NEO WARP

Near-Earth Objects Workshops to Assess Reconnaissance for Planetary Defense

Working Groups Final Report

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Executive Summary

Planetary defense against hazardous asteroid and comet impacts on Earth is an active and growing applied planetary science field with the aims of understanding the nature of near-Earth objects (NEOs), assessing the hazards and opportunities they present to us, and developing operational capabilities for defending ourselves by preventing NEO impacts on Earth. To these ends, a worldwide network of telescopes has been scanning the skies for hazardous NEOs for decades, NASA Headquarters established the Planetary Defense Coordination Office (PDCO) in 2016, the White House since published a National Preparedness Strategy & Action Plan for Near-Earth Object Hazards and Planetary Defense, and The National Academies included a chapter on planetary defense for the first time in its most recent Planetary Science and Astrobiology Decadal Survey 2023-2032.

With NASA's DART mission successfully completed and NASA's forthcoming NEO Surveyor space-based infrared telescope to find the undiscovered potentially hazardous NEOs in development, the Decadal Survey recommends that "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 (~50–100 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."

The Near-Earth Objects Workshops to Assess Reconnaissance for Planetary Defense (NEO WARP) were a series of three workshops held by the planetary defense community during 2023 to help address the challenges of NEO reconnaissance. One of the key NEO WARP recommendations was to form Working Groups (WGs) to delve more deeply into particular topic areas of interest:

a) Characterization;
b) Guidance, Navigation, and Control & Mission / Campaign Design;
c) Mitigation Modeling / Earth Impact Effects;
d) Spacecraft Design, Integration & Test / Rapid Response Launch; and,
e) Technology.

These WGs convened from March through September 2024 to perform their assessments. Summaries of their recommendations follow.

High-level summary of Characterization WG recommendations: Further studies are needed to quantify the various ways in which relevant asteroid properties influence the outcomes of asteroid deflection or disruption techniques. Robustly measuring the mass of an asteroid as small as 50-100 m in diameter remains challenging and solutions should continue to be studied. Techniques for characterizing an asteroid's internal structure are lacking and should be developed. Studies of asteroid strength-related properties should continue. There is a need to provide unified meanings for strength-related properties and understand how to model them for Earth impact risk assessment and mitigation mission planning.

High-level summary of GNC & Mission / Campaign Design WG recommendations: Reconnaissance missions for planetary defense have unique requirements, needing to inform planetary defense analysis processes and decision makers. Rapid response missions must be capable of launch readiness within very short time-frames compared to typical science missions.. We recommend: a study to compare the cost, benefit, and response time with the probability of a successful reconnoiter & deflection/disruption of an NEO for both ground and space based staging systems; mission design studies comparing monolithic and distributed rapid recon mission architectures, evaluating the potential of multi-satellite architectures; a study to assess current asteroid flyby capabilities; development of improved onboard computation capabilities for autonomy; and development of small gimbaled instrument platforms, high-resolution IR imagers, deployable instruments/platforms for mass measurements during fast flybys, low SWAPC high precision ranging instruments, and on-instrument data processing capabilities for autonomous operations.

High-level summary of Mitigation Modeling / Earth Impact Effects WG recommendations: The precision required in asteroid properties for mitigation and Earth impact models, and in the predictive outputs of those models for stakeholder decisions, are currently unknown. Identifying the required precisions can be done through modeling improvements, sensitivity studies, and developing thresholds for decision support. Areas currently lagging in modeling that would benefit from focused development include cascading hazards, tsunami modeling, and asteroid disruption modeling, with the goal of producing a complete suite of mature mitigation and Earth impact effects models. These improved models can be used to perform sensitivity studies to develop data-driven rules of thumb that inform the measurement precision required of reconnaissance missions in order to produce outputs with the necessary precision for decision support. Finally, working with stakeholders to identify decision thresholds is recommended, with the goal of developing metrics that support decisions and identify the level of certainty required to enable decisions.

High-level summary of Spacecraft Design, I&T / Rapid Response Launch WG recommendations: Determine the minimum payload suite for a rapid response recon mission; determine the time required to respond to credible threats; assess the response time capability of several potential levels of readiness; study the benefits and limitations of a space vs ground storage option; assess the historical launch opportunities that may have been used for a rapid response mission; collaborate with the launch industry to devise a strategy for future rapid procurement of a launch vehicle; and derive the mission requirements (e.g., delta-V, encounter distance, min distance from Sun) for a rapid response mission via a population study of synthetic impactors.

High-level summary of Technology WG recommendations: The time from first detection to close approach during a flyby reconnaissance mission is likely 1-7 days, instead of weeks as typical of science mission targets. Successfully navigating such flybys will require some onboard autonomy functions that have not yet been demonstrated. Rendezvous recon missions will also require new autonomy in areas such as low altitude proximity operations. Onboard computing requirements will necessitate improved onboard processors. Continued development of Solar Electric Propulsion (SEP) technology, including Power Processing Units (PPUs) and gimbals, is recommended. Further development of both SEP and chemical propulsion options for SmallSats is also recommended. Finally, propulsion technologies including solar sails, Variable Specific Impulse Magnetoplasma Rocket (VaSIMR), and DARPA's Nuclear Thermal Rocket Program (DRACO) would enable rendezvous with high inclination and/or high eccentricity asteroid orbits. Advocating for these future propulsion technologies and studying their planetary defense applications is recommended.

1. Introduction

Planetary defense against hazardous asteroid and comet impacts on Earth is a growing applied planetary science field with the aims of understanding the nature of near-Earth objects (NEOs), assessing the hazards and opportunities they present, and developing operational capabilities for defending ourselves by preventing NEO impacts on Earth. The consequences of NEO impacts can range from harmless meteorite falls; to catastrophic damage to metropolitan areas; to extensive regional devastation; to even extinction level events. With the smaller sized objects vastly outnumbering the larger ones, the most likely impact hazard at any given time is a small NEO that is still large enough to penetrate deeply enough into our atmosphere to deliver harmful amounts of energy to the ground. The most difficult of those to defend against are the smallest that are still large enough to be harmful, because those will also generally be the most difficult to detect far enough in advance to take effective defensive actions. Additionally, smaller NEOs are much more challenging targets for spacecraft navigation systems and measurement instruments than are larger NEOs.

Efforts to understand the natural impact hazard we face and develop the means to defend ourselves have been mounting for decades. At present, a worldwide network of ground-based telescopes searches the night skies for NEOs, continually adding to the catalog of those that are discovered. Automated computer systems monitor the orbit data for the cataloged NEOs, continually checking whether any might pose Earth impact hazards.

In 2016, NASA Headquarters established the Planetary Defense Coordination Office (PDCO) within the Planetary Science Division (PSD) of the Science Mission Directorate. Two years later, in 2018, the White House published the first National Near-Earth Object Preparedness Strategy and Action Plan, describing actions to be undertaken within multiple domains, and by multiple government agencies, to increase our preparedness to execute effective planetary defense measures when the need arises. Several years later, the White House published the related Report on Near-Earth Object Impact Threat Emergency Protocols (NITEP), describing specific protocols for responding to hazardous NEOs [National Science & Technology Council, 2021].

On September 26, 2022, NASA's Double Asteroid Redirection Test (DART) mission targeted the Didymos binary asteroid system and performed the world's first demonstration of the kinetic impact method for deflecting the course of an asteroid by measurably changing the orbit of the ~160 m size asteroid Dimorphos around its parent body, Didymos, and characterizing the deflection performance [Rivkin & Cheng, 2023; Cheng et al, 2023]. NASA has also been steadily working to develop the forthcoming Near-Earth Object Surveyor infrared space telescope, designed to complete the search for hazardous NEOs and discover as many future Earth impactors as possible, and in as far advance of their impact dates as possible, to maximize our opportunities for successful reconnaissance, Earth impact prevention missions, and, when necessary, emergency disaster response. NEO Surveyor is currently scheduled to launch during the fall of 2027.

During 2023, an update to the White House National NEO Preparedness plan was published [National Science & Technology Council, 2023] and, at the same time, NASA published its own Planetary Defense Strategy and Action Plan in support of the national plan [National Aeronautics and Space Administration, 2023]. The National Academies also published its new Decadal strategy report for planetary science and astrobiology for the 2023-2032 decade, and included a chapter on planetary defense for the first time [National Academies of Sciences, Engineering, and Medicine, 2023].

With the DART mission having been successfully completed and with the NEO Surveyor space telescope construction well underway, the Decadal report identified the need to prioritize the demonstration of a rapid response NEO reconnaissance mission to a challenging target object, described in the following two findings and associated recommendation [National Academies of Sciences, Engineering, and Medicine, 2023]:

> Finding: There is much to be learned about the physical characteristics of the NEO population. Only a handful of NEOs have been observed in situ and there are many unknowns concerning the range of physical properties that may be relevant for planetary defense. In addition, smaller NEOs (>50 m in diameter) are challenging to detect and characterize via ground-based methods, and represent the least understood, but statistically the most likely subset of the NEO population to require mitigation actions.
>
> Finding: Prior characterization of a hazardous NEO via an in situ reconnaissance mission is advisable to determine its physical characteristics and to develop an appropriate mitigation response based on the available warning time. Although rendezvous missions are preferred, fast flyby missions may be required to obtain timely characterization data for short warning time scenarios.
>
> Recommendation: 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 (~50–100 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.

Those findings and associated recommendation are in accord with the NITEP Benchmark for Recommending Space-Based Reconnaissance [National Science & Technology Council, 2021], which identifies 50 m as the asteroid size threshold for prompting consideration of reconnaissance mission execution:

> NITEP recommends that the Nation consider executing a reconnaissance mission in any scenario that meets all of the following conditions:
>
> - Meets all of the SMPAG guidelines[1] for initiating planning of in-space prevention missions:
>   - Impact predicted to be within 50 years;
>   - Impact probability is assessed to be greater than 1%; and

[1]https://www.cosmos.esa.int/documents/336356/1503750/SMPAG_5.1_Report_NASA.pdf/f399e4eb-5947-867c-2422-b9dcb7e3649c

    - Object is characterized to be greater than 50 meters in size, or roughly equivalent to absolute magnitude of 26 if only brightness data can be collected;
- **AND** there is sufficient time to conduct the mission prior to the predicted impact. This will likely require more than three years advanced warning.

To develop the operational capabilities needed to execute such a reconnaissance mission, the following two actions for reconnaissance preparation are specified in both the national preparedness plan and the supporting NASA preparedness plan [National Science & Technology Council, 2023; National Aeronautics and Space Administration, 2023]:

> 3.1 Collaborate on technologies for rapid response, reconnaissance, and characterization of in-space objects. Evaluate the capabilities of current and projected launch vehicle infrastructure to support short-warning planetary defense missions.
>
> 3.2 Create plans for the development, testing, and implementation of NEO reconnaissance mission systems.

