National Aeronautics and Space Administration

Spacecraft Mission Design for The Mitigation of The 2017 PDC Hypothetical Asteroid Threat

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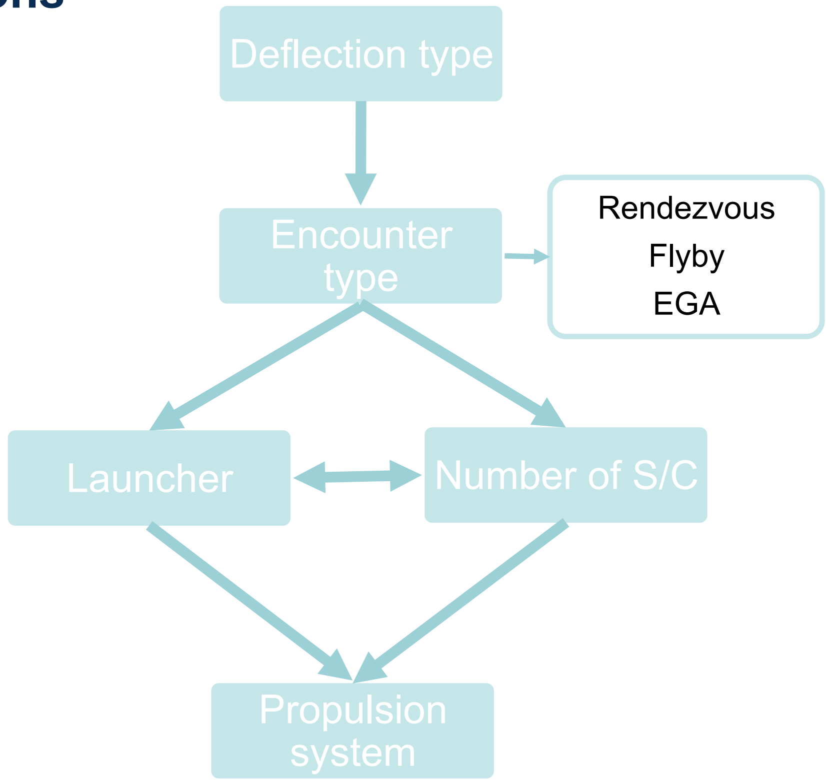
NAVIGATION & MISSION DESIGN BRANCH
NASA GSFC

Introduction

- Planetary defense is an important contemporary problem
  - 16106 known NEOs, and counting
  - 1797 known PHOs, and counting
  - ~Several dozens of NEOs >1000 m in size not yet found
  - >10000 NEOS between 100 m and 1000 m not yet found
  - ~Several millions of NEOs between 10 m and 100 m in size not yet found
  - Chelyabinsk impact February 15, 2013: ~20 m asteroid, 0.5 MT explosion, ~1600 injuries
- The 2017 PDC hypothetical asteroid impact scenario provides a valuable opportunity for studying possible responses to a realistic scenario
- Herein we consider a range of space-based responses including:
  - Reconnaissance of the 2017 PDC asteroid prior to a mitigation attempt
  - Mitigation via deflection or disruption
  - Monitoring of the asteroid during and/or after the mitigation attempt
- We consider two of the most mature concepts for asteroid deflection (Kinetic Impactor (KI) and Nuclear Explosive Device (NED)
  - We also consider the use of a NED to disrupt the asteroid in cases where deflection is impractical

