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Institutul Astronomic al Academiei Romane

Space and Exploration Technology Group

A Multi-Spacecraft Strategy for the Capture of Near-Earth Asteroids

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Asteroids

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- Different types of asteroids based one their observed albedos and reflectance spectra

  - C-type: carbonaceous asteroids
    - Most abundant and most desirable
    - Rich in water, other volatiles and metals
  - M-type: stony-iron or iron asteroids
    - Rich in platinum group metals
  - S-type: stony asteroids
    - Contain volatiles, metals and semi-conductors, but smaller quantities

Near-Earth asteroids

- Perihelion < 1.3 AU, aphelion distance > 0.983 AU

- Originate from the main asteroid belt

- Can be categorized according to orbit:
  - Amors: do not cross Earth’s orbit, are exterior to Earth’s orbit
  - Apollos: cross Earth’s orbit, semi-major axis larger than Earth’s orbit
  - Atens: cross Earth’s orbit, semi-major axis smaller than Earth’s orbit
  - Atiras: do not cross Earth’s orbit, are interior to Earth’s orbit

- Most easily accessible from Earth

Asteroid capture missions

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- Asteroid capture missions bring asteroids closer to Earth

- Interesting for:

  - Asteroid mining
  - Scientific research
  - Earth defence

Asteroid mining

- In-situ resource utilisation
  - Water, semi-conductors, metals can be used for life-support, propellant and in-space manufacturing
- Rare-Earth materials
  - Platinum group metals, selenium, gallium, used for renewable energy technologies

Asteroid deflection methods

- Gravity Tractor
  - Uses the gravity of the spacecraft to change the asteroids direction
  - Requires a long period of time
  - Uses thruster to maintain a distance from the asteroid
- Ion Beam
  - Momentum of asteroid changed with an ion thruster
  - Thruster on opposite side required to maintain position
- Laser ablation
  - Laser is pointed at asteroid for the ablation of the surface material
  - Ejecta plume is formed which delivers a thrust to change the direction

Asteroid deflection methods

- Tugboat
  - Spacecraft attaches to asteroids
  - Turns on thruster to change direction
  - Either low-thrust or chemical propulsion
- Nuclear detonator
  - Detonate nuclear explosive close to/on asteroid
  - Fragments of asteroid could still hit the Earth
  - Controversial
- Kinetic Impact
  - Spacecraft impacts the asteroid
  - Asteroid characteristics important
  - DART mission

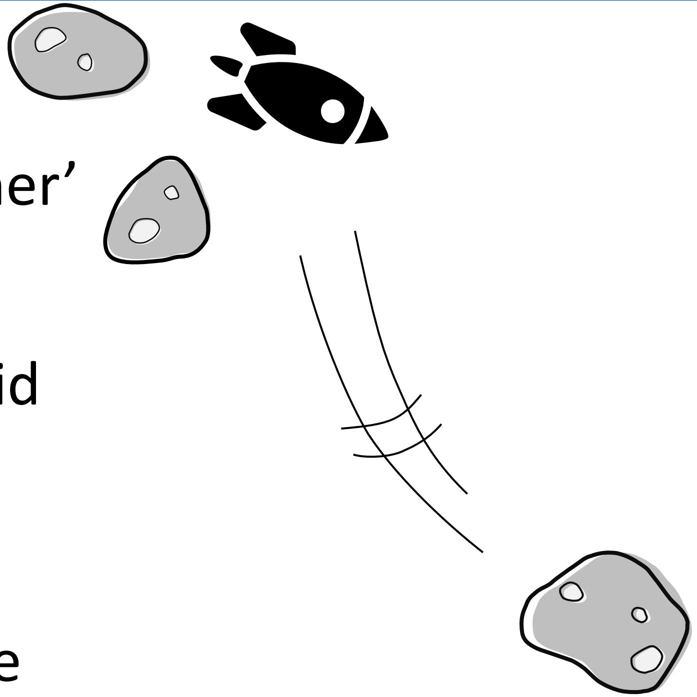
Asteroid capture missions

- Various concepts for asteroid capture missions have been studied
- Both chemical and low-thrust propulsion have been investigated
- A list of so-called ‘Easily Retrievable Objects’ has been identified (Garcia Yarnoz et al., 2013)
- Invariant manifolds are used to capture the asteroids

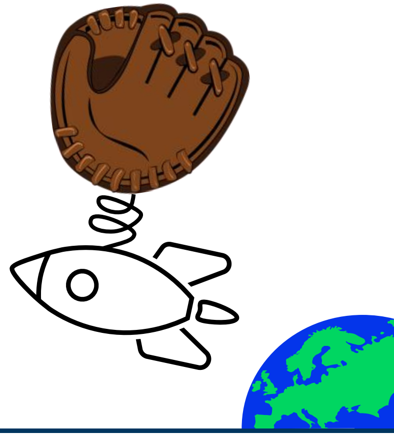
Invariant manifolds

- Dynamical structures in the three-body problem
- Consist of a set of trajectories
- End in an orbit around the collinear Lagrange points
- Both Earth-Moon system as Sun-Earth system have been considered

Two-spacecraft strategy



- Two spacecraft work together as a ‘pitcher’ and ‘catcher’
- The pitcher spacecraft hops from asteroid to asteroid and deflects the asteroids towards the Earth
- The catcher spacecraft is stationed at the Earth and captures the incoming asteroids



Publications with two-spacecraft strategy:

- L. Ionescu, C. R. McInnes, and M. Ceriotti, “A multiple-vehicle strategy for near-Earth asteroid capture,” *Acta Astronautica*, Vol. 199, Oct. 2022, pp. 71–85, 10.1016/j.actaastro.2022.07.004.
- L. Ionescu, C. R. McInnes and M. Ceriotti, “Use of powered Earth fly-bys to enhance mass retrieval for a two-spacecraft asteroid capture strategy”, proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Charlotte, NC, USA, August 7-11, 2022.

