9th IAA Planetary Defense Conference – PDC 2025
5–9 May 2025, Stellenbosch, Cape Town, South Africa

IAA-PDC25-03-133

TERP RAPTOR (Terrapin Engineered Rideshare Probe for Rapid-Response Asteroid Apophis Profiling Tracking, Observing, and Reconnaissance): Mission Concept Development

Adrienne N. Rudolph[a,1,*], Chinthan B. Prasad[a,1], Sean P. Philips[a,1], Kruti R. Bhingradiya[a,1], Rahul Vishnoi[b,1], Cameron J. Storey[a,1], Ryan Mahon[a,1], Brent W. Barbee[a,1], Mary L. Bowden[a,1], David L. Akin[a,1], Jarred Young[a,1], Paul A. Bernhardt[c,1], Yunghsin Chen[d,1], Mark Haynes[e,1], Joseph Huba[f,1]

[a] *The University of Maryland, 3181 Glenn L. Martin Hall, College Park, MD, 20742*
[b] *The University of Maryland, 1309 Kim Engineering Building, College Park, MD*
[c] *The University of Alaska Fairbanks Geophysical Institute, 2156 Koyukuk Dr, Fairbanks, AK 99775*
[d] *U.S. Naval Research Laboratory, 4555 Overlook Ave SW, Washington DC, 20375*
[e] *NASA Jet Propulsion Laboratory, 4800 Oak Grove Dr, La Canada Flintridge, CA 91011*
[f] *Syntek Technologies, 845 Baltimore Annapolis Blvd, Severna Park, MD 21146*

Abstract

The ~325-meter diameter Potentially Hazardous Asteroid (PHA) designated 99942 Apophis 2004 MN_4 will make a historic close approach of Earth on April 13th, 2029, passing within ~31,634 km of Earth's surface, ~4,152 km closer than our geosynchronous satellites. This is an extraordinarily unique opportunity for collecting data on a several hundred-meter size asteroid while it experiences the effects of close proximity to Earth's gravitational field. Current asteroid population models suggest that this is a 1 in 7500 years event. Apophis's Earth close encounter therefore provides a rare opportunity to observe planetary encounter effects on an asteroid. Our Terrapin Engineered Rideshare Probe for Rapid-response asteroid Apophis Profiling, Tracking, Observing, and Reconnaissance (TERP RAPTOR) is an Earth-orbiting mission concept in which a 12U CubeSat built by University of Maryland students would perform a flyby of Apophis, collecting data to address science questions regarding the asteroid's collisional and dynamical evolution, its surface and structural characteristics, and the effects of close proximity to Earth's gravitational field. This mission also supports planetary defense objectives by advancing our understanding of Apophis-sized objects and their potential Earth impact risks.

Keywords: Apophis, Asteroid flyby, Reconnaissance, Cubesat

1. Introduction

The Potentially Hazardous Asteroid (PHA) 99942 Apophis 2004 MN_4 is one of the best known PHAs and has been studied extensively via ground-based and space-based telescope and radar observations. It is poised to make an exceptionally close approach to Earth on April 13th, 2029 at roughly ~31,634 km altitude, offering an exceedingly rare opportunity for planetary science and planetary defense. In this paper, we describe our University of Maryland, student-led CubeSat mission concept for collecting in situ observations of Apophis during a flyby at the time of its closest approach to Earth: the Terrapin Engineered Rideshare Probe for Rapid-response asteroid Apophis Profiling, Tracking, Observing, and Reconnaissance (TERP RAPTOR).

---

[*] Corresponding author
Email address: `rudolpa@umd.edu` (Adrienne N. Rudolph)
[1] PhD Student, Department of Aerospace Engineering

1.1. Discovery of Apophis

Apophis was discovered in June of 2004 at Kitt Peak National Observatory. By December of 2004, additional tracking of the asteroid revealed an Earth collision probability of 2.7% in 2029, but further processing refined estimates of its orbit and ultimately ruled out any chance of it impacting Earth for at least the next 100 years. While Apophis may not have Earth's name written on it yet, Apophis's flyby of Earth is an extraordinarily rare event. Current asteroid population models suggest that an approach so close to our planet by an asteroid of Apophis's size is a 1 in 7500 year event [1]. For context, if Apophis were to strike Earth rather than miss, the impact would release the equivalent of 760 MT of energy, bringing devastation at the regional or continental level but falling well short of an extinction-level event.

