RAPID RESPONSE FLYBY EXPLORATION USING DEEP SPACE CONSTELLATION DEPLOYED ON ASTEROID CYCLERS Naoya Ozaki[1], Ryuki Hyodo[1], Yuki Takao[2], Darryl Z. Seligman[3], Michael E. Brown[4], Sonia Hernandez[4], Makoto Yoshikawa[1], Masaki Fujimoto[1], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa, 252-5210, Japan; ozaki.naoya@jaxa.jp; [2]Kyushu University, Fukuoka, Japan; [3]Department of Astronomy and Carl Sagan Institute, Cornell University, 122 Sciences Drive, Ithaca, NY, 14853, USA; [4]Division of Geological and Planetary Sciences, California Institute of Technology, CA, 91125, USA; [5]Continuum Space Systems Inc., Pasadena, CA, 91101, USA.

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Introduction:

The U.S. Decadal Survey [1] asserts the importance of rapid response flyby exploration for planetary defense. Specifically, they called for a better understanding of the characteristics of hazardous asteroids and the development of effective mitigation strategies. A plausible rapid response mission architecture requires sending a spacecraft in a dedicated launch vehicle immediately after target detection. This hypothetical architecture would require a dedicated launch vehicle capable of rapid response. However, this requirement would pose a significant hurdle — both technically and politically — for any country, including Japan.

In this study, we propose an alternative approach to the rapid response dilemma, among various other architectures. We propose loitering dozens of micro spacecraft in deep space, specifically in Earth-resonant flyby orbits, until a hazardous asteroid is detected. In an Earth-resonant flyby orbit, the Earth's orbital period and the spacecraft's orbital period have integer ratios, allowing repeated Earth flybys. In our proposed mission architecture, dozens of micro spacecraft are inserted into the Earth-resonant flyby orbits. This poses the advantage that each spacecraft will have the capability to perform an Earth flyby at a uniquely specified time. The spacecraft will be able to drastically change its trajectory toward the target object utilizing the Earth's gravity assist by performing small trajectory correction maneuvers several weeks before the Earth flyby.

For this concept to work, more than one spacecraft would need to perform an Earth flyby on a month-to-month cadence; that is, this concept requires a large-scale deep space constellation. This constellation can be built through rideshare opportunities to deep space or the Moon without the need for dedicated launch vehicles. Figure 1 shows an overview of the Earth-resonant flyby architecture via the proposed deep space constellation. Earth-resonant flyby orbits expand the "reachable region" — the region with lower ΔV requirements. This is because the spacecraft has a higher V_∞ with respect to the Earth than low-energy orbits, such as at Lagrange points [2]. These high-energy loitering orbits improve the probability of reaching interstellar objects (ISOs) [3, 4] and long-period comets (LPCs)[2].

This proposed mission architecture uniquely offers multiple flybys of near-Earth objects (NEOs) while loitering in an Earth-resonant flyby orbit [5, 6, 7, 8, 9], as will be demonstrated by JAXA's DESTINY$^+$mission [7]. We estimate that ~ 1 NEO can be directly explored every month if ~ 12 micro spacecraft are deployed via order of magnitude calculations. The proposed multiple NEO flyby concept would bolster our collective planetary defense efforts while amplifying the scientific returns of in-situ exploration of this population. It would also solidify our overarching technology for asteroid flyby exploration.

This paper mainly focuses on a statistical analysis of reachable hazardous asteroids and configuration options for deep space constellations. We also investigate the example of multiple NEO flybys in the loitering orbit. Mission design results indicate the amount of required fuel that can be used to estimate the size of the spacecraft system.

Deep Space Constellation Architecture:

The proposed architecture utilizes the Earth gravity assist as the rapid-response maneuver. Because frequent Earth gravity assists are needed to maximize the probability of NEOs/LPCs/ISOs encounters, this concept requires a spacecraft constellation in Earth-resonant flyby orbits. An Earth-resonant flyby orbit is an orbit in which the orbital period of the Earth and the spacecraft have an integer ratio, allowing the spacecraft to perform repeated Earth flybys.

