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

Mission analysis for potential threat scenarios: kinetic impactor and electromagnetic tag

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Space Mission Planning Advisory Group, 24-25/03/2021

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IAPS/INAF, IFAC/CNR

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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

Summary up to Jan 2020

- Kinetic impactor mission design
  - Parametric study for kinetic impact missions
  - Target asteroid selection
  - Definition of threat scenarios: direct hit and resonant scenario
  - Mission design for kinetic impactor direct hit
    - Mission analysis
    - System design
    - Additional scientific payload
- Gravity tug system design
- Kinetic impactor effect analysis
  - Improving direct hit scenarios with multiple fly-bys
  - Resonant hit scenarios
  - Optical autonomous guidance navigation and control during asteroid deflection technique
  - Impact cratering physics modelling and beta factor estimation

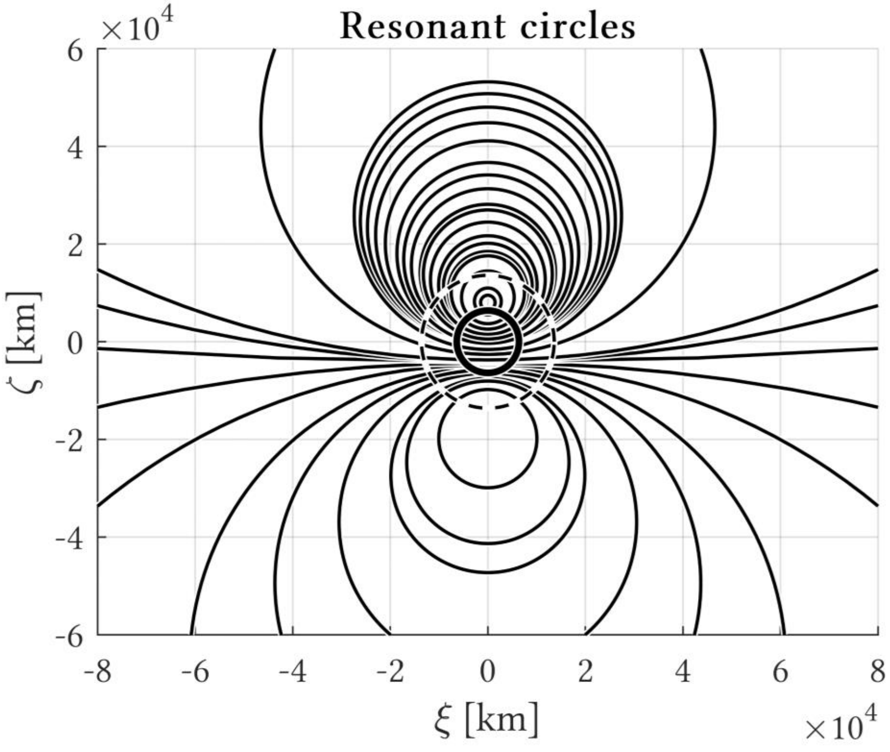
ACTIVITIES FROM JAN 2020 TO JAN 2021

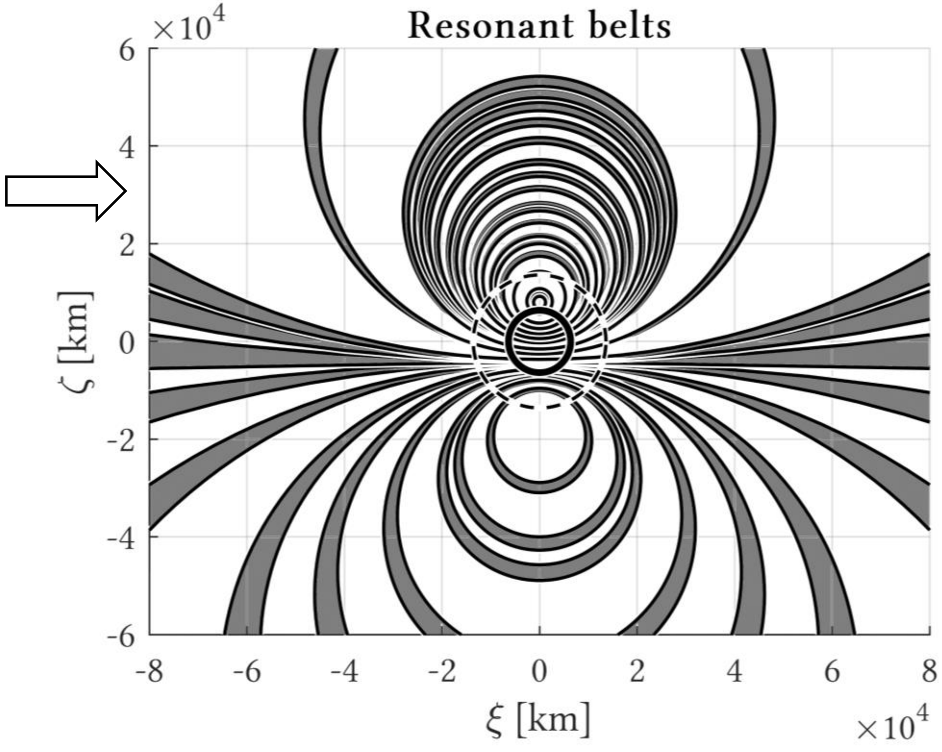
Alessandro Masat, Matteo Romano, Camilla Colombo

MODEL FOR RESONANT ENCOUNTERS FOR ROBUST DEFLECTION

Resonance cases

Models for robust deflection





B-plane resonance definition

Quasi resonance concept

Resonant belts

$$\left(\frac{k}{h}\right)^{\pm}_{quasi-j} = \left(\frac{k}{h}\right)_{j} (1 \pm \tilde{\Delta})$$

Aim: study robust deflection, i.e. deflect and do not come back!

B-plane

Characterising close encounters in the b-plane can tell more than the sole relative position of the asteroid.

Encounter within the belt? The asteroid will eventually return and re-threat us

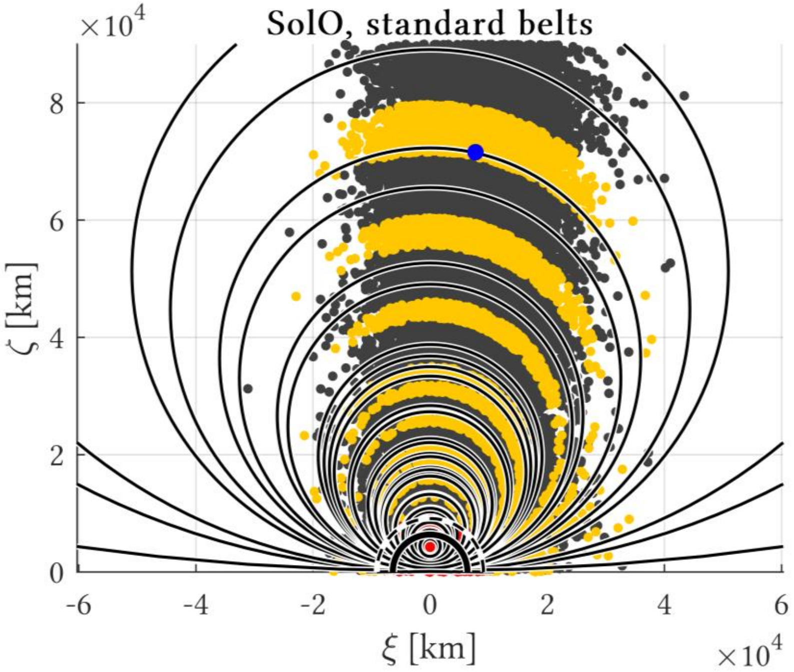
A. Carusi, G. B. Valsechi, and R. Greenberg, “Planetary close encounters: geometry of approach and post-encounter orbital parameters,” *Celest. Mech. Dyn. Astron.*, 1990.

