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

Mission analysis for potential threat scenarios: kinetic impactor

Camilla Colombo, Pierluigi Di Lizia, Lorenzo Bolsi, Mathieu Petit, Giovanni Purpura, Marta Albano, Marco Castronuovo, Roberto Bertacin, Alessandro Gabrielli, Ettore Perozzi, Giovanni Valsecchi, Elena Vellutini, Simone Pizzurro

Agenzia Spaziale Italiana, Space Mission Planning Advisory group, 13/02/2019

The team

Italian Space Agency

Marco M. Castronuovo, Marta Albano, Roberto Bertacin, Alessandro Gabrielli, Ettore Perozzi, Simone Pizzurro, Elena Vellutini.

Politecnico di Milano

Camilla Colombo, Pierluigi Di Lizia, Lorenzo Bolsi, Mathieu Petit, Giovanni Purpura

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IAPS/INAF, IFAC/CNR

Giovanni Valsecchi

INTRODUCTION

Introduction

Space Mission Planning Advisory Group (SMPAG)

Prepare a coordinated response protocol to an impact threat scenario

- Criteria and thresholds for impact response actions
- Mitigation mission types/technologies to be considered
- Mapping of threat scenarios to mission types
- Reference missions for different NEO threat scenarios
- A plan for action in case of a credible threat
- Communication guidelines in case of a credible threat
- Roadmap for future work on planetary defence
- Criteria for deflection targeting
- Toolbox for a characterisation payload

Chelyabinsk, Russia (2013), 17-30 m diameter asteroid

Tunguska, Siberia (1908), flattening 2000 km^2 of forest, 50-70 m asteroid

Introduction

Reference missions for different threat scenarios

- Define a number of typical Near Earth Objects (NEOs) threat cases (based on time to closest approach, material characteristics, dynamical properties)
- Set of reference mission identified (e.g. mass; orbit; time-to-closest-approach) and evaluated in accordance with criteria defined (e.g. time between the impact alert and the launch window opening, etc).
- Sensitivity analysis on accuracy of orbit determination
- Robust control on the magnitude and direction of the imparted delta-velocity, centre of impact point
- For each reference mission investigate political and financial implications and constraints in the risk mitigation analysis
- Considering several deflection strategies

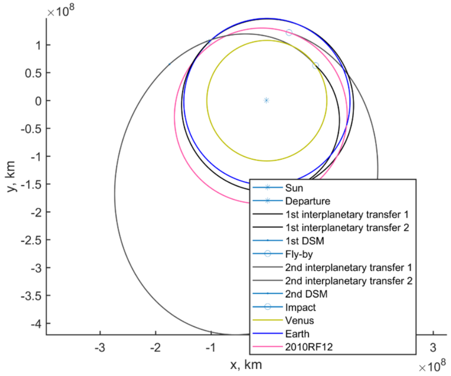
Summary till January 2018

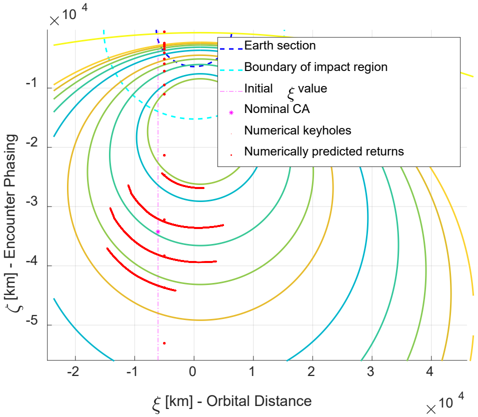
- Target asteroid selection
- Definition of threat scenarios: direct hit and resonant scenario
- Mission design for kinetic impactor direct hit
  - Mission analysis
  - System design
  - Additional payload to be agreed with Payload Toolbox task
- Preliminary gravity tug mission analysis

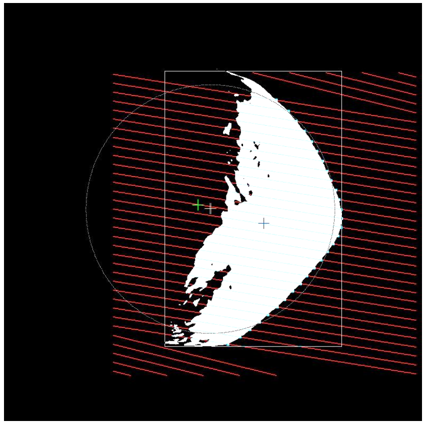
Insight into kinetic impactor design

Goals

- Improve trajectory design of the direct impact to improve deflection efficiency
  - Consider fly-bys during trajectory
- Study resonant encounter hit
  - Design of deflection manoeuvre robust to multiple encounters
  - Avoiding deflecting into a resonant return
- Guidance navigation and control of the approach phase
  - Navigation based on visual camera
  - Feedback on-board control algorithm







Lorenzo Bolsi, Camilla Colombo

IMPROVING DIRECT HIT SCENARIOS WITH MULTIPLE FLY-BYS

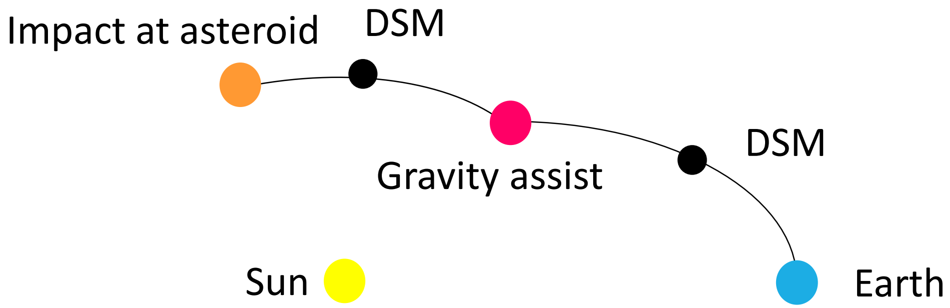
Introduction

Aims

- Introduce **gravity assist** of Earth, Mars and Venus in the design of a **deflection mission:**
  - Kinetic impactor
  - Maximise 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**

