RAPID RESPONSE

TO NEAR EARTH OBJECTS, LONG PERIOD COMETS, AND INTERSTELLAR OBJECTS

July, 2024

Keck INSTITUTE FOR SPACE STUDIES

Enabling Fast Response Missions to Near-Earth Objects (NEOs), Interstellar Objects (ISOs), and Long-Period Comets (LPCs)

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1 EXECUTIVE SUMMARY

Three classes of targets of compelling scientific interest—Near-Earth objects (NEOs), interstellar objects (ISOs), and long-period comets (LPCs)—require detailed investigation for planetary defense purposes that can be achieved through the use of in situ spacecraft. Exploration of the NEOs and its sub-class of potentially hazardous asteroids (PHAs), ISOs, and LPCs requires a paradigm shift towards a significantly more "rapid response" type of mission approach that can be implemented by the planetary community. The common thread between these three otherwise distinct classes of objects is that the most scientifically compelling of the targets are discovered only a short time before a mission launch would need to occur to encounter them. For both scientific and planetary defense purposes, it is critical to develop the capability to perform a rapid response mission for the next generation of small bodies exploration.

A group of international experts from academia, industry, and commercial space exploration gathered in October 2022 at the California Institute of Technology for a Keck Institute of Space Studies (KISS) workshop on rapid response spacecraft missions. The group was tasked to identify science drivers, key technology gaps, and enabling capabilities, and to explore potential architectures that could be applied to rapid response missions. The group concluded that the potentially most enabling near-term path to developing a rapid response capability is through planetary defense programs. The new National Academies Planetary Science and Astrobiology Decadal Survey (National Academies 2023) also recommends that NASA pursue a NEO rapid response demonstration mission as the next highest priority planetary defense mission after the NEO Surveyor mission.[1] The recommendation includes the caveat that any lessons learned during a demonstration mission could also apply to science-driven rapid response missions to ISOs or LPCs.

The KISS workshop participants agreed that it is critical for a rapid response demonstration mission to be part of a more general and sustainable mission capability, and not just a one-off demonstration. That is, rapid response must be a repeatable exercise and, at least in the case of planetary defense, funded as a sustained program. Companies within both the traditional aerospace sector as well as many of the emerging commercial startups, often dubbed "NewSpace" companies, provide opportunities for commercial partnerships to develop a sustained rapid response program, a significant component of which would be focused on planetary defense. In addition, new and emerging small spacecraft (SmallSat)

[1] https://www.jpl.nasa.gov/missions/near-earth-object-surveyor

capabilities offer a potentially standard approach to engineering, payloads, and mission operations, reducing cost and schedule significantly compared to traditional larger-class spacecraft and missions, but at the cost of lower payload mass and higher risk. New and smaller launch vehicles are also becoming well suited to deploying SmallSats with little forewarning, as is now being demonstrated by the U.S. Department of Defense (DoD) tactical launch program (e.g., Erwin 2023).

The KISS workshop participants evaluated two specific potential rapid response architectures: ground-based storage and space-based storage. An advantage of the ground-based storage option, where spacecraft are mostly pre-built and then stored until a launch date is set, is that the vehicles can be rapidly modified and tailored to a particular NEO/PHA, ISO, or LPC target while they are still on the ground. Another advantage is that minimal operations cost is required to maintain the flight systems for potentially long pre-flight durations. Upon detection of a suitable target, these ground-stored spacecraft could be prepared and, optimally, launched on a dedicated launch vehicle. Alternately, the space-based storage option has the advantages of leveraging rideshare opportunities to minimize the cost of delivery of multiple SmallSats to space in advance, and using autonomy to perform low-cost operations for a large constellation while awaiting the arrival of a suitable rapid response target. Another advantage of the space-based storage option is that the pre-deployed spacecraft can also perform opportunistic heliophysics or potentially even exploration of non-threatening NEOs while waiting for a higher-priority rapid response target to be identified.

In both architectures, the spacecraft would host relatively simple, high-heritage payloads, such as an imager with multiple filters to assess surface geology, topography, shape, and mineralogy; an infrared (IR) point spectrometer for more detailed surface compositional studies; a high-fidelity radio system and/or optical "gravity probes" to determine mass; and/or a thermal imager for thermophysical science and to better resolve target size from a safe standoff distance. Such an instrument suite could resolve key knowledge gaps in NEO, ISO, and LPC science, provide more robust assessments of each object's orbit, and provide critical data to inform potential future impact mitigation missions.

Workshop participants agreed that a rapid response flyby of an NEO is feasible based on available payload technologies. However, higher-fidelity instrumentation (such as miniaturized mass spectrometers and high-resolution infrared imaging spectrometers) is likely required to advance specific Decadal-class science objectives for ISOs and LPCs. In addition, further development of high-velocity dust spectrometers to obtain in situ samples from active objects at high speeds, system-level autonomy to operate spacecraft in dynamic environments and during dormant operations, and modularity for rapid modifications and optimization of ground-stored spacecraft would all enhance future rapid response missions.

The synergy between the discovery of large numbers of NEOs, ISOs, and LPCs by next-generation observatories and the rapidly developing capability of small satellites to conduct first-rate science has made now the optimal time to develop a rapid response capability. The knowledge gained from designing and demonstrating that type of mission first at an NEO will also have potentially critical planetary defense implications and pave the way forward for the more challenging exploration of ISOs and LPCs.

2 MOTIVATION

2.1 SCIENCE CASE FOR THE STUDY OF REMNANTS OF STAR SYSTEM FORMATION

Current and future technology is revolutionizing our understanding of planetary system formation. Though thousands of exoplanets and exoplanetary systems have been discovered to date, we are not at a stage where we can observe the detailed processes driving planetary formation that leads to habitable worlds. The *James Webb Space Telescope* (JWST) provides an unprecedented capability for characterization of extrasolar planets and their atmospheres. However, exploring the chemical and physical processes during the era of planetary formation will require the next generation of facilities in the 2030s.

We do have one planetary system—our own—that is both habitable and inhabited. To investigate the processes that occurred during the formation of our own solar system, we need to explore remnant vestiges of that early epoch represented in the surviving population of small bodies (**Figure 2-1**). Many of these objects, especially those that have primarily resided in the outer solar system, have not experienced significant evolution from solar irradiation and processing, and can therefore potentially preserve the physical and chemical signatures of their formation locations. Examples include icy asteroids and near-Earth objects (NEOs), and comets (several short-period comets have been visited by spacecraft, while long-period comets (LPCs) have only been studied from the ground). A recently discovered new class of small bodies, the interstellar objects (ISOs), likely represent planetesimals ejected from exoplanetary systems and therefore, represent similar opportunities for understanding exoplanetary science and contextualizing our solar system within its cosmic context. Only two ISOs have been discovered as of 2024, and they have been explored only via Earth-bound telescopes.

The first ISO, 1I/'Oumuamua, was discovered in 2017, and the second, 2I/Borisov in 2019 (e.g., Meech et al. 2017; Fitzsimmons et al. 2024; Fitzsimmons et al. 2019; Jewitt and Seligman 2023). Believed to be extrasolar planetesimals, these ISOs represent unique opportunities to study remnants of planet formation in other solar systems at an unprecedented level of detail. There is no other technique in the near to distant future that will allow an investigation of extrasolar material in such detail.

The discovery of these ISOs triggered major ground- and Earth-orbital telescopic observing campaigns resulting in over 200 refereed papers (many summarized in Fitzsimmons et al. 2024). While these ISOs are

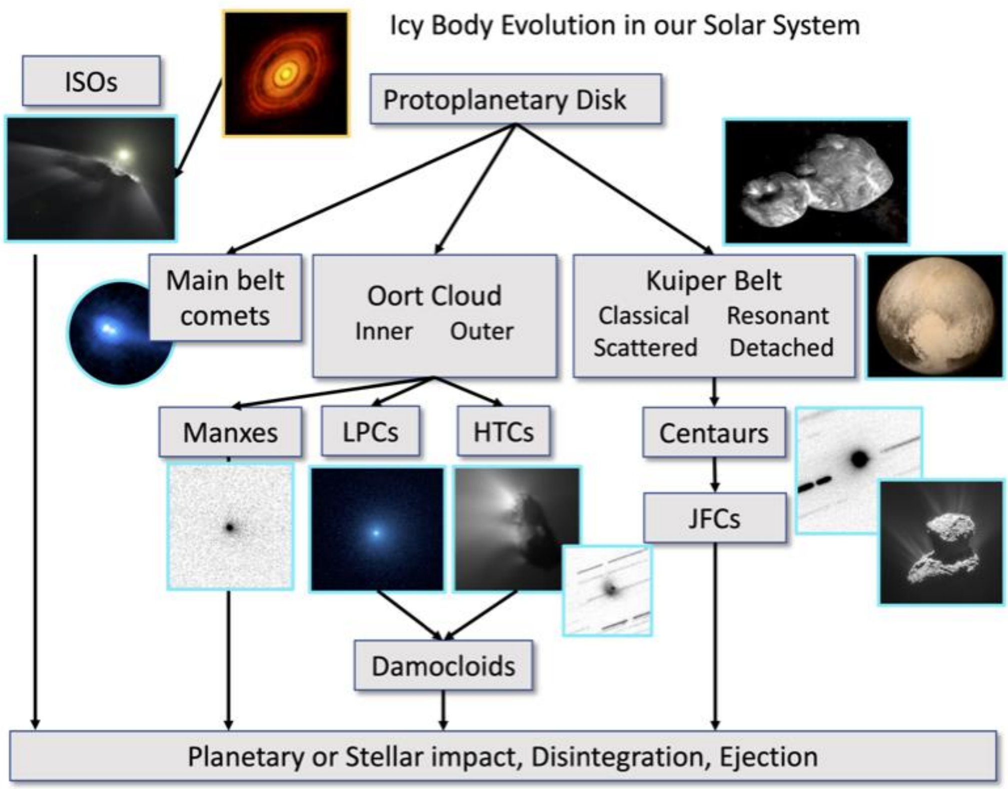


Figure 2-1. Many small bodies represent remnants from the earliest stages of planetary system formation in both our solar system and others. Most of these classes of objects, and especially the least-processed of them, have not been explored by spacecraft. Source: Fitzsimmons et al. 2024

similar to planetesimals in our solar system, there are notable differences. ‘Oumuamua appears asteroidal, but exhibits non-gravitational acceleration, which could potentially be explained by undetected outgassing (e.g., Fitzsimmons et al. 2024). The inferred chemistry suggests differences in the relative abundances of volatiles compared to comets in our solar system. One of the most enduring mysteries about ‘Oumuamua is its highly elongated shape and nongravitational acceleration despite its lack of a cometary tail; papers are still being published that explore possible explanations. Borisov, on the other hand, exhibits typical comet-like activity, with a depleted carbon-chain species chemistry like that seen in some solar system comets, but has an extraordinarily high CO abundance relative to H_2O (e.g., Cordiner et al. 2020; Bodewits et al. 2020). It is worth noting that since the discovery of 1I/‘Oumuamua, (Seligman et al. 2023) and Farnocchia et al. (2023) reported significant non-radial, non-gravitational accelerations on seven NEOs that also lack any detectable comet-like activity: the so called “dark comets.”

The fact that the first ISO discovered was asteroidal in appearance (thus making it harder to detect), suggests that at any given time there may be on average ~1 similar interstellar object in the inner solar system (e.g., Laughlin and Batygin 2017; Trilling et al. 2017; Do et al. 2018; Levine et al. 2021; Fitzsimmons et al. 2024). ‘Oumuamua approached from the direction of the galactic apex, passed interior to the orbit of Mercury at perihelion, and was discovered only 5 days *after* Earth close approach. Current (e.g., PanSTARRs and the Catalina Sky Survey) and upcoming (e.g., the Vera Rubin Observatory’s Legacy Survey of Space and Time, LSST) all-sky surveys will ensure more and hopefully sooner discoveries of these kinds of objects in the future, increasing the opportunities for in situ exploration.

2.2 SCIENTIFIC MOTIVATION FOR STUDYING LONG-PERIOD COMETS (LPCs)

LPCs, with orbital periods exceeding 200 years, offer unique insights into the early solar system's conditions and the processes that shaped its evolution (e.g., Kaib and Volk 2024). The study of these comets is scientifically motivated by several key factors:

Primordial Material: Long-period comets are considered some of the most pristine objects in the solar system, composed of material that has potentially remained largely unchanged since the solar system's formation ~4.6 billion years ago. This makes them invaluable for understanding the original composition of the solar nebula and for understanding the composition of volatiles delivered to the planets during their formation (e.g., Bergin et al. 2024; Simon et al. 2024).