Here we note that the "rapid-response, flyby reconnaissance mission targeted to a challenging NEO, representative of the population (~50–100 m in diameter) of objects posing the highest probability of a destructive Earth impact" recommended by the Decadal report [National Academies of Sciences, Engineering, and Medicine, 2023] as the highest priority planetary defense demonstration mission to follow DART and NEO Surveyor would directly contribute to accomplishing action 3.2, and in a manner conducive to the NITEP benchmark for recommendation space-based reconnaissance [National Science & Technology Council, 2021].

To help address the challenges of preparing to demonstrate and operationalize rapid response flyby NEO reconnaissance mission capabilities for asteroid targets as small as 50m, per the foregoing White House and National Academies directives and guidance, NASA's PDCO requested that the planetary defense technical community collaboratively discuss and assess NEO reconnaissance techniques and capabilities, identify knowledge and capability gaps, and document findings, recommendations, and ideas. This activity was executed as the Near-Earth Objects Workshops to Assess Reconnaissance for Planetary Defense (NEO WARP), a series of three workshops held by the planetary defense community during 2023.

The NEO WARP steering committee assembled a report documenting the proceedings and findings of the workshops, which was briefed to NASA's Small Bodies Assessment Group (SBAG) meeting in January 2024[2] and delivered in report form to NASA's PDCO in March 2024. Findings from the NEO WARP included:

- Reconnaissance missions for planetary defense are crucial.
- Both flyby and rendezvous reconnaissance capabilities should be developed for planetary defense.

[2] https://www.hou.usra.edu/meetings/sbagjan2024/presentations/Thursday/1445_Lyzhoft.pdf

- There are multiple technologies to advance planetary defense capabilities that are ready for a flight demonstration project.
- A sustained regular investment to fund planetary defense demonstration missions is needed to advance planetary defense readiness.
- Technology gaps exist in the domains of computation, autonomy, and calibration.
- However, technology gaps are not the largest barrier to performing reconnaissance missions—rather, it is the knowledge gap of unknown requirements for missions, i.e. for NEO characterization measurements, how good is "good enough."
- Knowledge gaps also exist in the domains of navigation requirements and mission design requirements.
- It is not clear how reconnaissance missions can be implemented to the same specifications consistently and repeatedly, while ensuring rapidity and cost effectiveness. Workshop participants suggested development of a toolbox to help accomplish this efficiently, and maintenance of an up-to-date pipeline.
- To close some potential gaps, trajectory studies and architecture studies must be pursued.
- The planetary defense community is strong, active, and growing.
- A set of working groups should be formed to make more detailed assessments.

The NEO WARP steering committee issued a broad invitation at the SBAG in Jan 2024 for community participation in Five Working Groups (WGs) to assess the following critical topics identified by the NEO WARP for importance and priority of next steps:

- Characterization
- Guidance, Navigation, and Control & Mission / Campaign Design
- Mitigation Modeling / Earth Impact Effects
- Spacecraft Design, Integration & Test / Rapid Response Launch
- Technology

These WGs convened from March through September 2024 to perform their assessments. The reports of their findings and recommendations are provided in the sections that follow.

2. Characterization

In Planetary Defense (PD), it is essential to accurately and rapidly assess and mitigate an upcoming hazardous NEO. Assessing these issues requires determining or constraining the characteristics of the target object. The Characterization WG under the NEO WARP effort compiles key physical properties contributing to anticipated planetary defense efforts in case a hazardous NEO is identified on short notice [Chodas, 2019]. This report defines the following terms:

- A terminal event occurs when a target body enters the Earth's atmosphere to explode or impact its surface, causing negative influences on existing activities and ecosystems if a mitigation action fails or is not executed. See the Supplemental Information at the end of this section for further details.

- Mitigation planning is the effort to seek effective techniques to mitigate an upcoming terminal event, preventing the Earth impact by either deflecting or disrupting the incoming NEO. The Characterization WG considers the following four mitigation technologies [Barbee et al., 2020b] as case studies: kinetic impactor (KI), nuclear explosive device (NED), gravitational tractor (GT), and ion beam deflection (IBD).
- Risk assessment is a process of assessing any outcome due to the impact of an asteroid. This is related to the damage caused by the terminal event.
- Measurement defines a quantity directly obtained by telescopic and/or instrumental observations without interpretation.
- Constraint defines a condition of the target body interpreted from modeling predictions and partial measurements.

The Characterization WG identifies properties of hazardous bodies that critically relate to PD, later known as contributing properties. This report summarizes how the contributing properties are related to a fast reconnaissance mission concept [National Academies of Sciences, Engineering, and Medicine, 2023]. This mission conceptualizes pre-mitigation efforts to measure or constrain the contributing properties from telescopic or in-situ observations within a tight time constraint [National Academies of Sciences, Engineering, and Medicine, 2023]. The later discussions apply the following conditions:

- PD consists of mitigation planning and risk assessment.
- Targets of highest concern are 50 m – 100 m in diameter [National Academies of Sciences, Engineering, and Medicine, 2023], without companions; there is limited observational evidence of companions for objects 50 m – 100 m in diameter [Margot et al., 2002].
- The readiness level of each mitigation approach is not within the scope of this report.

The Characterization WG finds PD-related priority areas and rates each property in the defined areas. Defining the rating metrics requires detailed and careful studies from various approaches in modeling, telescopic observations, and instrumental observations. However, limited data availability and existing knowledge gaps in both modeling and observations prevent providing their contributions to PD in numbers. All discussions below, therefore, are more qualitative than quantitative.

2.1. Contributing Properties

The Characterization WG identified and assessed 16 contributing properties that play critical roles in PD. Each contributing property is further categorized into three property categories: primary, secondary, and supporting properties.

- Primary property directly contributes to PD. The measurement of this property can be critical in mitigation planning and risk assessment.
- Secondary property directly contributes to PD if its measurement is provided, but in contrast to the primary property, this property only plays a critical role in mitigation planning or risk assessment, but not both.
- Supporting property can support PD but only provides supportive insights into either primary or secondary properties.

The identified properties are given in Table 1.

Table 1. Identified contributing properties with their categories and contributions. The Contribution column describes how each property contributes to PD. In this column, supporting properties show which primary or secondary property they offer supportive insights into. The cell colors show different property categories. Primary properties are given in light blue, secondary properties are in light green, and supportive properties are in light orange.

Property	Category	Contribution
Composition	Primary	Both risk assessment and mitigation planning
Mass	Primary	Both risk assessment and mitigation planning
Orbit	Primary	Both risk assessment and mitigation planning
Strength	Primary	Both risk assessment and mitigation planning
Center of mass	Secondary	Mitigation planning
Rotation	Secondary	Mitigation planning
Shape	Secondary	Mitigation planning
Boulder property	Supporting	Composition and strength
Density	Supporting	Mass and strength
Photometric property	Supporting	Composition
Porosity	Supporting	Mass
Radar property	Supporting	Composition
Rubble pile /monolithic structure	Supporting	Strength
Taxonomic type	Supporting	Composition and mass
Thermal property	Supporting	Composition and mass
Volume	Supporting	Mass

The Characterization WG categorizes each contributing property, as shown in Table 1. Below, further details are provided regarding the reasoning behind the provided categories.

Primary Property

- **Composition** can contribute to both mitigation planning and risk assessment. Its measurement can be critical in assessing the type of terminal event and mitigation technologies. Identifying stony, metallic, and icy compositions can offer useful information about PD. This property has subcategorized properties: elemental composition and mineralogical composition. Spectroscopic measurements can determine surface compositions, though internal compositions are not directly available through remote sensing observations. Spectroscopy [Gaffey et al., 1993; Reddy et al., 2015; Bibring et al., 2017] and sample returns [Nakamura et al., 2022; Lauretta et al., 2024] can determine compositional variations on local scales.
- **Mass** can contribute to both mitigation planning and risk assessment. Its measurement can play a critical role in assessing the scale of a terminal event and mitigation technologies. With orbit, this property provides the target's linear momentum and kinetic energy, critical information about the scale of the terminal event and key input for selecting an appropriate mitigation technique. Accurate mass measurements apply the target's gravity [Miller et al., 2002, Watanabe et al., 2019; Scheeres et al., 2020], though constraining its mass using the surface composition (with

meteoritic constraints) and volume is a general approach if gravity measurements are unavailable [Britt and Consolmagno, 2001; Consolmagno, et al. 2008]. Measuring the Yarkovsky effect on the heliocentric orbit can also determine mass via telescopic observations if size constraints are available [Chesley et al., 2003; Chesley et al., 2014].

- **Orbit** can contribute to both mitigation planning and risk assessment. Its measurement provides the position and velocity of a target at its terminal event and before/during/after mitigation. With mass, this property gives the target's linear momentum and kinetic energy. Astrometry and in-situ orbit determination can offer accurate information about orbit. Longer observational campaigns can also determine non-gravitational effects on the target's orbit [Giorgini et al., 2002, 2008; Farnocchia and Chesley, 2014].
- **Strength** can contribute to both mitigation planning and risk assessment. This property characterizes the coherence of the target beyond gravitational self-attraction and influences the nature of a terminal event and the effectiveness of mitigation technologies. Strength is a generalized term encompassing a set of properties; limited examples are identified and listed in the Supplemental Information. Given uncertainties in the definitions that can directly contribute to PD, the Characterization WG identifies that telescopic and in-situ observations poorly measure this property. In-situ observations can constrain this property [Biele et al., 2015; O'Rourke et al., 2020; Scholten et al., 2019; Robin et al., 2024]. The Characterization WG also excludes options for performing experiments adding kinetic energies at any scale as they can accidentally increase threats [Dotson et al., 2022].

Secondary Property

- **Center of mass** can contribute to mitigation planning. Its measurement can determine the point of mitigation, improving mitigation efficiency. This parameter can be determined using rotational and gravity measurements [Miller et al., 2002]. If gravity measurement is not available, photometric imagery may constrain the center of mass because the center of mass is always along the spin axis.
- **Rotation** can contribute to mitigation planning. Its measurement can determine the best timing of mitigation and the best target location on a target [Stalter et al., 2022]. An accurately determined spin state can enable a better selection process for mitigation technologies. Telescopic observations monitoring the change in the target's brightness for optical telescopes and echos for radio telescopes can measure the spin period. Determining the spin axis through telescopic observations needs careful assessments, while in-site observations of sufficient duration can uniquely determine it.
- **Shape** can contribute to mitigation planning. This property is also referred to as topography. Its measurement can determine the efficiency of mitigation. The shape of a target location can affect the outcomes of mitigation [Feldhacker et al., 2017; Bruck Syal et al., 2016]. Its child properties include global and local shapes. Shape can be determined through various approaches. Algorithms using in-situ photometric imagery and LIDAR measurements currently provide shape models at the highest resolution and accuracy [Gaskell et al., 2023; Palmer et al., 2022; Al Asad et al., 2021; Daly et al., 2020]. Reconstruction using radar echos can also offer highly accurate shapes, though radar data quality rapidly decreases with increasing distance between the target

and the Earth [Benner et al., 2015]. Brightness changes measured by photometric telescopes and occultation measurements can constrain shape with uncertainty.