Model formulation

- Impact modelled as a completely inelastic collision
- Deflection at MPOID computed through an analytical approach
- Include gravity assists manoeuvres with other planets
- Include Deep Space Manoeuvres (DSM)
- Design parameters to be optimised:
  - $$\boldsymbol{x} = \{\underbrace{\alpha_0 \quad \alpha_1 \quad ToF_1}_{\text{Total transfer time and timing between DSM}} \quad \underbrace{\gamma_2 \quad r_{p2} \quad \alpha_2 \quad ToF_2}_{\text{Gravity assist timing and parameters}} \quad \underbrace{\|\Delta v_0\| \quad \alpha_{\Delta v_0} \quad \delta_{\Delta v_0}}_{\text{Departing trajectory from Earth}} \quad \underbrace{m_{SC0}}_{\text{Initial wet mass}}\}$$



Results on a test case

Selection of the test case and definition of parameters

2010RF12 NEO-like selected for with 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

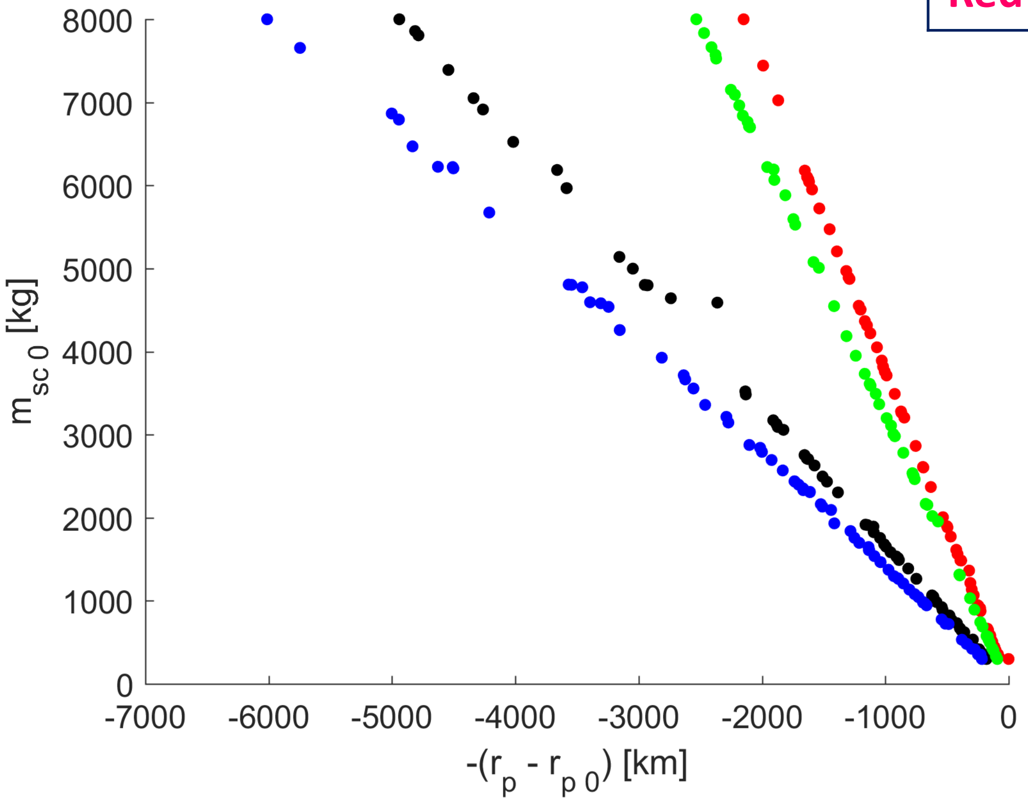
