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NEAR-EARTH ASTEROIDS 2006 RH_{120} AND 2009 BD: PROXIES FOR MAXIMALLY ACCESSIBLE OBJECTS?

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NASA's Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) has identified over 1,400 of the approximately 12,800 currently known near-Earth asteroids (NEAs) as more astrodynamically accessible, round-trip, than Mars. Hundreds of those approximately 1,400 NEAs can be visited round-trip for less change-in-velocity than the lunar surface, and dozens can be visited round-trip for less change-in-velocity than low lunar orbit. How accessible might the millions of undiscovered NEAs be? We probe that question by investigating the hypothesis that NEAs 2006 RH_{120} and 2009 BD are proxies for the most accessible NEAs we would expect to find, and describing possible future NEA population model studies.

INTRODUCTION

With the debut of the automated Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) system in March of 2012, NASA began automatically monitoring the mission accessibility of the known near-Earth asteroid (NEA) population.[1] At present, approximately 12,778 NEAs have been discovered, and 1,434 of them are classified as NHATS-compliant, by virtue of offering at least one trajectory solution complying with NHATS mission analysis criteria. Qualitatively, being classified as NHATS-compliant means that a NEA is more *astrodynamically* accessible for round-trip missions than is Mars (i.e., requiring less Δv and flight time). The specific NHATS mission analysis criteria, described in detail on the NHATS web-site, `http://neo.jpl.nasa.gov/nhats/`, include a maximum round-trip mission duration of 450 days (of which at least 8 days are spent at the NEA), a maximum total mission Δv of 12 km/s, and Earth departure between the years 2015 and 2040.

While all NHATS-compliant NEAs are at least more accessible than Mars, some are extraordinarily accessible. For example, 605 of the NHATS-compliant NEAs can be visited round-trip for less Δv than a round-trip mission to the lunar surface, and 51 can be visited round-trip for less Δv than a round-trip mission to a low altitude circular lunar orbit. Statistical models of the NEO population indicate that there are tens of thousands of undiscovered NEAs $>$100 m in size,[2] along with at least several million undiscovered NEAs $\leq$100 m in size (down to $\sim$3 m in size), and we seek to understand just how accessible the undiscovered NEAs might be.

Examination of historical data for NHATS-compliant NEA ephemerides reveals that some of the most accessible of these NEAs actually offered their maximum accessibility in the past, around the times when they were discovered. Of these, the two NEAs with maximal prior accessibility appear to be 2006 RH_{120}, at one time temporarily captured by the Earth, and 2009 BD. In the work described herein, we present detailed comparative mission analysis for these NEAs to address the question of whether they may be considered proxies for the most accessible NEAs in the undiscovered segment of the population.

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OVERVIEW OF 2006 RH$_{120}$ AND 2009 BD

Figure 1 shows the geocentric inertial motion of 2006 RH$_{120}$, which is estimated to be 2–3 m in size, from 2006-12-01 to 2007-07-01. The NEA was first captured by Earth's gravity (i.e., the specific mechanical energy of its geocentric motion became less than zero) during June of 2006, and that condition persisted until about September of 2007, by which time the NEA was perturbed away from its Earth-captured state. The Earth-captured motion of the NEA is evident in Figure 1, which shows that the distance between the NEA and Earth varied from less than a lunar distance at perigee to several lunar distances at apogee.

