Image credits: ESA Space in Images – 2015 – Hera in orbit

Optimal Deflection of Near-Earth Objects Through a Kinetic Impactor Performing Gravity Assist

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Introduction

Background

- Minor bodies in Solar System:
  - Asteroids
  - Comets
- **NEOs**: Near Earth Objects
  - $r_p < 1.3$ AU
  - Over 18,000 present in our Solar system
- **PHAs**: potentially hazardous asteroids
  - $MOID < 0.05\ AU$ & $H < 22$
  - Not null probability of impact with Earth
- Impact probability:
  - Airburst (few meters diameter)
  - Severe ($40\ m < d < 200\ m$): 1 every around 100 years
  - Catastrophic ($d > 1\ km$): 1 over millions of years

Image credits: Cheliabinsk, Fayerwayer.com; Tunguska, Space.com; Yucatan, noao.edu

Introduction

Deflection methods

- To **prevent a possible impact** several strategies have been studied
- **Kinetic impactor**
  - Consists of **hitting the NEO** with a spacecraft at high relative velocity to deflect it
  - **Highest TRL**
  - **Simplest technology**
- Missions:
  - AIM + DART – AIDA [1], [2]

Image credits: ESA Space in Images – 2015 – AIDA concept logo

[1] "NASA - DART," [Online]. Available: https://www.nasa.gov/planetarydefense/dart. [Accessed 16 August 2018].
[2] "ESA - Space Dart," [Online]. Available: https://m.esa.int/Our_Activities/Space_Engineering_Technology/Hera/Highlights/Space_DART. [Accessed 15 August 2018].

Introduction

Project aims

- Create a method in order to include the **gravity assist** of Earth, Mars and Venus in the design of a **deflection mission** (following [3] and [4]):
  - **Kinetic impactor**
  - **Maximise achievable deflection**
- Improve the method introducing **further techniques** aimed to increase the maximum achievable deflection
- Apply the method to a **single real NEO** and to a **synthetic population of NEOs** spread through all the spectrum of orbital parameters and analyse the **global qualitative results**

[3] A. Rathke and D. Izzo, "Keplerian consequences of an impact on an asteroid and their relevance for a deflection demonstration mission," Proceedeings of the International Astronomical Union, vol. 2, pp. 417-426, 2006.
[4] M. Vasile and C. Colombo, "Optimal Impact Strategies for Asteroid Deflection," Journal of Guidance, Control and Dynamics, vol. 31, no. 4, 2008.

Presentation outline

- **Model formulation**
  - Deflection
  - Mission design
  - Optimisation
  - Transfer stages
  - Multi-revolution Lambert model
- **Results on a single test case**
  - Direct Hit
  - Gravity assist
  - Multi-revolution Lambert model
  - Powered gravity assist
- **Deflection efficiency against a synthetic population of NEOs**
  - Model
  - Results
- **Conclusions**

MODEL FORMULATION

Model formulation

Mission stages

- **Mission design**
  - Launch from Earth
  - Interplanetary transfers
  - Deep space manoeuvres
  - Gravity assist

- **Deflection of the NEO**
  - Collision before MOID
  - Variation of orbital parameters (Gauss' planetary equations)
  - Deflection achieved (Proximal motion equations)

Model formulation

Deflection of the NEO

- The impact is modelled as a **completely inelastic collision**, the variation of velocity imparted to the asteroid is:

$$\delta \boldsymbol{v}_d = \beta \frac{m_{SC}}{(m_{SC} + m_{NEO})} \Delta \boldsymbol{v}$$

- The variation of orbital parameters of the NEO is computed through the **Gauss' planetary equations** [5]:

$$\delta \boldsymbol{\alpha}_d = \boldsymbol{G}_d \delta \boldsymbol{v}_d$$

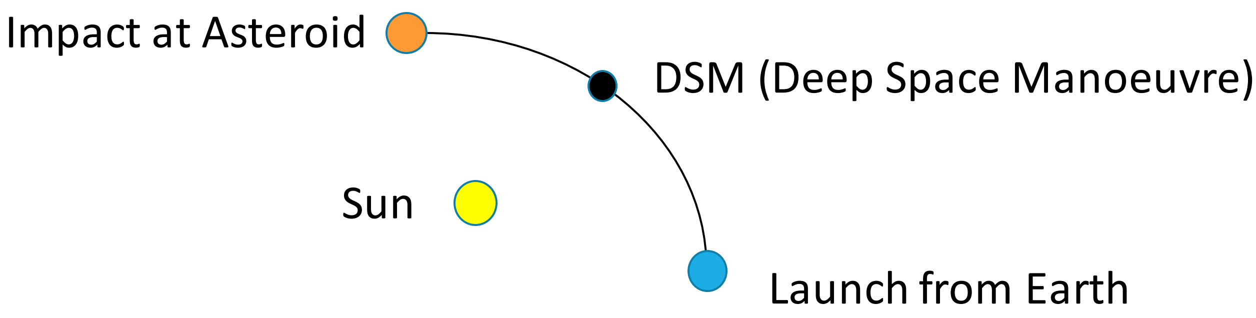
- Finally the deflection is computed through the use of the **proximal motion equations** [6]:

$$\delta \boldsymbol{r}_{MOID} = \boldsymbol{A}_{MOID} \delta \boldsymbol{\alpha}_d$$

[5] H. Schaub and J. L. Junkins, in Analytical Mechanics of Space Systems, Reston, American Institute of Aeronautics and Astronautics, 2003, pp. 592-623
[6] R. H. Battin and R. H., An Introduction to the Mathematics and Methods of Astrodynamics, Ohio: American Institute of Aeronautic and Astron autic, 1999, pp. 484-490.

