

MASS MEASUREMENT TECHNIQUES FOR HIGH-SPEED FLYBY RECONNAISSANCE MISSIONS OF POTENTIALLY HAZARDOUS ASTEROIDS

Justin A. Atchison^{a,1,*}, Rylie A. Bull^{a,2}, Gael Cascioli^{b,c,3}, Erwan Mazarico^{c,3}, Jay McMahon^{d,4},
Anivid Pedros-Faura^{d,5}, Evan Smith^{a,6}

^aJohns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD 20723 USA

^bUniversity of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250 USA

^cGoddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771 USA

^dUniversity of Colorado Boulder, 3775 Discovery Drive, Boulder, CO 80309 USA

Abstract

This study evaluates a technique for determining the mass of a potentially hazardous asteroid from a high-speed flyby, typical of a rapid reconnaissance scenario. We consider a host flyby spacecraft that dispenses a small cubesat, which acts as a test-mass. Both spacecraft must perform flyby targeting maneuvers. By incorporating short-range intersatellite measurements between the host and the test-mass, the mass measurement sensitivity is improved. We evaluate a proposed hardware architecture against the 2023 and 2025 Planetary Defense Conference hypothetical threats, as well as a hypothetical flyby of the 2024 YR4 asteroid. These scenarios differ predominantly in their flyby speeds, which span from 1.7 to 22 km/s. Based on these scenarios, we demonstrate that the approach is feasible for asteroids with diameters greater than at least 250 m. We then show that an improved intersatellite range measurement would enable us to achieve measurements of asteroids in the 140 m range, which is most relevant to planetary defense.

Keywords: asteroid mass, reconnaissance, gravity science

1. Introduction

Rapid reconnaissance flyby missions are the fastest means of obtaining asteroid characterization data in a planetary defense scenario. However, the small masses of potentially hazardous asteroids (PHAs) require unreasonably or impossibly close flyby distances to achieve useful mass measurements with ground-based radio tracking, the current state of practice. This capability gap limits the value of rapid reconnaissance flyby missions and means that decision makers are missing critical information in a planetary defense scenario (National Science & Technology Council, [1]).

Recent research has identified that relative tracking between multiple spacecraft can significantly increase flyby mass measurement sensitivity (*e.g.*, [2, 3, 4]). In these approaches, the flyby spacecraft deploys one or more trackable test-masses prior to the flyby. These test-masses are intended to pass very close to the asteroid, within 1-3 body radii of the surface. The short range of the test-mass to the asteroid produces a large perturbation to the test-mass's trajectory. The relatively short distance

*Corresponding author

Email address: Justin.A.Atchison@jhuapl.edu (Justin A. Atchison)

¹Principal Engineer, Astrodynamics & Controls Group, Space Exploration Sector

²Senior Engineer, Astrodynamics & Controls Group, Space Exploration Sector

³Assistant Research Scientist, Sciences and Exploration Directorate, Goddard Space Flight Center

⁴Research Associate, Sciences and Exploration Directorate

⁵Associate Professor, Smead Faculty Fellow, Colorado Center for Astrodynamics Research

⁶Senior Engineer, Systems & Analysis Group, Space Exploration Sector

between the host spacecraft and the test-mass (10's of km) facilitates a high accuracy measurement of this perturbation, allowing for a more sensitive mass determination. This concept is illustrated in Figure 1.

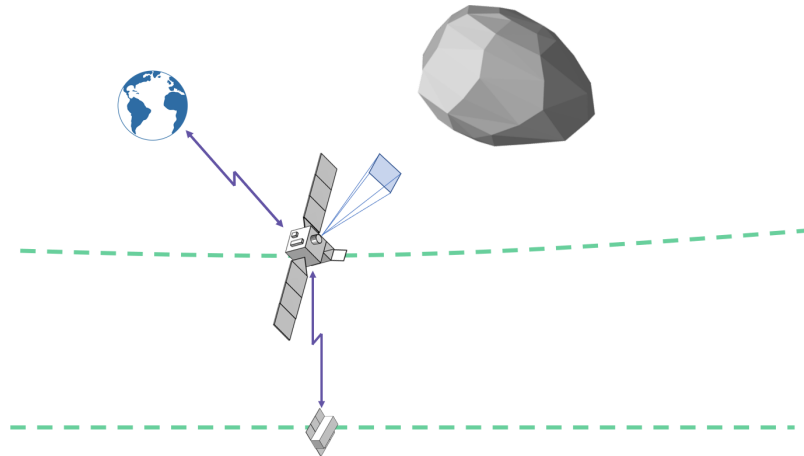


Figure 1: Illustration of Flyby Intersatellite Mass Measurement Concept

This study evaluates a proposed concept to achieve this using active two-way RF tracking (range and Doppler). The test-mass consists of a CubeSat that is three-axis controlled and can execute maneuvers. These techniques are modeled in the context of three reference scenarios given in Table 1. The first two are from the 2023 and 2025 Planetary Defense Conference (PDC) hypothetical scenarios. The final is a hypothetical flyby of real asteroid 2024 YR4. For the PDC scenarios, the asteroid's true properties are known. For 2024 YR4, we base the diameter on recent James Webb Space Telescope observations [5].

This study expands on former work (*e.g.*, [6, 7]) by modeling the full encounter concept-of-operations with representative spacecraft models and realistic measurement schedules. We model ground tracking throughout cruise and flyby operations, optical navigation (when the asteroid is detectable), pointing constraints, multiple approach targeting maneuvers, and a practical spacecraft and measurement schedule.