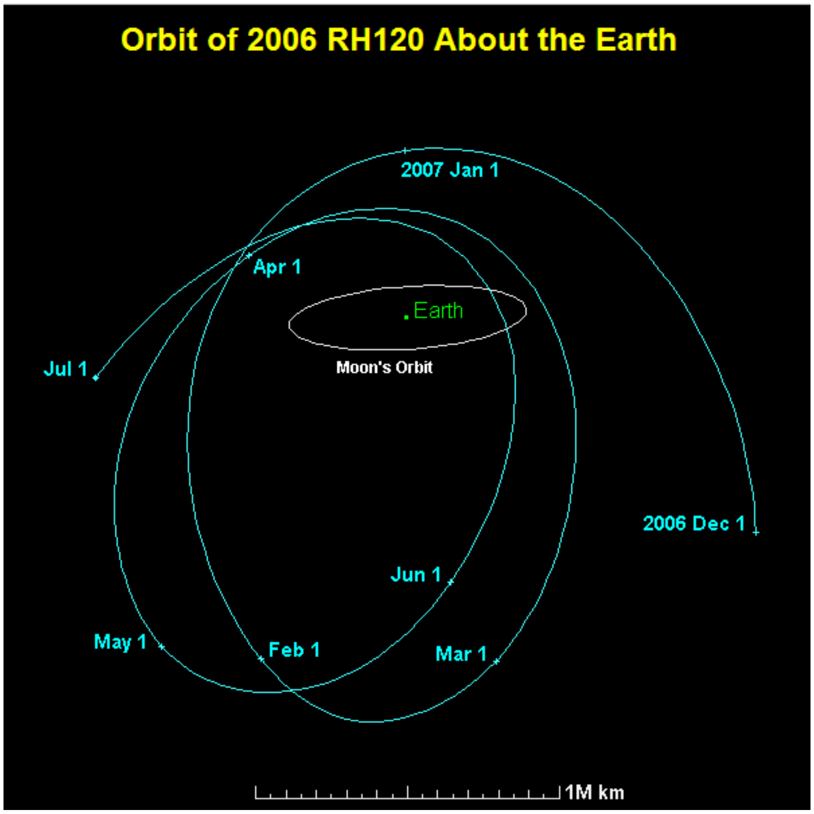


Figure 1. Motion of 2006 RH$_{120}$ Relative to Earth While Temporarily Captured By Earth's Gravity

The time frame of close proximity to Earth is important to the NEA's mission accessibility, and so it is instructive to also view the NEA's Earth-relative motion in a Sun-Earth rotating frame, as shown in Figure 2, which shows the motion of 2006 RH$_{120}$ from the beginning of 2006 until the end of 2007. In Figure 2 we see that the NEA is approaching Earth's vicinity in the months prior to its June 2006 Earth capture, and by the end of 2007 the NEA has completely departed the Earth's vicinity. We, therefore, expect attractive mission opportunities to visit the NEA to rapidly fall off during the latter portion of 2007.

Figure 3 presents a view of the motion of 2009 BD in a Sun-Earth rotating frame between the years 2012 and 2023. This motion plot spans approximately one ∼21-year synodic period between Earth and 2009 BD, as the NEA is departing the Earth's vicinity in 2012 and returning to the Earth's vicinity in 2023.

Figure 4 shows the motion of 2009 BD, which is estimated to be ∼4 m in size, relative to Earth in a Sun-Earth rotating frame, but over a shorter time interval and with a closer plot axis scale than Figure 3, which makes certain key features of the relative motion visible. In particular, we see that the NEA is quite near the Earth at the beginning of 2008 and is slowly phasing toward the Earth (each "loop" in relative motion plot takes approximately one year to complete) when it is discovered in early 2009. The NEA then remains in the Earth's vicinity for a couple of years after discovery, slowly phasing past the Earth until it begins a more

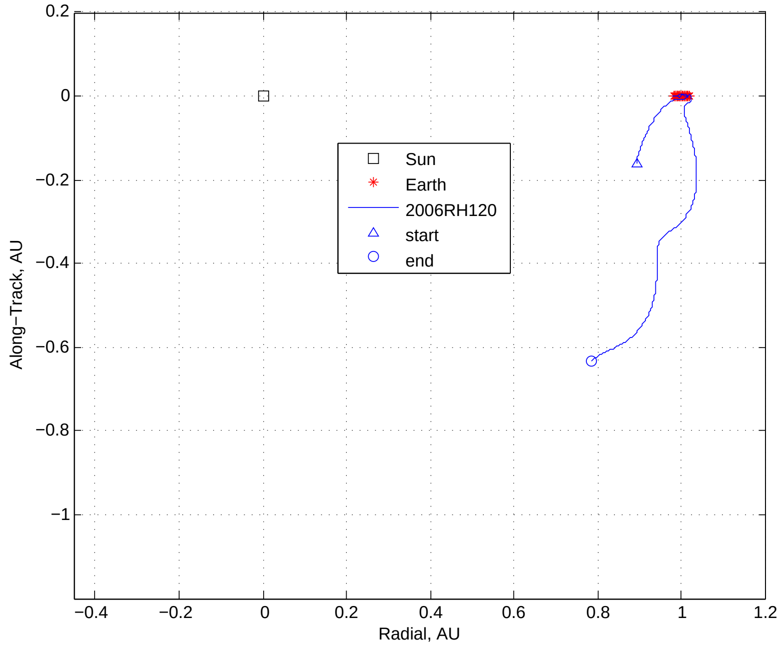


Figure 2. Motion of 2006 RH_{120} Relative to Earth Between 2006-01-01 and 2007-12-31, Expressed in a Sun-Earth Rotating Frame