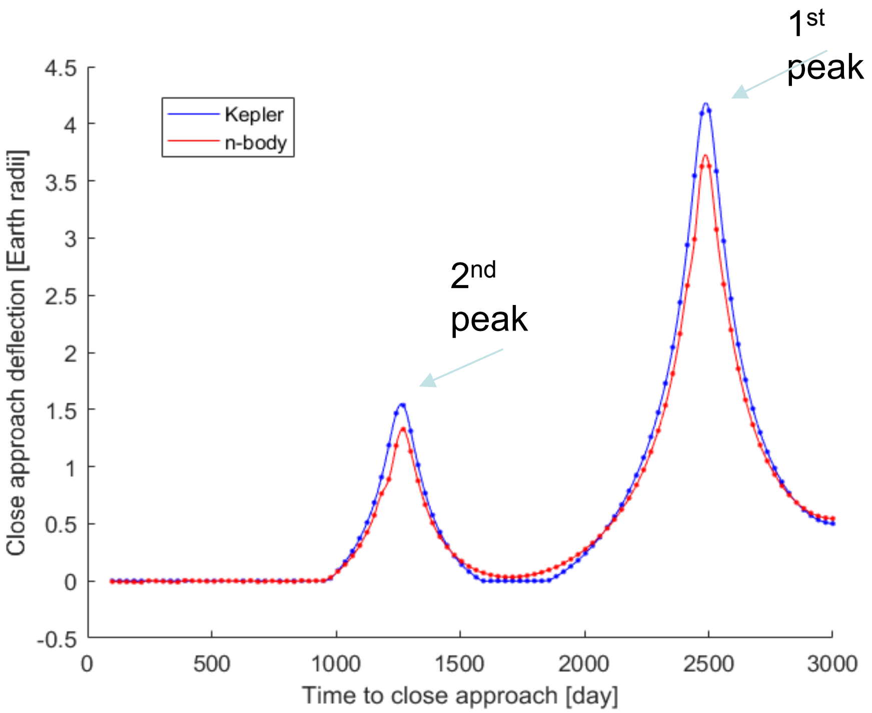
Study Concept

- Trade-off from different mission options
- Mission types
  - Survey, Deflection/Disruption
  - Order of operations
- Deflection methods
  - Kinetic impactor
  - Nuclear explosive device
- Launchers
- Trajectory options
  - Ballistic
  - Deep space maneuver
  - Low-thrust



Maximum Deflection Time Estimation

- Keplerian 2-body dynamics for peak deflection times
  - Completes quickly
- Uses linear correctors
- Imparted asteroid velocities
  - In direction of heliocentric velocity
  - Opposite direction
- Peak time used for initial guess for trajectory design



Mission Scenarios/Analysis (Constraints)

Constraint	Value	Reason
Launch date	after Aug. 1, 2019	2 years after the asteroids probability of Earth impact rises to 10%.
Launch declination	± 28.5	Declination bounds for the Kennedy launch complex.
Asteroid encounter phase angle	≤ 120	Upper limit to have enough of the asteroid illuminated for the spacecraft's terminal guidance system.
Sun minimum distance	0.7 A.U.	Lower limit for the spacecraft design to handle the more aggressive thermal and radiation environments.
Sun maximum distance	3.5 A.U.	Upper limit to design a large spacecraft (complicated) enough to handle power generation and Earth communications at greater distances is probably not compatible with a rapid spacecraft build timeline.
Earth Angle at asteroid encounter	≥ 3	Lower limit for the Deep Space Network to guarantee a viable RF link with the spacecraft.

Mission Scenarios/Analysis (Asteroid Cases)

Case	Asteroid Diameter (meters)	Asteroid Density (g/cm^3)	Asteroid Escape Velocity (cm/s)	Max Δv from NED (cm/s)
1	385	2.6	23.2099	6.123
2	100	1.5	4.579	63.808
3	150	1.5	6.8685	26.918
4	200	1.5	9.158	14.542
5	270	1.5	12.3633	7.623

Mission Scenarios/Analysis (Ballistic Kinetic Impactor)

