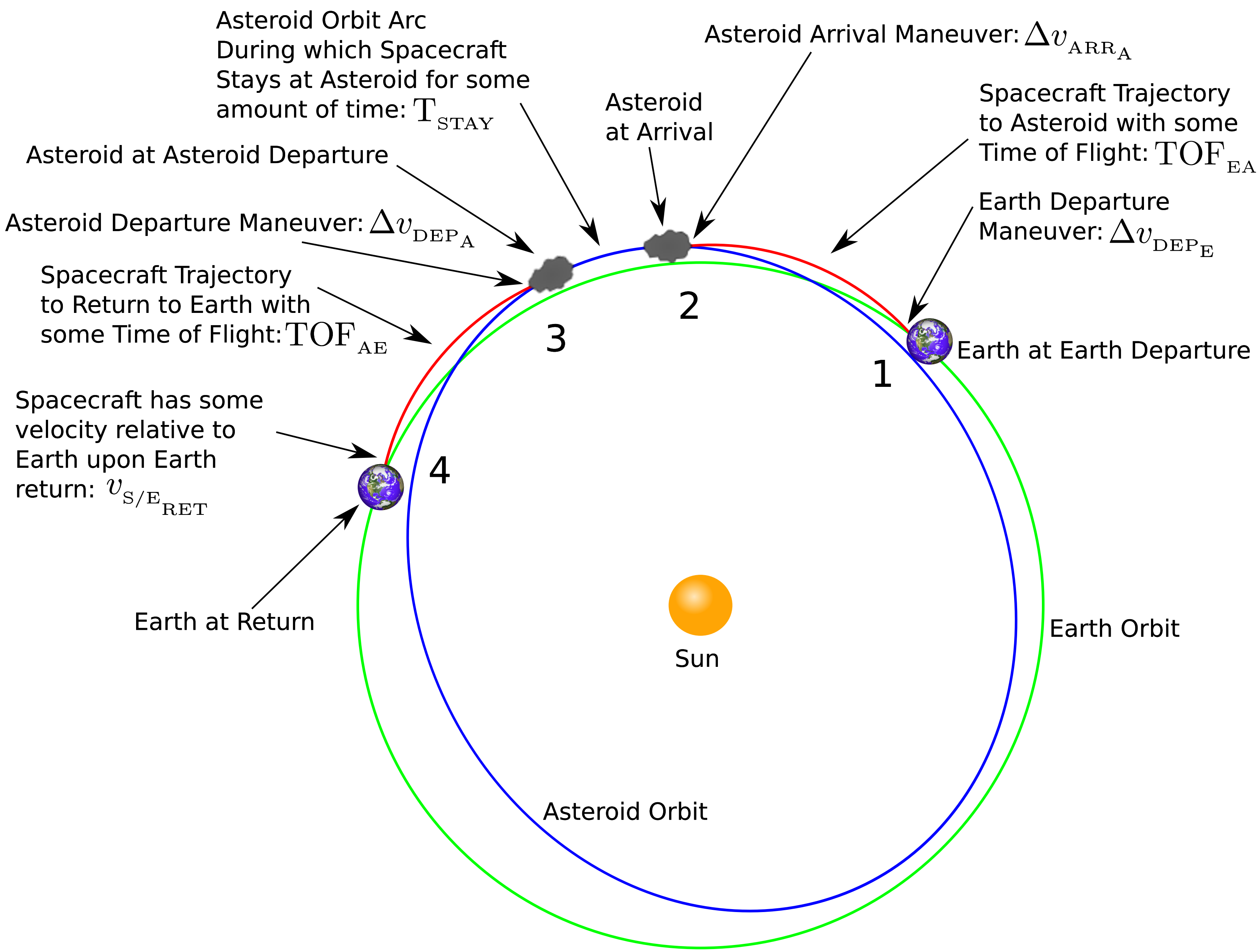
- **Solar system science**
  - NEAs are largely unchanged in composition since the early days of the solar system
  - Asteroids and comets may have delivered water and even the seeds of life to the young Earth
- **Planetary defense**
  - NEA characterization
  - NEA proximity operations
- **In-Situ Resource Utilization**
  - Could manufacture radiation shielding, propellant, and more
- **Human Exploration**
  - The most ambitious journey of human discovery since Apollo
  - NEAs as stepping stones to Mars



NHATS Background

- 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.
- Phase I of the NHATS, was performed during the month of September and October in 2010, and Phase II was performed during the months of February and March in 2011.
- The NHATS system was subsequently automated, and a web-site was constructed by NASA's NEO Program Office to house the NHATS data in a sortable, filterable interface; the NHATS web-site was publicly released on March 20th, 2012.
- 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.
- 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.

