Technology gaps for rapid response missions to near-Earth objects, interstellar objects, and long-period comets. Benjamin P. S. Donitz[1], Julie C. Castillo-Rogez[1], James F. Bell, III[2], Michael E. Brown[3], and Paul A. Abell[4]. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (Benjamin.p.donitz@jpl.nasa.gov), [2]Arizona State University, Tempe, AZ [3]California Institute of Technology, Pasadena, CA [4]NASA Johnson Space Center, Houston, TX.

Introduction: The last several years has seen the discovery of the first two interstellar objects [1][2], the first ever planetary defense mission [3], recommendation for a rapid reconnaissance planetary defense demonstration [4], and the continued emergence of a robust commercial small satellite industry [5]. The present and near future also consist of emerging next-generation observatories including Vera Rubin [6] and NEO Surveyor [7]. These seemingly disparate events converge in the context of rapid response: a cross-cutting capability that would enable NASA and the international community to quickly discover and respond to an emerging target such as a near-Earth object (NEO), interstellar object (ISO), or long-period comet (LPC) either for rapid characterization of a potential threat, or revolutionary science that would inform early solar system formation and evolution.

In late October 2022, subject matter experts gathered at the California Institute of Technology in a week-long workshop sponsored by the Keck Institute for Space Studies (KISS) to address enabling mission concepts for rapid response and key technology gaps (final report in progress). These experts concurred that the ability to respond on the order of a few months is necessary for rapid in-situ characterization of a NEO, ISO, or LPC, and that while there are several technology gaps, this capability could be realized in the near future.

Science Goals and Objectives: The capabilities discussed here respond to three different classes of targets, each with their own goals and objectives. The goal of rapid characterization of a PHA is to precisely determine the asteroid's orbit, mass, and relevant physical characteristics to inform a potential mitigation mission strategy. If a PHA were identified to have a >1% likelihood of impacting the Earth, it would be a national priority to characterize the target to the maximum extent possible as quickly as possible [8]. Note that this goal is not explicitly for science, but the measurement techniques are similar to scientific observation of a NEO.

ISOs and LPCs, meanwhile, are important targets for planetary and exoplanetary science. The explicit science case for ISOs is still being defined. The lack of context, small sample size, and unknown target origin makes it challenging to make inferences on generic solar system formation without a more in-depth population study. ISOs do remain, however, of paramount interest to the science community and general public as key exploration targets. ISOs also could provide ground truth for exoplanetary science, if their origins could be traced, and in general sit at a unique intersection between astrophysics and planetary science.

LPCs, and in particular dynamically new comets, are extremely valuable to understand the conditions under which the solar system formed. The volatiles that have been locked within these comets since the formation of the early solar system act as fossil records that are exposed upon close passage to the Sun. The science goal of a dedicated LPC rapid response mission would be to constraint the conditions of the protoplanetary disk and better understand the diversity amongst comets by characterizing the morphology of a long period comet, a class of targets with very few measurements by a dedicated mission [9].

Target Destination: From a planetary defense standpoint, the objects that would most likely need to be mitigated are the numerous 50m to 100m asteroids with orbits that approach or intersect Earth's. If they are on an impacting trajectory, they will have a node at 1 AU, given that at some point in time, the orbit will intersect with Earth. There is also a possibility that a hazardous object could be cometary in nature and thus would be active and possibly larger in size, but the probability of impacts from these types of objects are very low compared to asteroids.

LPCs have nuclei that can vary in size and reach up to 80 km, such as Hale-Bopp. Because these targets are often dynamically new, they tend to have a high level of activity. Recent models have shown grain sizes up to the millimeter-scale with relative velocities potentially in excess of 60 km/s [10].

There are little bounds on the physical and chemical makeup of an ISO. The two that have been observed so far look dramatically different with 'Oumuamua being a ~100m cigar-like reddish asteroid, and Borisov being a ~500m bright comet. Most likely, an ISO that is able to be detected from Earth with sufficient time to respond would be cometary, like Borisov. Thus, a mission to a LPC and a mission to an ISO could look quite similar from a flight system and instruments perspective.

Mission Architecture/Platform: The KISS workshop identified two primary mission architectures to address rapid response. In the first architecture, a spacecraft would be mostly pre-built in a batch of several spacecraft and stored on the shelf until a target is identified, after which the spacecraft would be rapidly integrated onto a launch vehicle and directly injected on an intercept trajectory. In the second architecture, a small constellation of spacecraft already deployed would be ready to respond to a new target. The spacecraft would be placed in orbits to maximize accessibility to a new target and would use a combination of on-board propellant and Earth gravity assists to inject into the intercept trajectory. The loitering spacecraft could spend their time performing gradient heliophysics from an Earth-like heliocentric orbit and could visit NEOs that pass close to the various spacecrafts' orbits.