Table 1: Simulated Planetary Defense Scenarios

| Asteroid | Diameter | Flyby Speed | Epoch |
|------------|----------|-------------|-------------|
| 2023 PDC | 800 m | 1.7 km/s | 01 Dec 2025 |
| 2024 PDC25 | 150 m | 8.1 km/s | 12 Apr 2028 |
| 2024 YR4 | 60±7 m | 22.0 km/s | 11 Nov 2028 |

Given that the measurement is very sensitive, the simulations were conducted using two independent orbit determination tools: the commercial tool Orbit Determination Tool Kit (ODTK) and the NASA JPL tool MONTE [8]. These tools largely agree, although fundamental differences in their underlying designs sometimes made precise validation challenging. Nonetheless, the quantitative results are consistent across tools, which gives us higher confidence in the realism of our results.

2. Concept of Operations

In this study, we consider a host spacecraft that releases a maneuverable CubeSat-scale test-mass (TM) spacecraft. Unlike prior concepts, we are here proposing that the test-mass remains distant from the asteroid, while the more capable host spacecraft targets a low-altitude close-approach. The Double Asteroid Redirection Test (DART) mission successfully demonstrated that a spacecraft could be guided to a precise encounter with a small asteroid [9]. Achieving similar precision of a flyby with a much smaller and less capable spacecraft like a CubeSat is more challenging and has not been demonstrated in flight. The concept we use here has the advantage that the more capable spacecraft is tasked

with executing the more challenging approach guidance. The test-mass need only conduct ground-commanded maneuvers to account for updates to the asteroid’s relative position and to minimize drift relative to the host spacecraft. In our approach targeting sequences, the test-mass only conducts 2 maneuvers, while the host conducts either 2 or 3 depending on the approach speed (higher speed flybys benefit from an additional targeting maneuver). The common parameters for each scenario are given in Table 2.

Figure 2 illustrates the nominal B-plane targets for the host and test mass. The host is targeted to pass at 4 body radii from the center of the asteroid. This gives it an effective altitude of 3 body radii from the asteroid’s spherical equivalent surface. We judge this distance to be a reasonable, though aggressive, altitude to target when accounting for uncertainties in the asteroid’s position and shape.

The asteroid’s diameter is a parameter we vary, with the goal of assessing the mass measurement performance by target size for different scenarios. Table 3 lists the asteroid sizes we consider, with the host’s targeted distance for each. The asteroid is modeled to have a fixed density of 2 gm/cm³. The smallest size of 50 m is consistent with the Decadal recommendation for a future planetary defense mission[10]. The 140 m size is consistent with the definition of a PHA, where this corresponds to an object with an absolute magnitude of 22 and an albedo of 0.14[†]. The absolute magnitude is used in this study to estimate the date that optical navigation measurements become available.

The test-mass’s 10 km close approach distance means that it is effectively unperturbed by the asteroid. It therefore serves as a distant ballistic reference that the host can measure its motion against.

The predominant uncertain perturbation is solar radiation pressure (SRP). We solve for a single scale-factor constant for each spacecraft with a spherical model. (In ODTK, this is accomplished by using a first-order Gauss Markov parameter with a half-life of 1 year.) Additionally, we model an approach that mitigates the SRP disturbance with the following: 1.) the B-plane targets are selected such that the nominal SRP perturbation acts orthogonal to the asteroid’s gravity; 2.) the test-mass does not have to conduct any attitude motion outside of short maneuvers; and 3.) both the host and test-mass have star trackers so that we can accurately reconstruct the attitude after-the-fact to support more elaborate N-plate models. Dedicated calibration campaigns earlier in cruise can help refine the SRP model. The simulations start with the host and test-mass having *a-priori* uncertainties of 5% 3 σ and 20% 3 σ respectively.

| Parameter | Value |
|--|--------------------|
| Host Mass | 500.0 kg |
| Host SRP Area | 5.5 m ² |
| Host SRP Nominal Cr | 1.0 |
| Host SRP Cr <i>a-priori</i> 1 σ | 1.667% |
| TM Separation | 10 cm/s |
| TM Separation 1 σ per axis | 5 cm/s |
| TM Mass | 12.0 kg |
| TM SRP Area | 0.2 m ² |
| TM SRP Nominal Cr | 1.0 |
| TM SRP Cr <i>a-priori</i> 1 σ | 6.667% |

Table 2: Common Simulation Parameters

| Sph. Equiv. Diam., km | Mass, kg | Host Flyby Radius, km | Abs. Mag |
|-----------------------|----------|-----------------------|----------|
| 0.050 | 1.31E8 | 0.100 | 24.3 |
| 0.100 | 1.05E9 | 0.200 | 22.8 |
| 0.140 | 2.87E9 | 0.280 | 22.0 |
| 0.200 | 8.38E9 | 0.400 | 21.3 |
| 0.300 | 2.83E10 | 0.600 | 20.4 |
| 0.400 | 6.70E10 | 0.800 | 19.8 |
| 0.500 | 1.31E11 | 1.000 | 19.3 |

Table 3: Simulated Asteroid Sizes

3. Measurements

The host is tracked by the Deep Space Network, as typical of prior flyby missions. We assume 3 passes per week during cruise, one pass per day in the final 10 days near close-approach and continuous coverage during the four days before and after close-approach.

The host has a telescope on-board, which is used for optical navigation “OpNav” images of the asteroid. We model the telescope with accuracy and noise characteristics similar to those of the DRACO instrument that flew on the Double Asteroid Redirection Test (DART) mission [11]. We assume a “burst” of 6 images every 4 hours, once the asteroid is brighter than a visual magnitude of 18.