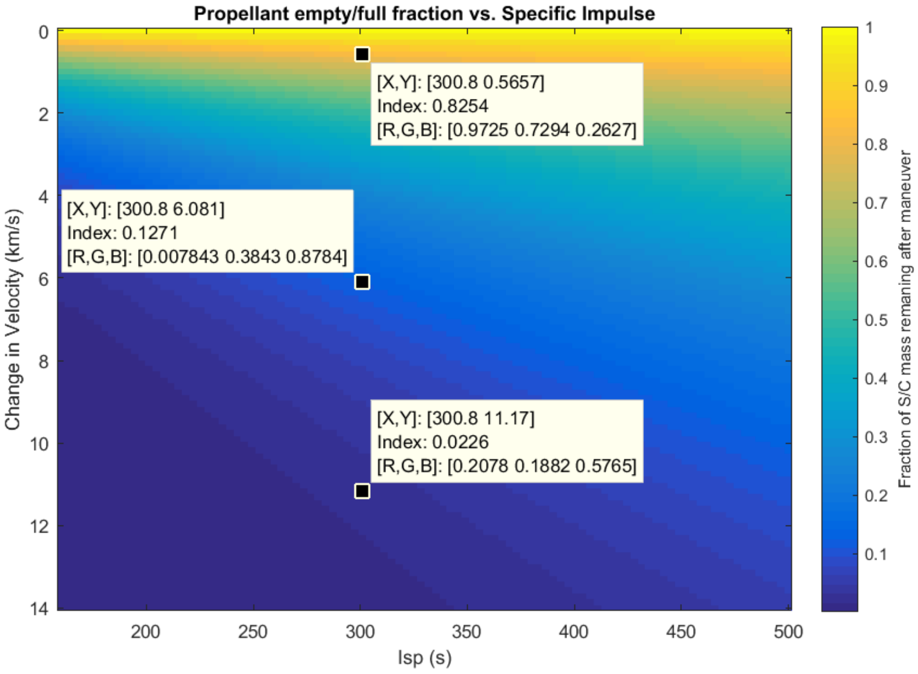
Cases	Mission Type	Launch Vehicle	# of Launches	Launch C3 (km^2/s^2)	Launch Date (MM-DD-YYYY)	Ast. Arrival Date (MM-DD-YYYY)	Asteroid ΔV (cm/s)	S/C Mass @ Arrival (kg)	Minimum Solar Distance (AU)	Rel. Speed at Asteroid (km/s)	Impact Specific Energy (J/kg)	Escape Velocity Fraction (DV/Vesc)	Deflection (Earth Radii)
1	BK	D	23	21.719	10/25/2022	2/17/2024	1.835	146051	0.7	9.759	89.52	0.079	1.034
	BK	S	4	21.719	10/25/2022	2/17/2024	1.788	142311	0.7	9.759	87.22	0.077	0.983
	BK	D	20	17.274	11/9/2021	11/9/2023	1.800	138255.5	0.7	10.117	91.07	0.078	0.933
	BK	S	3	17.274	11/9/2021	11/9/2023	1.487	114153.6	0.7	10.117	75.19	0.064	0.609
	BN	S	1	13.837	10/15/2022	2/17/2024	1.857	6118	0.7	4		0.080	1.114
	BN	D	1	13.837	10/15/2022	2/17/2024	1.857	7365	0.7	9.523		0.080	1.114
2	BK	A401	1	21.719	10/25/2022	2/17/2024	1.864	1500	0.7	9.759	90.93	0.407	1.066
	BK	A401	1	17.274	11/9/2021	11/9/2023	1.932	1500	0.7	10.117	97.73	0.422	1.072
	BK	A421	1	30.77	8/11/2023	2/7/2024	1.440	820.5226	0.5	13.784	99.25	0.314	0.529
	BK	A421	1	53.537	9/10/2023	2/17/2024	1.544	948.9111	0.5	12.783	98.71	0.337	0.682
	BK	A551	1	72.5	9/20/2023	2/17/2024	1.506	896.96	0.5	13.188	99.31	0.329	0.577
3	BK	D	1	21.719	10/25/2022	2/17/2024	1.835	4983.266	0.7	9.759	89.52	0.267	1.034
	BK	A551	1	21.719	10/25/2022	2/17/2024	1.470	3993.51	0.7	9.759	71.74	0.214	0.643
	BK	A401	2	17.274	11/9/2021	11/9/2023	1.543	4043.16	0.7	10.117	78.05	0.225	0.666
	BK	A421	1	17.274	11/9/2021	11/9/2023	1.246	3265.35	0.7	10.117	63.04	0.181	0.372
	BK	A551	1	17.274	11/9/2021	11/9/2023	1.669	4373.13	0.7	10.117	84.42	0.243	0.796
	BK	D	1	30.77	8/11/2023	2/7/2024	1.448	2785.14	0.5	13.784	99.82	0.211	0.537
	BK	A551	1	30.77	8/11/2023	2/17/2024	1.448	2785.14	0.5	13.188	99.82	0.211	0.537
	BK	A421	1	30.77	8/11/2023	2/17/2024	1.236	2377.11	0.5	13.188	85.20	0.180	0.334
	BK	A551	3	72.5	9/20/2023	2/17/2024	1.506	3027.23	0.5	13.188	99.31	0.219	0.577
	BK	D	2	72.5	9/20/2023	2/17/2024	1.506	3027.232	0.5	13.188	99.31	0.219	0.577
	BK	D	1	53.537	9/10/2023	2/17/2024	1.509	3128.74	0.5	12.783	96.44	0.220	0.646
	BK	A551	2	53.537	9/10/2023	2/17/2024	1.557	3228.74	0.5	12.783	99.52	0.227	0.695