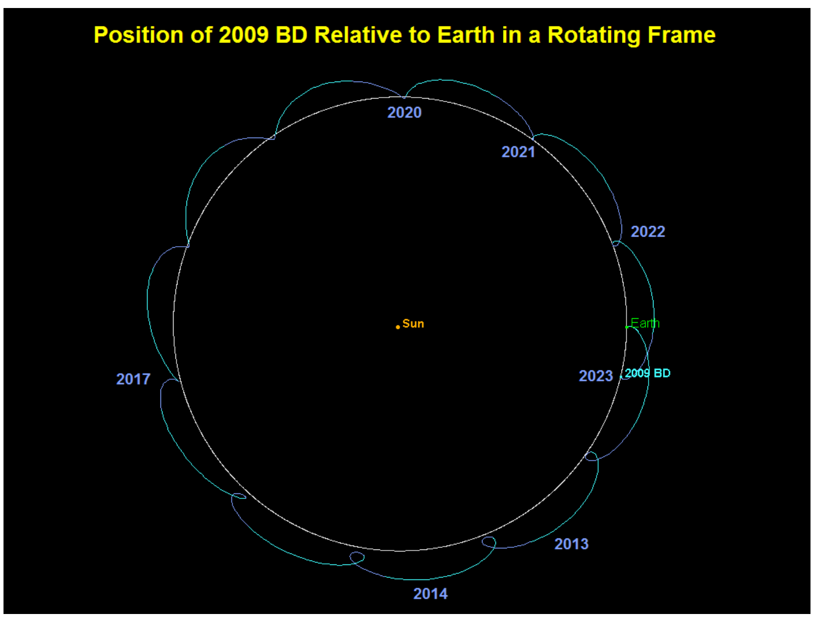


Figure 3. Motion of 2009 BD Relative to Earth Between 2012 and 2023, Expressed in a Sun-Earth Rotating Frame

rapid departure by the end of 2011. The change in the pace of the NEA's Earth-relative phasing is driven by perturbations of the NEA's heliocentric orbit by Earth's gravity, particularly effects on the NEA's orbital semi-major axis.

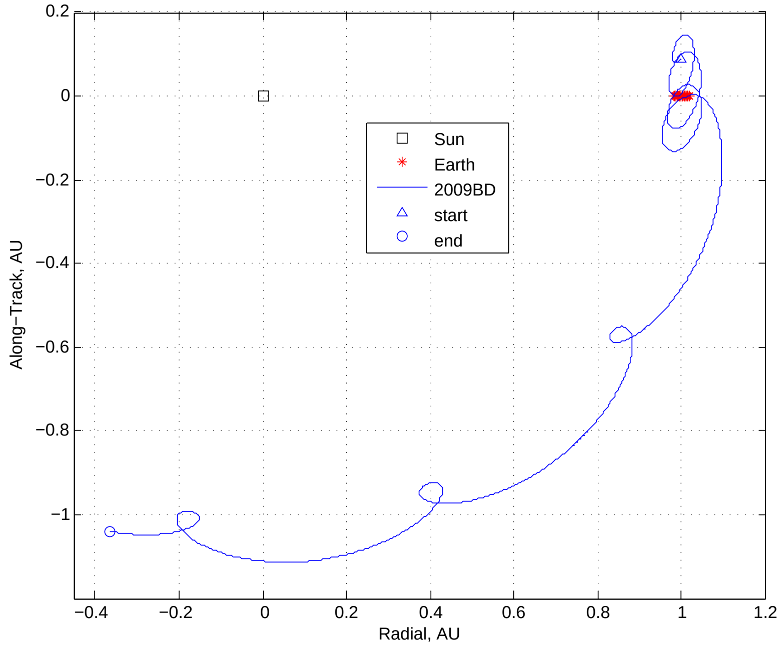


Figure 4. Motion of 2009 BD Relative to Earth Between 2008-01-01 and 2014-12-31, Expressed in a Sun-Earth Rotating Frame

MISSION ANALYSIS

The round-trip mission accessibilities of 2006 RH_{120} and 2009 BD are calculated using the NHATS embedded trajectory grid algorithms,[1,3,4] but with Earth departure dates spanning the time frames during which the NEAs were discovered. For 2006 RH_{120}, we analyze Earth departure dates between 2006-01-01 and 2007-12-30. For 2009 BD, we we analyze Earth departure dates between 2008-01-01 and 2012-12-29. We then compare these accessibility results for the NEAs with their NHATS accessibility results (for which the Earth departure dates are within the years 2015 through 2040). As is the case for the NHATS calculations, precision ephemerides for the Earth and the NEAs are obtained from the Jet Propulsion Laboratory (JPL) Horizons system.*

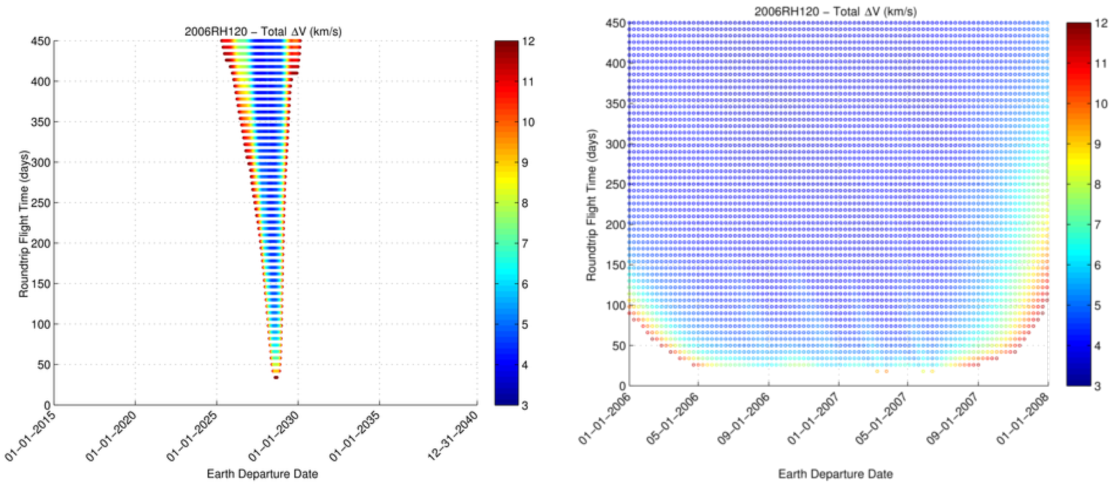
We also compare the discovery time frame mission accessibilities for the NEAs to the mission accessibilities of other notable NEAs and the projected accessibility of an object occupying a Distant Retrograde Orbit (DRO) around the Moon. The latter case is representative of a retrieved NEA boulder, according to the current plans for NASA's proposed Asteroid Redirect Mission (ARM) concept.