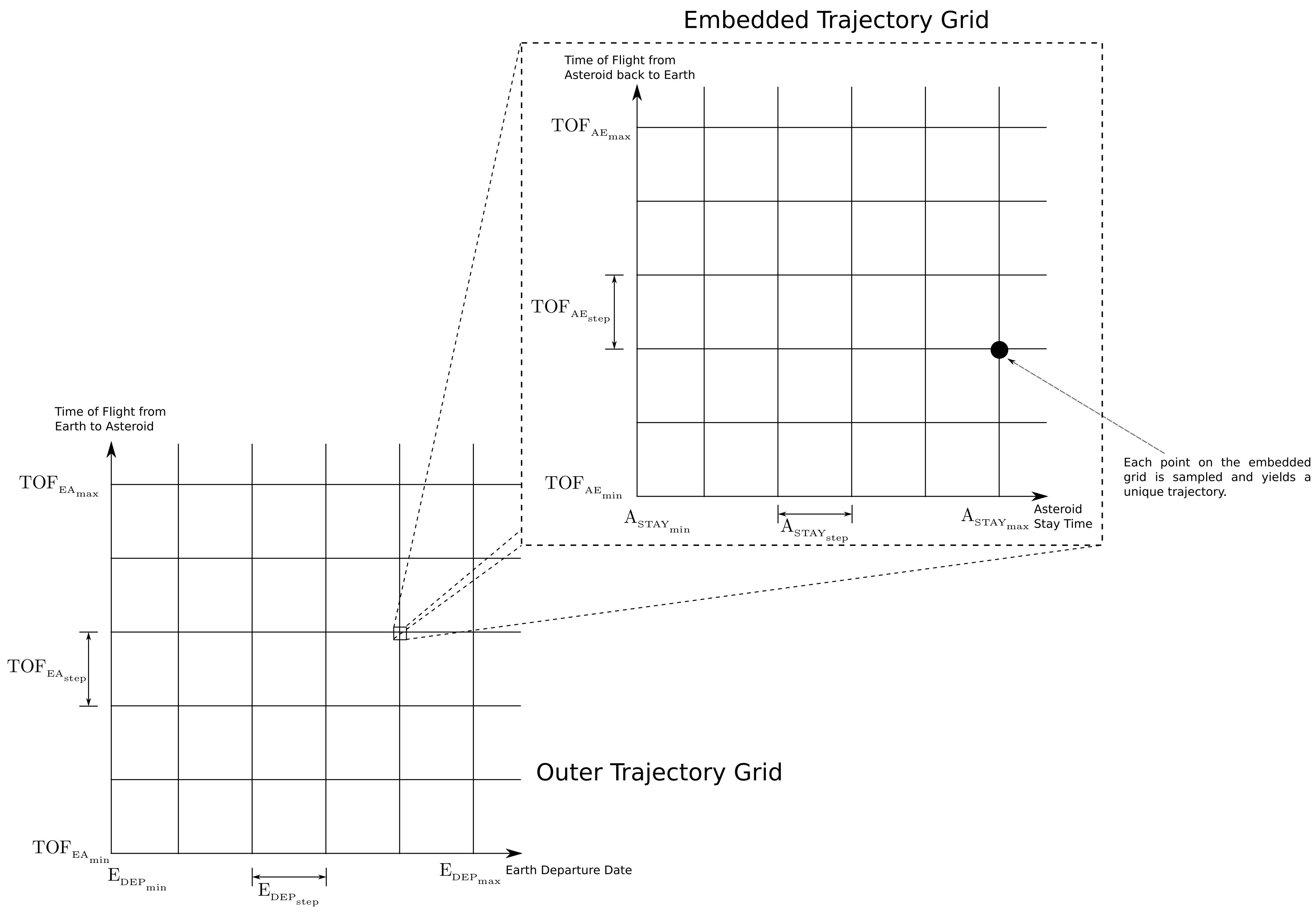
Profile of a Human Mission to a NEA



NHATS Analysis Constraints

- In order to be classified as NHATS-compliant, a NEA must offer at least one round-trip trajectory solution that meets the following constraints:
  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 $\leq$ 450 days.
  5. Stay time at the NEA $\geq$ 8 days.
  6. Earth atmospheric entry speed ≤ 12 km/s at an altitude of 125 km.
- 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.

Embedded Trajectory Grids



NHATS Web-site Table

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

+ View the NASA Portal

Near Earth Object Program

NEO BASICS | SEARCH PROGRAMS | DISCOVERY STATISTICS | ACCESSIBLE NEAs | NEWS | FAQ

ORBIT DIAGRAMS | ORBIT ELEMENTS | CLOSE APPROACHES | IMPACT RISK | IMAGES | RELATED LINKS

Near-Earth Object Human Space Flight Accessible Targets Study (NHATS)

This list of potential mission targets should *not* be interpreted as a complete list of viable NEAs for an actual human exploration mission. As the NEA orbits are updated, the viable mission targets and their mission parameters will change. To select an actual target and mission scenario, additional constraints must be applied including astronaut health and safety considerations, human space flight architecture elements, their performances and readiness, the physical nature of the target NEA and mission schedule constraints.

[show instructions]

total dV <= 6 km/s | total dur. <= 360 days | stay >= 8 days | launch: 2015-2040

H <= 26 | OCC <= 7 | Sort by number of viable trajectories | Descending sort

Display Table

Constraints described below — reset all constraints and sorting to defaults

Column headings described below — [Selected **24** out of **1052** records]

Object Designation	Orbit ID	H (mag)	Estimated Diameter (m)	OCC	Min. delta-V [delta-V, dur.] (km/s), (d)	Min. Duration [delta-V, dur.] (km/s), (d)	▵ Viable Trajectories	Next Optical Opportunity (yyyy-mm [Vp])	Next Arecibo Radar Opportunity (yyyy-mm [SNR])	Next Goldstone Radar Opportunity (yyyy-mm [SNR])
(2000 SG344)	13	24.8	19 - 86	2	**3.556**, 354	5.973, **114**	3302718	2028-04 [19.2]	2028-05 [2800]	2028-05 [55]
(2012 UV136)	13	25.6	13 - 60	5	**5.051**, 354	5.975, **282**	2119115	2013-08 [20.4]	2013-10 [20]	*none*
(2006 BZ147)	9	25.4	14 - 64	3	**4.184**, 354	5.972, **250**	1672928	2034-12 [19.5]	2035-02 [1400]	2035-02 [37]
(2001 FR85)	9	24.5	22 - 98	3	**4.557**, 354	5.987, **162**	1618605	2038-02 [23.9]	2039-03 [120]	2039-09 [11]
(2012 MD7)	1	24.1	27 - 120	7	**5.071**, 354	5.989, **314**	867652	2013-04 [23.1]	*none*	*none*
(2007 YF)	6	24.8	19 - 86	5	**5.426**, 346	5.965, **250**	791463	2021-12 [23.6]	*none*	*none*
(2010 JK1)	21	24.4	23 - 101	1	**5.514**, 306	5.971, **282**	775615	2033-03 [22.9]	*none*	*none*
(2001 QJ142)	19	23.5	35 - 159	0	**5.593**, 354	5.940, **338**	638369	2013-03 [23.9]	2024-04 [88]	*none*
(2012 HK31)	12	25.4	15 - 65	6	**5.746**, 322	5.924, **306**	627317	? *2022-03 [22.0]* ?	*none*	*none*
(2012 BB14)	7	25.0	18 - 79	4	**5.181**, 354	5.998, **306**	590985	2022-12 [21.7]	*none*	*none*
(2009 HC)	29	24.8	19 - 86	4	**4.504**, 354	5.997, **298**	554669	2025-08 [23.1]	2027-04 [5600]	2025-10 [42]
(1999 CG9)	9	25.2	16 - 70	6	**5.328**, 354	5.990, **330**	541164	2033-08 [22.9]	2034-02 [61]	*none*
(2007 UY1)	29	22.9	46 - 207	2	**5.543**, 354	5.947, **338**	537652	2019-09 [23.4]	2020-10 [32]	2022-02 [19]
(2011 UX275)	1	25.8	12 - 53	6	**5.903**, 354	5.903, **354**	521511	? *2030-12 [23.2]* ?	*none*	*none*

NHATS Web-site Trajectory Details

NHATS Object/Trajectory Details

This page provides some details about the selected target NEA (near-Earth asteroid) and related mission/trajectory parameters. The table below shows parameters specific to the selected NEA. The **Mission Trajectories Table** (second table below) provides information for two mission scenarios to the target NEA: one for the minimum delta-V mission and one for the minimum duration mission (in some cases the two missions may be identical). Next to the **Mission Trajectories Table** is the plot of total mission dV as a function of departure date and roundtrip flight time (mission duration), which summarizes the many potential mission trajectories. Note that these mission trajectories span a range of possible stay times at the NEA, though this cannot be shown in a two-dimensional plot. Please consider the assumptions and caveats related to these data.

Constraints: [total dV <= 6 km/s] [total dur. <= 360 days] [stay >= 8 days] [launch: 2015-2040]

Column headings described below

Object Designation	Orbit ID	H (mag)	Estimated Diameter (m)	OCC	Min. delta-V [delta-V, dur.] (km/s), (d)	Min. Duration [delta-V, dur.] (km/s), (d)	Viable Trajectories	Next Optical Opportunity (yyyy-mm [Vp])	Next Arecibo Radar Opportunity (yyyy-mm [SNR])	Next Goldstone Radar Opportunity (yyyy-mm [SNR])
(2000 SG344)	13	24.8	19 - 86	2	**3.556**, 354	5.973, **114**	3302718	2028-04 [19.2]	2028-05 [2800]	2028-05 [55]

