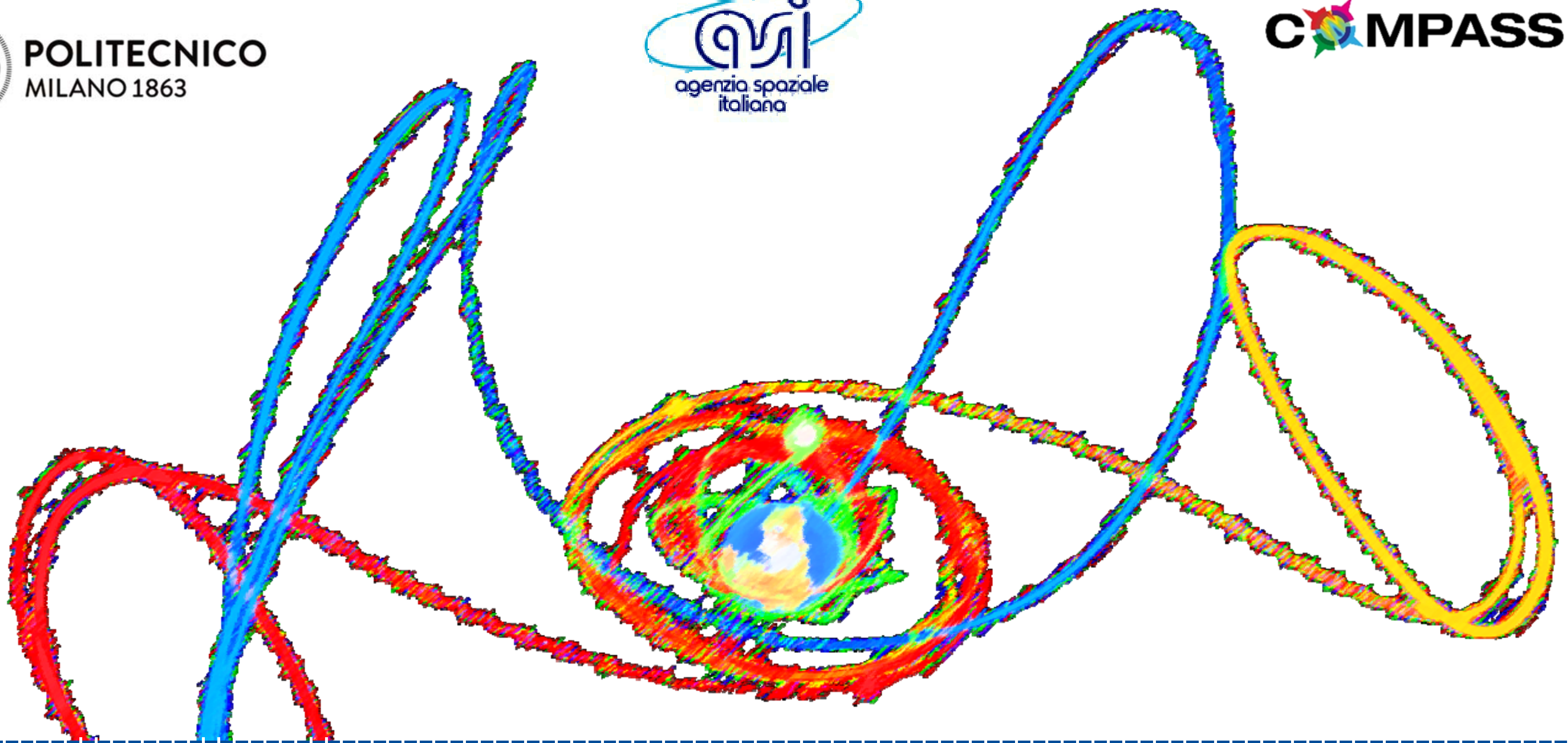

# Mission analysis for potential threat scenarios: kinetic impactor

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*SMPAG Meeting 18 Oct 2018*

# The team

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# 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
- Gravity tug system design

# Insight into kinetic impactor design

## Goals

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

# 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 **population of NEOs** spread through all the spectrum of orbital parameters and analyse the **global qualitative results**

# Direct hit 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 |
|---|---|---|---|---|
| $1.58 \cdot 10^8 km$ | $0.187$ | $0.911\ deg$ | $162\ deg$ | $267\ deg$ |

