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Retasking In-flight Spacecraft for Rapid Response Reconnaissance in Planetary Defense Exercises

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Abstract

Discussions of rapid response reconnaissance missions for planetary defense exercises have typically focused on dedicated spacecraft, that are built for the purpose of surveying potentially hazardous asteroids. Such spacecraft have many advantages, but it takes time for them to launch and arrive at the asteroid. Redirecting spacecraft that are already in flight has the potential to cut down on this time significantly, allowing for more responsive reconnaissance at the cost of the spacecraft's original mission. We show the feasibility of using in-flight NASA spacecraft for the purposes of surveying the hypothetical asteroids in the Interagency Table Top Exercise #5 and Planetary Defense Conference 2025 exercise scenarios, as well as for the real asteroid 2024 YR4.

Keywords: rapid reconnaissance, flyby, exercise

1. Introduction

In planetary defense exercise scenarios, most discussions of rapid response reconnaissance missions focus on dedicated spacecraft. These are typically new spacecraft, designed and built specifically for the purpose of surveying a newly discovered asteroid that is potentially threatening Earth. A new reconnaissance spacecraft takes approximately three to five years to reach the launch pad, and then still has to travel months or years to reach the asteroid. As an alternative to a new spacecraft, we consider spacecraft already in flight that could potentially be redirected from their original missions to instead survey the hazardous asteroid.

Retasking a spacecraft has the potential to be much more responsive while saving development costs. The spacecraft has already been built, tested, and launched, which are significant drivers in the schedule and budget of any new mission, but especially for planetary defense when time is of the essence. However, it requires case-by-case analysis of each in-flight spacecraft to determine if it has a sufficiently capable propulsion system with enough propellant and adequate thrust capacity to reach the hazardous asteroid. Additionally, the redirection trajectory must not violate any spacecraft hardware limitations such as minimum or maximum solar range. Even when redirection is possible, additional analysis is required to determine if the payload suite, likely designed for a different use case, can be adapted for planetary defense reconnaissance.

In this work, we examine the feasibility of retasking in-flight NASA spacecraft (OSIRIS-APEX, Lucy, and Psyche) for two exercise scenarios: the Interagency Table Top Exercise #5 held in April, 2024,

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and the Planetary Defense Conference 2025 hypothetical exercise. We also studied whether these spacecraft could be used to survey the real asteroid 2024 YR4. In both exercises and for the real asteroid, we found that it is possible to redirect one or more spacecraft to fast flybys of the exercise asteroids. For the PDC scenario, we additionally conducted preliminary analysis of the performance the spacecrafts' imagers for the flyby scenarios.

2. Candidate In-flight Spacecraft

In considering re-tasking spacecraft for PD reconnaissance, there are a few key questions that must be answered. The first is whether the target asteroid is even accessible to the spacecraft from trajectory and spacecraft propellant perspectives. If the spacecraft cannot encounter the asteroid, either as a rendezvous or a fast flyby, then it is not a candidate to re-task. If the spacecraft can encounter the asteroid, then a natural follow-on question is how late the decision to re-task can be made, and whether there is time to wait for more ground-based data to come in before making that decision.

If the spacecraft can physically reach the asteroid within the remaining propellant budget, the next question to answer is whether the spacecraft's payload is suitable for the type of encounter. For PD reconnaissance, the cameras are arguably the most important instruments for characterizing the asteroid's size and refining the asteroid's orbit and potential impact location, although other instruments could also provide valuable composition information [1]. A spacecraft originally designed for rendezvous may have difficulties returning useful data in a fast flyby because its payload suite was intended for low speeds and close proximity operations. If a spacecraft could be redirected, but would not return actionable data for the PD scenario, it is not a suitable candidate.

A last, related question, is whether the spacecraft hardware itself is suitable for the trajectory and the type of encounter. The redirect trajectory could also take the spacecraft closer or farther from the Sun than it was designed for. To conduct a successful fast flyby, the spacecraft likely needs the ability to detect the asteroid with enough time to perform optical navigation to target the flyby. Cameras intended for the slow speeds of a rendezvous approach, or for approach to much larger asteroids, may not be able to detect the threatening asteroid early enough for navigation purposes. Additionally, high speed flybys may require faster attitude rates or additional guidance and control algorithms than what the spacecraft was originally designed for.

Here we briefly review currently in-flight small body spacecraft that are potential options to re-task to survey newly discovered asteroids. In this paper, we focus primarily on the trajectory accessibility and initial detection timeline questions. Additional detailed study and simulation is required to answer the full payload suitability questions.

2.1. OSIRIS-APEX

OSIRIS-APEX was launched in 2016 as OSIRIS-REx, an asteroid rendezvous and sample return mission to 101955 Bennu [2]. After successfully completing its primary mission, it was renamed OSIRIS-APEX with an extended mission to rendezvous with 99942 Apophis just after Apophis' close approach with Earth in April 2029 [3]. The planned trajectory for OSIRIS-APEX includes three Earth gravity assists (EGAs), which are advantageous for potential re-tasking, as these EGAs can be retargeted for relatively small amounts of ΔV. Table 1 lists the key trajectory events for OSIRIS-APEX. As of early 2024, OSIRIS-APEX had approximately 540 m/s of ΔV remaining.

The OSIRIS-APEX payload suite includes thermal and infrared spectrometers, a laser altimeter, and a camera suite. The OSIRIS-APEX camera suite (OCAMS) consists of three imagers, MapCam, SamCam, and PolyCam [4]. With the highest resolution, PolyCam would be used to make initial detection of the asteroid on approach as it was used for Bennu, and in the case of a flyby PolyCam would also likely be used for approach optical navigation and targeting.

2.2. Lucy

Lucy is a multiple flyby tour mission launched in 2021 to explore the Jupiter Trojan asteroids, with additional encounters with main belt asteroids [5]. The nominal trajectory visits six Trojans and two main belt asteroids, as well as three EGAs [6]. A selection of Lucy's key events are summarized in Table 2. Lucy performed its second EGA in 2024 during the analysis period for some of the scenarios discussed here and does not have another EGA until 2030, which significantly constrains the flexibility of redirecting the spacecraft [7]. After the completion of both DSM-2 burns in early 2024, Lucy had approximately 900 m/s of remaining ΔV.