In this concept, ~ 10 spacecraft are placed in the Earth-resonant flyby orbit, and each spacecraft makes an Earth flyby at a different time (Fig. 1). By performing small trajectory correction maneuvers several weeks to a month before the Earth flyby, the spacecraft can rapidly change its trajectory to-

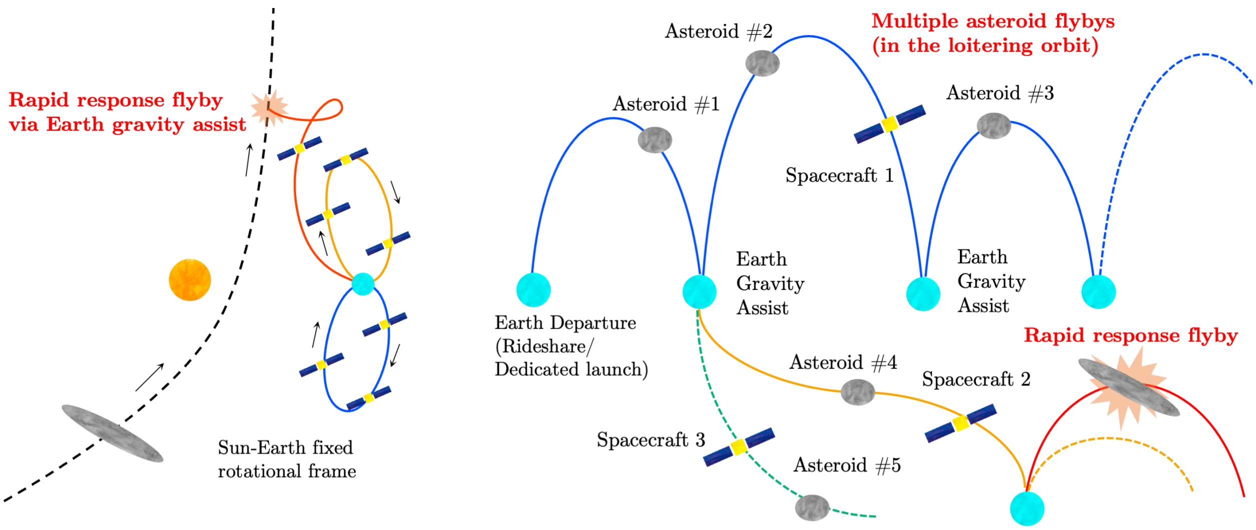


Figure 1: Deep space constellation architecture.

ward the target object using Earth's gravity assist. The Earth-resonant orbit allows the spacecraft to hold a higher V_∞ with respect to the Earth. This enables us to explore LPCs and/or ISOs with less fuel and a larger encounter probability.

This mission concept utilizes an orbit called the asteroid flyby cycler [5, 9], which allows for multiple flybys of NEOs while loitering in an Earth-resonant flyby orbit. Building a fleet of 12 spacecraft would allow for the direct exploration of ~ 1 NEO per month, increasing the scientific value of the mission while contributing to planetary defense. This mission concept has the potential not only to improve our understanding of NEOs but also to solidify the technology for asteroid flyby exploration. In addition, the deep space constellation has the potential to facilitate other science missions, such as those designed for heliophysics. Figure 1 shows an overview of the deep space constellation architecture.

Asteroid flyby cycler orbits can be achieved with a small ΔV of about tens of m/s per year. This advantage makes the mission feasible even with CubeSats and micro spacecraft, or an advanced propulsion system including solar sail spacecraft. Since a deep space constellation can be built with micro spacecraft, it is possible to take advantage of rideshare launch opportunities, including lunar transportation opportunities. In the case of lunar transportation, the maximum V_∞ for Earth escape is $\sim$ 1.5 to 1.8 km/s[10]. V_∞ leveraging maneuvers [11] after deep space escape will be necessary to increase the probability of achieving rapid exploration.

