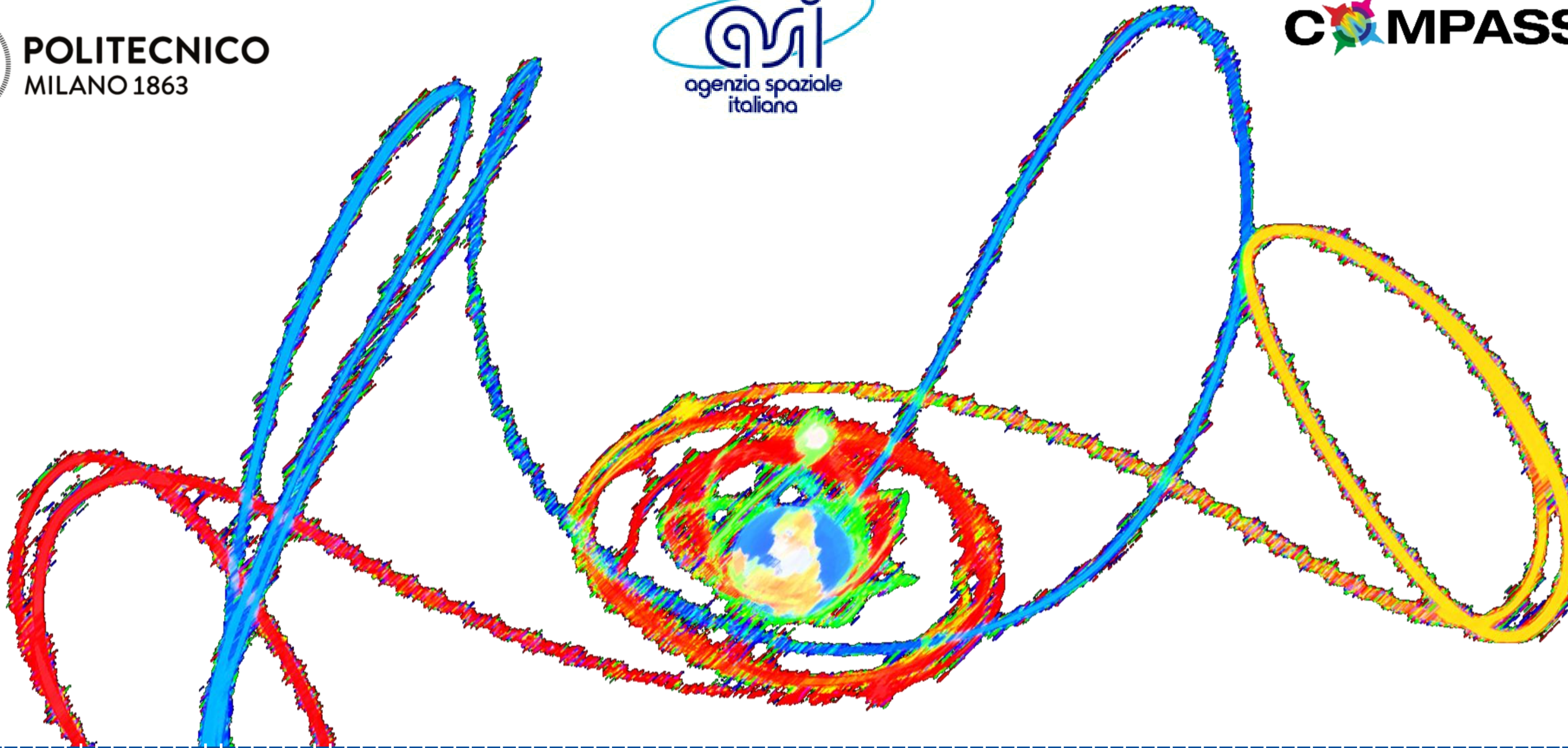
POLITECNICO MILANO 1863

agenzia spaziale italiana

COMPASS

erc



Mission analysis for potential threat scenarios: kinetic impactor

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

SMPAG Meeting UN Vienna 31 Jan 2018

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

IAPS/INAF, IFAC/CNR

Giovanni Valsecchi

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

TARGET ASTEROID SELECTION

Definition of threat scenarios

Criteria

- Different NEO threat cases analysed to identify a restricted number of scenarios, to be adopted as reference use-cases for the mission definition.
  - Dimensions of NEO
  - Type of orbit (direct-impact, resonant, …)
  - Time to closest approach
  - Amount of available information
  - Representativeness of known NEOs population