1.2. A Singular Opportunity for Planetary Science and Public Engagement

This rare encounter provides the opportunity to collect data on a several hundred meter size asteroid while it experiences the effects of close proximity to Earth's gravitational field. Modeling efforts have indicated that a significant change in Apophis's rotational state is likely, and motion and/or overturning of surface regolith is also possible. Should sufficient overturning of regolith occur, this could alter Apophis's apparent age based on observations of the state of its surface material weathering, prompting revisions of our models of asteroid evolution across time. Apophis's passing in 2029 is sure to capture the imaginations and attention of people worldwide. Although the asteroid will be naked eye visible in the night sky in Europe and Africa, people all over the world will be eagerly anticipating up-close views of the asteroid afforded by spacecraft missions. The European Space Agency's Ramses mission plans to rendezvous with Apophis prior to the Earth encounter, then accompany the asteroid during its Earth flyby to observe changes in its morphology. However, whether Ramses will be fully funded for flight remains unknown until November of 2025. NASA's OSIRIS-APEX mission [2], which is a funded extended mission for the spacecraft formerly named OSIRIS-REx, will rendezvous with Apophis a couple months after the asteroid's close approach with Earth to study its trajectory and composition. However, it will not be able to collect any data before and during the close encounter, so it will need other methods of discerning changes to Apophis due to Earth's gravity.

Our TERP RAPTOR concept for an Earth-orbiting flyby mission to Apophis is under development at the University of Maryland. TERP RAPTOR is dedicated to studying the physical and surface characteristics of Apophis during its Earth close approach. Image data collected by our TERP RAPTOR spacecraft will be used to augment data collected by ground-based observatories, OSIRIS-APEX, Ramses, and any other spacecraft that may be launched toward Apophis. The motivation for our mission to Apophis is three-fold: planetary science, planetary defense, and university leadership, wherein we aim to address important questions posed by the scientific community using an innovative approach enabled by our unique capabilities at the University of Maryland. In doing so, we will also be the world's eyes at Apophis during its historic close approach of our planet in 2029.

2. Science Overview

The National Academies of Science, Engineering, and Medicine (NASEM) Decadal Survey for Planetary Science and Astrobiology 2023-2032 [3] provides an in-depth look at the questions posed by the scientific community, particularly about the evolution of small bodies in the Solar System, such as asteroids and comets. Apophis's close approach to Earth in April 2029 provides a rare chance to answer some of these questions, specifically the ones below:

- Q.3. How and when did the terrestrial planets, their moons, and the asteroids accrete, and what processes determined their initial properties?
- Q4.1b. How has collisional and dynamical evolution affected small body populations now found in stable reservoirs within the inner and outer solar systems?
- Q.4.1c. What are the life cycles (physical states and rotational properties) of small bodies in the solar system and how are they affected by collisions, thermal changes, and non-gravitational forces?

Inspired by mission-level and instrument capability recommendations made in the Decadal Survey as well as the NASA Small Bodies Assessment Group (SBAG) Apophis Specific Action Team Report [4], our TERP RAPTOR team has derived our own science questions that we seek to answer.

1. How has the collisional and dynamical evolution of Apophis affected its surface and structural characteristics?

2. How will the close encounter with Earth affect the surface material on Apophis?

Apophis is classified as an Sq-class asteroid, a siliceous (or ”stony”) object, most closely analogous to LL (low-iron, low-metal) chondrites [4]. Similar compositions have been observed in the Chelyabinsk meteorite and the Itokawa asteroid. As Sq-class asteroids represent the second most common compositional type in the Solar System, studying Apophis's surface properties and validating its reflectance spectra in situ may provide significant insight into the characteristics of a substantial portion of the small body populations of our Solar System. Additionally, we will study the size and shape of Apophis as well as how it will react to Earth's gravitational field. Ground-based radar is the only routinely used technique for measuring the size of an object. As such, there remains uncertainty in Apophis's actual size and shape. Obtaining optical measurements of the asteroid, including its boulder and crater distributions, during in situ operations may reveal much about Apophis's collisional and dynamical history. Furthermore, comparing our images with pre- and post-close encounter data from Ramses and OSIRIS-APEX may reveal to what extent Earth's gravity affected the surface material on Apophis. In the context of planetary defense, understanding the asteroid's physical parameters and size-frequency distribution of surface material will improve our models of how other Apophis-like asteroids may behave in response to deflection or disruption techniques.