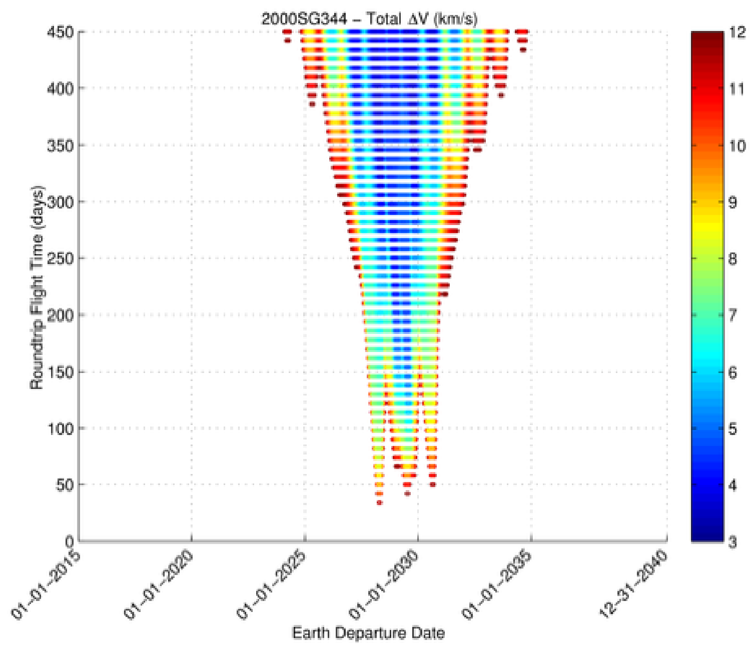
Mission Trajectories Table

Column headings described below

(2000 SG344)	Min. delta-V Parameters	Min. Duration Parameters
Total Mission delta-V (km/s)	**3.556**	5.973
Total Mission Duration (d)	354	**114**
Outbound Flight Time (d)	145	49
Stay Time (d)	8	8
Inbound Flight Time (d)	201	57
Launch date (YYYY-MM-DD)	2028-04-22	2029-07-22
C_3 (km^2/s^2)	1.737	3.009
Departure $V_{infinity}$ (km/s)	1.318	1.735
Earth Departure dV (km/s)	3.256	3.314
dV to Arrive at NEA (km/s)	0.113	1.067
dV to Depart NEA (km/s)	0.187	1.592
Earth return dV (km/s)	0.000	0.000
Entry Speed (km/s)	11.133	11.214
Depature Declination (deg)	-8.950	-22.493
Return Declination (deg)	-5.933	22.663
NHATS Trajectory Solution ID	890465	2046652

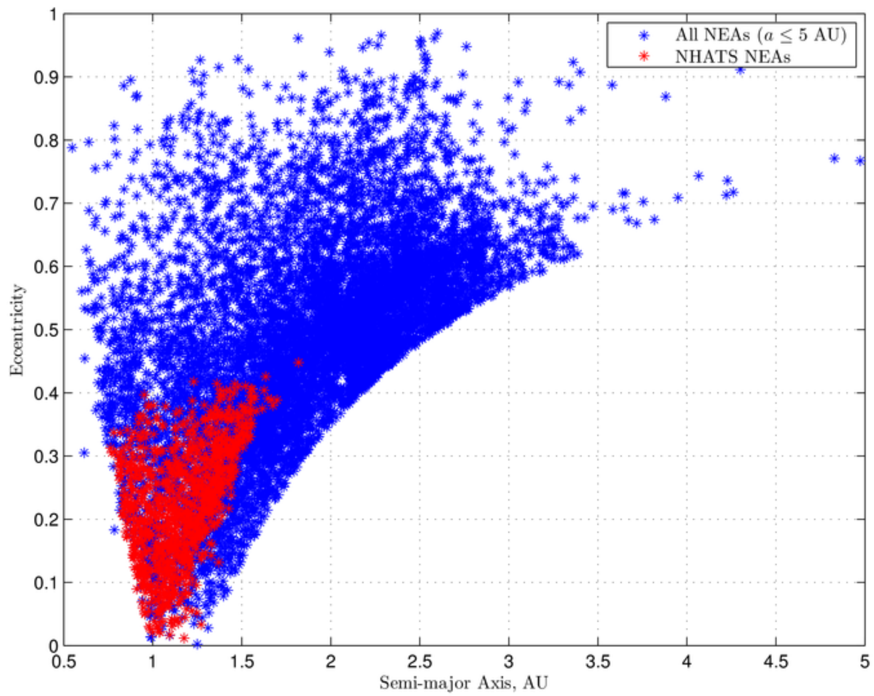
These data were computed on 2012-01-06 using the latest available orbital parameters.

Total Mission delta-V as a Function of Departure Date and Mission Duration

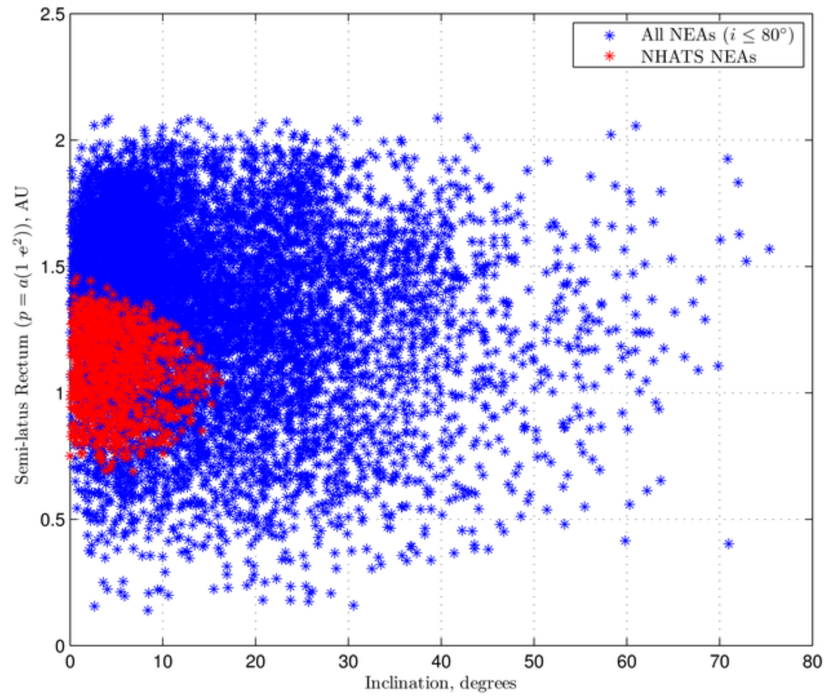


The plot above shows total mission delta-V as a function of Earth departure date and total round-trip flight time (mission duration). It summarizes the many potential mission scenarios by plotting, for each case, the total round-trip delta-V values (color-coded) required for each launch date and round trip flight time considered. Note that these trajectories span a range of possible stay times at the NEA.

Orbital Characteristics of NHATS NEAs



a versus e for the known NEAs.

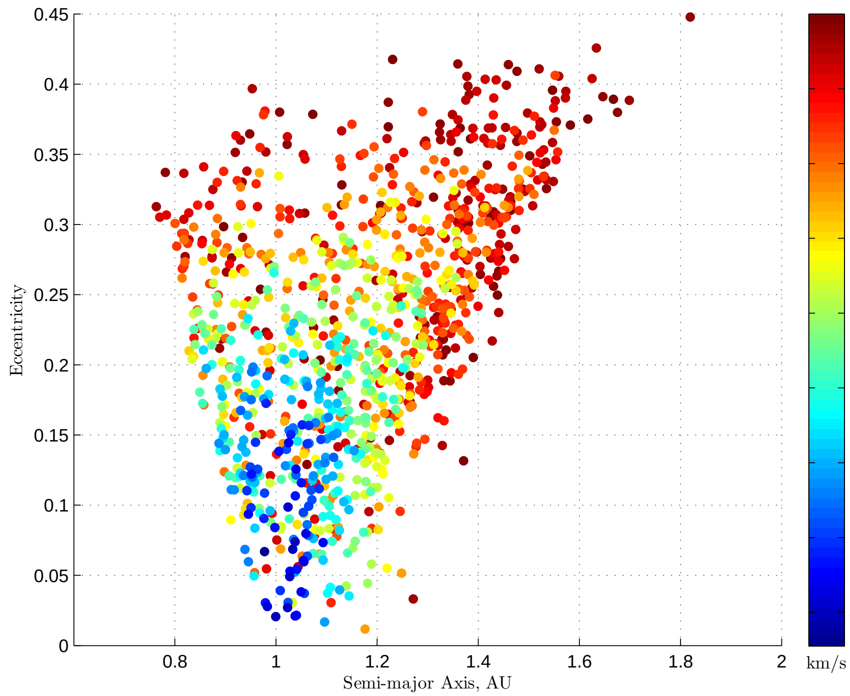


i versus p for the known NEAs.