[†]<https://cneos.jpl.nasa.gov>

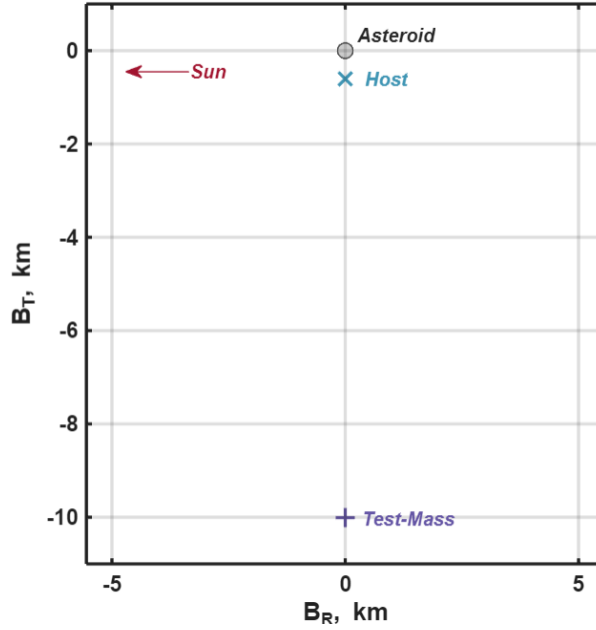


Figure 2: Nominal B-Plane Targets for a 0.3 km Diameter Asteroid

Table 4: Measurement Accuracy Models

| Measurement | 1σ |
|------------------------------|-----------|
| DSN Doppler Noise | 0.1 mm/s |
| DSN Range Noise | 0.5 m |
| DSN Range Per-Pass Bias | 1.5 m |
| Optical Meas (RA, Dec) Noise | 1 urad |
| Intersatellite Doppler Noise | 0.1 mm/s |
| Intersatellite Range Noise | 10.0 m |
| Intersatellite Range Bias | 1.5 m |

The test-mass is deployed after the first optical navigation images are downlinked, giving the team an opportunity to execute a large correction maneuver if necessary. We model the deployment as a fixed 10 cm/s separation with a large *a-priori* uncertainty of 5 cm/s (1σ) about each axis.

The host is able to track the test-mass optically, which we call “OpGrav”. The OpGrav measurements are taken with the same telescope used for OpNav. We model a burst of 6 OpGrav measurements after every OpNav measurement.

The host can also construct two-way intersatellite range and Doppler measurements with the test-mass. Unlike typical ground-links, the short intersatellite distance enables accurate measurements without the need for precision oscillators. We call the intersatellite range and Doppler “DopGrav”. These measurements are generated every minute continuously throughout the simulation period, starting an hour after the test-mass’s deployment.

Table 4 gives the as-used measurement accuracies.

4. Case 1: 2023 PDC

The first case we consider is the 2023 Planetary Defense Conference hypothetical threat*, which was named 2023 PDC. This is the slowest flyby case, with a speed of only 1.7 km/s. We formerly studied this case with fewer maneuvers, with a more realistic operation measurement cadence, with the test-mass targeting the low altitude close-approach, and with different B-Plane targets [7].

*<https://cneos.jpl.nasa.gov/pd/cs/pdc23/>

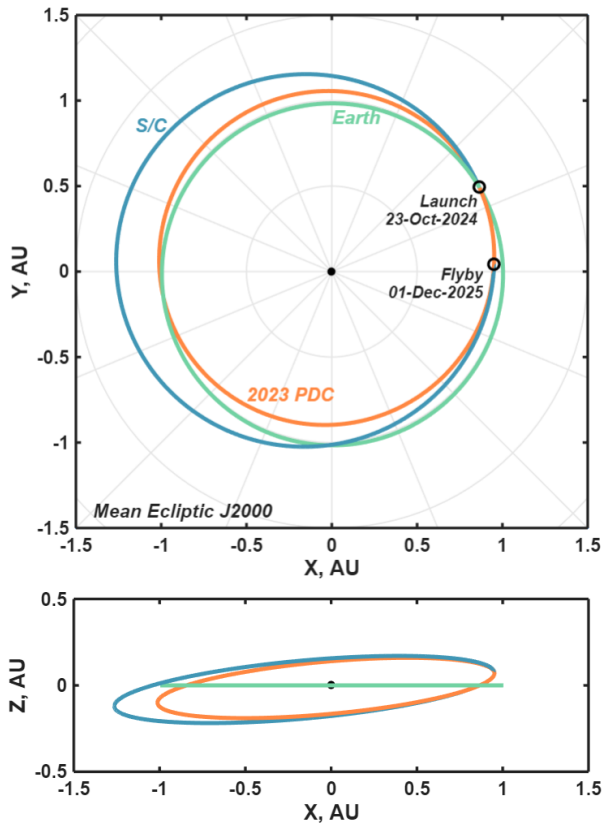


Figure 3: Flyby Trajectory to 2023 PDC

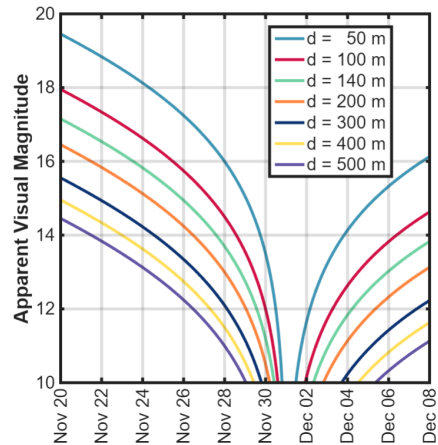


Figure 4: 2023 PDC Apparent Magnitude from Spacecraft

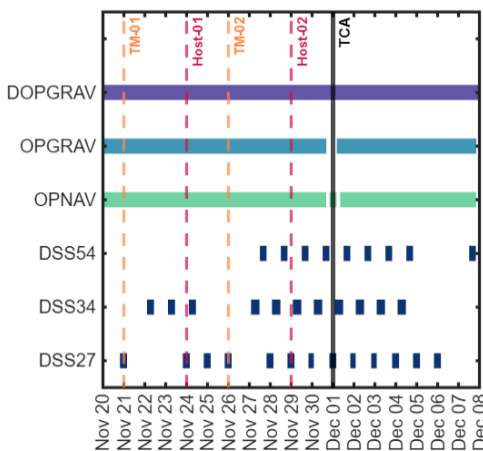


Figure 5: 2023 PDC Measurement Schedule

The interplanetary trajectory is shown in Figure 3. The apparent magnitude and the nominal measurement schedule are shown in Figures 4 & 5. The solar phase angle over the pre-encounter time period decreases from 120° to 111° . The close approach occurs on 01 Dec 2025.