- To guarantee the representativeness of the scenarios a "reverse approach" has been adopted through "adjustments" of representative real NEO cases to fulfil all desired characteristics

Definition of threat scenarios

Synthetic case: 2010 RF12 like NEO

- Adopted NEOs classification:
  - Small-size NEOs: ~10 m equivalent diameter
  - Medium-size NEOs: ~100÷200 m equivalent diameter
  - Large-size NEOs: ~1000÷2000 m equivalent diameter

Scenario A: Direct hit scenario

Reference diameter	100 m
Magnitude	21÷20
Mean density	2600 kg/m^3
Estimated Total Mass	1.3614 x 10^9 kg
Detection Time	2085
Expected Impact Time	2095
Type of impact	Direct hit
Orbital parameters	as 2010RF12

Scenario B: Resonant hit scenario

Reference diameter	1000 m
Magnitude	17÷18
Mean density	2600 kg/m^3
Estimated Total Mass	1.3614 x 10^{12} kg
Detection Time	**Before 2059**
Expected Impact Time	2095
Type of impact	Resonant hit
Orbital parameters	as 2010RF12

Direct hit scenario

MISSION DESIGN KINETIC IMPACTOR

Direct hit scenario

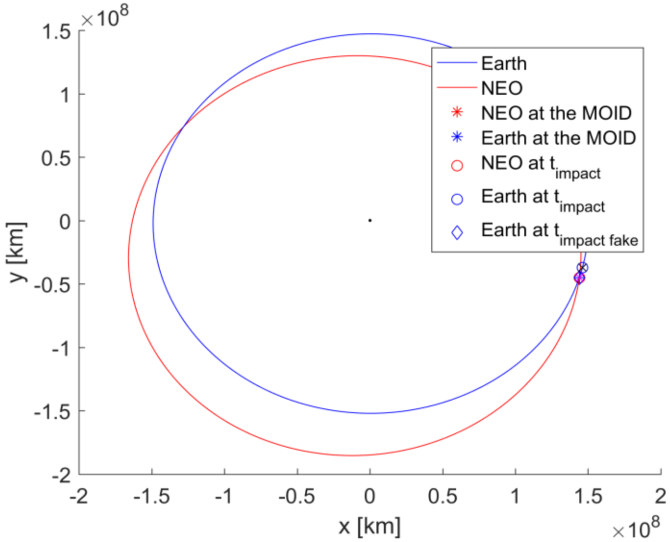
Problem formulation

Expected impact time 2095

Asteroid detected 10 year in advance

$$t_{0,\min} = t_{MOID} - 10 \text{ years}$$

Earth and NEA trajectory



The design parameters for the deflection mission

$$x = \begin{bmatrix} \eta_{t_0} & \eta_{DSM} & ToF & \Delta v_0 & \alpha_0 & \delta_0 & m_{s/c0} \end{bmatrix}$$

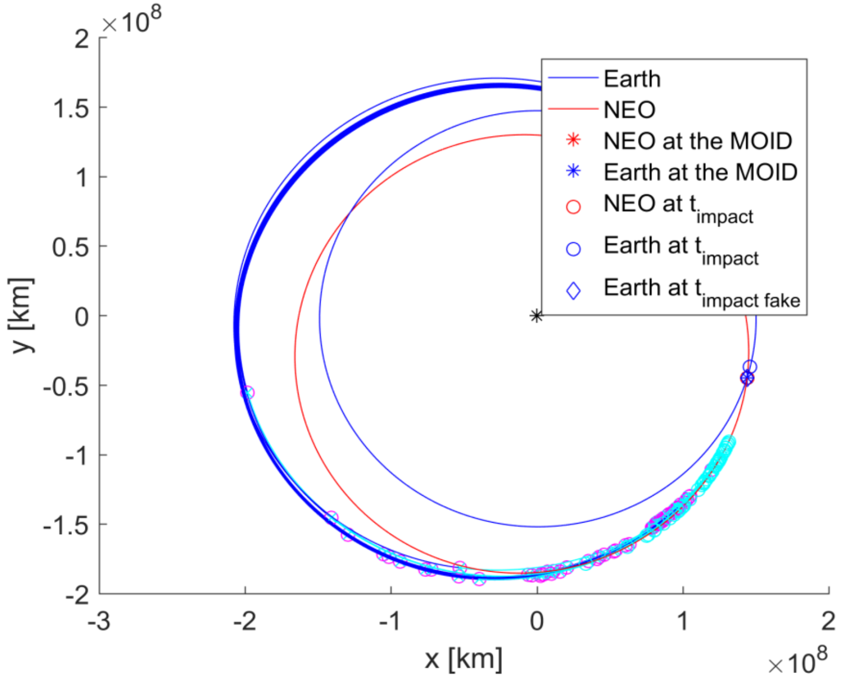
ToF: time of flight for the interplanetary trajectory