Two-spacecraft strategy

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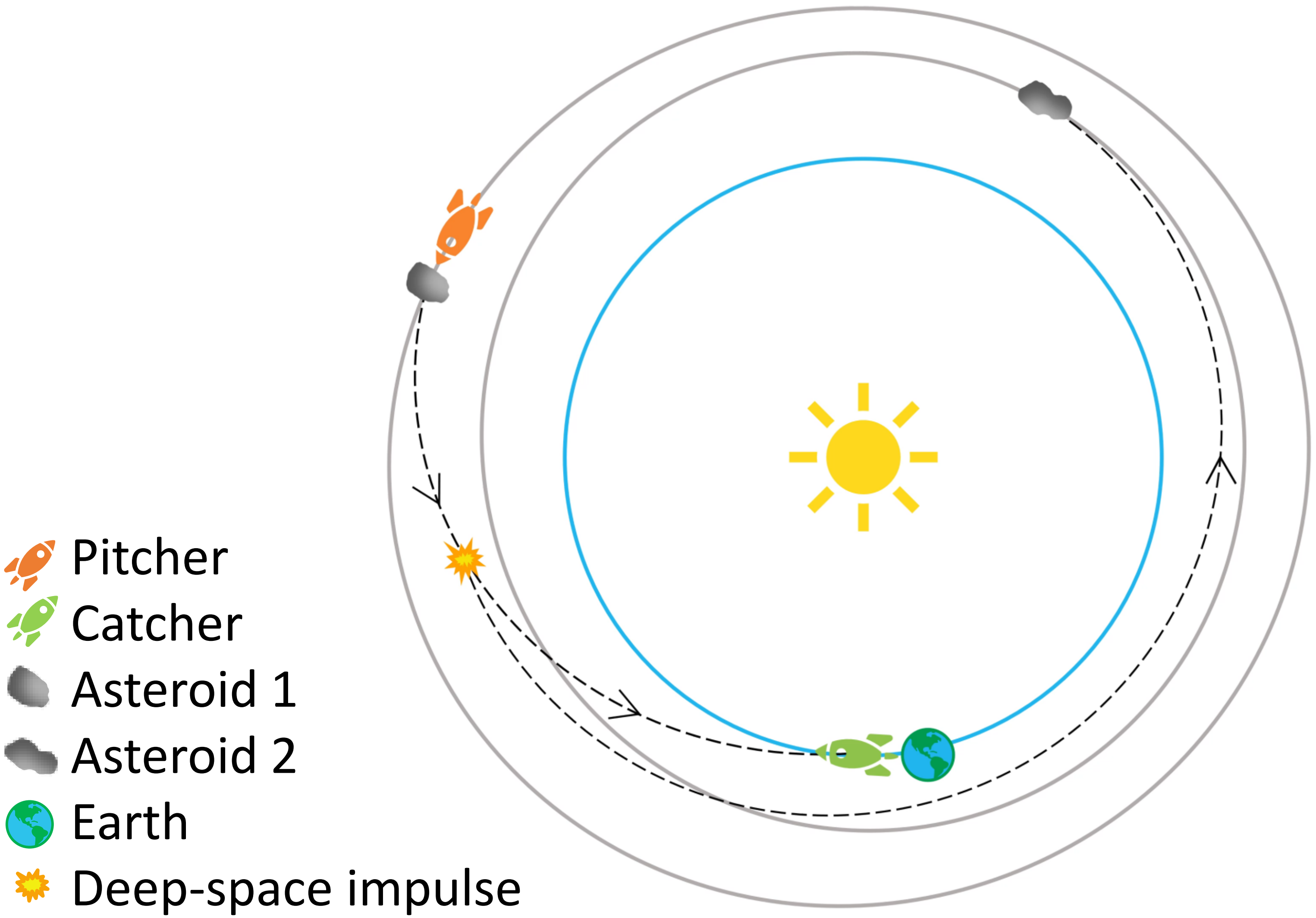

Capture of one asteroid:

1. Deflect asteroid 1
2. Deep-space impulse (separate from asteroid)
3. Arrive at asteroid 2

(4. Repeat)

One-spacecraft strategy

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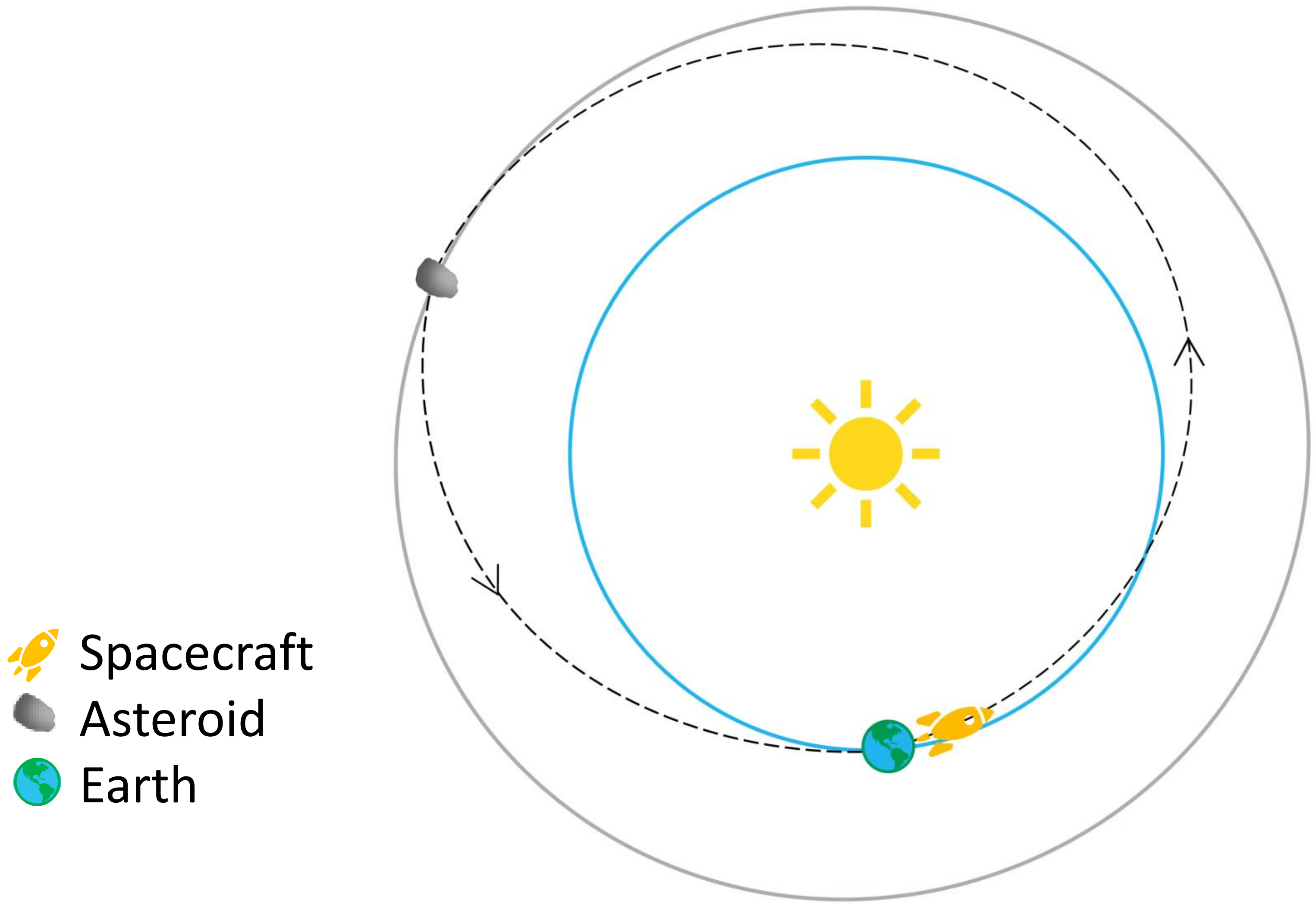