Table 1: OSIRIS-APEX Key Events

Event	Date
Divert	24 Sep 2023
DSM-1 (1 m/s)	17 Jul 2024
EGA1	25 Sep 2025
DSM-2 (0.11 m/s)	7 Oct 2026
EGA2	17 Mar 2027
DSM-3 (146 m/s)	28 Jun 2027
EGA3	13 Apr 2029
Apophis Arrival	22 Apr 2029

Table 2: Lucy Key Events

Event	Date
Dinkinesh Encounter	1 Nov 2023
DSM-2A (100 m/s)	31 Jan 2024
DSM-2B (816 m/s)	3 Feb 2024
EGA2	13 Dec 2024
DSM3 (316 m/s)	11 Apr 2027
DSM4 (116 m/s)	29 Sep 2027
DSM5 (346 m/s)	23 Jul 2028
EGA3	26 Dec 2030

Lucy carries multiple imagers and a thermal spectrometer. L'LORRI is the narrow angle, high resolution imager [8] which would be used for initial detection and optical navigation. As Lucy was designed for fast flybys, its payload and operations are well-suited for a PD reconnaissance fast flyby, but not for a rendezvous.

2.3. Psyche

Psyche is a rendezvous mission to the main belt asteroid, 16 Psyche, that launched in 2023 [9]. Unlike OSIRIS-APEX and Lucy, Psyche uses solar electric propulsion (SEP). SEP is enabling for many missions, because it can allow for significantly higher mission total ΔV's than chemical propulsion. However, SEP complicates the analysis for re-tasking an in-flight spacecraft, as the continuous thrusting over long arcs means that mission's remaining propellant can vary day-to-day in a way that does not happen with chemical trajectories where the maneuvers are discrete events. This can also incentivize redirecting a SEP spacecraft as soon as possible, which adds pressure to the decision-making timeline. Psyche has a planned Mars gravity assist in May 2026, and as of September 2024 had used about 140 kg of propellant.

Psyche carries a spectrometer, a magnetometer, and the Psyche Multispectral Imager (PMI). Like the other candidate missions, the PMI would be the critical payload in a redirection scenario for detecting the threatening asteroid and navigating toward it [10]. Like OSIRIS-APEX, Psyche and the PMI are designed for a rendezvous mission, not a flyby, and it would require additional analysis to determine the expected performance and data return of PMI if Psyche were re-tasked to a fast flyby.

2.4. Other Missions

For the purpose of the PDC 2025 international exercise, we focused on NASA spacecraft. However, other space agencies have small body missions that could also potentially be rerouted. These include the JAXA Hayabusa2 spacecraft [11], currently on its extended mission, and the ESA Hera spacecraft [12], which launched while the PDC exercise was ongoing. Both are designed for rendezvous, however as part of its extended mission Hayabusa2 will be attempting a fast flyby, which will be a valuable test of using a rendezvous spacecraft for a task it was not originally designed for.

Additionally, there are other small body missions in development that could be considered for repurposing in an emergency. These include NASA's Janus spacecraft [13], ESA's RAMSES [14], JAXA's DESTINY$^+$ [15], and the UAE Space Agency's EMA [16]. Depending on the scenario, these spacecraft could potentially be redirected in flight, or if the timing is favorable they could be re-tasked before launch, allowing for direct trajectories to a potentially threatening asteroid, with encounter types that match the design of the spacecraft.

3. Interagency Tabletop Exercise 5

The Planetary Defense Interagency Tabletop Exercise 5 (TTX5) took place on 2-3 April, 2024. The full details of the exercise hypothetical scenario can be found on the CNEOS website[6] and the outcomes of TTX5 are detailed in the after action report [17]. We briefly summarize some of the key details of the scenario that are relevant to the re-tasking analysis.

In the scenario, the hypothetical asteroid 2023 TTX was discovered on 4 October 2023. At the time of TTX5, the asteroid had a 72% probility of impacting Earth on 12 July 2038, a little over 14 years after the exercise. It was expected that the impact uncertainty region would shrink to the size of Earth in November 2024. The most likely size range was 100-320 m in diameter, and it would take a reconnaissance mission to refine this range. The earliest a newly built spacecraft could arrive at 2023 TTX for a flyby reconnaissance mission was around July 2028, while the fastest rendezvous mission would arrive in December 2032.

We find that for this scenario, all of OSIRIS-APEX, Lucy, and Psyche could be re-tasked to do fast flybys of 2023 TTX. Each of these options have different pros and cons, between the spacecrafts' capabilities, their possible arrival times at the asteroid, and the timeline to make a decision to re-task them.

3.1. OSIRIS-APEX for 2023 TTX

OSIRIS-APEX has the first EGA of its mission in September 2025. By performing a modest maneuver ahead of the EGA, it is possible to move the EGA by a few days to set up a second EGA and eventual flyby of 2023 TTX in April 2028. Figure 1 shows the corresponding trajectory. With a total required ΔV of 91 m/s, this is well within the remaining capabilities of the spacecraft. The flyby speed and phase angle are reasonable, and OSIRIS-APEX would arrive a few months before a new build spacecraft could. However, OSIRIS-APEX was not built for flybys, so the data return may be less than what a dedicated mission could achieve with the same flyby characteristics. We have not found it to be possible for OSIRIS-APEX to be redirected to a rendezvous with 2023 TTX.

The baseline trajectory for OSIRIS-APEX has a maneuver in July 2024, so the decision to redirect would need to be made quite quickly, before it was certain in the scenario whether the asteroid was going to hit Earth or not. The redirected trajectory has substantial ΔV margin, so it is possible that the decision could be made after the nominal DSM, at the cost of additional ΔV. This tradeoff between ΔV and decision timeline would require additional analysis if this was a real PD scenario.