Δv_0, α_0, δ_0 : magnitude, in-plane and out-of-plane angles of the of the delta velocity at departure from Earth, with respect to the heliocentric velocity

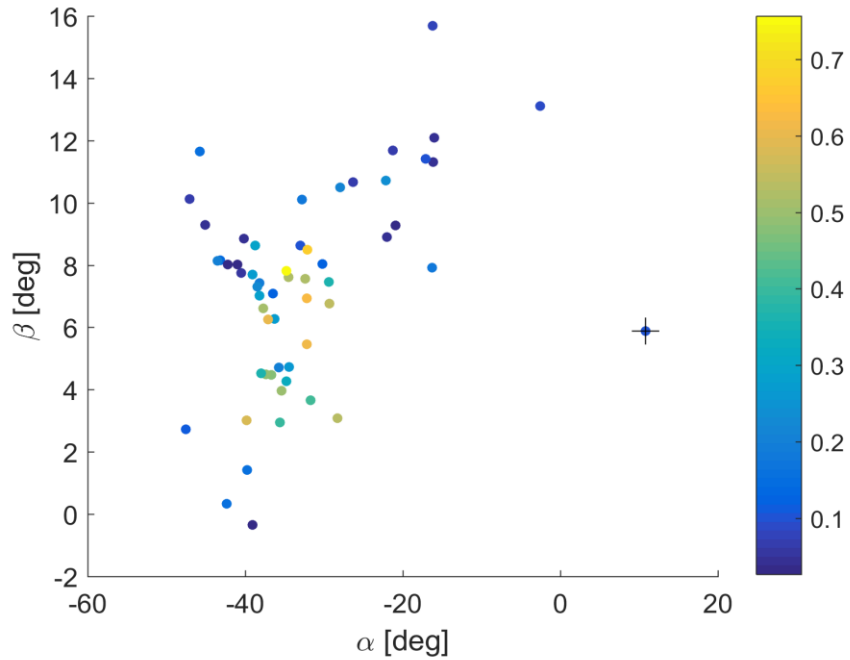
m_{sc0}: wet mass of the spacecraft at launch

η_{t0}, η_{DSM}: timing of departure and deep space manoeuvre

Direct hit scenario



Sample of deflection trajectories



Direction of the deflection manoeuvre applied to the asteroid

Agreement with previous studies

Probability of a deflection system to deflect a generic impact threat

Seriousness of an impact based on the impact energy

Impact hazard categories

Combination of relative frequency of impact and size

Type of event	Approximate range of impact energies (MT)	Approximate range size of impactor	Relative event frequency
Airburst	1 to 10 MT	15 to 75 m	~177,000 of 200,000
Local Scale	10 to 100 MT	30 to 170 m	~20,000 of 200,000
Regional Scale	100 to 1,000 MT	70 to 360 m	~2400 of 200,000
Continental Scale	1,000 MT to 20,000 MT	150 m to 1 km	~600 of 200,000
Global	20,000 MT to 10,000,000 MT	400 m to 8 km	~100 of 200,000
Mass Extinction	Above 10,000,000 MT	>3.5 km	~1 of 200,000

Type of event	Warning time				
	20 year	15 years	10 years	5 years	2.5 years
Airburst	99.4%	99.0%	98.1%	88.8%	26.9%
Local Damage	92.5%	88.3%	**80.7%**	51.4%	9%
Regional Damage	43.0%	31.7%	22.8%	9.5%	0.6%
Continental Damage	3.9%	1.8%	0.6%	0.03%	0%
Global Damage	0%	0%	0%	0%	0%

- Sanchez, Colombo, “Impact Hazard Protection Efficiency by a Small Kinetic Impactor”, JSR 2013

