# CAMELOT
# Computational-Analytical Multi-fidelity Low-thrust Optimisation Toolbox

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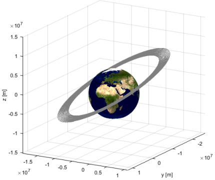
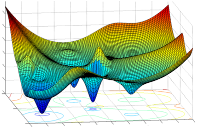
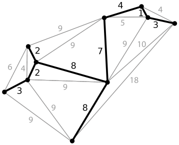
# Computational-Analytical Multi-fidelity Low-thrust Optimisation Toolbox (CAMELOT)

Preliminary design and optimisation of multiple-target low-thrust missions.

- **FABLE**: Fast Analytical Boundary-value Low-thrust Estimator
- **MP-AIDEA**: Multi-Population Adaptive Inflationary Differential Evolution Algorithm
- **AIDMAP**: Automatic Incremental Decision Making And Planning algorithm





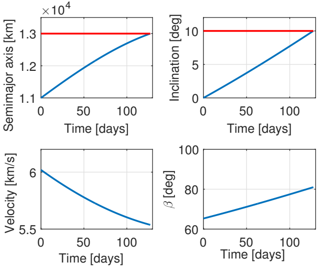
# FABLE

Cost estimation of low-thrust orbital transfer using **multi-fidelity** analytical approach and **surrogate** models.

- **Low-fidelity** fast analytical estimation of low-thrust transfer cost.
  Analytical low-thurst control law:

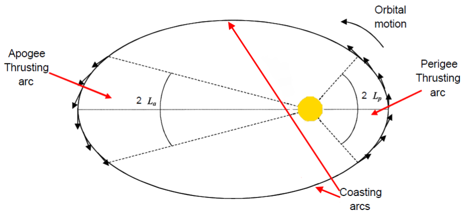
| Transfer type | Reference |
|---|---|
| $a_0 \rightarrow a_f$ | Ruggiero et al. (2011) |
| $(a_0, i_0) \rightarrow (a_f, i_f)$, $e = 0$ | Edelbaum (1961) |
| $(a_0, i_0) \rightarrow (a_f, i_f)$, $e = 0$, $a < \bar{a}$ | Kechichian (2010) |
| $(a_0, \Omega_0) \rightarrow (a_f, \Omega_f)$, $e = 0$ | Kechichian (2010) |
| $(a_0, e_0, \omega_0) \rightarrow (a_f, e_f, \omega_f)$ | da Silva et al. (2015) |
| $a_0 \rightarrow a_f$, $e_0 = e_f$ | Burt (1967) |
| $e_0 \rightarrow e_f$ | Ruggiero et. al. (2011) |
| $e_0 \rightarrow e_f$, $a_f = a_0$ | Burt (1967) |
| $(e_0, i_0) \rightarrow (e_f, i_f)$, $a_f = a_0$ | Pollard (2000) |
| $i_0 \rightarrow i_f$ | Ruggiero et al. (2011) |
| $\omega_0 \rightarrow \omega_f$ | Ruggiero et al. (2011) |
| | Pollard (2000) |
| | Petropoulos (2003) |
| $\Omega_0 \rightarrow \Omega_f$ | Ruggiero et al. (2011) |

Change of semimajor axis and inclination of circular orbit (Edelbaum):



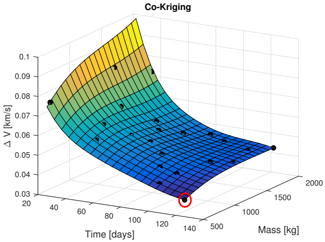
# FABLE

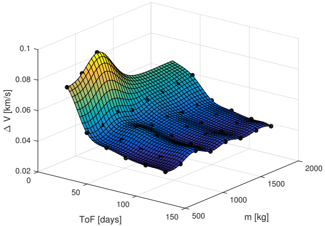
- **Higher-fidelity** analytical model:
  - **Osculating analytical propagator** based on analytical formulas for the perturbed Keplerian motion (first order expansion in the perturbing acceleration):
    - low-thrust acceleration
    - J2 zonal harmonic
    - atmospheric drag
    - solar radiation pressure (eclipses)
  - **Averaged analytical propagator**
  - Different control parametrisation can be implemented