Launcher and NEO properties

warning time	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

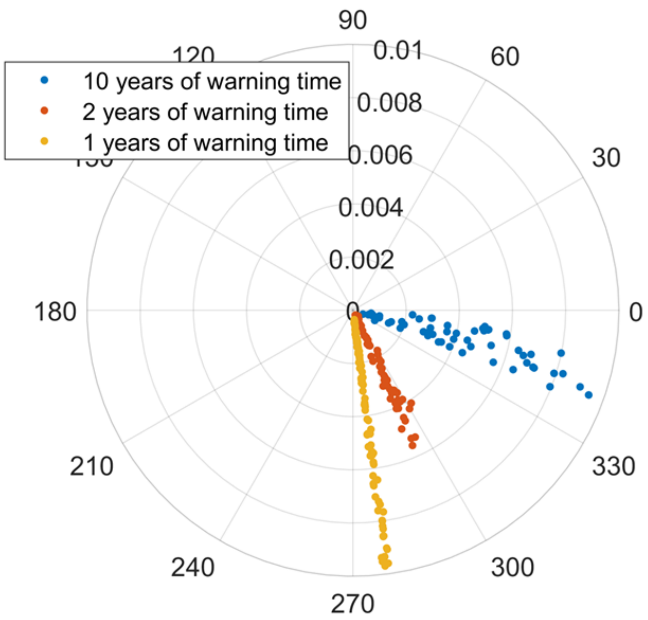
Gravity assists trajectories

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

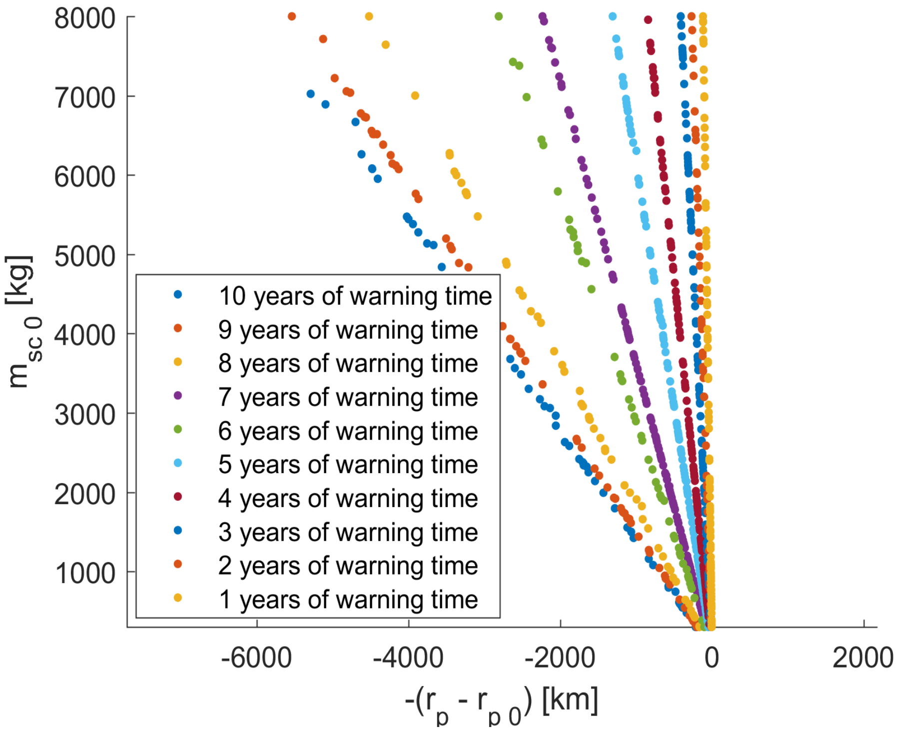


Results on a test case

Variation of warning time



Direction of delta velocity imparted to asteroid

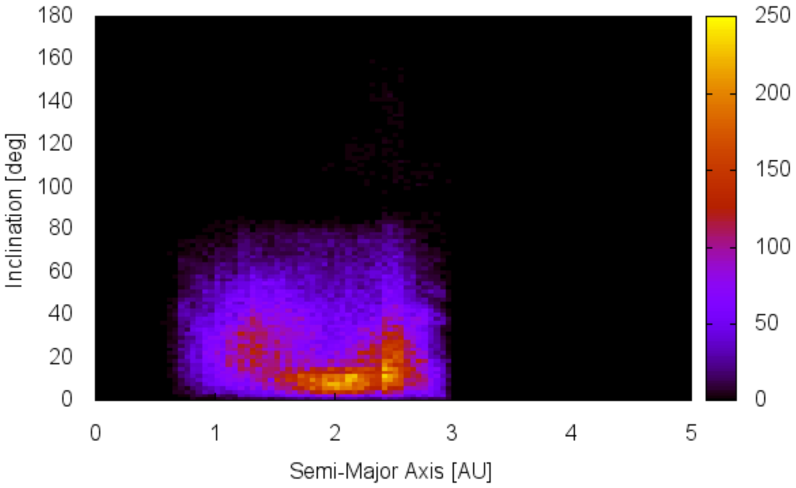


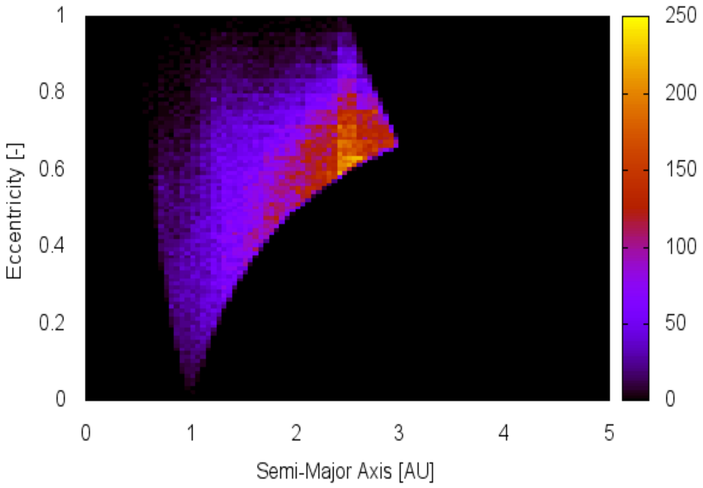
Initial mass vs deflection for different warning times

Deflection efficiency on NEO population

Model – Population generation

- Perform analysis on **NEAs population (NEOPOP software)** from ESA to generate a realistic set of orbital parameters defining every possible NEO
  - **Density of orbital distribution, collision probability, relative frequency**
- **Filter** $40\ m < d < 200\ m$ → severe event
- 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