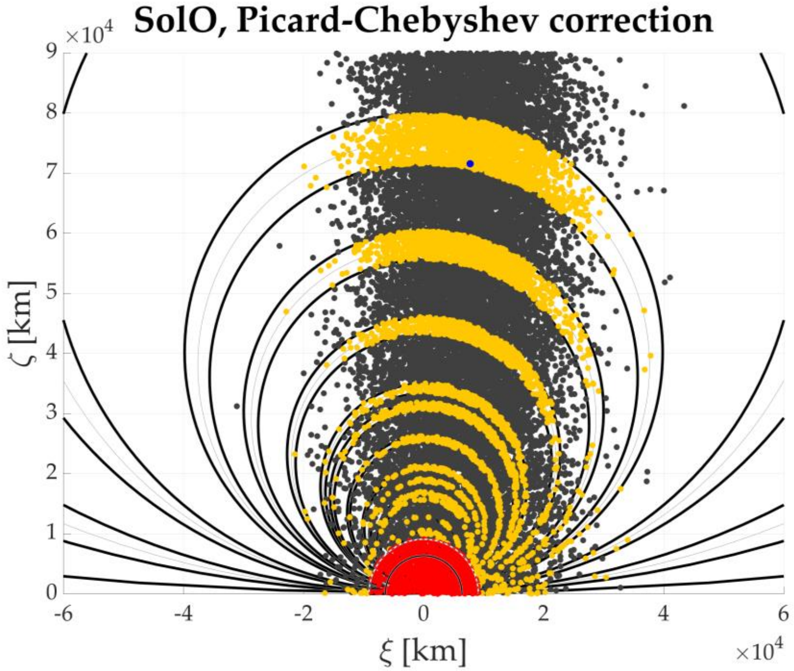
Resonance cases

Semi-analytical model

Semi-analytical technique that allows to spot close approaches leading to orbital resonances ***a priori*** and accounting for ***any*** perturbing effect.

Example: Monte Carlo of an uncontrolled disposal object (Solar Orbiter's upper stage of launcher encountering Venus), exactly like asteroids' orbital dynamics.





Relative % error of standard (simple close approach dynamics) and corrected resonant belts (drawn in black) **vs simulated resonances** (yellow dots), for the three closest belts to the reference sample.

k/h	Standard	Picard-Chebyshev
5/4	24.460%	<0.1%
6/5	52.669%	<0.1%
9/7	17.499%	<0.1%

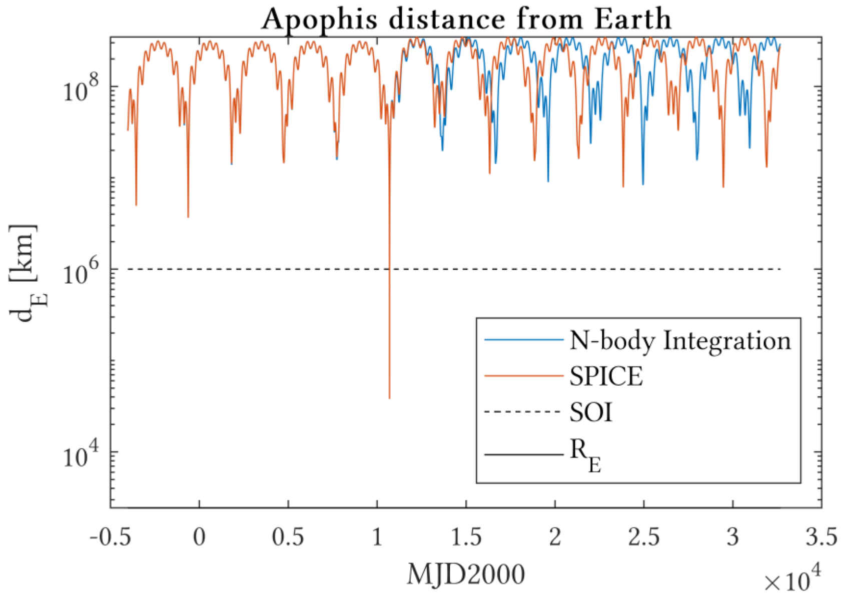
A. Carusi, G. B. Valsechi, and R. Greenberg, "Planetary close encounters: geometry of approach and post-encounter orbital parameters," *Celest. Mech. Dyn. Astron.*, 1990.
G. B. Valsecchi, A. Milani, G. F. Gronchi, and S. R. Chesley, "Resonant returns to close approaches: Analytical theory," *Astron. Astrophys.*, 2003.
T. Fukushima, "Picard integration method, Chebyshev polynomial approximation and global numerical integration of dynamical motion", *The Astronomical Journal,* Vol. 113 N° 6, June 1997