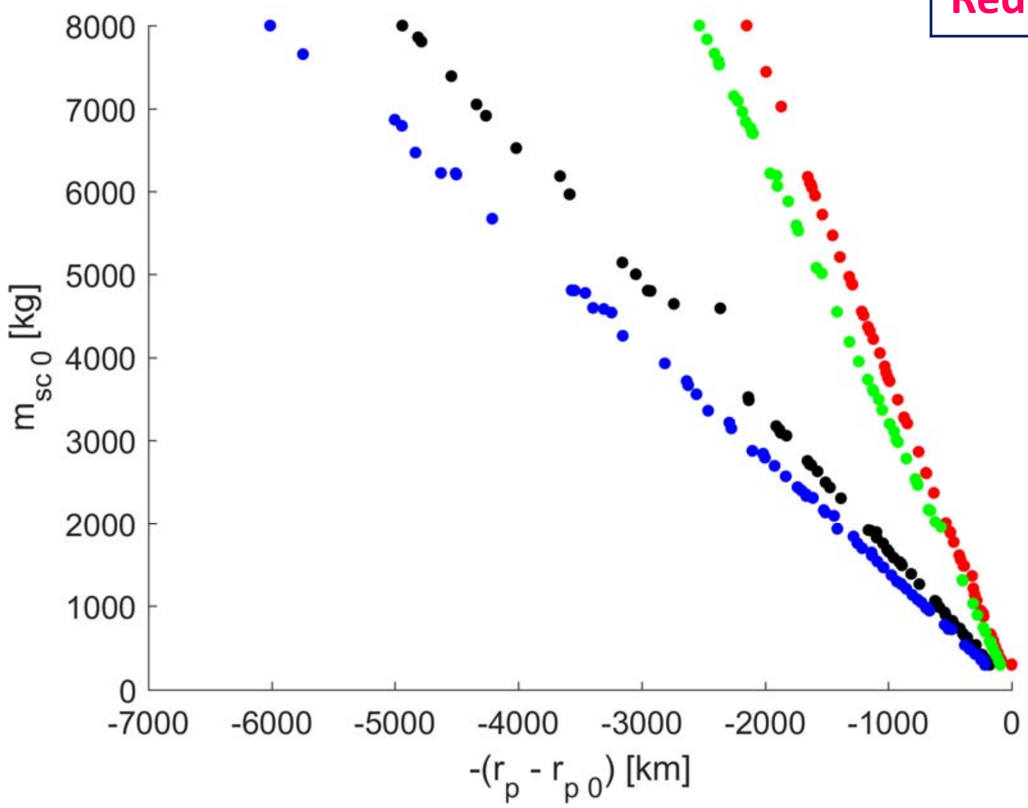
Launcher and NEO properties

| | |
|---|---|
| $warningTime$ | $10\ years$ |
| $\Delta v_{launch}$ | $1\ km/s$ |
| $I_{sp}$ | $300\ s$ |
| $D_{NEO}$ | $100\ m$ |
| $\rho_{NEO}$ | $2600\ kg/m^3$ |
| $\beta$ | $1$ |

# Direct hit test case

Gravity assists trajectories

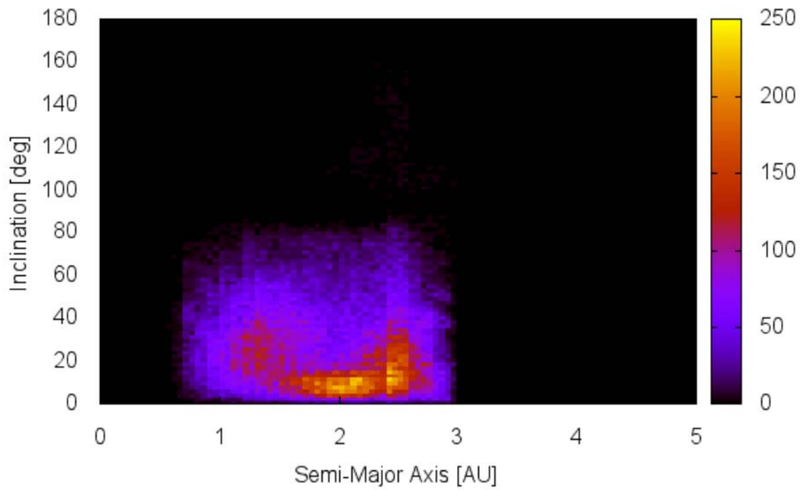
| | |
|---|---|
| **Black** | Direct hit |
| **Blue** | Earth gravity assist |
| **Green** | Venus gravity assist |
| **Red** | Mars gravity assist |