Mission Analysis Results for 2006 RH_{120}

Figure 5(a) shows the round-trip mission opportunities to visit 2006 RH_{120} during the late 2020s, as reported by the automated NHATS system. Figure 5(b) shows the round-trip mission opportunities to visit 2006 RH_{120} during the years 2006 and 2007, which encompasses the time span during which the NEA was discovered while temporarily captured by the Earth's gravity.

Although the horizontal scales of Figures 5(a) and 5(b) are different, inspection of the figures shows that 2006 RH_{120} was more deeply accessible (reachable for lower Δv and shorter mission durations) during the time frame surrounding its discovery and temporary capture by the Earth than it will be during its next close encounter with Earth around the year 2027.

*http://ssd.jpl.nasa.gov/?horizons



(a) Standard NHATS Analysis 2015–2040 (b) NHATS-like Analysis 2006–2007

Figure 5. PCC Plots Showing Mission Opportunities to 2006 RH$_{120}$ During the NHATS Time Frame and the NEA's Discovery Time Frame

Table 1 summarizes the optimal round-trip trajectory results produced by the NHATS algorithms for 2006 RH$_{120}$. The four leftmost columns consider total mission Δv as high as 12 km/s (the maximum considered in the standard NHATS analysis). Within this, the two lefthand columns show the minimum Δv and minimum mission duration solutions; thus, these two solutions are those that are already available on the NHATS web-site.* The next two columns apply the standard set of NHATS constraints, except that instead of Earth departure date in the range of 2015–2040, Earth departure date is restricted to the years 2006 and 2007, in order to focus exclusively on the special time period when 2006 RH$_{120}$ was both in close proximity to Earth and a temporarily captured object.

Table 1. Optimal (Minimum Δv, Minimum Duration) Round-Trip Trajectories to 2006 RH$_{120}$ Under Various Constraints

	$\Delta v \leq 12$ km/s, Dur ≤ 450 d				$\Delta v \leq 5$ km/s, Dur ≤ 150 d			
	2015–2040		2006–2007		2015–2040		2006–2007	
	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.
Total Δv (km/s)	3.972	11.942	3.501	9.147	4.711	4.993	3.843	**4.451**
Total Duration (days)	450	34	386	18	146	122	146	**58**
Earth Dep Date	18-Aug-2027	4-Aug-2028	18-Jun-2006	9-Mar-2007	3-Jul-2028	3-Jul-2028	1-Mar-2007	**12-Jan-2007**
Return Entry Speed (km/s)	11.083	12.000	11.085	11.811	11.101	11.112	11.075	**11.091**

The results show that the minimum Δv solution available between 2015 and 2040 is 3.972 km/s (in 2027), while the minimum Δv solution available between 2006 and 2007 is 471 m/s lower at 3.501 km/s (in June of 2006, shortly after the NEA was captured by Earth). Furthermore, the mission duration associated with the minimum Δv solution between 2015 and 2040 is 450 days (the maximum value considered in the analysis), while the duration for the 2006 minimum Δv solution is $\sim$2 months shorter at 386 days. Finally, while the 2015–2040 minimum duration solutions uses up all of the allowed 12 km/s of mission Δv to achieve a round-trip duration of 34 days, the 2006–2007 minimum duration solution only uses 9.147 km/s of the allowed 12 km/s Δv and achieves a $\sim$50% shorter round-trip mission duration at only 18 days. From these

*http://neo.jpl.nasa.gov/cgi-bin/nhats?sstr=2006RH120&dv=12&dur=450&stay=8&launch=2015-2040

data we conclude that 2006 RH_{120} was indeed much more accessible during its discovery as a temporarily Earth-captured NEA than it will be during its next close encounter with Earth during the year 2027.