3. Mission Overview

3.1. Mission Design Requirements

TERP RAPTOR defines several L-1 requirements to guide the design and hardware specifications of the spacecraft. These requirements are listed below and serve as the primary mission success criteria.

TERP RAPTOR shall:

1. Perform a flyby of asteroid Apophis during its close approach to Earth in 2029
2. Not collide with Apophis
3. Launch as a rideshare to a suitable orbit no less than 30 days prior to Earth close approach
4. Adhere to design safety guidelines of the selected rideshare program
5. Collect and transmit imagery of Apophis to Earth
6. Be no larger than 12U in volume
7. Adhere to NASA Procedural Requirements for Limiting Orbital Debris for End-of-Life operations

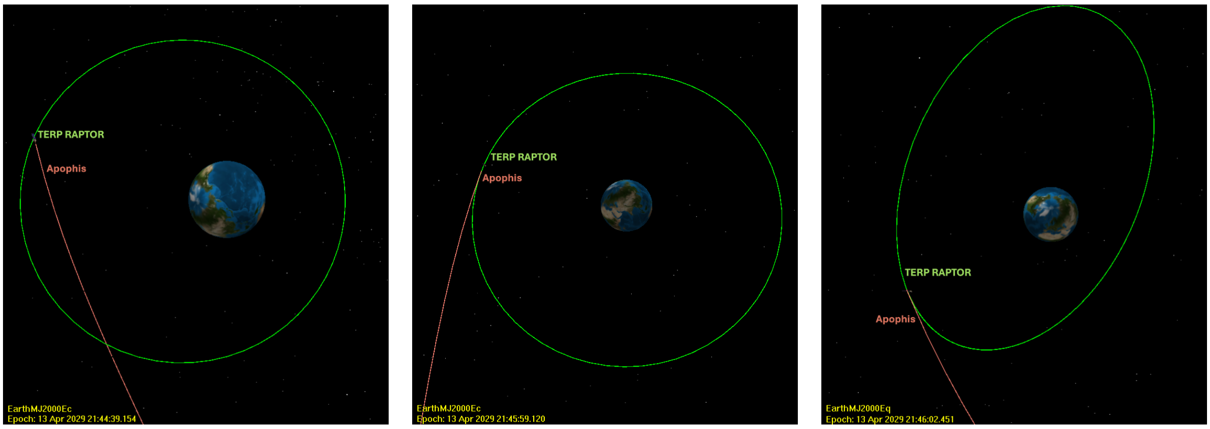
3.2. Rideshare Considerations and Mission Design Reference Orbits

Mission success is predicated on TERP RAPTOR reaching an orbit that enables its flyby of Apophis on April 13th, 2029. In order to match Apophis' orbit at the time of close approach and subsequently provide the optimal image output, the ideal orbit will feature a semi-major axis of 22,288 km, eccentricity of 0.7055, and an orbital inclination of 39.36°. However, the search space of attainable orbits requires additional consideration of existing rideshare providers and their delivery capabilities. The three rideshare-compatible launch vehicles considered in this analysis were the SpaceX Falcon [5], Rocket Lab Electron [6], and Blue Origin Blue Ring [7]. Using the aforementioned ideal orbit parameters, an in-depth optimization was conducted.

This optimization resulted in the selection of three design reference cases (DRC) to serve as the basis for mission design. These are summarized in the list below:

- DRC 1: Standard Falcon 9 rideshare to 28.5° inclination plus ~1700 m/s perigee raise ΔV from launch vehicle upper stage
- DRC 2: Custom Electron rideshare to 39° inclination
- DRC 3: Blue Ring rideshare into lunar swingby for retrograde orbit