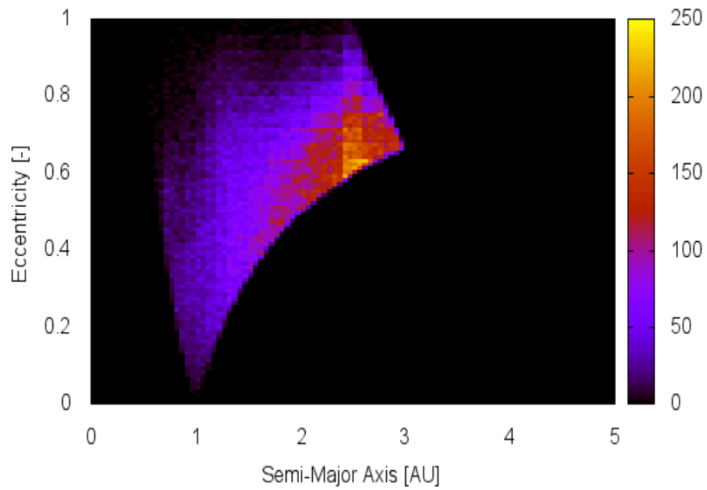


# Deflection efficiency

## Model – Population generation

- Perform analysis on **NEAs population (NEOPOP software)** from ESA [6] to generate a realistic set of orbital parameters defining every possible NEO
- **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** → $\Omega_{impact}$ and $\omega_{impact}$ are easily computed