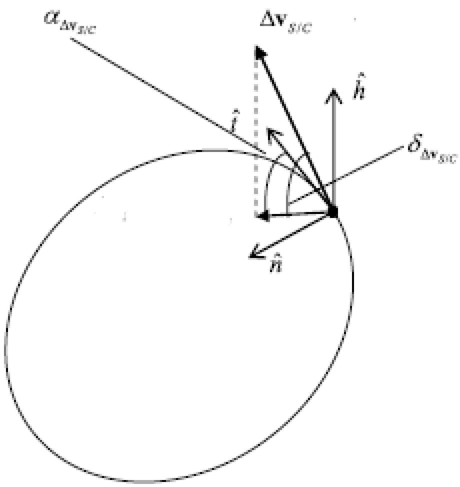
Model formulation

Mission design – Direct Hit



- Design variable:

$$\boldsymbol{x} = \{\alpha_0 \quad \alpha_1 \quad ToF_1 \quad \|\Delta v_0\| \quad \alpha_{\Delta v_0} \quad \delta_{\Delta v_0} \quad m_{SC0}\}$$

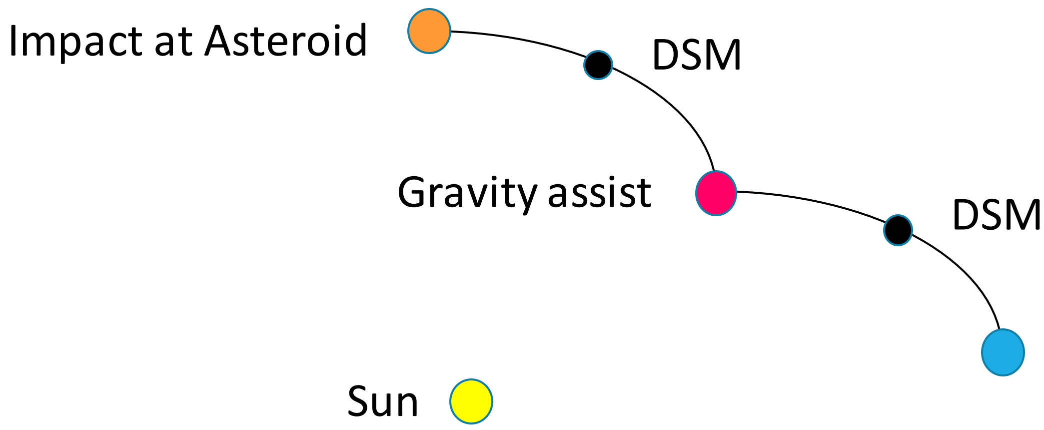


- $t_0 = t_{init} + \left(t_{MOID} - t_{init} - \sum_{i=1}^{2} ToF_i\right) \cdot \alpha_0$
- $t_{init} = t_{MOID} - warningTime$
- $t_{DSM1} = t_0 + \alpha_1 \cdot ToF_1$

Image credits: J. C. C. Sanchez, "Impact Hazard Protection Efficiency by a small Kinetic Impactor," Journal of Spacecraft and Rockets, vol. 50, no. 2, 2013.

Model formulation

Mission design – Gravity assist scenario



- Design variable:
  $\boldsymbol{x} = \{\alpha_0 \quad \alpha_1 \quad ToF_1 \quad \gamma_2 \quad r_{p2} \quad \alpha_2 \quad ToF_2 \quad \|\Delta v_0\| \quad \alpha_{\Delta v_0} \quad \delta_{\Delta v_0} \quad m_{SC0}\}$
  - γ_2: angle to identify the plane for the gravity assist
  - r_{p2}: pericentre of the hyperbola for the gravity assist

Model formulation

Optimisation

- Definition of a function to optimise:

$$J = \{-(r_p - r_{p0}) \quad m_{SC0}\}$$

  - **Multi-objective function**
  - r_p: distance of the NEO from Earth after deflection
  - r_{p0}: distance of the NEO from Earth before deflection
- Optimisation using a Global Evolutionary algorithm [7]
- To achieve the convergence:
  - **Define the bounds** for the design variable
  - Work on **optimisation parameters**, in particular on the Number of individuals and Function Evaluations

[7] M. Vasile, "Robust Mission Design Through Evidence Theory and Multi-Agent Collaborative Search," *Annals of the New York Academy of Sciences,* vol. 1065, no. 1, pp. 152-173, 2005.

Model formulation

Transfer stages – Interplanetary transfer

- **Two branches**:
  - 1) From first planet to the DSM
  - 2) From DSM to second planet/NEO
- 1) Modelled through the **Keplerian orbit propagation** with Restricted 2 body problem assumption, knowing initial velocity
- 2) Modelled solving the **Lambert problem**, knowing the starting point, the arrival point and the time of flight

Model formulation

Transfer stages – Gravity assist

- **Not-powered gravity assist**
  - $v_{\infty 2} = v_{\infty 1}$
  - $\delta = 2\,\theta_\infty - \pi$

- **Powered gravity assist**
  - $v_{\infty 2} \neq v_{\infty 1}$
  - $\delta = \theta_{\infty 1} + \theta_{\infty 2} - \pi$
- In this case the design variable becomes:

$$\boldsymbol{x} = \begin{Bmatrix} \alpha_0 & \alpha_1 & ToF_1 & \gamma_2 & r_{p2} & \Delta v_{POW} \\ \alpha_2 & ToF_2 & \|\Delta v_0\| & \alpha_{\Delta v_0} & \delta_{\Delta v_0} & m_{SC0} \end{Bmatrix}$$

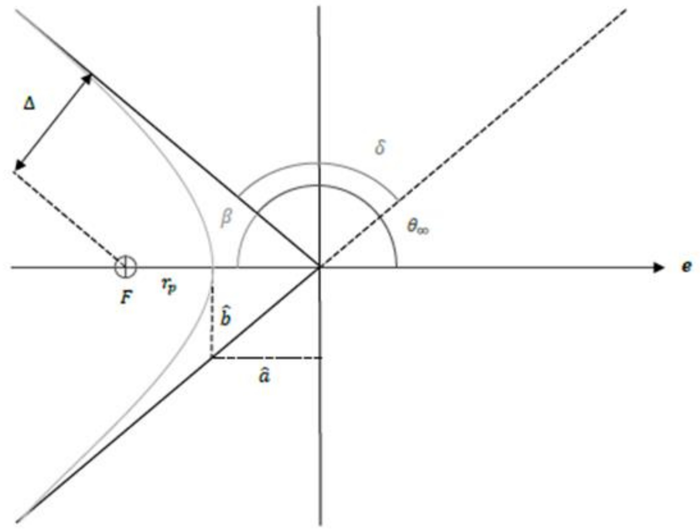


Image credits: M. Petit, Optimal deflection of Resonant Near-Earth Objects using the b-plane, Master thesis, Milano: Milano Theses service, 2018.