# FABLE

- Use of **surrogate models** to model the cost of the transfer to allow for fast evaluation of complex trajectories
- Surrogate models:
  - **Kriging**
  - **Co-Kriging** (few samples from higher-fidelity model, many samples from low-fidelity model)
  - **Tchebycheff** sparse grid
- Multi-fidelity optimisation: maximisation of **expected improvement** associated to Co-Kriging
  - Maximisation of expected improvement: point where the likelihood of achieving an improvement is maximised

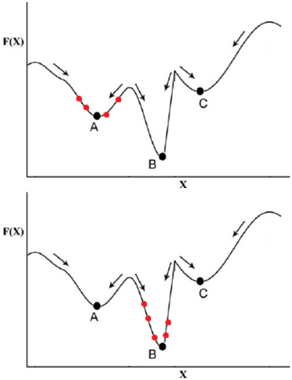


# MP-AIDEA

**Multi population** single objective adaptive global optimiser based on the combination of **Differential Evolution** with **Monotonic Basin Hopping**

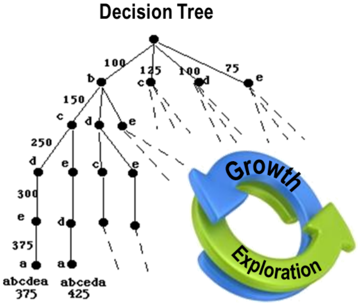
- Automatic adaptation of the parameters of Differential Evolution and Monotonic Basin Hopping
- **Local search** after Differential Evolution
- **Local restart**: transition from one local minimum to another
- Strategy to avoid multiple detection of the same local minima
    - Basin of attraction
    - **Global restart**



# AIDMAP

Single objective **incremental decision making algorithm** for the solution of complex **combinatorial optimisation problems** such as tasks planning and scheduling.

- AIDMAP decision making map based on **tree-like** topology:
  - Nodes: decisions made
  - Edges: cost associated to decision
- Tree built **incrementally with time** through **exploration** and **growth** by virtual agents
- Possible heuristics:
  - **Deterministic**: Branch-and-Cut algorithm
  - **Probabilistic**: bio-inspired Physarum algorithm

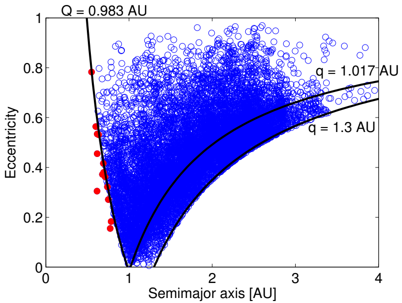


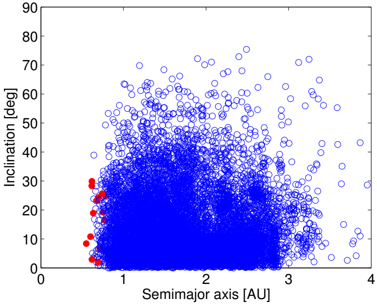
# Applications

- Multiple Atira Asteroids Fly-by Mission
- Multiple Active Debris Removal Mission

# Multiple Atira Asteroids Fly-by Mission

- $a < 1$ AU, $Q < 0.983$ AU
- 14 known Atira asterois - many more IEOs are expected to exist
- Observation of the inner Solar System: limitations of ground-based survey (Sun in the instrument field of view)
- Fly-by at the nodal points of the asteroids' orbit