Capture of one asteroid:

1. Transfer to asteroid
2. Rendezvous with asteroid
3. Deflect asteroid
4. Capture asteroid

Optimization method – real NEAs

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- Each mission targets a **sequence** of 3 asteroids
- Subset of near-Earth asteroids from the JPL database
- All permutations of each combination of 3 asteroids are optimized
- Three-dimensional, Keplerian model with instantaneous impulses
- Optimization done with genetic algorithm

Objective functions

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One-spacecraft strategy:

$$m_{n,1sc} = n \frac{f_{dry} - e^{-\Delta V_{total,1sc}/V_e}}{\sum_{i=1}^{2n-1} \left((-1)^{i-1} e^{-\sum_{j=2i+1}^{4n} \Delta V_j / V_e} \right) - 1}$$

Two-spacecraft strategy:

$$m_{n,2sc} = n \frac{\frac{M_a}{M_{0,C}} \frac{M_a}{M_{0,P}}}{\frac{M_a}{M_{0,C}} + \frac{M_a}{M_{0,P}}}$$

Ratio of asteroid mass per unit of wet spacecraft mass

Objective functions

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One-spacecraft strategy:

$$m_{n,1sc} = n \frac{f_{dry} - e^{-\Delta V_{total,1sc}/V_e}}{\sum_{i=1}^{2n-1}\left((-1)^{i-1} e^{-\sum_{j=2i+1}^{4n} \Delta V_j/V_e}\right) - 1}$$

Two-spacecraft strategy:

$$m_{n,2sc} = n \frac{\frac{M_a}{M_{0,C}} \frac{M_a}{M_{0,P}}}{\frac{M_a}{M_{0,C}} + \frac{M_a}{M_{0,P}}}$$

↓

Pitcher: $$\frac{M_a}{M_{0,P}} = \frac{f_{dry} - e^{-\Delta V_{total,P}/V_e}}{\sum_{i=1}^{n}\left(e^{-\sum_{j=3i}^{3n+1} \Delta V_j/V_e} - e^{-\sum_{j=3i+1}^{3n+1} \Delta V_j/V_e}\right)}$$

Catcher: $$\frac{M_a}{M_{0,c}} = \frac{f_{dry} - e^{-\Delta V_{total,C}/V_e}}{\sum_{i=2}^{2n}\left((-1)^{i} e^{-\sum_{j=i}^{2n} \Delta V_j/V_e}\right) - 1}$$

Results – real NEAs

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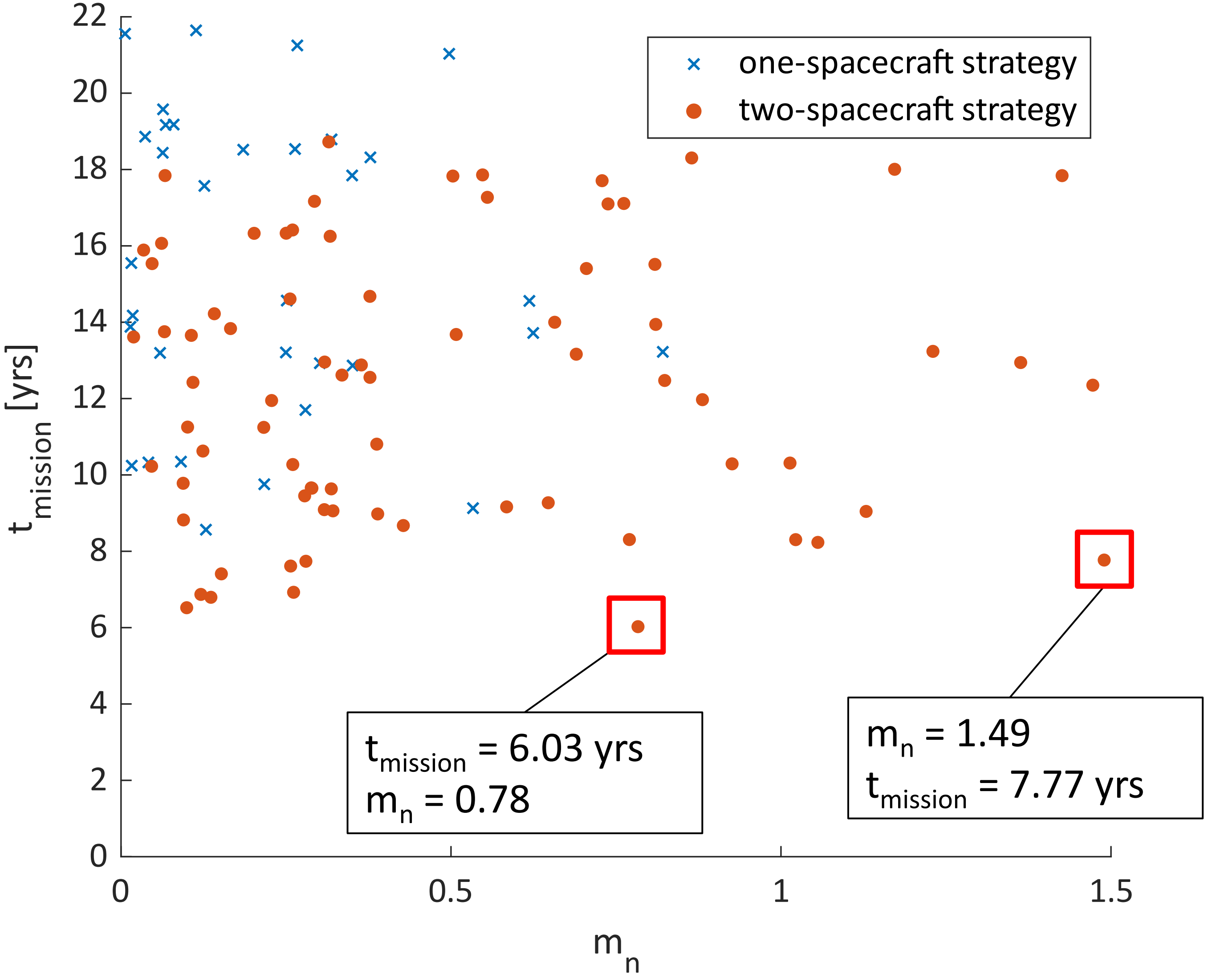