Each of the DRCs are shown in Figure 1 below. The associated ΔV and relative velocities to Apophis at close encounter are as follows: DRC 1 with a ΔV requirement of 64.7 m/s and a relative velocity of 9.588 km/s, DRC 2 with a ΔV requirement of 128.9 m/s and a relative velocity of 6.151 km/s, and DRC 3 with a ΔV requirement of 2648 m/s and a relative velocity of 4.644 km/s. It is worth noting that while a retrograde orbit features the optimal relative velocity to Apophis during the flyby, it requires significant launch provider involvement to set up the lunar swingby. Additionally, both DRC 1 and DRC 2 assume at least 200 m/s of ΔV is supplied by the launch provider for phase change manuevers. Consequentially, when evaluating the feasibility for a 12U CubeSat in the absence of additional ΔV supplied by the launch provider, DRC 1 is chosen as the design reference case moving forward, placing a ΔV = 264.1 m/s requirement on TERP RAPTOR propulsion system.



(a) DRC 1 **(b) DRC 2** **(c) DRC 3**

Figure 1: Orbital Design Reference Cases

3.3. *Concept of Operations*

The nominal concept of operations for TERP RAPTOR is summarized below:

1. Launch and rideshare: TERP RAPTOR is delivered to DRC 1
2. Deployment: TERP RAPTOR separates from the rideshare provider
3. Commissioning: TERP RAPTOR tests critical systems and confirms operational readiness
4. Loiter: TERP RAPTOR remains in stable orbit and visually acquires Apophis
5. Flyby: TERP RAPTOR executes science objectives during flyby with Apophis
6. Downlink: TERP RAPTOR transmits data to ground station
7. Decommissioning: TERP RAPTOR maintains compliance with space debris mitigation guidelines

A detailed overview of the flyby operations is documented in the following section.

3.4. *Flyby Operations*

During TERP RAPTOR's close approach with Apophis, cameras onboard the spacecraft will capture images of the asteroid to fulfill the mission's science objectives. The timeline of flyby operations is structured as first detection, then camera pointing, and finally asteroid flyby and imaging. To understand when Apophis will first illuminate a pixel in the onboard cameras, it is necessary to calculate the limiting magnitudes of the cameras and the apparent visual magnitude of Apophis as a function of the spacecraft distance from the asteroid.

3.4.1. *TERP RAPTOR Cameras and Their Limiting Magnitudes*

The two cameras selected for this mission are the Mantis imager, developed by Dragonfly Aerospace, and the Orion12MP-550 imager, manufactured by Infinity Avionics. The Mantis imager is capable of operating in RGB, multispectral, or hyperspectral modes. However, for this mission, our calculations are based on the specifications of Mantis configured in the RGB mode. Orion12MP-550 is another optical imager suitable for a range of space applications and will be used for near-infrared imaging of Apophis.

The limiting magnitude of each camera is proportional to the square root of the exposure time - longer exposure times mean that dimmer objects can be detected, up to a certain length of exposure time where the limiting magnitude levels off. From our analysis [8], the Orion imager can detect objects one magnitude dimmer than the Mantis imager, rendering it more likely to register an illuminated pixel first despite its more narrow field of view (FoV). Nevertheless, during close approach, Apophis is expected to appear very bright, reducing the challenge of first detection altogether.

3.4.2. *Apophis Visual Magnitude*

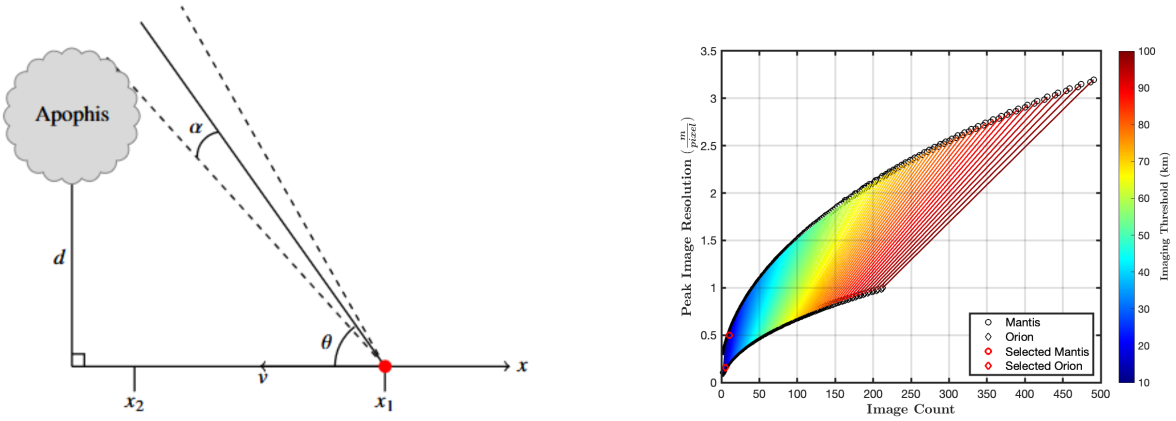
Apophis's apparent magnitude with respect to the sun and the TERP RAPTOR spacecraft is reliant on the change in solar phase angle. The solar phase angle is the angle between the line connecting the Sun to the asteroid and the line connecting the spacecraft to the asteroid. At the epoch of TERP RAPTOR's flyby of Apophis, the solar phase angle is approximately 83 degrees [8]. At this angle, the