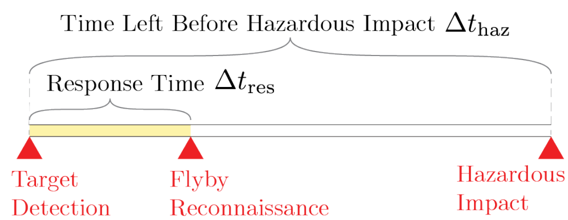


Figure 2: Definition of flyby reconnaissance timeline.

Rapid Response Mission Design Approach: Here we present the mission design approach of rapid response flyby via deep space constellation. Figure 2 defines the timeline for conducting a flyby reconnaissance after a hazardous asteroid is discovered. *The warning time* Δt_{warn} is expressed as the time between the initial discovery and the hazardous collision to the Earth. *The response time* Δt_{res} is defined as the time between the initial discovery and the completion of the flyby reconnaissance. A *rapid* response time ($\Delta t_{\mathrm{res}} < \Delta t_{\mathrm{warn}}$) is required because a hazard mitigation mission such as DART [12] will likely be conducted after the flyby reconnaissance is completed.

Spacecraft trajectories in the deep space constellation are designed based on the following assumptions.

1. Spacecraft are evenly distributed along the longitude.

2. All spacecraft have the same V_∞ relative to Earth in the Earth's gravity assist.

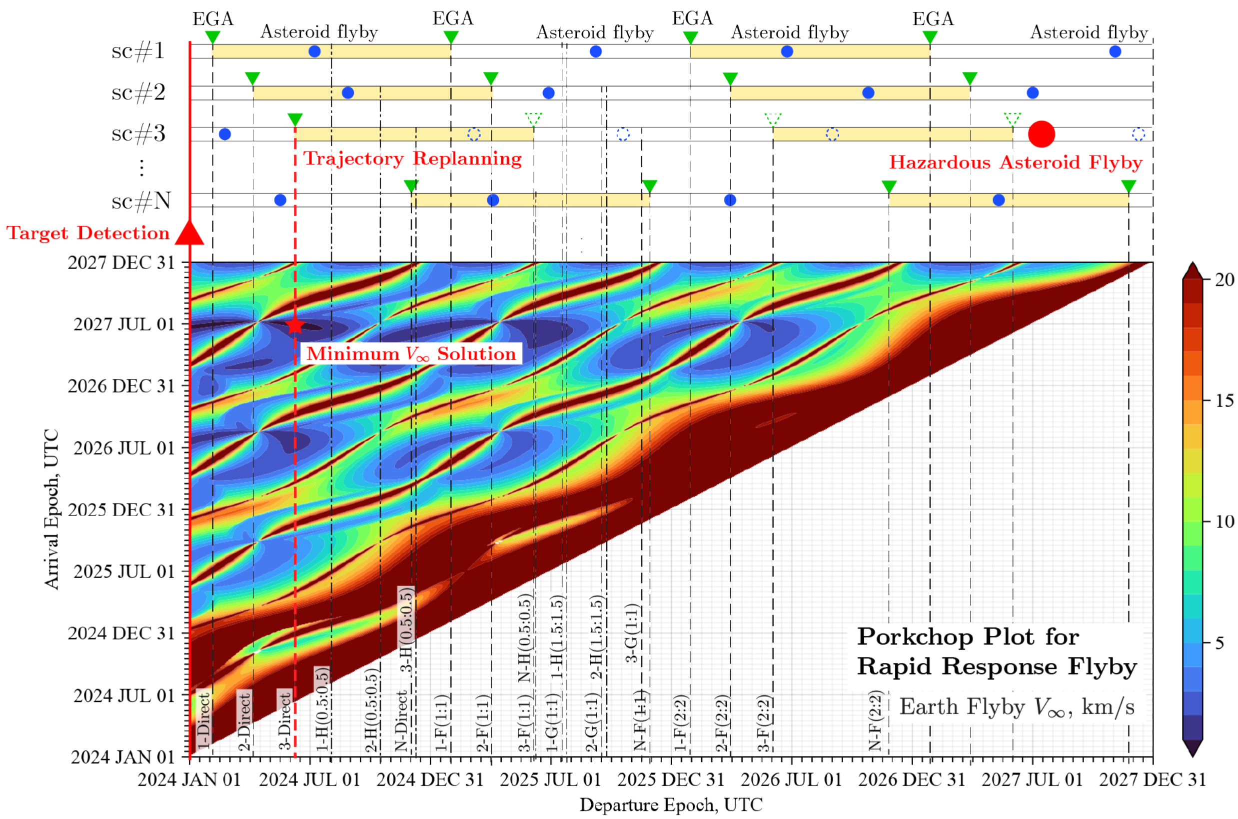


Figure 3: Mission design approach of rapid response flyby via deep space constellation. The plot shows the minimum ΔV required for a representative example of an Earth to 99942 Apophis ballistic transfer with the response time $\Delta t_{\text{res}} = 4$ years.

3. All spacecraft fly on a 1:1 Earth resonance flyby orbit. In other words, each spacecraft has an opportunity for an Earth gravity assist each year.
4. The dynamics of spacecraft and asteroids are governed only by the sun's gravity and the Earth gravity assist is modeled by a zero-radius sphere-of-influence patched-conics approach.

With 12 deep space probes ($N = 12$), the constellation has one Earth gravity assist opportunity per month. This means that once a month, at least one spacecraft can respond to a hazardous asteroid with an Earth gravity assist.