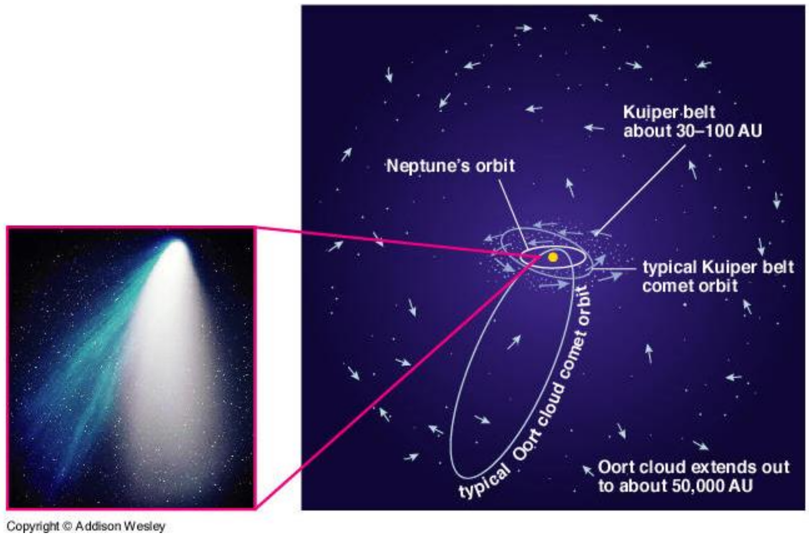


Figure 2-2. Illustration of a LPC orbit compared to a Kuiper belt comet orbit. Source: https://people.highline.edu/iglozman/classes/astronotes/media/comets.jpg

Solar System Formation and Evolution: LPCs provide important clues in models attempting to unravel the dynamical history of the solar system. Their current orbits provide a potential forensic history of the gravitational influences of giant planets and the effects of stellar encounters over billions of years (e.g., Dones et al. 2004).

Oort Cloud Exploration: LPCs are believed to originate from the Oort Cloud, a distant spherical shell of icy bodies surrounding the solar system. The trajectories and compositions of these objects enable investigations of the Oort Cloud population, which remains largely observationally inaccessible.

Organic Molecules and Prebiotic Chemistry: The volatile compounds and organic molecules found in LPCs and other comets are critical for understanding the potential for life's chemical precursors in the early solar system. Comets contain complex organic molecules, shedding light on the potential for prebiotic chemistry in the solar system's formative years (e.g., Bockelée-Morvan et al. 2004; Altwegg et al. 2016).

Impact Hazards: LPCs, due to their high velocities and random distribution of orbital inclinations, pose a potential impact threat to Earth (e.g., Nuth and Barbee 2018). Understanding their orbital mechanics and physical properties is thus essential for planetary defense assessments and the potential to mitigating their impact risks.

2.3 SCIENTIFIC MOTIVATION FOR STUDYING INTERSTELLAR OBJECTS (ISOs)

The initial conditions present at the formation of our solar system dictated the distribution of volatile and refractory materials and the formation and evolution of the planets. Thus, the initial composition of other planetary systems should influence the resulting planets that formed around other stars. Constraints on the compositions of small body materials from other planetary systems—especially when compared to similar measurements to the elemental abundances in our solar system—would enable predictions about the likelihood that Earth-like planets could be produced in that system. They also will inform our understanding of the composition of protostellar disks and the regions from which planetesimals are ejected, potentially due to giant planet ejection. Measurements of the composition of dust and volatiles from visiting ISOs is the most compelling way to obtain these measurements for the foreseeable future, besides using limited remote telescopic observations.

Of particular interest is the presence, absence, and timing of injection of ^{26}Al in the protoplanetary disk. This radioactive isotope has a half-life of 700 kyr and was one of the primary sources of heating for planetesimals and giant planet systems in the early solar system (e.g., Bizzarro et al. 2005). A fundamental question is whether or not ^{26}Al is expected to be a frequent feature of exoplanetary systems (e.g., Gounelle 2015; Reiter 2020) based on the early enrichment from either supernovae or in situ formation. Constraining the quantity of ^{26}Al in other planetary systems at the time of their formation will enable determination of whether they are analogous with our solar system, or how they differ. The easiest way of determining the original ^{26}Al content in our solar system is to look for isotopic anomalies in the calcium-aluminum-rich inclusions (CAIs) found in meteorites. If we can collect CAIs from an ISO, or measure the isotopic fraction of aluminum, magnesium, and calcium in situ, we could contextualize the ISO's system of origin and begin to answer these fundamental questions.

Another approach is using the volatile content of ISOs to probe the formation location within their original protostellar disks. For example, Jewitt and Seligman (2023) demonstrated how future measurements of the production rates of H_2O, CO_2, and CO in interstellar comets can be used to estimate their carbon-to-oxygen ratios, which trace formation locations within their original protoplanetary disks. Identifying the formation location with respect to the CO snowline in exoplanetary systems would provide key insights into the efficiency of and mechanisms for cometary ejection from those systems (**Figure 2-3**).

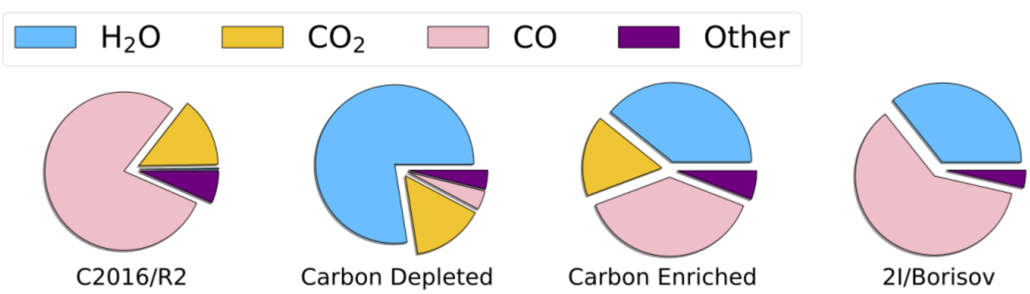


Figure 2-3. The composition of the LPC C/2016 R2, the ISO 2I/Borisov, and typical carbon enriched and depleted solar system comets. From Jewitt and Seligman (2023).

Finally, ISO analogues that form in distant regions of exoplanetary systems could provide significant metal enrichments to exoplanetary atmospheres; the analogues may be potentially observable by JWST. Cometary enrichment could provide a significant source of volatile delivery to extrasolar planets as well, and this could be constrained with measurements of ISO compositions and exoplanetary atmospheres (e.g., Seligman et al. 2022).

2.4 PLANETARY DEFENSE CASE

Planetary defense is the identification, characterization, and, if necessary, mitigation of natural objects, like asteroids, that could pose an impact threat to Earth and its inhabitants. NASA has recently been chartered with the responsibility to carry out planetary defense activities on behalf of the U.S. Government. Planetary defense is an international activity also coordinated through international organizations like the United Nations.[2]

Like ISOs, and LPCs, the detection of a potentially hazardous asteroid (PHA) may necessitate a rapid response to characterize the asteroid and/or mitigate the threat to the Earth. In fact, the recently released Planetary Science and Astrobiology Decadal Survey (National Academies 2023) highlighted the need for a rapid response mission capability and recommended it as the next planetary defense mission after NEO Surveyor:

> *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.*

This KISS study directly responds to this charter from the National Academies to develop a rapid response capability. Furthermore, in NASA's official response, the Associate Administrator for science at the time acknowledged that the development of a rapid response capability for planetary defense feeds directly into rapid response for an ISO or LPC.[3]

As planetary defense increases in national priority and as additional NEOs are discovered, it is imperative that the nation develops the capability to detect, characterize, and if necessary, mitigate a threat posed by a potentially hazardous asteroid. Section 3 of this study report addresses gaps in characterization of a potentially hazardous asteroid, which may require a rapid response flyby mission. The principles discussed herein could also be applicable to a mitigation mission, which likely would also require a rapid response capability. Rapid response is a strategic technical gap in the nation's planetary defense capability and should be a priority for future study and demonstration.

[2] https://science.nasa.gov/planetary-defense

[3] https://science.nasa.gov/wp-content/uploads/2023/05/Initial90_daywrittenresponsetothe20232032PlanetaryScienceandAstrobiologyDecadalSurvey.pdf

3 RAPID RESPONSE MISSION STRATEGY

3.1 GENERAL MISSION CONCEPT TO VISIT AN NEO, ISO, OR LPC

Rapid response is defined as the ability to quickly respond to a previously unknown, emerging target with a dedicated mission. For example, rapid response may be necessary to characterize a newly discovered near-Earth object that could pose a threat to Earth. Rapid response is also applicable to some underexplored and fascinating science targets, like interstellar objects and long-period comets, that are discovered without significant advanced warning, and after a flyby though the inner solar system, may not return for a long time.

The timelines and target parameters for rapid response are target dependent and not well-defined. NEOs may be discovered decades before a potential impact, but immediate reconnaissance with a flyby spacecraft is useful to refine the target's orbit and mass and to plan for a future mitigation mission. Dynamically new LPCs may be discovered five or more years before a close approach to the Sun, demanding a mission turnaround time that is still relatively short compared to the development of traditional science missions. ISOs are the most demanding in terms of timeline with discoveries and confirmations made within a small number of months due to their rapid motion relative to the solar system. The two ISOs that have thus far been identified were only discovered one month after perihelion and four months before perihelion, respectively. The next generation of surveys from large telescopes, such as LSST (first light in early 2025), will likely improve the discovery-to-response timeline (e.g., Hoover et al. 2022).

For all objects, rapid response can be broken into three primary phases: Discovery and Confirmation, Preparation, and Operation. The timeline for rapid response begins upon discovery of the target and ends with the flyby. The duration of the Operation phase is driven by the orbital dynamics of the target and is unpredictable. Therefore, the objective of rapid response is to minimize the Discovery and Confirmation and Preparation phases of rapid response.

The Discovery and Confirmation phase begins with discovery of the target and ends with confirmation that a target merits a rapid response mission. Part of the rapid response strategy is minimizing the duration of this phase by employing well-defined protocols to trigger a rapid response mission. For a PHA, merit may be defined by exceeding some probability of Earth impact in the long term. For an LPC or ISO, merit may be defined by some physical characteristics and orbital parameters as constrained on the ground—performed in the span of days to weeks for the first two ISOs. A well-defined flow and "checklist" to provide a go/no-go for rapid response is necessary for any type of rapid response target.

The Preparation phase is the time between the "go" confirmation for a rapid response mission and departure into the intercept trajectory. For a ground-storage mission, this may include any rapid implementation and testing required, procurement of a launch vehicle, and acquisition of regulatory licenses for launch and operations. In both the ground-storage and space-storage architectures, the Preparation phase also includes development of trajectory and navigation plans to successfully intercept the target. Throughout this phase and the Operations phase, the target ephemeris may be improved as the number and duration of Earth-based observations increases. The evolving ephemeris may drive changes to trajectory design and navigation solutions developed on the ground, or may necessitate onboard propulsion to make trajectory corrections after launch and in flight. In the ground-storage architecture, the Preparation phase concludes with launch. In the space-storage architecture, the Preparation phase concludes with an impulsive burn or Earth gravity-assist to put the spacecraft on an intercept trajectory with the target.

The Operations phase is the period of time that the spacecraft is on its way to the target and ends with a successful flyby and return of data to Earth. During this phase, the spacecraft may be performing trajectory correction burns and terminal guidance burns to accurately flyby at the required distance. It is also in this phase that the spacecraft makes its key observations and delivers the data back to Earth.

For the context of this report, rapid response is effectively defined as "as-fast-as-possible" with no quantitative timeline. The focus of the report is primarily on the Preparation and Operations phases. The triggers for a planetary defense rapid response mission are well-defined and illustrated in a variety of planetary defense-related policy documents. The development of analogous triggers for an ISO and LPC are considered future work and out of the scope of this document.

Lastly, this report emphasizes the need for the introduction of a rapid response capability, meaning an always-available mechanism for rapid response for planetary defense. Technically, this means either a spacecraft already built and ready to be deployed or a well-defined plan to rapidly implement a spacecraft for the individual target. Programmatically, that may mean a dedicated initiative with funding always available for rapid response, and coordination among space agencies worldwide. Any meaningful demonstration of a rapid response mission concept should also demonstrate a sustainable capability with limited non-recurring costs between missions rather than a one-off mission that would not feed forward to a future capability. The development of a rapid response capability for planetary defense also directly feeds forward to a rapid response mission for an ISO or LPC.

3.2 DEFINITIONS OF RAPID

"Rapid" in the context of rapid response is a loose term that varies for the different classes of targets discussed in this paper. Extensive study of how quickly a system would need to respond was not included in the scope of this study but several participants have previously conducted studies on this very topic (e.g., Mages et al. 2022).

