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LOW-COST MISSION ARCHITECTURES TO SMALL BODIES

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Extended Abstract—
The 30,000+ known Near Earth Objects are some of the closest objects in our solar system to the Earth. A few dedicated missions such as NEAR, Hayabusa-1 and -2, OSIRIS-Rex, and DART have revealed a lot about their nature, with more to come from ESA's Hera mission, and others. Dedicated space missions to individual NEOs are relatively costly, however, so we seek to find a way to reduce costs so that the composition and structure of more NEOs can be fully characterized, and we can continue to explore how to change the trajectory of selected objects, as was done with DART. Here we describe a low-cost approach to NEO missions for small body science and planetary defense that makes use of existing or planned space vehicles.

The Lesson Learned from Space-X's Reusable Booster trials —
Let us start by examining how Space-X made the long-sought breakthrough to achieve truly reusable rocket boosters, so that, in the words of their founder Elon Musk "we don't do the equivalent of throwing away a Boeing 747 every time we launch" [1]. Tests of the reusable booster were executed on the first stage of Falcon-9 rockets after the primary payload had separated from the launch vehicle. Space-X experienced several failures during these tests, learning more on each attempt. But an important point is that the reusable booster tests were *not the primary objective of each launch*, and they could be carried out at minimal risk to the customer who had paid for their primary payload to be lofted into space. Put differently, Space-X achieved their reusable booster capability as a piggyback on the primary launches, *at a fraction of the amount that a dedicated reusable booster program would have cost.* A similar approach to infusing new technology that can be fully utilized on future missions has been routinely practiced by UK company Surrey Space Technology Limited, who tend to fly new developments as part of the second string of their spacecraft subsystems.

Robotic Sample Return Missions and other Small Body Missions —

One lesson to be drawn from Space-X's experience is that a closer look at the mission elements we routinely dispose of/dispense with may be beneficial to NASA. For example, NASA's OSIRIS-Rex mission team, once it has achieved its primary mission objective of returning an entry probe carrying a sample of the NEA Bennu to Earth, plans to re-purpose the carrier spacecraft to rendezvous with NEO Apophis, shortly after its closest approach to Earth in 2029 [2]. Similarly, the Hayabusa-2 spacecraft, having successfully delivered its sample from the near-Earth asteroid Ryugu in 2020, has now been repurposed to execute a fly-by of (98943) 2001 CC21 in July 2026 and a rendezvous with asteroid 1998 KY26 in July 2031 [3]. These are current missions; looking back in time there is almost a tradition of small body missions being re-purposed to achieve new objectives, including the transformation of Deep Impact into the EPOXI mission to flyby a second comet, Hartley 2, and NEAR, which was not planned to land on Eros as part of its baseline mission. The lesson of reuse and repurposing is relevant to NASA's Planetary Defense and Small Body Science objectives, as expressed in the most recent decadal survey for Planetary Science and Astrobiology [4].

OSIRIS-Rex and Hayabusa-2 both exhibit a common architecture for robotic sample return missions, in which a sample is acquired at some distant object within our solar system, and placed in a sample return capsule, which is then escorted back to Earth by the carrier (or mother) spacecraft. As they near Earth, the sample return capsule and the carrier spacecraft separate hours or even days before closest approach, giving the carrier spacecraft ample time to apply thrusters to adjust its trajectory so that it swings by the Earth, instead of burning up in the atmosphere. In the case of OSIRIS-Rex and Hayabusa-2, this trajectory adjustment is used to slingshot, using the Earth's gravity to place the spacecraft on a heliocentric orbit path that sets up future encounters with NEOs.

This reuse/repurpose concept can apply to similar extended missions to address planetary defense and small body science objectives for other robotic sample return missions over the next decade, such as ESA's

Earth Return Orbiter baselined for Mars Sample Return, and JAXA's Martian Moons Exploration mission (MMX) which will return a sample from Phobos in 2029. NASA could direct that *all* future robotic sample return missions look for additional objectives they could fulfill, following the completion of their primary mission. This would make for interesting codas to future missions under consideration to return a sample from a comet, or Ceres, for example.

SmallSat Flyby and Rendezvous missions —
ESA's plans for its M-ARGO CubeSat mission are worth some consideration [5]. With a nominal launch date in 2024, M-ARGO is a 25 kg, 12U CubeSat with its own propulsion system that hitches a ride as a secondary launching to the L2 Earth-Sun Lagrange point. On arrival it goes into a halo orbit, from which it can rendezvous with any one of an estimated 140 NEOs, using the ~3.5 km/s of Delta-V provided by its ion engine. M-ARGO has the capacity for only 1U of science payload, but with advances in miniaturization of instruments for CubeSats, that may be enough to accommodate both a multi-band VNIR imager and a lidar. The 3.5 km/s Delta-V value that M-ARGO baselines is similar to the Delta-V value for a NEO rendezvous mission given in [6].