Further insight is gained by tightening the analysis constraints, as shown in the results presented within the four rightmost columns of Table 1. For those four columns the total round-trip mission Δv is restricted to be no greater than 5 km/s and the total round-trip mission duration is restricted to be no greater than 150 days. Within those four columns, the first two use the standard NHATS Earth departure date range of 2015–2040, while the second two only consider Earth departure dates during the years 2006 and 2007. Here we see that opportunities will exist in the year 2028 to visit 2006 RH_{120} with $\sim$4.7–5.0 km/s of Δv and mission durations of $\sim$4–5 months. However, the results also show that a $\sim$5 month round-trip mission was possible in March of 2007 for only 3.843 km/s of Δv, and, most strikingly, a mission requiring only 58 days of round-trip flight time and $\sim$4.5 km/s of Δv was available in January of 2007. This round-trip trajectory is depicted in Figure 6.

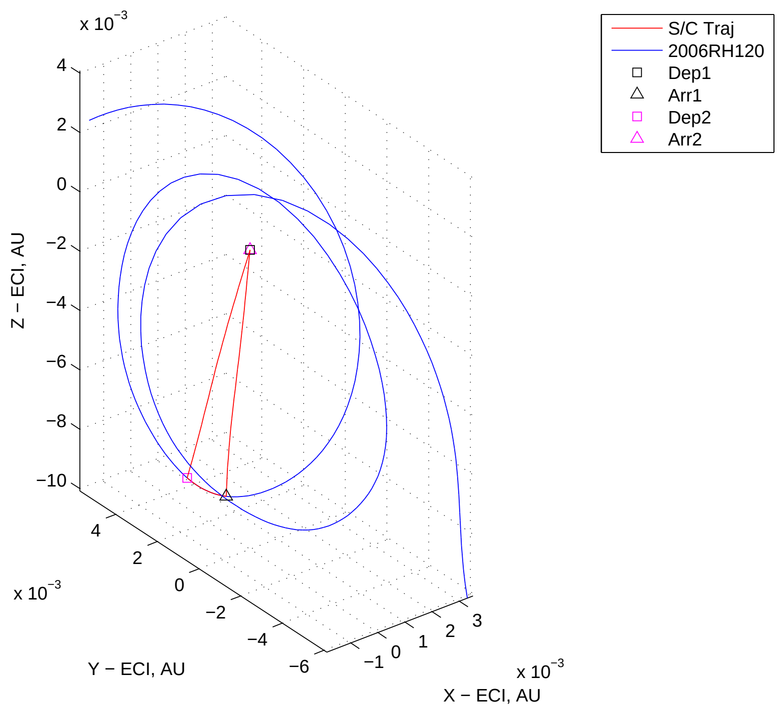
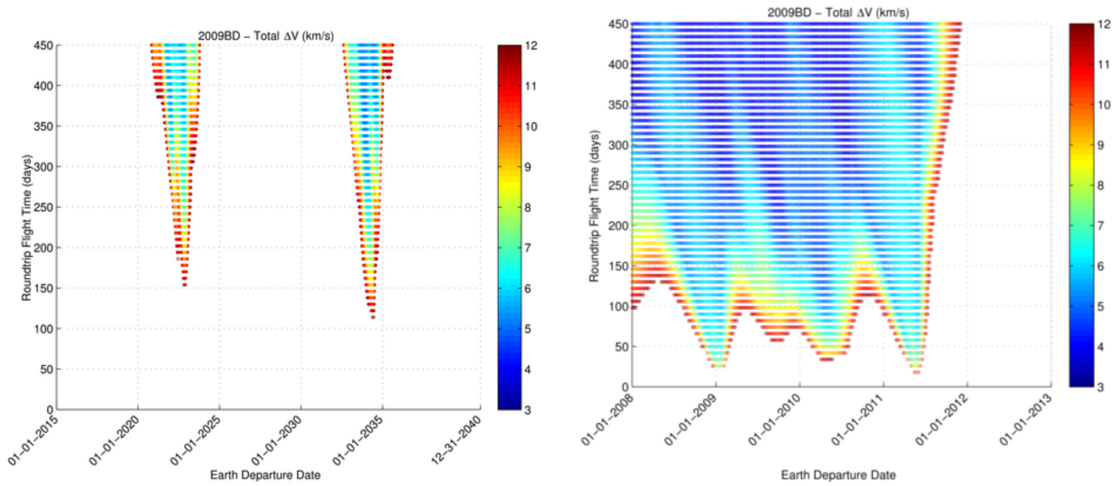


Figure 6. Round-Trip Trajectory for a 58-day Mission to 2006 RH_{120} Departing Earth 2007-01-12

Unfortunately, missions to 2006 RH_{120} during 2006 and 2007 would not have been feasible, largely because the object was not immediately recognized as a genuine NEA. A sufficiently long arc of observations is required in order to ascertain whether an object is natural or artificial, and there was not enough time available to collect that long arc of observations. 2006 RH_{120} did not receive its minor planet designation until 2008-02-18, a full year after its peak mission accessibility season had elapsed and several months after the NEA had departed Earth's vicinity, not to return for approximately 20 years. Had the NEA been discovered at least several years prior to 2006, when it was still in the process of phasing toward Earth, and had humanity possessed the capabilities to deploy human missions to the NEA during the 2006/2007 era, then the attractive mission opportunities shown in Table 1 could have been feasible.