3.2.1 *Rapid Response to an NEO*

For planetary defense, the general consensus is that a potential threat requires a rapid response. Mitigation missions are most effective when they take place as early as possible since a mitigation mission would slightly alter the orbit of an asteroid; having more time for that change to propagate over several revolutions around the Sun minimizes the magnitude of the mitigation maneuver. A rapid response mission to characterize a potentially hazardous asteroid would seek to do three things:

1. determine whether or not a target would impact the Earth (i.e., precisely determine its orbit);
2. if the object is determined to likely impact the Earth, determine whether or not that would pose a threat to life or property on Earth (i.e., determine the mass and/or volume of the object); and
3. if the object is determined to likely impact the Earth and to pose a threat, provide initia-2 measurements to support a future mitigation mission.

Obtaining early information on target parameters gives decision-makers and technical teams the most time to develop a plan to assess and mitigate, if necessary, the risk posed by a target.

Additional details of rapid response to NEOs and PHAs are discussed extensively in Chapter 18 of *Origins, Worlds, and Life*, the recently released Planetary Science and Astrobiology Decadal Survey (National Academies 2023). Furthermore, Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and Applied Physics Laboratory (APL) recently collaborated on three workshops entitled Near-Earth Object Workshops to Assess Reconnaissance for Planetary defense (NEO-WARP) that studied the planetary defense case in more detail. The reports for those studies are still in work.

3.2.2 *Rapid Response to an LPC*

Unlike NEOs and ISOs, we can look back in history to identify a large number of scientifically compelling targets that have flown through the inner solar system. Extensive mission design and analysis work to LPCs was performed in support of ESA's Comet Interceptor Mission. That body of work demonstrates that about 50% of LPCs are detected more than 5 years out from perihelion, which serves as a good proxy for launch time (e.g., ESA 2019).

3.2.3 *Rapid Response to an ISO*

ISOs are likely the most driving in terms of response time. So far, there are only two confirmed ISOs and both were identified extremely late relative to a required launch date. There have been several studies on accessibility to a synthetic population of ISOs that reveal that response times on order of one year are required to enable the exploration of a large number of active (comet-like) ISOs (e.g., Cook et al. 2016;

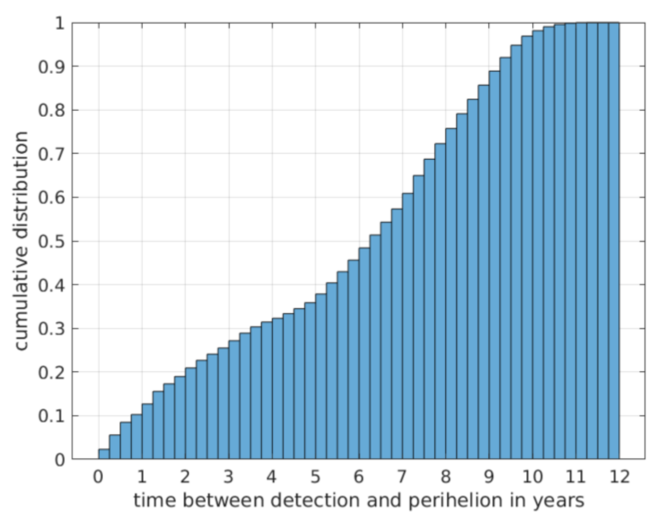


Figure 3-1. Long-period comet time from detection to perihelion. From ESA (2019).

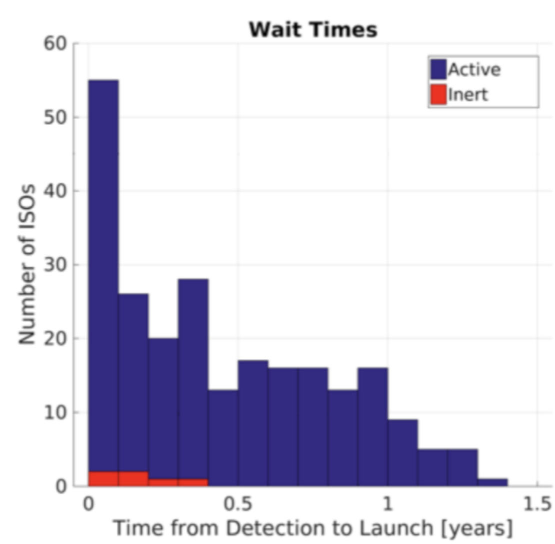


Figure 3-2. Response times for an ISO.

Engelhardt et al. 2017; Seligman and Laughlin 2018; Hoover et al. 2022; Stern et al. 2024). Exploring an inert (asteroid-like) ISO would be extremely difficult due to their low brightness and very late detection. **Figure 3-2**, from a recent study at JPL (Mages et al. 2023), shows that a launch within one year is necessary to access an ISO from the studied synthetic population. The red items show the low number of inert, accessible targets and that the response time is very low for those targets.

3.3 NOTIONAL MEASUREMENTS AND PAYLOAD SUITES

3.3.1 *Payload Suite*

The spacecraft's payload meets requirements for characterizing NEOs during an initial reconnaissance mission. In an effort to maintain the simplicity of the spacecraft and minimize cost, the payload suite suggested here is the absolute minimum set required to obtain key measurements of the spacecraft mass and surface morphology. A visible camera is used to roughly determine shape and surface morphology of the asteroid. A gimbal enables the camera to slew at high rates during the fast flyby. A set of small gravity probes released from the spacecraft are tracked optically to determine the mass of the PHA to a precision of 20%; these gravity probes have been previously considered and are currently under development, for example at JPL and APL (e.g., Christensen et al. 2021; Bull et al. 2021). While the exact characteristics of the payload are still being determined, reasonable estimates of payload resources, based on current SmallSat state-of-the-art, would be a mass of <30 kg and power of <50 W, with the exact details set by measurement requirements. If the target were active, like a comet, a dust shield would be added to protect the vehicle from the coma, as well as a periscope to capture images around the dust shield, similar to what has been done for the Stardust mission. A hypervelocity dust spectrometer could obtain bulk composition from an active target, depending on the mission science objectives. **Table 3-1** shows examples of measurements required and their associated instruments that would be desired for NEOs, LPCs, and ISOs, as well as an estimate of their mass and power needs.

Table 3-1. Notional instruments for various target types.

Target	Measurement	Instrument	Example	Mass/Power Estimate
NEO	Mass/gravity	Gravity probes (low TRL)	OpGrav/SIMMEE (APL)	16.5 kg / NA
	Diameter	Thermal Imager	TIR on Hayabusa2 (JAXA)	3.3 kg / 18 W (avg)
	Surface composition	Multispectral imager	mAPIC (JPL)	6 kg / 13 W (max)
LPC	Composition	Low-z volatile mass spectrometer	QIT-MS (JPL)	~10 kg / 30 W (max) Mass reduction possible
		Dust spectrometer	Mini-SUDA (evolved from Europa Clipper SUDA) (LASP)	<5 kg / TBD* W
		Infrared spectrometer	BIRCHES (1–4 micron) evolved from OVIRS (OSIRIS-REx) (GSFC)	2 kg / 10–15 W (point spectrometer)
ISO	Surface composition	Impactor	Needs to be tailored	Mass needs to be computed / Power is N/A (unless active impactor)
	Diameter	Thermal Imager	TIR on Hayabusa2 (JAXA)	3.3 kg / 18 W (avg)
	Composition	Dust spectrometer	Mini-SUDA (evolved from Europa Clipper SUDA) (LASP)	<5 kg/ TBD* W
	Others	TBD science investigation		
*Additional study is needed to quantify the power of a miniaturized SUDA				

3.3.1.1 Imager

A camera has dual engineering and science purposes on a small bodies mission. An imager is required for optical navigation to ensure that the spacecraft flies by its target at the required distance. During the flyby, the imager also has the opportunity to obtain key science data, such as the body shape and size, surface features, and color. The addition of filters could enable spectrometry to gain insight into the surface composition. These images would help the science team determine the target's mass, volume, type, composition, and possibly origins.

3.3.1.2 Gravity Probe

Likely the most important measurement for planetary defense is the object's mass, which directly informs the type of mitigation mission required. Small gravity probes or beacons could be released from a spacecraft shortly before close encounter with the target. By mapping the flyby path of those small beacons, scientists could resolve the gravity field and mass of the target (Christensen et al. 2021; Bull et al. 2021). Coupled with images that help determine diameter and infer volume, scientists would also be capable of inferring the object density. Combined with compositional constraints, the density would constrain the bulk porosity in the interior. Gravity probes are an enabling technology to resolve target mass via a flyby. This type of measurement is critical for NEOs/PHAs and planetary defense purposes, and would be valuable in determining the composition and porosity of an ISO or LPC.

3.3.1.3 Dust Spectrometer

Some targets, especially active comets, have large dust clouds or comas that enshroud the nucleus. Dust spectrometers are instruments that can measure the composition of the ejected dust and material to determine the composition of the parent body. Dust spectrometers, like the Europa Clipper's SUrface Dust Analyzer (SUDA), have a long history of flying planetary science missions (see Grün et al. 2019 for a review). They are an excellent way to determine surface composition of a target that is contained in an optically thick cloud of dust or that has too large of a debris field for a close flyby approach. Hypervelocity dust spectrometers would be especially enabling for the high-velocity flybys that are characteristic of the targets discussed in this report.

3.4 STORE ON THE GROUND ARCHITECTURE

3.4.1 *Overview*

One architecture studied was to design and build a batch of small spacecraft with a standard payload suite and store the spacecraft until needed for a launch to a NEO. The spacecraft could also be readily repurposed to launch to an LPC or ISO with small modifications to the payload and flight system to optimize for the active targets. Batch builds and standard enveloping requirements would drive down the cost of individual spacecraft and enable a fleet of vehicles ready to respond on very short notice.

3.4.2 *Spacecraft Design*

The series of small spacecraft would undergo a design process relatively similar to most science spacecraft. A set of enveloping requirements would drive the ability to respond to a large number of targets without needing to make major redesigns for the particular target. The precise requirements would be determined both through a comprehensive analysis of the NEO population to determine bounding locations of a required encounter for reconnaissance and by exploring major cost drivers within the spacecraft itself. An objective of the spacecraft architecture is to minimize recurring engineering cost for subsequent batch builds since the intention is to continue to build spacecraft on a rolling basis. SmallSats naturally lend themselves to lower-cost, repeatable spacecraft. **Figure 3-3** depicts a 75 kg SmallSat designed for a rapid build to encounter a LPC that can be imagined as an initial platform for a modular rapid response spacecraft.

Figure 3-3. Representative SmallSat flight system for an ISO flyby mission.

For a NEO, the spacecraft would likely encounter the target near 1 AU, given that the object is guaranteed to have a node near Earth (the object must have an Earth-crossing trajectory if it poses an impact threat). The encounter distance from the Sun would drive power requirements and distance from Earth would drive communications system requirements. These distances could be easily bounded for an NEO/LPC.

The spacecraft would likely require a direct injection by a launch vehicle to achieve the launch energy required for the target, so most of the deterministic delta-V would come from the launch rather than the spacecraft itself. However, because the target ephemeris may not be well known at launch and because the spacecraft would require terminal navigation to perform the fast flyby, the spacecraft would also require an onboard propulsion system. Short cruise times likely makes electric propulsion systems infeasible, so the delta-V would need to come from an onboard chemical propulsion system. Delta-Vs are likely on order of 100s m/s but a higher-fidelity analysis of cruise and terminal guidance will clarify the needed delta-V (**Figure 3-4** and **Figure 3-5**). Ephemeris knowledge, which can vary dramatically over the course of cruise (**Figure 3-6**), at launch drives the delta-V requirements since the spacecraft would need to perform a propulsive maneuver to correct for any trajectory uncertainty. Another major driver is the presence of non-gravitational accelerations. The upper plot in **Figure 3-4** assumes relatively low non-gravitational accelerations due to things like outgassing or other perturbations, while the lower plot assumes a significant amount.

Some PHA, ISO, and LPC flyby trajectories tend towards low perihelia mission designs, which could pose a major threat to the thermal system. Trajectories that are much closer to the Sun than Venus can be extremely technically challenging. The sensitivity of thermal complexity and cost to responsiveness and delta-V is still under trade. Other spacecraft systems including the attitude control system (ACS), command and data handling (C&DH), and mechanical system are relatively nominal with minimal expected variation required for specific targets. The addition of non-standard instruments (i.e., beyond the suite of instruments discussed earlier in the report) would require some modularity within the C&DH system to enable straightforward interfacing of new devices. The spacecraft would require high pointing stability to enable long-exposure images for optical navigation and some level of onboard autonomy for autonomous navigation, but the spacecraft requirements are assumed to be within currently available capabilities.