Fly-bys

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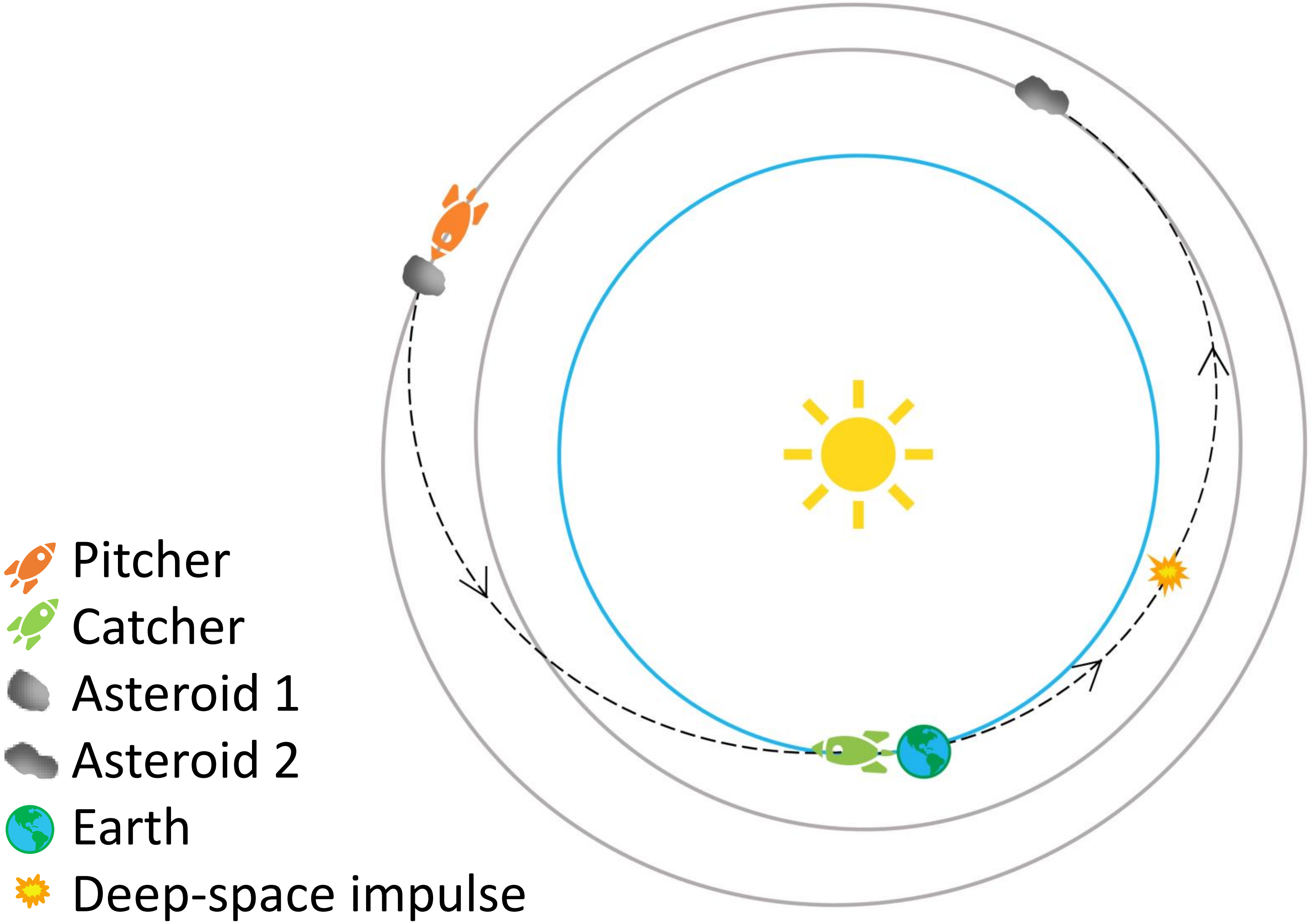
- Fly-bys added to the two-spacecraft strategy:
  - Pitcher performs an **unpowered fly-by** with the Earth
  - Pitcher performs a **powered fly-by** with the Earth
- Earth capture is included
- Two-dimensional, patched-conic Keplerian model with instantaneous impulses

Unpowered fly-by



Capture of one asteroid:

1. Deflect asteroid 1
2. Perform unpowered fly-by (at Earth)
3. Deep-space impulse
4. Arrive at asteroid 2

Powered fly-by

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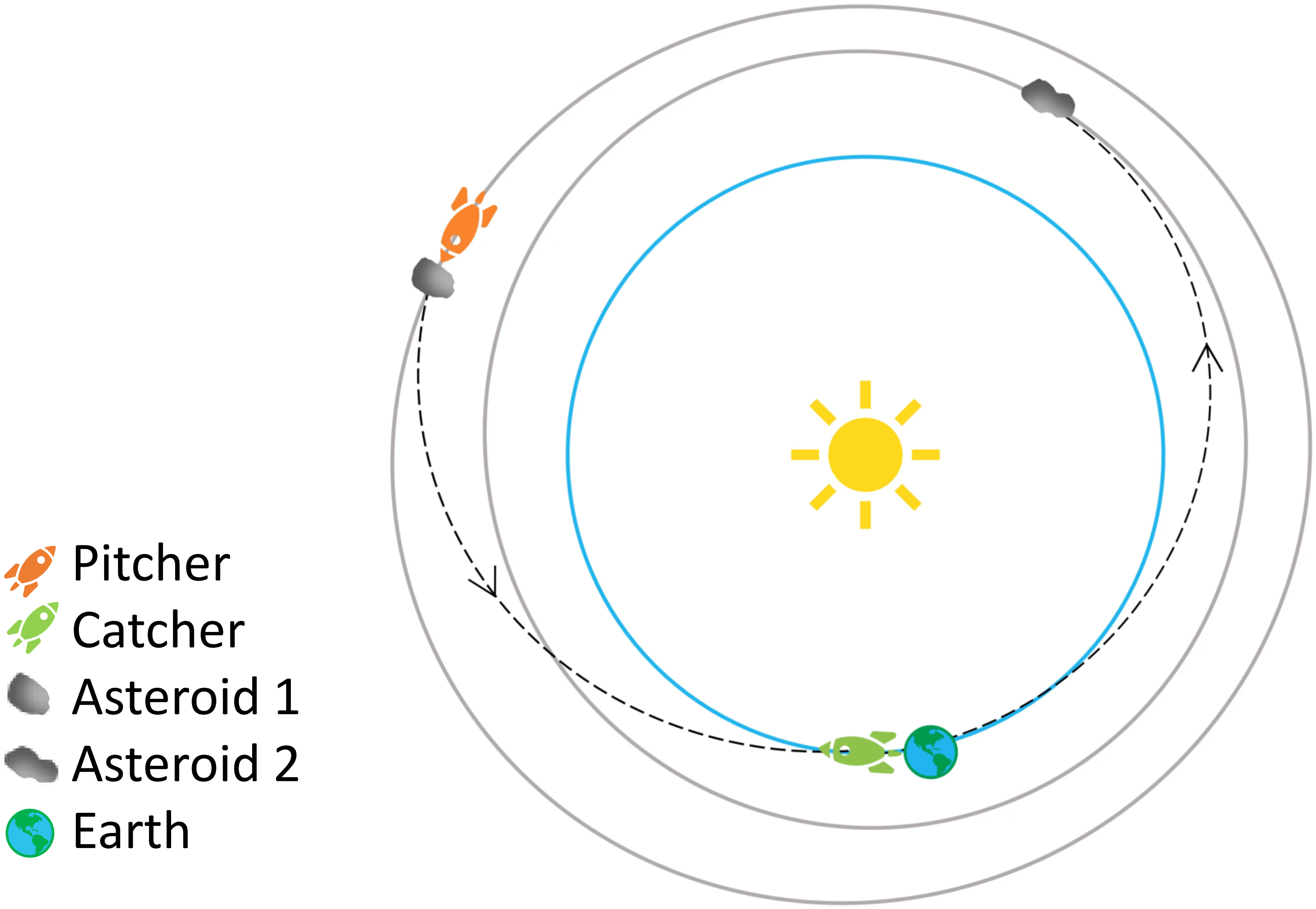