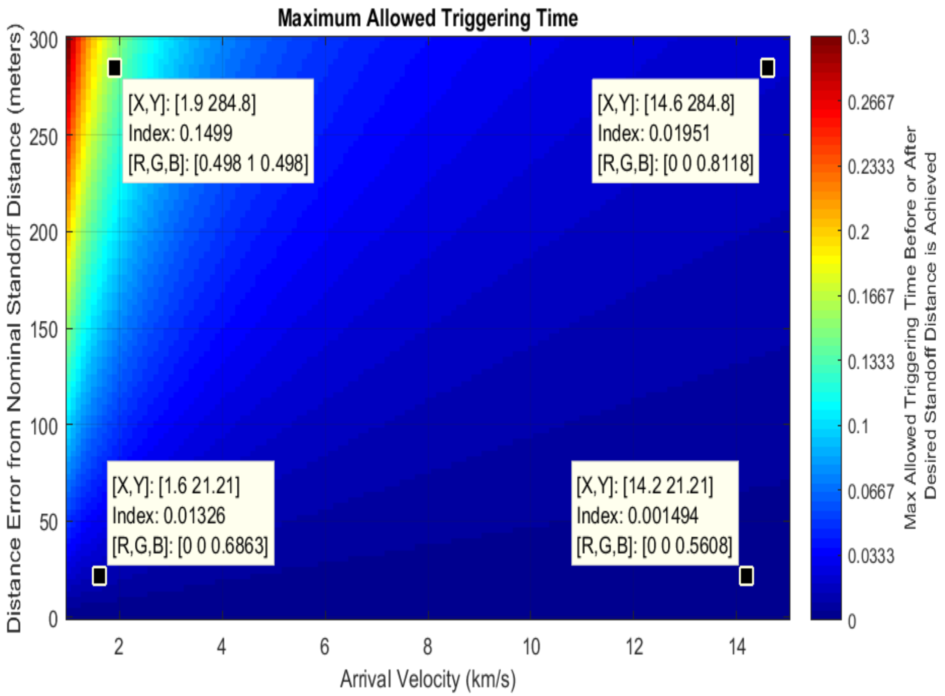
Mission Scenarios/Analysis (Ballistic Kinetic Impactor)