Regularisation and perturbation toolkit for orbit representation

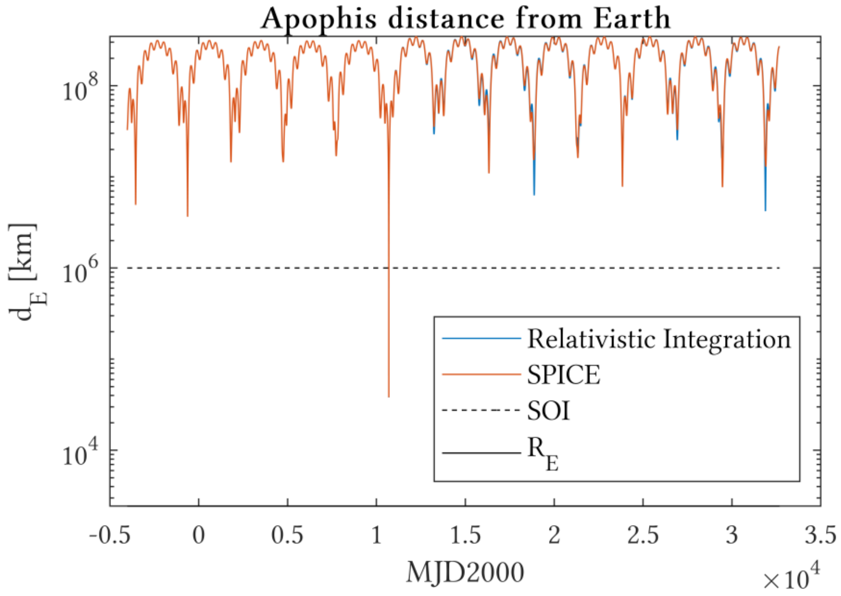
- High precision, optimised MATLAB toolkit with relativistic orbital simulation strategy.
- SPICE Toolkit (JPL's ephemerides data) interface, full force dynamics. SPICE precision matched.
- Performance example: 100 years integration in about 15 s on laptop.

Precisely and efficiently predicting the trajectory of newly spotted threatening asteroids can make the difference

Common n-body integrator



RAPTOR



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Renato Cirelli, Juan Luis Gonzalo, Camilla Colombo