Capture of one asteroid:

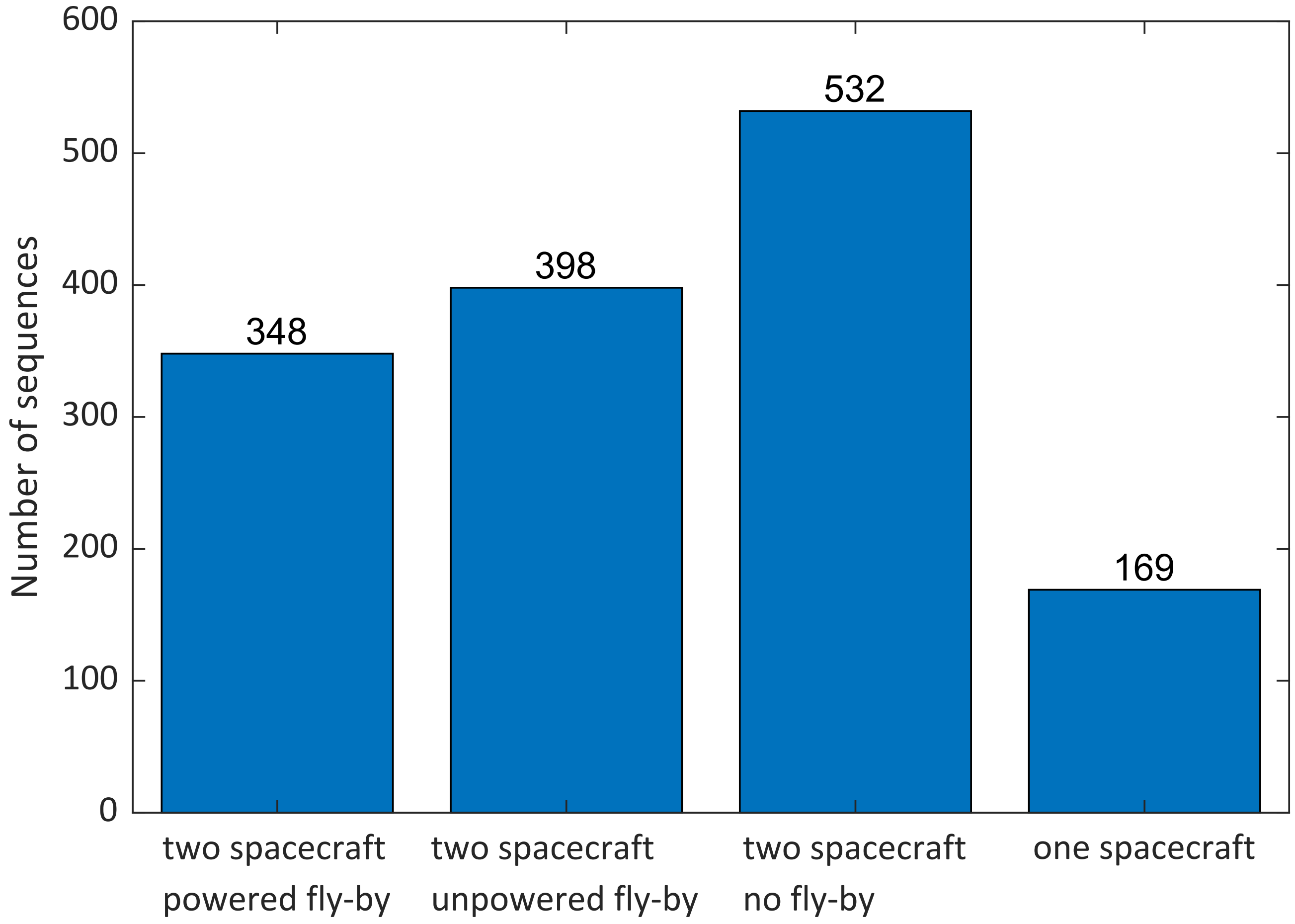
1. Deflect asteroid 1
2. Perform powered fly-by (at Earth)
3. Arrive at asteroid 2

Optimization method

- Each mission targets a **sequence** of 3 asteroids
- 2000 sequences of asteroids are optimized for each strategy
- The orbital elements of the asteroids are randomly generated
- Optimization done with genetic algorithm