Cases	Mission Type	Launch Vehicle	# of Launches	Launch C3 (km^2/s^2)	Launch Date (MM-DD-YYYY)	Ast. Arrival Date (MM-DD-YYYY)	Asteroid ΔV (cm/s)	S/C Mass @ Arrival (kg)	Minimum Solar Distance (AU)	Rel. Speed at Asteroid (km/s)	Impact Specific Energy (J/kg)	Escape Velocity Fraction (DV/Vesc)	Deflection (Earth Radii)
4	BK	D	2	21.719	10/25/2022	2/17/2024	1.973	12700.09	0.7	9.759	96.25	0.215	1.186
	BK	A401	3	21.719	10/25/2022	2/17/2024	0.835	5377.42	0.7	9.759	40.75	0.091	0.024
	BK	A551	3	21.719	10/25/2022	2/17/2024	1.861	11980.52	0.7	9.759	90.79	0.203	1.063
	BK	A401	6	17.274	11/9/2021	11/9/2023	1.953	12129.48	0.7	10.117	98.79	0.213	1.094
	BK	A401	3	17.274	11/9/2021	11/9/2023	1.953	6064.74	0.7	10.117	49.39	0.107	0.122
	BK	A421	3	17.274	11/9/2021	11/9/2023	1.577	9796.06	0.7	10.117	79.78	0.172	0.701
	BK	A551	2	17.274	11/9/2021	11/9/2023	1.408	8746.26	0.7	10.117	71.23	0.154	0.53
	BK	D	1	17.274	11/9/2021	11/9/2023	1.113	6912.78	0.7	10.117	56.30	0.122	0.245
	BK	D	2	30.77	8/11/2023	2/7/2024	1.440	6562.18	0.5	13.784	99.22	0.157	0.528
	BK	A551	2	30.77	8/11/2023	2/7/2024	1.447	6594.42	0.5	13.784	99.71	0.158	0.535
	BK	A551	6	72.5	9/20/2023	2/17/2024	1.516	7223.73	0.5	13.188	99.31	0.166	0.587
	BK	S	1	72.5	9/20/2023	2/17/2024	1.506	7175.66	0.5	13.188	99.31	0.164	0.577
	BK	A551	2	30.77	8/11/2023	2/7/2024	1.447	6594.42	0.5	13.784	99.71	0.158	0.535
	BK	D	3	53.537	9/10/2023	2/17/2024	1.544	7591.29	0.5	12.783	98.71	0.169	0.682
	BK	A551	4	53.537	9/10/2023	2/17/2024	1.557	7650.86	0.5	12.783	99.49	0.170	0.695
5	BK	D	5	21.719	10/25/2022	2/17/2024	1.835	29062.4	0.7	9.759	89.52	0.148	1.034
	BK	D	4	21.719	10/25/2022	2/17/2024	1.203	19050.13	0.7	9.759	58.68	0.097	0.368
	BK	S	1	21.719	10/25/2022	2/17/2024	1.788	28318.19	0.7	9.759	87.22	0.145	0.983
	BK	D	4	17.274	11/9/2021	11/9/2023	1.810	27651.1	0.7	10.117	91.53	0.146	0.942
	BK	D	3	17.274	11/9/2021	11/9/2023	1.357	20738.33	0.7	10.117	68.65	0.110	0.48
	BK	D	3	30.77	8/11/2023	2/7/2024	1.407	15776.37	0.5	13.784	96.95	0.114	0.497
	BK	S	1	72.5	9/20/2023	2/17/2024	1.261	14787.2	0.5	13.188	83.18	0.102	0.345
	BK	D	6	53.537	9/10/2023	2/17/2024	1.544	18677.42	0.5	12.783	98.71	0.125	0.682

Mission Scenarios/Analysis (Ballistic NED)

- **Any KI mission solution can be used for NED**

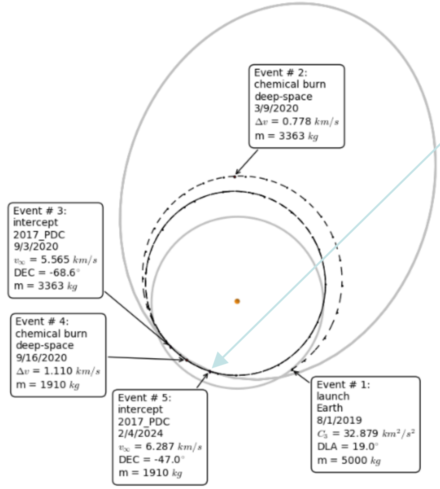




Mission Scenarios/Analysis (DSM)