Model formulation

Multi-Revolution Lambert model

- Lambert problem have also **multi-revolution solution**
- For a fixed Time of flight, we can define a number $N_{max} \geq 0$ of complete revolutions that the spacecraft can perform in the given Time of flight to go from starting point to arrival point
- All the solution having a number $N \leq N_{max}$ of complete revolutions are also possible
- For $N \geq 1$, we can have **2 solutions** solving the Lambert problem
  - Low e and high energy orbit
  - High e and low energy orbit
- **Present work limited to the case $\boldsymbol{N = 1}$**, that in the gravity assist scenario implies 9 different solutions (3 for each interplanetary transfer)

RESULTS ON A SINGLE TEST CASE

Results on a test case

Selection of the test case and definition of parameters

- 2010RF12 NEO selected for its probability of an impact in the end of 2095

Semi-major axis	Eccentricity	Inclination	Right ascension of ascending node	Argument of the periapsis
$1.58 \cdot 10^8 km$	0.187	$0.911\ deg$	$162\ deg$	$267\ deg$

- Launcher and NEO properties

$warningTime$	$10\ years$
Δv_{launch}	$1\ km/s$
I_{sp}	$300\ s$
D_{NEO}	$100\ m$
ρ_{NEO}	$2600\ kg/m^3$
β	1

Results on a test case

Direct Hit

Variable	α_0	α_1	ToF_1	$\|\Delta v_0\|$	$\alpha_{\Delta v_0}$	$\delta_{\Delta v_0}$	m_{SC0}
Lower bound	0	0	$0.01\ P_{max}$	$0\ km/s$	$-\pi\ rad$	$-\pi/2\ rad$	$300\ kg$
Upper bound	0.99	1	$4\ P_{max}$	$3\ \Delta v_{launch}$	$+\pi\ rad$	$+\pi/2\ rad$	$8000\ kg$

Bounds for the design variables – Direct hit scenario [8]

Case	Function evaluations	Number of individuals
Colombo	100,000	100
Present work	500,000	200

Optimisation parameters [8]

[8] C. Colombo, M. Albano, R. Bertacin, M. M. Castronuovo, A. Gabrielli, E. Perozzi, G. Valsecchi and E. Vellutini, “Mission analysis for two potential asteroids threat scenarios: optimal impact strategies and technology evaluation,” 2017.

Results on a test case

Gravity assist

Variable	γ_2	r_{p2}	α_2	ToF_2
Lower bound	$-\pi\ rad$	1.1	0	$0.01\ P_{max}$
Upper bound	$+\pi\ rad$	66.0	1	$4\ P_{max}$

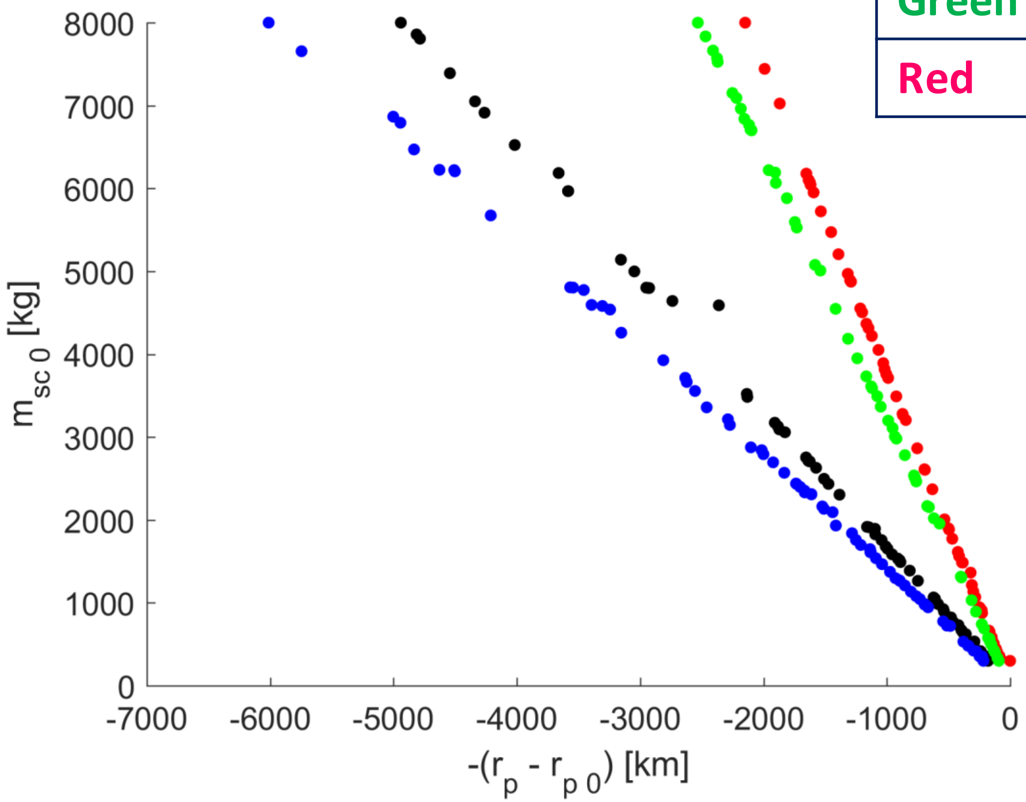
Bounds for the design variables – Gravity assist scenario

- Same set of optimisation parameters as direct hit scenario
- Simulation repeated for each one of the three planets