3.2. Lucy for 2023 TTX

In April 2024 at the time of TTX5, Lucy had not yet performed its second EGA that would take its aphelion to the Trojans. As such, it was conceivable to retarget this EGA to potentially reach 2023 TTX instead. By doing a maneuver in early November 2024, Lucy can skip its nominal December 2024 EGA to instead do a large DSM at the end of 2025, followed by EGAs in September 2026 and 2028. This would set up Lucy for a flyby encounter with 2023 TTX in November 2028 with a favorable flyby speed and phase angle. This trajectory is shown in Figure 2.

This trajectory would arrive around the same time as a newly built flyby spacecraft could, without the needed development time and cost. Additionally, Lucy is built for fast flybys, making it well-suited to provide actionable data. However, would be very stressing for the spacecraft's propulsion capabilities. At the time of TTX5, Lucy had approximately 900 m/s of ΔV remaining, and 880 m/s of that would be required to enable the flyby of 2023 TTX. While technically doable, this leaves very little margin for statistical maneuvers like targeting and cleanup maneuvers, or for contingencies.

Thus, while attractive in some ways, the small margins make it a difficult decision to re-task Lucy. In this exercise scenario, there would also not be much time to make the decision. It would need to be made by November 2024, to conduct the targeting maneuvers to either fly Lucy's nominal trajectory or redirect to 2023 TTX. In the scenario, Earth impact may not be certain from ground-based measurements at the time the decision must be made.

[6] https://cneos.jpl.nasa.gov/pd/cs/ttx24/

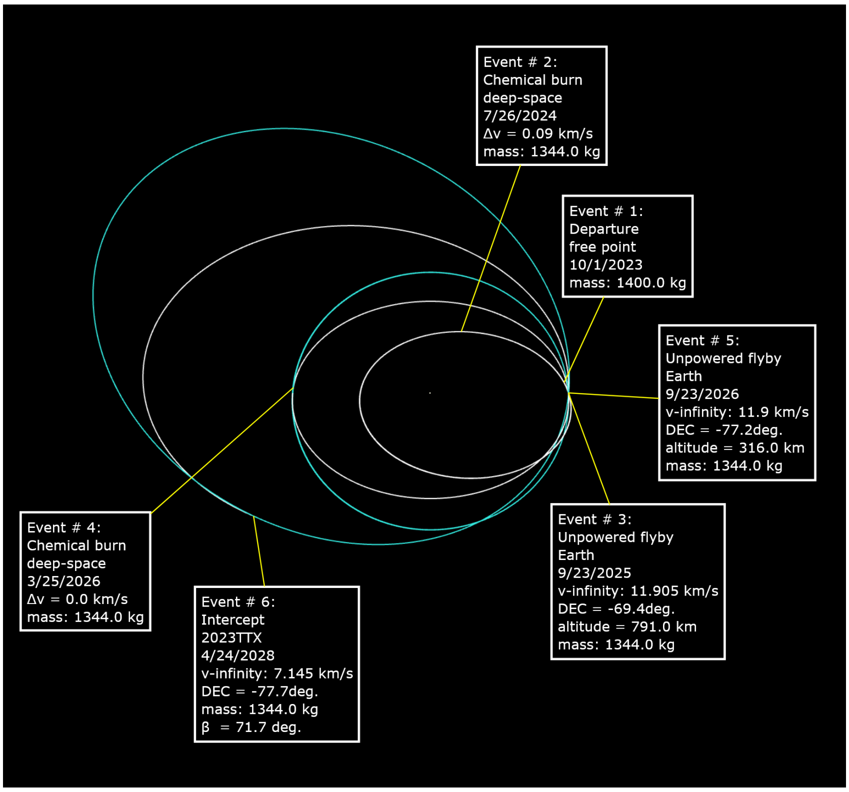

Figure 1: Candidate trajectory to redirect OSIRIS-APEX to a fast flyby of 2023 TTX for the TTX5 exercise.

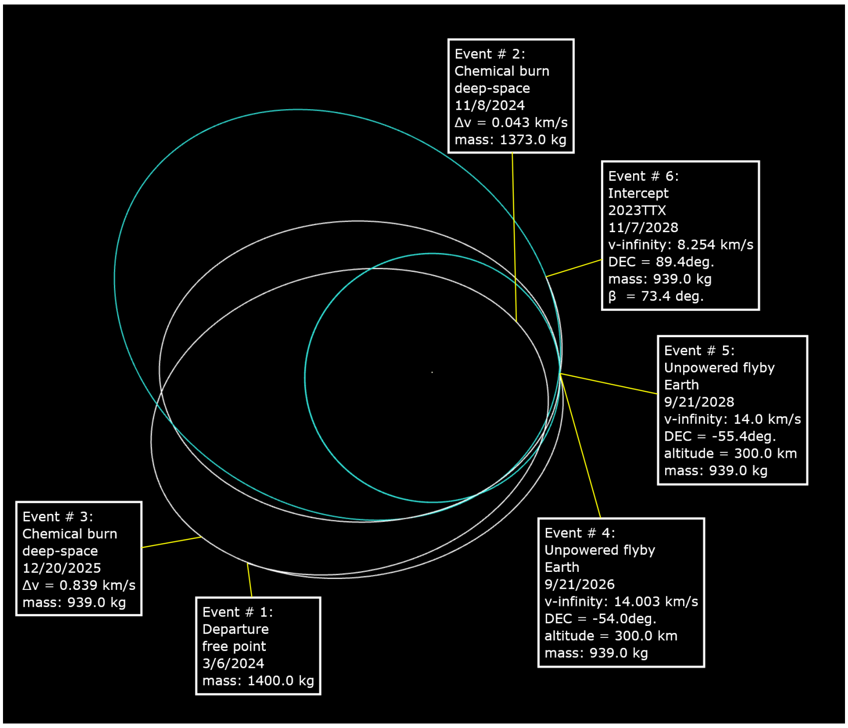

Figure 2: Candidate trajectory to redirect Lucy to a fast flyby of 2023 TTX for the TTX5 exercise.