M-ARGO is just one example of a feasible mission to a small body. Another, the Janus mission, which will send two SmallSats on a flyby to explore a binary asteroid, was selected under NASA's last SIMPLEx call [7]. Janus will carry similar Visible and IR cameras to those used on OSIRIS-Rex to characterize a TBD asteroid. Further, in a white paper from the small bodies community submitted to the Planetary Science and Astrobiology Decadal Survey [8], it was argued that SmallSats are well-suited to NEO flyby and rendezvous missions as geophysical investigations for Planetary Defense

Artemis —
Artemis-1 (see Figure 1) is the first of a series of missions that mark an ambitious return to the Moon for NASA and its partners. A key goal of the program is to land astronauts on the surface of the Moon and return them safely to Earth within this decade, possibly as early as 2024. Artemis launches (both crewed and uncrewed) are planned on a cadence of roughly one per year, beginning in 2022 with Artemis-1. Artemis-1 is an uncrewed mission with a profile similar in some respects to Apollo 8, with the objective of demonstrating the safe return of the Orion capsule, after completing a circuit of the Moon.

The primary purpose of the Interim Cryogenic Propulsion Stage (ICPS) of Artemis-1 is to inject the Orion Capsule and European Service Module (ESM) onto a translunar trajectory. It can be seen from the figure that the ICPS (which has a 3.5-ton dry mass) is then disposed of in a heliocentric orbit, after deploying a total of 13 mostly 6U CubeSats after the translunar injection burn and separation from Orion/ESM. At least two of those CubeSats were targeted for release onto a heliocentric orbit. NASA's CubeSat Launch Initiative has issued a call for 6U and 12U secondary payloads for Artemis II.

Following its brief tour of the Moon, the European Service Module's propulsion system provides the thrust to return both Orion and the ESM to Earth. These two modules separate on approach, Orion entering Earth's atmosphere and executing its landing sequence, while the approximately 6.5-ton service module (including the Crew Module Adapter) burns up in the Earth's atmosphere. The ESM is quite a capable space vehicle, with 380 kg of payload capacity, besides the consumables needed for its primary mission, and solar panels that can generate 11.2kW of power.

Several possibilities exist:

1. If the 4-ton ICPS is still a live vehicle with some residual propellant in its tanks (and prudent mission designers always build in margin), and it can be maneuvered onto a trajectory that crosses the path of a suitable NEO, it provides a starting point for a very effective kinetic impactor mission, provided the finer details of precision navigation to such an object can be solved in the case of the ICPS.
2. If the ICPS hosted 12 SmallSat spacecraft on every launch, that is potentially up to 12 different NEO rendezvous missions on every Artemis launch. With reliable launch opportunities on a near-annual cadence, the cost of a 12U NEO rendezvous CubeSat could be drastically reduced via bulk production. A 12U CubeSat launched on an ICPS module could even be deployed to observe a kinetic impact (see 1). Not all the SmallSats must be NASA spacecraft, providing opportunities for non-traditional organizations some of which might not be current space faring nations. It might be preferable to have two or more spacecraft head to each target: for redundancy in case one fails, but also to provide some flexibility in the payload and target viewing geometry. Each could carry a camera, but then one might carry a multi-band imager/laser combination, and the other a ground penetrating radar, for example. Note that the 12U number may not be an upper limit for CubeSats/SmallSats hosted on other ICPS vehicles - larger spacecraft may be feasible.
3. For some missions that require more ambitious scientific instrument payloads, re-purposed robotic sample return missions (e.g., OSIRIS-

Rex, Haybausa-2, MMX, MSR) may be best suited.

4. The ESM could be redirected to encounter and impact or rendezvous with a NEO. With its approximately one order of magnitude larger mass (~6.5 t) than the DART impactor, it would give an interesting new data point regarding asteroid deflection. For a fly-by or rendezvous, it has enough payload capacity to carry a significant science instrument payload. After concluding its primary mission, the ESM will still contain a considerable amount of propellant left in the ESM tanks. For example, at the end of the ARTEMIS-II mission, there should still be more than 2.5t of remaining propellant, giving an available delta-v of more than 1 km/s. For ARTEMIS-II, this would for example enable rendezvous with the NEOs 2014 MF18 and 2002 NV16 or impact/flyby with the previously mentioned NEOs or Itokawa, 2011 AM24, 2001 CQ36 and 2011 CG2. Design add-ons would need to be integrated, as some of the spacecraft functions are relying on the Crew Module. The additions would include an extension of the existing S-Band communication hardware, an additional Onboard-Computer, a battery and some additional GNC sensors (i.e., star trackers and Inertial Measurement Unit). These design add-ons could be added in the unpressurized cargo area and would reduce the available payload capacity by an amount (assumed to be less than 100 kg, leaving still 280 kg for scientific payload). Moreover, the Flight-Software would need to be updated for the new flight configuration. For higher delta-v missions, the solar panels could power one or more ion beam deflectors like the MASMI unit discussed in the study report (or perhaps more powerful ones).