Mission Analysis Results for 2009 BD

Figure 7(a) shows the round-trip mission opportunities to visit 2009 BD during the early 2020s and mid 2030s, as reported by the automated NHATS system. Figure 7(b) shows the round-trip mission opportunities to visit 2009 BD between the years 2008 and 2011, inclusive, which encompasses the time span during which the NEA was discovered while slowly phasing through the Earth's vicinity.



(a) Standard NHATS Analysis 2015–2040

(b) NHATS-like Analysis 2008–2011

Figure 7. PCC Plots Showing Mission Opportunities to 2009 BD During the NHATS Time Frame and the NEA's Discovery Time Frame

Although the horizontal scales of Figures 5(a) and 5(b) are different, inspection of the figures shows that 2009 BD was more deeply accessible (reachable for lower Δv and shorter mission durations) during the time frame surrounding its discovery and loitering in Earth's vicinity than it will be during either of its next close encounters with Earth in the early 2020s and mid 2030s. This illustrates some important concepts: NEAs will tend to closely approach the Earth at regular intervals (largely driven by the NEA's synodic period with respect to the Earth), but the Earth's gravity can perturb the heliocentric orbit of an NEA such that the NEA's mission accessibility is diminished during future close approaches to the Earth.

Table 2 summarizes the optimal round-trip trajectory results produced by the NHATS algorithms for 2009 BD. The four leftmost columns consider total mission Δv as high as 12 km/s (the maximum considered in the standard NHATS analysis). Within this, the two lefthand columns show the minimum Δv and minimum mission duration solutions; thus, these two solutions are those that are already available on the NHATS web-site.* The next two columns apply the standard set of NHATS constraints, except that instead of Earth departure date in the range of 2015–2040, Earth departure date is restricted to 2008–2011, to encompass the time frame when 2009 BD was discovered as it was slowly phasing by the Earth.

Table 2. Optimal (Minimum Δv, Minimum Duration) Round-Trip Trajectories to 2009 BD Under Various Constraints

	$\Delta v \leq 12$ km/s, Dur ≤ 450 d				$\Delta v \leq 6.0$ km/s, Dur ≤ 270 d			
	2015–2040		2008–2011		2015–2040		2008–2011	
	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.	Min. Δv	Min. Dur.
Total Δv (km/s)	4.978	11.876	3.464	11.054	5.876	5.964	3.843	**5.998**
Total Duration (days)	370	114	354	18	266	258	258	**50**
Earth Dep Date	30-Nov-2033	25-May-2034	15-Jun-2010	17-May-2011	10-Feb-2034	10-Feb-2034	8-Sep-2009	**15-Apr-2011**
Return Entry Speed (km/s)	11.131	11.909	11.138	11.871	11.181	11.204	11.123	**11.141**

*http://neo.jpl.nasa.gov/cgi-bin/nhats?sstr=2009BD&dv=12&dur=450&stay=8&launch=2015-2040

The results show that the minimum Δv solution available between 2015 and 2040 is 4.978 km/s (in 2033), while the minimum Δv solution available between 2008 and 2011 is 1514 m/s lower at 3.464 km/s (in June of 2010). Furthermore, the mission duration associated with the minimum Δv solution between 2015 and 2040 is 370 days, while the duration for the 2010 minimum Δv solution is $\sim$2 weeks shorter at 354 days. Finally, while the 2015–2040 minimum duration solutions uses up all of the allowed 12 km/s of mission Δv to achieve a round-trip duration of 114 days, the 2008–2011 minimum duration solution only uses 11.054 km/s of the allowed 12 km/s Δv and achieves a substantially shorter round-trip mission duration at only 18 days. From these data we conclude that 2009 BD was indeed much more accessible during the time frame surrounding its discovery than it will be during its next close encounters with Earth during the early 2020s and mid 2030s.

Further insight is gained by tightening the analysis constraints, as shown in the results presented within the four rightmost columns of Table 2. For those four columns the total round-trip mission Δv is restricted to be no greater than 6 km/s and the total round-trip mission duration is restricted to be no greater than 270 days. Within those four columns, the first two use the standard NHATS Earth departure date range of 2015–2040, while the second two only consider Earth departure dates during the years 2008–2011. Here we see that opportunities will exist in the year 2034 to visit 2009 BD with $\sim$6 km/s of Δv and mission durations of $\sim$9 months. However, the results also show that a $\sim$9 month round-trip mission was possible in September of 2009 for only 3.843 km/s of Δv, and, most strikingly, a mission requiring only 50 days of round-trip flight time and $\sim$6 km/s of Δv was available in April of 2011. This round-trip trajectory is depicted in Figure 8.