Supporting Property

- **Boulder property** supports determining composition and strength. Boulder textures, size distributions, and spectral features are related to these properties. In general, boulder property provides surface conditions only. However, the observed surface conditions may be used to infer the internal conditions, such as the existence of rubble pile structures [Barnouin et al. 2019; Daly et al. 2023; Pajola et al., 2024]. However, the connections between interiors and surfaces for the boulder size frequency distributions have been neither confirmed nor validated. Spectral signatures can determine boulders' compositions, while such signatures can contribute to strength. This property is also subcategorized into geological property and distribution.
- **Density** supports determining mass and strength. The bulk density is the most common quantity, while material density with porosity is another value used for small body studies [Flynn et al., 1999; Britt and Consolmagno, 2001; Consolmagno et al., 2008]. The most accurate approach for determining the bulk density is to determine mass and volume. The Yarkovsky effect at high accuracy can also determine density if tight conditions are met [Chesley et al., 2014]. The density value offers some insights into strength.
- **Porosity** supports determining mass. Given volume and material density, this property provides mass. No demonstrations have been made for direct measurements of this property. A classical approach is to interpret it from bulk density compared to material density.
- **Radar property** defines its supporting role in composition and topography [Virkki et al., 2014]. This quantity mainly focuses on surface/shallow subsurface layers, measurable by telescopic and instrumental observations. The property consists of two child properties: dielectric permittivity and wavelength-scale roughness.
- **Rubble pile/monolithic structure** supports determining strength. This property illustrates a target's internal structure. Classical approaches use surface morphologies to imply the internal structure [Barnouin et al. 2019; Daly et al. 2023; Pajola et al., 2024]. Direct measurements may be possible; however, technological demonstration is still necessary [Kofman et al., 2015; Hérique et al., 2018]. Future missions will test the feasibility of direct measurements [Michel et al., 2022].
- **Taxonomic type** supports determining composition and mass. This property classifies a target's surface composition. Given a measured volume and reasonable porosity, this quantity can also be used to interpret mass. Both telescopic and instrumental spectroscopy can identify the surface compositions at different resolutions.
- **Thermal property** supports determining composition and mass. This property characterizes the thermal responses of surface/shallow subsurface layers. It also correlates with the surface morphologies, such as boulder size distributions. Surface density may be used to constrain mass if volume is available. Telescopic and instrumental observations can measure this quantity [Delbo et al., 2015].
- **Volume** supports constraining mass, given the information about density. Similar to shape, in-situ photometric imagery and LIDAR measurements may achieve the most accurate measurement of this property [Benner et al., 2015; Daly et al., 2023; Palmer et al., 2022; Gaskell et al., 2023].

Radar echos can determine highly accurate volume within an allowable distance of the target from the Earth. Photometric brightness can also constrain volume with limited accuracy. Occultation measurements can also constrain this property.

2.2. Properties in Five Priority Areas

The Characterization WG identifies five priority areas for the contributing properties and rates how each property contributes to the defined priority areas. Below is the list of these five areas.

- Contributions to mitigation planning
- Contributions to risk assessment
- Ability to offer measurements and constraints given a warning time
- Advantages and limitations of using optical telescopic observations
- Advantages and limitations of using radar telescopic observations

2.2.1. Mitigation Planning

This priority area assesses how each property contributes to mitigation planning to select the most approachable mitigation technique (KI, GT, IBD, and NED) for an upcoming threat. The primary and secondary properties are ranked high or low for each mitigation technique. Rated high, a property is considered critical for the technique, giving essential information that enables the design and assessment of it. Rated low, the property is not considered critical. The rating is also low when the property needs other properties to give crucial input to mitigation planning. Table 2 compiles the ratings of the properties, including the child properties.

The ratings suggest that both primary and secondary properties offer critical information for KI, mainly coming from the recent findings from NASA/DART [Daly et al., 2023; Li et al., 2023; Thomas et al., 2023; Cheng et al., 2023; Dotto et al., 2024]. The confidence levels of the ratings of the listed properties are low for other mitigation techniques (GT, IBD, and NED). Although theoretical and numerical studies have been continuously reported for these mitigation techniques, the Characterization WG did not identify how the listed properties contribute to these mitigation techniques. Regardless of higher uncertainties for GT, IBD, and NED, mass and orbit are identified to be high for all techniques.

Table 2. Priority area rated for mitigation planning. Each row gives ratings for contributing properties (primary and secondary properties only) and their child properties if such exist.

Property	Child property	Mitigation planning rating
Composition	Elemental	KI-low; GT-low; IBD-low; NED-high
	Mineralogical	KI-high; GT-low; IBD-high; NED-high
Mass		KI-high; GT-high; IBD-high; NED-high
Orbit		KI-high; GT-high; IBD-high; NED-high
Strength		KI-high; GT-low; IBD-high; NED-high
Center of mass		KI-high; GT-high; IBD-high; NED-low
Rotation		KI-high; GT-low; IBD-high; NED-high
Shape	Global shape	KI-high; GT-low; IBD-high; NED-low
	Local shape	KI-high; GT-low; IBD-high; NED-low

2.2.2. Earth Impact Damage Risk Assessment

This area defines how critical each property is to Earth impact damage risk assessment. It depicts each property's contribution by evaluating the scale, type, location, and timing of a terminal event on the Earth. This priority area only considers the primary and secondary properties. Rated high, each property is considered critical for risk assessment. Otherwise, the property is ranked low. Table 3 compiles the ratings of the primary and secondary properties for risk assessment.

Composition (except for elemental composition), mass, orbit, and strength are rated high, given their contributions to assessing the scale, type, location, and timing of a terminal event. The types of terminal events depend on composition and strength. How easily the target is disrupted in the Earth's atmosphere changes the outcomes. If the target is disrupted due to its low strength that cannot resist high aerodynamic pressure, it explodes and produces shock waves that are strong enough to reach the ground and cause non-negligible damage [Aftosmis et al., 2019]. Otherwise, the remnant reaches the ground, causing a hypervelocity impact. Mass and orbit determine linear momentum and kinetic energy, which is critical information about the scale of the terminal event. Orbit also offers the timing and location of the terminal event.

Any secondary properties are found to be less influential on risk assessment (also see Table 1). While these properties do not offer direct information about how easily the target's disruption occurs in the Earth's atmosphere, they may improve the accuracy of risk assessment. However, the lack of studies causes limited insights into their contributions to the terminal event.

Table 3. Priority area rated for Earth impact damage risk assessment. Each row gives ratings for contributing properties (primary and secondary properties only) and their child properties if they exist.

Property	Child property	Risk assessment rating
Composition	Elemental	Low
	Mineralogical	High
Mass		High
Orbit		High
Strength		High
Center of mass		Low
Rotation		Low
Shape	Global shape	Low
	Local shape	Low

2.2.3. Warning Time

This area defines a priority related to warning time, the timespan between threat detection and a terminal event. It rates how quickly the property can be measured or constrained for PD. There are four timescales.

- Shortest: Telescopic observations are enough to measure a contributing property.
- Shorter: Flyby operations are enough to measure a contributing property.
- Longer: Rendezvous operations are enough to measure a contributing property.

- Longest: Lander operations on top of rendezvous operations are enough to measure a contributing property.
- Unavailable: Neither measurements nor constraints are available.

The Characterization WG identifies that sample returns are useful in measuring or constraining contributing properties. The present scope, however, is to identify contributing properties during rapid reconnaissance, while sample returns likely require a much longer timescale. This report excludes sample returns from consideration. Table 3 shows the ratings of the listed properties, given the above metrics. Table 4 lists the types of in-situ observations if a property needs to be measured or constrained. For many properties, the ratings in this area focus on their surface conditions. If the internal conditions are in scope, they are unavailable. Such properties include composition, shape, radar property, taxonomic type, and thermal property.

Properties measurable by telescopic observations are identified to be measured on the shortest timescale. However, telescopic observations do not usually offer properties at high spatial resolution, except that radar telescopic observations can do so if the target is close to the Earth. Contributing properties are rated longer if their spatial distribution is preferred or necessary, as in-situ observations are suitable for obtaining them at high resolution. The Characterization WG concludes that strength is unavailable for its measurement. Its constraint may be available as soon as a shorter timescale.

Mass can be constrained, given measurements of (or constraints on) volume and composition. Composition and assumed porosity can offer the bulk density, thus constraining mass. In classical approaches, mass measurement requires gravity measurement, while recent efforts have attempted to assess its feasibility during fast flyby [Bull et al., 2021]. An approach measuring the Yarkovsky drift demonstrated its capability of measuring mass (and bulk density) at high accuracy. This approach only needs telescopic observations [Chesley et al., 2014]. Mass and density measurements may be the shortest if this approach is available. However, the approach needs further validation to quantify how it can robustly be applied to hazardous objects.

Table 3. Priority area rated for timescale. The third column gives the timescale necessary to obtain proper property measurements, while the fourth column offers that to acquire constraints on each property. Shape may be measurable by radar telescopic observations if a target approaches the Earth closely enough during earlier apparitions.

Property	Child property	Timescale (Measurement)	Timescale (Constraint)
Composition	Elemental	Shortest-longer	Shortest
	Mineralogical	Shortest-longer	Shortest
Mass		Shortest-longer	Shortest
Orbit		Shortest	Shortest
Strength		Unavailable	Shorter-longest
Center of mass		Longer	Shortest
Rotation		Shortest	Shortest
Shape	Global shape	Shortest-longer	Shortest
	Local shape	Longer	Shorter
Boulder property		Longest	Shorter
Density		Shortest-longer	Shortest

Photometric property		Shortest	Shortest
Porosity		Longest	Longer
Radar property	Dielectric permittivity	Shortest-longer	Shortest
	Wavelength-scale roughness	Shortest-longer	Shortest
Rubble pile/monolithic		Longer	Shorter-longer
Taxonomic type		Shortest-longer	Shortest
Thermal property		Shortest-longer	Shortest
Volume		Longer	Shortest

*Table 4. Type of in-situ observation. The third column gives the types of in-situ observations for a designated property. Those measurable within the shortest warning time are not discussed in this table. The listed types are examples, and there are affordable approaches other than those listed. A type with * (asterisk) means sufficient flight demonstrations are necessary even if the warning time is the longest.*

Property	Child property	Type of in-situ observation
Composition	Elemental	Spectroscopy
	Mineralogical	Spectroscopy
Mass		Gravity
Orbit		[-]
Strength		[-]
Center of mass		Gravity, dynamics
Rotation		[-]
Shape	Global shape	3D reconstruction using images, LIDAR
	Local shape	3D reconstruction using images, LIDAR
Boulder property		Imaging, spectrometry
Density		Gravity
Photometric property		Spectrophotometry
Porosity		In-situ radar measurement*, gravity measurement
Radar property	Dielectric permittivity	[-]
	Wavelength-scale roughness	[-]
Rubble pile/monolithic		In-situ radar measurement*, gravity measurement
Taxonomic type		Spectroscopy
Thermal property		Imaging, spectroscopy
Volume		3D reconstruction using images, LIDAR

2.2.4. Optical Telescopic Observations

Below are the feasibility metrics for the contributions of optical telescopic observations to getting information about the contributing properties. This area particularly covers telescopic observations that detect signatures at any wavelengths, mainly originating from reflection and re-emission of sunlight, in contrast to radar telescopic observations using power generated by observers. Table 5 lists the ratings of the contributing properties for this area.