Sun is slightly less than perpendicular to TERP RAPTOR's line-of-sight (zero degrees would place the Sun directly behind the spacecraft), almost fully illuminating the closest side of Apophis. Using a range of solar phase angles, the apparent visual magnitude of Apophis during the CubeSat's flyby is between 0 and 5, indicating the asteroid will be very bright (smaller magnitude values = brighter objects). Our analysis also shows that Apophis will be clearly visible up to 12 hours before the flyby [8].

3.4.3. Imaging during Flyby

In order to determine the potential image capture during the Apophis flyby, two scenarios were considered: continuous tracking and fixed pointing. Mathematically, slewing for the duration of the flyby would enable the maximum image return. However, additional consideration must be given to the resolution of the resulting images, and more importantly the feasibility of perfect tracking. A feasibility analysis was conducted to determine the required slew rate and resulting peak torque in order to track the asteroid throughout the duration of the flyby [8]. Given current slewing capabilities of 12U CubeSat infrastructure, TERP RAPTOR would need to maintain a flyby distance of 100 km to slew effectively. This results in an insufficient image resolution of 3.2 m/pixel and 1.0 m/pixel for the Mantis and Orion Imagers respectively [8]. Furthermore, the image fill percentage, representing the number of pixels populated within a single image frame, is 0.224% and 0.765%. Mission science requirements dictate that the image resolution be at least 0.5 m/pixel in order to identify tangible surface weathering effects. Consequently, slewing for the duration of the flyby is determined to be infeasible.

While tracking the asteroid within the camera field-of-view (FOV) is not feasible, orienting TERP RAPTOR upon a fixed pointing angle relative to Apophis is possible. The geometry for this configuration is shown in Figure 2a, where a fixed pointing angle θ, close encounter distance d, and camera FOV 2α can be used to determine imaging return. Equation 1 is used to compute the resulting imaging duration and serves as the primary optimization metric.



(a) Fixed Pointing Angle Flyby Geometry

(b) Solution Space for Imaging Configurations

Figure 2: Flyby Geometry and Imaging Optimization

$$\Delta t = \left| \frac{d\left(\frac{1}{\tan\theta-\alpha} - \frac{1}{\tan\theta+\alpha}\right)}{v} \right| \tag{1}$$