Results on a test case

Comparison between the results

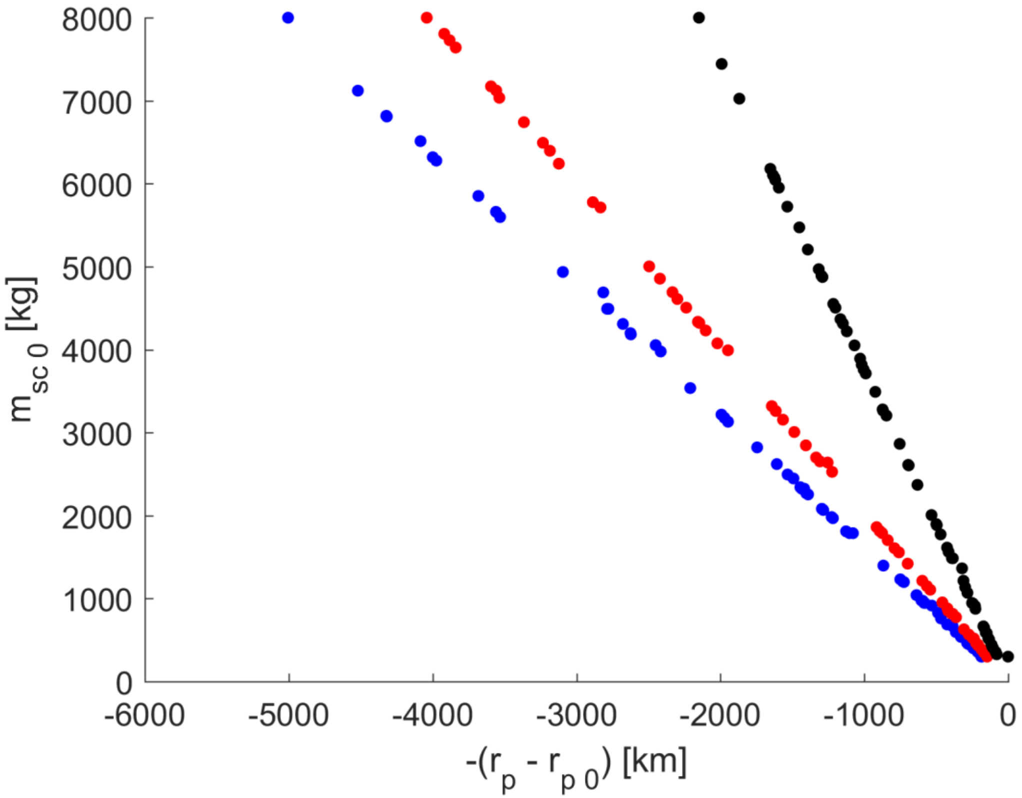
Black	Direct hit
Blue	Earth gravity assist
Green	Venus gravity assist
Red	Mars gravity assist



Results on a test case

Improved solutions – Multi-revolution Lambert model

For the multi-revolution case a single round of optimisation is not enough to converge to the optimal solutions



Black	Standard case
Blue	Multi-revolution Lambert, 2 round of optimisation
Red	Multi-revolution Lambert, 1 round of optimisation
Referred to Mars gravity assist	

