Accessible Near-Earth Objects (NEOs)

Presented to the 12th Meeting of the NASA Small Bodies Assessment Group (SBAG)

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Defining NEO Accessibility Factors

- **Astrodynamical**
  - Earth departure dates; mission $\Delta v$; mission duration; stay time; etc
- **Physical**
  - NEO size(?); rotation rate; dust/satellites environment; chemistry; etc
- **Architectural**
  - Launch vehicle(s); crew vehicle(s); habitat module(s); budget; etc
- **Operational**
  - Operations experience; abort options/profiles; etc

Astrodynamical Accessibility is the starting point for understanding the options and opportunities available to us.

Here we shall focus on Astrodynamical Accessibility.

Development of accessibility aspects may occur in parallel.
Astrodynamical Accessibility (NHATS)

- Earth departure date between 2015-01-01 and 2040-12-31
- Earth departure $C_3 \leq 60 \text{ km}^2/\text{s}^2$
- Total mission $\Delta v \leq 12 \text{ km/s}$
  - The total $\Delta v$ includes (1) the Earth departure maneuver from a 400 km altitude circular parking orbit, (2) the maneuver to match the NEA’s velocity at arrival, (3) the maneuver to depart the NEA and, (4) if necessary, a maneuver to control the atmospheric re-entry speed during Earth return.
- Total round trip mission duration $\leq 450$ days
- Stay time at the NEA $\geq 8$ days
- Earth atmospheric entry speed $\leq 12 \text{ km/s}$ at an altitude of 125 km

A near-Earth asteroid (NEA) that offers at least one trajectory solution meeting those criteria is classified as NHATS-compliant.

http://neo.jpl.nasa.gov/nhats/
The purpose of NASA’s Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) (pron.: /ˈnæts/) is to identify known near-Earth objects (NEOs), particularly near-Earth asteroids (NEAs), that may be accessible for future human space flight missions. The NHATS also identifies low $\Delta v$ robotic mission opportunities.
Putting Accessibility Into Context

▶ What does “accessible NEO” mean? “Accessible” compared to what?
▶ Other solar system destinations:

<table>
<thead>
<tr>
<th>Destination</th>
<th>Total $\Delta v$ (km/s)</th>
<th>Round-Trip Mission Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar orbit</td>
<td>~5</td>
<td>~One to several weeks</td>
</tr>
<tr>
<td>Lunar surface</td>
<td>~9</td>
<td>~One to several weeks</td>
</tr>
<tr>
<td>Mars Surface</td>
<td>12.53</td>
<td>923 (500 day stay)</td>
</tr>
<tr>
<td>Elliptical Mars Orbit</td>
<td>6.29</td>
<td>923 (500 day stay)</td>
</tr>
<tr>
<td>Elliptical Mars Orbit</td>
<td>12.14</td>
<td>422 (7 day stay)</td>
</tr>
<tr>
<td>Elliptical Mars Orbit (w/ Venus flyby)</td>
<td>12.81</td>
<td>485 (45 day stay)</td>
</tr>
<tr>
<td>Elliptical Mars Orbit (w/ Venus flyby)</td>
<td>8.12</td>
<td>588 (45 day stay)</td>
</tr>
<tr>
<td>Mars flyby</td>
<td>9.01</td>
<td>501 (0 day stay)</td>
</tr>
<tr>
<td>Mars flyby (w/ Venus flyby)</td>
<td>6.07</td>
<td>582 (0 day stay)</td>
</tr>
<tr>
<td>Phobos/Deimos</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Similar requirements to Mars

▶ Many Mars/Phobos/Deimos mission trajectories pass within Venus distance (~0.7 AU) of the Sun, or closer (thermal/radiation issues)

No round-trip mission to Mars (orbit, surface, or flyby) or Phobos/Deimos is possible with both $\Delta v \leq 12$ km/s AND mission duration $\leq 450$ days.
As of 2014-12-06, **1317** NHATS-compliant NEAs have been discovered.

Of those,

- **49** can be visited and returned from for less $\Delta v$ than **Lunar orbit**
- **556** can be visited and returned from for less $\Delta v$ than **the lunar surface**
- All **1317** are more accessible than **Mars, Phobos, or Deimos**

More and more NHATS-compliant NEAs are being discovered and identified.