- High – Optical telescopic observations can measure a contributing property.
- Medium – Optical telescopic observations can constrain a contributing property.
- Low – Telescopic measurements can neither constrain nor measure a contributing property.

Orbit can be measured with high confidence. If higher resolution is necessary, the property is rated medium. Mass is rated medium-high. If an approach using the Yarkovsky drift is available, mass is rated high, though it may need radar telescopic observations. Otherwise, volume and composition can only constrain this property, leading to a medium rate. Occultations offer orbit determination at high accuracy and constrain volume and shape. Better measurements of volume and shape need a large campaign of occultation [Hilton, 2002; Buie et al., 2020; Arimatsu et al., 2024].

Strength is rated medium. A higher spin rate with a roughly constrained shape can offer a lower limit of cohesive strength, a parameter related to strength. However, the derived cohesive strengths may be much lower than the actual value, particularly when a target object with 50-100 m in diameter is monolithic [Hirabayashi and Scheeres, 2019]. The Characterization WG concludes that this technique may not adequately constrain the range of the strength level sufficiently for mitigation planning and Earth impact damage risk assessment. Center of mass is rated medium, given that observing a rotation mode constrains the center of mass in 3D space. Density can be constrained given taxonomic type and (the knowledge of) porosity. This constraint can be tighter if high-resolution measurements of composition, mass, and volume are available. Performing lightcurve observations can measure rotation at high accuracy and constrain shape. Lightcurve data can be used to reconstruct a shape, but this approach encounters challenges in characterizing the concavity of detailed shapes [Kaasalainen and Torppa, 2001]; however, recent efforts improve this issue, which enables a better reconstruction of shape [Bartczak and Dudziński, 2018].

Table 5. Priority area ranked for telescopic observations excluding radar telescopic observations. The third column is the feasibility metrics, and the fourth column shows a limited list of telescopic types. The type of Imaging means optical telescopic observations at a single band or multiple bands to measure brightness and its variations over time.

Property	Child property	Feasibility	Type of observation
Composition	Elemental	Medium-high	Spectroscopy
	Mineralogical	Medium-high	Spectroscopy
Mass		Medium-high	[-]
Orbit		High	Imaging, occultation
Strength		Low	[-]
Center of mass		Medium	Imaging
Rotation		High	Imaging
Shape	Global topography	Medium	Imaging, occultation
	Local topography	Low	[-]
Boulder property		Low	[-]
Density		Medium	Imaging
Photometric property		High	Imaging
Porosity		Low	[-]
Radar property	Dielectric permittivity	Medium-high	[-]
	Wavelength-scale	Medium-high	[-]

	roughness		
Rubble pile/monolithic		Low	[-]
Taxonomic type		Medium-high	Spectroscopy
Thermal property		Medium-high	Spectroscopy
Volume		Medium	Imaging

2.2.5. Radar Telescopic Observations

This area discusses the priority for radar telescopic observations. Below are the feasibility metrics for this area.

- High – Radar telescopic observations can measure a contributing property.
- Medium – Radar telescopic observations can constrain a contributing property.
- Low – Radar telescopic observation can neither measure nor constrain a contributing property.

This priority is only for ground radar telescopic observations, not including radar instruments for spacecraft. The Supplemental Information discusses a brief description of the difference between radar telescopic and in-situ radar observations. The Characterization WG finds limitations and advantages of radar telescopic observations. While radar telescopic observations are only available for short distances and time, they can be far more likely to be useful during earlier apparitions. Table 6 shows the ratings of the contributing properties for this area.

Radar telescopic observations can significantly improve the uncertainty of orbit. Rotation is also rated high. Radar telescopic observations are the only telescopic technique for accurately measuring the shape of a target asteroid at high spatial resolution. This approach's strength is in characterizing detailed and complex topographic geometries. One caveat of using radar telescopic observations is that a target must be closer to radar telescopes, i.e., the Earth. However, this issue may be resolved if it approaches the Earth at earlier apparitions multiple times before its terminal event.

Table 6. Priority area ranked for radar telescopic observations. The third column is the feasibility metrics.

Property	Child property	Feasibility
Composition	Elemental	Low
	Mineralogical	Low
Mass		Low
Orbit		High
Strength		Low
Center of mass		Low
Rotation		High
Shape	Global topography	High
	Local topography	Low
Boulder property		High
Density		Low
Photometric property		Low
Porosity		Low
Radar property	Dielectric permittivity	High
	Wavelength-scale roughness	High

Rubble pile/monolithic		Low
Taxonomic type		Low
Thermal property		Low
Volume		High

2.3. Findings and Recommendations

The final part of Characterization offers the WG's findings and recommendations based on the earlier discussions.

<u>Findings</u>

- Quantifying how the contributing properties for PD affect both mitigation planning and risk assessment is still challenging, with limited data availability. How the uncertainty of each property changes the outcomes of mitigation planning and risk assessment is largely uncertain.
- The recent success of NASA's DART impact on the target asteroid Dimorphos provided key breakthroughs in quantifying how the contributing asteroid properties can offer insights into kinetic impactor deflection performance. However, the ratings of asteroid properties for GT, IBD, and NED are at a lower confidence level due to the lack of knowledge about how they contribute to these mitigation techniques.
- Composition, mass, orbit, and strength are identified to be primary. Center of mass, rotation, and shape are found to be secondary. Other properties are found to support either primary or secondary properties.
- Mass measurement at high accuracy is identified to be critical. In-situ mass measurement techniques may encounter challenges when a target's size becomes small because gravity measurement needs higher accuracy to detect small gravity. An approach that uses telescopic observations to determine the Yarkovsky effect demonstrated mass measurements at high accuracy. This approach, however, needs further tests to ensure its robustness.
- There is no universal and uniquely observable quantity for strength. Computer simulation and laboratory work have been performed regarding the effects of certain strength parameters on threat mitigation models.
- Density, porosity, and rubble pile/monolithic structure are supporting properties that do not have rigorous measurement techniques. Gravity and in-situ radar measurements are identified to measure their properties but do not offer unique solutions for heterogeneous distributions. In-situ radar measurements also do not have enough demonstrations for robustness.

<u>Recommendations</u>

- Studies should build quantitative knowledge about how the contributing properties influence mitigating planning and risk assessment in a wider space of the contributing parameters and reduce the uncertainties of their influences on PD.
- Further investigations for mitigation planning are urgently necessary to quantify how the contributing properties influence the outcomes of these mitigation techniques.

- Future efforts should establish robust measurement techniques for the mass of a target object with 50 m – 100 m in diameter.
- Measurement techniques to characterize a target body's internal structure (density, porosity, and rubble pile/monolithic structure) should be improved to robustly and uniquely measure these properties.
- Future efforts should formulate and quantify strength-related properties that can offer unified meanings. Comprehensive analysis should understand the importance of the full range of strength parameters and models, their effects on a broader set of mitigation scenarios, and their ability to be implemented for Earth impact damage risk assessment and mitigation planning.

2.4. Supplemental Information

This section provides supplemental information for the above discussions.

- A terminal event in this report considers two types of terminal events: airburst in the atmosphere and impact on the ground. Airburst creates shock waves in the atmosphere when a target is disrupted due to high aerodynamic strength [Dotson et al., 2024]. If strong enough, the shock waves reach the ground, causing damage. An impact occurs when the target's body survives without complete disruption in the atmosphere. Under this definition, if the goal of mitigation is to disrupt the target and allow it to collide with Earth as smaller remnants, causing negligible impacts, they are not part of a terminal event.
- Strength is the property that holds a wide range of meanings, which may also change interpretations, depending on the use. The Characterization WG identifies representative child properties but decides not to list them because many related property candidates exist. The identified parameters related to strength are but not limited to friction, cohesion, damage, fragility, degree to which material has been shocked, and hardness.
- The capability of radar measurements generally depends on wavelengths. Shorter wavelengths, which are more used by ground radar telescopes, have the advantage of characterizing top-surface conditions, contributing to measuring orbit, shape, and rotation, but not significantly to composition. On the other hand, longer wavelengths, which tend to be applied to spacecraft instruments, are preferable for use in characterizing subsurface regions. Recent efforts predict the capability of both short- and long-wavelength measurements to detail surface compositional features.

3. Guidance, Navigation, and Control & Mission / Campaign Design

Planetary defense reconnaissance missions to NEOs will, like all robotic interplanetary missions, have a particular set of performance requirements in multiple domains, including guidance, navigation, and control. Additionally, the ability of reconnaissance missions to be deployed rapidly and effectively will be predicated on having identified sufficiently performant strategies for designing both individual reconnaissance spacecraft missions and campaigns of multiple reconnaissance spacecraft missions. In this section, we treat the topics of mission / campaign design and guidance, navigation, and control in turn. Within each topic, we discuss avenues for improving the state of the art and closing knowledge and capability gaps, aiming towards future operational rapid response NEO reconnaissance capabilities.

3.1 Mission / Campaign Design Studies

Reconnaissance missions for planetary defense represent a unique class of mission with distinct requirements, constraints, and risk posture from past missions to NEOs and other small bodies with a primary purpose of scientific exploration. The design of a single mission or a campaign of multiple missions to reconnoiter a potentially hazardous asteroid must deliver required measurements to planetary defense analysis processes and mission design efforts that will ultimately inform decision makers. Additionally, rapid response missions must be capable of launch readiness within the potentially short time-frame between initial detection and the opening of favorable launch periods. Given the unique nature of these considerations, mission and campaign design studies are needed to inform preparations and planning for rapid response NEO reconnaissance.

3.1.1 Studying In-Space vs. Ground Staging of Reconnaissance Spacecraft Systems

Goal 3 of the National Preparedness Strategy and Action Plan for Near Earth Object Hazards and Planetary Defense outlines objectives for rapid response of reconnaissance, deflection, and disruption missions, with Goal 3.1 specifying the need to evaluate capabilities for short-warning planetary defense scenarios [National Science & Technology Council, 2023]. Pre-staging (ground or space based) satellites could reduce the lengthy developmental phase before mission launch in a time sensitive scenario to increase possible early reconnaissance flyby, rendezvous, or deflection opportunities. We recommend a study to compare the cost, benefit, and response time with the probability of a successful reconnoiter & deflection/disruption of an NEO for both ground and space based staging systems by completing the following objectives:

1. Determine current/future capabilities and define performance metrics associated with the staging systems' cost success and improvements over non staged missions.
   Analysis and metrics should be defined in a way that can be applied to both current and future capabilities with regards to launch and propulsion. Technological gaps that increase success probability for each system should be identified.
2. Define the possible ground staging architectures that could be utilized and its associated time to launch / costs.
   Ground staging could include a lively planetary exploration program progressing at a steady pace and an active commercial space environment, both of which could have sufficient spare hardware in stock or in continuous production, broad expertise and well-practiced AIV personnel and facilities, pre-fabricated satellites in storage, and possibly even a stacked satellite/launch vehicle on the pad at multiple locations. Feasibility, cost, and time to launch should be analyzed for this continuum of systems.
3. Determine the cost to performance of a space-staged architecture.
   The orbit characteristics for a space based staged satellite or constellation of satellites should be defined to increase the probability of successful intercept over a wide range of NEO trajectories. Perform an analysis to determine the cost to success probability against a comprehensive set of possible impact trajectories.
4. Compare ground and space based systems.