Figure 3 shows a porkchop plot of a ballistic transfer from Earth to an asteroid. The horizontal axis indicates the time of leaving Earth and the vertical axis indicates the time of arriving at the asteroid. The color map shows the Earth departure V_∞. The porkchop plot is drawn for the response time period after the initial detection of the asteroid. We can choose any point on the porkchop plot for an ideal direct launch with no lead time and no constraints on the Earth's escape direction. For the deep space constellation, the Earth departure times are constrained to discrete values that allow for an Earth swing-by. The departure times at which an Earth swing-by is possible are indicated by the dashed lines in Fig.3. The dashed lines are drawn at intervals of at least $1/N$ years. These lines are denser for trajectories with later departure dates because each spacecraft also has the option of using a free-return orbit to Earth, such as 0.5 years, 1 year, and 1.4 years [13, 14], to phase the orbit. It is important to note that because the target detection epoch is randomly chosen, the spacecraft may have to wait $1/N$ year for the Earth's departure. For simplicity, this analysis ignores the limits on the deflection angle during the Earth swing-by and the geometric constraints on the arrival of the asteroid. The deflection angle constraint limits the V_∞ direction of the Earth departure. To leave Earth in any direction, the number of spacecraft must be increased (e.g., by a factor of two if V_∞ is less than 5 km/s).

Numerical Results:

Now we statistically evaluate the minimum V_∞ required for a rapid response flyby using a deep space constellation. We use small bodies with $\mathrm{MOID} < 0.05\ \mathrm{au}$ from JPL's Small-Body Database Query as the targets [retrieved 04 March 2023]. The minimum orbit intersection distance (MOID) epoch is calculated with the target detection time set as the time when the orbit is backpropagated for a period of Δt_{warn} for each target.

Figure 4 illustrates the cumulative distribution function (CDF) of the minimum V_∞ for a range of response times. The encounter is feasible if the minimum V_∞ to fly by the target is greater than that of the constellation. The probability on the vertical axis of the CDF indicates what percentage of all asteroids can be visited. Keeping a large V_∞ allows most asteroids to be visited. However, a larger V_∞ will (i) reduce launch opportunities and (ii) cause the swing-by deflection angle to become constraining. For reference, we also show an ideal direct launch solution that achieves global minimum V_∞.