System design

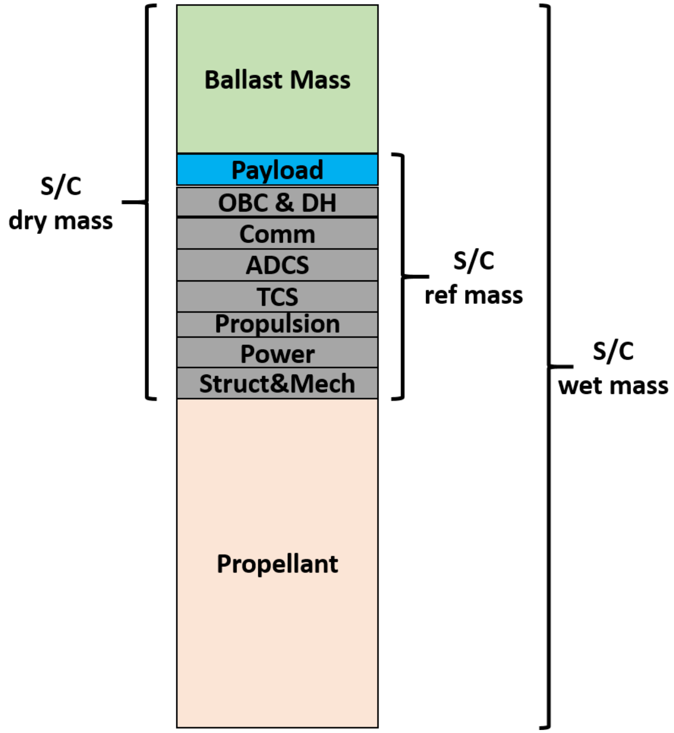
Requirements

- The spacecraft shall be able to perform autonomously the navigation toward the asteroid and the final targeting of the impact point by use of OBC and high resolution images;
- The spacecraft shall be able to operate at a maximum distance of 1.5 AU from the Sun and to communicate with Earth at a maximum distance of 2 AU;
- Low cost technologies with a TRL ≥ 7 shall be adopted for the spacecraft design and integration to reduce the time required by the spacecraft development phase
- The spacecraft shall be configured in order to assure a high level of AOC performances, mainly in the targeting and approaching phase

System design

	Max. Value (including 25% margin) [kg]
Payload	12.5
S/C Subsystems	279
ADCS	25
OBC&DH	12
Power	190
Propulsion	17
Thermal	10
TT&C (Comm)	25
Structures & Mechanisms	20% of S/C dry mass

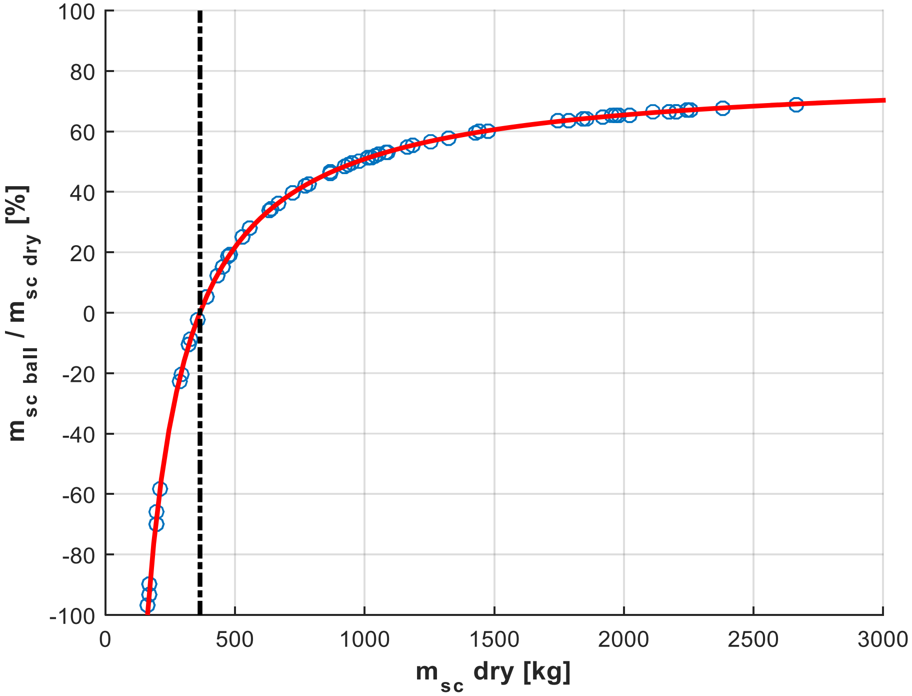
Preliminary results of S/C subsystems mass budget estimation