Identify the advantages/disadvantages and use cases for each system. Define and compare the initial and recurring costs as well as expected lifetime.

5. Perform mission design study.
   Compare a non-staged mission design with ground and space based staging concepts to find cost to benefit of both systems.

This study should generate both ground and space based staged systems designs, and their respective costs / performance should be evaluated in the context of a reference mission design concept for a pre-defined scenario (e.g., U.S. government TTXs and PDC Hypothetical Asteroid Impact Threat Scenarios), comparing with a non staged design to determine increases in flyby, rendezvous, or mitigation opportunities.

3.1.2 Studying Distributed vs. Monolithic Architectures for Reconnaissance

Goal 3.1 of the U.S. National Preparedness Strategy and Action Plan for NEO Hazards and Planetary Defense calls for "evaluation of dedicated reconnaissance via spacecraft flyby or rendezvous" [National Science & Technology Council, 2023]. Multi-satellite architectures have the potential to enhance both the probability of success as well as the information return of flyby or rendezvous missions. Emerging technologies from the commercial sector are enabling and enhancing the capabilities of commercial off the shelf hardware for multi-satellite missions. Evaluating the potential benefits, costs, and complexities of multi-satellite architectures supports Objective 3.1 by ensuring rapid reconnaissance missions maximize both the probability of success and information return from a crucial early encounter with a potentially hazardous asteroid.

This task consists of mission design studies comparing monolithic and distributed rapid reconnaissance mission architectures. The study shall:

1. Identify multi-point measurement techniques and/or observation campaigns applicable to both fast-flyby and rendezvous rapid reconnaissance missions.
   Consider scenarios where multiple spacecraft carry the same payload, offering different observation geometries, as well as scenarios where each spacecraft carries different payload(s). Identify key requirements concerning encounter geometry, relative trajectory, navigation accuracy, inter-satellite communication, and time synchronization.
2. Develop reference mission designs for both fast-flyby and rendezvous rapid reconnaissance missions using a distributed architecture.
   Include scenarios where multiple similar spacecraft are co-manifested on a single launch, separating immediately after orbit insertion, as well as scenarios where a single spacecraft carries multiple dissimilar sub-satellites that are deployed prior to fast-flyby encounter or after propulsive rendezvous maneuvers. Address key requirements identified in step 1.
3. Evaluate the probability of success for distributed architectures in comparison to traditional, monolithic architectures.
   Identify key redundancies and points of failure to determine the extent to which distributed architectures improve the probability of mission success. Make summary recommendations based on this result and the overall cost/complexity of mission concepts surveyed.

The results of this study would include documentation of the mission concepts studied and recommendations regarding the inclusion of distributed architectures in rapid reconnaissance mission planning.

3.2 Guidance, Navigation, and Control (GNC) Hardware Technology

While our recommendations regarding GNC techniques hardware technology are oriented towards supporting National Plan / NASA Plan Goals 3.1 and 3.2, we note that some of our recommended efforts would utilize NEO modeling capabilities from within efforts related to Goal 2 and there is the possibility that contributions to Goal 2 efforts could arise serendipitously. Similarly, any international collaborations undertaken in the performance of our recommended efforts could result in serendipitous contributions to Goal 4.

3.2.1 Ascertaining the Current State of the Art in Asteroid Flyby Capabilities

In the latest Decadal Survey, a rapid response flyby mission to characterize a potentially hazardous asteroid was deemed a high priority in the area of planetary defense [National Academies of Sciences, Engineering, and Medicine, 2023]. The flyby option was the preferred initial choice due to generally being capable of reaching an NEO sooner than a rendezvous mission, making it more likely to be able to access a recently identified PHA for reconnaissance. The purpose of the flyby mission would be to assess the physical characteristics of the asteroid, such as size, shape, mass, composition, morphology (among others), as well as refine estimates of its orbit to precisely determine if and where the asteroid would impact. The ability to acquire the desired data is challenging due to the sizes of the asteroids in question (50 – 100m), as well as the flyby velocities (100s of m/s to many km/s).

The question arises as to whether our current capabilities are sufficient to handle the needs of flyby missions for planetary defense. In order to properly answer the question, we must first generate a historical perspective on the problem. Space agencies around the world have collectively flown close to 20 flybys of small bodies, beginning with the European and Soviet encounter of Halley's comet in 1986; the most recent was NASA's Lucy mission which flew by asteroid Dinkinesh in 2023. These flybys have been over a wide range of body sizes, flyby velocities, and distances, and with various spacecraft capabilities and concepts of operations to successfully execute the flybys. Thus, there is a wealth of historical information to draw from to see what data was gathered from these encounters, inventory the available heritage technology that enabled these flybys, and identify lessons learned regarding what worked well, what could be improved, and whether we currently have capability gaps for planetary defense flyby missions that should be addressed. We therefore propose conducting a study to ascertain the current state of the art in asteroid flyby capabilities.

The goals of the proposed study are threefold: 1) analyze the complete range of parameters the reconnaissance mission would need to handle (e.g., flyby velocities, phase angles, distances, asteroid sizes, etc.), 2) mine data from all past small body flyby missions to assess how existing capabilities are or are not sufficient to handle the set of parameters identified in #1, and 3) identify any potential gaps in technology (hardware, software, algorithms) and/or techniques (e.g, onboard vs ground-in-the-loop conops) between current and needed capabilities. For item #3, the study will include determining what stage any new technologies/capabilities are in (e.g., almost there with minor improvements vs. early TRL and lots of investment to mature for flight readiness).

3.2.2 Advancing Sensors and Instruments

The GNC system for a reconnaissance mission - whether a flyby or rendezvous - relies on the capabilities of the on-board sensor packages to successfully execute the mission. Unlike for payload-maximized planetary science missions, the set of instruments may be reduced or/and limited in size based on mission level constraints. These restrictions are likely to lead to shared use of sensors and instruments for GNC and characterization observations, a desire to choose small low SWAPC instruments, and the need to choose readily available instruments to prevent long procurement. Based on these system drivers, as well as the need to respond to physical constraints that may be present in a fast reconnaissance mission (e.g. extreme phase angles in fast fly-by, short viewing windows etc) we find that the following areas of investment could greatly enhance the GNC capabilities for such missions:

- Small gimbaled instrument platforms for tracking during fast flyby with low altitude to enable high precision, and also for spacecraft with high inertia e.g. due to large solar panels for electric propulsion in rendezvous
- High-resolution IR imagers to improve information return from high phase angle observations
- Development and demonstration of deployable instruments/platforms for mass measurements during fast flybys or for improved coverage during rendezvous. Rendezvous missions may present opportunities for sample return during long warning time scenarios.
- Development of low SWAPC high precision ranging instruments for ranging to asteroid(s) and between multiple spacecraft platforms
- On-instrument data processing capabilities to enable autonomous operations

3.2.3 Improving Onboard Computation

NEO reconnaissance missions could greatly benefit from increased on-board computation capabilities. Fast flyby or time critical rendezvous missions have time pressure that can be primarily addressed through increased autonomy (as discussed elsewhere in this report). In order to support the needs of such autonomous missions, on-board computation must be increased. Even in cases where there are no time-critical constraints, there are operational and budgetary benefits to decreasing DSN usage by doing more processing on-board. Many autonomy algorithms have been developed by the community that can’t run in real time on current spacecraft processors which are orders of magnitude slower than terrestrial systems that use similar algorithms (such as autonomous cars and drones). To enable GNC use of sensor data, on-board processing of such data will be necessary, including computation hungry sensor fusion capabilities. The variety of tasks that will be run on-board include data manipulation to produce derived products like a shape model, orbit determination and navigation, flight path control or trajectory optimization, anti-collision autonomy, and station-keeping control. These tasks require two types of computation: radiation hardened processors that can operate through single-upsets for real-time critical operations, and radiation resilient computing that will safely survive but does not need to operate continuously through single-event upsets. Therefore there will also be a need to operate multiple computers of various designs in parallel with communication across the entire architecture.

4. Mitigation Modeling / Earth Impact Effects

Models of mitigation methods and Earth impact effects are used during planetary defense scenarios to support a variety of decisions and planning activities. Models of mitigation methods are essential inputs to the design and selection of mitigation missions. Models of Earth impact effects support decisions to commit to missions (reconnaissance and/or mitigation). In addition, Earth impact effects models can, if needed, provide actionable inputs to emergency response plans. While the utility of these models for decision support and planning activities depends on the maturity and demonstrated validity of the models – another limiting factor is the accuracy of the inputs to these models for a specific scenario. The general expectation of a planetary defense reconnaissance mission, rapid or otherwise, is that it will characterize aspects of the approaching asteroid that could not be measured using available telescopic observations and significantly reduce the uncertainties of key inputs to mitigation and Earth impact effect models. The features deemed vital for any mitigation or outcome assessment are trajectory, size, mass, and material response.

Trajectory

The asteroid's trajectory has a clear effect on both mitigation modeling and Earth impact effects. For mitigation modeling, it determines the velocity that needs to be applied to the asteroid in order to deflect it. For Earth impact effects, the trajectory determines the impact location, which plays an obvious role in how many people are affected and by what hazards. In addition, the entry speed and angle can play a role in the magnitude of the hazard.

Size

Asteroid size is easier to measure than many other parameters by a wide variety of mission profiles. Asteroid size can be leveraged to estimate asteroid mass. In addition, size and shape (e.g., how elongated, contact binary or not, rubble pile or not) can also affect response to a mitigation attempt and penetration into the atmosphere/ground impact.

Mass

The mass of an asteroid is directly correlated with the momentum required to deflect it as well as the hazards associated with atmospheric entry and impact.

Material Response / Cohesive Strength

The response of the asteroid to a force (whether imparted by a mitigation technique or the Earth's atmosphere) can play a major role in mitigation and Earth impact effects models. The cohesive strength of the asteroid plays a major role in the deflection efficacy of a kinetic impactor and may affect Earth impacts and disruption missions as well. For instance, for kinetic impacts, varying the cohesive strength can be the difference between deflection and disruption, and the momentum enhancement factor, $\boldsymbol{\beta}$, can vary by more than a factor of 2.

4.1 Towards Reconnaissance Mission Requirements for Mitigation and Earth Impact Effects Modeling

The more precisely the key properties are known, the less uncertainty will remain in the results from mitigation and Earth impact models -- and less uncertainty in model results can support more robust decisions. This reasoning leads to the conclusion that mitigation and Earth impact effects modeling require measurements from reconnaissance missions with the highest precision possible. However, in practice, it is preferable to know how precise a measurement is required from a reconnaissance mission to enable models that can support specific decisions. The forward work required to enable determination of reconnaissance mission requirements to support decisions falls into three categories: modeling improvements, model sensitivity studies, and identifying precision thresholds required for decision support.