DESIGN OF ELECTROMAGNETIC TAG MISSION

Design of electromagnetic tag mission

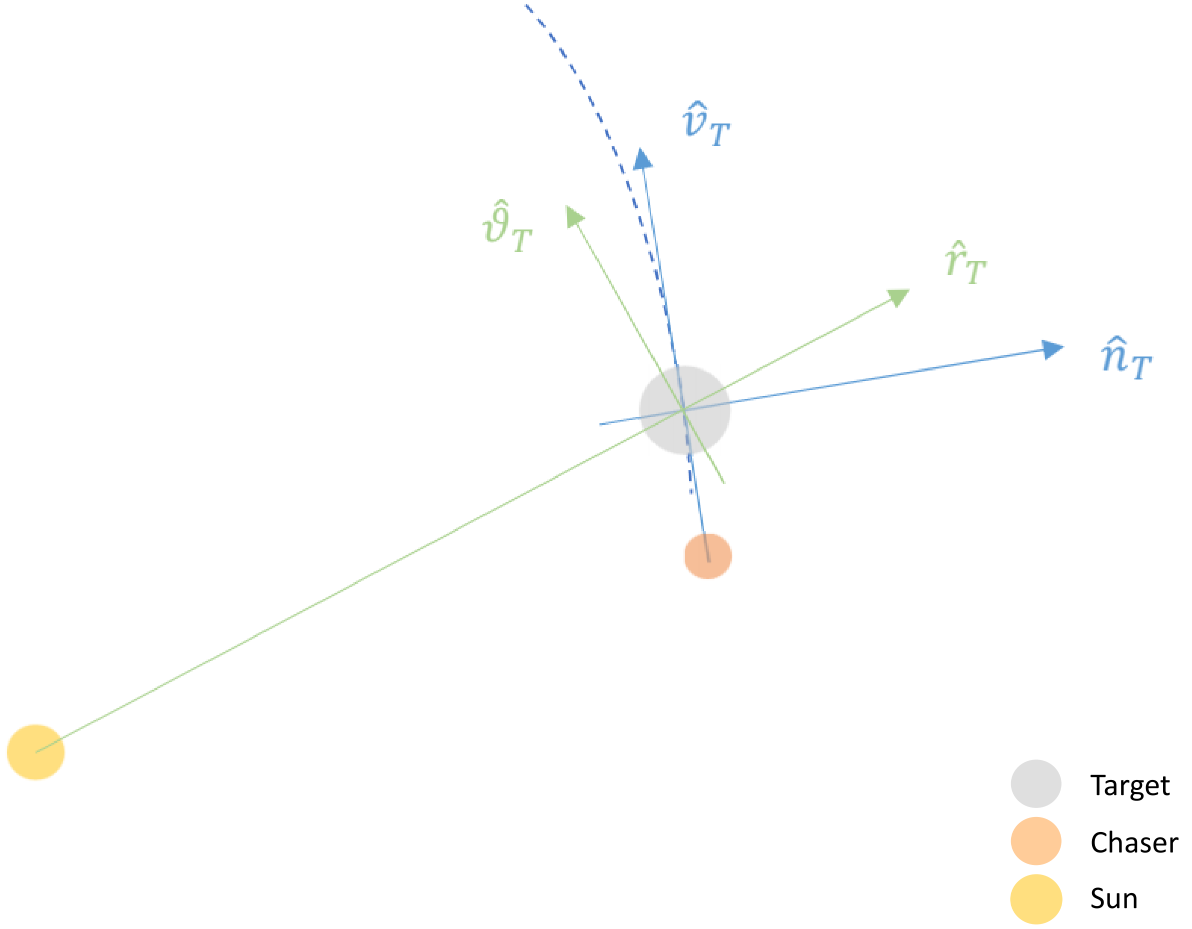
Introduction

Aim

Evaluate the possible advantages of a magnetic interaction in addition to the gravitational attraction between a spacecraft (i.e., chaser) and a uniformly magnetized asteroid (i.e., target) for orbital deflection purposes.

Reference low-thrust technique: Gravitational tug (GT

- Non inertial hovering along the asteroid velocity vector, on its orbital plane
- Hovering from behind
- Fixed hovering point



1] Renato Cirelli, Gravitational-magnetic tug, MCs thesis in Space Engineering at Politecnico di Milano (Italy).