ISOs and LPCs may not have the same conveniences in encounter geometry as a NEO. The target ecliptic pierce point could be anywhere with respect to the Earth and Sun, and the ability to encounter a particular non-NEO target of opportunity would be driven by the spacecraft's pre-designed capabilities. The spacecraft would not be capable of encountering a target that falls outside of a predetermined accessibility region.

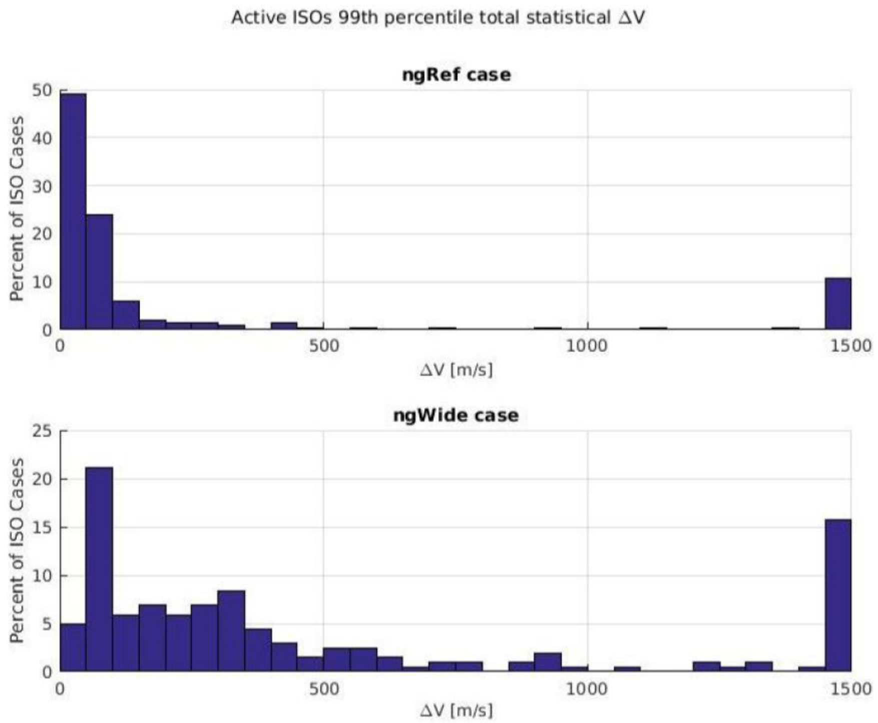


Figure 3-4. Cruise delta-V required to navigate to ISOs.

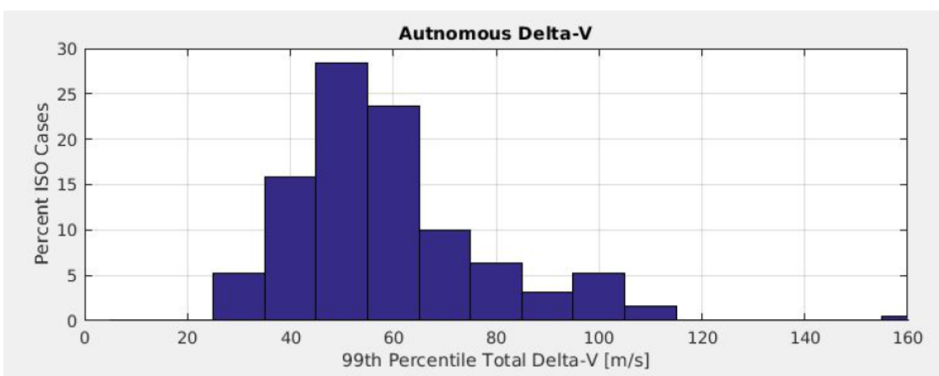


Figure 3-5. Final, autonomous delta-V required to navigate to ISOs.

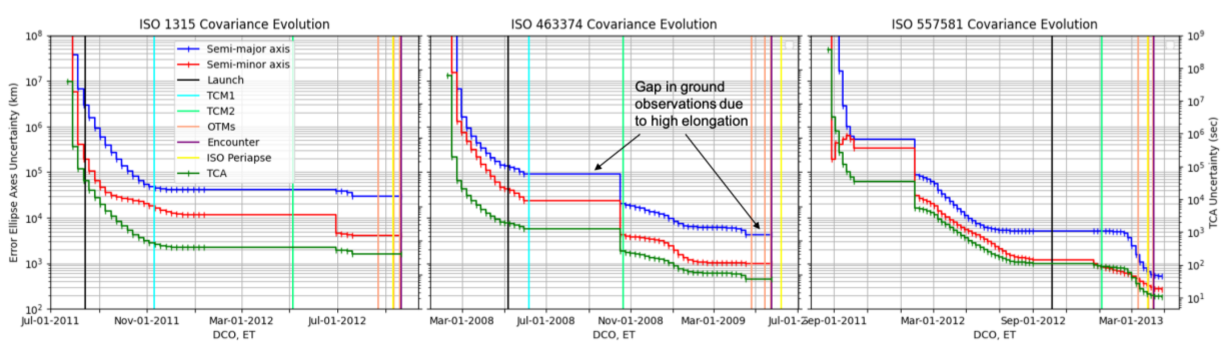


Figure 3-6. Covariance estimation for three sample ISOs.

3.4.3 *Modularity*

Modularity could be required prior to launch after detection of the target. In particular, the geometry of the encounter could drive the need to reconfigure the fields of view of the solar array and antenna and any possible dust shield. As mentioned previously, an active target may require different elements and an altered payload from the standard NEO spacecraft. Modularity would enable the ready inclusion of a dust shield to protect the flight system from high-velocity dust impacts and the ability to modify the payload suite for an active target. In particular, universal interfaces would enable several payloads to be readily integrated onto the flight system without major upgrades to the spacecraft C&DH system. A modular propulsion system, primarily meaning propellant tank size, would maximize the amount of mass available for payload and maximize the probability of fitting on a given launch vehicle. Additive manufacturing is one emerging technology that could enable rapid manufacturing of components like propellant tanks.

3.4.4 *Test and Launch Operations*

Presently, the U.S. Department of Defense (DoD) has an initiative to enable tactical launch. The DoD is focused on getting a payload from delivery to launch within 24 hours. While this timeline is not required for this application, many of the lessons being learned through the DoD tactical launch can be applied to a NEO, LPC, or ISO rapid response. The timeline from notification of target detection and required launch would be on order of three months. During this time, four tracks would begin preparation for launch: spacecraft preparation, regulatory preparation, launch vehicle preparation, and operations preparation. Each of these tracks would be motivated by well-documented plans and trained teams to minimize the likelihood of missing the rapidly approaching launch window.

Spacecraft preparation would consist of final integration and functional testing. The three-month window is consistent with no modification of the spacecraft. Modifications, such as adding a dust shield or dust spectrometer for an active target, may require additional time for spacecraft qualification. The details of this timeline were not developed during the workshop and we recommend a feasibility study for modifying and testing a spacecraft within a short timescale. The pre-built spacecraft would have been built considering long-term storage, with consumables and volatile components stored in a parts pool and ready to be integrated on a short timescale. The primary component that would not be stored for long durations would be the battery. After battery integration, the spacecraft would undergo critical functional testing prior to shipping to the launch site. If there were to be a system failure during testing, another flight system would be taken from the batch and prepared for launch while the faulty spacecraft would be relegated for further testing and anomaly resolution; this drives the need for batch spacecraft to be built and stored together with more than one spacecraft always ready to respond.

Regulatory preparation consists of obtaining the required licenses from regulatory authorities, primarily the Federal Communications Commission (FCC) for communications and Federal Aviation Administration (FAA) for launch authority. Rather than starting from scratch, this would be the initiation of a prepared plan to minimize the time to obtain necessary licenses. Regulatory challenges can hamper the ability to launch quickly so it is imperative to work with regulatory bodies during the planning process to maximize the likelihood of a smooth execution. This track would also support preparing communications networks, including the Deep Space Network, for the rapid response mission.

The launch vehicle procurement process would begin immediately upon identification of a target. It is not expected, though it is possible, that a launch vehicle be always available for deployment. We intend to rely on regular and robust launch cadence from a variety of potential providers to prepare a launch vehicle according to a pre-established plan. In the case of launch, all performance analysis would have already been performed prior to storing the spacecraft. We would rely on contracts with launch vehicle providers to "bump the line" and inject into a potentially busy launch manifest to ensure that a launch could be made available within the three-month timeline. Upon delivery of the spacecraft to the launch site, launch vehicle providers can leverage lessons learned from DoD tactical launch to quickly integrate the spacecraft into the launch vehicle, perform necessary checkouts, and launch the spacecraft to the required orbit. All target-specific launch vehicle analysis can take place while the vehicle is being prepared for launch.

The operations planning includes refining the target ephemeris and orbit, performing navigation analysis to verify sufficient onboard propellant for statistical navigation. This navigation analysis will likely only take on the order of months, but increasingly long observation arcs from ground-based observatories will continue to refine the target position, which can increase the fidelity of the navigation analyses.

3.4.5 *Risks*

The risks of this architecture fall under technical, programmatic, and cost. Technically, this architecture binds the spacecraft to Earth's orbit phasing, limiting the number of accessible targets. Another technical risk is that the response time is limited to three months. For ISOs, this can be significantly constraining. According to a population study, 25% of ISOs are no longer accessible with a 3-month delay between discovery and launch as compared to a ten-day delay between discovery and launch (see **Figure 3-2**). On the spacecraft side, there are risks associated with the very rapid test campaign required for final spacecraft certification and launch vehicle integration.

Programmatically, there is a risk of ensuring that the personnel required to prepare the spacecraft for launch and eventually operate it will be available at the necessary time. Either a standing army is required to leap into action when ready, or agreements must be in place to borrow personnel from other ongoing projects to provide immediate support for the rapid response mission. There may be perceived risks associated with ground storage and parts degradation over time, and a desire to make modifications and upgrades to the spacecraft, which could delay the launch.

The primary cost driver for this architecture is that it requires more external partners to be involved from the start including a spacecraft partner to store and prepare the spacecraft when needed, a launch vehicle partner to provide a launch vehicle upon detection, and regulatory partners to ensure that the spacecraft is promptly approved for launch. All these partnerships would require contractual, and likely cost, obligations. This architecture also makes it impossible, or at least highly improbable, to rely on a rideshare to reach the launch energies necessary to reach these classes of targets. While the cost of launch vehicles is decreasing with increased competition in the marketplace, the cost of a dedicated launch is still significantly more than the cost of a rideshare to a more commonly visited destination like low-Earth orbit (LEO) or geostationary orbit (GEO).

3.4.6 *Benefits*

The ground-based storage architecture does not require the same large amount of delta-V on board to reach a target given the ability to take full advantage of a launch vehicle's capability. Most of the orbit energy would be injected from the direct launch with onboard propulsion only required to clean up launch dispersions and perform terminal guidance when approaching the target. SmallSat onboard propulsion is a major technology gap and by not requiring significant delta-V, the stored spacecraft has a high likelihood of remaining a SmallSat class and not a larger spacecraft. Since a launch vehicle can provide a significant amount of energy, a spacecraft could access a larger number of targets via a dedicated launch than exclusively relying on the spacecraft onboard propulsion system.

The ground-based storage option is more likely to feed forward to encounters beyond 1 AU given the greater launch energy capability. A spacecraft in a loitering orbit is going to be more bound to the 1 AU band given the additional energy required to send a spacecraft far beyond 1 AU using only onboard propulsion. The ability to perform small modifications to the flight system and the payload (without jeopardizing responsiveness) makes this architecture ideal to encounter either a NEO, or an active ISO or LPC. It may be cheaper to store a spacecraft on the ground rather than in-space, but increased autonomy is reducing costs associated with dormant operations.

3.4.7 *Technology Gaps*

Most of the technologies required to enable a ground-stored spacecraft already exist. There remain technology gaps associated with a modular spacecraft that could readily modify its payload and with hypervelocity flybys of inert NEOs or active ISOs and LPCs. While not technological in nature, there are programmatic gaps that pervade rapid response and present as a greater barrier to enabling this capability than technology gaps.

Modularity could increase the number of accessible targets and accessible classes of targets of a generic spacecraft stored on the ground. Modularity can come at two levels: at the flight system and payload level.