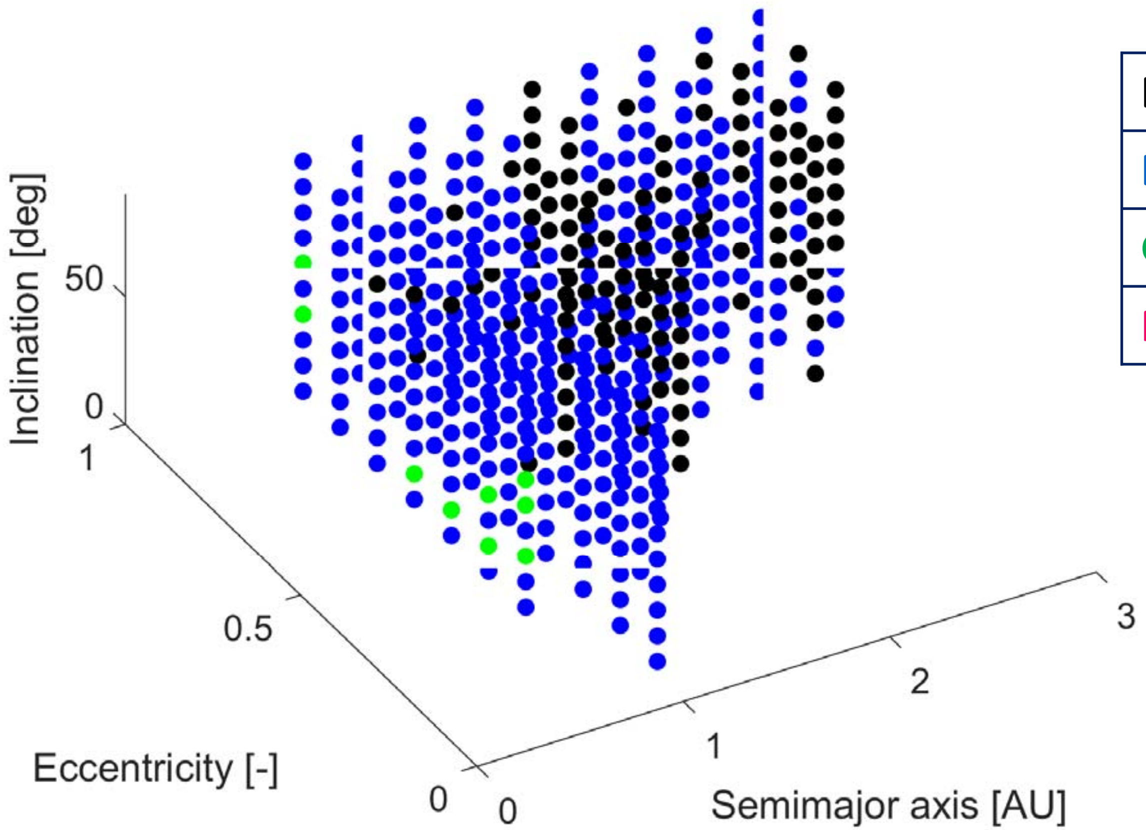



M. Granvik, J. Vaubaillon and R. Jedicke, "The population of natural Earth satellites," *Icarus,* vol. 218, no. 1, 2012.

# Deflection efficiency on NEO population

## Results




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

# 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

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

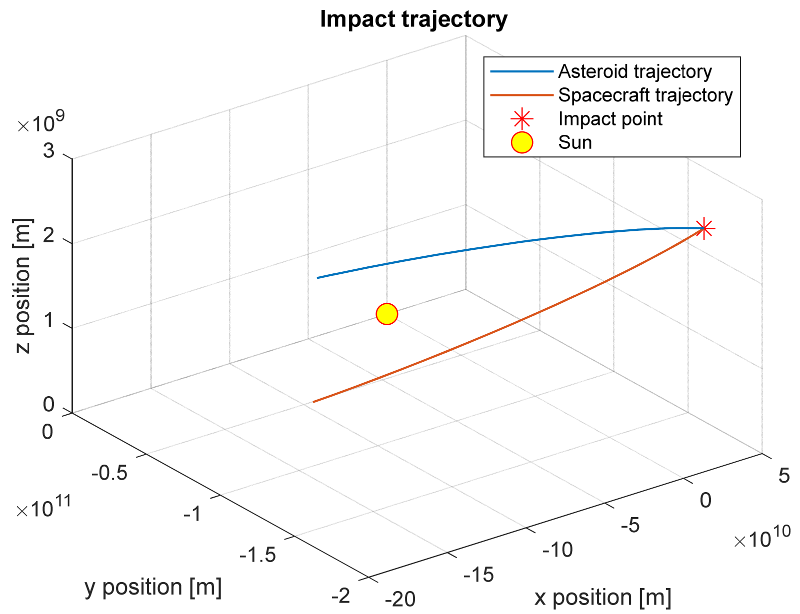
**Conclusions**: Results to be included in final report

# 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 analyzed 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

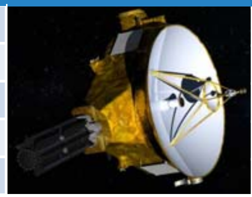
Five different optics-sensor combinations have been simulated:

- 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.

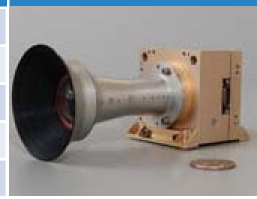
| Proposal | |
|---|---|
| Focal length | 150 mm |
| FOV | 5 deg |
| Resolution | 1944 px |
| Sensor size | 13.1 mm |
| Pixel size | 6.7 µm |

| 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.