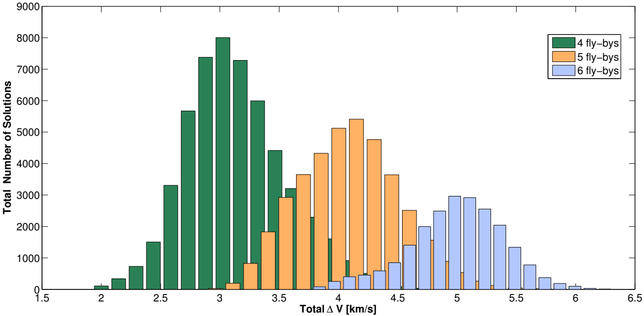
# Multiple Atira Asteroids Fly-by Mission

- AIDMAP

  Identification of optimal:
  - sequence of asteroids
  - departure dates
  - times of flight

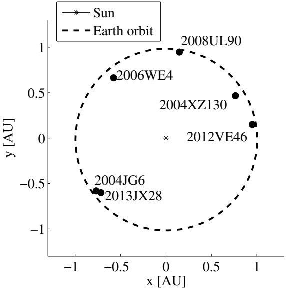
  Impulsive model: Lambert arcs with departure dates at steps of 10 days.

  133,761 solutions identified:



# Multiple Atira Asteroids Fly-by Mission

- AIDMAP
  Best Solution: fly-by with 6 asteroids, $\Delta V = 3.77$ km/s




| | Asteroid | Departure Date | ToF [days] | $\Delta V$ [km/s] |
|---|---|---|---|---|
| | 2013JX28 | 2020/09/29 | 205 | 0.87 |
| | 2006WE4 | 2022/05/14 | 215 | 0.86 |
| | 2004JG6 | 2023/06/14 | 235 | 0.61 |
| | 2012VE46 | 2024/09/11 | 265 | 0.36 |
| | 2004XZ130 | 2026/09/15 | 205 | 0.73 |
| | 2008UL90 | 2028/07/31 | 195 | 0.34 |
| TOT. | | | | **3.77** |

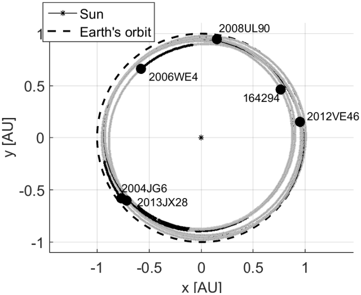
# Multiple Atira Asteroids Fly-by Mission

- MP-AIDEA
  - Identification of **new departure dates leading to reduced $\Delta V$**
  - Global optimisation with search space defined allocating **time window of $\pm$ 10 days** around previously identified departure dates

| | Asteroid | AIDMAP Dep. Date | **MP-AIDEA Departure Date** | AIDMAP $\Delta V$ [km/s] | **MP-AIDEA $\Delta V$ [km/s]** |
|---|---|---|---|---|---|
| | 2013JX28 | 2020/09/29 | 2020/09/20 | 0.87 | 0.95 |
| | 2006WE4 | 2022/05/14 | 2022/05/24 | 0.86 | 0.69 |
| | 2004JG6 | 2023/06/14 | 2023/06/12 | 0.61 | 0.61 |
| | 2012VE46 | 2024/09/11 | 2024/09/05 | 0.36 | 0.34 |
| | 2004XZ130 | 2026/09/15 | 2026/09/18 | 0.73 | 0.72 |
| | 2008UL90 | 2028/07/31 | 2028/08/10 | 0.34 | 0.29 |
| TOTAL | | | | **3.77** | **3.61** |

# Multiple Atira Asteroids Fly-by Mission

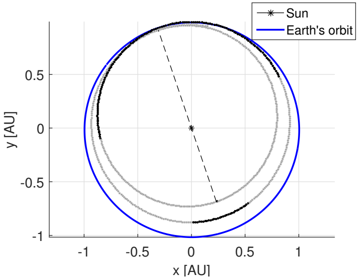
- FABLE
  - Direct optimisation method and multiple shooting algorithm
  - Spacecraft injected into an hyperbolic escape orbit from Earth that encounters the first asteroids at its nodal point.
  - Low-thrust engine: $T = 0.07$ N, $I_{sp} = 3000$ s



