DEFINING THE REQUIREMENTS FOR A PLANETARY DEFENSE RAPID-RESPONSE FLYBY RECONNAISSANCE DEMONSTRATION MISSION. Nancy L. Chabot[1], Justin A. Atchison[1], Rylie Bull[1], Andrew S. Rivkin[1], R. Terik Daly[1], Ronald-L. Ballouz[1], Olivier S. Barnouin[1], Andrew F. Cheng[1], Carolyn M. Ernst[1], Angela M. Stickle[1], Jodi R. Berdis[1], Dawn M. Graninger[1], and Sarah Hefter[1], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA (Nancy.Chabot@jhuapl.edu).

Introduction: The 2023 Decadal Survey for Planetary Science and Astrobiology [1] recommended that *"the highest priority planetary defense demonstration mission to follow DART and NEO Surveyor should be a rapid-response, flyby reconnaissance mission targeted to a challenging NEO, representative of the population (~50-to-100 m in diameter) of objects posing the highest probability of a destructive Earth impact."* This recommendation followed a 2017 recommendation from the United-Nations-endorsed Space Mission Planning Advisory Group (SMPAG) [2] that identified a 50-m-diameter object as the smallest for which a reconnaissance mission is recommended, and in 2021, the same guidance was adopted in the United States Report on Near-Earth Object Impact Threat Emergency Protocols (NITEP) [3]. A 50-m object impacts the Earth roughly every thousand years [4], more frequently than larger objects, and is capable of local devastation with the potential for regional effects. Even following the successful completion of NEO Surveyor operations [5], roughly half of the 50-m NEO population will be left undiscovered. As a result, 50-m impactors may not be found with long warning times, and a rapid-response flyby mission may be the only reconnaissance possible.

In this study, we use the high-level Decadal Survey recommendation to define the requirements for a planetary defense rapid-response flyby reconnaissance demonstration mission. As commonly noted in the community, in planetary defense, you don't pick the asteroid – the asteroid picks you. Thus, a planetary defense flyby reconnaissance demonstration mission is not about just flying by an asteroid, but rather it is about developing a robust capability for the objects that are most likely to require a short-warning-time, space-based response to provide critical information to decision makers. We use this overarching motivation to define four major requirements for a planetary defense flyby reconnaissance demonstration mission.

Requirement 1 – Enable a flyby of >90% of the potential asteroid threat population: A synthetic threat population was created by adjusting the orbital phase of the population of the existing 2340 potentially hazardous asteroids to achieve their minimum Earth distance in the early 2030s. Ballistic spacecraft trajectories were computed for each object in the synthetic threat population, and post-processing of the millions of possible trajectories was used to determine the range of flyby conditions to access the targets. Solar electric propulsion, gravity assists, and deep-space maneuvers were excluded in the analysis. Many of the trajectory parameters are correlated, and **Figure 1** shows the combined results for two of the more challenging flyby conditions – approach solar phase angle and flyby speed. **Table 1** gives a sample design point for a flyby demonstration mission that encompasses >90% of the potential threat population.

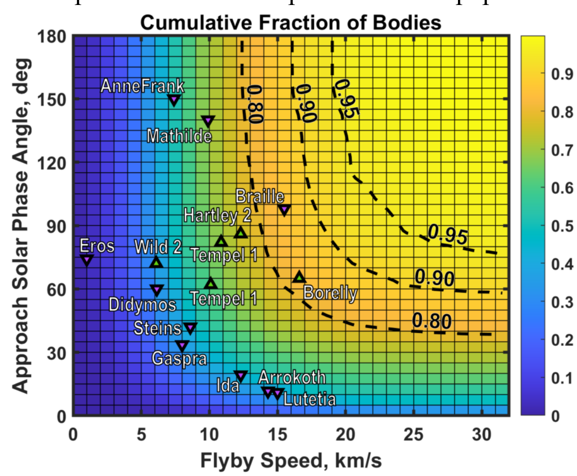

Figure 1. Approach solar phase angle versus flyby speed for the synthetic threat population. The 0.9 line identifies flyby conditions for 90% of the population. Previous asteroid (upside down pink triangles) and comet (green triangles) flybys are also plotted.

Table 1. Flyby conditions for >90% completeness.

Max time of flight	Min solar dist.	Max solar dist.	Max approach solar phase angle	Max flyby speed	Max launch C3
2.5 yrs	0.9 AU	2.0 AU	90 deg	25 km/s	30 km^2/s^2

Requirement 2 – Demonstrate the flyby reconnaissance for a ~50–100 m NEO: A ~50–100 m sized object is the most likely threat that the Earth will face that will currently warrant a reconnaissance mission [1–3]. A demonstration mission is essential for validating that the as-designed system can reliably perform when needed. If an asteroid threat to the Earth was identified, the flyby event would represent a critical, singular opportunity to gather the reconnaissance information required for decision makers to develop an effective mitigation plan. A preventable spacecraft failure would be intolerable. The demonstration mission must identify any potential failures and test the limits of the spacecraft's performance in a stressing flyby. The demonstrated capability could then also be applied to the less challenging case of a larger object, should such a need arise in the future.