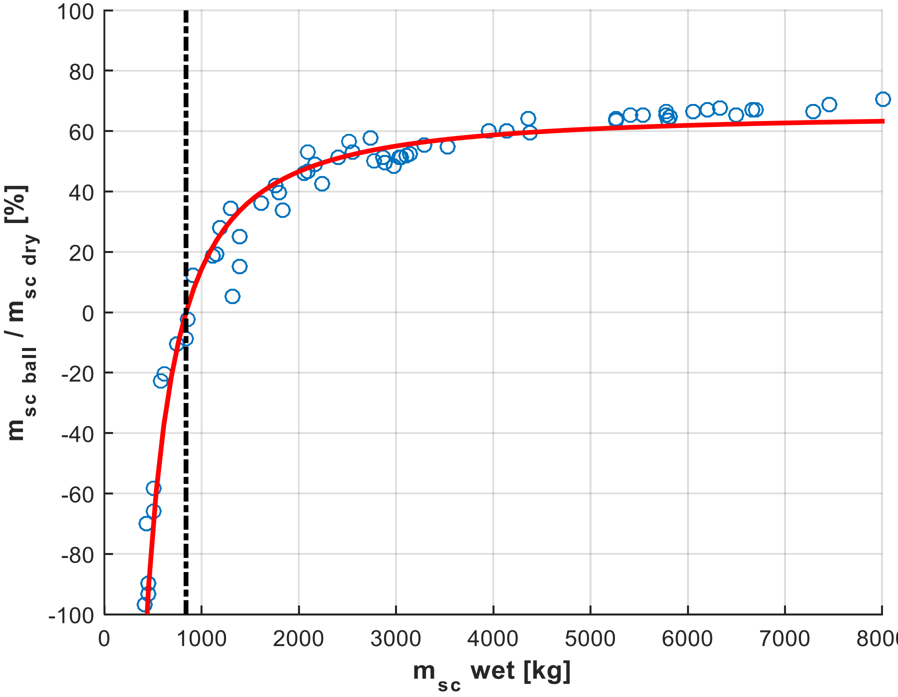
Spacecraft mass budget definitions

System design

Ballast mass – Interaction needed with Payload Toolbox Task



Ballast mass percentage as function of S/C dry mass



Ballast mass percentage as a function of S/C wet mass.

Minimum feasible S/C dry mass is about 370 kg, which corresponds to about 840 kg once equipped with propellant needed to perform orbital transfer

INSIGHT INTO KINETIC IMPACTOR DESIGN

Insight into kinetic impactor design

Goals

- Improve trajectory design of the direct impact to improve deflection efficiency
  - Consider fly-bys during trajectory
  - Include trajectory navigation correction manoeuvres
  - Extend to multiple kinetic impactor mission
- 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

Fly-by mission for direct hit scenario

Intermediate fly-bys

Aim: Improving mission performance (i.e., increase the achievable deflection of the asteroid at the MOID or use a cheaper launcher)

Exploit a sequence of gravity assists of the planets before reaching and hitting the asteroid.

New vector of design parameters for the deflection mission:

$$x = [\, \eta_{t0} \ \eta_{DSM1} \ ToF_1 \ r_{p2} \ \gamma_2 \ DV_2 \ \eta_{DSM2} \ ToF_2 \ \dots \ r_{pn} \ \gamma_n \ DV_n \ \eta_{DSMn} \ ToF_n \,]$$

r_{pi} pericentre radius of the flyby at i^{th} planet ;

γ_i angle to decsribe flyby at the i^{th} planet;

DV_i impulse given at the pericenter of the flyby of the i^{th} planet;

The other parameters are the same as simple hit trajectory.

i = 1,…,n planets encountered by the spacecraft.