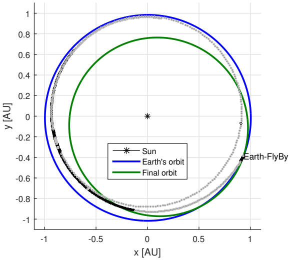

| | Asteroid | $m_0$ [kg] | $m_f$ [kg] | $\Delta V$ [km/s] |
|---|---|---|---|---|
| | 2013JX28 | **700** | 700 | - |
| | 2006WE4 | 700 | 673.45 | 1.12 |
| | 2004JG6 | 673.45 | 642.07 | 1.37 |
| | 2012VE46 | 642.07 | 633.47 | 0.39 |
| | 2004XZ130 | 633.47 | 600.89 | 1.51 |
| | 2008UL90 | 600.89 | **594.17** | 0.30 |
| TOT. | | | | **4.69** |

# Multiple Atira Asteroids Fly-by Mission

- FABLE
  - Transfer to a **reduced perihelion orbit (0.725 AU)** for observation of asteroids of the inner Solar System
  - Transfer: low-thrust propulsion or Earth gravity-assist
  - $T_0 \ / \ T_\oplus = 0.88$
  - $T_f \ / \ T_\oplus = 0.78$



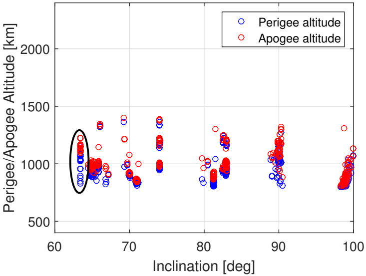

| $\Delta V$ [km/s] | ToF [days] |
|---|---|
| 1.79 | 422 |




| $\Delta V$ [km/s] | ToF [days] |
|---|---|
| 1.31 | 565 |

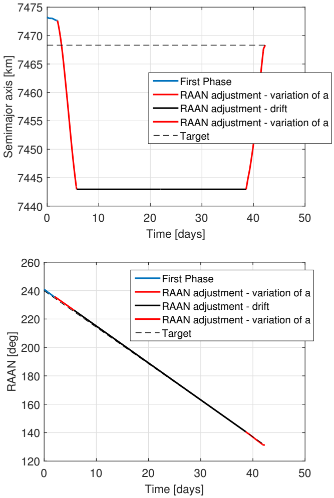
# Multiple Active Debris Removal Mission

- Deorbiting of **large satellites from LEO** (800 - 1400 km) using a **low-thrust servicing spacecraft** ($T = 0.1$ N, $I_{sp} = 1600$ s, $m = 1000$ kg)
- Two possible strategies:
  - multi-target delivery of **de-orbiting kits** (100 kg) to perform a controlled re-entry;
  - low-thrust **fetch and deorbit** using the single servicing spacecraft.
- Selected targets: 25 objects with high Criticality of Spacecraft Index and low inclination (J2 drift to change $\Omega$)



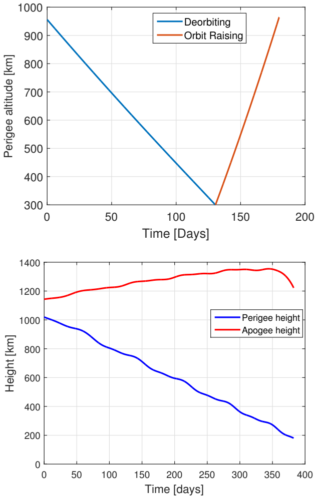
# Multiple Active Debris Removal Mission

- FABLE: transfer between two satellites (multi-target delivery of deorbiting kit)



# Multiple Active Debris Removal Mission

- FABLE: transfer between two satellites (multi-target delivery of deorbiting kit)
- FABLE: deorbiting of objects (fetch and de-orbit)
  - Spiral with negative tangential acceleration: $\gamma = 0$ deg
  - Increase of eccentricity (negative thrust at apogee and positive thrust at perigee): $\gamma = 1.5$ deg