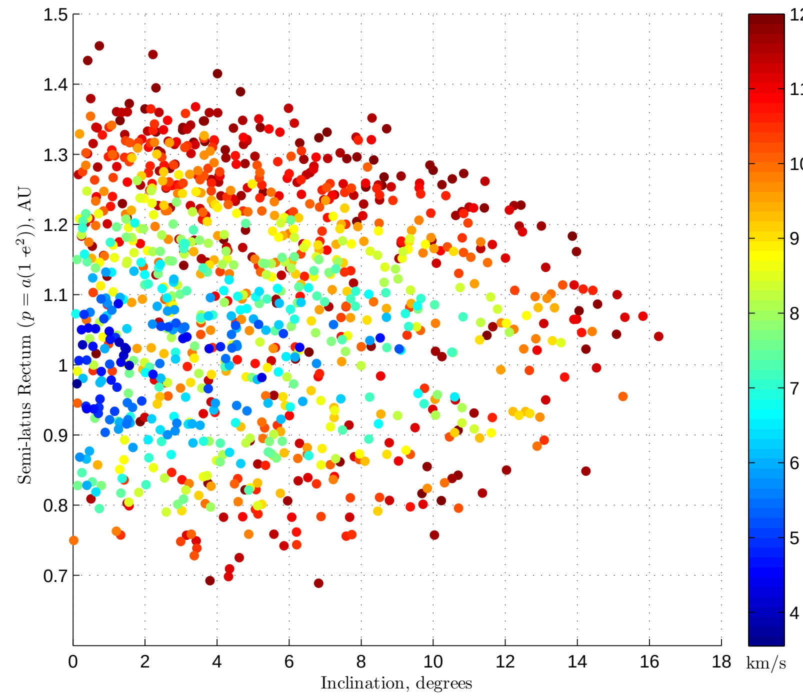
Uncorrelated statistics for the a, e, and i of NHATS-compliant NEA orbits.

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°

Orbital Characteristics of NHATS NEAs



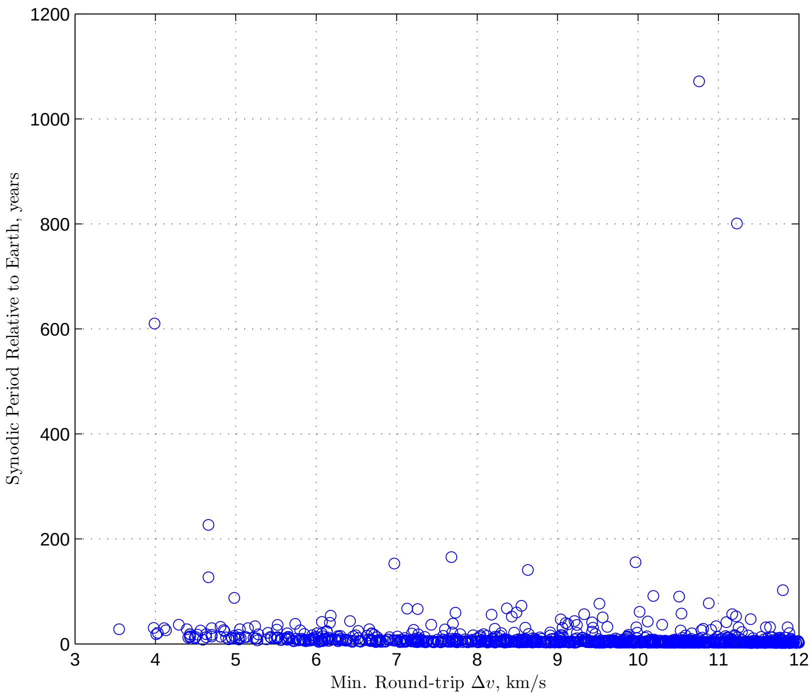
Minimum round-trip Δv as a function of a and e.



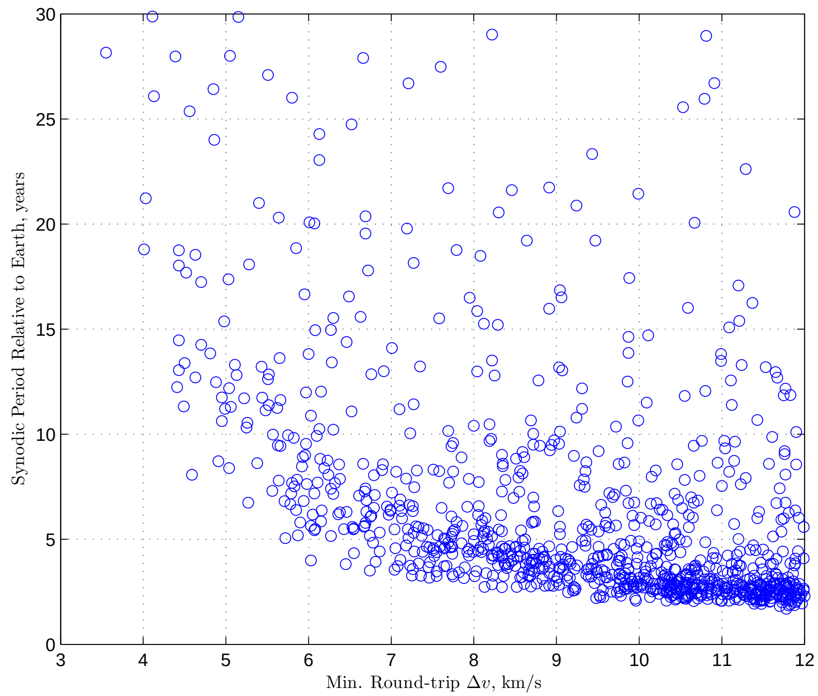
Minimum round-trip Δv as a function of i and p.

- NHATS-compliant NEAs generally have relatively Earth-like orbits compared to the overall known NEA population; this is especially true for the most accessible (lowest Δv) NHATS-compliant NEAs.