The NHATS data processing is automated, observers are automatically notified, web-site is updated daily.
Comparisons to ARM

All NEA Mission Earth Return Entry Speeds 11.101 – 11.962 km/s

Round-Trip Flight Time, d

Total Round-Trip $\Delta V$ (from LEO), km/s

- ARM Crewed (5d stay)
- 2000 SG344 (8d stay), 2029 launch
- 2006 RH120 (8d stay), 2028 launch
- 2010 UE51 (8d stay), 2023 launch
- 2009 BD (8d stay), 2021/22 launch
- 2011 MD (8d stay), 2023 launch
- 2008 HU4 (8d stay), 2025 launch
- Itokawa (8d stay), 2035 launch
- Bennu (8d stay), 2036 launch
- 2008 EV5 (64d stay), 2024 launch
Putting it all together ...
Accessible Near-Earth Asteroids (NEAs)

Goals of the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS):
- Monitor the accessibility of the NEA population for exploration missions.
- Characterize the population of accessible NEAs.
- Rapidly notify observers so that crucial follow-up observations can be obtained.

**NHATS Daily Updates:** [https://lists.nasa.gov/mailman/listinfo/nhats](https://lists.nasa.gov/mailman/listinfo/nhats)

*Chart by: Brent W. Barbee (NASA/GSFC)*

**Selected NHATS Statistics:**
- **Known NEAs:** 11,374
- **NHATS NEAs:** 1,245 (~11.0% of known)
- **Mean H for Known NEAs:** 94.80
- **Mean H for NHATS NEAs:** 24.796
- **NHATS NEAs by Orbit Type:**
  - Aten: 0% (0% of Atens)
  - Apollo: 23% (33% of Apollo)
  - Amor: 17% (5% of Amors)
- **NHATS NEA SMA (AU):** 0.76, 1.16, 1.82
- **NHATS NEAs ECC:** 0.01, 0.22, 0.45
- **NHATS NEAs INC (deg):** 0.02, 5.18, 16.29

**Round-Trip to Lunar Surface**
- Notes on Earth re-entry speed:
  - Earth re-entry speed is approx. 11 km/s for lunar missions / ARRM / Max Earth re-entry speed for NHATS is 12 km/s; many NHATS mission opportunities have < 12 km/s re-entry.

**Round-Trip to Low Lunar Orbit (no landing)**
- ARRM (human visitation of captured NEA in lunar DRO)

**62,138 Selected Mission Opportunities to 1,245 NHATS NEAs, departing Earth 2011–2040:**
- Minimum ΔV from LEO to Earth Escape Reference Line
- Round-Trip Flight Time = 450 days Reference Line

**Note:** No round-trip Mars mission opportunities are less than 12 km/s and less than 450 days.

**2031–2046 Earth Departures:**
- ~500 day stay on Mars surface.
- 12 km/s max Earth re-entry

**Note:** Some round-trip trajectories to Mars will require additional ΔV, up to 1 km/s, considering the cost of incoming/outgoing asymptotic alignment. This is not reflected in the data shown here.

**Mars Trajectory Data Sources:**
- *[web adjustments by B. W. Barbee for 12 km/s max Earth re-entry]*

Communicating all of this to the public, and even to technical folks who are non-specialists, is very challenging.
BEFORE Dr. Richard Binzel’s 8 July 2014 Letter to the NRC and NAC pointing out the existence of NHATS data ...

10km/s delta-v

0km/s delta-v

- ISS
- Mars Flyby
- Mars Orbit 500 Days
- Martian Moons 500 Days
- Mars Surface 500 Days
- Mars Orbit 30 Day Stay
- Mars Surface < 30 Day Stay
- Martian Moons 30 Day Stay
- More NEAs
- Few NEAs
- Moon: Lunar Sortie
- Moon: Lunar Outpost
- Cis-Lunar: ARM
- Cis-Lunar: L2 Outpost

0 mission days | 200 mission days | 400 mission days | 600 mission days | 800 mission days

30 km/s delta-v

20 km/s delta-v

NASA
Adding The Missing NHATS Data

The missing NHATS data overlaid on the original NRC figure, from Dr. Richard Binzel’s 8 July 2014 Letter to the NRC and NAC
Figure 1.9 in:
http://www.nap.edu/catalog/18801/pathways-to-exploration-rationales-and-approaches-for-a-us-program
**MISSION REQUIREMENTS**

A mission to a near-Earth asteroid would require less propulsion and a shorter mission duration than a human mission to Mars. Less than 1% of the most-accessible asteroids are currently known (yellow circles), but a dedicated survey (filling in the yellow-hatched region) would reveal abundant asteroid stepping-stone opportunities as a gateway for human interplanetary exploration.