For the flight system, modularity could be as simple as reconfigurability to move the locations of certain components depending on the encounter geometry. For example, since it is important to have communication with Earth during the encounter to best refine the orbit of the target, it would be necessary to configure the spacecraft antenna so that it is facing the Earth during the encounter and to configure the instrument to be pointing towards the target at encounter. These geometric specifics would not be well-known until the target has been identified. Flight system modularity could also consist of optimizations and swapping out of components for the particular target. Varying solar arrays would enable the spacecraft to reach a greater band of solar ranges without jeopardizing the system-level performance and varying telecommunications parameters, such as antenna size or amplifier power to communicate data back from different Earth ranges post-encounter. Finally, components, like dust shields, may need to be added to the flight system if the target were active.

Payload system modularity would require the reconfigurability and reoptimization or addition of particular components with the added complication of data interfaces. Electrical and mechanical interfaces are, for the most part, well known and standardized. Data communications within spacecraft remain fragmented with multiple communications protocols currently in use. A universal adapter would be required to facilitate communication between a new instrument and the spacecraft C&DH system. Alternatively, the selection of a standard communication protocol would alleviate the need for this universal adapter.

3.5 MICROCONSTELLATION ARCHITECTURE

3.5.1 *Overview*

One of the architectures is to place about 10 spacecraft into a variety of positions with respect to the Earth until discovery of a target. If each spacecraft is placed in such a way, they offer more diversity in departure conditions available. The flexibility that is offered by the variety of departure conditions allows a limited spacecraft design to cover more PHA flyby possibilities without the need for more delta-V on board.

The placement of the spacecraft cannot be arbitrary and requires consideration of the three-body problem involving the gravity of the Sun, Earth, and spacecraft. The key motivation is for the spacecraft to be capable of response in short transfer arcs, once called on for a PHA flyby opportunity. Presumably, there would be 1 of 10 spacecraft that is preferable to transfer to the PHA. Each time that a spacecraft is released from its post to target a PHA, the advantage of multiple spacecraft is weakened. Therefore, a replenishment approach would be taken to place new spacecraft as required. The constellation approach and placement of spacecraft in possible orbits would be dictated by time to encounter the PHA in time of flight.

We recommend a trade study aimed at identifying an orbital architecture that is reachable by many launch vehicle options including rideshare launch opportunities while offering short transfer times to the locations where PHAs exist most frequently.

3.5.2 *Constellation Options*

This study considers two major options of loitering orbits that allow for rapid-response flybys to the object as shown in **Table 3-2**. One of the options utilizes the Earth gravity assist as the rapid-response maneuver. Because frequent Earth gravity assists are needed to maximize the probability of NEO/LPC/ISO encounters, this option requires placing many spacecraft in Earth-resonant flyby orbit. The Earth resonant orbit allows the spacecraft to hold a higher V-infinity with respect to the Earth, thus enabling exploration of LPCs/ISOs with less fuel, or more encountering probability, than the other option. The other method is for the multiple spacecraft to linger at a Lagrangian point (of either Sun-Earth or Earth-Moon system) and achieve a rapid-response flyby with the assistance of a three-body dynamical system. This option allows the spacecraft to leave Earth at almost any time; nevertheless, since V-infinity relative to Earth is smaller, it requires more fuel for exploration of the LPCs/ISOs.

Table 3-2. Constellation options for a rapid response NEO reconnaissance.

		Lagrange Point	
	Earth-Resonant Flyby	**Sun-Earth L1/L2**	**Earth-Moon L1/L2**
Minimum number of spacecraft	Large (>10 spacecraft)	Small (1 spacecraft)	Small (1 spacecraft)
V-infinity relative to Earth (=Encountering probability)	Large (>1.5 km/s; up to launch vehicle)	Small (<1.5 km/s) i.e., Larger interplanetary delta-V is required	Small (<1.5 km/s) i.e., Larger interplanetary delta-V is required
Spacecraft system size	Small (>12U CubeSat)	Medium (>100 kg TBC)	Medium (>100 kg TBC)
Science during loitering	• Multiple NEO flybys (about 1 body/year/ spacecraft) • Heliophysics	• Space telescope • Heliophysics	• Lunar missions • Gateway-related missions

3.5.2.1 Earth-Resonant Flyby Options

An Earth-resonant flyby orbit is an orbit in which the orbital period of the Earth and spacecraft have an integer ratio, allowing the spacecraft to perform repeated Earth flybys. In this option, about 10 spacecraft are inserted into the Earth-resonant flyby orbit, and each spacecraft performs an Earth flyby at a different time. By making small trajectory correction maneuvers several weeks to a month before the Earth flyby, the spacecraft can rapidly change its trajectory toward the target object utilizing the Earth's gravity assist. For this concept to work, at least one spacecraft would need to perform an Earth flyby every few weeks to a month (TBC); that is, this concept requires a large-scale deep space constellation. **Figure 3-7** shows an overview of the Earth-resonant flyby architecture via deep space constellation.

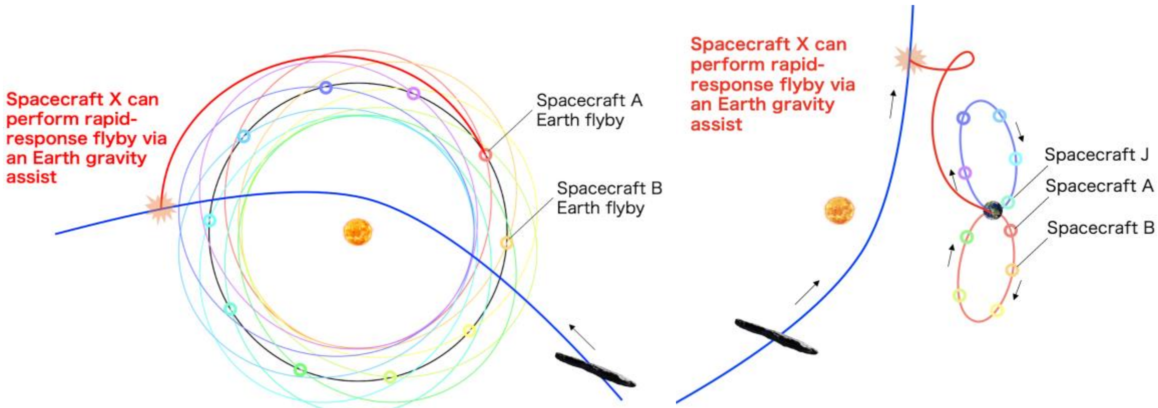


Figure 3-7. Earth-resonant flyby options (Left: Example orbit in the inertial frame, Right: Example orbit in Sun-Earth fixed rotational frame).

Furthermore, with this option, multiple flybys of NEOs can be realized while loitering in an Earth-resonant flyby orbit (e.g., Ozaki et al. 2022b; Ozaki et al. 2022a; Alkalai et al. 2019; Veverka et al. 1995), as shown in Figure 3-8 and Figure 3-9. If 10 spacecraft could be deployed, about 10 NEOs could be flyby per year. This multiple NEOs flyby concept would amplify the scientific value (including planetary defense) and solidify the technology for asteroid flyby exploration. Such a deep space constellation allows us to consider other science missions, such as heliophysics.

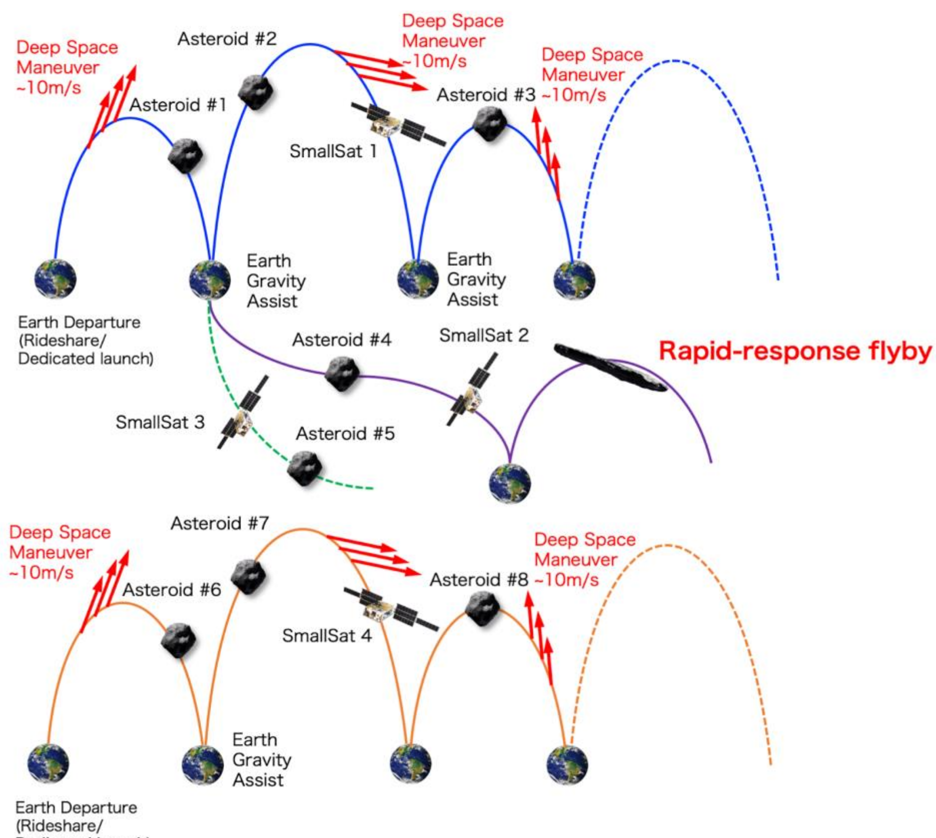


Figure 3-8. Earth-resonant flyby orbit concepts with multiple asteroid flybys.

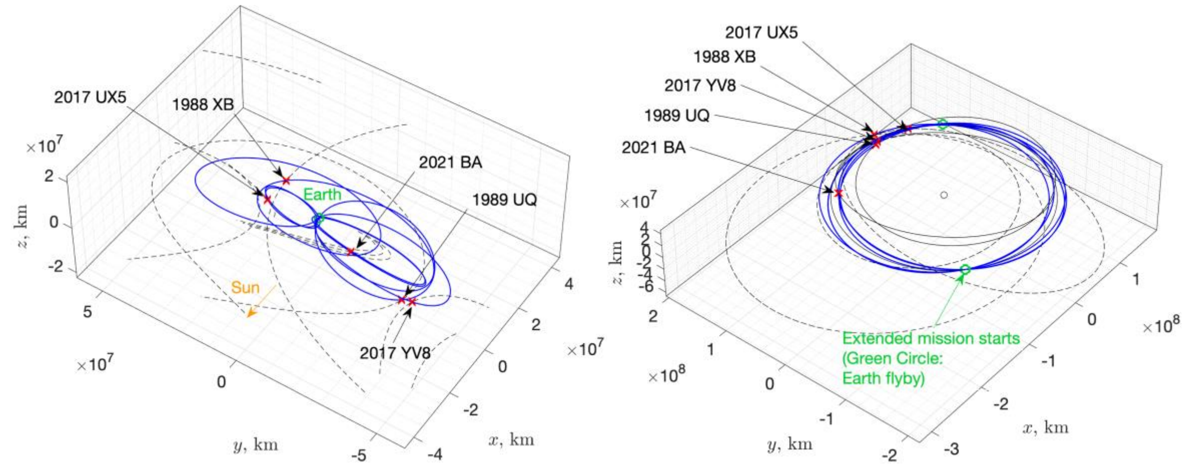


Figure 3-9. Example of asteroid flyby cycler trajectory (from (Ozaki et al. 2022b).

3.5.2.2 Lagrange Point Option

There are five Lagrange points L1–L5 in the restricted three-body system. Of these five Lagrange points, the L1, L2, and L3 points are positions of unstable equilibrium, and particularly the L1 and L2 points are greatly affected by the gravity of the secondary body (Earth in the Sun-Earth system and Moon in the Earth-Moon system). A spacecraft staying in an L1 and L2 libration orbits, as shown in **Figure 3-10**, can make a large orbit change utilizing the gravity of the secondary body without a large amount of ΔV. The Comet Interceptor (Jones et al. 2024) chooses this Lagrange point option where the spacecraft will be stationed at Sun-Earth L2 with the ARIEL mission, waiting for an opportunistic chance to get to an LPC. According to the Comet Interceptor analysis (Sánchez et al. 2021), a lunar flyby is effective in increasing the probability of reaching the LPC. Note that the maximum achievable V-infinity utilizing ballistic lunar flyby is about 1.8 km/s (Casalino and Lantoine 2020). This Lagrange point option could also perform science missions in a loitering orbit.