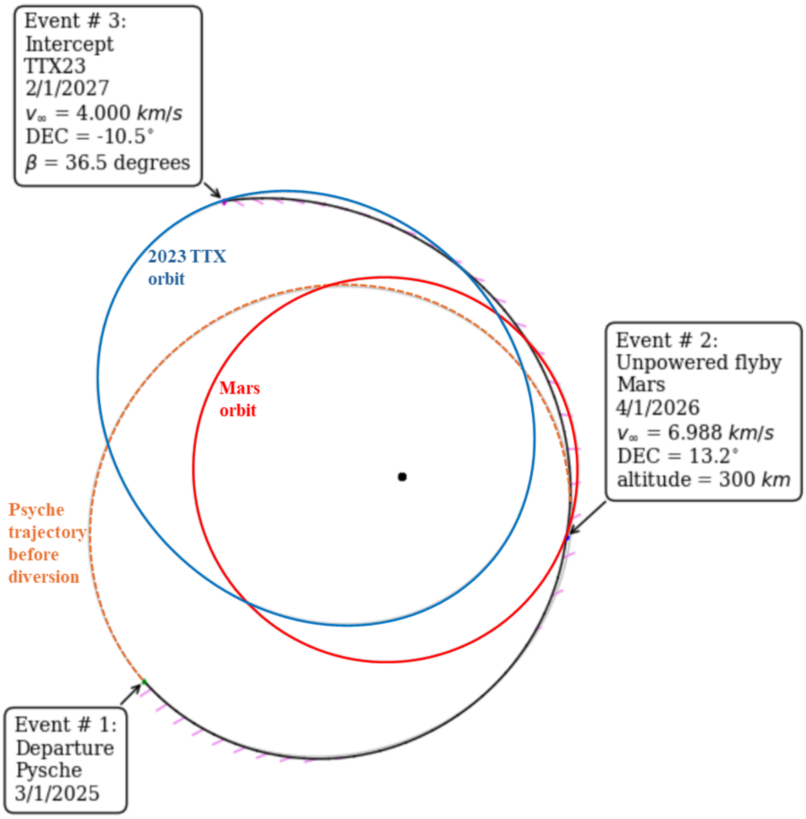

Figure 3: Candidate trajectory to redirect Psyche to a flyby of 2023 TTX for the TTX5 exercise.

3.3. Psyche for 2023 TTX

When the the impact probability for asteroid 2023 TTX reaches 100% in November 2024, the planned Mars gravity assist in May 2026 for the Psyche spacecraft will be 18 months away. This period prior to the Mars gravity assist allows the Psyche SEP system to shape the trajectory so that the gravity assist can be exploited for a subsequent flyby of 2023 TTX instead of towards asteroid Psyche with relatively low thrusting. If a decision is made to divert the Psyche spacecraft to 2023 TTX by March 1, 2025, four months after the impact probability reaches 100%, Psyche can reach 2023 TTX by mid-January 2027 with a flyby speed of roughly 7 km/s for as little as 100 kg of xenon propellant. Alternatively, a 6 km/s flyby as early as November 1, 2026 is possible with the same diversion date, but with more thrusting by the SEP system and approximately 800 kg xenon. Since the Psyche spacecraft was not designed for a flyby mission, achieving a low flyby speed and a low solar phase angle are important factors in the viability of retasking Psyche. A high-performance solution that balances flyby speed, solar phase angle, and flyby date is a trajectory that is diverted on March 1, 2025, performs a gravity of Mars in April 2026, and then executes a 4 km/s flyby of 2023 TTX on February 1, 2027 at a solar phase angle of 36.5 degrees, as illustrated in Figure 3. The diverted trajectory requires 790 kg of xenon, assuming an initial wet mass of 2800 kg and a 10% propellant margin. Additionally, a 90% thruster duty cycle 10% power margin are assumed with three of the four SPT-140 Hall effect thrusters being allowed to thrust simultaneously. If more than 310 kg of the initial xenon load at launch is expended prior to the March 1, 2025 diversion date, the flyby speed can be increased or the flyby date can be delayed to reduce the propellant demand.

4. Planetary Defense Conference 2025 Exercise

In the exercise scenario for the 2025 Planetary Defense Conference (PDC25), a new, hypothetical asteroid is discovered on 5 June 2024. At Epoch 1, the start of the exercise on 1 August 2024, the impact probability has risen to 1.6%, meeting the threshold for IAWN notification. The potential impact is 24 April 2041, about 17 years in the future. If the asteroid is on an impact trajectory, it likely will not be certain until around August 2025, one year after Epoch 1. A the time of Epoch 1, the asteroid is

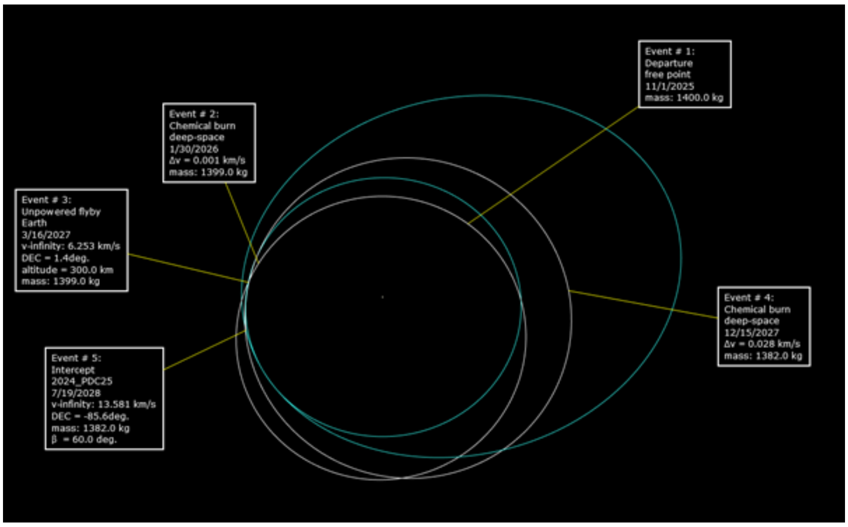

Figure 4: Candidate trajectory to redirect OSIRIS-APEX to a fast flyby of 2024 PDC25 for the PDC 2025 exercise.

most likely 90-160 m in diameter. The earliest a dedicated flyby reconnaissance mission could arrive to confirm the size and other physical characteristics of the asteroid is around April 2028. Additional details for this scenario are also available on the CNEOS website[7].