JAXA plans to launch the DESTINY$^+$ mission in 2024 [7]. The mission will consider multiple asteroid encounters via an asteroid flyby cycler as an extended mission after the 3200 Phaethon flyby. V_∞ relative to Earth will be $\sim$ 3 km/s at the beginning of the extended mission. With this value, a 3-year response time allows about 70% of the NEOs to be explored in a rapid response flyby, as shown in Fig.4c. To bolster this value, if we deploy a deep space constellation of $N = 5$, the percentage of explorable NEOs can be increased to about 85%.

Figure 5 shows an example of the multiple asteroid flyby orbits to be used during the loitering period. The required ΔV to fly by 5 asteroids is 124 m/s, which can be achieved with micro/nano spacecraft or CubeSat. A 50 kg class micro spacecraft could carry a scientific payload of $\sim$ 10 kg.

Discussion:

The concept of building a deep space constellation for rapid response flybys is significant not only from the perspectives of "planetary defense" but also from "planetary science" and "space exploration technology". Once the constellation is built, even a single set of constellations will achieve all of these aspects. Below, we briefly highlight the importance and challenges of missions from these three perspectives.

Planetary Defense: This mission will contribute to planetary defense through rapid response flyby reconnaissance and multiple flybys of PHAs to understand their characteristics. Compared to a direct launch from Earth, this mission is significant in that it can contribute to planetary defense even for countries that do not have a launch vehicle capable of immediate launch. This mission is feasible at a low cost because it can be accomplished by 50 kg class micro spacecraft placed in asteroid flyby cycler orbits, taking advantage of rideshare opportunities for lunar and planetary exploration. From a planetary defense perspective, asteroid gravity estimation technology is a special challenge to solve[15].

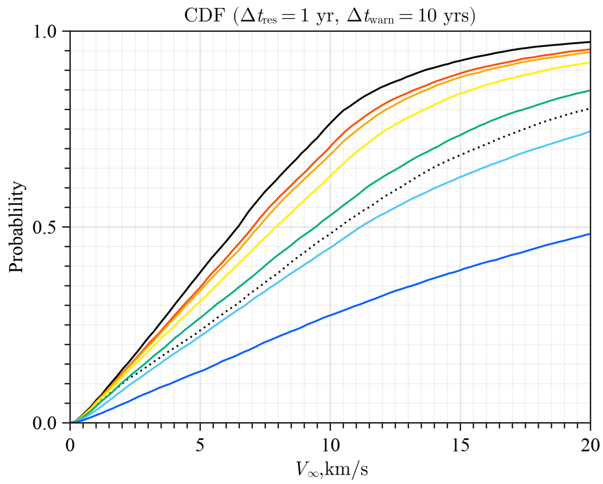
Planetary Science:

Today, more than 1,000,000 asteroids have been found, while only $\sim$10 asteroids have been visited so far. Asteroids are the remnants of planet formation and are a treasure trove for unraveling the mystery of the formation of the Solar System. Asteroids are not unique and have different shapes and morphologies as well as diverse chemical and isotopic signatures.

