PDC 2019
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- [ ] **Key International and Political Developments**
- [ ] **Advancements in NEO Discovery**
- [ ] **New NEO Characterization Results**
- [ ] **Deflection & Disruption Modeling and Testing**
- [x] **Mission & Campaign Design**
- [ ] **Impact Consequences**
- [ ] **Disaster Response**
- [ ] **The Decision to Act**
- [ ] **Public Education and Communication**

Spacecraft Mission Design For The Mitigation Of The 2019 PDC Hypothetical Asteroid Threat

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In this paper we will present detailed mission design and analysis results for the 2019 Planetary Defense Conference (PDC) Hypothetical Asteroid Impact Scenario, which is described at `https://cneos.jpl.nasa.gov/pd/cs/pdc19/`. We will design mission campaigns to respond to the hypothetical asteroid, including reconnaissance of the asteroid to characterize it and assess the threat it poses to Earth. The mission campaigns will also involve threat mitigation via kinetic impactor deflection, nuclear explosive device (NED) deflection, or NED disruption. Assessments of kinetic impactor and NED performances will be based on appropriate simplified models during broad searches of the mission design

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space. Detailed high-fidelity computer models of kinetic impactor and NED performance will then be executed for the individual solutions of greatest interest.

Relevant scenario parameters will be varied within a range of values, to assess the sensitivity of the design outcome to input values, including: asteroid bulk density, asteroid diameter, momentum enhancement factor (β), spacecraft launch vehicle, mitigation system type, and other parameters.

We will examine a range of spacecraft trajectory types in our analysis, from purely ballistic to those involving optimal deterministic midcourse maneuvers, planetary gravity assists, and/or low-thrust solar electric propulsion. Both asteroid rendezvous and flyby trajectory options will be considered. Our trajectory design constraints are summarized in Table 1.

Table 1: Spacecraft trajectory design constraints.

Constraint	Value
Earth departure date (d)	Sept 1, 2022 $\leq d \leq$ April 1, 2027
Launch declination	within ±28.5
Spacecraft-asteroid relative velocity at intercept	≤10 km/s
Asteroid solar-phase angle at intercept	≤120°
Spacecraft propellant mass fraction	≤0.5
Spacecraft distance from the Sun (d_S)	0.7 $\leq d_S \leq$ 3.5 au
Sun-Spacecraft-Earth angle at critical events	≥3°
Individual Δv imparted to asteroid	≤8% asteroid surface escape velocity (4.795 cm/s)
Deflected asteroid perigee altitude	≥1 Earth radius

Herein we present brief descriptions of some preliminary results, assuming that the hypothetical threatening asteroid is spherical with a diameter of 200 m (corresponding to an absolute magnitude of 21.7 and geometric albedo of 0.092), has a bulk density of 1.5 g/cm^3, and has a rotation period of 4 hours.

As noted on the aforementioned webpage (`https://cneos.jpl.nasa.gov/pd/cs/pdc19/`), the hypothetical 2019 PDC asteroid is discovered on March 26th, 2019 and subsequently found to have a potential Earth impact date of April 29th, 2027. The hypothetical asteroid's orbital elements are summarized in Table 2, and ecliptic plane projections of the asteroid and Earth heliocentric orbits are shown in Figure 1.

Table 2: Hypothetical asteroid 2019 PDC's approximate orbital elements at epoch 2458602.668738426 JD (8 years prior to simulated Earth impact on April 29th, 2027).

Heliocentric Keplerian Orbital Element	Value
Semi-major axis	1.919 au
Eccentricity	0.534
Inclination	18.000°
Right Ascension of Ascending Node	38.430°
Argument of Perihelion	226.724°

In our preliminary work, we assumed that authority to proceed with spacecraft mission preparation would be given when the asteroid's Earth impact probability rises to 10%. We further assume that the Earth impact probability will rise to 10% by September 1st, 2019 (although the actual evolution of the Earth impact probability will not be revealed until the conference). We also assume that—very optimistically—it would take at least three years to prepare a spacecraft for launch, using current infrastructure. Thus, the earliest launch date allowed in our analysis is September 1st, 2022.

Figure 2 displays a map of the Δv that must be imparted to the asteroid to deflect it from Earth impact to a 1 Earth radius perigee altitude at Earth encounter, assuming that the Δv is applied in the direction of the asteroid's heliocentric inertial velocity vector. Note that opportunities to deflect the asteroid generally fall on or around the asteroid's perihelion passages, and the required Δv is generally on the order of 2–4 cm/s (except when very close to the Earth impact epoch, at which time the required Δv for deflection would be much higher).

Applying the aforementioned constraint on launch date (launch no earlier than September 1st, 2022) drastically reduces the number of deflection opportunities, as shown in Figure 3.