Both the host and test-mass perform two post-separation maneuvers to target their respective B-plane crossings and ensure simultaneous flyby epoch. The maneuver epochs are illustrated as vertical dashed lines in Figure 5. The maneuvers are designed to represent a scenario where a 50 km B-plane error is identified 14 days out, and a 10 km B-plane error is identified 7 days out. The host's maneuvers are approximately 4 and 2.5 cm/s. The test-mass's maneuvers are approximately 80 cm/s and 15 cm/s. The test-mass's higher maneuver magnitudes are required to cancel the drift that accumulated between its separation and its first maneuver.

The asteroid's uncertainty at the start of the scenario was provided by the PDC scenario developers. The host spacecraft's uncertainty was produced by simulating three weekly DSN passes for the duration of its cruise, with a pre-separation maneuver conducted on 17 Nov 2025, 14 days before the flyby. Separation occurs on 19 Nov 2025, 12 days before the flyby. Our encounter simulations then start immediately after the separation.

5. Case 2: 2024 PDC25

The second case we consider is the 2025 Planetary Defense Conference hypothetical threat[†], which was named 2024 PDC25. This is our medium flyby-speed case, with a speed of 8.1 km/s. The interplanetary trajectory is shown in Figure 6. The apparent magnitude and the nominal measurement schedule

[†]<https://cneos.jpl.nasa.gov/pd/cs/pdc25/>

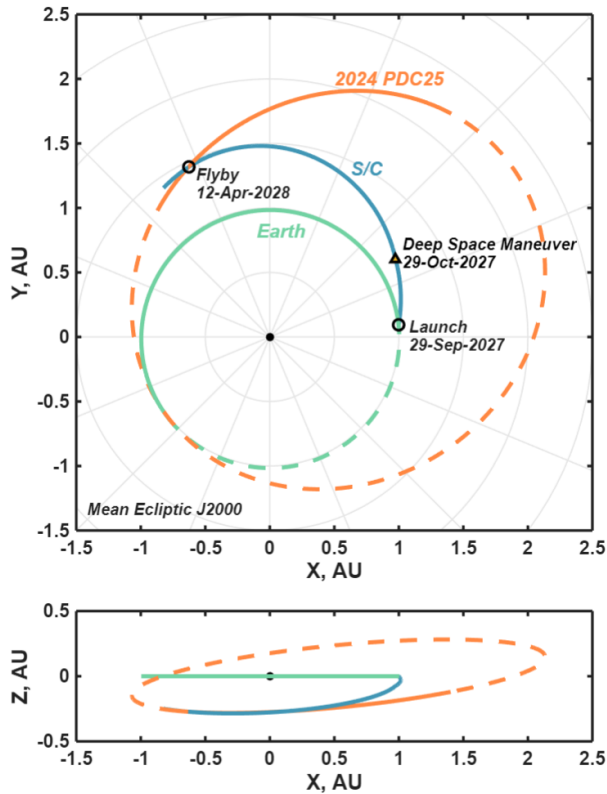


Figure 6: Flyby Trajectory to 2024 PDC25

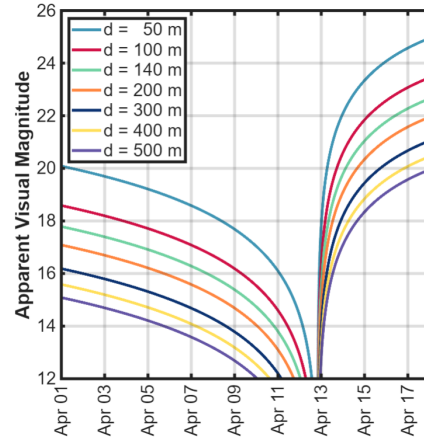


Figure 7: 2024 PDC25 Apparent Magnitude from Spacecraft

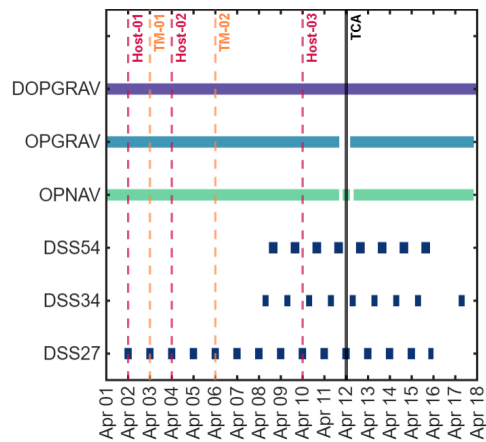


Figure 8: 2024 PDC25 Measurement Schedule

are shown in Figures 7 & 8. This trajectory includes a large deep space maneuver of 2 km/s one month after launch. The solar phase angle over the pre-encounter time period increases from 24° to 30° . The close approach occurs on 12 Apr 2028.

As in Case 1, the asteroid's uncertainty at the start of the scenario was provided by the PDC scenario developers and the host spacecraft's uncertainty was produced by simulating three weekly DSN passes for the duration of its cruise. The deep space maneuver was modeled to have a 2 m/s (1σ) magnitude uncertainty and 1 deg (1σ) direction uncertainty.

Separation occurs on 01 Apr 2028, 12 days before the flyby. As before, our encounter simulations then start immediately after the separation.