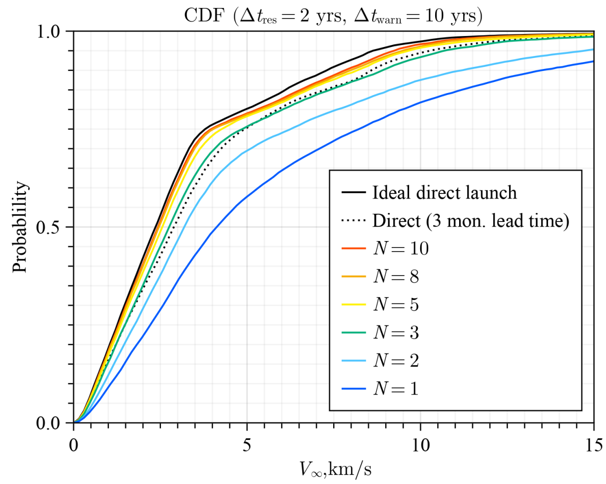
A sample-return mission or a rendezvous mission is an advantageous way to study a particular target in more detail, while a multiple flyby mission (deep space constellation architecture) is valuable and essential for briefly characterizing the diversity of asteroids. These different mission architectures are both needed and comprehensive to fully address the nature of asteroids.

This architecture could also enable a rapid response to an interstellar object and a long-period comet. In the past five years, we have discovered two definitive interstellar macroscopic objects passing through the inner Solar System, 1I/'Oumuamua [16] and 2I/Borisov. These two objects displayed significantly different properties. 1I/'Oumuamua displayed no cometary tail [17, 18], had an elongated shape [19] and exhibited significant nongravitational acceleration [20] 2I/Borisov displayed definitive cometary activity and the coma was enriched in hypervolatile CO with respect to H_2O [21, 22]. By performing an in-situ flyby with an interstellar comet, we could obtain detailed compositional measurements which may inform how planet formation varies throughout the galaxy.

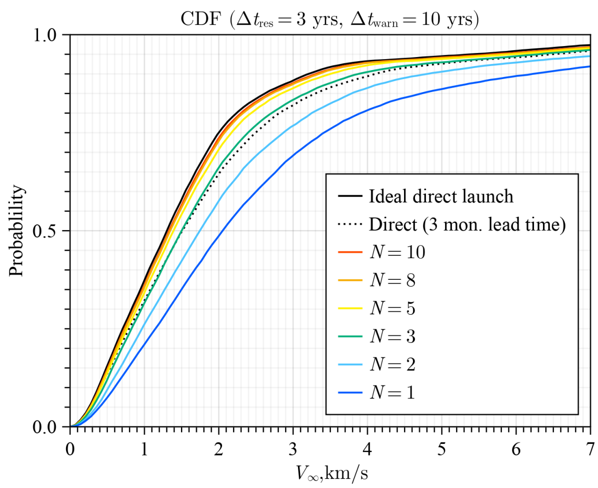
Planetary Exploration Technology: This mission, as well as the low-Earth orbit constellation, will provide an opportunity for continued demonstration of space exploration technologies, thereby enhancing technical capabilities. Even if one spacecraft is lost or its performance is