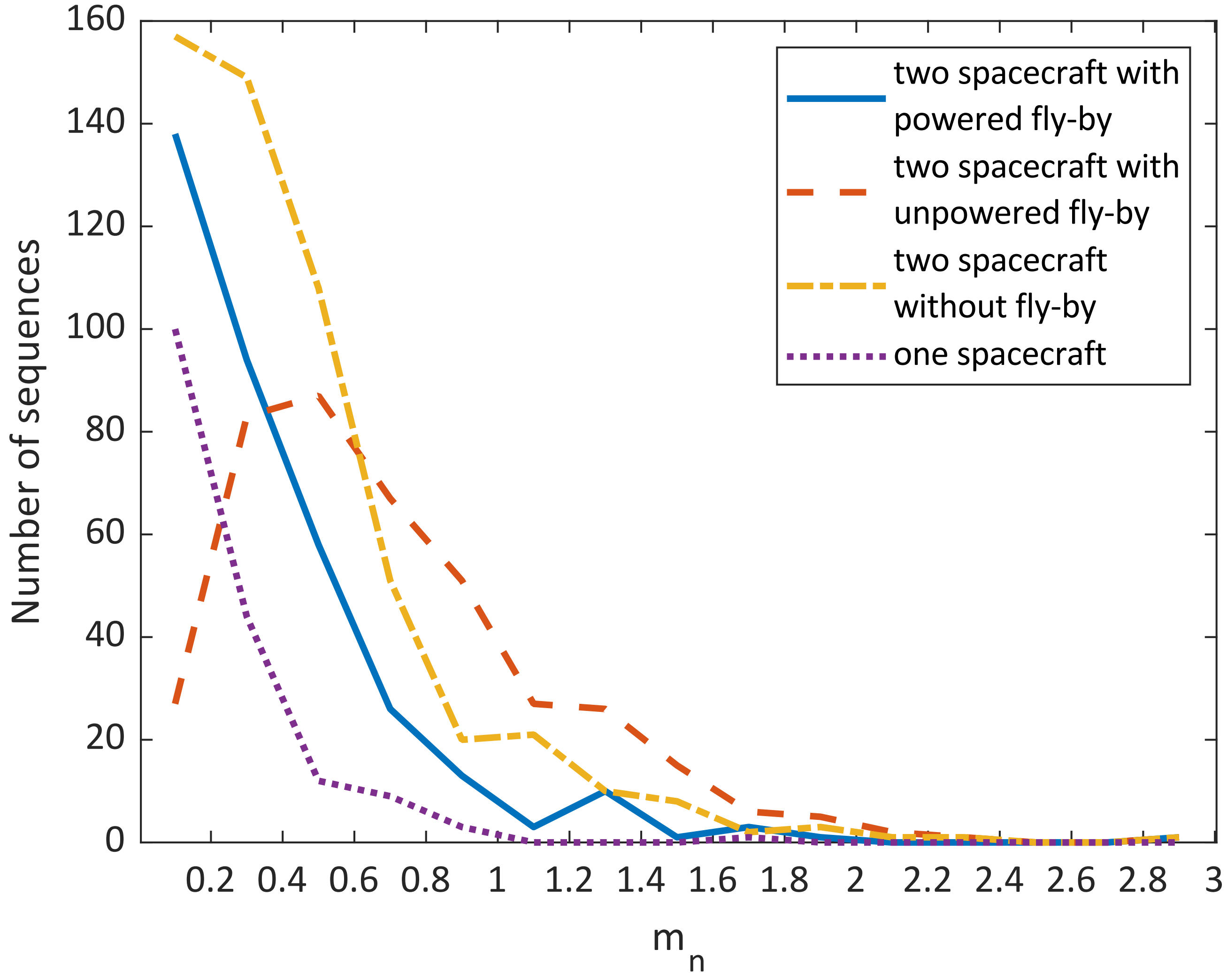
Results

712 sequences with feasible solutions



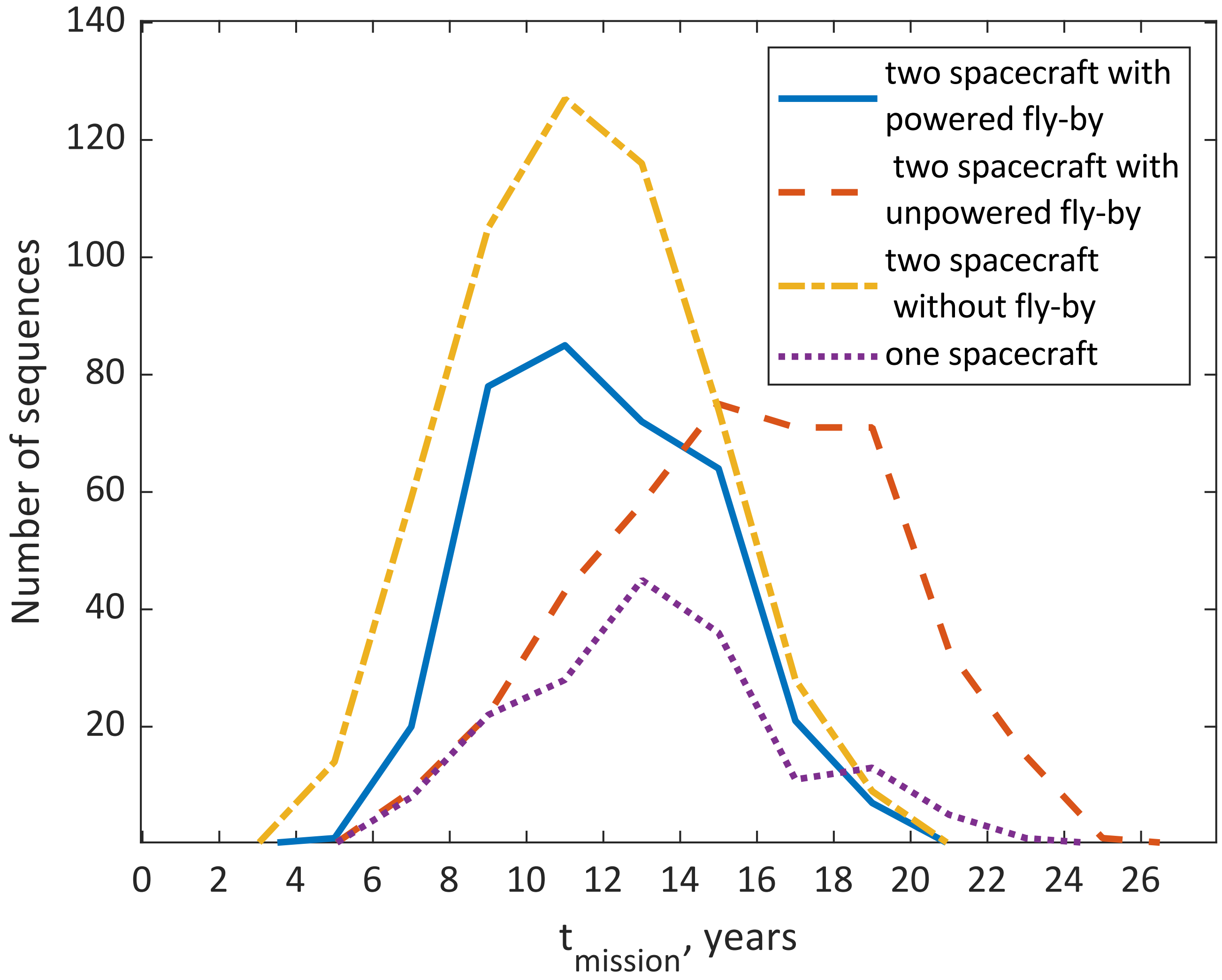
Results

Results for m_n divided into bins of interval 0.2 for each strategy



Results

Results for $t_{mission}$ divided into bins of interval 2 years for each strategy