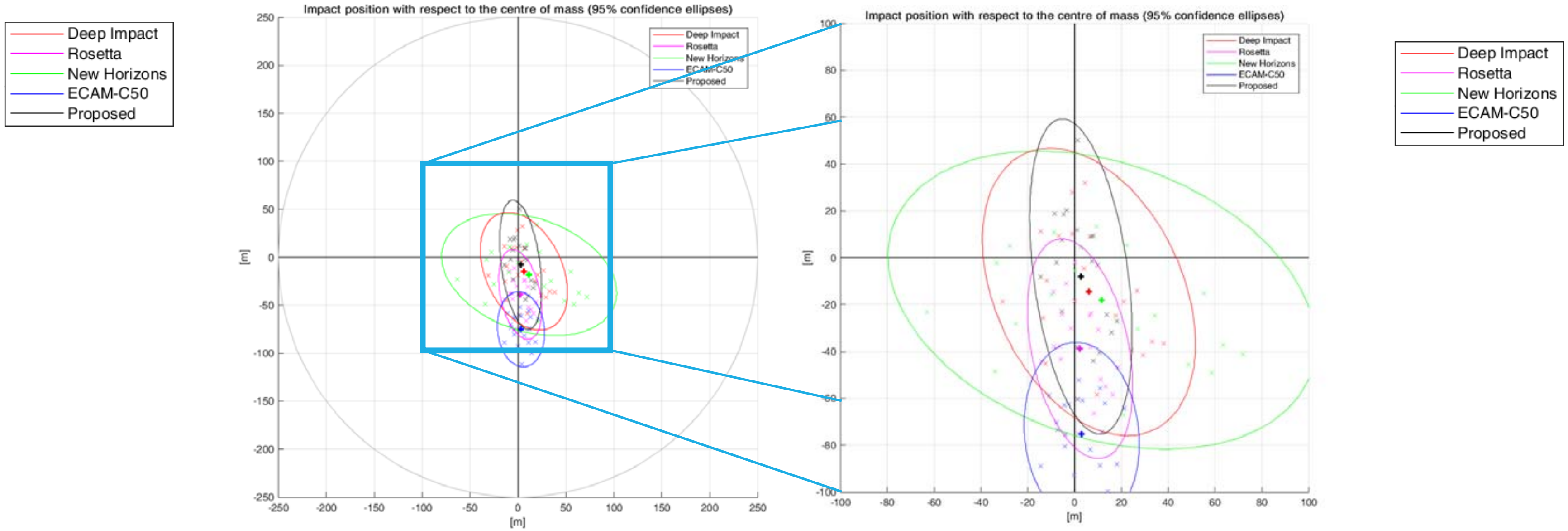
| | | Deep Impact | Rosetta | New Horizons | ECAM-C50 | Proposed |
|---|---|---|---|---|---|---|
| Focal Length | [mm] | 2000 | 152.5 | 263 | 12.6 | 150 |
| FOV | [deg] | 0.6 | 5 | 0.29 | 19 | 5 |
| Resolution | [px] | 1024 | 1024 | 1024 | 1944 | 1944 |
| Sensor size | [mm] | 20.9 | 13.3 | 1.3 | 4.2 | 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.



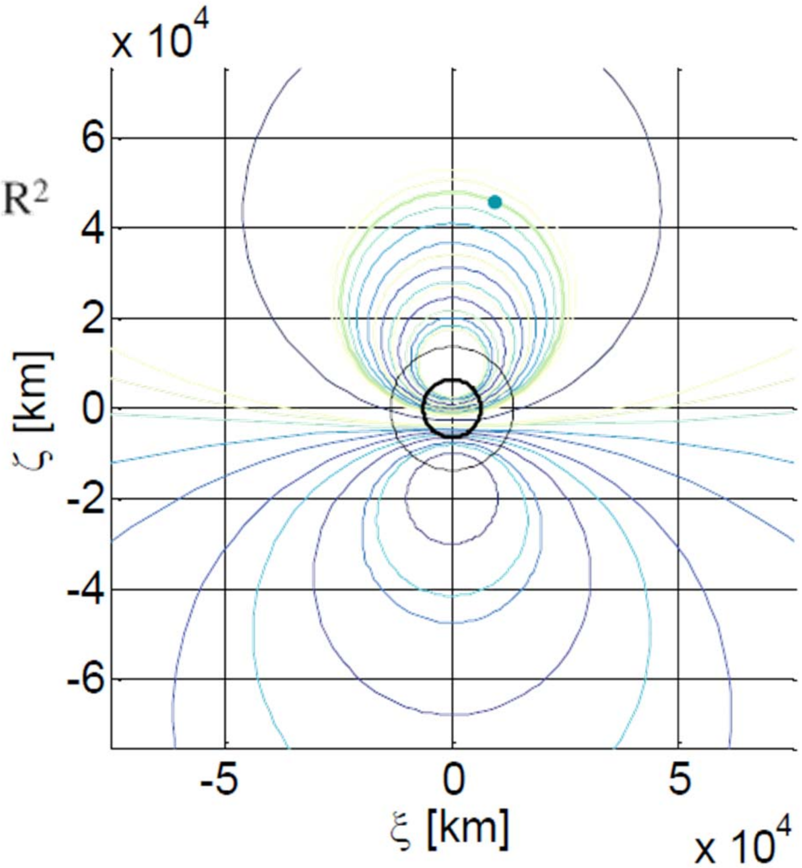

*Resulting impact points and error ellipsis (center of image axes = center of mass)*