For both architectures, the spacecraft would perform a fast flyby of a target, possibly at extremely high velocities (30+ km/s). For active targets, like comets, the flight system might require a Whipple shield to protect the vehicle from high-velocity impacts from dust. In the ground storage architecture, the fight system could be modified before launch to include a shield and in the constellation architecture, a fraction of the spacecraft could include shields.

Expected Measurements: In all cases, the measurements would consist of visible and thermal images using a gimbaled camera with multiple filters to characterize shape, rotation, volume, limited compositional information, and surface morphology and deployed small gravity probes to determine the target mass. The ground-stored spacecraft would include an optional hypervelocity dust spectrometer to determine bulk composition of active. In general, the ground-stored system would rely on modularity to be applicable to a variety of targets while the space-stored system would make use of a fixed payload suite to characterize NEOs, and possibly an opportunistic low-activity ISO or LPC.

Target Solicitation: The science obtained from a LPC fast flyby would directly address science goals highlighted in the Planetary Science and Astrobiology Decadal Survey. They are not identified as targets in the New Frontiers list for the upcoming decade but LPCs could make for a very strong Discovery target. While there is precedence within the European Space Agency for a mission with a storage period (i.e. Comet Interceptor), NASA's science mission program parameters are not amenable to these kinds of missions. Rapid response missions targeting PHAs could potentially fit within the programmatic landscape of Planetary Defense, and such reconnaissance missions have been recommended by the 2023-2032 Planetary Science and Astrobiology and Decadal Survey.

The KISS workshop recommended a new initiative for rapid response, primarily focused on planetary defense with an opportunity to apply lessons learned from the planetary defense rapid response demonstration to an ISO or LPC target of opportunity. The initiative would consist of regularly procured spacecraft from commercial vendors to be deployed as a fleet, stored either on the ground or in space and ready to respond within a few months (as per the architectures previously described).

These NEO-reconnaissance spacecraft could provide preliminary insight into an ISO or LPC but would not provide the same science return as a dedicated Discovery mission. With increased modularity for the ground-stored system, payloads more appropriate for a cometary flyby could be integrated, including a dust shield which may be necessary for any close flyby of an active target. It would be more difficult to re-purpose a space-based system to visit a LPC if it were designed for an asteroid-like target. The space-based system could also perform a population study of non-threating NEOs to better inform the diversity and key characteristics of those types of targets.

Technology Challenges and Opportunities: The technical challenges fall primarily into two categories: 1) challenges related to rapid implementation, integration, testing, and launch and 2) challenges related to hypervelocity flybys of small target and/or active bodies (i.e., comets).

Rapid implementation, integration, testing, and launch require new technologies and practices. Technologies that would enable rapid data interfacing, such as universal adapters, could enable the flight system to make small modifications to the payload suite without a significant change to the overall vehicle or instrument design. Further modularity, like modular propellant tanks, communication systems, and power systems, can increasingly optimize the spacecraft for an individual target and flyby geometry, maximizing the potential payload mass and probability of having sufficient launch energy to encounter the target without sacrificing response time. Modularity might also increase the ability to encounter an ISO or LPC farther from 1 AU. Rapid testing might require regular maintenance of ground-stored spacecraft, rapid battery integration and test, and a suite of flight system checkouts that could be performed within several weeks of notification of target identification. On-going Department of Defense activities related to rapid launch vehicle integration provides a useful template for how something similar might be achieved with NASA [12].

Hypervelocity flybys drive the need for instruments that can operate in more extreme conditions and autonomous navigation that can successfully navigate by a target with minimal ground intervention. There already exist remote instruments that are suitable for high velocity and high slew rate flybys, like the APIC camera developed at JPL [12], although advances in detector sensitivity and changes in filter bandpasses will be required to accommodate extremely high flyby velocities. However, there remains a gap in in-situ instruments like dust spectrometers that can effectively sample material in-situ and meet the spectral resolution required for origin science (e.g., volatile isotopes). Shields that can withstand millimeter-sized grain particles at speeds in excess of 60 km/s would also be required for a flyby of an active target or one that has undergone fracturing. For autonomous operations, AutoNav presents a good framework for navigating to a high velocity target without ground in the loop [13][14]. At such high velocities, there is insufficient time for the ground to calculate a required trajectory correction maneuver and uplink the command for execution by the spacecraft. Furthermore, stochastic effects like thruster execution uncertainty can propagate at a rate faster than the ground can control, risking a failed flyby. Technologies required for precise autonomous navigation include miniaturized deep space autonomous clocks, advanced AutoNav algorithms, and algorithms that can identify the nucleus of an active target. In all cases, the technology should be compatible with small spacecraft platforms.

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