THE ACCESSIBILITY OF POTENTIALLY HAZARDOUS ASTEROIDS FOR BALLISTIC RAPID RECONNAISSANCE FLYBY MISSIONS Justin A. Atchison[1], Rylie A. Bull[2], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 USA; Justin.Atchison@jhuapl.edu; [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 USA

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Introduction: Rapid reconnaissance flyby missions represent the fastest means of characterizing a potentially hazardous asteroid in a planetary defense scenario [1]. Flyby trajectories can often reach the asteroid with launches every year and cruise durations as short as months. In these scenarios, the design, fabrication, and testing of the spacecraft is the longest duration event in the overall timeline. In an effort to achieve a faster response capability and shorten this timeline, we could consider developing the spacecraft and instrument suite in advance of the asteroid's discovery. This would even offer an opportunity to test and demonstrate the spacecraft prior to a critical threat when any mission failures could be catastrophic.

This study seeks to characterize the mission design requirements and trade-space for a flyby spacecraft capable of performing reconnaissance of an as-yet undiscovered threat. Our goal is to help define a set of requirements the spacecraft must meet in order to be applicable for some percentage (*e.g.* 90%) of the modeled threat population.

Our approach is to generate a large set of candidate trajectories to a synthetic population of hazardous asteroids. We then post-process the set to identify combinations of trajectory parameters that satisfy appreciable fractions of the asteroid population. These parameters can then be used to design a capable rapid response spacecraft in advance of identifying a specific threat.

As an example, spacecraft power engineers must size the solar arrays to the maximum solar distance the spacecraft is expected to experience. With this set of trajectories, we can compute the maximum spacecraft aphelion solar distance that is compatible with feasible trajectories to 90% of the synthetic population. The same type of question can be addressed for all of the most relevant mission design parameters: encounter flyby speed; encounter lighting and geometry; solar distances; Earth distances; and angles between the Earth, Sun, and asteroid.

Approach: We take the existing population of 2340*,† potentially hazardous asteroids (PHAs) and rephase them so that they pass close to Earth in the early 2030's. This is illustrated in Figure 1. We note that although this synthetic population is based on true asteroid data, this approach risks observation bias.

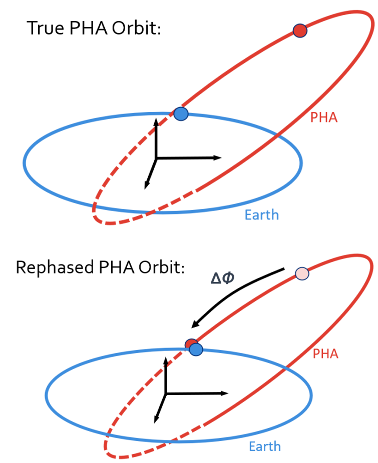

Figure 1: Illustration of PHA Rephasing to Create a Synthetic Population.

We then make a series of suppositions to narrow the trade-space:

- A flyby mission would need to encounter the PHA no later than 0.75 orbit periods prior to new Time-of-Close-Approach (TCA).
- A rapid response would need to launch no earlier than 3.5 years before this latest encounter.
- A viable flyby mission would not require a heavy-lift launch vehicle. To that end, we limit the available launch energy (C3) to 30 km^2/s^2, which supports up to a 500 kg spacecraft on at least two medium-lift launch vehicles.
- Deep space maneuvers and gravitational assists can be neglected.

*NASA JPL Small Body Database Query accessed 06/2023, https://ssd.jpl.nasa.gov/tools/sbdb_query.html.

†Two of the 2340 asteroids have orbital periods greater than 30 years and are removed from the set.

Finally, we compute trajectories to each PHA using simplified two-body Lambert arcs. The time grid is 5 days, such that the trajectory search includes cases departing Earth every 5 days and passing the asteroid every 5 days. We remove any asteroids that violate the assumed constraints above. This leaves over 32M trajectories that we can sort and filter.