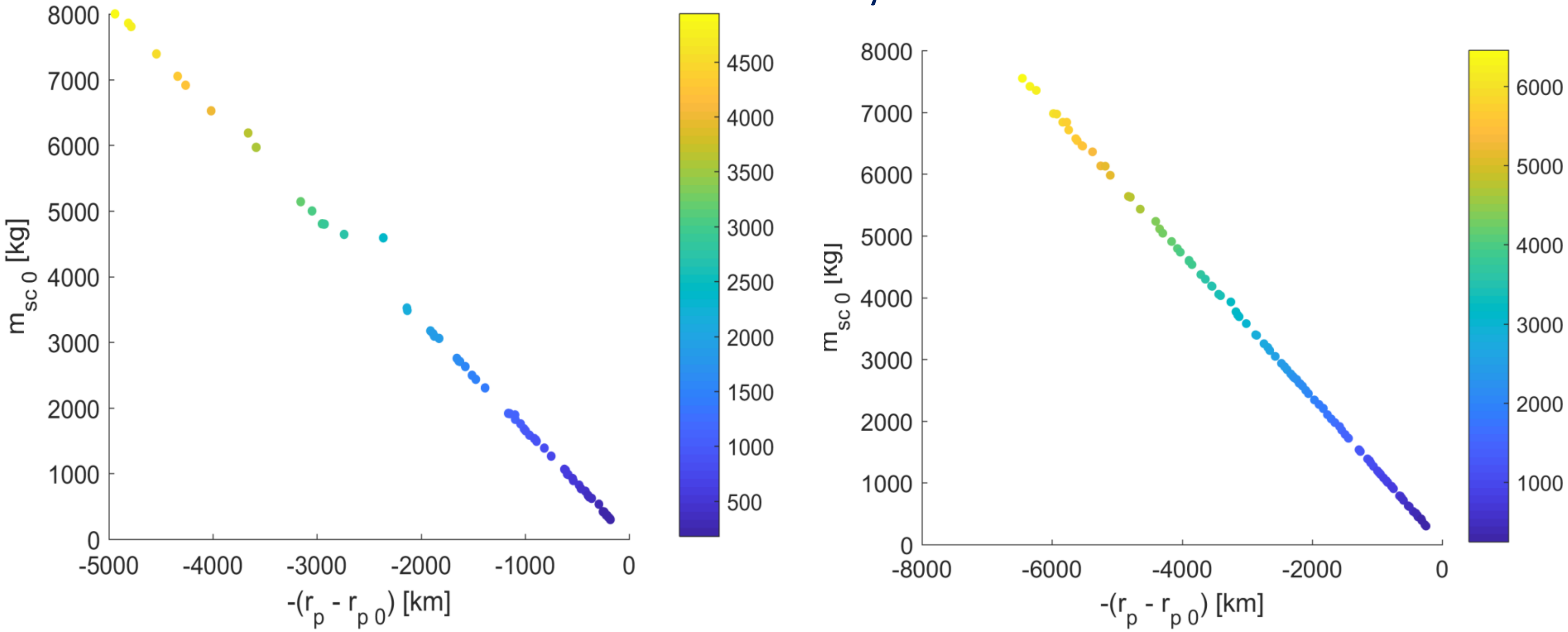
Results on a test case

Improved – Powered gravity assist

Upper bound	$0\ km/s$
Lower bound	$3\ km/s$

Definition of bounds for the impulse of the powered manoeuvre

Earth Gravity Assist

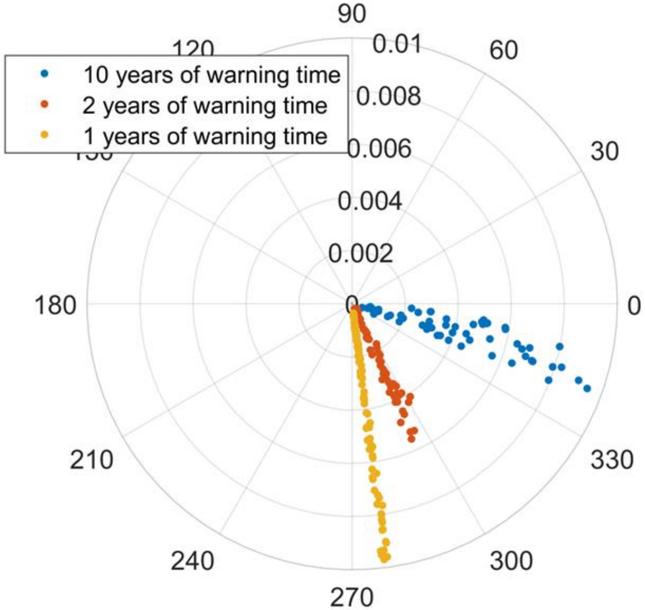


Not powered

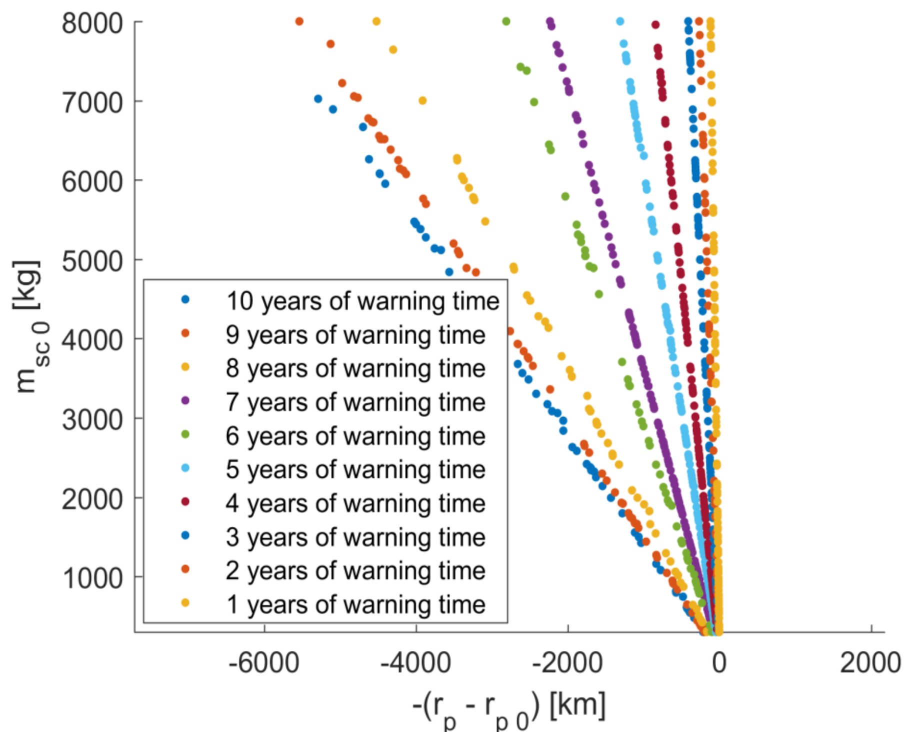
Powered

Results on a test case

Qualitative results – Variation of warning time



Polar plot for variation of velocity imparted to asteroids



Pareto fronts

Results on a test case

Qualitative results – Relations

- **Linear dependence** between achievable deflection and initial mass, **inverse proportionality** between achievable deflection and NEO mass
- Linear relation visible in all the Pareto fronts showed
- Analytically explained:
  - Assumption: $m_{SC} \ll m_{NEO}$
  - Assumption: only the tangential component of the deflection velocity is relevant

$$\delta \boldsymbol{v}_d = \beta \frac{m_{SC}}{(m_{SC} + m_{NEO})} \Delta \boldsymbol{v}$$

$$\delta \boldsymbol{\alpha}_d = \boldsymbol{G}_d \delta \boldsymbol{v}_d$$

$$\delta \boldsymbol{r}_{MOID} = \boldsymbol{A}_{MOID} \delta \boldsymbol{\alpha}_d$$

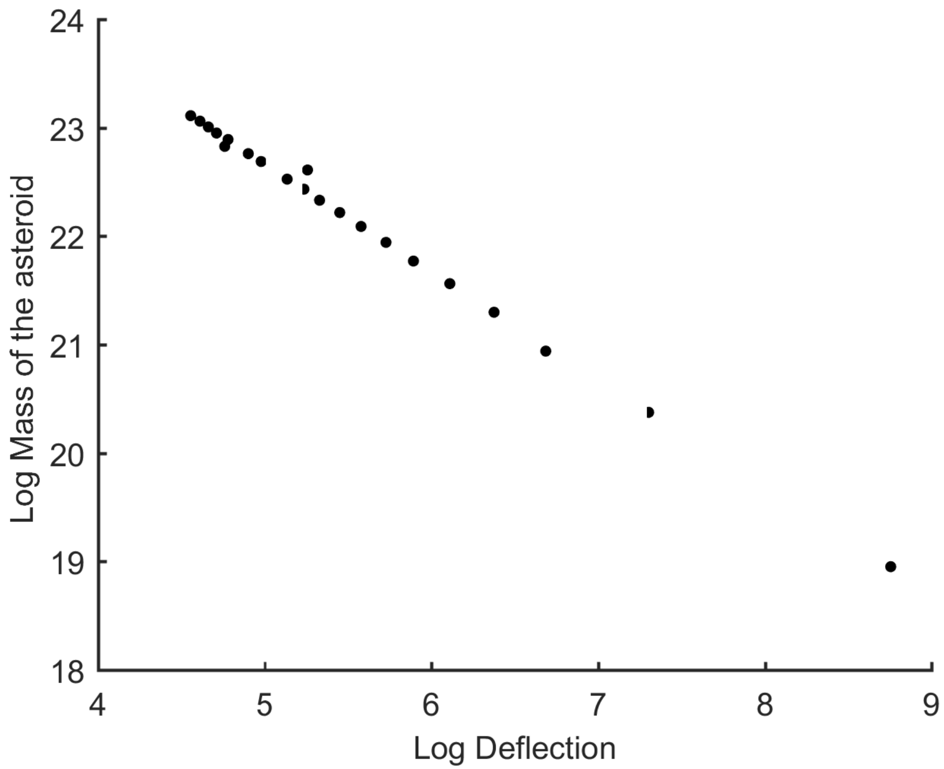
- This implies:

$$r_p = K \cdot \frac{m_{SC0}}{m_{NEO}} \cdot \delta v_t$$

Results on a test case

Qualitative results - Relations

Inverse proportionality between NEO mass and achievable deflection



Results on a test case

Qualitative results - Relations

- This results allow to **reduce the objective function** to a single-objective function

$$J = -\left(r_p - r_{p0}\right)$$

- It is possible to fix the spacecraft initial mass and recover solutions for different initial masses exploiting the linearity
- It is possible to fix the NEO mass and recover solutions for different masses exploiting the inverse proportionality