4.1.1 Modeling Improvements

The majority of models for mitigation and Earth impact effects are relatively mature and have been utilized to support numerous planetary defense exercises. While these models largely represent the state of the art, they have room for improvement and require regular maintenance to ensure they are available when needed. The following areas would benefit from focused development.

- Cascading Hazards: Robust models of the follow-on effects (e.g. downstream and downwind effects) of asteroid impacts are currently under development. Substantial forward work is required to mature the models of cascading hazards sufficiently to enable decision support and disaster planning.
- Tsunami modeling: Modeling improvements are needed in order to reflect the range of asteroid impact-driven tsunami hazards, including airwave-driven tsunamis. In addition to improving the high fidelity tsunami models, the development of a fast-running tsunami model that incorporates the range of effects and the range of shoreline geography is an outstanding task.
- Disruption modeling: An asteroid could be disrupted accidentally or on purpose by a mitigation mission. The thresholds that can be used to identify when disruption would occur is an area of active study. Furthermore, the hazard due to a disrupted asteroid is not fully understood.

4.1.2 Sensitivity Studies

In order to determine how precise a measurement is required to enable evaluation relative to a decision threshold, it’s essential to understand how sensitive the model outputs are to input uncertainties. Past planetary defense exercises have enabled the community to develop intuition about these sensitivities, but detailed sensitivity assessments take significant time and effort. The goal of these sensitivity studies is to develop data-driven rules of thumb to inform how precise a measurement is required by reconnaissance missions.

- Risk Assessment Sensitivity: How does the level of uncertainty resulting from a risk assessment vary as there are improvements in knowledge about the asteroid?

- Hazard models: How does the range of results produced by high fidelity hazard models (including blast, thermal, tsunami, cascading, and global effects) vary as knowledge about the asteroid improves?
- Mitigation methods: How does the range of outcomes of mitigation missions of all varieties (including kinetic impactor, nuclear explosive device, ion beam deflection, etc) vary as knowledge about the asteroid improves?

4.1.3 Thresholds for Decision Support

Determining the thresholds required to support various decisions is an interdisciplinary task, requiring input by a wide variety of experts including mission designers and emergency managers (in addition to modelers). There are two components to this work: determining what metrics are most informative for what decisions, and establishing thresholds based on those metrics. There is significant forward work to be pursued in both areas.

5. Spacecraft Design, Integration & Test / Rapid Response Launch

We divide this topic into two parts: considerations for the Reconnaissance Spacecraft and considerations for the Mitigation Spacecraft. We acknowledge that there will be major overlap between studies of these vehicles. We will present various options for study and comment by the Planetary Defense Community related to Rapid Response scenarios.

5.1 Reconnaissance Spacecraft

Because our group was tasked with "Rapid Response Launch" scenarios, we have concentrated on fly-by missions. We acknowledge that a rendezvous mission will always yield more information about the target, but a rendezvous typically requires a longer lead-time to achieve orbit that is not always going to be available for every scenario, whereas a fly-by is achievable in a much larger fraction of short-warning-time scenarios. We will discuss a combined rendezvous-mitigation scenario at the end of this report.

The major goal of the Reconnaissance Spacecraft is to precisely determine the position of the threat in its orbit to determine if the object will strike the Earth. Given that the spacecraft will be launched when the threat exceeds some pre-determined level (5% - 10% probability of impact), in the majority of cases the spacecraft will determine that the object will not impact the Earth. Thus, no further special effort will be required.

If the object is on a collision course with Earth, then it is desirable to use the Reconnaissance Spacecraft to determine as much information as possible about the threat. Four important characteristics needed to plan a mitigation mission are a shape model, mass, composition and spin state of the object. Other than composition, these characteristics are not necessarily fully achievable during a fly-by mission. Their determination will depend critically on the speed of the fly-by, the phase angle, the distance of the encounter from the Sun, the rotation rate and the size, shape and albedo of the target.

We suggest as a guiding principle that the Reconnaissance Spacecraft be kept as simple as possible, with a minimal instrument complement and maximum fuel capacity. This will keep the spacecraft down to a minimum dry mass with an option to top off the propellant tanks to achieve the widest range of possible reconnaissance scenarios envisioned using a range of launch vehicles. **We recommend that a study to define such a minimal payload be supported by the Planetary Defense community**.

Another aspect of Rapid Reconnaissance is the time required from Authorization to Proceed (AtP) with a reconnaissance mission to the time the mission arrives at the target. There are three basic readiness levels to consider.

1. Do nothing until a threat is detected at a specified impact probability.
2. Design and review (at the PDR level) a reconnaissance spacecraft and update this design on a regular cadence.
3. Build and store one or more spacecraft prior to need. These could be stored either on the ground or at some location(s) in space. Note that conducting trade studies to compare performance between storing on the ground or storing in space are recommended in section 3.1.1.

Readiness level 1 allows the inclusion of advances in new off the shelf spacecraft designs enabling more rapid procurement of spacecraft, including integration and testing. Standardization as an enabler for rapid design and implementation may facilitate rapid response. Recent demonstrations of rapid launch by the DoD and launch partners like Firefly demonstrate the feasibility of this approach. Recognition of the need for streamlining processes in things like licensing and compliance (e.g., National Information Technology Agency (NITA), Federal Communications Commission (FCC), Federal Aviation Administration (FAA), National Environmental Policy Act (NEPA), etc.) may also result in improvements in rapid response.

Readiness level 2 allows careful design and thorough community review of the Reconnaissance Spacecraft that takes into account all recent advances in spacecraft components and instruments. Updating this design on a regular cadence is reasonably inexpensive and could result in the least obsolescent spacecraft design possible. Procurement of parts, build and test could begin immediately following AtP.

Readiness level 3 allows deployment of a functional Reconnaissance Spacecraft rapidly after AtP. We consider two potential storage options and their potential advantages and flaws.

Storage in Space

The major advantage of a functioning Reconnaissance Spacecraft stored at some location in space is that it can be deployed to a potential threat immediately upon AtP and the community does not need to be concerned with the availability of a suitable launch vehicle. A disadvantage is that the spacecraft cannot use the capabilities of a launch vehicle to enable a shorter flight time to the target. Since the spacecraft is stored in the harsh space environment, there will inevitably be some system degradation due to space exposure. A final disadvantage of in space storage is the difficulty of providing regular system testing and maintenance that could result in extending the useful life of the spacecraft.

Storage on the Ground

The major disadvantage of ground storage is the time required to get the Reconnaissance Spacecraft into space. A launch opportunity must be secured, the spacecraft must be integrated and tested prior to storage, and there is some risk that the launch does not go as expected and the spacecraft cannot reach the target. An additional one or two identical, redundant spacecraft could mitigate the potential launch failure or instrument malfunction. The advantage of ground storage is that the spacecraft remains in a benign environment where regular testing and maintenance can keep the vehicle in excellent condition. Regular updates of flight hardware and instruments can keep the spacecraft at the state-of-the-art.

Until a threat appears, we cannot predict the importance of rapid reconnaissance. However, we can study the time required under each of the scenarios above to respond to a threat after AtP. **We suggest a study to determine the time required for each of these options to deliver a complete payload to a specific, likely threat, where each method is required to have the same probability of mission success. For option 3, a separate study of the benefits and problems with space vs. ground storage options is also required.** The time-period would begin when the threat reaches the level that triggers the AtP and ends on the arrival of the payload to do the threat assessment.

We suggest a study comparing the past 5 years, and the past year to examine what launch opportunities could be requisitioned at any given time in an emergency and how that distribution is likely to change in the future (next decade?). Are any new policies required to ensure that a launch vehicle would always be available within a specific time such as a month's notice?

In order to understand the required capabilities of the Reconnaissance spacecraft, we suggest a population study to determine both the most likely (and the most extreme) mission requirements:

- Create a synthetic population of impactors by reverse propagating Earth-impacting trajectories (some work on this has already been done).
- Simulate observations by Earth-based telescopes including the Vera C. Rubin Observatory (VRO) / Large Synoptic Survey Telescope (LSST), Pan-STARRS, NEO Surveyor, and possibly the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST) and to create statistics of detectability of the population of synthetic impactors (attribute a reasonable range of different absolute magnitudes to the impactors)
- Generate trajectories post-detection to determine the following requirements:
    - Time from detection to necessary launch to drive schedule/architecture
    - Earth-distance from flyby to drive comm system
    - Sun-distance from flyby to drive power system (likely 1 AU)
    - Minimum and maximum distance from the sun to drive power/thermal system
    - Delta-v requirements to drive propulsion system

With this data, we could draw conclusions about required flight system attributes in order to successfully perform flyby reconnoiter of TBD% of simulated impactors.

5.2 Mitigation Spacecraft

The primary purpose of the Mitigation Spacecraft is to move the threat along its orbit such that it will no longer impact the Earth. There have been many suggestions for mechanisms to achieve this goal, including the use of gravity tractors, ion beams, and lasers. However, since we are concerned with short warning time scenarios, only Kinetic Impactors (KIs) or Nuclear Explosive Devices (NEDs) are considered here.

As with the Reconnaissance Spacecraft, three levels of preparation are considered:

1. Do nothing until a threat is identified.
2. Design a KI Spacecraft, a NED Spacecraft, and/or a Hybrid Spacecraft.
3. Design, build and test KI, NED or Hybrid Spacecraft and warehouse them until needed.

The advantage of **Option 1** is that once the threat and the impact timescale are identified, the spacecraft built to carry out the mitigation can be designed for that specific threat rather than for some generic threat. We will know if a NED is required or if a KI will work and we can make a reasonable estimate if two or more copies of the Mitigation Spacecraft will be required.

Option 2 allows for the optimization of specific spacecraft design either as a KI, a NED carrier, or a simple Hybrid. A Hybrid could carry a NED, but might also be equipped to carry extra mass in specific unit increments depending on the intercept trajectory to maximize KI effectiveness.

Option 3 requires ground storage of the Mitigation Spacecraft. The NED cannot be stored in space due to international treaty obligations regarding nuclear weapons. In addition, NASA is neither trained nor authorized to control NEDs. In this scenario, the Mitigation Spacecraft would be warehoused without the NED. The NED would be integrated into the spacecraft at the launch site by NNSA personnel at the same time as the spacecraft is integrated with the launch vehicle. While a KI spacecraft might potentially be stored in orbit, such storage would preclude use of the launch vehicle to maximize the intercept velocity of the KI vehicle with the threat.

As with the case of the Reconnaissance Spacecraft, we suggest that a study be conducted to estimate the time required to launch a Mitigation Spacecraft starting after AtP for each of the three readiness levels.

For Long Warning Times:

If a threat is identified where we have several decades prior to impact, then mitigation options other than KI or NED could be viable. Rendezvous Spacecraft are then the preferable choice for both reconnaissance and NED-mitigation. Rendezvous allows precise determination of the orbit, mass, shape, spin state and composition of the threat. Rendezvous allows precise placement of the NED for optimal threat mitigation. Rendezvous also allows the use of additional mitigation techniques such as gravity tractors or ion beams, while precluding use of KIs without use of additional spacecraft.