Single S/C

- Survey + Deflection



2nd peak

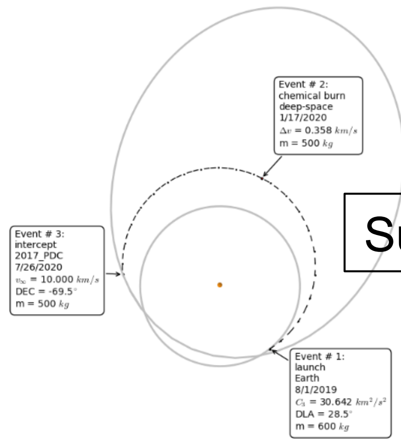
Two flybys

No Rendezvous Solution

Double S/C

- Survey

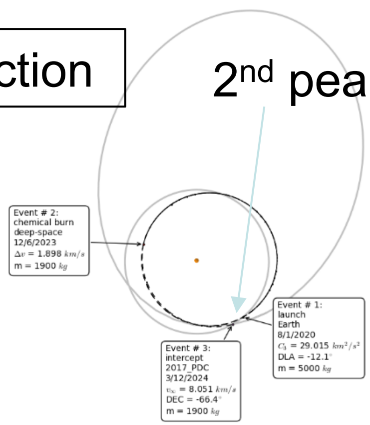
- Deflection



Survey

Deflection

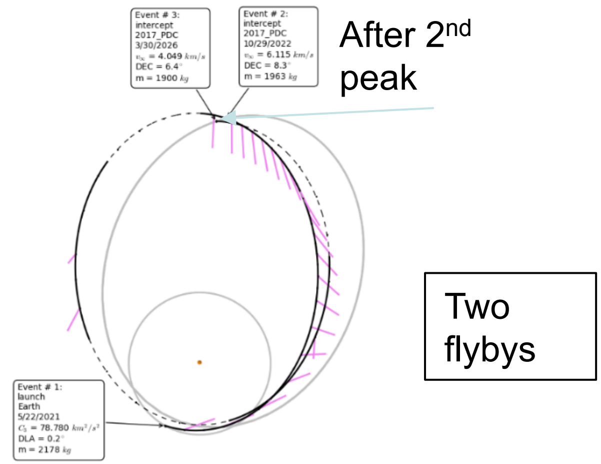
2nd peak

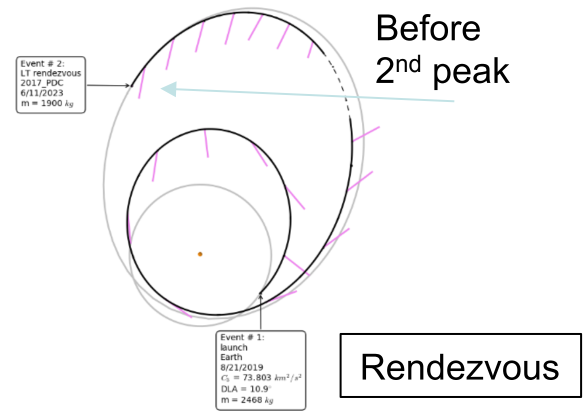


Mission Scenarios/Analysis (Low-Thrust)