# RESONANT HIT SCENARIOS

# B-plane

## Resonances

- Circle on the b-plane $\xi^2 + \zeta^2 - 2D\zeta + D^2 = R^2$
- Requirement: Tisserand criterion < 3
- Hypotheses: 2-Body Problem, Circular Earth orbit
- For a given close encounter, the **post-encounter semi-major axis** is computed. The resulting period is compared to the ones of **possible** resonances. $kT_P = hT' \longrightarrow a'$
- A circle can be drawn on the b-plane for each couple of integers $(h, k)$



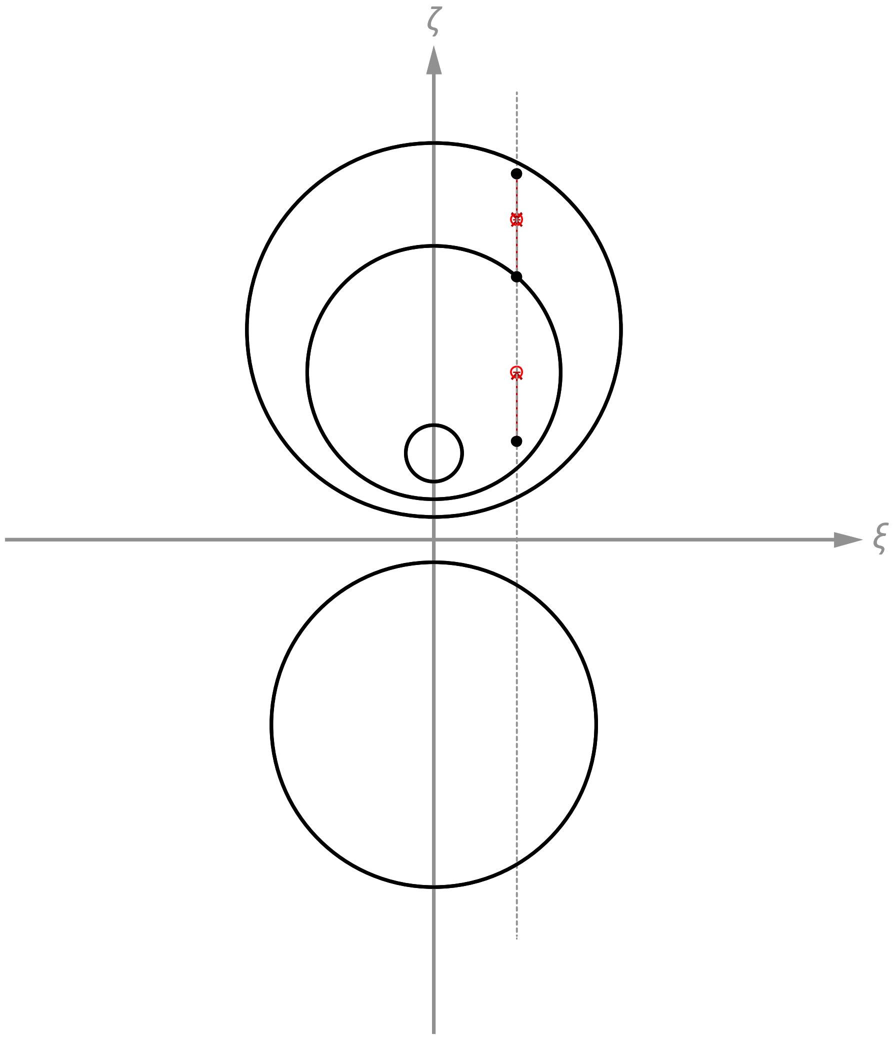

*Resonance plotted according to their k value: dark low k, light low k*

➢ 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

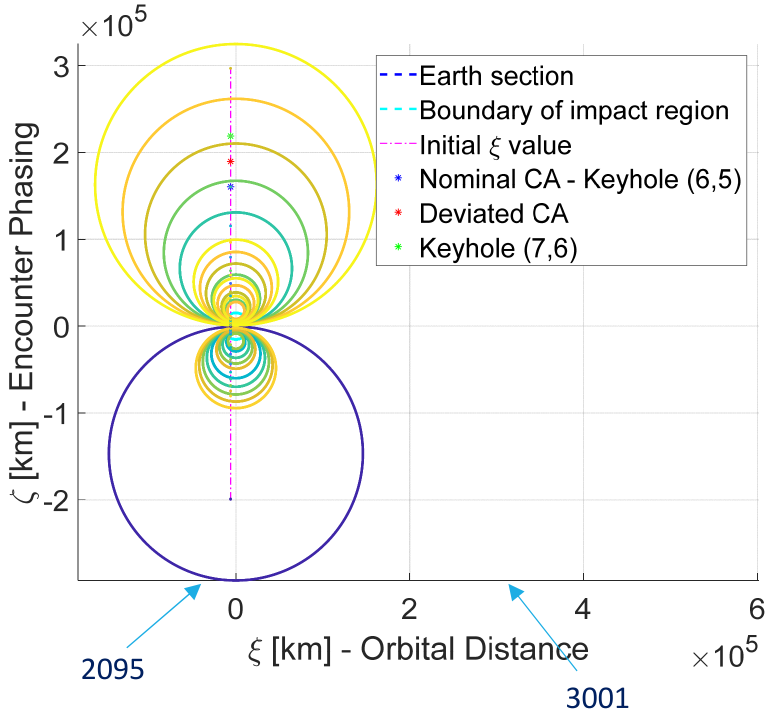
- A deviation along $\zeta$ is considered (early deflections)