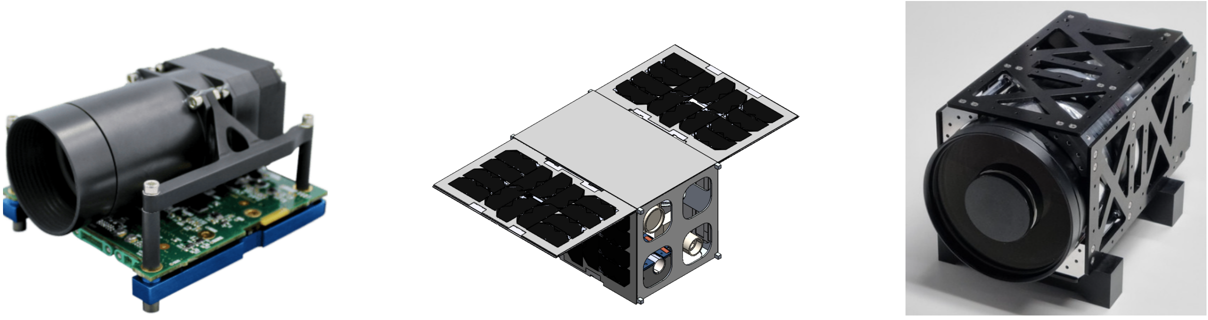
An additional imaging threshold constraint is imposed on the optimization in order to identify imaging configurations that only consider images taken from within a certain direct line-of-sight distance. This is imposed to prevent unconstrained solutions that may exist outside of the feasible imaging threshold of the cameras [8]. The resulting imaging configurations are provided in Figure 2b above. Each solution is represented as a colored line connecting a corresponding (image count, peak image resolution) configuration for both imagers. The colored line corresponds to the imaging threshold imposed on the solution space. As the imaging threshold is relaxed, the image count increases by virtue of the increased imaging duration, at the expense of peak image resolution. An imaging configuration that meets the mission science objective of 0.5 m/pixel resolution was selected. The computed $\langle$image count, peak image resolution$\rangle$ was $\langle$10, 0.498 m/pixel$\rangle$ and $\langle$5, 0.155 m/pixel$\rangle$ for the Mantis and Orion imagers respectively.

4. Spacecraft Design

To achieve the scientific goals laid out, the spacecraft design of TERP RAPTOR displayed in Figure 3 must account for many components and subsystems. Key subsystems include Propulsion, Attitude Determination and Control (ADCS), Guidance, Navigation, and Control, Power, Instrumentation, Communications, Flight Software, Radiation, Micrometeoroid and Orbital Debris Protection, and Structures. Each subsystem has its own set of requirements that, when met, achieve the overarching goals set forth.

TERP RAPTOR's propulsion design utilizes an Aerojet Rocketdyne Modular Propulsion system 4U model. The system will primarily be used during two maneuvers in DRC1 in addition to any correction maneuvers required. The Guidance, Navigation, and Control system works in hand with the Propulsion system to determine whether these additional maneuvers are required in addition to controlling when the predetermined maneuvers are performed. The ADCS system is used to properly orient the spacecraft and cameras towards Apophis in the flyby phase, the onboard antenna toward Earth in the downlinking phase, and the solar panels toward the Sun for charging the batteries.

Of high importance to the mission is the instrumentation, comprised of the imaging systems mentioned previously and displayed in Figure 3 below, as well as an additional receiver antenna supplied by a collaboration between the Naval Research Laboratory (NRL), The University of Alaska Fairbanks (UAF), and the High-Frequency Active Auroral Research Program (HAARP). In previous years, HAARP has used its ground-based bi-static radar to illuminate asteroids and collect signals reflected back to understand more about asteroid interiors. TERP RAPTOR will house a receiver to collect reflected reflected radar signals from Apophis. Those data will help characterize portions of Apophis's internal structure.



(a) Mantis Imager **(b) View of TERP RAPTOR** **(c) Orion12MP-550 Imager**

Figure 3: TERP RAPTOR Spacecraft and Imagers

The Flight Software subsystem is critical to operations as it connects and controls all electrical components and is accomplished using Microchip's PolarFire System on Chip. The FPGA fabric allows for smooth integration of all of the COTS components while the hard processors run NASA's Core Flight System maintaining the system's state. The Structures subsystem is responsible for the size, shape, mass, and volume of the spacecraft as well as ensuring those parameters meet requirements of rideshare providers. Also important to this subsystem is the determination of where each subsystem and its subsequent components are positioned in the spacecraft. The overarching umbrella of the structures subsystem includes the protection of TERP RAPTOR from radiation and micrometeoroid and orbital debris in the form of an aluminum shield that surrounds the components, defending them against the harsh space environment.

5. Mission Logistics

5.1. Assembly, Integration, and Testing (AI&T)

TERP RAPTOR must undergo rigorous testing before launch. An initial FlatSat test will measure the functionality level of individual spacecraft components and help address any mechanical, electrical, or software issues that may be found. Subsystem assembly will follow. After this, TERP RAPTOR will be subjected to flight-proof vibration and thermal testing to ensure that it can withstand the vibrational and thermal loads it will experience in space. Lastly, a radio compatibility test will determine whether our communications system will operate under transmission conditions. Specific testing sites are being discussed and several local facilities are under consideration for our mission's AI&T needs.