The host performs three post-separations maneuvers, and the test-mass performs 2 maneuvers. The maneuver epochs are illustrated as vertical dashed lines in Figure 8. We found that the additional host maneuver enabled a scenario where the host and test-mass are slowly separating after the flyby.

6. Case 3: 2024 YR4

The third case we consider is a hypothetical flyby of the Near-Earth Asteroid 2024 YR4 and represents our fast flyby case. 2024 YR4 has the distinction of having reached the highest probability of Earth impact, with a value of $3.1\%^{\ddagger}$ in mid-February 2025. Prior to the risk becoming negligible[12], we developed rapid reconnaissance flyby options, including the trajectory we consider here. This trajectory launches in May of 2028 and flies past the asteroid 3 months later in August 2028. It is compatible with

[‡]<https://cneos.jpl.nasa.gov/sentry/>

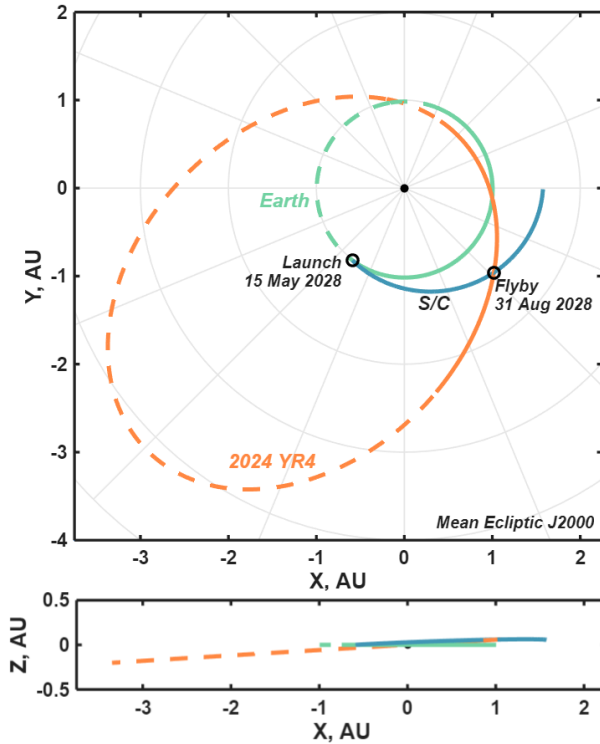


Figure 9: Flyby Trajectory to 2024 YR4

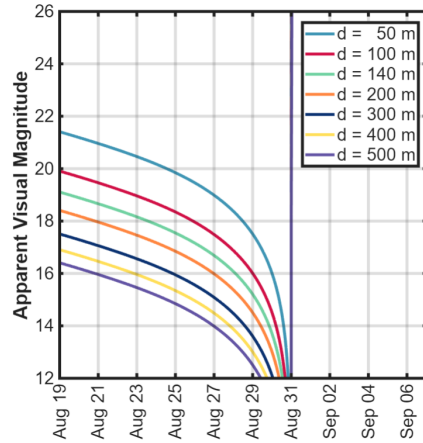


Figure 10: 2024 YR4 Apparent Magnitude from Spacecraft

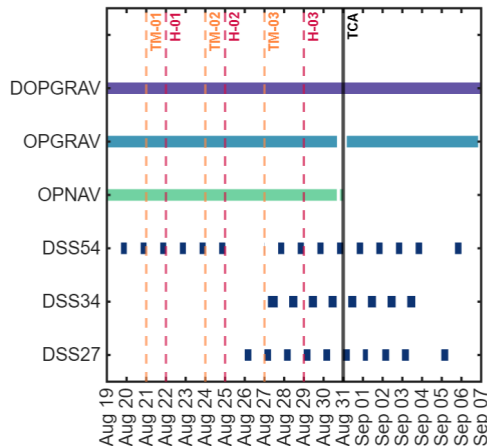


Figure 11: 2024 PDC25 Measurement Schedule

a “medium class” launch vehicle, with no deterministic maneuvers. The flyby speed is 22.1 km/s and the approach solar phase angle spans from 2° to 5° over the 12 days before close approach. While this means that the approach lighting is ideal for OpNav, it also means that departure OpNav imaging is not feasible, since the imager would need to point back almost exactly at the Sun.

The interplanetary trajectory is shown in Figure 9. The apparent magnitude and the nominal measurement schedule are shown in Figures 10 & 11.

To approximate the asteroid’s uncertainty at the start of the scenario, we took the predicted covariance matrix provided by the Center for Near Earth Object Studies (Solution #76) and scaled it to have a maximum 1σ uncertainty of 100 km in inertial position and 0.1 m/s in inertial velocity.

7. Results

The three cases were simulated in both Monte and ODTK. Monte produced more stable results thanks to its design as an epoch state filter. ODTK, as a typical sequential filter, has a tendency to diverge near the very sensitive region of the flyby. However, using ODTK’s underweighting features, we were able to reach good agreement. Example results from Monte are shown for each of the three cases in Figures 12-14, which model the asteroids as having a diameter of 300 m. Each figure includes the 1σ time-history for a specified set of states. The top-left figures show the host and test-mass solar radiation pressure time-histories. The top-right figures show the inertial velocity uncertainty, with spikes at the times of maneuvers. The lower-left figures show the B-Plane semimajor and semiminor axes. This represents the knowledge of the spacecraft relative to the asteroid. And finally the lower-right figure shows the asteroid’s mass uncertainty as a percent. The SRP, inertial velocity, and B-Plane uncertainties are predominantly independent of the asteroid’s diameter.