Results: For any relevant mission design parameter, we can sort the set of trajectories and count the number of asteroids that are accessible for a specified bound. For example, Figure 2 shows the fraction of asteroids that have at least one trajectory with a flyby speed less than or equal to a given value. This shows that about 92% of the population has a trajectory that flies by the PHA with a speed $\leq$ 22 km/s.

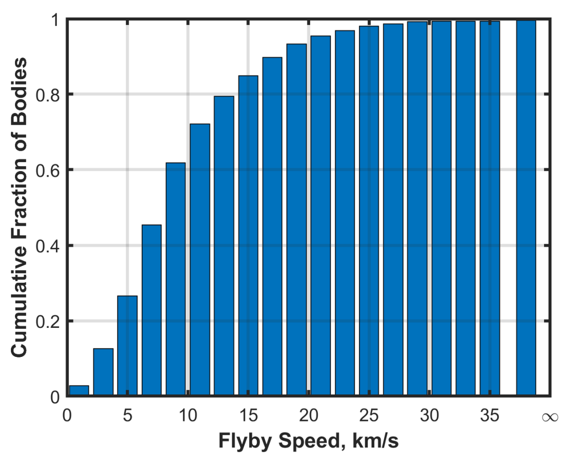

Figure 2: **Sample 1D Histogram for Flyby Speed.**

It turns out that most parameters are highly correlated. For example, few asteroids have feasible trajectories with both a low flyby speed and a low solar phase angle. The 2D histogram for this case is given in Figure 3 with dashed line contours of 80%, 90%, and 95%.

We can then look across combinations of parameter bounds to identify feasible sets that meet an appreciable fraction of the population. One preferable set [2], which meets 90% of the population, is given in Table 1.

Conclusions: It is challenging to design a single spacecraft that can accommodate flybys of the entire synthetic population modeled in this study. However, it appears to be feasible to find a design that meets roughly 90% of the population, as demonstrated in Table 1.

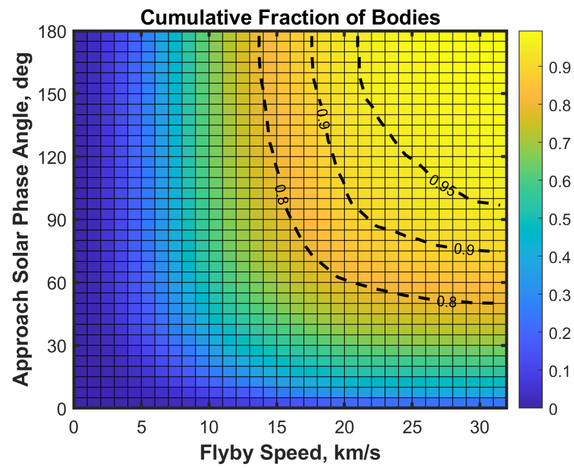

Figure 3: **Sample 2D Histogram with Contours Showing Percent of Accessible PHA Population.**

Table 1: **Sample Parameter Set that Meets 90% of the Population**

Parameter	Bound
Max Time of Flight	2.5 yr
Max Launch Energy	30 km^2/s^2
Min Solar Distance	0.9 AU
Max Solar Distance	2.0 AU
Max Solar Phase Angle	90°
Max Flyby Speed	25 km/s

The next steps for this study are:

- Consider different suppositions for trajectory search constraints, including a wider range of launch dates, higher launch energies, and inclusion of maneuvers and gravity assists.
- Assess if our conclusions change when applied to an unbiased synthetic population.
- Iterate further with systems and payload engineers to refine a requirement set that is feasible, comprehensive, and low-cost.

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References: [1] National Science & Technology Council (2018) *National Near-Earth Object Preparedness Strategy and Action Plan*. [2] N. Chabot, et al. (2024) *International Astronautical Congress* IAC-24-E10.1.1.