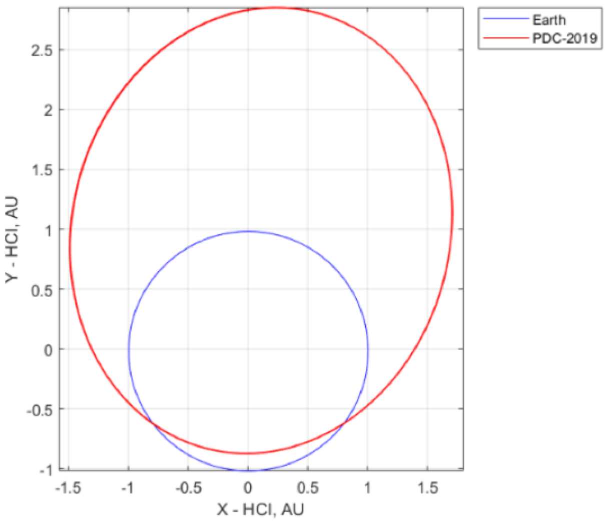

Figure 1: **Ecliptic plane projection of Earth and 2019 PDC heliocentric orbits.**

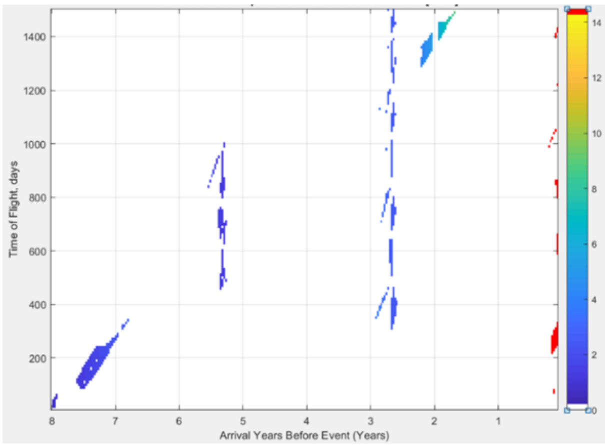

Figure 2: **Δv required to deflect the asteroid from Earth impact to a 1 Earth radius perigee altitude at Earth encounter, assuming the Δv is applied along the asteroid's heliocentric inertial velocity direction.**

It should be noted that a low-strength or strengthless asteroid may begin to weakly disrupt if a Δv greater than or equal to ~10% of its surface escape velocity is applied to the asteroid. The hypothetical asteroid considered herein has a surface escape velocity of 4.79 cm/s (computed using the aforementioned assumptions for the asteroid's physical properties), and so the required Δv for deflection (~2–4 cm/s) is well in excess of ~10% of the asteroid's surface escape velocity, raising the possibility of accidental weak disruption of the asteroid, which is undesirable. We will present approaches to dealing with this situation in our final paper.

In our preliminary work thus far we have begun analyzing various types of low-thrust and chemical propulsion spacecraft flyby and rendezvous trajectories to reach the asteroid for reconnaissance or deflection/disruption. For the preliminary results presented herein, we are optimizing the trajectories to maximize the spacecraft mass delivered to the asteroid. Additionally, these preliminary results assume use of the SpaceX Falcon Heavy launch vehicle, onboard spacecraft chemical propulsion systems with a specific impulse of 320 seconds, and, for the low-thrust trajectories, solar electric low-thrust propulsion via dual BPT-4000 thrusters using the high-thrust setting, and with 30 kW of power at 1 au from the Sun, a duty cycle of 90%, and a reserved propellant margin of 10%.

Figure 4 shows preliminary example low-thrust and chemical propulsion rendezvous trajectories for potential deflection missions. These trajectories reach the asteroid in September of 2024, providing enough time to position a nuclear explosive device (NED) and detonate at the appropriate time for asteroid deflection. However, note that the spacecraft mass delivered by these trajectories is relatively

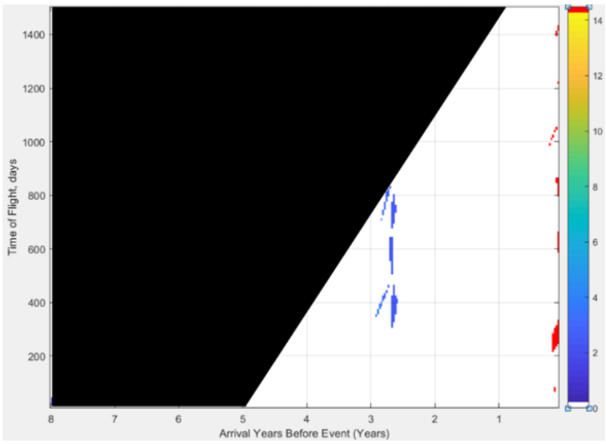

Figure 3: **Δv required to deflect the asteroid from Earth impact to a 1 Earth radius perigee altitude at Earth encounter, assuming the Δv is applied along the asteroid's heliocentric inertial velocity direction. The black shaded area covers up deflection opportunities rendered unavailable by the constraint to launch no earlier than September 1st, 2022.**

low: 999 kg delivered by the low-thrust rendezvous, and a mere 149 kg delivered by the chemical propulsion rendezvous (which also requires a very high, and almost certainly impractical, rendezvous Δv of ~5.1 km/s). We have also found some example trajectories delivering less mass—but potentially still useful for reconnaissance—that rendezvous with the asteroid several months before September 2024. Additionally, we have found trajectories that deliver more spacecraft mass, but those trajectories arrive about a year later than September 2024, which may be too late for effective deflection (but, perhaps, not too late for disruption).