DEFLECTION EFFICIENCY ON A SYNTHETIC POPULATION OF NEOS

Deflection efficiency against a population of NEOs

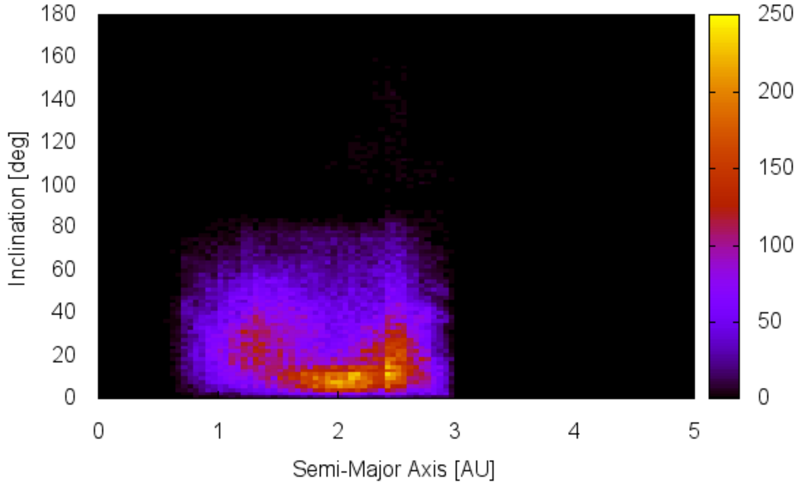
Model – Population generation

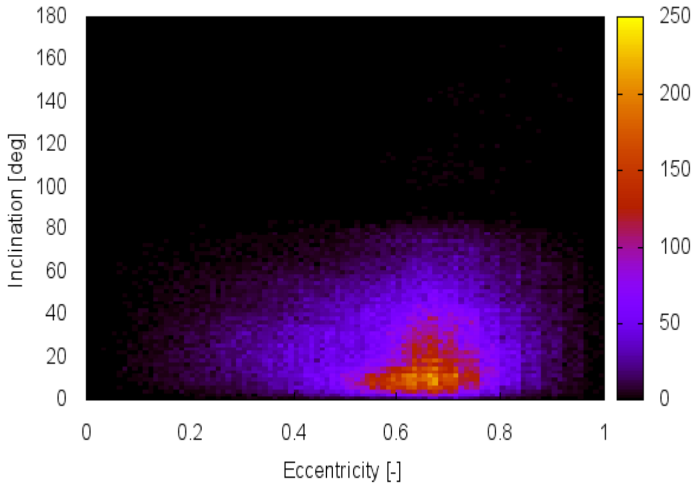
- In order to analyse the optimal way to deflect a population of asteroid, first it is necessary to **generate the population**
- **NEOPOP software** from ESA [9] generates a real set of orbital parameters defining every possible NEO
- **Filter activation** to reduce the population:
  - $40\ m < d < 200\ m$ → severe event
  - Pericentre radius smaller than 1AU & Apocentre radius larger than 1 AU, so that **orbit intersection** with that of Earth is possible
- This model allows to define the **NEO density distribution**

[9] M. Granvik, J. Vaubaillon and R. Jedicke, "The population of natural Earth satellites," *Icarus,* vol. 218, no. 1, 2012.

Deflection efficiency against a population of NEOs

Model – Population generation





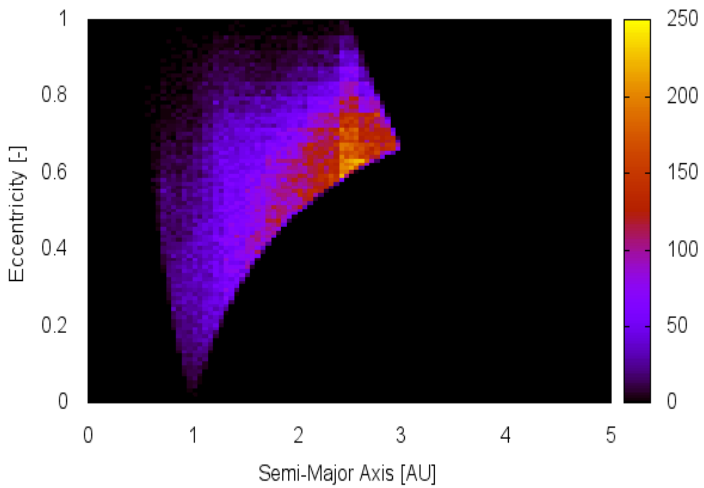


Image credits: NEOPOP software

Deflection efficiency against a population of NEOs

Model – Population generation

- Following the model in [10], a synthetic population of asteroid is created
- Defined by a grid of **homogeneously distributed** points in a 3-dimensional space, formed by $\{ a , e , i \}$ orbital parameters
- Discarded all the points with pericentre larger than 1 AU or apocentre smaller than 1 AU
- Assumptions:
  - Earth and asteroid are **both at MOID** at a fixed time t_{MOID}
  - Earth orbit is **circular** → Ω_{impact} and ω_{impact} are easily computed
- This model allows to find also the **collision probability** of each one of the synthetic NEO generated
- Multiplying collision probability with NEO density distribution to have the **relative frequency** of each impactor

[10] P. Sanchez, C. Colombo, V. Vasile and G. Radice, "Multicriteria Comparison Among Several Mitigation Strategies for Dangerous Near-Earth Objects," *Journal of Guidance, Control, and Dynamics,* vol. 32, no. 1, pp. 121-142, 2009.