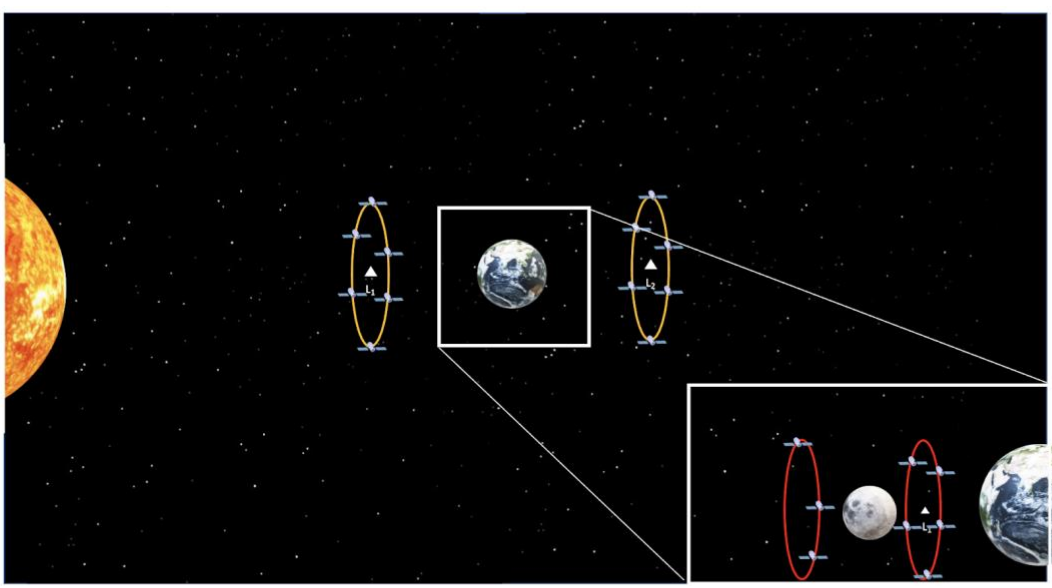


Figure 3-10. Lagrange point option.

3.5.3 *Operational Considerations*

Maintaining a constellation of spacecraft in loitering orbits would require significant operational resources that would stress a typical ground system. Generally, deep space mission operations and navigation teams control individual spacecraft using data and command activities specific to each spacecraft. With multiple spacecraft in a large deep space constellation, the complexity of this type of "manual" operational strategy would scale proportionally with the number of spacecraft. Operating a deep space constellation of multiple spacecraft would require maintaining a large team and substantially increase the operational cost of the overall system. Thus, to keep costs within the target range of the proposed mission concepts, the operational system must be reimagined.

One solution for decreasing operational costs would be to increase the level of the spacecraft's ability to automate both regular spacecraft maintenance as well as navigation and orbit maintenance. This has been done extensively for Earth-orbiting spacecraft over the past decades, however many of these large-scale autonomous operations rely heavily on continuous access to the Global Positioning System (GPS) and frequent access to ground stations. Large communications mega-constellations that are coming online such as Starlink and Kepler would alleviate this problem and enable autonomous operations. While this provides a great solution for autonomous operations in Earth-orbit, it does not directly scale or is directly applicable to deep space missions, in part due to the lack of GPS capability and fewer antennas capable of deep space communication.

For the case of an autonomous navigation system, having the ability for each spacecraft to perform its own orbit determination and execute required station-keeping maneuvers would substantially decrease the need to perform manual navigation on the ground.

3.6 DEMONSTRATION MISSION CASE STUDY

With the exception of the items mentioned in Section 4, Technology Gaps, of this report, rapid response is ready for a demonstration. The 2023 Planetary Science and Astrobiology Decadal Survey (National Academies 2023) recommends that NASA pursue a rapid response demonstration mission as the highest priority planetary defense mission after NEO Surveyor. The participants of this study concur with that recommendation and believe we are ready to begin planning for demonstration of a rapid response capability.

Phase I of a demonstration mission would consist of the development of a rapid response mission capability. This entire phase would be conducted without knowledge of the future rapid response target, since in a real-world situation the target would not be known in advance. Development of the capability would include initial development of a generic flight system that could access a variety of potential targets, trade studies to determine if a ground-storage or space-storage option is more financially feasible and technically versatile, and agreements with regulatory agencies and launch providers (if needed) to minimize the target response time. Phase I represents the preparation that is required prior to identification of the target.

Phase II of a demonstration mission would be the enactment of the plan developed in Phase I, this time with a target identified. Phase II should be conducted as realistically as possible, only using information about the target learned after the simulated discovery including orbital and physical characteristics. Phase II is a simulation of the identification and response to a potential planetary defense threat.

Phase I of a planetary defense rapid response mission should begin as soon as possible so that Phase II can become the top priority after NEO Surveyor launches before the end of the decade. We recommend that international space agencies including NASA, the European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA) should begin to commission studies to define Level 1 requirements for a rapid response demonstration mission including classifying the types of targets that need to be accessible, defining a response timeline, and identifying budgetary constraints. Having a concrete set of top-level constraints will provide a firm foundation to develop the future of rapid response technical and programmatic capabilities.

4 TECHNOLOGY GAPS

4.1 SMALLSAT PROPULSION

All rapid response missions will require some amount of delta–V to be imparted within a relatively short period of time through impulsive maneuvers. For a direct-launch architecture, the spacecraft would require propulsion to clean up launch vehicle dispersions, for any cruise trajectory correction maneuvers, and for terminal guidance; the delta-V for a direct-inject architecture is likely on the order of low 100s of m/s. For a loitering spacecraft, more delta-V may be required for injection into an intercept trajectory since that spacecraft cannot make use of a launch vehicle's high energy capacity. One option is an upper stage, but long-term storage of solid propellant can be a risk. The safer approach is to utilize onboard propulsion to inject into the proper intercept trajectory, possibly with the use of Earth or lunar gravity assists. A spacecraft injecting from a loitering orbit would likely require 500–1000 m/s of delta-V, with more challenging targets requiring even more delta-V. Liquid propellant upper stages are becoming more prevalent, for example, the RocketLab Photon, but are still relatively new to the market. There are few liquid propulsion systems specifically designed for SmallSats currently available on the market. Many recent SmallSats that require propulsion have leveraged a collaboration between Georgia Tech and NASA Marshall Space Flight Center that produced a Green Propellant propulsion system, but it is unclear if that system will become available for the larger market. For now, SmallSat propulsion remains a significant technology gap to enabling rapid response and SmallSat deep space missions in general.

4.2 RAPID SPACECRAFT INTEGRATION

The ability to quickly mobilize a spacecraft for launch is paced by three program phases: design, design verification (qualification), and flight fabrication/assembly/test. Typical durations for these phases are shown in Table 4-1.

In order to meet a 3-month launch-ready goal, the design, design-verification, and fabrication phases must be complete prior to the call-up.

Table 4-1. Typical space program phase durations.

Phase	Duration	Notes
Design	1–2 years	These durations are for minor to moderate design modifications relative to an existing design (not a clean-sheet design)
Design verification	0.5–1 year	Qualification or proto-qualification testing
Fabrication	1–2 years	Fabrication is the production and acceptance testing of components and sub-assemblies
Assembly	1 month	Assembly is the mechanical installation of equipment to create the spacecraft assembly. This duration assumes the assembly process has been successfully executed previously.
Test	2–6 months	Test is functional and environmental testing of the spacecraft (bus integrated with payload). This duration assumes the test program has been successfully executed previously.

As semi-commoditized items, spacecraft buses may be in continuous production, however, the likelihood of a commercially available bus having the capabilities and interfaces needed for a flyby mission is unlikely without an intentional design effort. Either a bus (or set of buses) must be designed to accommodate specific flyby payloads, or a set of flyby payloads should be designed/redesigned to match commercially available bus interfaces and capabilities. In either case, the resulting spacecraft design should be qualified as part of preparation for an eventual mission.

Particularly with ongoing issues within the supply chain, component and subassembly fabrication durations are both unacceptably long and uncertain. Building components and subassemblies to inventory eliminates this duration and uncertainty. Maintaining the inventory at the component level, as opposed to continuing to build up the bus and/or spacecraft, still results in an acceptable call-up duration while allowing for a possible "refresh" concept of operations where components are allowed to be consumed by other programs and inventory is replenished. This would be one way to ensure that expendable elements such as batteries can be kept in a flight-ready state over long periods of storage, while minimizing cost. Additionally, keeping inventory at the component level facilitates the availability of spares for remove-and-replace action if a failure occurs at the spacecraft level.

Starting with an accepted, full bill of materials (BOM), and assuming the spacecraft assembly process has been vetted, spacecraft assembly can be accomplished in 1 month.

Spacecraft testing may take as long as 6 months if using traditional, largely manual test practices, and assuming a traditional spacecraft test program (functional and environmental testing). To reduce this phase duration, improvements in test automation, maintaining component spares for remove-and-replace action, and designing a test program that reflects a Class D mission posture will be necessary gap closures.

4.3 RAPID LAUNCH VEHICLE INTEGRATION

After fabrication, the spacecraft would need to be rapidly integrated onto a launch vehicle. In 2023, Firefly Aerospace demonstrated that they could launch a spacecraft delivered to their facility with only 24 hours' notice. Several other launch providers have been funded to perform similar demonstrations. With well-defined interfaces, it is clear that rapid launch vehicle integration is feasible and does not require significant technology development.

4.4 AUTONOMOUS CRUISE NAVIGATION

Autonomous interplanetary navigation and maintenance of a Sun-centered orbit, as desired for a constellation concept to reduce operations costs, has effectively been demonstrated by Deep Space 1 with the AutoNav system. Every 7 days, Deep Space 1 used onboard logic to determine what planets and asteroids were visible, imaged those targets, registered those images to derive "optical navigation" (OpNav) measurements. With those OpNav measurements of multiple targets in a short time period, Deep Space 1 was able to triangulate its position effectively. Using this trajectory estimation method, Deep Space 1 was able to determine autonomously when trajectory correction maneuvers were required, calculate the magnitude of the required trajectory correction maneuvers, and command those maneuvers.

A system like this enables a level of autonomous orbit maintenance. However, there are limitations in the trajectory estimation accuracy one can achieve with only OpNav measurements of likely distant planets and asteroids. Deep Space 1 achieved orbit estimation errors on the order of a few thousands of kilometers. Depending on the dynamics of the constellation orbits, this may or may not be sufficient. Gravity assists for example would likely require much higher accuracy. Technology in development, like the Deep Space Atomic Clock (DSAC), has the potential to improve this by allowing AutoNav to include 1-way radiometric data without ground involvement (Ely et al. 2021). Implementation of a system like this that includes autonomous OpNav collection and 1-way radio with DSAC is a technology gap.

4.5 AUTONOMOUS TERMINAL GUIDANCE

For flybys with small PHAs, LPCs, and ISOs, three different regimes of autonomous *terminal guidance* (final few hours before close approach) will likely be needed to enable successful science imaging and delivery of gravity probes. In order of highest to least challenging: autonomous acquisition, autonomous maneuvering, and autonomous tracking. All three of these regimes have been demonstrated previously with the AutoNav system for flybys of comets Borrelly, Wild 2, Tempel 1 (with impactor), Hartley 2, asteroid Annefrank, and impacts with Tempel 1 and Dimorphos.

The technology gap is small but exists as many of these missions operated under fairly ideal conditions, while a planetary defense LPC/ISO mission must be capable under the most challenging conditions. For PHAs, this mainly includes close flybys of small high solar phase PHAs that may require autonomous acquisition and an autonomous maneuver to deliver gravity probes, followed by an autonomous divert maneuver and autonomous tracking. The framework and basic technology exist to execute this but development is needed to put it all together. LPCs and ISOs on the other hand present extreme relative velocities that require autonomous tracking while the dust environment may require intelligent vision for hazard detection and avoidance capability. This vision, capable of handling unknown targets, is novel and would need development. All of the above onboard processing drives the need for a capable onboard computing system.

4.6 NEXT-GENERATION PROCESSORS

A new generation of processors, more capable than the RAD750, is coming online. In particular, the Mars Helicopter (Ingenuity) uses a version of the SnapDragon processor from Qualcomm (SnapDragon 855), as a step toward maturing a radiation-hard version of this processor that may be used in future missions. Image processing benchmarking reported in Lightholder et al. (2023) indicates that SnapDragon 855 is on average 40 times faster than the RAD750, which has been the standard for deep space missions for over 20 years.

Table 4-2. Example of science data processing tasks applied to a 20 MPx visible detector array and the observed performance using the SPHINX computer (equivalent to RAD750) and the SnapDragon 855. From Lightholder et al. (2023).