Results

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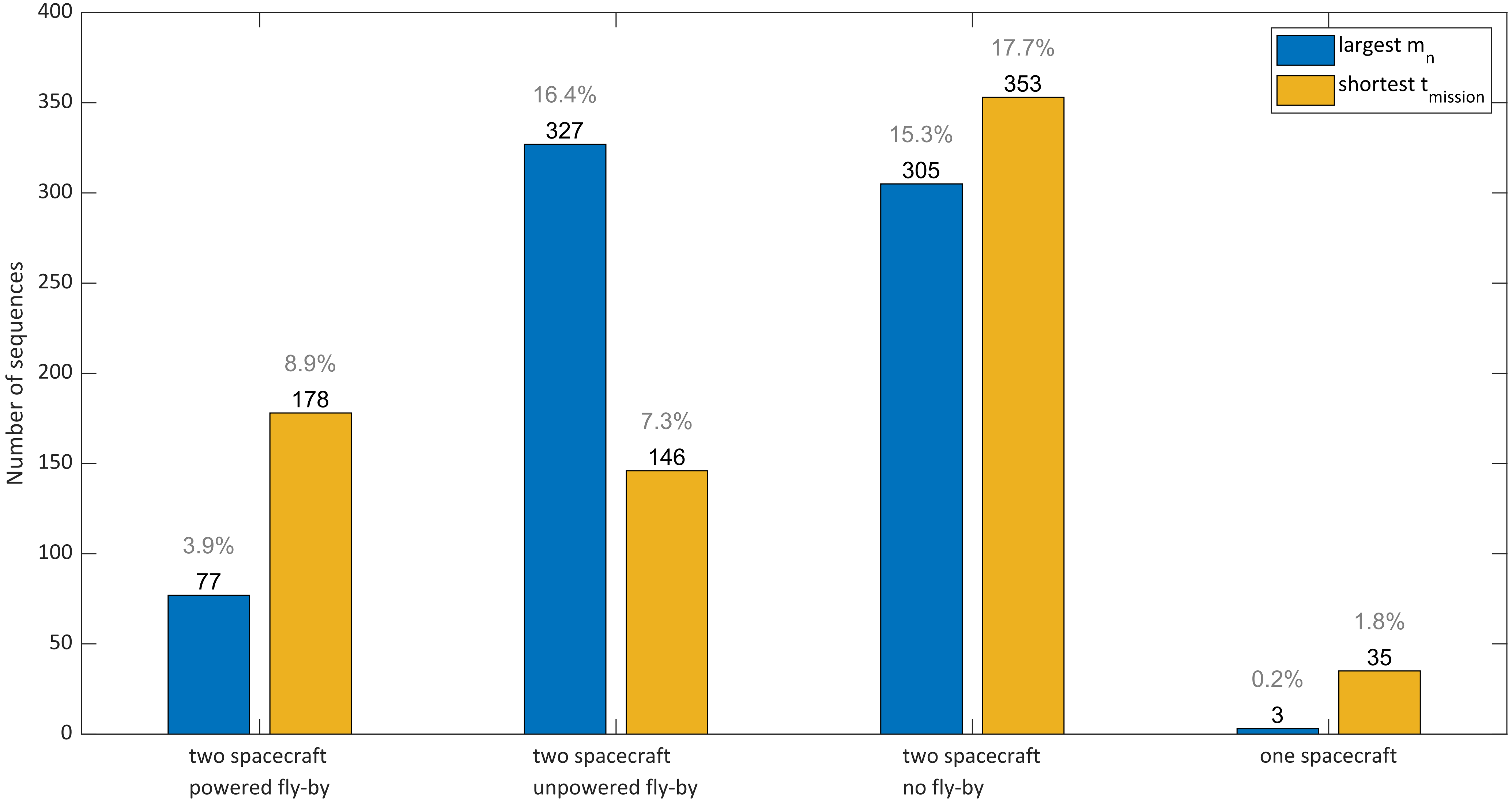