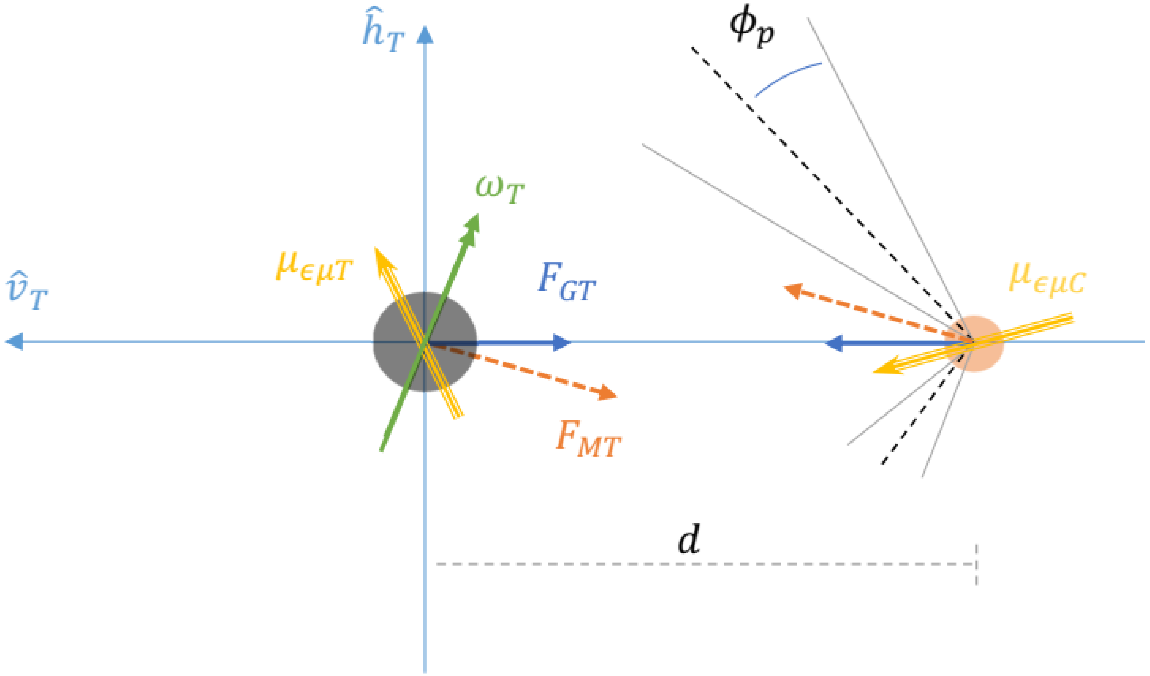
2] Renato Cirelli, Dr. Juan Luis Gonzalo Gómez and, Dr. Camilla Colombo - GRAVITATIONAL-MAGNETIC TUG: COMBINED GRAVITATIONAL AND MAGNETIC INTERACTIONS FOR ASTEROID DEFLECTION - 7th IAA PDC Conference 2021

Design of electromagnetic tag mission

Test target and test chaser

- **Test Target: Apophis[1]**
  - Uniform magnetisation state, uniform density distribution, spherical shape and, tumbling motion
  - Asteroid specific magnetic dipole as Braille $\mu_{\epsilon\mu T}/m_T = 0.0251\, Am^2/kg$
  - Asteroid mass $m_T = 6.1\ 10^{10} kg$
  - Asteroid radius $R_T = 185\ m$

- **Test Chaser[2]**
  - Spherical shape, ion engines in symmetric canted configuration, fixed performance and, equipped with a Super Magnet Subsystem (SMS)
  - Initial mass $m_0 = 1500\ kg$
  - Exhaust cone half angle $\phi_P = 20°$
  - Thrust subsystem efficiency $\xi_{Th} = 34\ mN/kW$
  - Power subsystem efficiency $\tau_{Pw} = 25\ \mathrm{kg/kW}$
  - Specific impulse $Isp = 3100\ s$
  - Power mass over dry mass ratio $POD = 0.5$