The analysis for trajectory reach ability for re-tasked spacecraft is done using the information about 2024 PDC25 known at Epoch 1. We find that OSIRIS-APEX and Lucy could be re-tasked to perform fast flybys of the asteroid. Rendezvous is not possible with either spacecraft, and additionally it is not possible to redirect Psyche.

Epoch 2 in the scenario begins on 28 April 2028, shortly after the dedicated flyby reconnaissance mission arrived at the asteroid and narrowed down the size to be 145-155 m in diameter. This informs the analysis later in this section for when the instruments on OSIRIS-APEX and Lucy could make initial detection of the asteroid on approach.

4.1. OSIRIS-APEX for 2024 PDC25

OSIRIS-APEX can be redirected to 2024 PDC25 by retargeting its second EGA in March 2027, for a flyby in July 2028. It can perform its first EGA as normal for its planned mission to Apophis, and can delay the divert maneuver at least as late as January 2026, well after ground observations will confirm if the asteroid will impact Earth. This trajectory, shown in Figure 4, requires 30 m/s of ΔV, so it is conceivable that the divert maneuver could be delayed further at the cost of some ΔV.

The flyby would have favorably lighting conditions with a 60 deg phase angle, allowing for initial target acquisition at a further distance. However, at 13.5 km/s, it is a fast flyby by historical standards, and this could be challenging for a spacecraft and payload not designed for flybys. This flyby speed directly effects detection time.

Initial target acquisition using MapCam or PolyCam may require certain exposure times and or image stacking depending on the desired Signal-to-Noise ratio (SNR) and pointing stability of the spacecraft. Figure 5 shows the detection, using PolyCam, of a 127 meter 2024 PDC25 asteroid. For this case, the acquisition time is 3.9 days prior to the flyby. For further MapCam and PolyCam performances, see Table 3. MapCam, when having longer exposure times and a larger number of stacked images, is able to detect the 100^{th} percentile target (278 meter diameter) with approximately 2.5 days before flyby. Further work is required to determine what level of target state uncertainty is acceptable for thruster limitations and acquisition time before flyby.

4.2. Lucy for 2024 PDC25

As with the TTX5 scenario, by doing a small maneuver to retarget the December 2024 EGA it is possible to send Lucy to a fast flyby of 2024 PDC25. This would require only 3 m/s of ΔV. The flyby

[7] https://cneos.jpl.nasa.gov/pd/cs/pdc25/

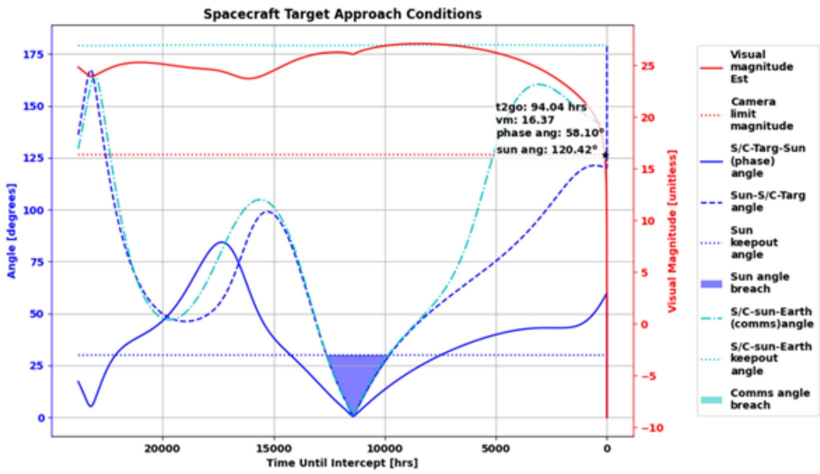

Figure 5: Expected performance of OSIRIS-APEX's PolyCam for the 50th percentile asteroid (127.05 meter diameter) for the PDC 2025 exercise. Signal-to-noise min: 7; Exposure time: 500 milliseconds; Stacked images: 100.

Table 3: APEX instrument detection capabilities comparison. Pointing stability is 0.035 mrad/s.

Instrument	Target Diameter (m)	Exposure Time (ms)	Images Stacked	Detection SNR	Detection Time (hrs before flyby)
MapCam	77.09 (5th perc.)	90	1	10	1.9
	77.09 (5th perc.)	90/500	100	7	9.2/19.9
	152.8 (75th perc.)	90	1	10	2.50
	152.8 (75th perc.)	90/500	100	7	9.85/23.14
	277.84 (100th perc.)	90/500	100	7	14.38/30.99
PolyCam	77.09 (5th perc.)	90	1	10	8.2
	77.09 (5th perc.)	90/500	100	7	40.6/70.4
	152.8 (75th perc.)	90	1	10	10.92
	152.8 (75th perc.)	90/500	100	7	43.10/99.61
	277.84 (100th perc.)	90/500	100	7	63.4/110.3