Optical autonomous GNC

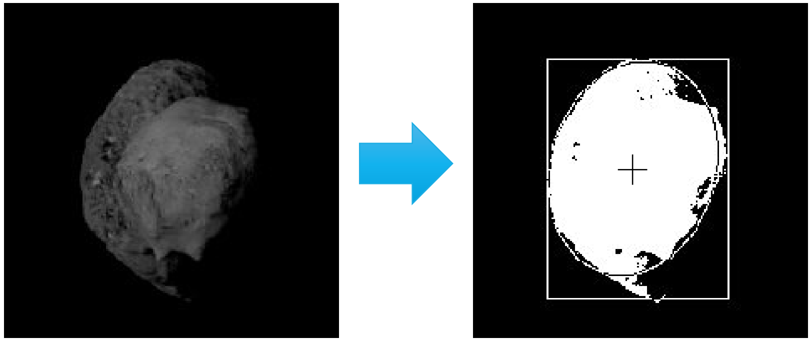
Overview

- Input from previous work: arrival orbit parameters with uncertainties
- Current GNC strategy to impact:
  - On-board autonomous GNC to have fast response
  - Asteroid in Keplerian orbit around the Sun
  - Spacecraft dynamics in the asteroid's local vertical local horizontal frame
  - Only optical sensor (telescopic camera)
  - State reconstruction with Extended Kalman Filter
  - Control strategy developed taking into account state-of-the-art actuators
- Output: impact position and velocity w.r.t. center of mass with uncertainties, derived from Monte Carlo simulations

Optical autonomous GNC

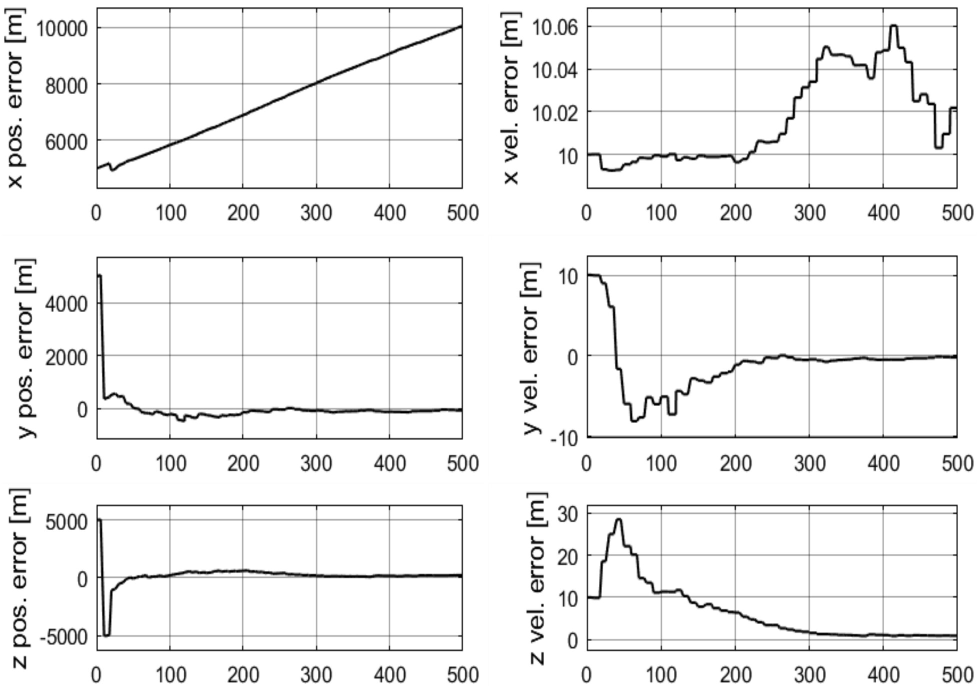
Optical navigation

- To detect the asteroid at long distance (>10000km), the spacecraft is considered to be equipped with a telescopic camera. Images acquired by the camera are simulated with the computer graphics software Blender, taking into account the relative pose and camera's focal properties
- The asteroid position is currently detected by brightness centroiding.