The targeted flyby distance was 0.6 km from the center of the asteroid. The B-Plane uncertainty time-histories indicate that this knowledge is met for 2023 PDC, because it is achieved before the final host spacecraft maneuver. For 2024 PDC25 and 2024 YR4, with the highest flyby speeds, this criteria is met after the final host maneuver. This suggests that the concept of operations would need to be refined, perhaps by conducting the first two maneuvers earlier and delaying the final maneuver. This would also help to increase the number of useful optical navigation measurements.

In the 2023 PDC and 2024 PDC25 cases, for a 300 m diameter asteroid, the GM relative uncertainty is appreciably reduced, reaching values of about 20% and 35% respectively. If the tracking duration were extended later, this value might even be further improved. For the case of 2024 YR4, with the highest flyby speed, there is little to no reduction in GM uncertainty for a 300 m diameter asteroid.

Figure 15 shows the mass uncertainty (1σ) across a range of asteroid diameters spanning 50 meters to 500 meters, as specified in Table 3. This plot shows results for all three cases. If we assign 25% 1σ as a metric to indicate a useful measurement, then: the slowest case works at a 275 m diameter asteroid, the medium case works at a 375 m diameter asteroid, and the fastest case is marginal ($\sim 35\%$) for a 500m diameter asteroid.

In an effort to better understand the sensitivity of these results to the intersatellite measurement accuracy, we reran the 2024 YR4 case with varying levels of intersatellite range accuracy. In addition to the baseline of 10 m (1σ), we considered 1 m, 10 cm, 1 cm, 1 mm, and 0.1 mm. All other parameters were held constant. The results of this parametric study are shown in Figure 16. If the intersatellite range can be improved by two orders of magnitude, from 10 m to 10 cm, then all our cases, including the fastest case, are feasible down to ~ 140 m diameter asteroids. If we were able to improve the accuracy to 1 cm, then even 50 m asteroids would be measurable, although we caution that this scenario merits further study given the very close flyby distance.

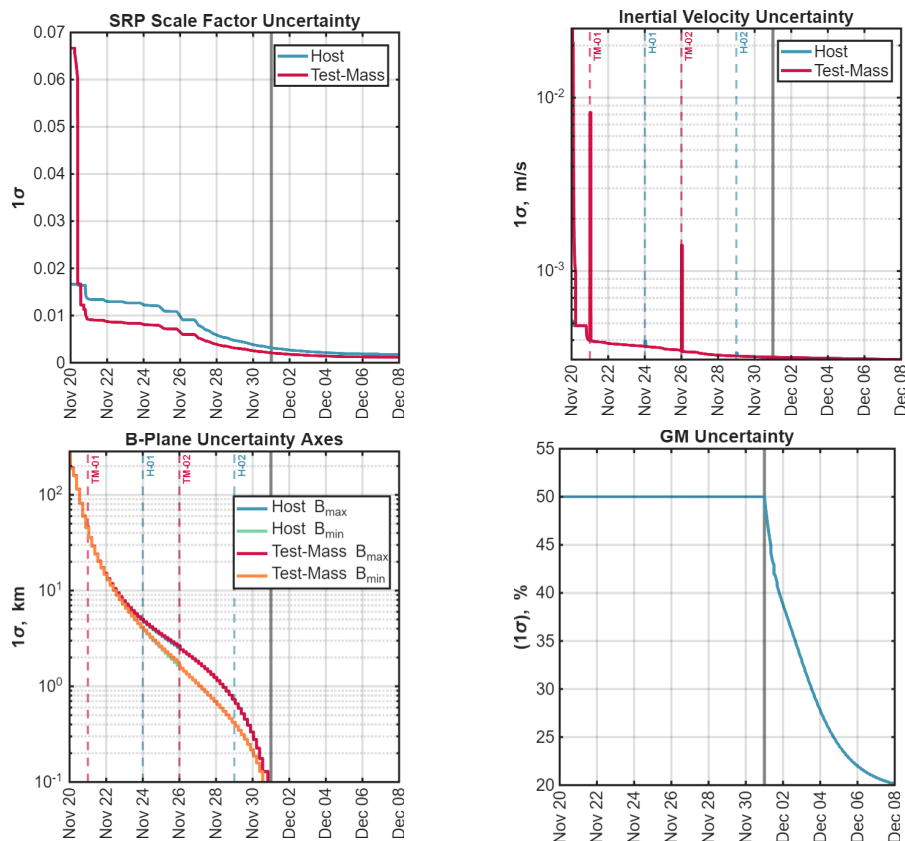


Figure 12: 2023 PDC Results for a 300 m Diameter Asteroid.