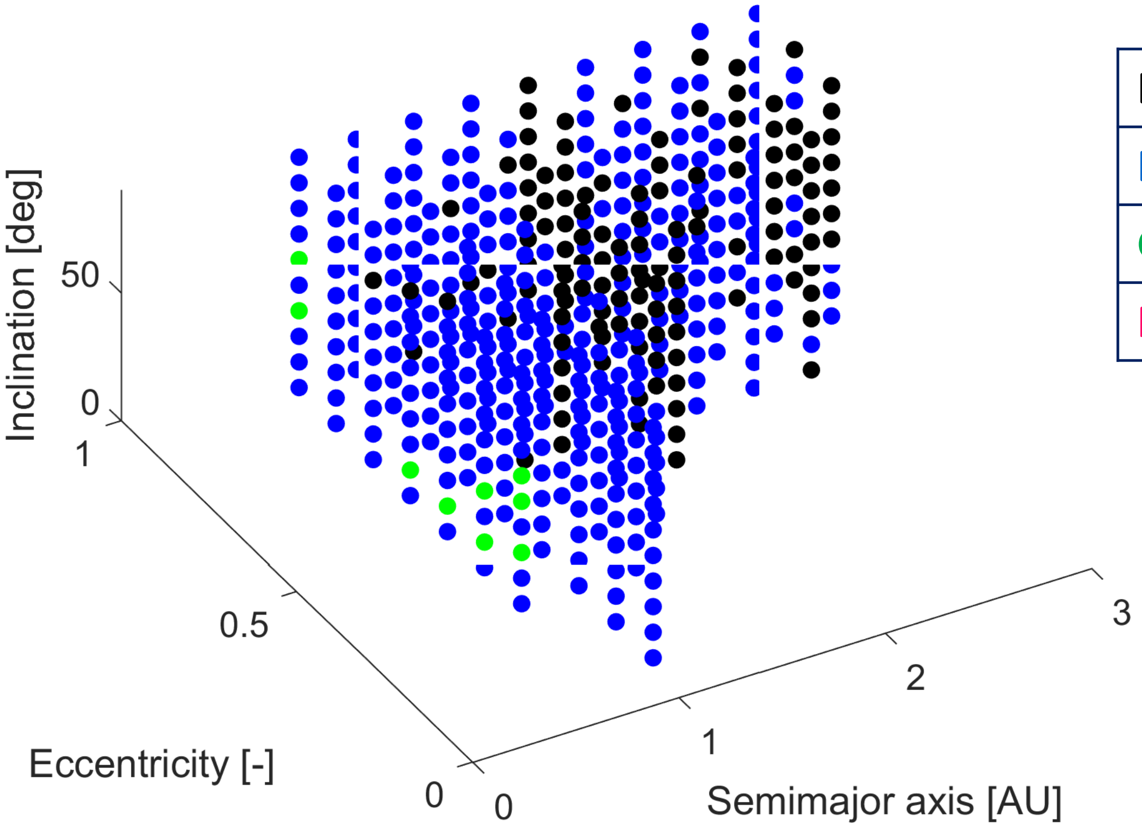




➢ M. Granvik, J. Vaubaillon and R. Jedicke, "The population of natural Earth satellites," *Icarus*, vol. 218, no. 1, 2012.

Deflection efficiency on NEO population

Results

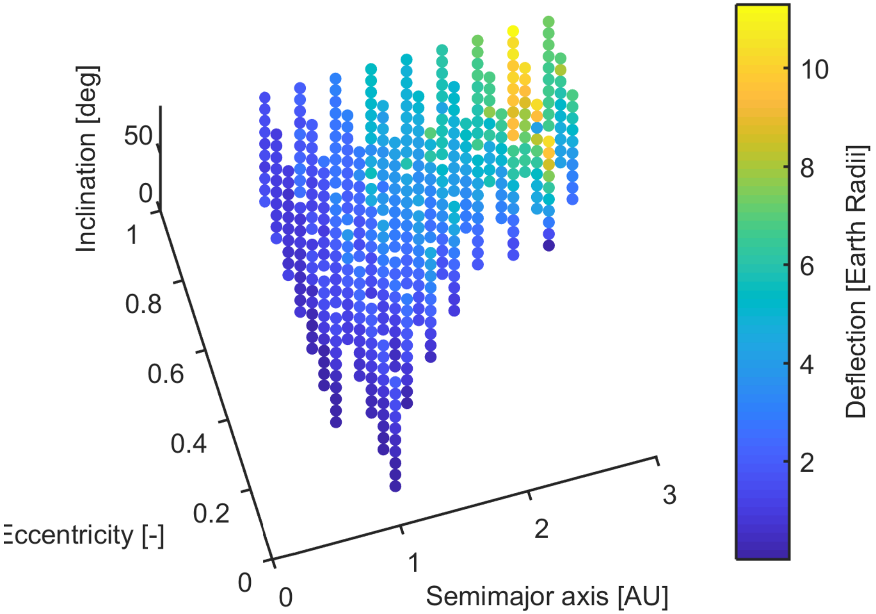


Black	Direct hit
Blue	Earth gravity assist
Green	Venus gravity assist
Red	Mars gravity assist

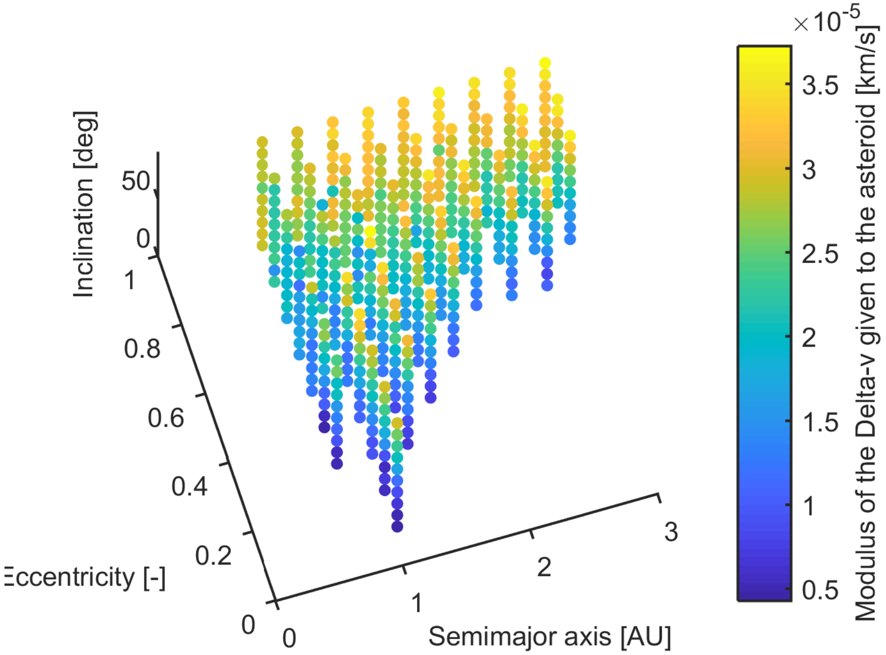
Deflection efficiency on NEO population

Results

Earth gravity assist



Deflection



Delta-v given to asteroid

Conclusions

- **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 do not seem to improve performances. **Changing the time of close approach** can boost their performances, due to phasing effect
- **Ready algorithm** able to run many mission cases also with other deflection strategies