With sufficient warning time, there is no advantage to having a fully designed or fully built and tested Mitigation Spacecraft already in place. With decades of warning, we can optimize both the reconnaissance and mitigation missions to fully study the threat and safely determine the best course of action to mitigate it.

6. Technology

The Technology Working Group is tasked with collating the NEOWARP workshop findings on Autonomy and Advanced Propulsion, two technologies that are important for future planetary defense missions. Other working groups have addressed other relevant technologies, including: instruments, guidance algorithms, and spacecraft hardware for rapid development.

6.1 Autonomy

Autonomy is the ability of a system to achieve goals while operating independently of external control [Fong et. al., 2018]. For robotic space missions, autonomy means the spacecraft's onboard software makes decisions and takes actions, in the presence of uncertainties, to execute the mission and respond to internal and external changes without human intervention (i.e., ground support). The Planetary Science and Astrobiology Decadal Report [NASEM, 2023] recommended autonomy as one of the top technologies in need of maturation and testing. To date, autonomy has not been incorporated into space missions except when *necessary* to achieve a mission (e.g., Entry, Descent, and Landing on Mars and the terminal guidance for DART). Onboard autonomy for navigation and science operations could effectively mitigate the need for multiple Deep Space Network (DSN) passes and potential limits on data collection plans. (However, this will not completely eliminate the anticipated DSN contention issues and should be considered in NASA's future plans to support the increasing number of missions relying on its use.)

The traditional (non-autonomous) approach for fly-by reconnaissance of small bodies involves pre-computing the estimated location of the small body during the fly-by; and "tiling" that region with multiple images that cover the 99% probability uncertainty ellipse so that a few of the images are guaranteed to capture the small body. With onboard autonomy, the spacecraft could first estimate the small body orbit in real-time and then focus its cameras on the expected, true position of the small body to take multiple images from different orientations. The spacecraft could also detect regions of interest on approach and target higher resolution imaging of high-priority targets during the close flyby without needing a data- and time-intensive ground in the loop validation and command cycle. This would greatly increase the quality of data produced by fly-by missions. Note that such autonomous algorithms were first tested in the Deep Space 1 mission's flyby of asteroid 9969 Braille in 1998, but failed in this first attempt. Since then, the software was improved, and the technique has been highly successful, first on Deep Space 1's flyby of comet Borrelly in 2001, and subsequently on many missions, including Stardust (flybys of asteroid Annefrank in 2002, comet Wild 2 in 2004, and comet Tempel 1 in 2011), Deep Impact (comets Tempel 1 in 2005 and Hartley 2 in 2010), and Lucy (asteroid Dinikesh in 2023). Note that in all cases, the tiling was not needed, and the target body was captured from numerous angles throughout the flyby.

The traditional (non-autonomous) approach for rendezvous reconnaissance missions of small bodies is to first slowly approach the small body for ground-based estimation of its size and mass; and then orbit the small body at sufficiently large distances to enable ground-based estimation of its shape model and gravity parameters. This process is heavily constrained by the communication bandwidth between spacecraft and ground control (which is used to send large images and other relevant data for ground-based orbit determination algorithms) and the time it takes for ground operations to process this data, estimate orbits and small body parameters, and send new commands for trajectory correction maneuvers and other tasks that the spacecraft needs to undertake. The autonomous spacecraft with sufficient onboard processing power could perform all these operations onboard with much higher frequency and better results, since they won't be constrained by the above limitations. For example, the autonomous spacecraft could collect and process more data for the onboard orbit determination algorithms or pre-selection of observation data than if it were exclusively limited by communication bandwidth constraints. Moreover, it could send the onboard estimates of orbits and small body parameters and only some representative images to ground control for validation. Similarly, it could orbit the small body at closer distances since the spacecraft can autonomously adjust its trajectories. Thus onboard autonomy could enable more complex missions at small bodies, resulting in more science returns and follow-on mitigation strategies.

In either the case of a flyby or rendezvous, autonomy can be used to perform onboard processing and return vital information to stakeholders rather than raw data, which can take much more time to transmit. The implementation of this type of autonomy can also enable the use of much smaller and simpler or otherwise mass- or volume-constrained spacecraft with more limited telecommunications capabilities. These spacecraft can have smaller antennas, reducing the complexity of the mechanical configuration, and lower power amplifiers, reducing the size of the electrical and power subsystems. SmallSats could be built and tested faster in more commonly available facilities and launched on faster escape trajectories.

Required Capabilities

General autonomy-related technology gaps relevant to all of the subsequent sections include the following [Swindle et. al. 2019].

- Monitoring and management of spacecraft health. Fault detection, isolation, and recovery onboard without ground in-the-loop or transitioning to a Safe Mode.
- Management and coordination of multiple assets, including multiple homogeneous or heterogeneous spacecraft or multiple instruments on a single spacecraft, to survey, monitor, characterize and identify targets. This includes multi-asset information sharing, model building, reasoning, and decision making.
- Verification and Validation (V&V). Current V&V approaches are limited to well-defined functions that operate within specific constraints. Development of software techniques that would enable generalization and scaling to more complex systems and scenarios for onboard decision-making algorithms are crucial gaps.
- Spectral Analysis. Provide the capability to autonomously tune and set spectral instrument parameters.

Concept of Operations

Autonomy has multiple roles in planetary defense scenarios, including target detection, approach, flyby operations, and rendezvous operations as described in the following sections.

This section describes the autonomy required in key phases of a flyby or rendezvous with a Potentially Hazardous Asteroid (PHA). Since the definitions of these phases are not codified, we provide a description of those phases here for reference:

- *Detection* is defined as the event where the spacecraft's onboard camera is able to identify the target, and can occur anywhere from many months prior to encounter, or in extreme cases, hours before. This activity can either be verified as complete through ground confirmation (typical) or onboard autonomy.

- *Approach Phase* begins when the uncertainty in the ephemeris of the target body as determined by the onboard sensor is noticeably reduced from the a priori knowledge of the ephemeris from ground observations. At this point, targeting maneuvers can be computed to guide the spacecraft to its desired aimpoint relative to the body, whether for flyby, impact, or matching the body's orbit for a rendezvous. A subphase, Terminal Guidance, can be defined if onboard closed-loop orbit determination and maneuvers are needed to fine tune the aimpoint at a cadence faster than can be done from ground-in-the-loop operations.
- *Flyby Operations* refers to the activities that the spacecraft needs to perform at Time of Closest Approach (TCA). This may include science instrument data collection, specific attitude control of the spacecraft, actuation of gimbals, and rapid acquisition of data.
- *Rendezvous Operations* refers to the activities that the spacecraft needs to perform after rendezvous with the target.

6.1.1 Detection

Detection of targets with low albedo and/or high orbital uncertainty can prove challenging. Both conditions are likely to be present when designing missions to asteroids posing planetary defense concerns. For flyby missions, onboard target detection provides higher flexibility in mission design, enabling mission navigation solutions to be designed with best available knowledge at launch, and refined onboard as new data becomes available. As the distance between the spacecraft and target is closed, reconnaissance imaging can be performed to isolate the target in the existing uncertainty ellipse. Once the target has been detected, follow-on observations can be leveraged to collect additional information for target characterization and reduction of uncertainty in orbital parameters. Onboard data reduction techniques can isolate the position of the target and key reference stars from imagery to greatly reduce data volumes (such techniques have been employed on several missions to date, including Deep Space 1, Deep Impact, and DART). Rapid downlink of this information allows operations teams to incorporate new target and orbit properties into the mission navigation plan and modify spacecraft trajectory as needed. Rapid incorporation of this information is of particular importance to missions leveraging low thrust propulsion (e.g., solar sails, ion thrusters) as the distances required to meaningfully modify their trajectories are increased.

Required Capabilities

- Onboard Target Detection: Capability to detect and identify sub-pixel, low albedo targets from a field of view driven by orbital uncertainty of the target at launch. These techniques have been used successfully in ground processing (for example, on New Horizons on the Arrokoth flyby and DART on approach to the Didymos system), successfully detecting objects as low as 19 magnitude. Transitioning this to onboard was developed for the solar sail NEAScout, but never flight proven. Detection can be improved, however, with improvements in camera capabilities, specifically the ability to have high dynamic range such that dim targets can be exposed simultaneously with brighter stars.
- Target Revisit and Data Summarization: Capability to revisit previously detected targets (ephemeris lock). Perform extraction of target, and key reference star, locations in instrument FOV for downlink to perform uncertainty reduction on target orbit.

6.1.2 Approach and Terminal Guidance

With high encounter speeds of a small object, the timeline from detection to close-approach may be too short for human-in-the-loop operations. Autonomy would ensure the spacecraft maneuvers to either a desired flyby-point or impacting the body itself, orients the instruments correctly, and collects reconnaissance data (in the case of a flyby). A failed flyby or impact could be catastrophic in a planetary defense scenario, so reliability in the autonomous system is essential.

Required Capabilities

The main autonomy capability is autonomous navigation, which has been demonstrated on numerous missions: Deep Impact and DART demonstrated the capability to impact the body, while Deep Space 1, Stardust, Deep Impact, and LICIACube all demonstrated the ability to track the object through the flyby.

For fast approaches/flybys, the target object is typically a point source until the last hours or minutes prior to impact/closest approach, and navigation using feature tracking is not practical. If the approach is very slow (under ~500 m/s), either with or without the intent of rendezvousing, however, navigation using various feature-based methods may be useful.

- For Landmark-based feature tracking, transition from ground-based manually-intensive terrain-relative navigation to automated landmark extraction plus V&V of feature tracking algorithms.
- For orbit determination, develop autonomous relative navigation between the spacecraft and the body using onboard feature tracking.
- Perform onboard autonomous shape reconstruction with the ability to handle uncertainties in the spacecraft orbit and attitude, body rotation, and lighting variations to achieve object 3D modeling.
- For SmallSats, mature the control of low-thrust maneuvers for precision rendezvous.

6.1.3 Flyby Operations

Flyby operations pose one of the more challenging mission scenarios due to the inability to complete ground-in-the-loop planning during the short duration critical event. The predominant limitation of a flyby mission is the single opportunity to collect data. Traditionally data collection strategies are planned before the flyby, when little to no proximity data about the target has been collected. Based on collected data, mission operations teams plan a flyby sequence with few or minor modifications. Autonomy can support the transition to a higher level goal based commanding structure. Dynamic onboard planning and scheduling with feedback from first order processing of data collected mid-flyby allows the plan to be modified to complete objectives specified by ground operators. Data collection activities will be reprioritized based on data already collected to optimize the short data collection period. This replaces pre-planned sequences which are designed with minimal situational awareness and cannot be modified based on early data collected.

Required Capabilities

- Onboard Raw Data Characterization: Ability to rapidly evaluate raw data collected and estimate progress with higher level planned objectives.
- Onboard Data Sufficiency Estimation: Ability to characterize data missing to create derived products. Capability to autonomously translate data collection needs into follow-on action.