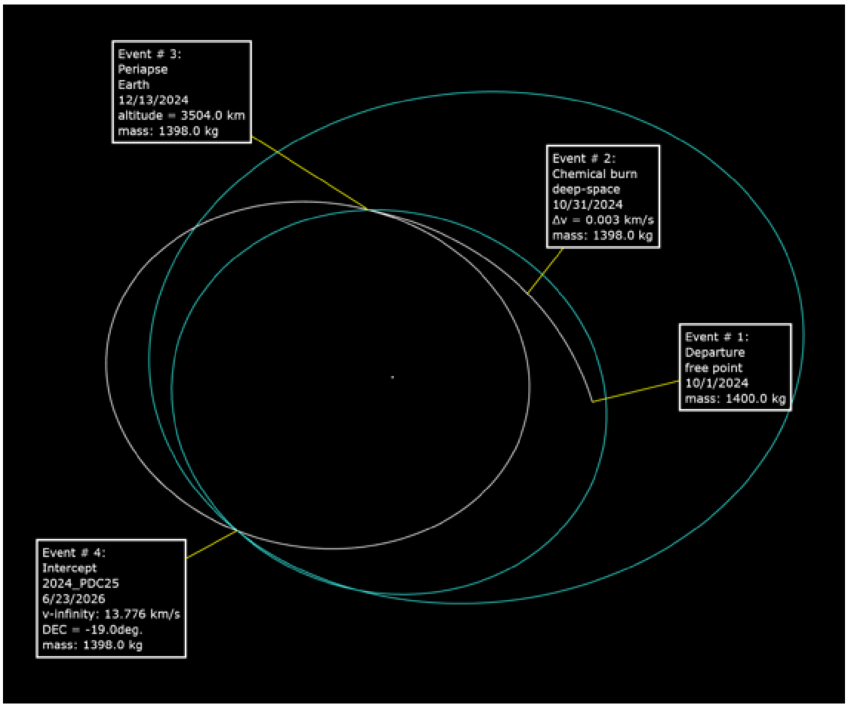

Figure 6: Candidate trajectory to redirect Lucy to a fast flyby of 2024 PDC25 for the PDC 2025 exercise.

of the asteroid would be in June 2026, nearly two years before a dedicated mission could arrive. This makes re-tasking Lucy a potentially valuable option, because getting additional knowledge about the asteroid sooner can be critical to forming the appropriate response to prevent an Earth impact. This trajectory is shown in Figure 6.

However, also like the TTX5 scenario, the decision to redirect Lucy would have to be made before it is certain that 2024 PDC25 will impact Earth or not. In this case, the timeline is even more compressed, with decision-makers only having a handful of months from the start of Epoch 1 to Lucy's nominal EGA. After the nominal EGA, it is no longer possible to send Lucy to 2024 PDC25, so the window of opportunity is short. Additionally, with a high phase angle for the encounter, the initial detection with L'LORRI and the navigation timeline for the encounter would be challenging.

Initial acquisition times range from a few hours (single image and small asteroid) to approximately 1.5 days (stacked images, longer exposure, and large targert). Figure 7 shows the detection profile for a target that is 172.8 meters in diameter, only have 32.7 hours before flyby. Table 4 provides a better breakdown of asteroid size and detection time. As stated previously, the high phase angle makes it difficult to acquire even the largest 2024 PDC25 asteroid at a time greater than 38 hours before the approach. However, if the uncertainty of the target is low and any corrections needed are within the capabilities of the Lucy spacecraft, the short acquisition time before flyby may still acceptable.

5. 2024 YR4

2024 YR4 was discovered on 27 December, 2024. Over the course of January-February 2025, its Earth impact probability for a possible impact in December 2032 rose as high as 3.1%, before additional observations ruled an Earth impact out. Unlike 2023 TTX and 2024 PDC25, 2024 YR4 is a real asteroid, that briefly met the threshold for an IAWN notification. While SMPAG was not activated and formal mission recommendations were not made for 2024 YR4, the asteroid and potential impact still served as a "real world" practice for the mission options evaluation that could happen when another potential impactor is discovered.

In the case of 2024 YR4, re-tasking an existing spacecraft has extra appeal because of the constrained timeline. Most options for new build reconnaissance missions need to launch in 2028 in order to reach the asteroid before 2031. This leaves only 3 years from discovery to decide on a mission and to build, integrate, test, and launch it. This is a challenging development timeline based on historical deep space missions.

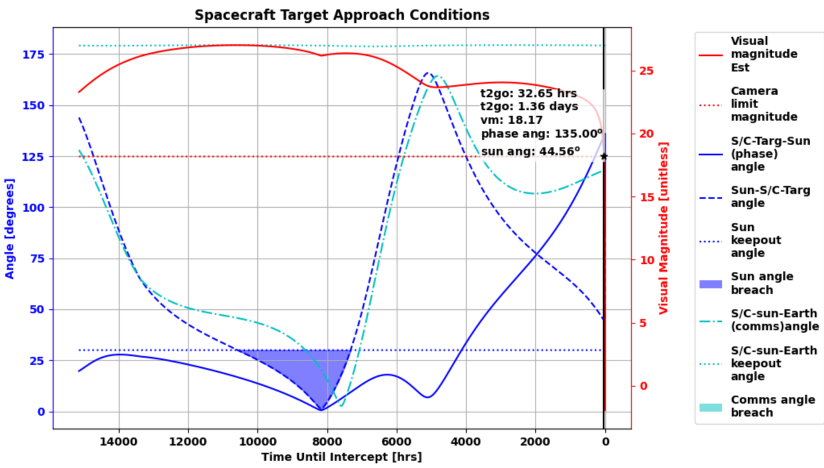

Figure 7: Expected performance of Lucy's L'LORRI for the 75th percentile asteroid (152.8 meter diameter) for the PDC 2025 exercise. Signal-to-noise min: 6; Exposure time: 500 milliseconds; Stacked images: 200.

Table 4: L'LORRI instrument detection capabilities. Pointing stability is 0.002 mrad/s.