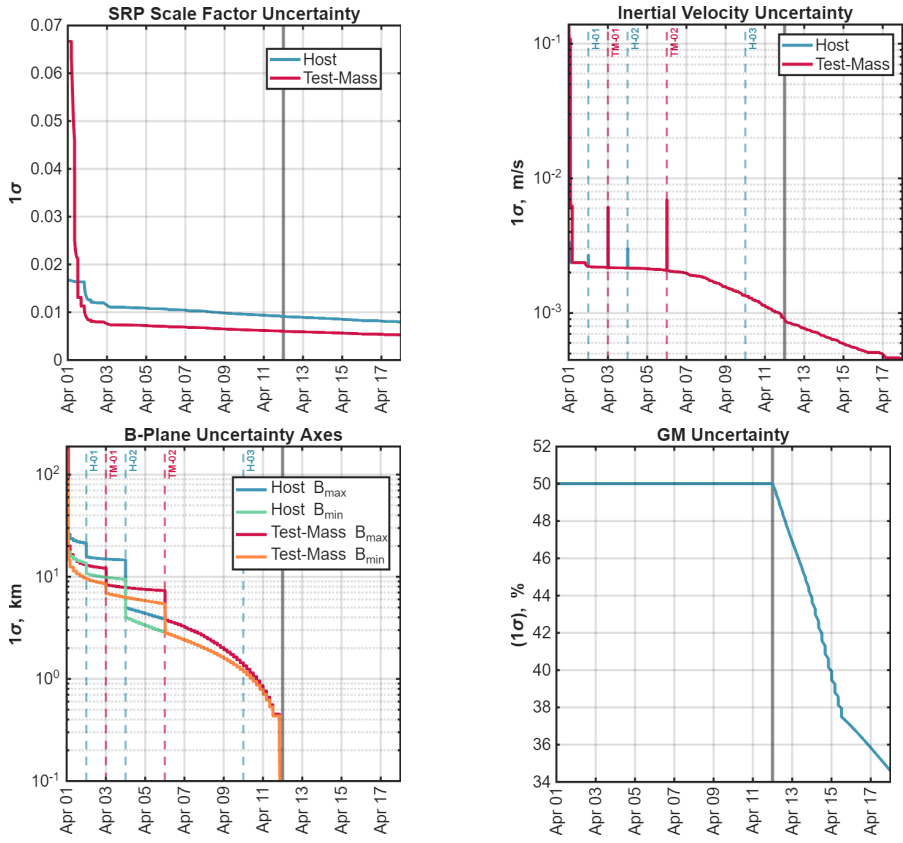


Figure 13: 2024 PDC25 Results for a 300 m Diameter Asteroid.

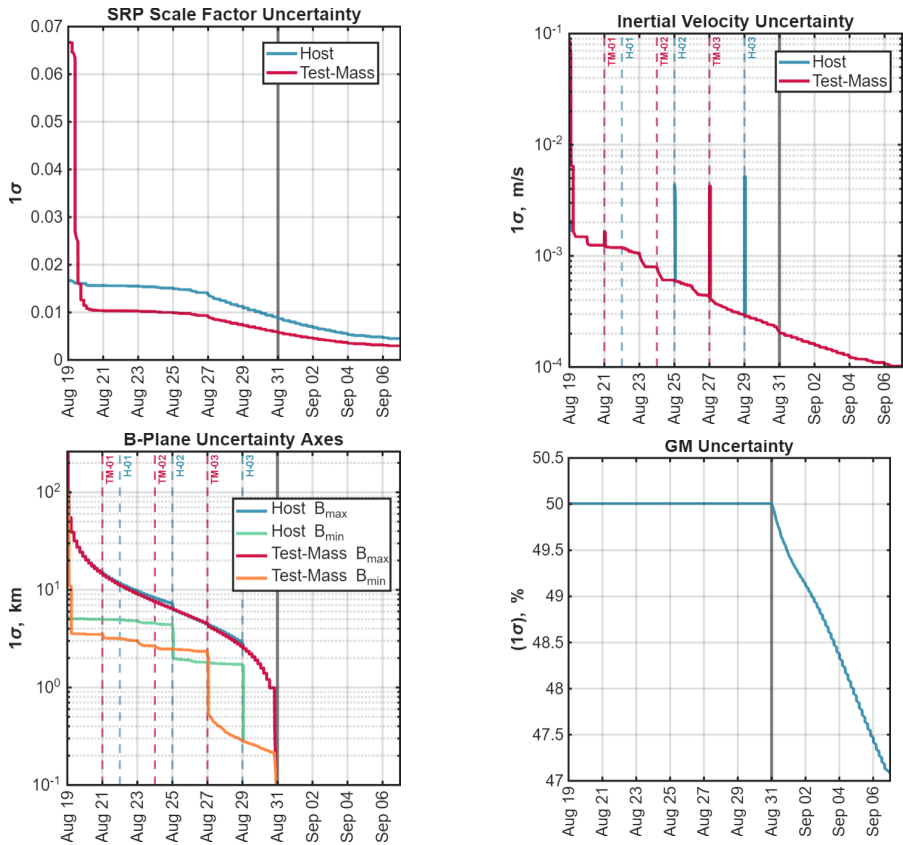


Figure 14: 2024 YR4 Results for a 300 m Diameter Asteroid.

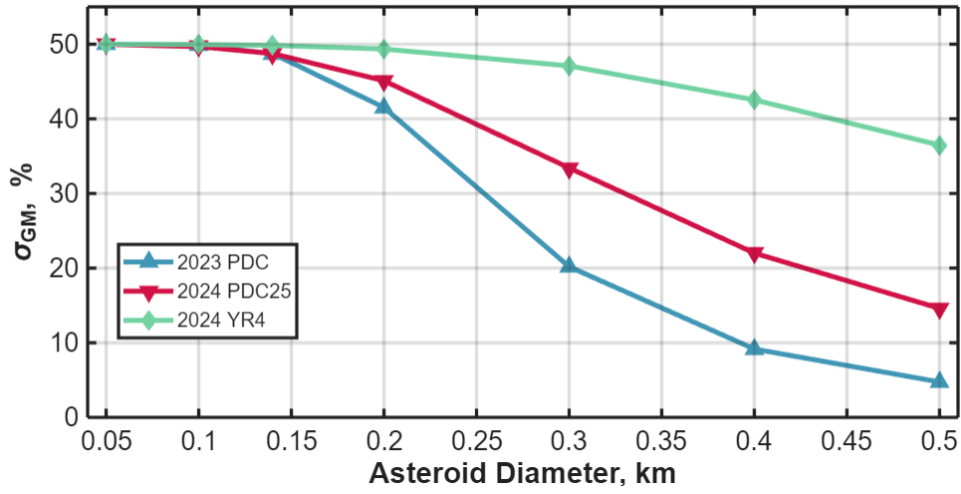


Figure 15: Mass Uncertainty vs Asteroid Diameter for all 3 Cases.