- Dynamic Onboard Planning and Scheduling: Onboard interpretation and understanding of measurement analyses to inform subsequent activities. Ability to translate known data gaps into follow-on activities. Perform prioritization of follow on data acquisition activities given limited resources and schedule constraints.

6.1.4 Rendezvous Operations

For very small asteroids, the spacecraft will need to operate at very low altitudes to measure the gravity field and produce a shape model. These low distances likely will challenge ground-commanded operations concepts. Instead, the spacecraft may need to rely on autonomy to safely approach the asteroid and collect low-altitude data. The OSIRIS-REx mission demonstrated autonomous operations during the ~8 hour descent for sample acquisition that could be further extended to ensure this important data is available quickly and safely.

While orbiting the asteroid (or co-orbiting with the asteroid) provides an extended duration for reconnaissance activities, there is still a driving need to get actionable information to the ground as soon as possible. Traditional operations often downlink all the unprocessed measurements and generate products on the ground, but bandwidth limitations, lower performing telecom systems, or availability of DSN resources may make it impossible to downlink all the requisite, raw data. Instead, it may be faster and more effective to process the measurements on board and downlink only the products. (Or downlink the products first and the measurements later). This also opens up the opportunity for the spacecraft to acquire and store significantly more data since previously, acquisition of data was effectively limited by the amount that could be downlinked; there is no reason to take a measurement if it cannot be downlinked. The principal products we envision are the shape model, the spin state, and the gravity field. This level of data processing would require a substantial increase in onboard computing hardware that could be addressed by differentiated architectures using high-performance nodes for these advanced tasks as well as high-reliability nodes for the essential mission and vital spacecraft control tasks.

Required Capabilities

- Onboard Data Reduction: Ability to create higher level derived products (shape model, spin state, gravity field, etc.) from onboard raw data.
- Data Prioritization: Ability to prioritize actionable data for downlink. Downlink priority for derived products and supporting raw data. This optimizes DSN use and minimizes data redundancy and loss.
- Proximity Operations: Ability to perform onboard orbit determination and maneuver design and execution in the small body environment, including tumbling and fast-rotating asteroids.
- Onboard Data Sufficiency Estimation: Ability to characterize data missing to create derived products. Capability to autonomously translate data collection needs into follow-on action.
- Ability to store much more data on board than can be downlinked in time for decision making.
- All-sensors data fusion with highly configurable tools on board: use science instruments and engineering sensors for multi-modal purposes; a science radar can be an engineering altimeter at the same time, or a GNC IMU a surface characterization instrument (with touch-down or sampling).
- Human-machine interfaces for quick turn-around ground support of autonomy and decision making.
- Extending main spacecraft autonomy capabilities to the preparation, separation, scheduling and operation of sub-spacecraft e.g. sub-satellites and landers for close-up observations, gravity measurement, or surface operations.

6.1.5 High Performance Spacecraft Processors

Autonomy is a driving need for more capable spacecraft processors. In addition to traditional functions such as command attitude control algorithms, and data handling and storage, more powerful processors would allow for onboard planning and scheduling, onboard navigation, and other autonomous capabilities. For small body missions, this might enable onboard data processing to reduce the downlink data volume for distant missions, more capable terrain relative navigation algorithms for autonomous in-situ operations, or perhaps formations of networked spacecraft cooperating while in orbit about a small body. Many deep space missions have used the BAE RAD-750 computer which originated from a late 1990s PowerPC architecture. Recently, BAE Systems announced that it will no longer be producing this computer, leaving future missions to explore other options. One promising technology in development is the High-Performance Space Computer (HPSC), a joint effort by NASA and Microchip, which will be radiation-hardened by design. Alternate options include commercially available processors such as the Qualcomm Snapdragon that was developed for the automotive industry. Commercial products are lightweight, low power, and cost effective, and have performed surprisingly well in the harsh environment of space, including successfully flying on NASA's Ingenuity Helicopter on Mars. Adapted from [SBAG, 2024]

6.2 Propulsion

The rapidity of a reconnaissance or mitigation mission can depend on the available spacecraft propulsion, especially for options that require rendezvous. A study in support of this workshop by Matt Vavrina illustrated that some objects are inaccessible for rendezvous without a very capable propulsion system. Additionally, propulsion techniques were discussed in the context of Ion Beam Deflection, a candidate mitigation technique.

6.2.1 Solar Electric Propulsion

Solar Electric Propulsion (SEP) uses solar power to ionize and accelerate plasma to high velocities and achieve a change in spacecraft momentum. SEP thrusters have high propellant-efficiency at the expense of requiring high input power and delivering low thrust. The two most common SEP thrusters are gridded ion thrusters and Hall thrusters. Broadly speaking, for a given input power, gridded ion thrusters offer higher efficiency (specific impulse), while Hall thrusters offer higher thrust.

The NEXT-C thruster is the U.S.'s highest power gridded ion thruster, with an input power range spanning 0.5 to 7 kW. NEXT-C was one of the candidates in the rendezvous study presented at the third NEO WARP workshop, illustrating its applicability for rapid reconnaissance missions. The Advanced Electric Propulsion System is the US's most capable Hall thruster with an input power range of 6 to 13 kW. It was developed and qualified for the Gateway Power and Propulsion Element (PPE). For lower power missions, NASA's Small Spacecraft Electric Propulsion (SSEP) system is a Hall thruster with an input power range of 0.2 to 1.0 kW.

SEP is the most likely candidate for many rapid response rendezvous missions due to its ability to deliver very high delta-Vs with relatively low mass and near-off-the-shelf availability. The planetary defense community should support activities to advance the TRL of SEP systems. The electric propulsion system includes the thruster, the power processing unit (PPU), the gimbals, and any associated avionics. PPUs are often described as the most challenging engineering development besides the thruster. They are responsible for controlling large power loads to the thruster over a wide range of operating conditions. We recommend activities to qualify a commercially available NEXT-C PPU and an AEPS PPU over the full available thruster throttle range. Additionally, we recommend activities to develop gimbals for these systems. While gimbals are not a technology development, they are a necessary engineering development that will take time to complete. If not completed in advance of a rapid response scenario, these systems may be unavailable due to these time constraints.

Recommendation

Continued Advocacy - Planetary defense is one of many applications for SEP developments. We recommend that planetary defense leadership advocate for continued support of these technologies. This would include support of studies that demonstrate their utility in rapid response scenarios, but would not include direct funding of the technologies themselves.

6.2.2 SmallSat Propulsion

Rapid response, and especially rapid fly-by missions, can be enabled by the use of SmallSat systems. Their low mass can enable launch vehicles to deliver spacecraft to very high launch energies, which are often needed to encounter potentially hazardous asteroids, and often leverage significant commercial advancements to compress traditional implementation schedules. However, propulsion systems remain a gap for SmallSats with very few reliable commercial solutions.

Electric propulsion systems can enable SmallSats to achieve high delta-V when response times are sufficiently long that they allow for long cruise durations and come in small, contained packages. Chemical propulsion systems can be more complicated since propulsion tanks, lines, valves, and other hardware is often distributed within a flight system, a complicated task for a commercial spacecraft platform. Chemical propulsion systems have the benefit of being able to perform impulsive maneuvers to impart a greater delta-V or trajectory change in a short duration and are often more amenable to short cruise durations associated with rapid response missions.

There is also a role for separable smallsat propulsion modules that can augment an existing spacecraft design to achieve much higher propulsion capability. This was recently demonstrated on the LISA Pathfinder mission, where an independent propulsion module was used essentially like an upper stage to achieve higher launch energy and orbit insertion.

We advocate for additional investment in SmallSat electric and chemical propulsion systems. These technologies would enable reliable, low-cost initial exploration of a potential target via a dedicated flyby reconnaissance mission.

6.2.3 Advanced Propulsion

Over the course of the workshop, three advanced propulsion technologies, aside from solar electric propulsion were discussed: solar sails, VASIMR, and Nuclear Thermal Rockets. These technologies are potentially particularly useful in scenarios where the spacecraft must rendezvous with high inclination (e.g., >30 deg) and/or high eccentricity (e.g., >0.8) asteroids and comets.
Solar sails reflect or refract solar photons to achieve a controllable acceleration. In principle, solar sails can operate indefinitely with no propellant needs, only limited by the lifetime of their mechanisms. In the context of the NEO WARP workshops, it was determined that these scenarios are not currently rapid enough to be applicable to a fast-response capability. However, once solar sails are developed and

demonstrated, they offer the capability for rendezvous to the most challenging target orbits. Current solar sail technology limits the available spacecraft bus and payload mass, although recent advances in equipment miniaturization can potentially mitigate this limitation. Further, a gradual transition from large lightweight solar panel powered SEP to solar sailing is possible via solar-power sail approaches such as JAXA's OKEANOS project. Several membrane, booms, materials, and deployment demonstrations have been flown, as well as initial sail control and navigation demonstrations including the interplanetary IKAROS mission by JAXA in near-Venus space, 2010-2015. However, a flight demonstration gap remains in precise control and navigation of agile performance-optimized sails and small high-performance solar-electric spacecraft.

SmallSats may present a viable near-term implementation of solar sail technologies. In one approach, they can be equipped with large lightweight photovoltaic arrays on deployable membranes. These offer both high available power and an improved area-to-mass ratio instead of a propellant wet-to-dry mass ratio. In this scenario, solar sailing can be combined with SEP using the generated solar power on the photovoltaic membranes.

The VAriable Specific Impulse Magnetoplasma Rocket (VASIMR) has been studied for roughly 50 years. If it can be successfully matured, it may offer efficient high-thrust electric propulsion. VASIMR is a very high-power technology with the lowest power versions still processing over 100 kW of power. At very high power levels, multimegawatts or greater, where few other electric thruster technologies have been developed, VASIMR may offer a viable option, so it is worth monitoring its development and evaluating its applicability to planetary defense applications.

Finally, DARPA's nuclear thermal rocket program DRACO promises higher thrust than solar electric propulsion technologies and higher specific impulse than the best chemical rocket engines. This may enable rapid rendezvous opportunities. This technology could change the trade-space for reconnaissance options but is still early in its development.

Recommendation

In the case of all three advanced propulsion technologies, a rapid response planetary defense scenario is not the driving or primary application. Given the scope of their development challenges, we recommend that planetary defense leadership continue to monitor these technologies, advocate for their development, and study applications, but not dedicate planetary defense resources to their development.

7. Conclusion

The results of the dialogues conducted by the NEO WARP Working Groups between March and September 2024 have been documented in the sections of this report. The planetary defense community is strong and growing, and has produced knowledge and skills needed to advance the frontiers of planetary defense capabilities in a manner that is pursuant to our guiding documents from the White House, NASA, and the National Academies. We stand ready to continue engaging in the processes available to us to further these ends, including cultivating and participating in opportunities to expand both support for planetary defense and the resources available for its development. To the extent that such opportunities continue to be generated, our nation and world will become increasingly prepared to prevail against the next NEO impact hazard that nature presents to us.

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