Single S/C

- Survey + Deflection

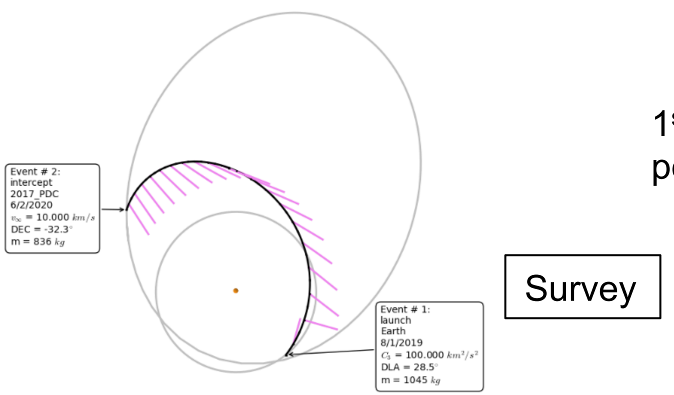


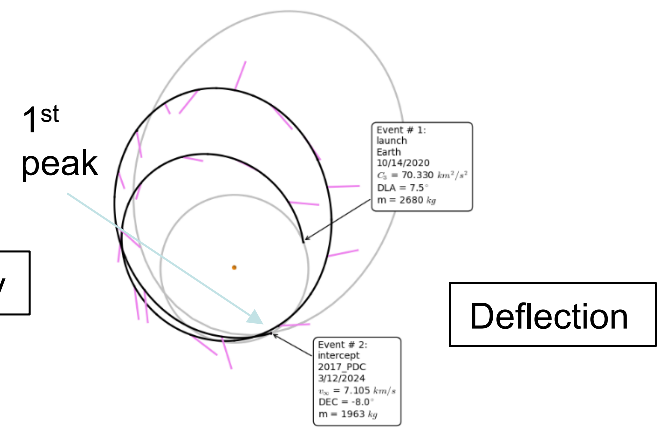


Double S/C

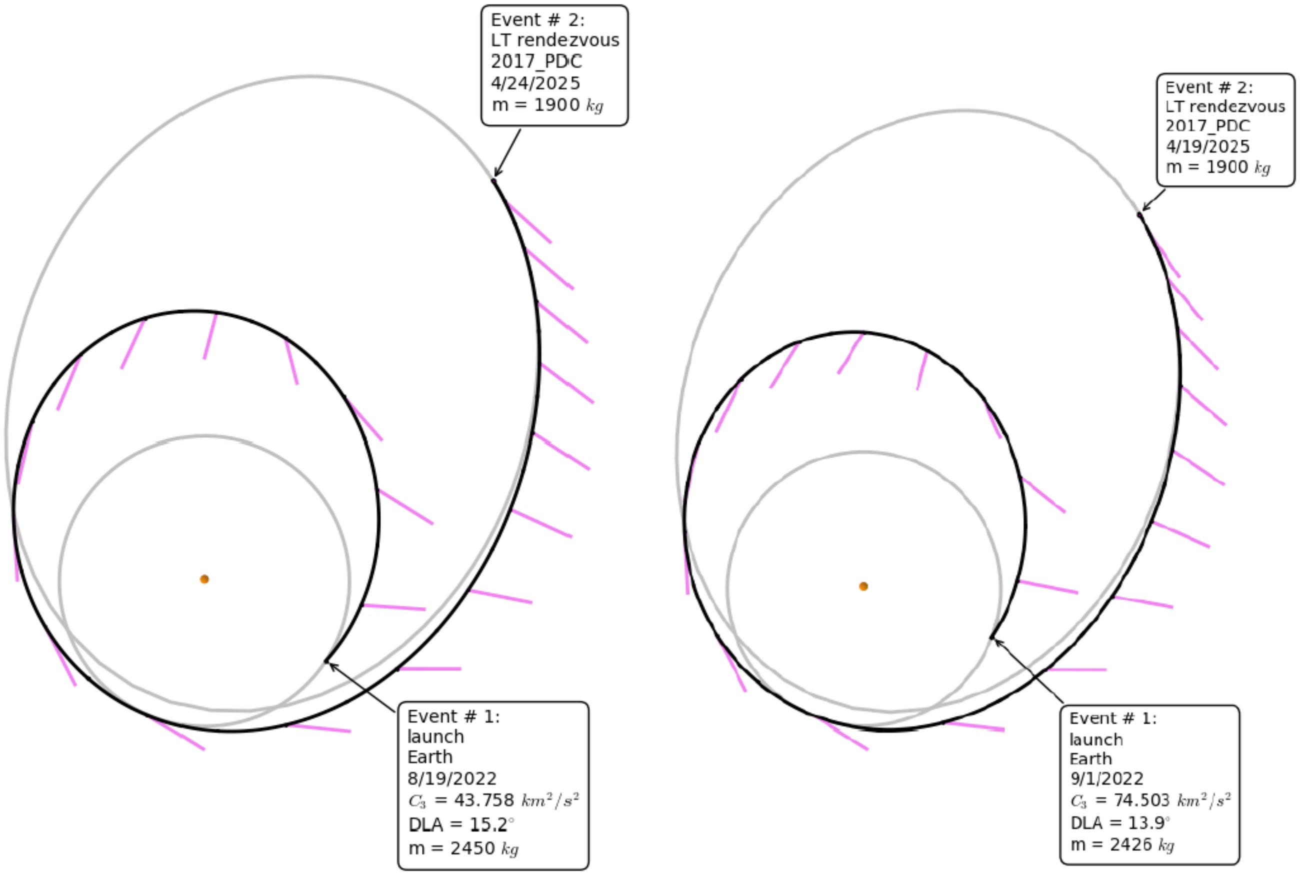
- Survey

- Deflection





Disruption Low-thrust (Rendezvous)



(a) Atlas V

(b) Delta IV

Conclusion

- Developed planetary defense mission concepts for 2017 PDC hypothetical asteroid impact scenario
- Trade study of different mission concepts
  - Deflection and disruption strategies
- Identified peak deflection times using a fast and robust algorithm
- Successfully obtained desirable mission trajectories for maximum deflection or observation missions
  - Ballistic scenarios
  - DSM
  - Low-thrust
- Small asteroids cannot withstand KI or NED deflection
  - Disruption is the only practical solution