- Target $\zeta$ value
  - Nominal encounter within a keyhole
    - The middle point between the keyhole and the closest one
  - Nominal encounter between keyholes
    - The middle point between the considered keyholes
- $\boldsymbol{\delta v}$ vector direction through eigenvector problem
- Not a pure maximisation when trying to avoid a keyhole

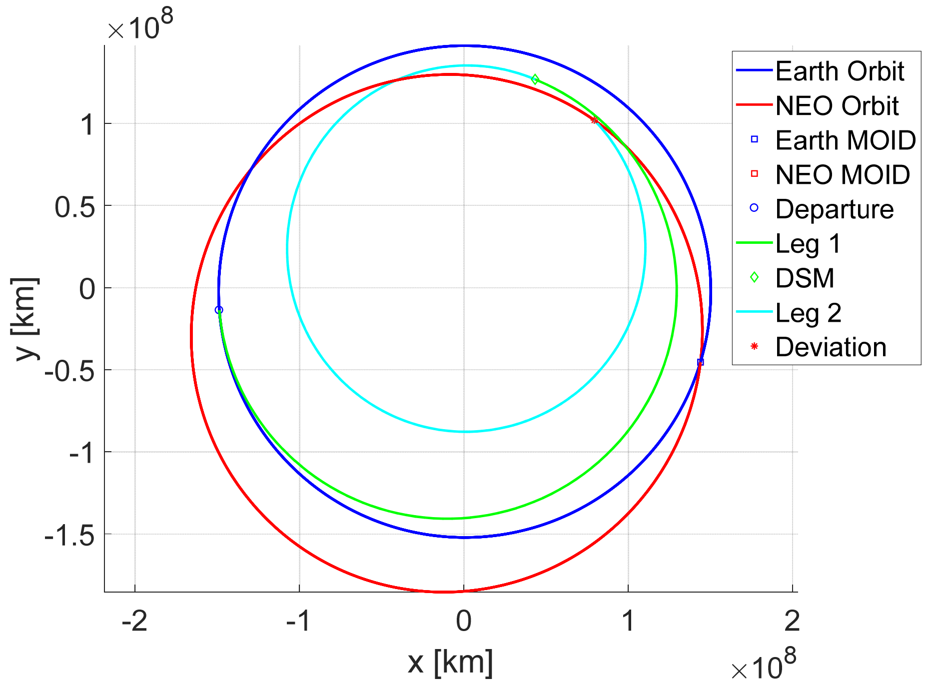


# Results

## Preliminary Deflection Mission Design

- 2095 encounter of 2010 $RF_{12}$-like with the Earth - (6,5) keyhole
- Target $\zeta$ value between keyholes (6,5) and (7,6)
- Escape, DSM, impact
- Max distance from the closest keyholes
- Min initial s/c mass



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