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PDF: [http://www.nature.com/polopoly_fs/1.16216!/menu/main/topColumns/topLeftColumn/pdf/514559a.pdf](http://www.nature.com/polopoly_fs/1.16216!/menu/main/topColumns/topLeftColumn/pdf/514559a.pdf)
NAC Findings/Recommendations

Excerpt from page 4 of the 4 August 2014 letter to the NASA Administrator from the NASA Advisory Council (NAC); note that (1) the date is after Dr. Richard Binzel’s 8 July 2014 Letter to the NRC and NAC, and (2) the NAC letter uses the same references as the 8 July 2014 letter

**Major Reasons for Proposing the Recommendation:** NASA’s current Asteroid Initiative has three elements: (1) the search for and identification of Near Earth Asteroid (NEA) targets; (2) redirection of one NEA target to near-lunar orbit; (3) astronaut crew to cis-lunar space to rendezvous with the target and conduct operations. The cost of the second element (asteroid redirect, e.g., ARM) is poorly defined at present. The other elements of the Asteroid Initiative (target search and flights to cis-lunar space) still have merit even if the redirect mission does not take place. It must also be noted that ARM is not a substitute for a mission to an asteroid in its native orbit, which appears to be possible at a lower launch energy than previously believed based on recent data. Such a long duration deep space mission would be a logical step toward the horizon goal of humans to Mars. We have concerns that the ARM mission as currently defined may pose an unacceptable cost and technical risk. A prudent response to such concerns is to conduct and independent cost and technical assessment prior to selection.

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([http://www.nasa.gov/offices/nac/meetings/JULY-30-31-2014_presentations.html](http://www.nasa.gov/offices/nac/meetings/JULY-30-31-2014_presentations.html))


How Accessible Can NEOs Be?

- How many accessible NEOs are out there waiting for us to find them?
- And, how accessible are they?
- In future studies we may apply the NHATS algorithms to simulated NEOs predicted by modern NEO population models.
- That will at least tell us what additional accessible NEOs are predicted by our population models.
- But we won’t really know until we deploy a space-based NEO survey telescope.
- In the meantime, we can look at some historical NEO accessibility data to gain a sense of just how accessible NEOs in their natural orbits can be.
The NHATS system monitors NEA accessibility for missions departing Earth 2015–2040.

However, some NEAs offered their best mission opportunities during time frame surrounding when they were discovered.

To illustrate this, during July of 2014 Paul Chodas and I investigated the mission accessibility of two NEAs: 2006 RH$_{120}$ (∼2–3 m in size) and 2009 BD (∼4 m in size).

- 2006 RH$_{120}$ was temporarily captured by the Earth from about September 2006 to June 2007.
  - But was not given a minor planet designation until February 18, 2008.
- We believe objects the size of 2006 RH$_{120}$ are captured by the Earth about once per decade.
## Mission Trajectories Comparison

### 2006 RH\textsubscript{120}

<table>
<thead>
<tr>
<th></th>
<th>( \Delta v \leq 12 \text{ km/s, Dur} \leq 450 \text{ d} )</th>
<th>( \Delta v \leq 4.5 \text{ km/s, Dur} \leq 150 \text{ d} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. ( \Delta v )</td>
<td>Min. Dur.</td>
<td>Min. ( \Delta v )</td>
</tr>
<tr>
<td>Total ( \Delta v ) (km/s)</td>
<td>3.972</td>
<td>11.942</td>
</tr>
<tr>
<td>Total Duration (days)</td>
<td>450</td>
<td>34</td>
</tr>
<tr>
<td>Earth Dep Date</td>
<td>18-Aug-2027</td>
<td>4-Aug-2028</td>
</tr>
<tr>
<td>Return Entry Speed (km/s)</td>
<td>11.083</td>
<td>12.000</td>
</tr>
</tbody>
</table>