Deflection efficiency against a population of NEOs

Results – Parameters setting

- Looking at the figure from NEOPOP software we can **bound the orbital parameters** in this way:
  - a is bound between 0.05 AU and 3 AU
  - e is bound between 0 and 1
  - i is bound between 0 deg and 90 deg
- Simulation repeated 4 times (1 for direct hit scenario, 3 for the gravity assist scenarios)
- Set of parameters for simulation:

m_{NEO}	$1.36 * 10^9\ kg$
m_{SC0}	$1000\ kg$
$warningTime$	$10\ years$

Deflection efficiency against a population of NEOs

Results – Parameters setting

- Design variable

$$\boldsymbol{x} = \{\alpha_0 \quad \alpha_1 \quad ToF_1 \quad \gamma_2 \quad r_{p2} \quad \Delta v_{POW} \quad \alpha_2 \quad ToF_2 \quad \|\Delta v_0\| \quad \alpha_{\Delta v_0} \quad \delta_{\Delta v_0}\}$$

- Bounds definition

Variable	α_0	α_1	ToF_1	γ_2	r_{p2}	Δv_{MAN}
Lower bound	0	0	$0.01\ P_{max}$	$-\pi\ rad$	1.1	$0\ km/s$
Upper bound	0.99	1	$2\ P_{max}$	$+\pi\ rad$	66.0	$3\ km/s$
Variable	α_2	ToF_2	$\|\Delta v_0\|$	$\alpha_{\Delta v_0}$	$\delta_{\Delta v_0}$	
Lower bound	0	$0.01\ P_{max}$	$0\ km/s$	$-\pi\ rad$	$-\pi/2\ rad$	
Upper bound	1	$2\ P_{max}$	$3\ \Delta v_{launch}$	$+\pi\ rad$	$+\pi/2\ rad$	

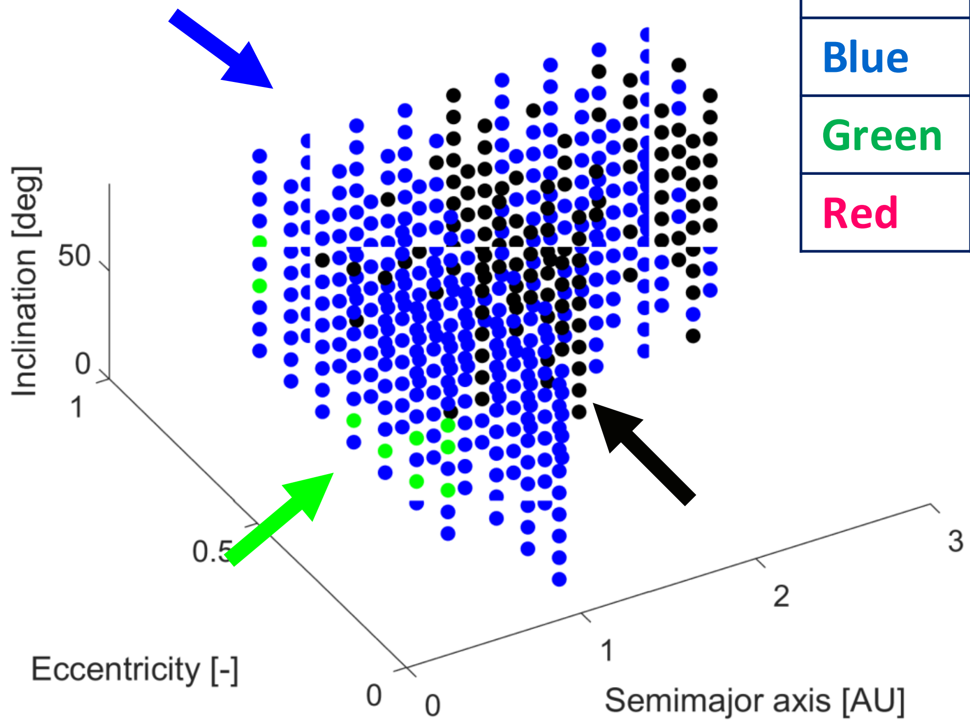
- Optimisation parameters

Case	**Function evaluations**	**Number of individuals**
Multiple asteroids	500,000	200

Deflection efficiency against a population of NEOs

Results

- Comparison between simulations



Black	Direct hit
Blue	Earth gravity assist
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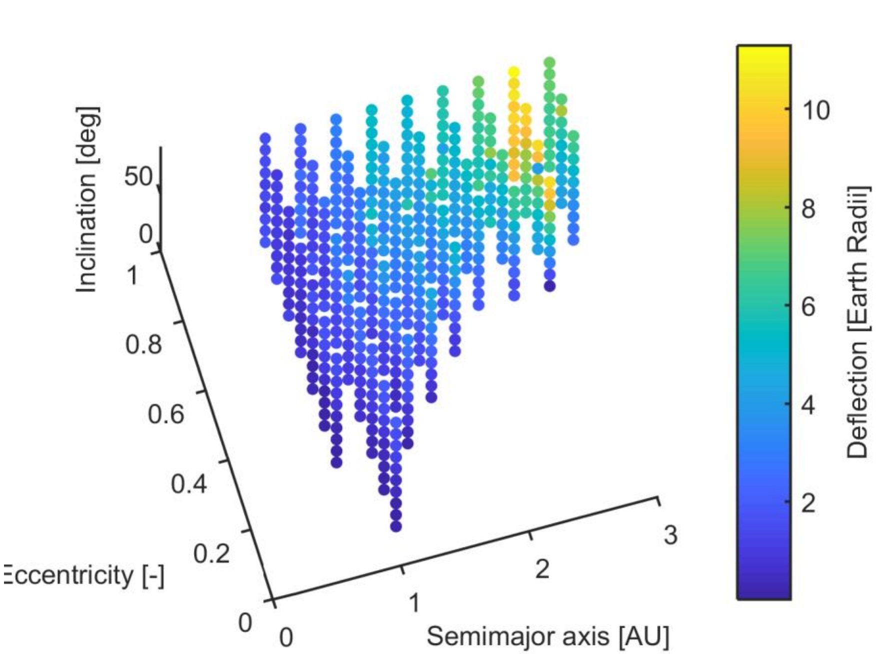
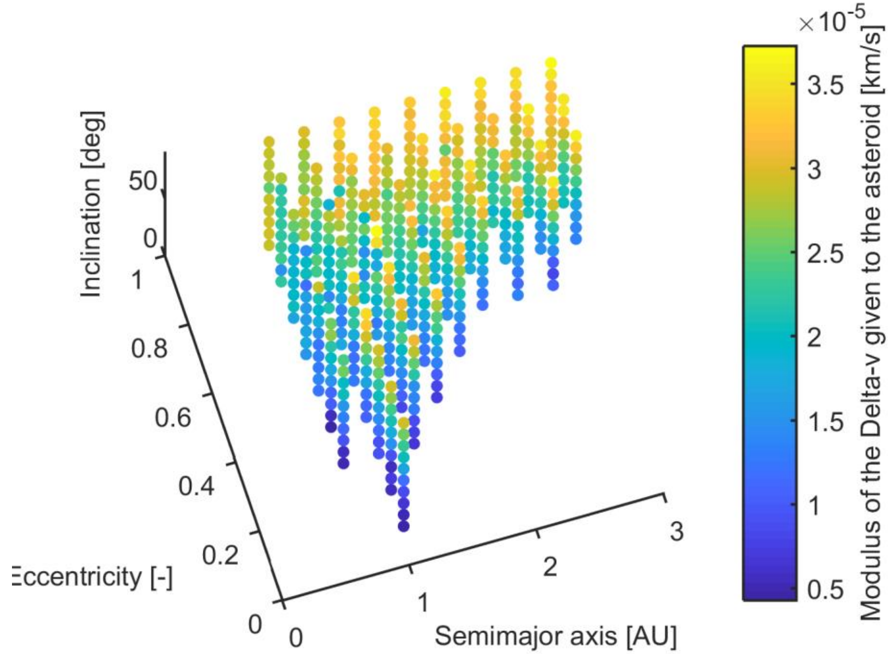
Deflection efficiency against a population of NEOs