NHATS-compliant NEA Synodic Periods



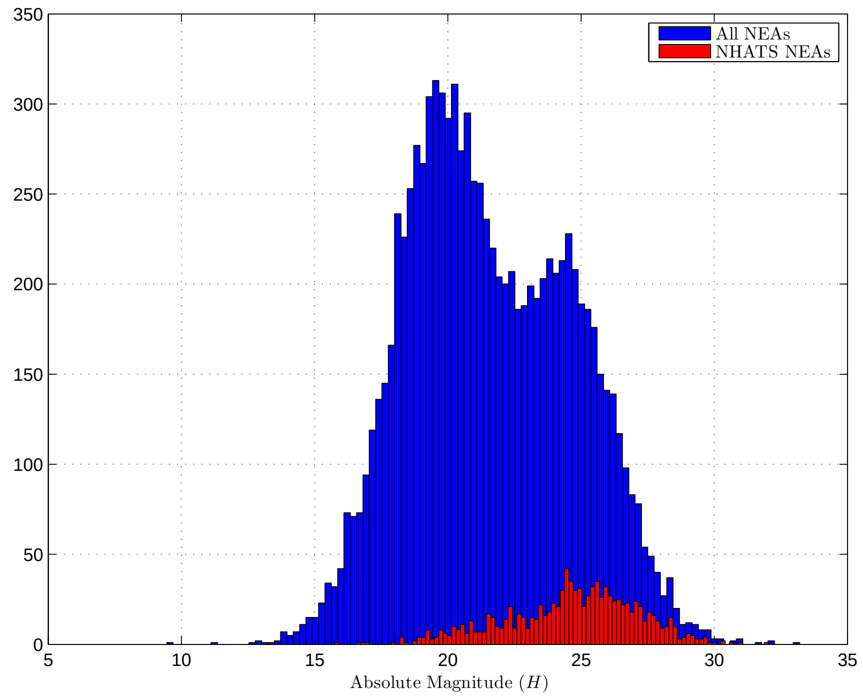
Minimum round-trip Δv versus synodic period relative to Earth.



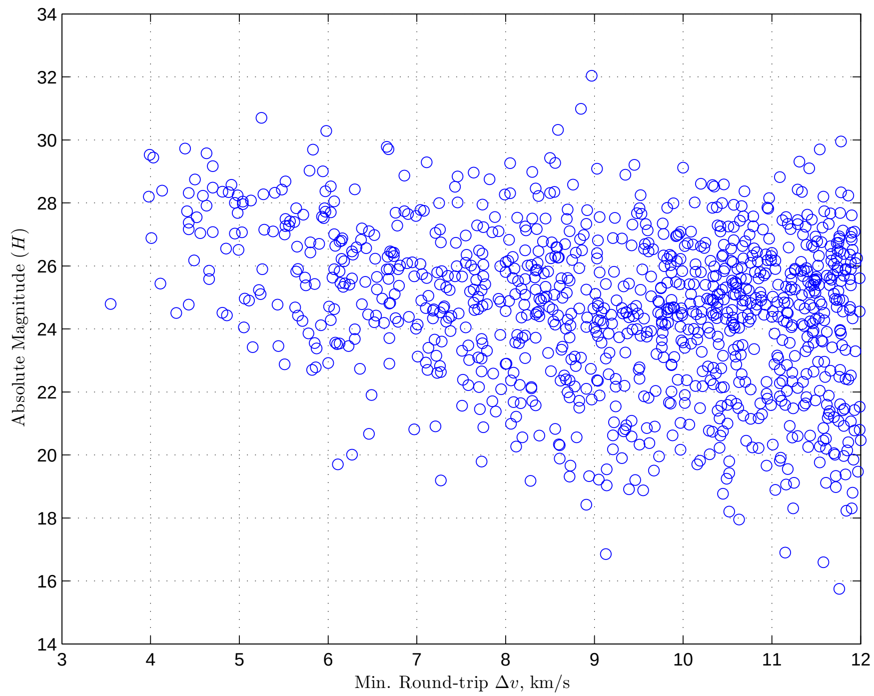
Only showing synodic periods $\leq$ 30 years.

- The most accessible of the NHATS-compliant NEAs tend to have relatively long synodic periods, in many cases spanning decades or centuries.
- This can interfere with plans to observe and/or deploy missions to these NEAs because proximity to Earth is important for both.

Absolute Magnitude (H) for NHATS NEAs



Distribution of H.



Minimum round-trip Δv versus H.

- NHATS-compliant NEAs tend to be physically smaller than other NEAs: The mean H for all NEAs is 21.595 while the mean H for NHATS-compliant NEAs is 24.657.
- The most accessible (lowest Δv) NHATS NEAs tend to be particularly small.
- This phenomenon may be due to observational biases and/or dynamical evolution of the NEA population.

NHATS-Compliant NEAs by Δv / Duration

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 2015 and 2040, no restriction on H, and no restriction on OCC.

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

- 37 NEAs offer mission opportunities requiring less total Δv than round-trip missions to lunar orbit or Earth-Moon Lagrangian point orbits.
- 431 NEAs offer mission opportunities requiring less total Δv than round-trip missions to the lunar surface.
- All 1042 NHATS-compliant NEAs (1057 as of 2013-04-06) offer mission opportunities requiring less total Δv than round-trip missions to the martian surface, Mars orbit, or Phobos/Deimos.

NHATS-Compliant NEAs by Δv / Duration

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, $H \leq 23.0$, and OCC ≤ 5.

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

Example Round-Trip Trajectory Solutions

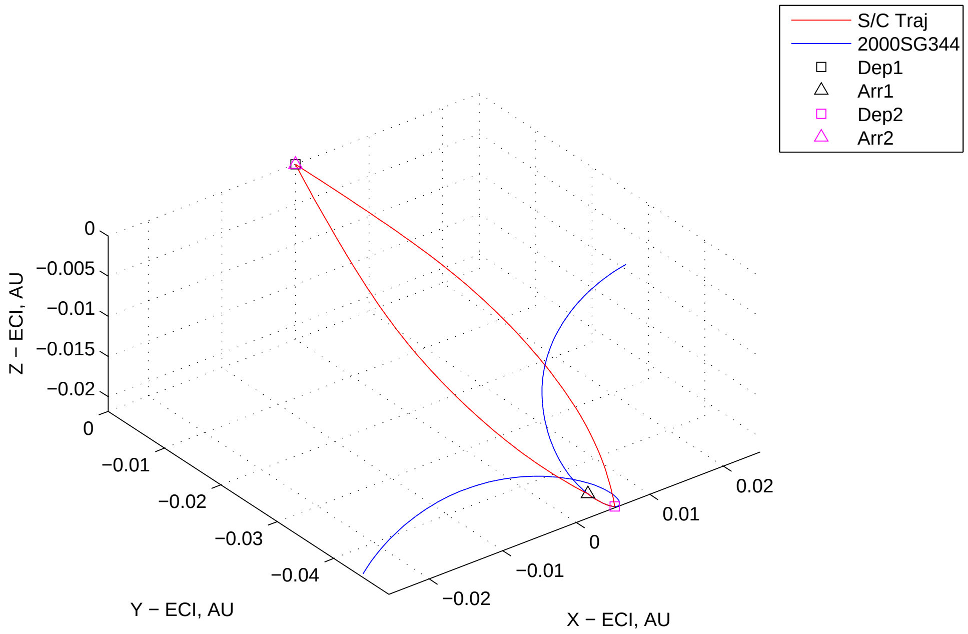
Round-trip mission opportunities departing Earth between 2024 and 2029 for selected NHATS-compliant NEAs.