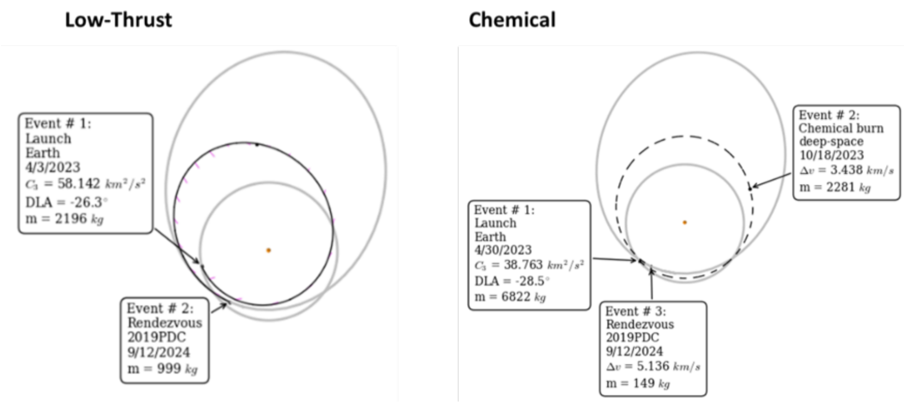

Figure 4: **Example preliminary trajectories to rendezvous with the hypothetical asteroid during a desirable timeframe for asteroid deflection.**

Figure 5 shows preliminary example low-thrust and chemical propulsion flyby trajectories for potential deflection (or disruption) missions. These trajectories reach the asteroid at the desired timeframe for deflection, September 2024, and deliver enough mass to carry sufficient nuclear explosives for deflection (and, possibly, disruption). Both the low-thrust and chemical propulsion trajectories shown here involve a high relative speed at asteroid arrival of 10 km/s. This was achieved by enforcing the constraint on relative speed at asteroid intercept, and it may be possible to reduce the relative speed at arrival at the cost of spacecraft mass, if desired/warranted.

We will complete our analysis of various combinations of mission campaign options and identify those that appear best for responding to the 2019 PDC hypothetical threat scenario. We will also generalize some design principles that could be applied during an actual planetary defense scenario. The following topics will also be discussed:

- The number of redundant mitigation mission spacecraft that should be deployed to ensure suf-

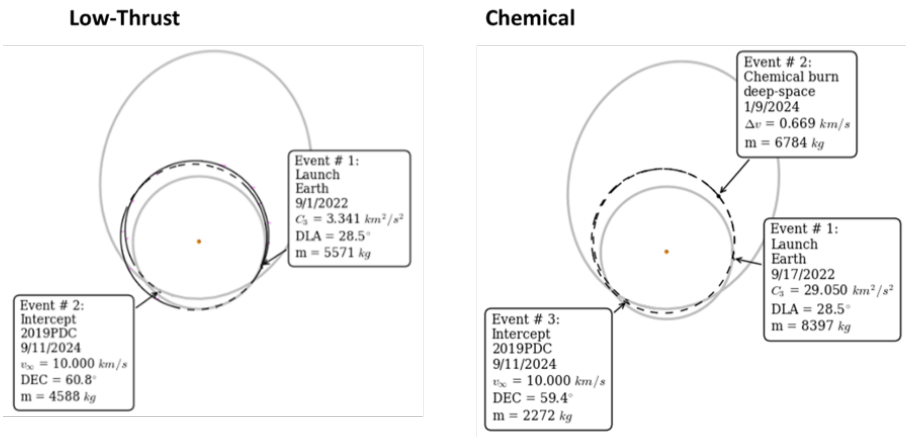

Figure 5: Example preliminary trajectories to perform high-speed flyby of the hypothetical asteroid during a desirable timeframe for asteroid deflection.

ficient mission reliability. Solutions that achieve mission success with only a single mitigation spacecraft are preferred. Several copies of such spacecraft could be deployed to provide sufficient mission reliability.

- What particular asteroid characterization data are needed from the reconnaissance missions for various purposes, including informing subsequent mitigation activities and predicting Earth impact effects.
- What asteroid characterization data is obtainable by a spacecraft during a hypervelocity asteroid flyby.
- The spacecraft and mission requirements, e.g., absolute and relative navigation, sensor performance, etc.
- Issues associated with terminal guidance, navigation, and control for hypervelocity asteroid intercept.
- Constraints on asteroid/spacecraft range sensing and timing performance for standoff NED detonation during hypervelocity intercept.

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