APOPHIS AS A TEST-CASE FOR FLYBY RECONNAISSANCE MISSIONS FOR PLANETARY DEFENSE. R.-L. Ballouz, R.-L.[1], A.K. Davis[1], D. M. Graninger[1], J.R. Berdis[1], C.M. Ernst[1], O.S. Barnouin[1], A. Cheng, F.E. Siddique[1], [1]Johns Hopkins University Applied Physics Lab, Laurel, MD (ronald.ballouz@jhuapl.edu)

Introduction: The close approach of (99942) Apophis in 2029 presents a unique opportunity to test planetary defense reconnaissance missions, as there is strong scientific interest in observations both before and after its near-Earth encounter. In many planetary defense scenarios, very little is known about the hazardous asteroid (HA) in advance of an impact due to limitations on the resolving ability for small objects of Earth-based sensors. Sending a reconnaissance mission to the HA before a mitigation attempt would provide critical information needed to enhance a mitigation missions' chances for success by providing detailed, up-close observations. Two main options exist for a reconnaissance mission: a flyby or a rendezvous.

For a planetary defense mission, the relevant properties that can be learned from spacecraft reconnaissance are the HA's mass, multiplicity, shape, and surface properties [1]. While rendezvous missions can provide detailed characterization of these properties with months to study an object, extended development times and challenging trajectory constraints may prevent their use in a crisis. With little warning time, orbital mechanics may restrict the mission options and a flyby would be necessary, limiting observations to what can be accomplished in passing at relative velocities of kilometers per second. There are ongoing debates on the cost-benefit analysis of data provided by a flyby mission given the observational constraints, which Apophis presents an opportunity to address.

Here, we present a mission concept that would use the Apophis close approach in April 2029 as an opportunity to demonstrate a rapid planetary defense flyby reconnaissance design. In this demonstration, we would use small satellite systems equipped with commercial off the shelf (COTS) cameras to characterize Apophis prior to its close-encounter with Earth through a flyby, which could then be followed by a rendezvous mission for detailed characterization of Apophis after its 2029 encounter. This planetary defense demonstration would provide evidence of the quality of data generated by a flyby mission, with the added benefit of establishing a baseline for the physical characteristics of Apophis, that may be compared against by post-encounter ground- and space-based observations (high-quality "truth data") at an arbitrary later date to establish the relative usefulness of flyby information for planetary defense.

Background and Planetary Defense Objectives: Spacecraft exploration of small near-Earth asteroids (NEAs) have shown that these objects are covered by a regolith surface layer that is often dominated by large meter-scale boulders (Fig. 1 a-e, [2-4]). From direct surface interaction with the surface of NEAs, we know that their regolith cover is weakly cohesive and impacts on to the NEA may be dominated by the weak gravity of these objects [5]. However, high resolution observations of (101955) Bennu's boulders have revealed craters on their surfaces, indicating that the regolith possesses relatively strong constituent material [6]. Detailed characterization of Bennu's crater population at meter scales further confirm the determination of a strength-dominated boulder population that effectively armors the surface against impacts [7]. In addition to this boulder shielding, numerical impact simulations have shown that the momentum enhancement factor imparted by a kinetic impactor, is strongly influenced by near-surface porosity and strength [8,9]

While surface characteristics of a HA can influence the impact response, the largest deciding factor is the mass of the asteroid itself. Mass of asteroids are difficult to determine directly from flybys (though new technologies are being developed that may enable such measurements [10]). Here, we will estimate the mass of Apophis by measuring its size, shape and determining a meteoritic analog through imaging by multispectral cameras. This imaging campaign will have an added benefit of characterizing the color heterogeneity of the surface, providing a basis for post-close-Earth-encounter observational comparisons investigating resurfacing due to tidal forces.

Finally, a key complication for the deflection of an HA would be the presence of a satellite that may be un-resolved by ground-based observations. Apophis has no known natural satellites. However, large satellites of a HA may pose an additional hazard and/or complicate deflection operations. Furthermore, if Apophis does have a natural satellite, it may be stripped by the tidal encounter with Earth [11].

In summary, we define the following Planetary Defense Objectives (PDOs) for our mission concept:

PDO #1: Characterize the boulder distribution of Apophis at 1 m-scales.