Example: rendering and centroiding of asteroid Itokawa

Case study Itokawa asteroid (Initial distance of 30000 km and initial velocity of 10 km/s): filter is able to reconstruct the relative position and velocity in the directions normal to the LOS with 1 image per min



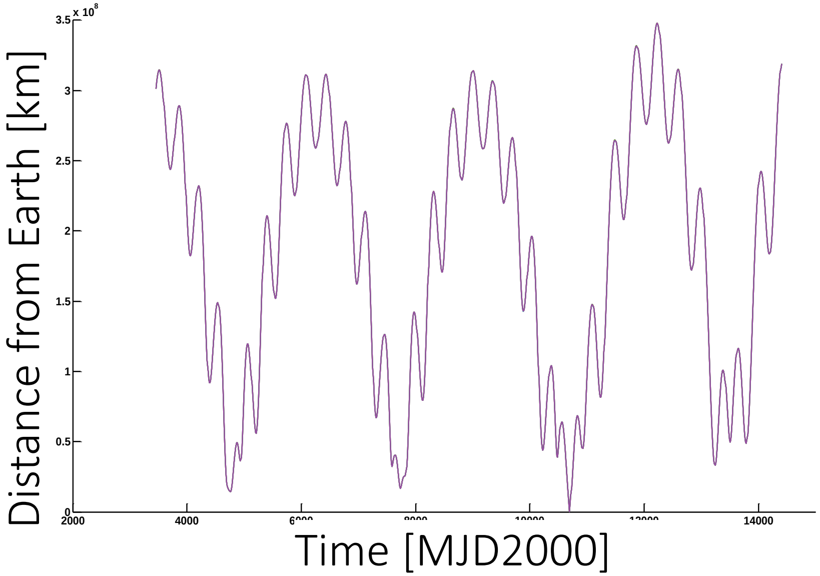
EKF state estimation

Resonant encounter asteroid deflection

Introduction

In the cases of an Earth's resonant encounter hit

- The deflection has to be studied "on the long term"
- Considerer the effect of resonances in the deflection trajectory



➤ Letizia F., Colombo C., Van den Eynde J. P.J.P., Armellin R, Jehn R., SNAPPshot suite for numerical analysis of planetary protection, ICATT, 2016, Darmstadt, Germany.

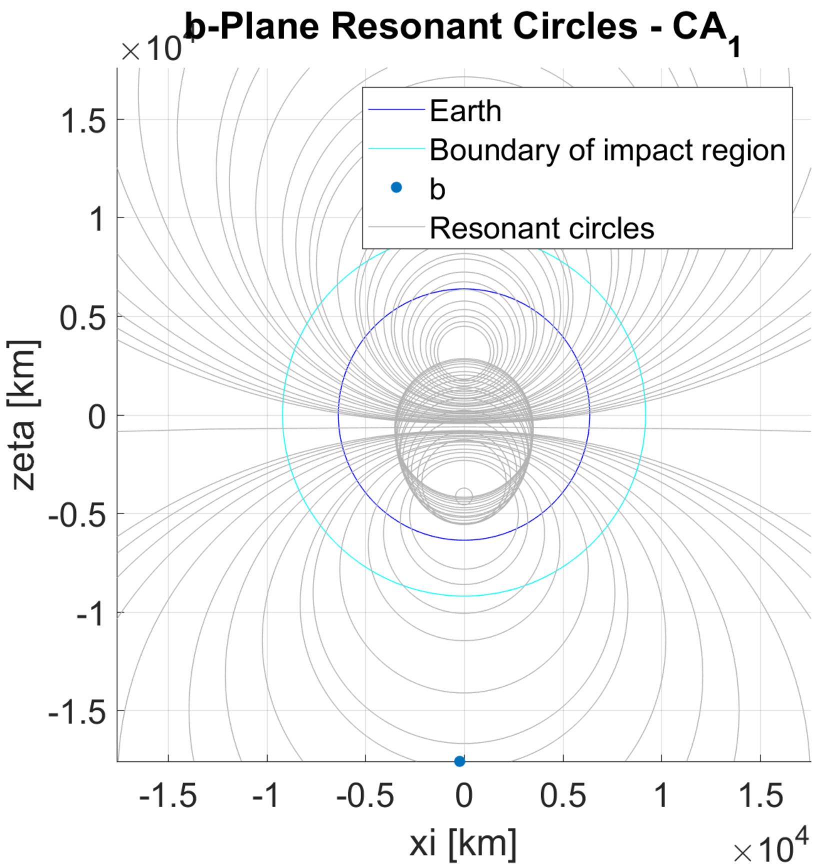
Resonant encounter asteroid deflection

Resonant circles

- Observe b-plane's characteristics
  - Delay/Advance
- Resonant circles are regions of the b-plane that correspond to conditions that will lead the small body to perform a new close approach after a given number of orbits

Aim: deviate the object to a zone in the b-plane as far from a resonance condition as possible

Example of an advance in an encounter



The resonant circles represented in grey

Resonant encounter asteroid deflection

Current work

- Trajectory propagation
  - Consider effects of uncertainties in the deflection manoeuvre and the asteroid's response to the deflection action (SNAPPshot tool)
- Resonant encounters
  - Optimisation of the deflection manoeuvre to place the objects in regions of the b-plane not leading to further close encounters in a given time frame

➢ Letizia F., Van den Eynde J., Colombo C., SNAPPshot ESA planetary protection compliance verification software, Final Report, 2016.