	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

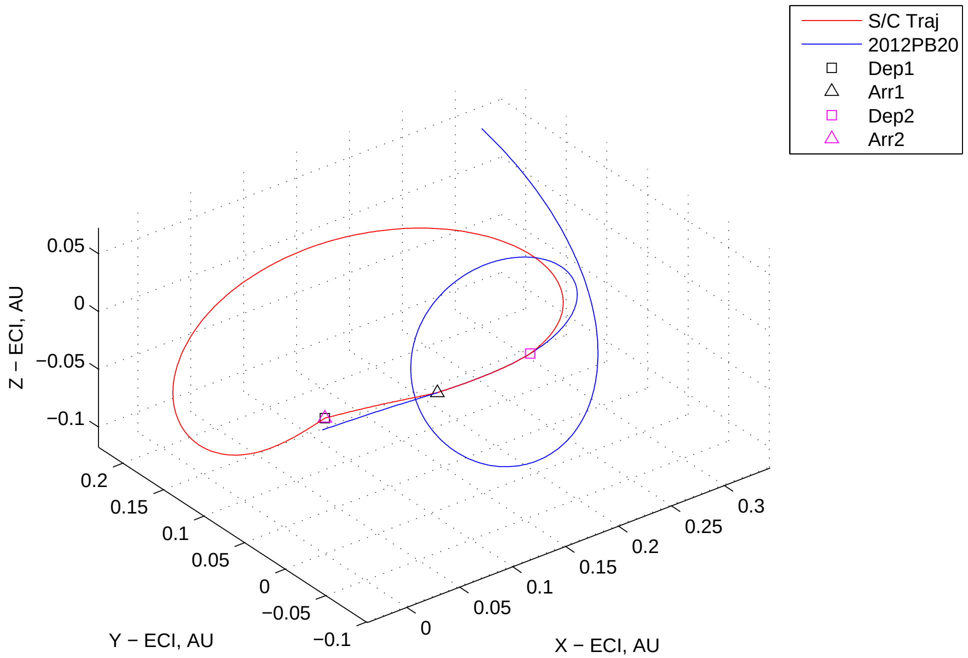
Osculating orbital elements at epoch 2013-04-18.0 TDB and orbit group classifications.

	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

Geocentric Trajectory Views



154 day round-trip trajectory to 2000 SG_{344}.



354 day round-trip trajectory to 2012 PB_{20}.

Distances from Sun and Earth for selected round-trip NEA mission trajectories.

	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

Conclusions

- NEAs represent a unique and powerful intersection of planetary defense interests, fundamental solar system science, and pioneering human exploration beyond the Earth-Moon system.
- The NHATS provides a comprehensive, continuously updated view of the NEA accessibility landscape and has defined a unique subpopulation of the NEAs, the NHATS-compliant NEAs, that are unusually accessible relative to the NEA population as a whole.
  - Round-trip missions to any of the 1057 currently known NHATS-compliant NEAs require less Δv than Mars.
  - Hundreds of the currently known NHATS-compliant NEAs require less Δv than the lunar surface.
  - Dozens of the currently known NHATS-compliant NEAs require less Δv than lunar orbit or Earth-Moon Lagrangian point orbits.
- The NHATS web-site and email system make the data available to all who are interested and provide timely notifications to observers.
- The most accessible NHATS-compliant NEAs tend to have relatively Earth-like orbits, although there are some interesting exceptions.
- 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.
  - 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.

Acknowledgments

The NHATS is made possible by close collaboration between NASA Headquarters, NASA/GSFC, and NASA/JPL. NHATS research, the development and maintenance of the NHATS automated processing system, and the development and maintenance of the NHATS web-site are all supported by NASA's Near-Earth Objects Observations (NEOO) Program.

NHATS web-site:

http://neo.jpl.nasa.gov/nhats/

NHATS data table:

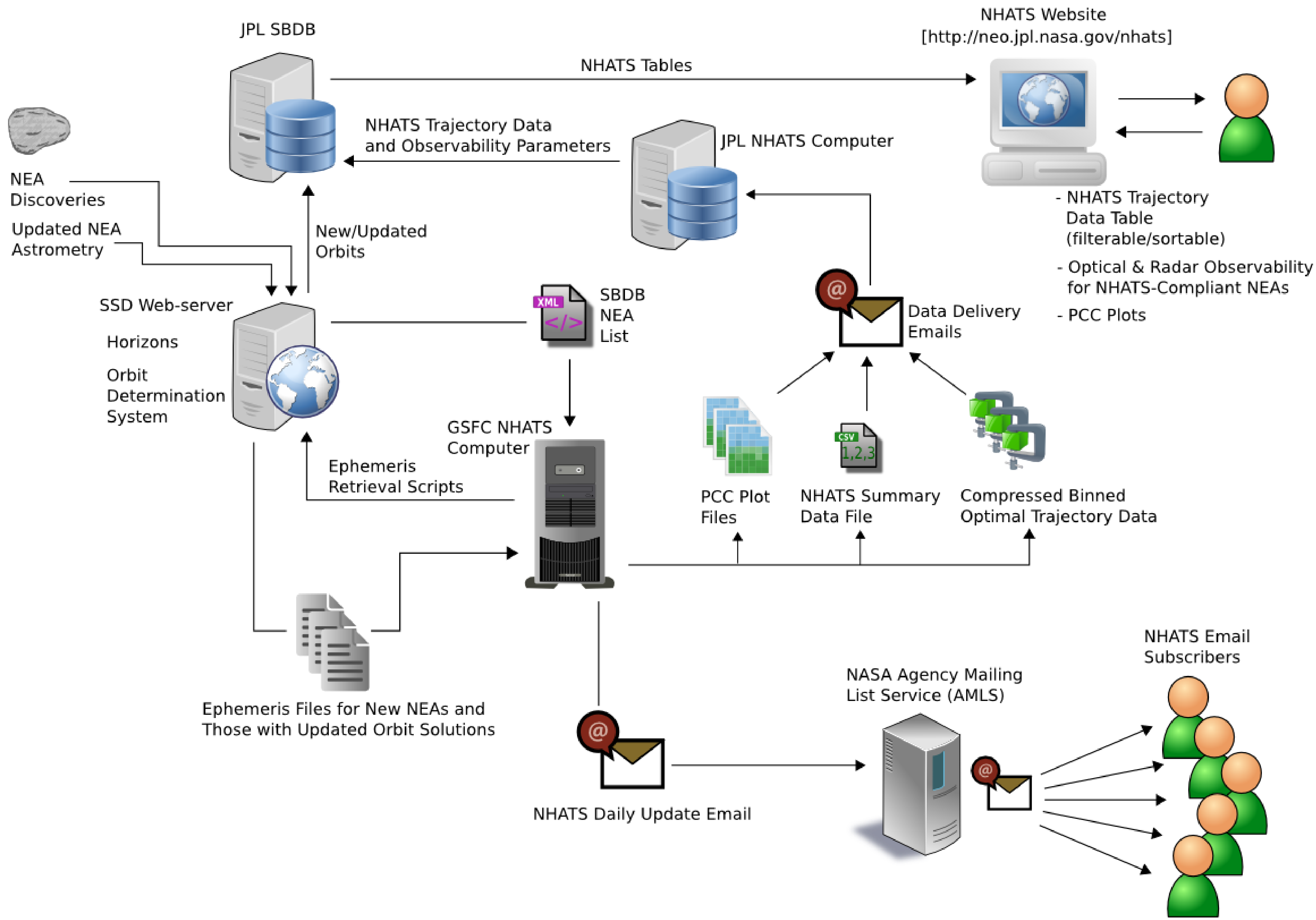
http://neo.jpl.nasa.gov/cgi-bin/nhats

NHATS mailing list:

https://lists.nasa.gov/mailman/listinfo/nhats

Appendices

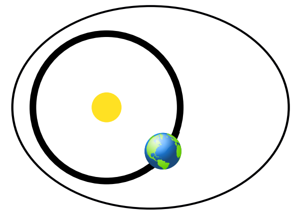
Automated NHATS Processing



NEA Groups According to Orbit Type

Amors

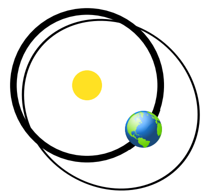
Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid (1221) Amor)



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

Apollos

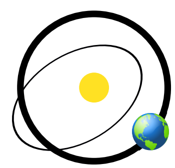
Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid (1862) Apollo)