Command	SPHINX Time (s)	Snapdragon (s)	Speedup
Mask update	88.3	0.4	220x
Image statistics	46.2	0.7	66x
Crop image	11.0	0.3	37x
Compress image	22.4	0.5	45x
Downsample image	9.5	0.3	32x
Level 1 calibration	93.0	1.9	49x
Coadd images	298.9	31.1	10x
Subtract with blurring	806.5	14.4	56x
Subtract without blurring	125.4	1.4	90x

The enormous growth in automotive electronics ($230B worldwide) has resulted in substantial engineering and manufacturing investments to produce extremely low component defect levels (parts per billion) that are equal to or better than heritage space grade parts. Interest in the use for the SnapDragon process capability in Class B missions has led to rad-hard qualification procedures. Transient (single-event effects) and cumulative (total ionizing dose) must be characterized for each mission environment to ensure sufficient operating margin for all aspects of expected operational conditions. The low-cost nature of the modern automotive components has allowed us to build a large number of boards and perform a variety of environmental stresses (thermal, long life, etc.) that are designed to address and either retire or reduce system risk for Class B mission requirements and would thus be directly applicable to higher risk missions (Classes D and C).

4.7 CAMERAS

A camera system developed for a rapid-response mission is arguably the most critical instrument and needs to meet a number of requirements. The main priority is an imaging system capable of performing optical navigation. As discussed in detail in Section 3.4.2, the position of newly discovered targets may only be known to an accuracy of hundreds to even thousands of kilometers. It is therefore critical the spacecraft be able to image the target on approach and reduce those uncertainties to enable a close flyby.

This is a significant challenge for NEO and ISO/LPC rapid-response missions. The NEO diameters highlighted by the 2023 Planetary Decadal Survey are 50–100 meters. At these sizes, asteroids are extremely dim and thus difficult to detect. The later the target is detected, the later its trajectory can be accurately estimated, and the later a maneuver can be executed to target this improved trajectory. If detection is delayed to only days before flyby, this correction maneuver becomes increasingly expensive and drives a highly compressed ground operations timeline. If detection only occurs hours out, this will require advanced autonomy capable of searching for the asteroid and executing at least one if not multiple large maneuvers.

4.8 RAPID RESPONSE KEY OPPORTUNITIES

4.8.1 *Build and Store (“Know, then Go!”)*

The commercial launch sector is an area of rapid and exciting developments that may be leveraged to establish the desired rapid-response capability. By employing the newest generation of small-to-medium-class launch vehicles, high energy trajectories with substantial inclinations can be made available to

SmallSats. Options such as RocketLab's Neutron are expected to offer lower costs than preexisting vehicles—whose capabilities may not be fully required—while also offering faster response times. While the period from initial customer contact to launch is presently placed at 2 months, multiple companies have reported a goal of achieving 24-hour responses to launch requests in the future. This capacity for rapid launch execution is of special interest to the defense community (USSF/SSC), which would allow for complementary development programs. A further programmatic benefit is to provide a complementary capability to that being demonstrated by the upcoming ESA Comet Interceptor mission, which will utilize an on-orbit staging approach at the L2 Lagrange point.

In addition to the unique advantages provided by these upcoming launch vehicles, dedicated launches provide certain general advantages over on-orbit staging. By moving the majority of delta-V requirements from the spacecraft to the launch vehicle, the spacecraft's propulsion system may be simplified or made smaller. The remaining propellant capacity may also be primarily allocated to accounting for uncertainty in the ephemerides at launch or mid-course corrections, rather than any in-flight requirements imposed by the trajectory itself. Finally, by freeing the trajectory timeline from the orbital phasing needed to enable Earth gravity assists (EGAs), the departure from Earth may always occur at the optimal time for a given trajectory.

By forgoing the construction of a large constellation of spacecraft, the "Build and Store" plan can provide a rapid response capability with only a single spacecraft, while also providing the desired cost savings of construction in bulk by storing the additional spacecraft near launch sites around the world. While the customization of individual spacecraft should be avoided to minimize cost and programmatic creep, the storage on the ground permits for improvements and modifications to be made in response to the lessons learned from ongoing or past missions. For example, scientific equipment could be changed to better match an expected target or hardware upgraded to match spacecraft ordered at a later date. This strategy would also allow unrelated missions to utilize a single, proven spacecraft design, with a minimum level of modifications between missions.

4.8.2 *Microconstellation Model*

There are several advantages to the microconstellation model. First and foremost, it takes the time from build to launch out of the response equation. A constellation of capable spacecraft would be fully commissioned and already operated by a trained team in place, with detailed procedures on the shelf for rapidly executing a new mission objective. Since the constellation would be built and launched before the rapid-response need, its deployment would be well suited for rideshares, which could have significant pre-launch cost savings. Existing commercial industry product lines could be leveraged to build, test, and launch a constellation of identical satellites, much like the SpaceX Starlink and OneWeb models.

A microconstellation of satellites provides unique opportunities for in-situ science while waiting for the demonstrative PHA(s) of interest. The fleet could conduct close encounters with opportunistic near-Earth asteroids (NEAs), significantly increasing our knowledge set of this unique population of objects. This dataset will not only help us characterize common and unique geophysical parameters in this population, but also provide compositional characterization for resource mining. A fleet of spacecraft could also provide opportunities for heliophysics investigations, providing unique geometries for monitoring solar activity. While the fleet will carry a minimum payload suite for PHA characterization, there could be margin for a guest payload on each satellite, providing opportunity for commercial, military, and international partners.

Innovations and advancements in autonomy could enable the operation of a constellation of spacecraft without a large team of ground operators, reducing the cost and resources required to operate the constellation for a long duration. Continued investment in "lights-out" operations would further enhance this architecture.

The primary challenge for a microconstellation arises when considering costs over planetary defense timelines. Whereas a build-and-store concept is akin to a one-time purchase per rapid response, a microconstellation is akin to a subscription service. Real asteroid threats may only appear at rates on the order of one per hundred years. At these time scales, a microconstellation "subscription" can present a very large total cost, with potentially several complete replacement cycles of the constellation. This requires consistent funding support no matter the administration priorities. Reducing costs and leveraging in-situ science partners is key to making this cost model digestible.

4.8.3 *Small Satellite and Launch Vehicle Industries*

The cost to access space is decreasing with the emergence of an industry around smaller spacecraft that can host powerful payloads. The reduction of cost of a payload to orbit is a combination of the advent of the small satellite, or SmallSat, a satellite platform that uses commercial-off-the-shelf (COTS) components, batch builds, and standard interfaces to drive down costs, and the emergence of small launch vehicles and rideshare opportunities, both of which leverage reusability and highly optimized platforms to deliver lower mass spacecraft to orbit for a lower cost than a large launch vehicle. The industry is also being supported by a number of other companies performing communications, operations, trajectory design, space situational awareness, and other key activities to enable the successful development, launch, and operations of small, low-cost spacecraft.

SmallSats are challenging the bespoke, design-around-a-payload architecture for spacecraft design and are instead relying on fixed capabilities with room for modification to suit a large variety of customers with different payloads and requirements. Well-defined interfaces and little variation in spacecraft buses for different customers allows SmallSat manufacturers to use common assembly lines, common parts, and common testing practices to reduce the time and cost to design a new flight system for every use case. Fixed bus interfaces redistribute the non-recurring design process from the spacecraft bus to the payload elements. Instead of the bus being designed to accommodate the payload, payloads are now being designed to fit within the fixed accommodation requirements of the spacecraft bus. This may put additional cost and complexity on the payload system but since payloads are often newer designs than the spacecraft buses, it is often faster and cheaper to design the payload around the bus than vice versa. The limited resources and capabilities on a SmallSat also cap the size and complexity of the payloads that the spacecraft can host. Some of the most capable science instruments are too massive, require too much power, or require too much data to fit on a SmallSat.

Small- and medium-class launch vehicle companies have also emerged to deliver these smaller spacecraft to space without significant waste. Companies like RocketLab and Virgin Orbit can deliver 100s of kg to low Earth orbit and companies like FireFly and ABL can deliver around 1000 kg to low Earth orbit. Many of these vehicles can be coupled with a propulsive upper stage to increase the amount of mass that can be delivered beyond low Earth orbit. Separately, large launch vehicle companies like SpaceX are offering rideshare services to make use of extra mass on high capability vehicles. Dedicated launch vehicles have greater flexibility in injection orbits since rideshare opportunities are restricted to the primary launch vehicle payload destination.

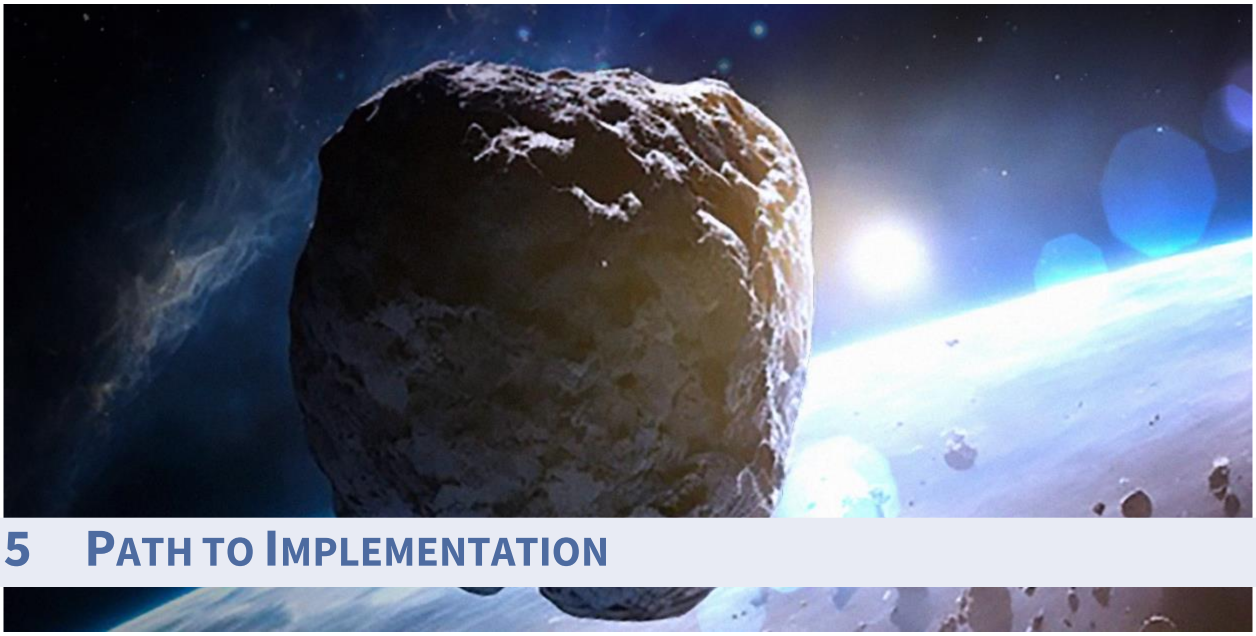
Commercial space services are the third prong in a continuously developing commercial space industry. Kongsberg Satellite Services (KSAT) and Amazon Web Services are leading commercial companies providing communications services for spacecraft operating in Earth orbit, with low-data rate capabilities for beyond-

Earth communication. Companies like Continuum Space Services are providing trajectory and constellation design and other mission services, and companies like LeoLabs are providing conjunction analysis and space situational awareness to prevent in-space collisions. All these new players are part of a commercial space ecosystem that is taking advantage of economies of scale to reduce the cost to design, build, launch, and operate spacecraft in Earth orbit and cislunar space, with deep space operations just on the horizon.

Rapid response spacecraft can take advantage of this growing international ecosystem to reduce the long-term cost of maintaining this capability and alleviate pressure from already oversubscribed national space agency resources, like the Deep Space Network (DSN) or the European Space Tracking (ESTRACK) network. Batch-built spacecraft designed to be stored on the ground can rely on the emerging small satellite manufacturing industry to rapidly and inexpensively design and manufacture spacecraft and can rely on commercial mission design companies to rapidly determine optimal trajectories to intercept the target, once identified. These spacecraft can also use lower-cost launch vehicles to directly inject onto the optimal trajectory using a dedicated launch vehicle. Spacecraft launched to a loiter orbit can leverage commercial communication networks and operations teams to minimize the cost of maintaining a constellation of spacecraft in orbit. Many commercial space companies are developing constellations of their own, Planet Labs, Starlink, OneWeb, and Capella, for example, so the tools being developed to operate large constellations can be directly applied to operate the loitering rapid response microconstellation.

4.8.4 *U.S. Department of Defense Tactical Launch*

The DoD has been sponsoring initiatives to significantly reduce the time required to launch a spacecraft into orbit. The DoD recently awarded a contract to put a satellite into orbit within 24 hours of delivery of the payload to the launch site; Firefly Aerospace successfully took delivery of a spacecraft and launched it into orbit within 24 hours in 2023. While response times on the order of hours is not typically required for this type of rapid response, lessons learned and practices being developed in support of tactical launch are directly applicable. The civil space community can look towards the defense industry as an initial framework for instantiating rapid launch vehicle procurement. We recommend continued engagement between the civil and defense aerospace sectors to share lessons learned on topics that relate to both rapid response for planetary defense and for DoD applications, including tactical and responsive launch.