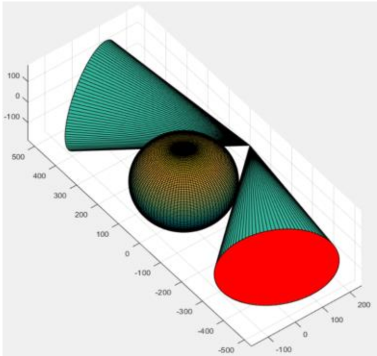
MISSION DESIGN GRAVITY TUG

Gravity tractor

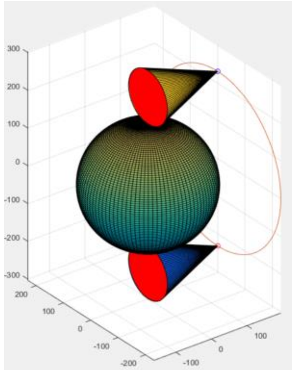
- Sample asteroid: 320 m diameter, 2600 kg/m^3 density
- Required deflection corresponding to $\Delta V = 2 \cdot 10^{-6}\ m/s$

Two strategies have been analysed

A: single fixed spacecraft



B: # of S/Cs in forced Halo orbit



The distance between the center of the asteroid and the fixed S/C, or the center of the Halo orbit, is chosen so to compensate the gravitational attraction with the thrust.
A fundamental mission requirement is that the thrust plume does not impinge on the asteroid's surface.

Gravity tractor

Criticality: it is necessary to have a continuous variation of the thrust over time, to maintain constant the position (in the first strategy) or the orbit (in the second strategy) wrt the asteroid

A: single fixed spacecraft

Pros

- Single spacecraft needed
- Wide range of the initial S/C mass

Cons

- S/C must have at least two symmetric motors, in order to remain in position
- The thrust is tilted, so the net thrust is lower
- Longer time to obtain the desired deflection

B: # of S/Cs in forced Halo orbit

Pros

- No tilt angle of the thrust, net thrust maximized and propellant consumption minimised
- Shorter time to obtain desired deflection

Cons

- Two or more S/Cs in symmetric flight formation needed
- Initial mass of S/C constrained by asteroid dimension and propulsion system

Gravity tractor

The two strategies have been compared

A: single fixed spacecraft

- Mass 5,060 kg
- Two motors of 0.053 N, I_s of 3,100 s, thrust plume cone 40 deg
- 436 m from asteroid's COG
- 41 deg tilt angle
- Deflection time 13 days
- Propellant consumption 7.84 kg

B: 2 S/Cs in forced Halo orbit

- 2 S/Cs with same propulsion system
- Mass 2,530 kg
- Halo orbit at 196 m from asteroid's COG, radius 231 m
- Deflection time 10 days
- Propellant consumption 2.93 kg

Conclusion

The complexity of strategy B, related to the control of the formation flying, makes solution A much preferred.

Proposed interaction for SMPAG

- In Toulouse splinter meeting on
  - 5.2 Mitigation mission types and technologies to be considered (UKSA)
  - 5.3 Mapping of threat scenarios to mission types (ESA)
  - 5.4 Reference missions for different NEO threat scenarios (ASI)
  - 5.5 A plan for action in case of a credible threat (NASA/IAA)
  - Italy, UK and USA performed deflection analysis on a number of mission scenarios.
- Share and compare these results in order to improve the knowledge on the analysis, the cooperation of countries and use the common and final results as inputs for further mission analysis and action plan. → could be merged in a single report
  - Representation of the results as function of asteroid initial orbit, mass and characteristics
  - Building a mission database (e.g., s/c mass, achievable deflection, etc.)
  - Including existing mission plans and the detailed studies.
- Format of results (it can be discussed) can be circulated to interested delegations
- If interested, get in touch!

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)

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