Instrument	**Target Diameter (m)**	**Exposure Time (ms)**	**Images Stacked**	**Detection SNR**	**Detection Time (hrs before flyby)**
L'LORRI	77.09 (5th perc.)	90	1	10	2.67
	77.09 (5th perc.)	90	100	7	11.27
	77.09 (5th perc.)	500	200	6	23.70
	152.8 (75th perc.)	90	1	10	3.61
	152.8 (75th perc.)	90	100	7	15.36
	152.8 (75th perc.)	500	200	6	32.65
	277.84 (100th perc.)	90	1	10	4.15
	277.84 (100th perc.)	90	100	7	17.77
	277.84 (100th perc.)	500	100	6	37.99

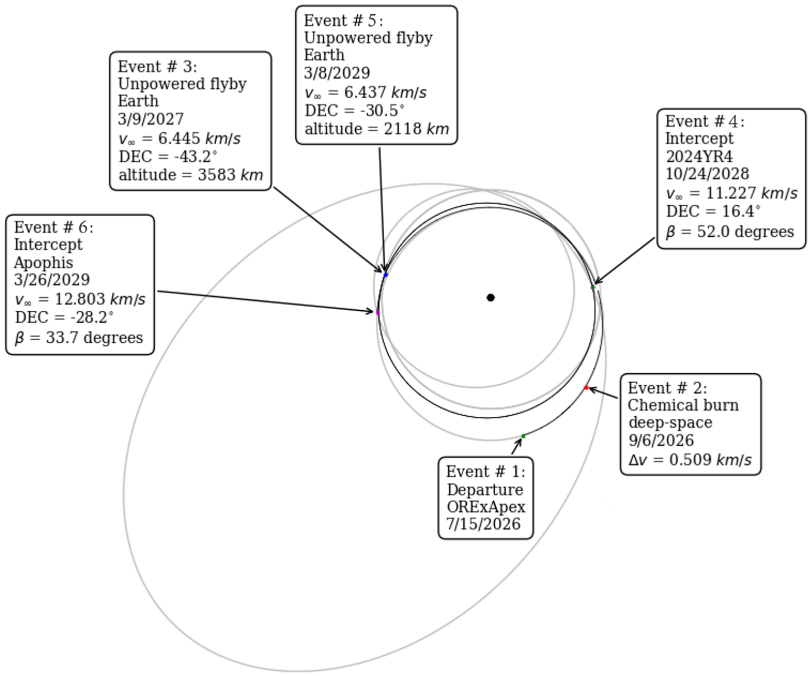

Figure 8: Candidate trajectory to redirect OSIRIS-APEX to a fast flyby of 2024 YR4.

5.1. OSIRIS-APEX for 2024 YR4

Of the in-flight NASA missions, we find that only OSIRIS-APEX would be capable of reaching 2024 YR4 in an operationally relevant time frame, in this case for a fast flyby. At the time of discovery, Lucy had already completed in December 2024 EGA and was on its way to the Trojans, leaving little leverage to redirect the spacecraft. Similarly the orbit geometry for Psyche is not favorable. OSIRIS-APEX, because of its multiple EGAs, has more flexibility.

This flexibility extends to potentially even returning to Apophis for a flyby, such that OSIRIS-APEX would not need to forgo its entire planned mission. Table 5 lists three candidate options for re-tasking OSIRIS-APEX. Option A delays the divert maneuver and uses the least propellant, meaning that this option would both allow the most time to make the decision to redirect while also being well within the capabilities of the spacecraft. This option does not return to Apophis. By diverting earlier and using significantly more propellant, Options B and C are able to return to Apophis for fast flybys. These options trade propellant for arriving before or after Apophis' close encounter with Earth in April 2029. Option C, which would reach 2024 YR4 in October 2028 and Apophis in March 2029, is shown in Figure 8.

Table 5: Options for Re-tasking OSIRIS-APEX to 2024 YR4

Option	Diversion Date	2024 YR4 Flyby Date	2024 YR4 Flyby Speed (km/s)	Apophis Flyby Date	Apophis Flyby Speed (km/s)	Total ΔV (m/s)
A	08 May 2027	01 Nov 2028	9.9	N/A	N/A	1
B	14 Oct 2026	14 Oct 2028	9.9	18 Sep 2030	11.2	300
C	07 Sep 2026	24 Oct 2028	11.2	26 Mar 2029	12.8	510

6. Conclusion

We have successfully shown that for each of the most recent hypothetical impact scenarios, TTX5 and PDC 2025, as well as for the real PHA 2024 YR4, it is possible to redirect at least one in-flight spacecraft to survey the asteroid. This in itself is a significant finding, as *a priori* there is not reason to assume any specific spacecraft could reach any specific asteroid. In most cases, the redirection is achieved by retargetting one or more Earth gravity assists as the EGAs offer signifcant leverage to modify the trajectory of the spacecraft. In some ways, this is similar to the idea proposed by Ozaki et al. of using a constellation of spacecraft in Earth cycler orbits to perform rapid reconnaissance [18].

Retasking a spacecraft can be enabling, either to arrive at the asteroid much sooner than would otherwise be possible such as Lucy to 2024 PDC25, or when the timeline is possibly too constrained to mount a dedicated mission, such as OSIRIS-APEX to 2024 YR4. We also note that independently Tsuda found that Hayabusa2 could be redirected to a flyby of 2024 YR4 [19], offering another option if the impact probability of 2024 YR4 had remained high.

However, there are also significant limitations to repurposing existing spacecraft. All of the candidate trajectories we found here are for fast flybys. Rendezvous is significantly more challenging to achieve. Using spacecraft that were not designed for flybys, like OSIRIS-APEX or Psyche, to do a flyby carries additional risks. The spacecraft have limited navigation and measurement capabilities. While for the PDC25 scenario we showed that the imager on OSIRIS-APEX could allow for enough time to detect the asteroid and navigate toward it on approach, there is additional work that would be necesary to assess the spacecraft's guidance & control system to make sure it could support the attitude control and pointing necessary to enable the flyby.

Even when a flyby is possible and the spacecraft was made for a flyby, such as Lucy in the TTX5 scenario, there may be undesirable risks. In that case, there would be almost no propellant margin if Lucy were to be retasked. While it is conceivable that in a short warning time situation there may be no option other than to accept low margins, having no room for error is unappealing when there are other options like sending a dedicated spacecraft.

Lastly, and significantly, retasking a spacecraft naturally forgoes most, if not all, of its original science mission. In many cases, the decision to redirect the spacecraft may have to be made before the impact probability has reached 100%. This could lead to the unenviable situation where a spacecraft is diverted, only for ground observations to later reveal that the asteroid will miss Earth. Surveying a previously unvisited asteroid would still provide interesting new science, but weighing that against the original mission is difficult.