### 2009 BD

<table>
<thead>
<tr>
<th></th>
<th>( \Delta v \leq 12 \text{ km/s, Dur} \leq 450 \text{ d} )</th>
<th>( \Delta v \leq 6.0 \text{ km/s, Dur} \leq 270 \text{ d} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. ( \Delta v )</td>
<td>Min. Dur.</td>
<td>Min. ( \Delta v )</td>
</tr>
<tr>
<td>Total ( \Delta v ) (km/s)</td>
<td>4.978</td>
<td>11.876</td>
</tr>
<tr>
<td>Total Duration (days)</td>
<td>370</td>
<td>114</td>
</tr>
<tr>
<td>Earth Dep Date</td>
<td>30-Nov-2033</td>
<td>25-May-2034</td>
</tr>
<tr>
<td>Return Entry Speed (km/s)</td>
<td>11.131</td>
<td>11.909</td>
</tr>
</tbody>
</table>
Comparisons to ARM

All NEA Mission Earth Return Entry Speeds 11.101 – 11.962 km/s

2009 BD (15-Apr-2011)

2006 RH120 (12-Jan-2007)

Legend:
- ARM Crewed (5d stay)
- 2000 SG344 (8d stay), 2029 launch
- 2006 RH120 (8d stay), 2028 launch
- 2010 UE51 (8d stay), 2023 launch
- 2009 BD (8d stay), 2021/22 launch
- 2011 MD (8d stay), 2023 launch
- 2008 HU4 (8d stay), 2025 launch
- Itokawa (8d stay), 2035 launch
- Bennu (8d stay), 2036 launch
- 2008 EV5 (64d stay), 2024 launch
58 Day Mission to 2006 RH\textsubscript{120}

Earth Departure 2007-01-12
50 Day Mission to 2009 BD

Earth Departure 2011-04-15
January 2007 is only a few months after the discovery of 2006 RH$_{120}$, and a year before the object received its minor planet designation; sufficient time (a long enough arc of observations) is needed to ascertain whether an object is artificial or natural.

Such considerations will generally be important to mission analysis for small NEAs in any context.

On the other hand, April 2011 is a full 2 years after the discovery of 2009 BD and so would likely be a feasible launch date for a mission, at least from the perspective of having a sufficiently long observation arc.
2006 RH120 was only observable from Earth around the time of its maximum mission accessibility.
Observability and Accessibility Coinciding

2009 BD was only observable from Earth a couple of years before its maximum mission accessibility (and at points during its accessibility season)
Remarks

- 2006 RH$_{120}$ was most accessible when near Earth, around the time of its discovery
  - When it was a temporarily captured object (“mini-moon”), 2006 RH$_{120}$ offered round-trip mission accessibility approaching that of an object in a lunar DRO
    - Same $\Delta v$, but $\sim$2 month round trip rather than $\sim$1 month round trip
    - Subject to the aforementioned caveats and additional considerations
- Though it was not a temporarily captured object, 2009 BD was also most accessible when near Earth, around the time of its discovery
- Both objects offered long accessibility seasons surrounding the times when they were discovered
- Enhanced NEO survey capabilities (e.g., a space-based NEO survey telescope) might have the potential to discover highly accessible NEAs such as these years in advance of their peak mission accessibility seasons, affording us the opportunity to prepare missions to visit them in their native orbits
Conclusions and Findings

- Many accessible NEOs have been discovered and identified.
  - We have an automated system to monitor the accessibility of the NEA population (NHATS).

- It is likely that many more accessible NEOs are waiting to be found.
  - Further study is required to learn what modern NEO population models have to say on this point.

- Findings: Current survey capabilities tend to discover NEOs very close to the times of their optimal mission opportunities.
  - A space-based NEO survey telescope is needed to discover NEOs with implementable mission opportunities (far enough in advance of their mission opportunities).
  - Such an asset would simultaneously benefit human exploration, planetary defense, and science.
A thorough survey is likely to find many similar future opportunities.
Appendices
PCC Comparison: 2006 RH\textsubscript{120}

Standard NHATS Analysis 2015–2040

NHATS-like Analysis 2006–2007
PCC Comparison: 2009 BD

Standard NHATS Analysis 2015–2040

NHATS-like Analysis 2008–2012
Motion Relative to Earth: 2006 RH$_{120}$

Image Credit: Paul Chodas/JPL
Motion Relative to Earth: 2006 RH$_{120}$

2006-01-01 to 2007-12-31
Motion Relative to Earth: 2009 BD

2008-01-01 to 2014-12-31

Radial, AU
Along-Track, AU

Sun
Earth
2009BD
start
end