Aim: characterise for any NEO orbit the best gravity assist sequence

Conclusions: Results will be included in final report

Giovanni Purpura, Pierluigi Di Lizia

OPTICAL AUTONOMOUS GNC

Optical autonomous GNC

Simulation overview

- Test case for the simulations:
  impact mission with asteroid 2010RF12
- Considered 3σ uncertainty:
  10 km in position and 1 m/s in velocity
- Simulations begin 2000 second before impact
- GNC strategy and simulation parameters:
  - On-board autonomous GNC
  - Only optical sensor
  - State reconstruction with Extended Kalman Filter
  - Asteroid shape: 101955 Bennu
    (the shape of 2010RF12 is unknown)
  - Asteroid diameter: 500 m
- Simulation output: impact position w.r.t. center of mass

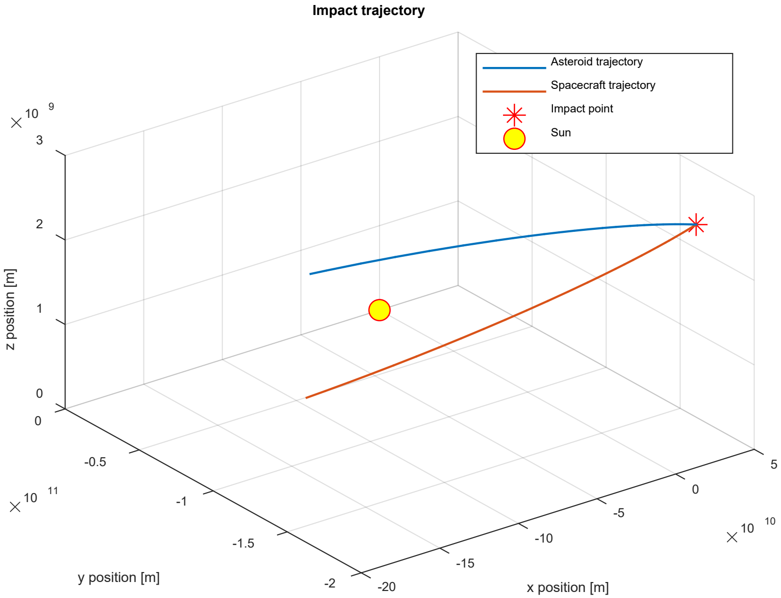
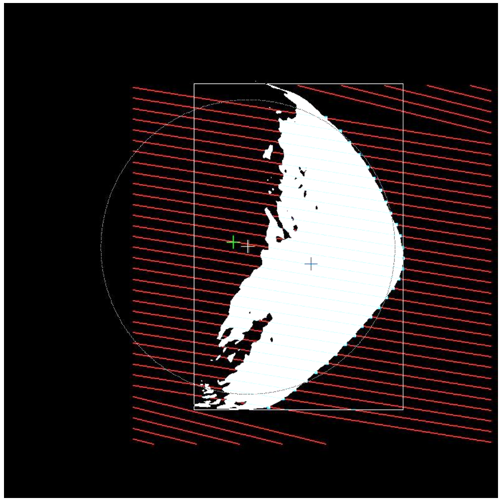


Image analysis algorithm

Circular fitting

- After the image is acquired, threshold filtering is performed.
- Image of the asteroid bounded with a rectangular box, then:
  - If box size < 10 px → Brightness centroiding
  - Else → Circular fitting (least squares)

- Fitting is performed using the points where brightness suddenly drops.
- In order to detect the fitting points, the pixels in the image are analysed over parallel lines.
- The orientation of the lines is computed using orbital and attitude data, which are known/estimated on board.



Demonstration of the image analysis algorithm

Control: Zero Effort Miss

- To correct the trajectory and secure the impact, a control algorithm based on the Zero Effort Miss parameter has been implemented.
- ZEM = difference in position between the asteroid and the spacecraft, computed integrating the motion with no control force, up to the instant at which the spacecraft misses (goes beyond) the asteroid.
- The optimal solution of the control, in terms of fuel consumption, requires a variable gain that is a function of the time remaining to the impact
- Then the thrusters are activated accordingly, taking into account the spacecraft mass.

Considered cameras

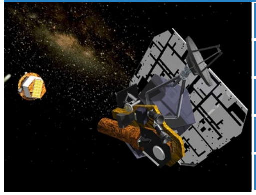
Five different optics-sensor combinations have been simulated:

- MCSS ECAM-C50: camera considered in the paper;
- A proposed device, not available off-the-shelf, having:
  - high resolution (as the ECAM-C50)
  - medium focal length (as the Rosetta NavCam).
- Three navigation cameras taken from actual space missions.
- These cameras have very different focal length, from the 12.6 mm of ECAM-C50 to the 2000 mm of Deep Impact’s camera.