Ultimately, repurposing in-flight spacecraft represents one tool in the planetary defense reconnaissance toolbox. In future exercises or real world events, such spacecraft can be an option, but they often will not be the most appealing option if it is feasible to send a dedicated spacecraft.

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References

[1] N. Chabot, J. Atchison, R. Bull, A. Rivkin, R. Daly, R. Ballouz, O. Barnouin, A. Cheng, C. Ernst, A. Stickle, E. Smith, J. Linden, B. Villac, J. Berdis, D. Graninger, S. Hefter, A mission to demonstrate rapid-response flyby reconnaissance for planetary defense, in: International Astronautical Congress, IAC-24-E10.

[2] D. Lauretta, S. Balram-Knutson, E. Beshore, W. Boynton, C. Drouet d'Aubigny, D. DellaGiustina, H. Enos, D. Golish, C. Hergenrother, E. Howell, et al., Osiris-rex: sample return from asteroid (101955) bennu, Space Science Reviews 212 (2017) 925–984.

[3] D. N. DellaGiustina, M. C. Nolan, A. T. Polit, M. C. Moreau, D. R. Golish, A. A. Simon, C. D. Adam, P. G. Antreasian, R.-L. Ballouz, O. S. Barnouin, et al., Osiris-apex: an osiris-rex extended mission to asteroid apophis, The Planetary Science Journal 4 (2023) 198.

[4] B. Rizk, C. Drouet d'Aubigny, D. Golish, C. Fellows, C. Merrill, P. Smith, M. Walker, J. Hendershot, J. Hancock, S. Bailey, et al., Ocams: the osiris-rex camera suite, Space Science Reviews 214 (2018) 1–55.

[5] H. F. Levison, C. B. Olkin, K. S. Noll, S. Marchi, J. F. Bell III, E. Bierhaus, R. Binzel, W. Bottke, D. Britt, M. Brown, et al., Lucy mission to the trojan asteroids: science goals, The Planetary Science Journal 2 (2021) 171.

[6] C. Olkin, M. Vincent, C. Adam, K. Berry, J. Englander, S. Gray, H. Levison, J. Salmon, J. Spencer, D. Stanbridge, et al., Mission design and concept of operations for the lucy mission, Space Science Reviews 220 (2024) 47.

[7] J. V. Mcadams, D. R. Stanbridge, D. R. Wibben, A. H. Levine, J. L. Geeraert, J. T. Fischetti, C. D. Jackman, K. Berry, Lucy mission design strategy in a dynamic operations environment from launch through first asteroid encounter, in: 46th Rocky Mountain AAS GN&C Conference, AAS 24-067.

[8] H. Weaver, J. Wilson, S. Conard, J. Adams, S. Begley, J. Burgum, E. Darlington, N. Dello Russo, R. Hacala, S. London, et al., The lucy long range reconnaissance imager (l'lorri), Space Science Reviews 219 (2023) 82.

[9] W. Hart, G. M. Brown, S. M. Collins, M. D. S.-S. Pich, P. Fieseler, D. Goebel, D. Marsh, D. Y. Oh, S. Snyder, N. Warner, et al., Overview of the spacecraft design for the psyche mission concept, in: 2018 IEEE Aerospace Conference, IEEE, pp. 1–20.

[10] J. Bell, L. Elkins-Tanton, C. Polanskey, M. Ravine, M. Caplinger, E. Asphaug, D. Bercovici, B. Bills, R. Binzel, W. Bottke, et al., The psyche multispectral imager investigation: Characterizing the geology, topography, and compositional properties of a metallic world (2016).

[11] M. Hirabayashi, Y. Mimasu, N. Sakatani, S. Watanabe, Y. Tsuda, T. Saiki, S. Kikuchi, T. Kouyama, M. Yoshikawa, S. Tanaka, et al., Hayabusa2 extended mission: New voyage to rendezvous with a small asteroid rotating with a short period, Advances in Space Research 68 (2021) 1533–1555.

[12] P. Michel, M. Küppers, A. C. Bagatin, B. Carry, S. Charnoz, J. De Leon, A. Fitzsimmons, P. Gordo, S. F. Green, A. Hérique, et al., The esa hera mission: detailed characterization of the dart impact outcome and of the binary asteroid (65803) didymos, The planetary science journal 3 (2022) 160.

[13] D. Scheeres, J. McMahon, J. Wood, E. Bierhaus, L. Benner, C. Hartzell, P. Hayne, J. Hopkins, R. Jedicke, L. LeCorre, et al., Janus: A nasa simplex mission to explore two neo binary asteroids, Lunar and Planetary Science Conference (2020).

[14] M. Kueppers, P. Martino, I. Carnelli, P. Michel, Ramses–esa's study for a small mission to apophis, in: AAS/Division for Planetary Sciences Meeting Abstracts# 55, volume 55, pp. 201–08.

[15] N. Ozaki, T. Yamamoto, F. Gonzalez-Franquesa, R. Gutierrez-Ramon, N. Pushparaj, T. Chikazawa, D. A. Dei Tos, O. Çelik, N. Marmo, Y. Kawakatsu, et al., Mission design of destiny+: Toward active asteroid (3200) phaethon and multiple small bodies, Acta Astronautica 196 (2022) 42–56.

[16] H. AlMazmi, P. Hayne, M. Landis, W. Bottke, E. M. to the Asteroid Belt Science Team, et al., Science overview of the emirates mission to the asteroid belt, in: AAS/Division for Planetary Sciences Meeting Abstracts# 55, volume 55, pp. 107–01.

[17] National Aeronautics and Space Administration Planetary Defense Coordination Office, Planetary defense interagency tabletop exercise 5 after action report, 2024.

[18] N. Ozaki, R. Hyodo, Y. Takao, D. Z. Seligman, M. E. Brown, S. Hernandez, M. Yoshikawa, M. Fujimoto, Rapid-response flyby exploration using deep space constellation deployed on asteroid flyby cyclers, in: Planetary Defense Conference 2023.

[19] Y. Tsuda, Planetary defense lessons for apophis 2029 as learned from hayabusa2, in: Apophis T-4 Years.