Results

- Earth gravity assist – Qualitative characteristics



Deflection

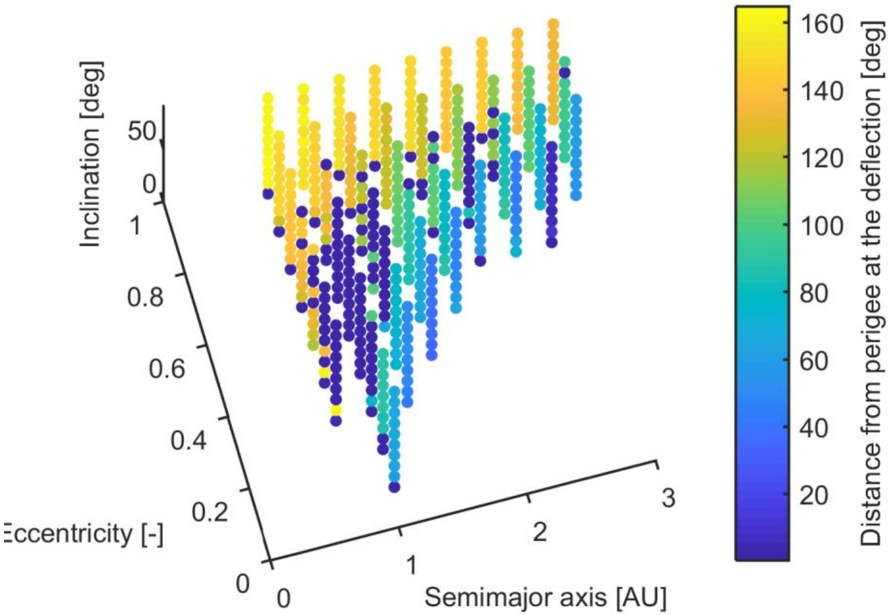


Delta-v given to asteroid

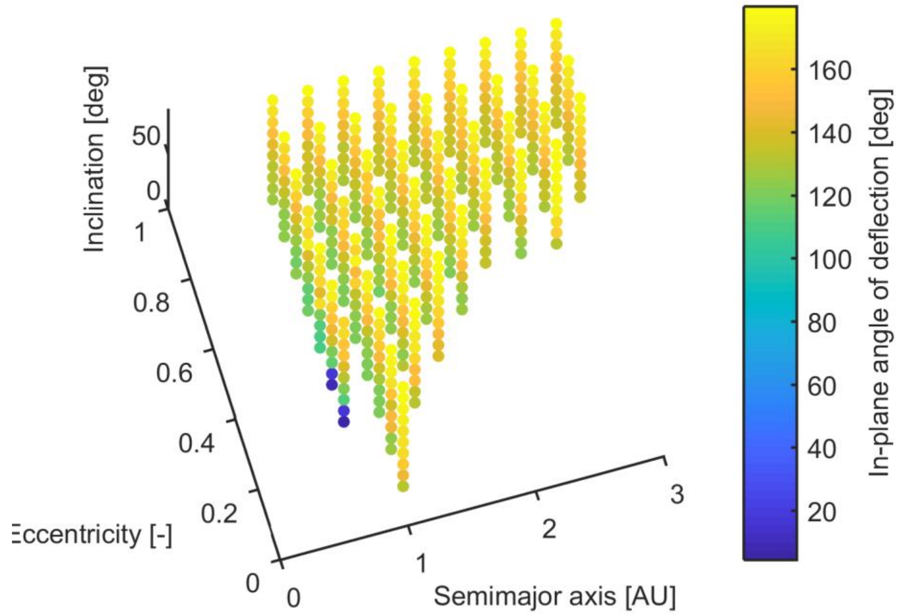
Deflection efficiency against a population of NEOs

Results

- Earth gravity assist – Qualitative characteristics



Distance from perigee at deflection



In-plane angle of deflection

CONCLUSIONS

Conclusions

Conclusions and future works

- **Best solution** in most of the case analysed is Earth's gravity assist:
  - Larger achievable deflections with the same initial mass of the spacecraft
  - Smaller initial mass required to have the same deflection (meaning a lower cost)
- Venus and Mars gravity assist don't seem to be good choices. **Changing the time of close approach** can boost their performances, due to phasing effect
- **Technique further improvable** by including more revolutions in the Lambert arc or more gravity assists to the mission concept
- Algorithm able to analyse rendez-vous mission by **changing optimisation function**

Thank you for your attention

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 679086 – COMPASS)

Image credits: ESA Space in Images – 2015 – Hera in orbit

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