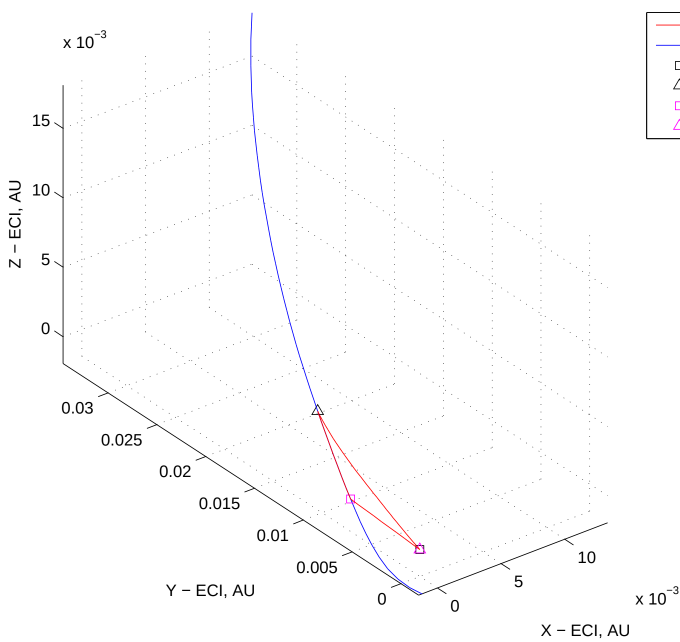


Figure 8. Round-Trip Trajectory for a 50-day Mission to 2009 BD Departing Earth 2011-04-15

Comparison to Other NEAs

The foregoing analyses demonstrate that 2006 RH_{120} and 2009 BD were at their most accessible during the time frames surrounding when they were discovered, but how do their accessibilities compare to the accessibilities of other NEAs? Figure 9 provides a graphical summary of the accessibilities of various notable NEAs, including 2006 RH_{120} and 2009 BD (both during their discovery time frames and within the 2020s/2030s). The notable NEAs in Figure 9 include: 25143 Itokawa (1998 SF_{36}), from which surface samples were returned in 2010 by JAXA's Hayabusa spacecraft; 101955 Bennu (1999 RQ_{36}), from which surface samples will be returned in 2023 by NASA's OSIRIS-REx spacecraft (scheduled to launch in September 2016); and 341843 (2008 EV_5), the intended target of ESA's MarcoPolo-R mission (not selected for flight) and the current reference target of NASA's proposed ARM concept (which would capture a boulder from the NEA and return the boulder to cislunar space). Also shown in Figure 9 are some of the most accessible NHATS-compliant NEAs, none of which have yet been visited by spacecraft: 2000 SG_{344}, 2006 RH_{120}, 2009 BD, 2010 UE_{51}, 2011 MD, and 2008 HU_4.

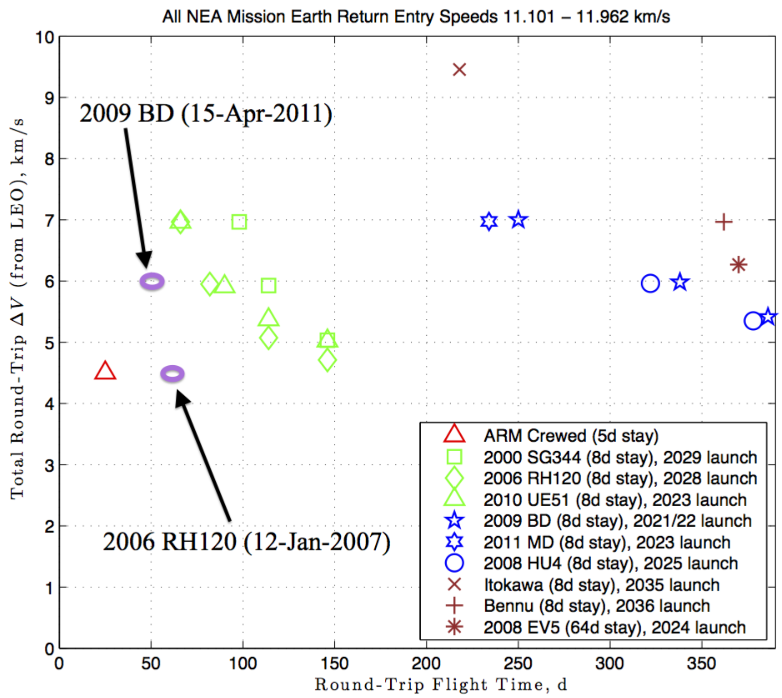


Figure 9. Comparison of Round-Trip Mission Accessibility for Selected NHATS-Compliant NEAs and an Object in Lunar DRO

The round-trip flight time versus total round-trip ΔV data shown for the NEAs in Figure 9 are obtained from the NHATS system. Also shown are annotated data markers corresponding to the previously discussed very low ΔV & very low flight time mission opportunities that were available for 2006 RH_{120} and 2009 BD during their discovery time frames. Inspection of the data in Figure 9 reveals that during their discovery time frames, 2006 RH_{120} and 2009 BD were considerably more accessible than even the most accessible of the currently known NHATS-compliant NEAs. Finally, Figure 9 shows a data marker representing the flight time and ΔV requirements for the crewed portion of NASA's proposed ARM concept, which would visit a captured asteroidal object in a lunar DRO. We see that the discovery time frame accessibilities of 2006 RH_{120} and 2009 BD approach the accessibility of an object on a lunar DRO. Thus, it is possible, in principle, to have round-trip missions to NEAs on their native orbits for which the mission flight time and ΔV requirements closely approach those of round-trip missions in cislunar space.