By re-purposing existing mission elements, and using lower cost, standardized approaches to SmallSats that can achieve planetary defense and small body science objectives, a comprehensive and affordable program is possible. Further opportunities to reduce cost can come from partnering with international space agencies.

Programmatics —

This paper describes a low-cost approach for planetary defense and small body science missions that can be implemented in the coming decade. The program can be made affordable by taking advantage of existing missions and mission elements from PSD robotic missions and planned Artemis missions that can be re-purposed to reach NEOs. Such a program lends itself to partnering among the NASA Centers engaged in Human Exploration and Planetary Science, and with international partners that already engage with NASA's Planetary Science Division, including ESA and JAXA. Standardization of spacecraft subsystems and easy access to launch services has led to a tremendous growth in CubeSats in Low Earth Orbit, with hundreds being launched every year [10]. If SmallSat NEO rendezvous missions can similarly be standardized, using easily procured subsystems, and the launch cadence remains steady at about one per year, deployments off the ICPS or the ESM can become an easy entry point for other spacefaring nations, keen to lose the bonds of Earth and go exploring the great beyond.

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Pre-Decisional Information – For Planning and Discussion Purposes Only.

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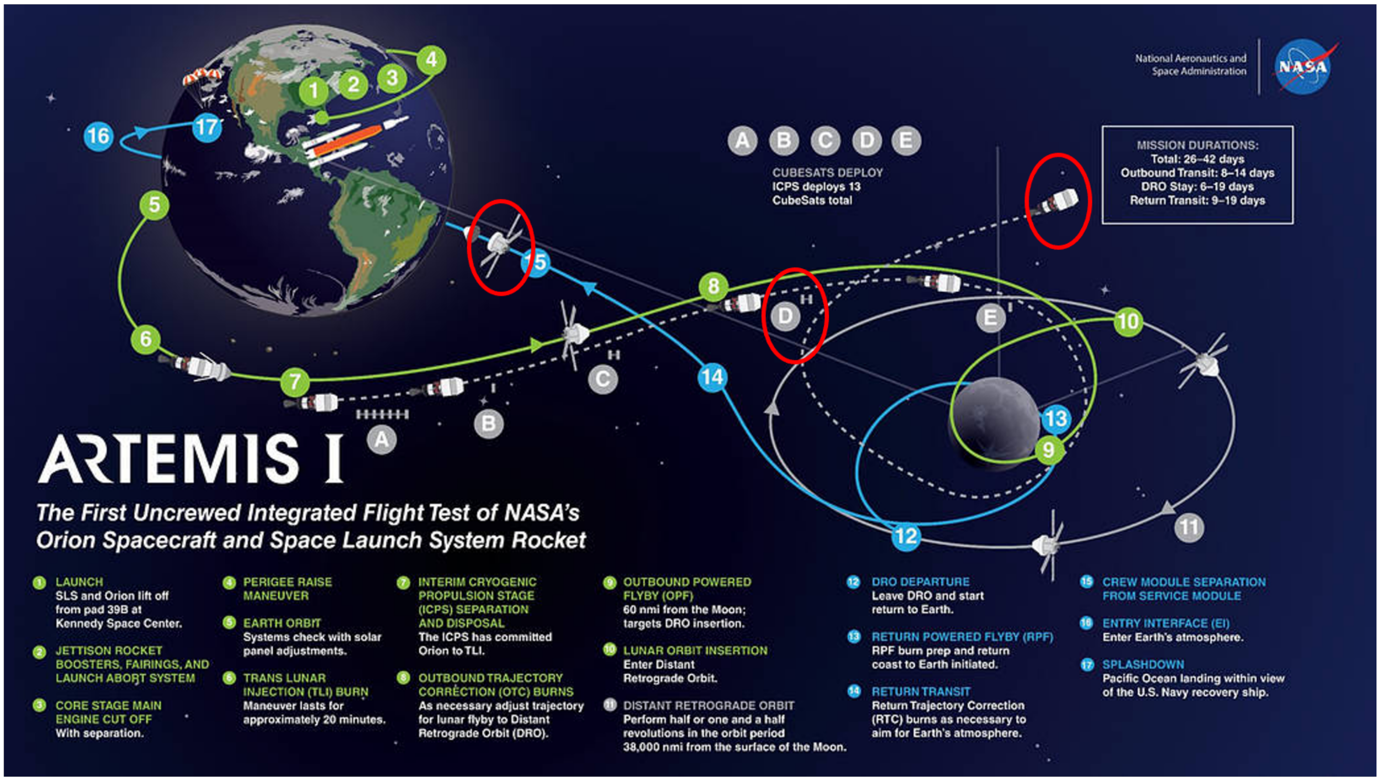

Figure 1: the Artemis 1 mission architecture [9]; opportunities to re-purpose mission elements to address planetary defense and small body science objectives are circled in red.