Proposal

Focal length	150 mm
FOV	5 deg
Resolution	1944 px
Sensor size	13.1 mm
Pixel size	6.7 µm

NASA Deep Impact

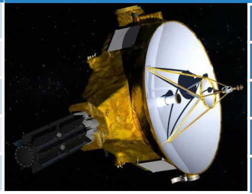


Focal length	2000mm
FOV	0.6 deg
Resolution	1024 px
Sensor size	20.9 mm
Pixel size	20.5 µm

ESA Rosetta

Focal length	152.5mm
FOV	5 deg
Resolution	1024 px
Sensor size	13.3 mm
Pixel size	13 µm

NASA New Horizons



Focal length	263 mm
FOV	0.29 deg
Resolution	1024 px
Sensor size	1.3 mm
Pixel size	1.3 µm

MCSS ECAM-C50

Focal length	12.6 mm
FOV	19 deg
Resolution	1944 px
Sensor size	4.2 mm
Pixel size	2.2 µm

Monte Carlo simulations results

Results of the Monte Carlo simulations starting 2000 seconds before impact.

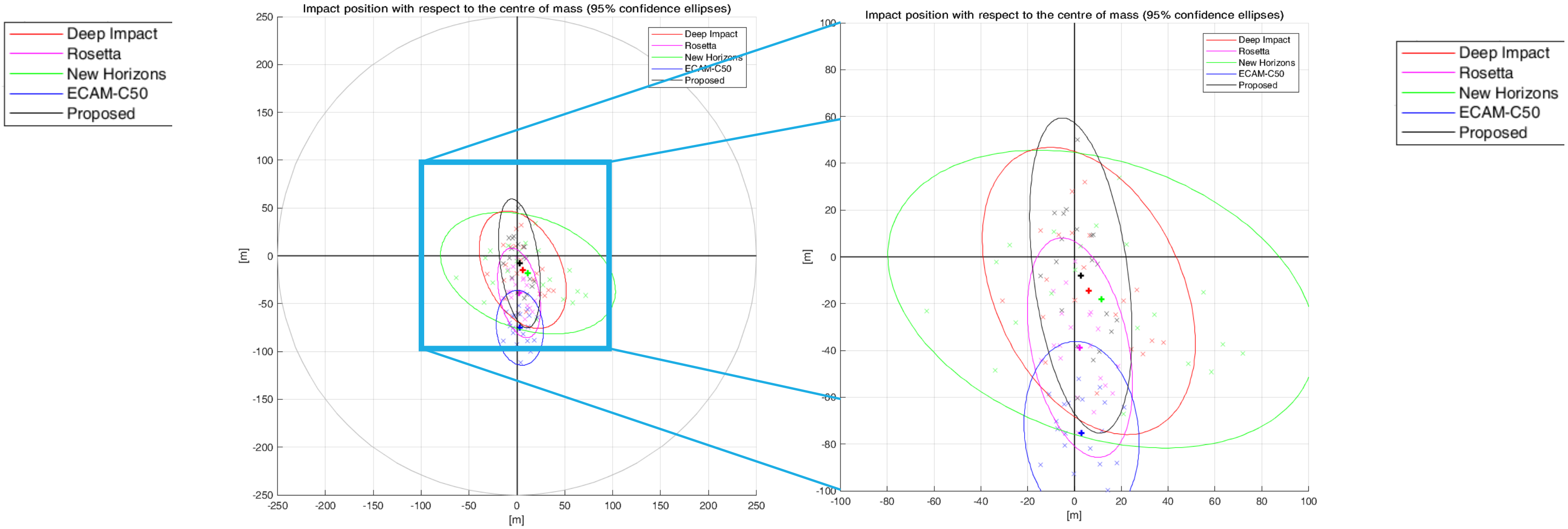
		Deep Impact	Rosetta	New Horizons	ECAM-C50	Proposed
Focal Length	[mm]	2000	152.5	263	12.6	150
FOV	[deg]	0.6	5	0.29	19	5
Resolution	[px]	1024	1024	1024	1944	1944
Sensor size	[mm]	20.9	13.3	1.3	4.2	13.1
Pixel size	[µm]	20.5	13.0	1.3	2.2	6.7
Simulation results						
Mean error	[m]	30.5	39.9	42.8	76.0	25.2
Required ΔV	[m/s]	8.5	11.1	8.1	14.1	9.8
Images ≥ 1px	[-]	138	143	125	92	143
Images ≥ 10px	[-]	138	56	125	27	108

- Deep Impact and New Horizons are able to use the circle fitting algorithm over all the acquired images.
- In terms of mean error, best results are achieved by the proposed camera (which has medium focal length and high resolution) and by Deep Impact (which has a lower resolution yet an extremely long focal).

Monte Carlo simulations results

Impact positions

- Monte Carlo simulations show that all the cameras allow to impact the asteroid, but the lowest error is achievable only with medium/long focal lengths.
- The proposed camera, with medium focal length and high resolution, gives the lowest average error.



Resulting impact points and error ellipsis (center of image axes = center of mass)