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

Atens

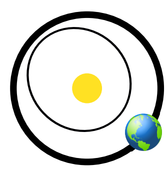
Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid (2062) Aten)



$$a < 1.0 \text{ AU}$$
$$Q > 0.983 \text{ AU}$$

Atiras

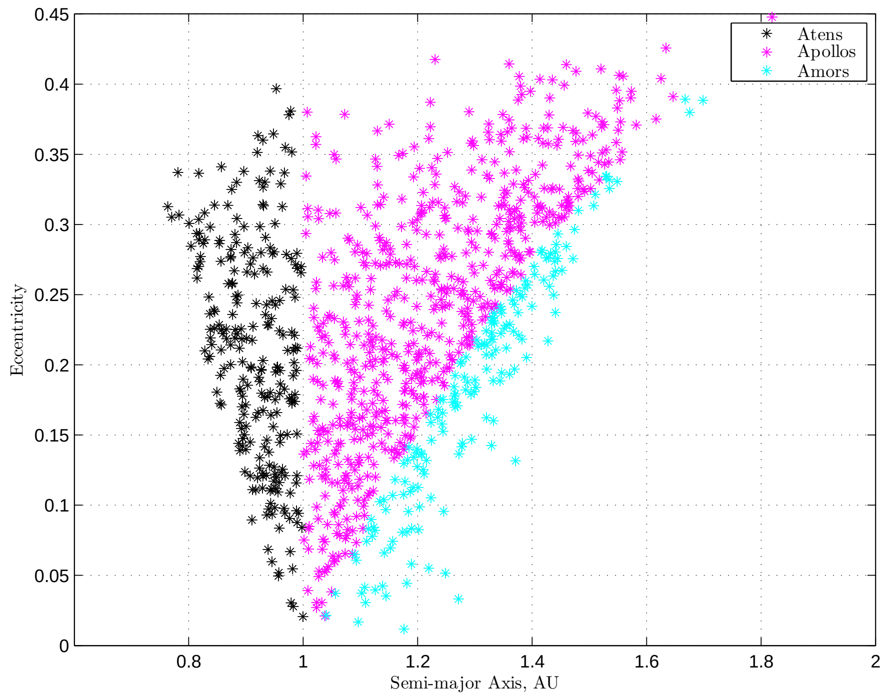
NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid (163693) Atira)



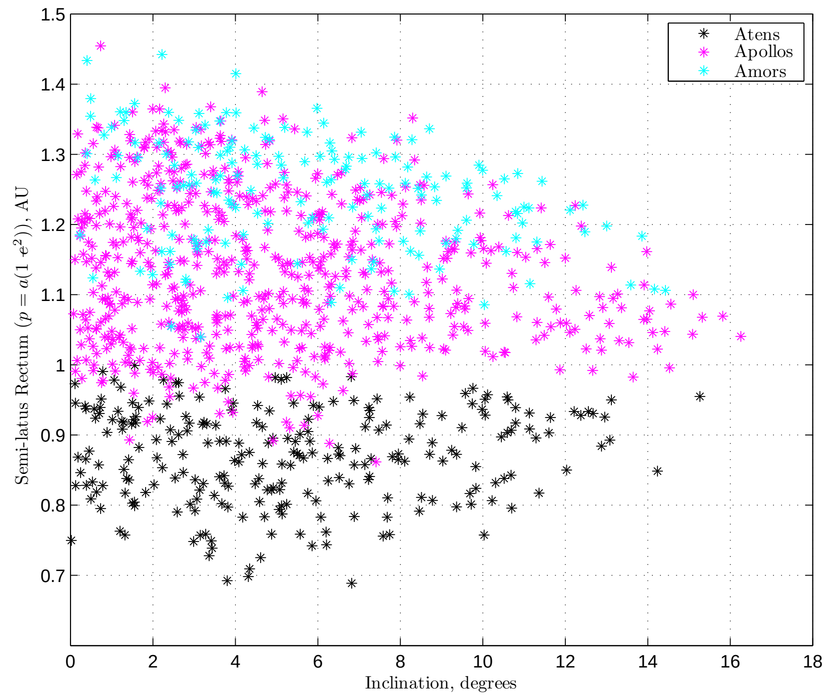
$$a < 1.0 \text{ AU}$$
$$Q < 0.983 \text{ AU}$$

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

Orbital Characteristics of NHATS NEAs



a versus e for the NHATS-compliant NEAs by orbit group.

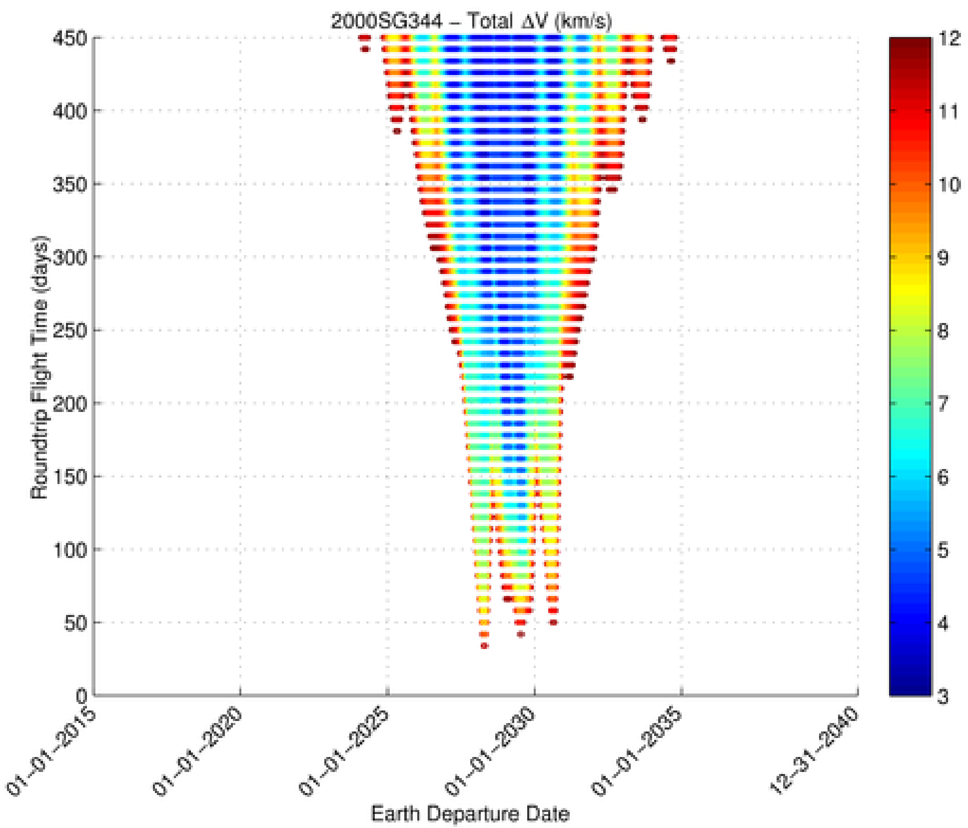


i versus p for the NHATS-compliant NEAs by orbit group.

