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.

Definition

Rapid Response Mission: Conducting a mission to a recently discovered, non-recurring object or high interest/consequence event. If no timely action is taken, future assessment, investigation, and exploration of the object is not possible.

Targets

Over the last several years there has been growing recognition that detailed knowledge of specific classes of small bodies can only be attained through rapid response missions. Specifically, these classes consist of the following objects:

- **Interstellar Objects (ISOs)** – Active or inactive objects that originate outside the solar system and are traveling on hyperbolic trajectories (e.g., 1I/'Oumuamua and 2I/Borisov)

- **Long Period Comets (LPCs)** – Comets with periods of >200 years, as opposed to short period comets (like Halley's Comet). These foundational objects are generally extremely active and contain volatiles from the early formation of the solar system (e.g., C/2022 E3 (ZTF)).

- **Near-Earth Objects (NEOs)** – Near-Earth asteroids (or comets) that pose a significant impact hazard to Earth and have short warning times.

Rapid Response & the Decadal Survey

More recently one of the primary recommendations from the National Academies Planetary and Astrobiology Decadal Survey 2023 – 2032 highlighted the need for developing a rapid response mission capability for planetary defense.

- *"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. Such a mission should assess the capabilities and limitations of flyby characterization methods to better prepare for a short-warning-time NEO threat" [1].*

The response to this recommendation from the NASA Science Mission Directorate Planetary Science Division stated that:

- *"NASA concurs with this recommendation and recognizes that the ability to determine the key characteristics of an imminently dangerous NEO quickly and accurately may be critical to the success of any future mitigation efforts. Moreover, developing a rapid-response capability may significantly enhance Planetary Science opportunities for the study of long-period comets and interstellar objects, which are unpredictable targets of opportunity"[2].*

Importance of New Survey Assets

One of the key factors for furthering knowledge of these small body populations are the emerging next-generation survey assets of the Vera Rubin Observatory and NEO Surveyor spacecraft which will come online in the coming decade.

These facilities will provide the data required to assess the population numbers in general and identify appropriate targets of opportunity which would enable NASA and the international community to quickly discover and respond to an emerging target.

KISS Rapid Response Study

In response to these developments, subject matter experts from around the world gathered at the California Institute of Technology W. M. Keck Institute for Space Studies (KISS) for a one-week workshop in October 2022 to address the challenges and opportunities for developing rapid response mission capabilities. (Note: Final report in progress.)

Participants from NASA, ESA, JAXA, academia, and industry met and identified overlapping architectural drivers, constraints, and synergies that could help enable development and deployment of a rapid response mission during the next decade.

Science Goals and Objectives

Rapid response missions may enable deployment of dedicated spacecraft to newly identified targets that would otherwise not be possible via regular mission development timelines.

- Development of rapid response mission capabilities could be necessary to characterize a recently discovered NEO that may pose a near-term threat to Earth. Such in situ characterization is necessary to adequately assess the physical characteristics of the NEO, determine the potential magnitude of the impact hazard, and ascertain whether a subsequent mitigation mission(s) to deflect or disrupt the NEO is warranted.
- Rapid response would enable planetary science missions to fascinating objects such as LPCs and ISOs that are typically challenging to investigate via in-situ spacecraft. Data from these objects could revolutionize understanding of early solar system formation and evolution.

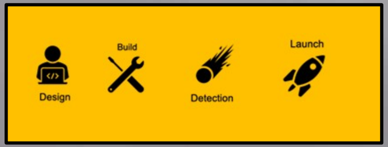
Traditional Mission Architecture

- **Traditional paradigm for missions – target must be identified well in advance and often relies on a regular cadence of announcements of opportunity (AOs)**

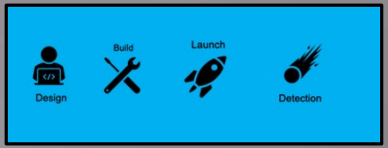
Rapid Response Mission Architectures

- **New alternatives based on rapid response paradigm – allows for flexibility in target selection and mission deployment**

1. **Ground Storage – Partial or Complete Build – Launch on detection**



2. **In Space Storage – Parking Orbit – Launch then loiter**



Rapid Response Architectures: Pros and Cons

Architecture	Pros	Cons	Applicability
Ground Storage	• S/C in controlled environment • Ready for deployment • Variety of mission classes • Can aim for specific target	• Minimal tailoring to target • Needs rapid, dedicated launch	• Wide range of missions • Target detected with enough time to set up launch
In Space Storage	• S/C operational; ready for deployment • Variety of mission classes • Bonus science possible while in orbit	• S/C cannot be tailored to target *(you get what you get…)* • Standby duration driven by cost and S/C aging • Less energy left to reach target	• Wide range of missions • The larger the propulsion system, the broader the pool of targets

References

[1] Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023 – 2032, The National Academies (2022) Chapter 18, Page 21. https://nap.nationalacademies.org/catalog/26522/origins-worlds-and-life-a-decadal-strategy-for-planetary-science

[2] NASA 90-day Initial Response to the Decadal Survey (August 2022) https://science.nasa.gov/science-red/s3fs-public/atoms/files/Initial%20(90-day)%20written%20response%20to%20the%202023%E2%80%932032%20Planetary%20Science%20and%20Astrobiology%20Decadal%20Survey.pdf

Technology Gaps: Challenges and Opportunities

The technical challenges fall primarily into two categories:

1. **Challenges for rapid implementation, integration, testing, and launch and,**
2. **Challenges related to hypervelocity flybys of small targets 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.

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, 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. 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.

Acknowledgements: We would like to acknowledge the W. M. Keck Institute for Space Studies (KISS) for sponsoring this workshop. We would also like to acknowledge the other participants of the workshop, all of whom contributed to the material in this poster: Coralie Adam (KinetX), Oketa Basha (Arizona State University), Paul Chodas (JPL), Sonia Hernandez (Continuum Space Systems), Geraint Jones (University College London), Joe Lazio (JPL), Declan Mages (JPL), Walid Majid (JPL), Anne Marinan (JPL), Joe Masiero (Caltech), Karen McConnell (Blue Canyon Technologies), Karen Meech (University of Hawaii), Daniel Miller (Massachusetts Institute of Tehcnology), Erica Molnar-Bufanda (University of Hawaii), Derek Nelson (KinetX), Naoya Ozaki (JAXA), Carol Raymond (JPL), Darryl Seligman (Cornell), Matt Shaw (Lockheed Martin), and Hajime Yano (JAXA).

The Ten Second Review

- Rapid response missions are valuable for interstellar objects, long-period comets and near-Earth objects.
- The Decadal Survey and NASA are supportive of rapid response missions.
- A W.M. Keck Institute of Space Studies was held in October 2022 to examine rapid response missions
- Two possible architectures for rapid response missions are Ground Storage and In Space Storage
- Technology challenges fall into two main areas - 1) rapid integration, testing, and launch; 2) navigation and data collection during hypervelocity flybys