5.2. Timeline

With the closest encounter of Apophis occurring in April of 2029, the general timeline of the mission is as follows. By the end of May of 2025 TERP RAPTOR must have both orbit scenarios planned and documented. In addition to this, optimal ground stations for communications shall be determined. By the end of June 2025, a components list must be finalized to allow for their purchasing, as well as the beginning of prototyping. By December 2025, initial prototyping should be complete and in January of 2027, TERP RAPTOR will undergo integration of all subsystems and integration testing over the course of the year. In January of 2028, Thermal, Vacuum, Vibration, and more testing will begin and run until September of 2028 when TERP RAPTOR will be delivered to the rideshare launch provider. Launch of TERP RAPTOR will occur by January of 2029, allowing adequate time before Apophis arrives in April for commissioning, orbital maneuvers, and loitering, followed by the remaining stages of the Concept of Operations.

5.3. Budget

Preliminary cost analysis was done using NASA's Project Cost Estimating Capability and Mission Operations Cost Estimating Tools. This revealed that the cost of materials and components estimate would total $620k, a rideshare could cost up to $1.1m depending on the provider, and operations would total to $1.5m as a conservative estimate. Before including the cost of labor (on the order of a few million $), the total cost of TERP RAPTOR comes to $3.2m as a lower limit which, as shown in Table 1, results in a cost per science image that is significantly lower than the cost per science image for previous asteroid/comet flyby missions.

Table 1: Comparison of Other Flyby Missions [8]

Mission-Asteroid/Comet	Image Count	Image Resolution (m/pixel)	Cost per Image ($M)
LUCY - 152380 Dinkinesh	76	2.2 to 10.0	13.01
Deep Impact - Tempel 1	43	10.0	7.674
LICIACube - 65803 Didymos	600	1.38	0.523
TERP-RAPTOR - 99942 Apophis	15	0.49851	0.227

6. Conclusion

The historic close approach of Earth by Apophis is only four short years away at the time of this writing. The entire world will be watching as we narrowly dodge an enormous cosmic bullet by the slimmest of margins. Without a mission to investigate Apophis in its most vulnerable state, there would be no way to know the details of Apophis's reaction to Earth's gravitational field - and that would be a terrible loss of a golden opportunity. Enabled by a combination of agility, creativity, and technical skills uniquely afforded by a university-led cubesat mission team, TERP RAPTOR is aiming to not let this golden opportunity slip from humanity's grasp. TERP RAPTOR is an innovative, affordable, university-built spacecraft design capable of providing a higher ratio of scientific return to mission cost than any previous mission to an asteroid or comet. On April 13th, 2029 the world will be watching, and the University of Maryland's TERP RAPTOR will be our eyes in space during this extraordinary natural event.

References

[1] D. Farnocchia, P. W. Chodas, A Recipe for Estimating the Frequency of Asteroid Close Approaches to Earth, Research Notes of the AAS 5 (2021) 257.

[2] Della Giustina, D. N., et al., OSIRIS-APEX: An OSIRIS-REx Extended Mission to Asteroid Apophis, The Planetary Science Journal 4 (2023). `https://doi.org/10.3847/PSJ/acf75e`.

[3] National Academies of Sciences, Engineering, and Medicine, Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032, The National Academies Press, Washington, DC, 2023.

[4] Dotson, J. L., et al., Apophis Specific Action Team Report, `https://www.lpi.usra.edu/sbag/documents/Apophis_SAT.pdf`, 2022.

[5] SpaceX, Falcon 9 User Guide, 2024. `https://www.spacex.com/media/falcon-users-guide-2021-09.pdf`.

[6] Rocket Lab, Payload User Guide, 2024. `https://www.rocketlabusa.com/assets/Uploads/Electron-Payload-User-Guide-7.0.pdf`.

[7] Blue Origin, Blue Ring — Blue Origin, 2024. `https://www.blueorigin.com/blue-ring`.

[8] Brent W. Barbee, et al., Mission Concept Development for the TERP RAPTOR (Terrapin Engineered Rideshare Probe for Rapid-response Asteroid Apophis Profiling, Tracking, Observing, and Reconnaissance), AIAA 2025-1401: Small Satellite Mission Studies and Upcoming Missions (2025).