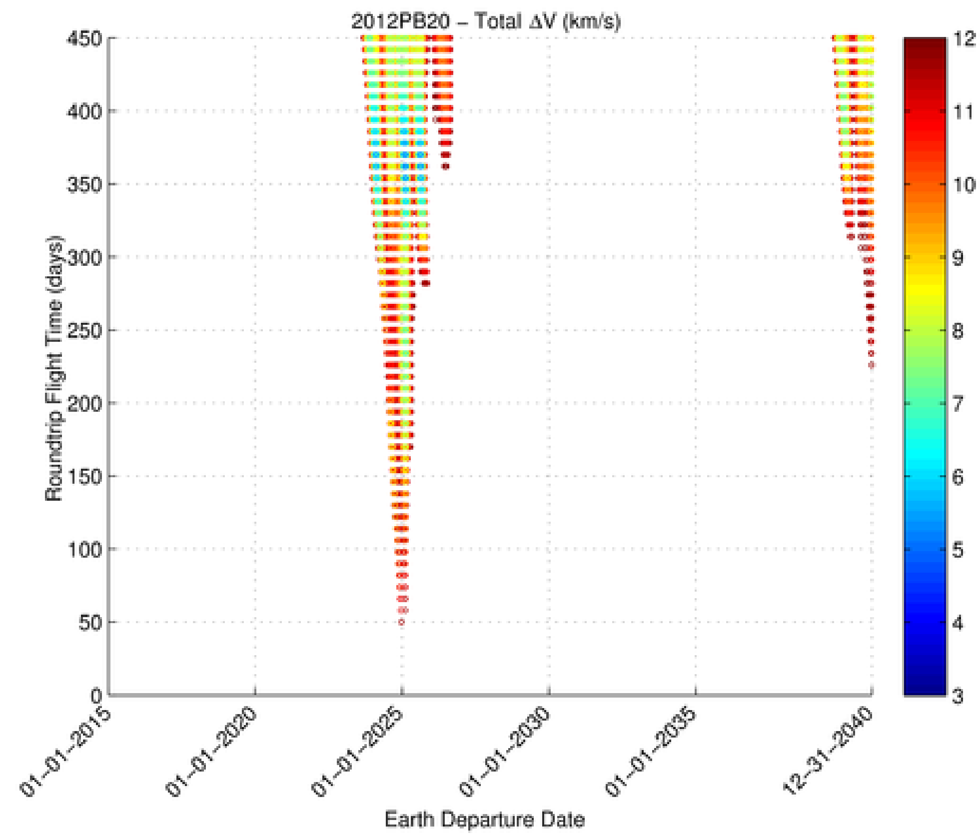
NHATS-compliant NEAs by orbit group.

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%

Pork Chop Contour (PCC) Plots

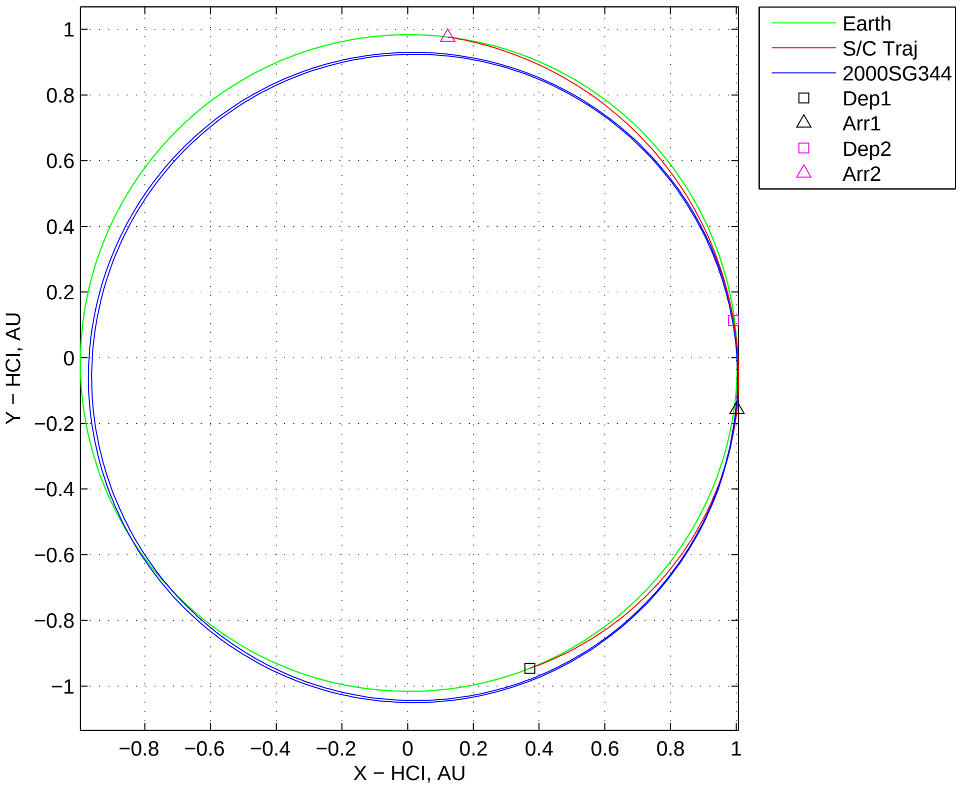


NHATS PCC plot for 2000 SG_{344}.

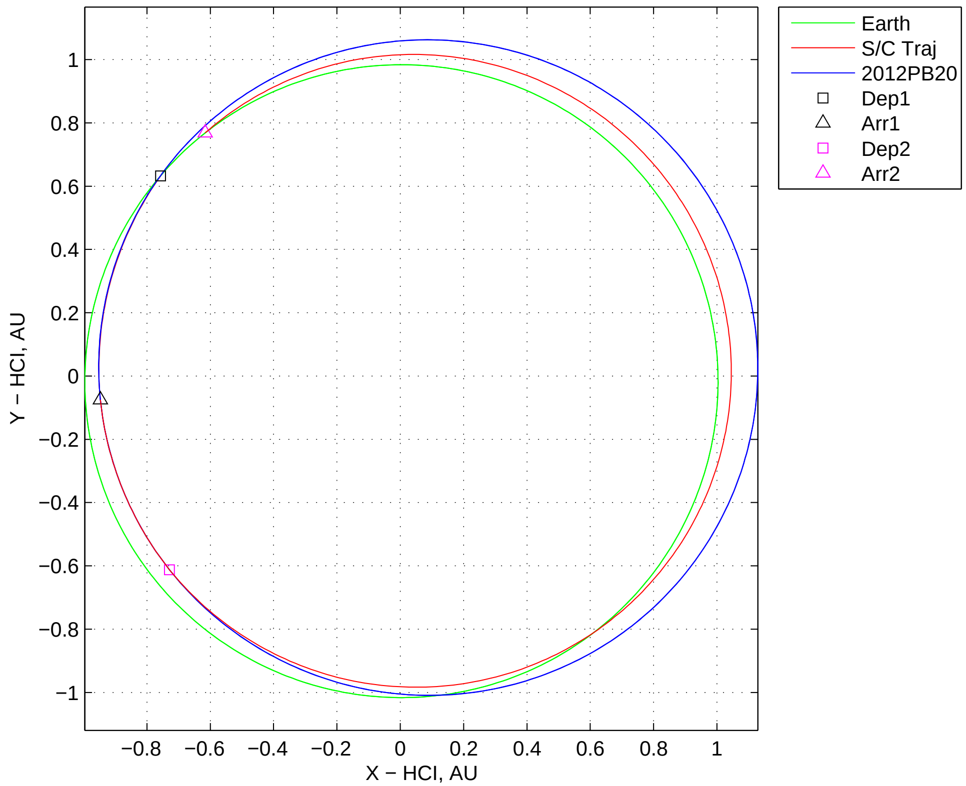


NHATS PCC plot for 2012 PB_{20}.

Heliocentric Trajectory Views



154 day round-trip trajectory to 2000 SG_{344}.



354 day round-trip trajectory to 2012 PB_{20}.