CONCLUSION

2006 RH_{120} was most accessible when it was near the Earth around the time at which it was discovered. In particular, when it was temporarily captured by the Earth, the NEA offered round-trip mission accessibility approaching that of an object in a lunar DRO (essentially equivalent ΔV requirement, but with a $\sim$2 month mission duration rather than the $\sim$1 month required by the mission to lunar DRO). Although 2009 BD was not a temporarily captured object, it was also most accessible when it was near the Earth around the time at which it was discovered. Additionally, both objects offered long accessibility seasons around the times at which they were discovered. Finally, we have shown that both objects were more accessible during their discovery time frames than even the most accessible of the currently known NHATS-compliant NEAs. From these results we conclude that the discovery time frame accessibilities of 2006 RH_{120} and 2009 BD are notionally representative of the maximum accessibility we expect to see in the NEA population. Thus, it is reasonable to treat 2006 RH_{120} and 2009 BD as proxies for maximally accessible objects.

However, although 2006 RH_{120} was discovered during the year 2006, it was not given its minor planet designation until 2008-02-18. Thus, this NEA was not recognized as such until well after the end of its peak mission accessibility season. Furthermore, the optimal mission time frame of January 2007 is only a few months after the NEA's discovery, and that is not a sufficiently long observation arc to ascertain whether the object is artificial or natural. Thus, deploying a mission to this NEA during the optimal time frame of January 2007 would not have been feasible for multiple reasons. On the other hand, the optimal mission time frame for 2009 BD of April 2011 is a full 2 years after the NEA's discovery and so would likely be a feasible launch date for a mission, at least from the perspective of having a sufficiently long observation arc to be reasonably confident that it is a natural object. Other considerations include: Having sufficient observations to know the NEA's orbit accurately enough to guide a spacecraft to rendezvous with the NEA; having sufficient physical characterization data on the NEA to ascertain whether it is a suitable destination for astronauts; whether the NEA has been visited by a robotic precursor spacecraft; and the available human space flight mission budget and infrastructure of the era.

Finally, it is important to emphasize that missions to especially accessible objects like 2006 RH_{120} and 2009 BD require adequate advance knowledge that those mission opportunities will be available. That requires discovering such a NEA sufficiently far in advance of its optimal mission time frame that there is enough time to adequately characterize the NEA and prepare the mission to visit it. Enhanced NEA survey capabilities, such as a dedicated space-based NEA survey telescope located away from Earth, might have the potential to discover highly accessible NEAs like 2006 RH_{120} and 2009 BD years in advance of their peak mission accessibility seasons, affording us the opportunity to deploy missions to visit them in their native orbits.

Future Work

While 2006 RH_{120} and 2009 BD are clearly among the most accessible of the known NEAs, and while their *past* accessibilities are quite extreme, several questions remain: Do NEAs with even higher accessibility exist in the population of undiscovered NEAs? How prevalent are such highly accessible NEAs in the overall NEA population (including the undiscovered NEAs)? Definitively answering these questions will require completing the NEA survey (i.e., discovering all not yet discovered NEAs). In the meantime, the study presented herein supports the notion that 2006 RH_{120} and 2009 BD are likely to be highly representative of most accessible NEAs and can, therefore, be considered as proxies for maximally accessible NEAs.

However, an intermediate step between our current work and the completion of the NEA survey (which is at least years in the future, if not decades) would involve extending the analysis described herein to current NEA population models. In that work we would systematically apply the NHATS algorithms to each member of a large set of simulated NEA orbit ephemerides, drawn from the latest NEA population models. The results would provide a quantitative assessment of what current NEA population models predict regarding the mission accessibility of the NEAs. This is clearly a large-scale computational problem, as it would involve running the NHATS algorithms on at least tens of thousands of NEAs. Furthermore, interpretation of the results will be complicated by several factors: (1) NEA population models are, of course, only models; (2) currently available statistics are incomplete for the population of NEAs <100 m in size, yet such NEAs are predicted to be much more numerous than NEAs ≥ 100 m in size, and, therefore, will comprise the majority of the analysis; and (3) currently available statistics are incomplete for Earth co-orbital NEAs and temporarily Earth-captured NEAs; such NEAs are clearly more likely to be highly accessible than other NEAs and should, therefore, be appropriately represented in a NEA population model used for a study of NEA accessibility.

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