5 PATH TO IMPLEMENTATION

5.1 RECOMMENDATION FOR A NEW INITIATIVE

A rapid response mission struggles to fit into any currently available funding paradigm. Comet Interceptor is an example of a mission that leverages in-space storage to maintain semblance of a more familiar mission development and operations profile, but NASA's current announcements of opportunity (AOs) do not allow for a similar storage option. On-ground storage or built-upon-detection do not have any past examples.

Therefore, the attendees of the KISS workshop recommend that international space agencies, either separately or together, develop a new initiative to develop and maintain a rapid response capability. Initially, planetary defense can provide a funding path to assess different architectures and develop the capability for rapid response. Lessons learned from the initial development of that rapid response capability can then be applied for rapid response to science targets such as ISOs and LPCs. The actual planetary defense flight system could be repurposed to visit an ISO or LPC with a slightly modified instrument suite and possibly the inclusion of a dust shield for active targets. Section 3 of this report discusses the implementation of different spacecraft architectures.

It is critical that any pathfinding rapid response missions are designed with feed-forward in mind. All mission concepts should be implemented with modularity and batch-builds as a primary driver so that this initiative could be demonstrated and sustained over time without driving significant non-recurring costs between builds. The rapid response capability recommended in this report includes multiple spacecraft, and a single demonstrator that does not consider future builds would not actually demonstrate a sustained rapid response capability.

5.2 STRATEGIC ADVOCACY

Rapid response is an important capability to a diverse set of stakeholders. Rapid response is needed for planetary defense and to access high-value science targets like ISOs and LPCs. We recommend advocacy to international stakeholders, beginning with stakeholders in planetary defense as an initial demonstrator of the capability.

Planetary defense is increasing in priority at NASA but is an international challenge. Other international space agencies, including ESA and JAXA, are involved with rapid response or planetary defense missions. LiciaCube, which accompanied DART (Double Asteroid Redirection Test) and took images after its impact of Dimorphos, and Hera, a follow-on mission to the Didymos system to observe the impacts of DART, are but two examples of ESA involvement with planetary defense. JAXA's involvement with Hera and its own dedicated small bodies and asteroid missions are also critical to planetary defense. Altogether, the concerted effort by multiple space agencies around the world demonstrates planetary defense as an international priority. Entities such as the United Nations are also involved with planetary defense through organizations like the Space Mission Planning Advisory Group (SMPAG) and could provide resources to implement a rapid response planetary defense mission.

We recommend advocating for rapid response, initially for planetary defense, to international space agencies and other governmental organizations such as the United Nations and the Committee on Space Research (COSPAR) to increase support and funding to develop this capability. We also recommend making it clear that while this capability is necessary for rapid response, there is a lot of potential to feed the capabilities forward for exploration of high-value science targets.

5.3 NEAR-TERM DEMONSTRATION

Planetary defense is the opportunity for a near-term demonstration of rapid response. NASA responded to the recently released Planetary Decadal Survey (National Academies 2023) by concurring with the recommendation to implement a rapid response planetary defense mission, and that the technologies developed for that mission can later be applied to ISO and LPC missions. Therefore, a planetary defense mission is the logical step for an initial demonstration mission of rapid response capabilities. The demonstration would come in two parts. In the first part, we would develop a capability for rapid response. This would include downselecting to a single robust architecture for a planetary defense flight system, which could be built and stored on the ground or stored in a loitering orbit, as discussed in Section 4.8. It would also include developing the ground-based tools to characterize a potential target and to operate the eventual reconnaissance spacecraft. The second part would be the actual demonstration of the capability, which should include the end-to-end simulation of a planetary defense rapid response mission from initial detection of an object, initial characterization, through development of a mission to perform a rapid flyby reconnaissance of the target. The first part of the demonstration would be performed entirely without knowledge of the eventual target since in a real-world situation, the target would not be known a priori.

The first part of the demonstration, the development of a rapid response capability, would provide a framework to conduct rapid response missions in the future. The technologies developed must be consistent with a sustained capability and not just a one-off mission. Small modifications could be made from the initial demonstration based on lessons learned before rolling out a sustained planetary defense rapid response initiative. The development of the capability would be similar to the development of other traditional space missions from a timeline perspective and would not be constrained by the discovery of an object.

The second part is the first ever demonstration of the newly developed capability. For demonstration purposes, the discovery of the object could be synthetic, in that the ground systematically determines the orbit of an already-known object but only based on observations starting on a given day. The demonstration of ground activities is equally as important as the demonstration of flight system development and operation. The entire end-to-end demonstration from synthetic discovery to fast flyby should be within a small number of years, successfully demonstrating that the capability can be implemented for rapid response.

A sustained program would follow the successful demonstration of the rapid response capability and the inclusion of any modifications based on lessons learned.

5.4 FEED-FORWARD OPPORTUNITIES

At this time, we envision two kinds of opportunities: the proposal of a competed mission in one of NASA's low-cost programs, Discovery or SIMPLEx (Small, Innovative Missions for PLanetary Exploration), and a directed mission.

5.4.1 *Competed Missions*

As currently scoped by NASA, the Discovery program does not explicitly allow missions to targets that are not already identified. The Discovery 2019 AO explicitly discards interstellar objects as proposal targets. Dr. Curt Niebur, NASA Program Scientist, recommended that the community interested in proposing this kind of mission advocate for an update of the Discovery AO (Niebur, pers. comm.) This change of scope has important implications that need to be addressed. One is about changing the way launch vehicles are provisioned. Principal Investigator–procured launch vehicles would enable missions to work directly with launch vehicle providers and procure affordable vehicles that meet mission requirements early in formulation. This closes many early trades and enables the team to progress through the mission lifecycle with a known launch vehicle and known environments from the onset.

The SIMPLEx program is currently not adapted for rapid response missions. This program was introduced to enable the dedication of extra mass available on interplanetary mission launch vehicles to smaller secondary payload. That is, the SIMPLEx is designed as a rideshare program whose secondary payload is entirely dependent on the primary payload. This has two major implications: the primary launch prescribes the space of possible destinations years before the launch date, and any delay of the primary mission development can severely affect the fate of the secondary payload. An unfortunate example is the JANUS mission that was slated to launch with the Discovery-class Psyche mission whose launch was delayed by more than one year. Accessing the two binary NEO systems initially targeted by JANUS could not be reproduced with the new launch parameters, and at this time, JANUS has been de-manifested.

The emergence of new, low-cost launch vehicles might lead to a change in paradigm for small missions. Its possible (although not verified as part of this study) that procuring a dedicated launch decreases the overall complexity and cost of flying SmallSat missions and increases the chance that these missions will meet their science objectives. The total energy capability of these smaller vehicles also needs to be studied to determine if they are capable of delivering the payloads to the necessary trajectories to intercept the target body.

5.4.2 *Directed Missions*

The NEO flyby mission recommended by Planetary Decadal Survey as the next mission priority in the Planetary Defense Coordination Office after the launch of the NEO Surveyor Mission (~2027) represents a perfect opportunity to use capabilities developed in the rapid response technology demonstration outlined above.

On several occasions, NASA has directed missions to achieve strategic goals, for example, the Lunar Reconnaissance Orbiter (LRO) and DART. Both missions were Class C, which means that they are medium to low complexity and some risk of not achieving success is acceptable. If the case could be made that a rapid-response mission is of significant value to NASA's Science Goals (e.g., Small Bodies Assessment Group 2020), then a similar path could be a possibility. The discussions in this report are directly applicable to the rapid response, flyby mission highlighted in the Planetary Decadal Survey.

Lastly, the international community should continue advocacy with their respective space agencies for the development of a coordinated fleet (Castillo-Rogez et al. 2018).

6 CONCLUSIONS AND RECOMMENDATIONS

Rapid response is an enabling technology to explore a new class of targets: NEOs, ISOs, and LPCs. While the necessary technology for rapid response exists today, a concerted effort is required to mature an architecture to enable future rapid response missions. Specifically, the authors recommend the following follow-on activities:

6.1 POPULATION STUDY TO DERIVE TECHNICAL RAPID RESPONSE REQUIREMENTS

- Develop a synthetic population of NEOs, LPCs, and/or ISOs
- Simulate the detection of the bodies using current and future observatories, such as NEO Surveyor, Vera Rubin Observatory, and Pan-STARRS
- Generate trajectories to synthetic targets and derive technical requirements including: delta-V required, minimum and maximum distance from the Sun for power and thermal, maximum distance from the Earth for communications

6.2 STRATEGIC PARTNERSHIPS WITH SPACECRAFT AND LAUNCH VEHICLE PROVIDERS

- Collaborate with industry to leverage emerging capabilities, such as rapid procurement, to understand a contract mechanism to enable rapid response missions
- Collaborate with spacecraft and launch vehicle providers to understand the drivers for a rapid procurement and timeline feasibility
- Identify enablers to reduce the duration to procure a flight system such as mature, ready-to-build designs, hardware ready for integration, or contract agreements to “skip the queue” for a vehicle

6.3 TECHNOLOGY MATURATION OF ENABLING INSTRUMENT TECHNOLOGIES

- Mature the designs for hypervelocity in-situ measurements for active comet sampling
- Develop techniques to directly measure mass/gravity, such as gravity probe concepts being developed at JPL and APL, for planetary defense characterization

6.4 STRATEGIC ADVOCACY FOR A RAPID RESPONSE INITIATIVE

- Build upon recommendations in the Planetary Science and Astrobiology Decadal Survey to demonstrate rapid response for planetary defense with feed forward to science opportunities
- Work with NASA and key stakeholders to understand the constraints behind a rapid response initiative to constrain the development of a realistic architecture
- Derive Level 1 requirements for a rapid response mission, such as programmatic cost and schedule constraints and key measurement requirements, to drive the mission architecture to a feasible point design

6.5 RAPID RESPONSE DEMONSTRATIONS

- Leverage natural opportunities to test and demonstrate rapid response technologies and architectures, such as the upcoming Apophis close approach in April 2029

To date, the world has missed the opportunity to explore at least two interstellar objects and multiple dynamically new long-period comets. Fortunately, the world has not yet had the need to explore an NEO for planetary defense, though asteroids like Apophis serve as stern reminders of the need for a rapid response and planetary defense capability. By continuing to mature rapid response architectures, we can be prepared when future targets present themselves and never again miss an opportunity for groundbreaking science. We strongly advocate for these five recommendations and other instrumental activities in making rapid response a reality.

Appendix A. ACRONYMS

ACS	attitude control system
AO	announcement of opportunity
APL	Applied Physics Laboratory
ARIEL	Atmospheric Remote-sensing Infrared Exoplanet Large-survey
BIRCHES	Broadband InfraRed Compact High Resolution Exploration Spectrometer
BOM	bill of materials
C&DH	computer and data handling
CAI	calcium-aluminum-rich inclusion
Caltech	California Institute of Technology
COSPAR	Committee on Space Research
COTS	commercial-off-the-shelf
DART	Double Asteroid Redirection Test
DoD	U.S. Department of Defense
DSAC	Deep Space Atomic Clock
EGA	Earth gravity assist
ESA	European Space Agency
ESTRACK	European Space Tracking
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
GEO	geostationary orbit
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
IR	infrared
ISO	interstellar object
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KISS	Keck Institute of Space Studies
KSAT	Kongsberg Satellite Services
LASP	Laboratory for Atmospheric and Space Physics
LEO	low-Earth orbit
LiciaCube	Light Italian Cubesat for Imaging of Asteroids
LPC	Long-Period Comet
LRO	Lunar Reconnaissance Orbiter
LSST	(Rubin Observatory) Legacy Survey of Space and Time

mAPIC	mini-Advanced Pointing Imaging Camera
NASA	National Aeronautics and Space Administration
NEA	near-Earth asteroid
NEO	near-Earth object
NEO-WARP	Near-Earth Object Workshops to Assess Reconnaissance for Planetary defense
OpGrav	Optical Gravimetry
OpNAv	optical navigation
OSIRIS-REX	Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer
OVIRS	OSIRIS-REx Visible and Infrared Spectrometer
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PHA	potentially hazardous asteroid
QIT-MS	Quadrupole Ion Trap Mass Spectrometer
SIMMEE	Small Body In-Situ Multi-Probe Mass Estimation Experiment
SIMPLEx	Small, Innovative Missions for PLanetary Exploration
SMPAG	Space Mission Planning Advisory Group
SSC	Space Systems Command
SUDA	(Europa Clipper) SUrface Dust Analyzer
TIR	Thermal Infrared Imager
USSF	U.S. Space Force

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