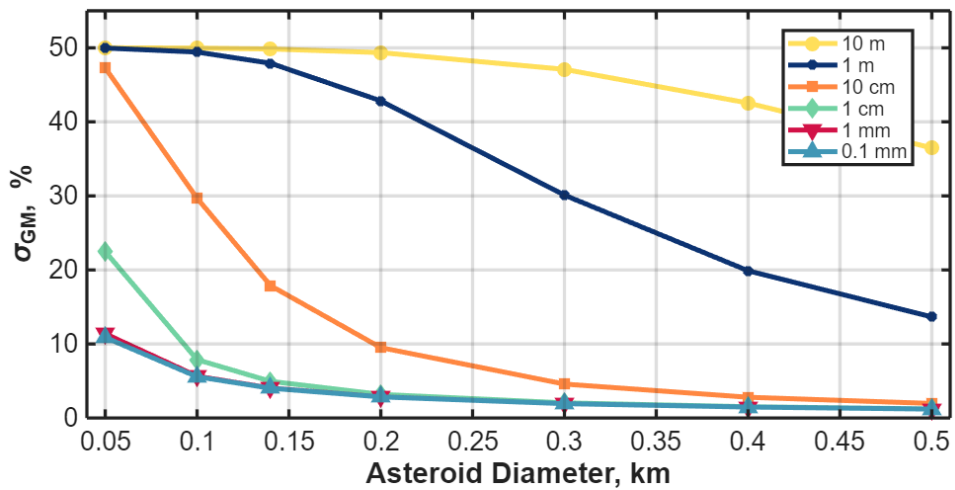


Figure 16: Mass Uncertainty vs Asteroid Diameter for the 2024 YR4 Encounter, with Varying Intersatellite Range Accuracy

8. Conclusion

This study demonstrates that a pair of spacecraft can operationally achieve sensitive measurements of asteroid mass from an asteroid flyby, provided the flyby is slow enough and the asteroid is large enough. This includes a comprehensive deployment and maneuver timeline to target the flyby that would be representative of the operations of real spacecraft.

The baseline assumed parameters do not yet achieve a meaningful mass measurement for asteroids as small as 140 m in diameter. However, we found that this goal is possible if we can reduce the intersatellite range accuracy down from 10 m to 10 cm (1σ). This motivates us to evaluate payloads that may be able to achieve this more accurate range measurement, including laser systems.

In addition to evaluating alternate payloads, our future work will: 1.) update the approach maneuver schedule to reflect the needed B-Plane knowledge at the time of the final maneuver's data-cutoff; 2.) perform Monte Carlo analyses of some stressing scenarios to ensure that the filter still converges to the correct truth states, and 3.) perform a sensitivity study for all of the measurement accuracies and cadences to determine if the improved precision can be met with some other changes to the system.

Acknowledgments

This work was funded by NASA under the 'Yearly Opportunities for Research in Planetary Defense' (YORPD) program from the Planetary Defense Coordination Office (80NSSC23K0501). The authors wish to thank Davide Farnocchia and Paul Chodas of JPL for providing the asteroid *a-priori* covariances and Jim Woodburn of Ansys for software support with ODTK.

References

- [1] National Science & Technology Council, National Near-Earth Object Preparedness Strategy and Action Plan, 2018.
- [2] L. Christensen, R. S. Park, J. F. Bell, Estimating asteroid mass from optically tracked radio beacons, *Journal of Spacecraft and Rockets* (2021).
- [3] R. Bull, R. Mitch, J. Atchison, J. McMahon, A. Rivkin, E. Mazarico, Optical gravimetry mass measurement performance for small body flyby missions, *Planetary and Space Science* 205 (2021) 105289.
- [4] L. Walker, M. Di Carlo, C. Greco, M. Vasile, M. Warden, A mission concept for the low-cost large-scale exploration and characterisation of near-earth objects, *Advances in Space Research* 67 (2021) 3880–3908.
- [5] A. Rivkin, T. Mueller, E. MacLennan, B. Holler, A. Burdanov, J. de Wit, P. Pravec, M. Micheli, M. Devogele, L. Conversi, et al., Jwst observations of potentially hazardous asteroid 2024 yr4, *Research Notes of the AAS* 9 (2025) 70.
- [6] J. A. Atchison, R. H. Mitch, C. Aplan, C. L. Kee, K. W. Harclerode, Small body in-situ multi-probe mass estimation experiment (simmee), 2017 IEEE Aerospace Conference (2017).
- [7] R. Bull, J. Atchison, J. Bradfield, J. Woodburn, Hypothetical asteroid 2023 PDC mass measurement via doppler gravimetry in a reconnaissance flyby, *Acta Astronautica* 214 (2024) 619–628.
- [8] S. Evans, W. Taber, T. Drain, J. Smith, H.-C. Wu, M. Guevara, R. Sunseri, J. Evans, MONTE: the next generation of mission design and navigation software, *CEAS Space Journal* 10 (2018) 79–86. Publisher: Springer Nature.
- [9] R. T. Daly, C. M. Ernst, O. S. Barnouin, N. L. Chabot, A. S. Rivkin, A. F. Cheng, E. Y. Adams, H. F. Agrusa, E. D. Abel, A. L. Alford, et al., Successful kinetic impact into an asteroid for planetary defence, *Nature* 616 (2023) 443–447.
- [10] 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, 2022.
- [11] Z. J. Fletcher, K. J. Ryan, B. Maas, J. Dickman, R. Hammond, D. Bekker, T. Nelson, J. Mize, J. Greenberg, W. Hunt, et al., Design of the didymos reconnaissance and asteroid camera for opnav (draco) on the double asteroid redirection test (dart), in: *Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave*, volume 10698, SPIE, pp. 602–612.
- [12] International Asteroid Warning Network, Final notification: No significant potential for future impact with earth by near-earth asteroid 2024 YR4, *IAWN Notifications* (2024).