PDO #2: Determine the size and shape of Apophis at 1 m resolution.

PDO #3: Characterize the composition and color heterogeneity of the Apophis surface.
PDO #4: Determine the presence of satellites >= 1 m around Apophis.

Flyby Mission to Apophis Architecture: We outline the mission architecture for a pre-close approach flyby of Apophis. Reaching Apophis before the close approach would provide the only detailed view of Apophis before tidal interactions alter its surface, spin state, and orbit. For this mission, two small satellites each equipped with a multi-spectral camera with at least four bandpass filters (b'=0.44-0.5 µm, v=0.52-0.58 µm, w=0.67-0.73 µm, x=0.82-0.89 µm) would be used to fly by Apophis, one for each side of the asteroid. By using two spacecraft, the surface could be imaged more completely. This will allow for near-complete characterization of the boulder population (PDO #1), improved determination of the shape (PDO #2) and therefore mass estimate, and characterization of surface heterogeneity (PDO #3). Prior to the closest approach with Apophis, we will conduct a satellite search (PDO #4). Therefore, a two-spacecraft flyby would provide a more scientifically interesting detailed understanding of the resurfacing caused by the close approach in addition to demonstration of general flyby reconnaissance capabilities. Furthermore, a two-flyby platform would enable superior stereo imaging of the surface, which would improve our ability to determine surface changes from the tidal encounter. Although the close approach is in only 7 years, there are launch opportunities that would allow a flyby spacecraft to arrive in advance.

Based on simulations of flyby at 15/25 km altitudes [12] and comparable mission analysis, we expect that a COTS multi-spectral camera could achieve ~1 m/pixel imagery. Such a pixel scale would be sufficient to characterize the color variegation on S-type (25143) Itokawa (500 m diameter, Fig. 1a,b) and the large dark 90-m boulder on Bennu (Fig. c,d). In comparison, the Chang'e-2 flyby of S-type (4179) Toutatis was able to characterize the color properties of one hemisphere at 8.6 m/pixel (Fig. 1e, [13]). Work by [12] has begun to outline the utility of the data that can be obtained using COTS and/or legacy hardware for such a mission concept.

Finally, we may be able to obtain a better constraint on the rotation state of Apophis by obtaining lightcurve measurements a few days prior to closest approach with the asteroid. While this may not improve our knowledge of Apophis' rotation significantly, it will demonstrate the ability of a quick reconnaissance planetary defense mission to perform this measurement for a HA.

Synergy with larger missions and Outlook: While a flyby opportunity may provide limited information on regolith and surface characterization, it will provide a vital test data set for how well flyby missions can characterize their targets that may be later validated by a larger-scale rendezvous mission to Apophis.

This mission would serve the first of its kind: a planetary defense reconnaissance test mission. With validation data available from a larger post-close-Earth-encounter mission, it would be possible for the first time to place uncertainty limits on the data that can be obtained from a planetary defense flyby reconnaissance mission with current technologies. *This would provide unequivocal evidence as to the utility of a flyby for planetary defense, while also establishing a baseline design for potential rapid future fielding.*

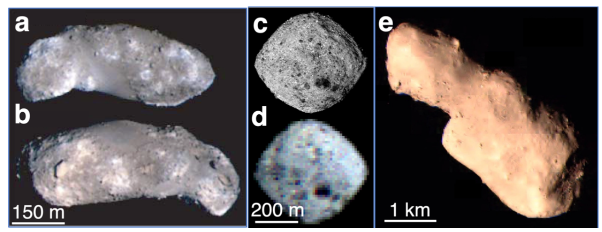

Fig. 1. a, Eastern and **b,** western hemispheres of 500-m (long-axis) S-type Itokawa as imaged by Hayabusa [14]. Color variegation at 10-100m scales on Itokawa is evident. **c**, PolyCam image (1.1 m/pix), and **d**, MapCam color mosaic (10.9 m/pix) of 500-m diameter C-type Bennu as imaged by OSIRIS-REx [3]. Coarse color imaging (**d**) provides information on surface heterogeneity. The dark boulder evident near the equator of Bennu in **c** and **d** is a ~90-m diameter buried boulder/outcrop. **e**, Flyby color mosaic of S-type Toutatis as imaged by Chang'e 2 [13].

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