Requirement 3 – Obtain the information needed to determine if and where the object would impact the Earth: SMPAG [2] and NITEP [3] policies state that a reconnaissance mission should be conducted if the Earth impact probability rises to >1%. Thus, knowing where the object will hit the Earth, if at all, will be the top priority question for decision makers. Conducting a flyby will provide the needed orbit information to definitively determine whether the object will impact the Earth and will constrain the impact location, with the location constraints that are possible being dependent on the specific scenario.

Requirement 4 – Determine key properties of the asteroid to inform decision makers: While in any threat situation, as much information as possible is always desired, a few key properties are priorities.

Determine the asteroid's size: Planetary defense exercises conducted since 2013 [6] illustrate the large uncertainty in the size of the asteroid that can occur when only information from Earth-based optical telescopes is available, as summarized in **Figure 2**. Constraining the size for a 50-m object is the most challenging case for the flyby concept and drives the requirement; requiring ≥10 pixels across a 50-m object yields a pixel scale of ≤5 m, and a one-pixel uncertainty on each side of the measured extent yields a ±10 m uncertainty. Approach and departure imaging is needed to constrain the maximum size extent. From **Figure 2** it is clear that this basic information on the size would vastly decrease the size uncertainties considered in the planetary defense exercise scenarios.

Determine if the asteroid is mostly rocky or metallic: While there is no known way to measure the mass directly of a small ~50–100-m object during a flyby, asteroid threat assessments are driven by having to consider the most extreme case of the object being Fe-Ni metal, as demonstrated in planetary defense exercises [6]. Iron meteorites are only 5% of observed meteorite falls, but their high density makes them more massive for their size, causing substantially more damage. The viewing geometry and target brightness necessary to obtain the radar, visible/near-IR spectroscopy, and/or mid-IR emissivity data that can reliably distinguish between rocky and metallic objects is not generally available for small objects, even from space telescopes and especially in the short-warning timescales relevant to this mission study. Therefore, appropriate measurements must be made by the spacecraft.

Determine if there is a single object or multiple objects of concern: Observations of NEO binary asteroids show that all secondaries have been found within distances of ~5 primary diameters [7], implying a distance of 500 m around a 100-m asteroid. Approach and departure imaging of this region to identify any objects >10 m, the smallest object with associated mitigation actions in the US NITEP [3], is required. Options to extend the imaging to cover the larger Hill sphere radius of 13 km should be examined.

Determine the asteroid's surface characteristics: Investigation of DART images at a range of pixel scales indicates imaging at ≤0.5 m/pixel is required to confidently identify surface features such as those seen on Dimorphos on a 50-m object, the most challenging case. Approach and departure imaging is required to provide insight into the surface characteristics of the small object and inform potential mitigation options.

Next Steps: The next steps are to take these requirements driven by planetary defense needs and to investigate implementation options for a flyby demonstration mission. In particular, we anticipate that navigation may be one of the largest technical challenges for this concept, given the fast flyby speed, high approach solar phase angle, and small, potentially low-albedo object. However, we don't have the luxury of choosing the asteroid, so addressing this challenge is necessary to advance our planetary defense preparedness capabilities.

References: [1] NASEM (2022) Decadal Survey for Planetary Science and Astrobiology 2023–2032. doi: 10.17226/26522 [2] SMPAG (2017) Meeting #08. https://www.cosmos.esa.int/web/smpag/ [3] National Science & Technology Council (2021) Report on the Near-Earth Object Impact Threat Emergency Protocols. [4] Harris & Chodas (2021) Icarus 365, 1144452. [5] Mainzer et al. (2023) PSJ 4, 224. [6] CNEOS. https://cneos.jpl.nasa.gov/pd/cs/ [7] Walsh & Jacobson (2015) Asteroids IV, p. 375.

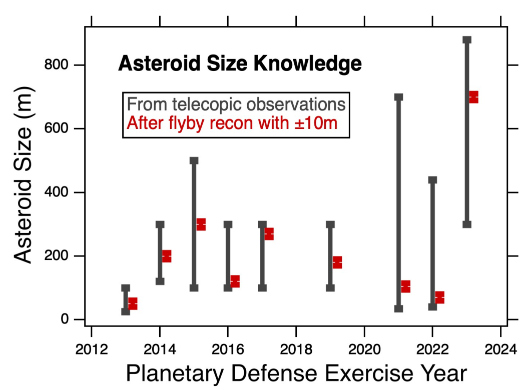

Figure 2. Planetary defense exercises and reported size uncertainties [6] and size knowledge after a flyby.