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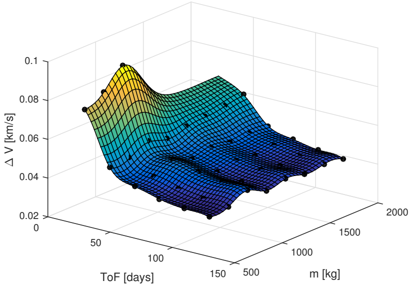
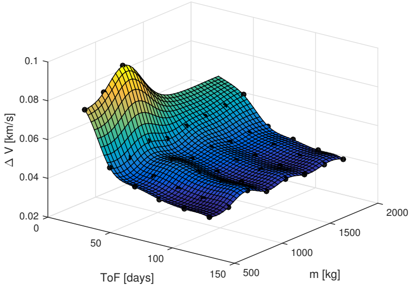
- FABLE: surrogate model of the cost of the transfer for different possible initial mass of the spacecraft and time of flight of the transfer



# Multiple Active Debris Removal Mission

- FABLE: transfer between two satellites (multi-target delivery of deorbiting kit)
- FABLE: deorbiting of objects (fetch and de-orbit)
  - Spiral with negative tangential acceleration: $\gamma = 0$ deg
  - Increase of eccentricity (negative thrust at apogee and positive thrust at perigee): $\gamma = 1.5$ deg
- FABLE: surrogate model of the cost of the transfer for different possible initial mass of the spacecraft and time of flight of the transfer
- AIDMAP: identification of the optimal sequence of targets to be removed using surrogate model



# Multiple Active Debris Removal Mission

Multi-target delivery of de-orbiting kits:

| | Departure Object | Arrival Object | $\Delta V$ [km/s] | $ToF$ [days] | $m_0$ [kg] | $m_f$ [kg] |
|---|---|---|---|---|---|---|
| 1 | 39015 | 40343 | 0.0628 | 30.43 | 1900.00 | 1892.40 |
| 2 | 40343 | 40340 | 0.1128 | 65.75 | 1792.40 | 1779.55 |
| 3 | 40340 | 39016 | 0.0595 | 33.14 | 1679.55 | 1673.19 |
| 4 | 39016 | 40342 | 0.0429 | 29.73 | 1573.19 | 1568.89 |
| 5 | 40342 | 40338 | 0.0339 | 42.28 | 1468.89 | 1465.72 |
| 6 | 40338 | 40339 | 0.0013 | 7.05 | 1365.72 | 1365.60 |
| 7 | 40339 | 39011 | 0.1116 | 44.55 | 1265.60 | 1256.63 |
| 8 | 39011 | 39012 | 0.0035 | 14.19 | 1156.63 | 1156.37 |
| 9 | 39012 | 39013 | 0.0448 | 28.04 | 1056.37 | 1053.34 |
| Total | - | - | **0.4731** | **294.17** | - | - |

Fetch and deorbit:

| | Departure Object | Arrival Object | $\Delta V$ [km/s] | $ToF$ [days] | $m_0$ [kg] | $m_f$ [kg] |
|---|---|---|---|---|---|---|
| 1 | 39244 | 36413 | 1.1307 | 159.91 | 3000.00 | 890.11 |
| 2 | 36413 | 39011 | 0.9811 | 182.32 | 2890.11 | 802.79 |
| Total | - | - | **2.1118** | **373.23** | - | - |

# Conclusions

CAMELOT, toolbox for the preliminary design of multi-target low-thrust missions:

- FABLE: low-thrust transfer estimator
- MP-AIDEA: single objective multi population adaptive global optimiser
- AIDMAP: single objective combinatorial optimiser

Applications:

- Multiple Atira Asteroids Fly-By Mission
  - Six asteroids fly-by in less than 10 years
  - Limited propellant consumption
- Multiple Active Debris Removal Mission
  - De-orbiting kits: 10 objects removed from LEO in less than 1 year
  - Fetch and deorbit: 3 objects removed from LEO

Thank you.
Questions?