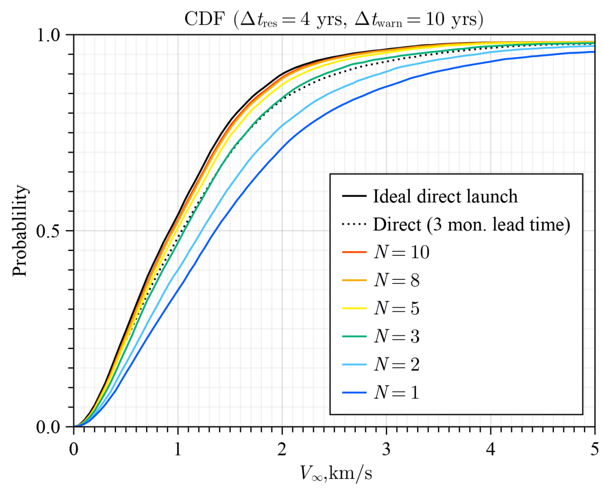
(a) Response time = 1 year



(b) Response time = 2 years



(c) Response time = 3 years



(d) Response time = 4 years

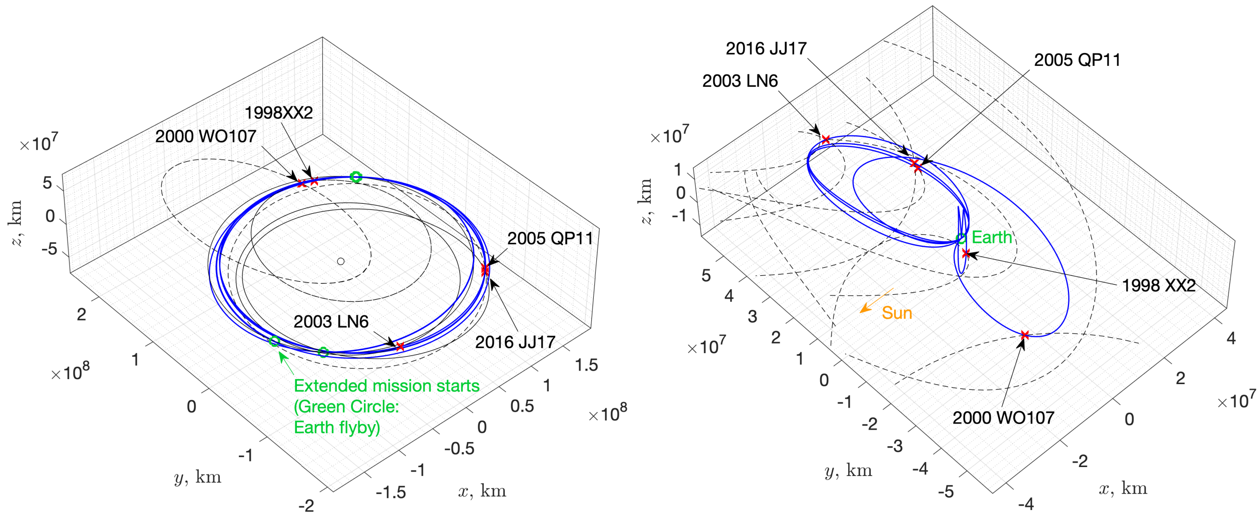
Figure 4: Cumulative distribution function of minimum V_∞

degraded, the remaining spacecraft can compensate for the loss or degradation, and the mission as a whole will not directly fail. In addition, by developing and operating multiple spacecraft, statistical information about the spacecraft itself can be obtained, which will greatly contribute to improving the quality of micro spacecraft. As for the propulsion system, an asteroid flyby cycler orbit can be maintained with a ΔV of about 10 m/s per year, making it an excellent opportunity to demonstrate solar sails and advanced propulsion systems.

Building a constellation of more than 10 spacecraft would make conventional ground station operations impossible for all the spacecraft. Moreover, unlike low Earth orbit constellations, deep space constellations cannot rely on GPS to determine their orbits. Current deep space exploration missions use radio navigation from ground stations to determine the spacecraft's orbit. Autonomous navigation technologies (e.g., optical navigation and X-ray pulsar navigation) that reduce ground station dependence are needed to make this concept a reality.

Conclusion:

The U.S. Decadal Survey reaffirms the importance of rapid flyby reconnaissance in planetary defense to understand the characteristics of hazardous asteroids and develop effective mitigation strategies. This study proposes an approach of loi-



(a) Sun-centered, inertial frame **(b) Earth-centered, Sun-Earth line fixed rotational frame**

Figure 5: Example of multiple asteroid flyby trajectory

tering dozens of micro spacecraft in deep space, specifically in Earth-resonant flyby orbits, until a hazardous asteroid is detected. This proposed mission architecture uniquely provides multiple flybys of NEOs while loitering in an Earth-resonant flyby orbit, where one NEO can be visited per month if 10 micro spacecraft are deployed. The numerical simulations to evaluate the capability of the rapid response flyby showed that a 5-vehicle configuration with a response time of 3 years and an Earth flyby V_∞ of 3 km/s would be able to explore 85% of the hazardous asteroids. This paper also discusses the importance and challenges of the proposed concept.

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