Results

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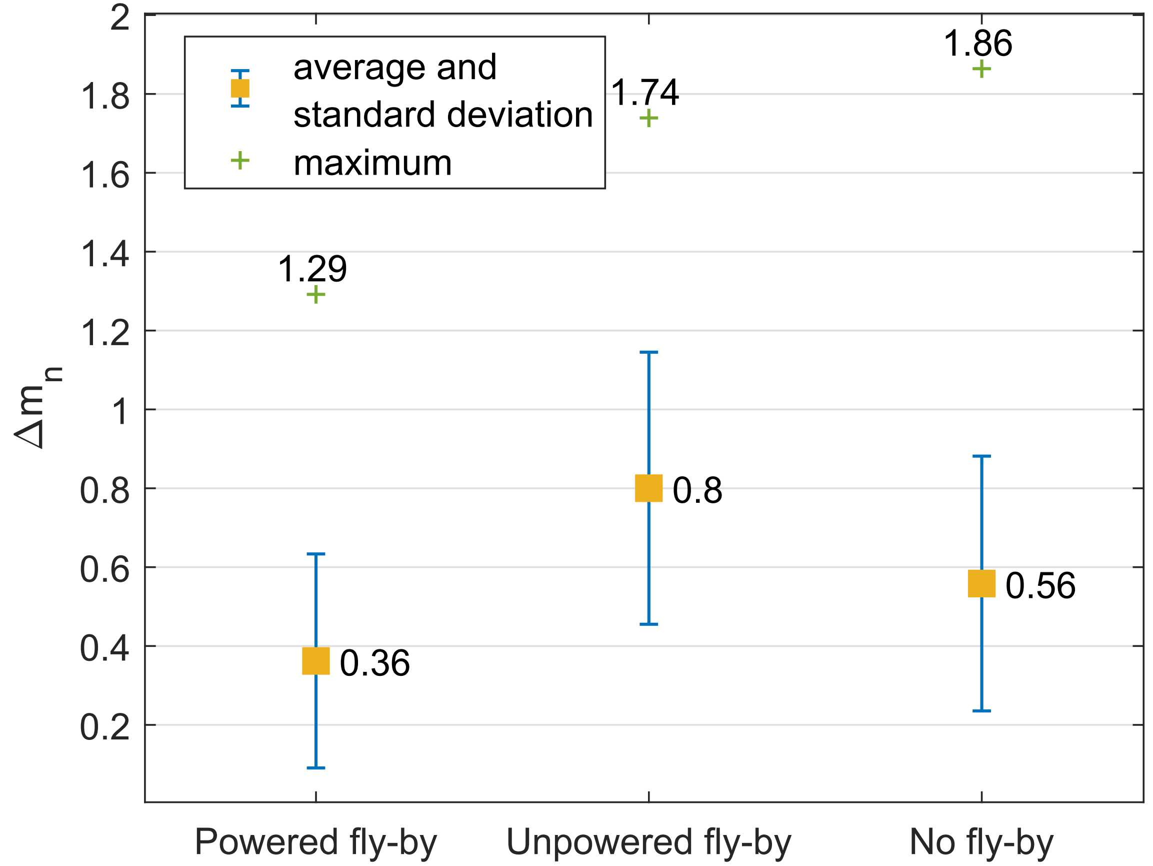
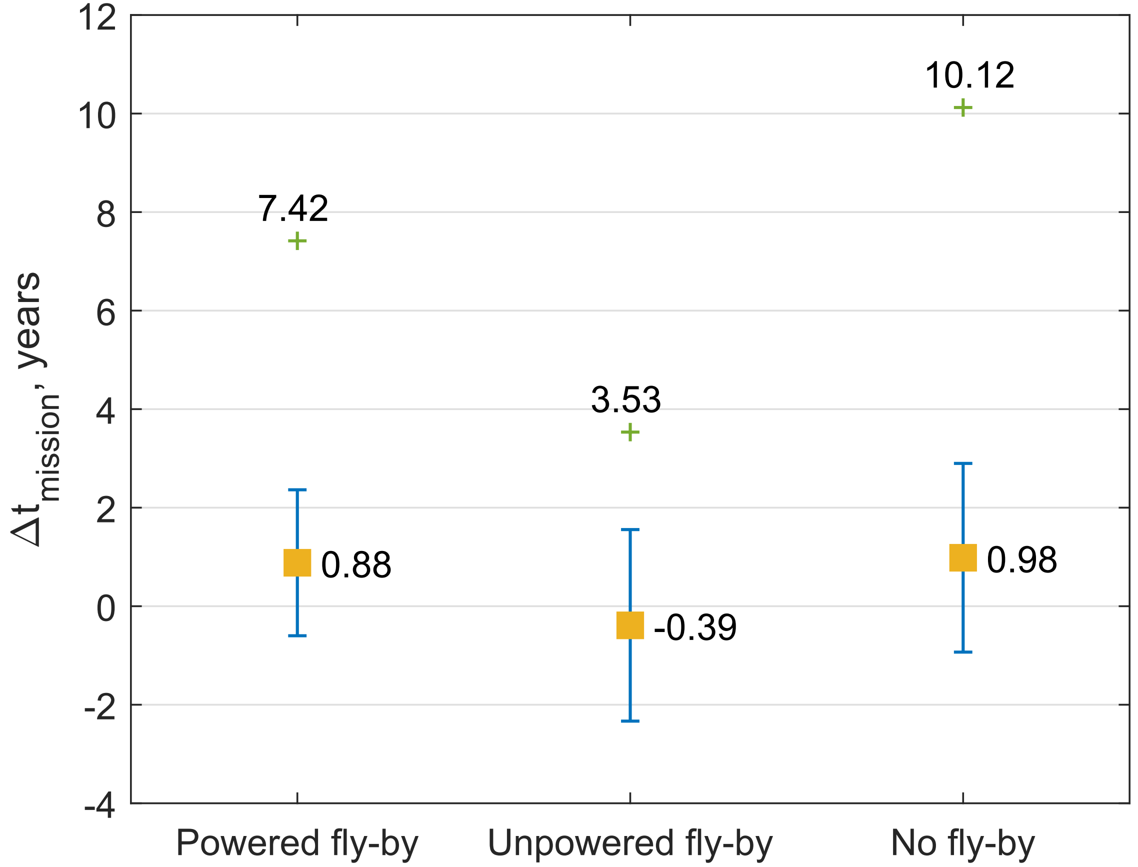
Comparison with one-spacecraft strategy

$\Delta m_n = m_{n,2sc} - m_{n,1sc}$



$\Delta t_{mission} = t_{mission,1sc} - t_{mission,2sc}$



Conclusions

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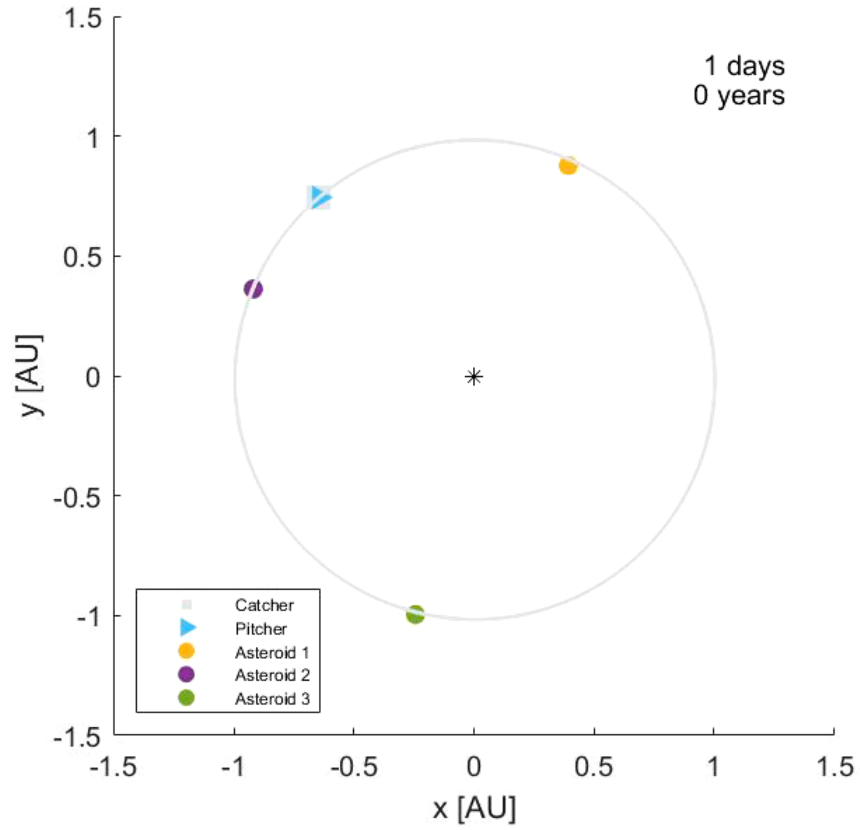
- Four strategies have been modelled:
  - Two spacecraft with powered fly-by
  - Two spacecraft with unpowered fly-by
  - Two spacecraft without fly-by
  - One spacecraft
- Two spacecraft return a larger mass on average than one spacecraft for the same launch mass
- Strategy with unpowered fly-by resulted in the largest m_n
- Shorter mission durations are achieved with a powered fly-by or without a fly-by

Powered fly-by best sequence:



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Thank you for your attention!

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