Mathieu Petit, Camilla Colombo

RESONANT HIT SCENARIOS

Introduction

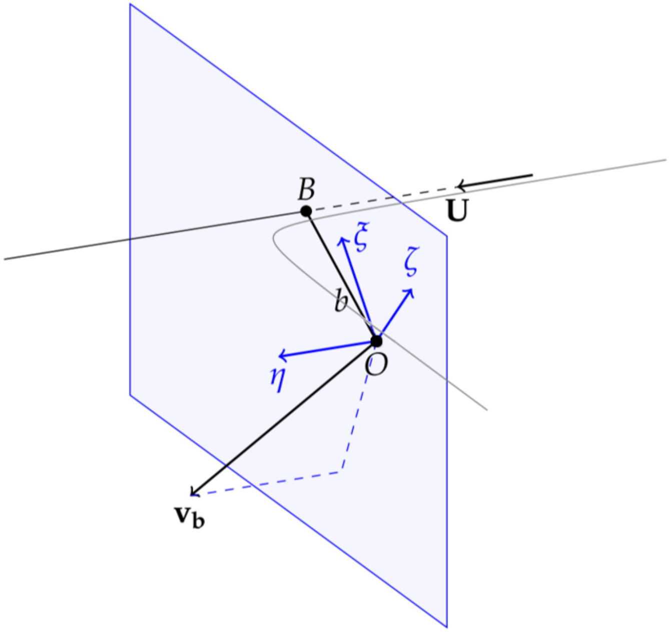
Aims

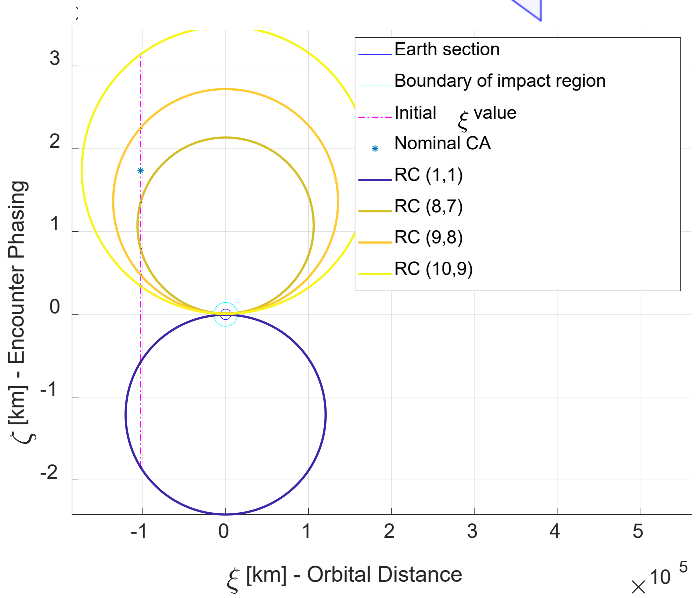
- Describe **NEOs resonant returns**
  - Exploit the b-plane representation
  - Obtain a convenient formulation correlating the deflection to the deviation on the b-plane
- Possibility of the Earth fly-by to insert the NEO on a return orbit to the Earth
  - Determine the optimal deflection direction to maximise the displacement on the b-plane
- **Design an optimal deflection strategy** aimed at **avoiding resonant returns of asteroids**

B-plane representation

Resonances

- **B-plane representation**
  - ξ-axis: geometric distance between the two bodies' orbits at the encounter (MOID)
  - ζ-axis represents a shift in the time of arrival of the object at the planet
- **Resonances** are circles on the b-plane
  - $k\mathrm{T}_P = h\mathrm{T}' \longrightarrow a'$
  - A circle can be drawn on the b-plane for each couple of integers (h, k)
- **Keyholes numerically computed** to refine analytical solution of resonant circles



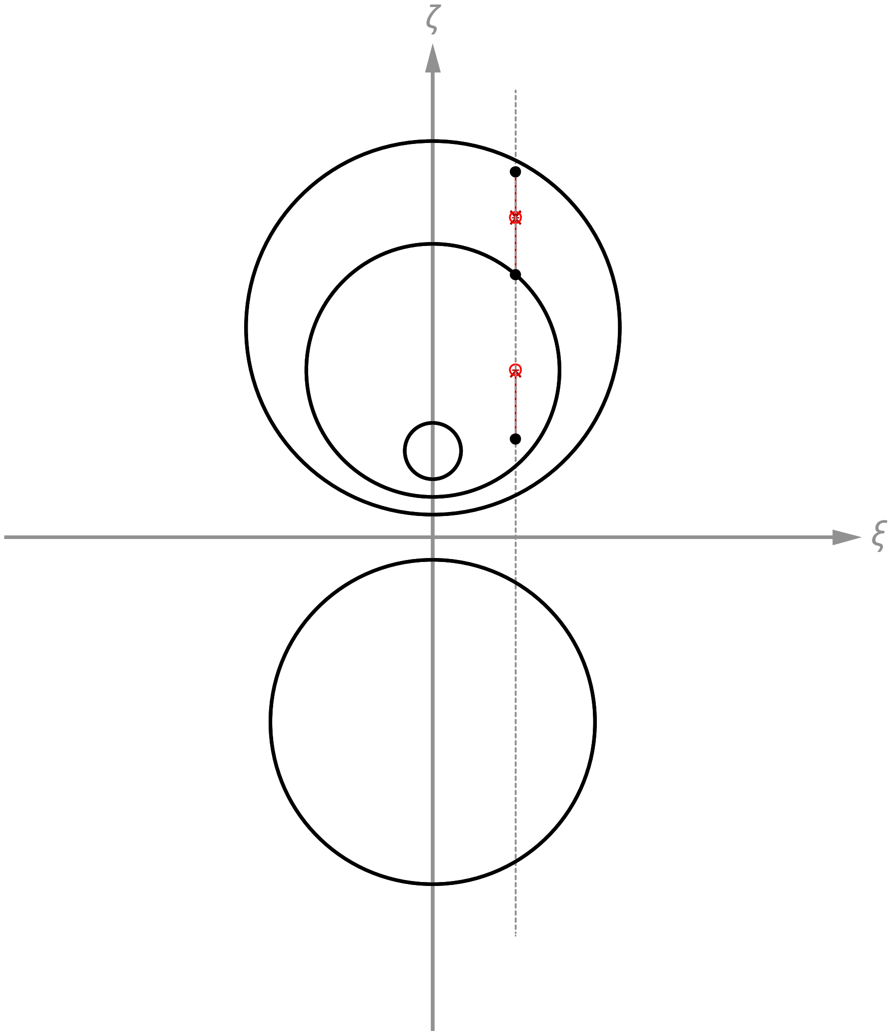


➢ Valsecchi G. B., Milani A., Gronchi G. F. and Chesley S. R., "Resonant returns to close approaches: Analytical theory", 2003

Deflection manoeuvre

Optimal deflection strategy to avoid keyholes

- A deviation along ζ is considered (early deflections)
- Nominal encounter within a keyhole
  - Target middle point between the keyhole and the closest one
- Nominal encounter between keyholes
  - Target middle point between the considered keyholes
- **Optimal deflection vector direction** computed through eigenvector problem
- Not a pure maximisation when trying to avoid a keyhole

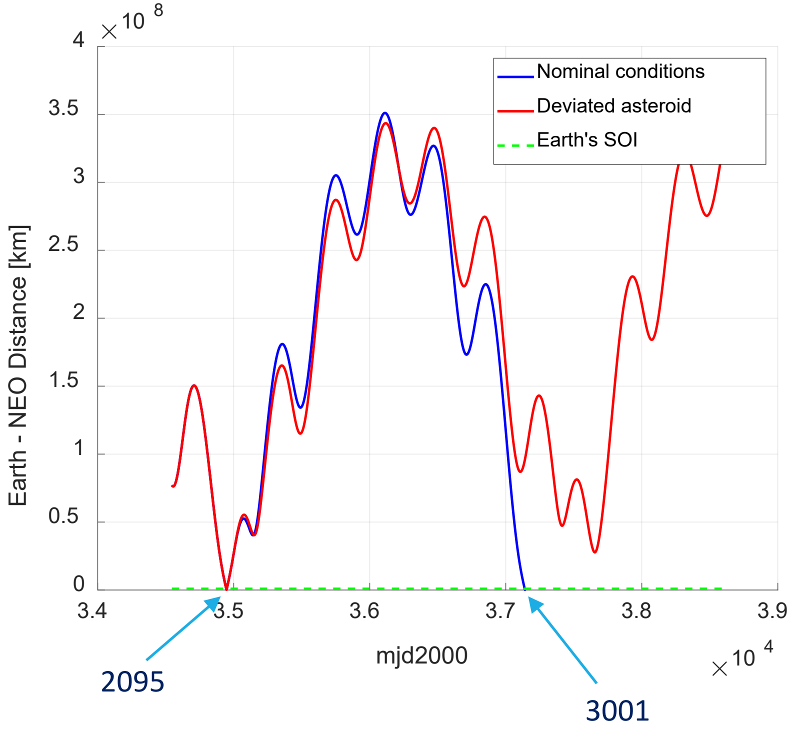


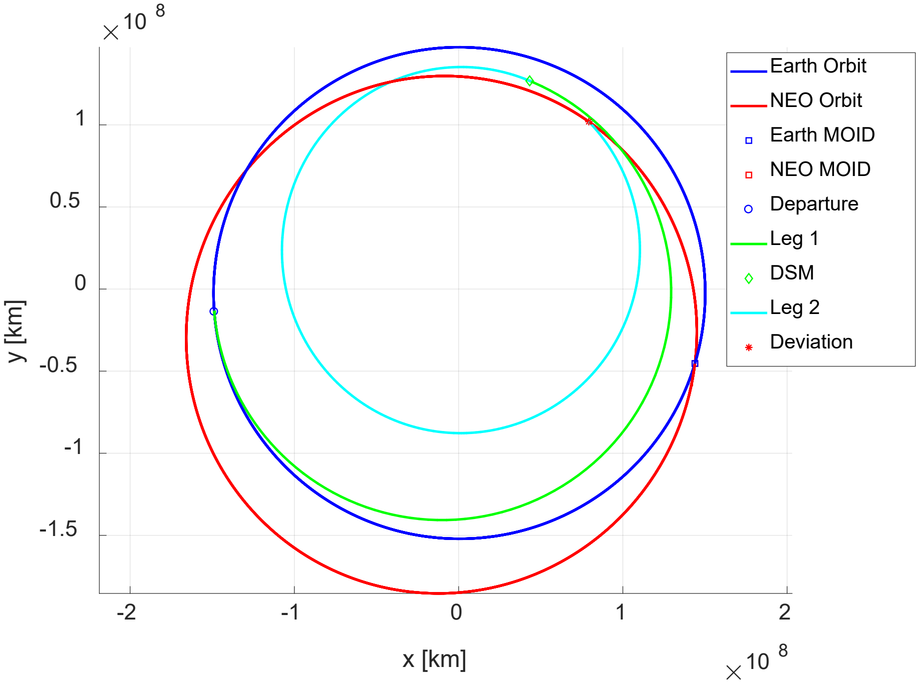
Results

Preliminary Deflection Mission Design

- 2095 encounter of 2010 RF_{12}-like with the Earth - (6,5) keyhole
- Target ζ value between keyholes (6,5) and (7,6)

- Escape, DSM, impact
- Max distance from the closest keyholes
- Min initial s/c mass





Conclusions

- Correlation between the deflection and the displacement on the b-plane has been obtained
- Optimal deflection technique has been devised to avoid the keyholes
  - Based on the knowledge that the deflection is most effective in the phasing (ζ-axis)
  - Aimed ad avoiding resonant returns (i.e. the keyholes)
  - A preliminary mission design supports the viability of the technique
- To be done: **apply to syntenic NEO population**

Aim: characterise NEO resonant encounters

Conclusions: Results will be included in final report

Next steps

- SMPAG report draft
  - Literature review and past work
  - Mission design work
  - Insight into kinetic impactor design
    - Improve trajectory design of the direct impact to improve deflection efficiency
    - Study resonant encounter hit
    - Guidance navigation and control of the approach phase
  - Gravity tug preliminary mission analysis
- Future work
  - Robust design: consider uncertainties in orbit determination, deflection manoeuvre and dynamical evolution
  - GNC embedded into trajectory design
  - System design applied to more missions
  - Asteroid exploration missions

A part of this study 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

Mission analysis for potential threat scenarios: kinetic impactor

Marco M. Castronuovo marco.castronuovo@asi.it
Camilla Colombo camilla.colombo@polimi.it
Pierluigi Di Lizia pierluigi.dilizia@polimi.it