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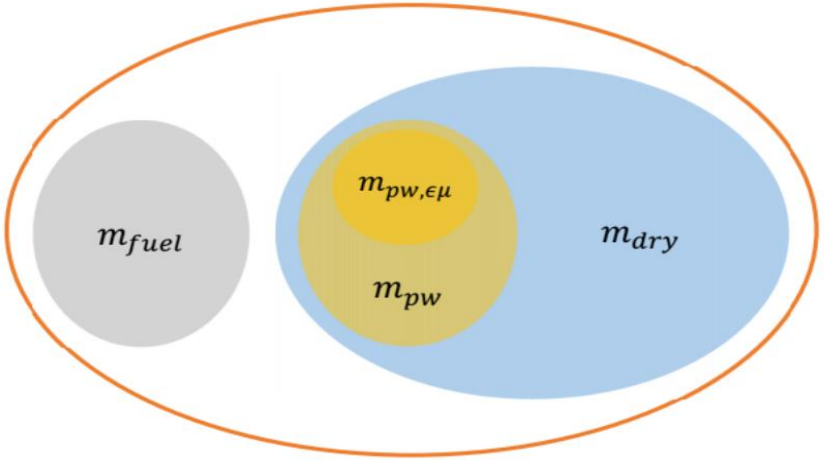
[1] Test target Apophis with magnetic properties as asteroid Braille (I. Richter et al., "First direct magnetic field measurements of an asteroidal magnetic field: DS1 at Braille,")

[2] J. P. Sanchez, C. Colombo, M. Vasile, and G. Radice, "Multicriteria Comparison Among Several Mitigation Strategies for Dangerous Near-Earth Objects

[3] E. Fabacher, S. Lizy-Destrez, D. Alazard, F. Ankersen, and Jean-FranJourdas, Guidance and navigation for electromagnetic formation flight orbit modification.

Design of electromagnetic tag mission

Sustainable and feasible tug



- **Power mass repartition** between thrust and dipole generation
- **Hovering distance** kept **constant**, found imposing the chaser's exhaust mass **non impingement** and **tug sustainability** for a given total tugging time
- **Comparison** done with fixed mass at interception + fixed chaser performance.

- Investigated **Tugging Mode** (TM)
  - **TM1** Magnetic force $\nu_{\epsilon\mu}$ times the gravitational one at interception + compensation of the chaser's mass loss due to thrust
  - **TM2** Magnetic force always $\nu_{\epsilon\mu}$ times the gravitational one
  - **TM3** Constant magnetic force set at $\nu_{\epsilon\mu}$ times the gravitational one at interception epoch

- Investigated **Dipole Control Law** (DCL)
  - **Target pointing DCL**
    Magnetic force always pointing the target
  - **B-field aligned DCL**
    Magnetic torque always null on the chaser

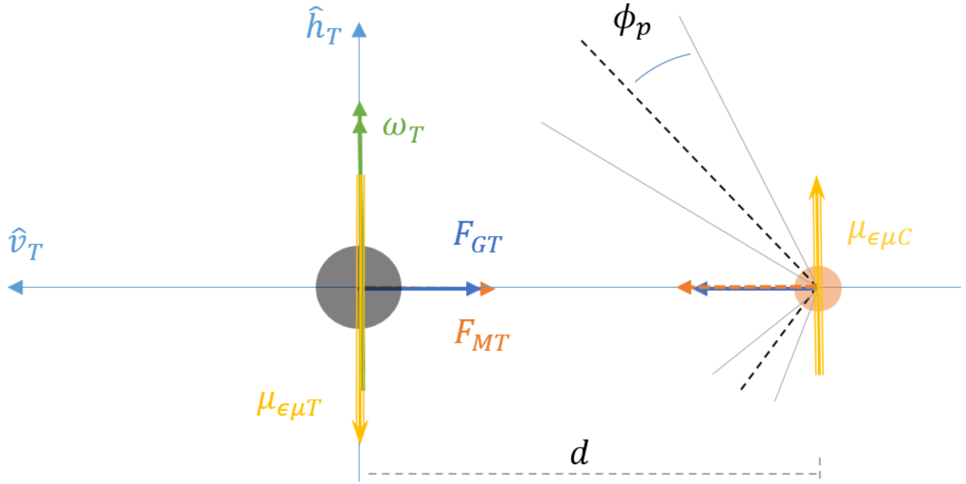
Design of electromagnetic tag mission

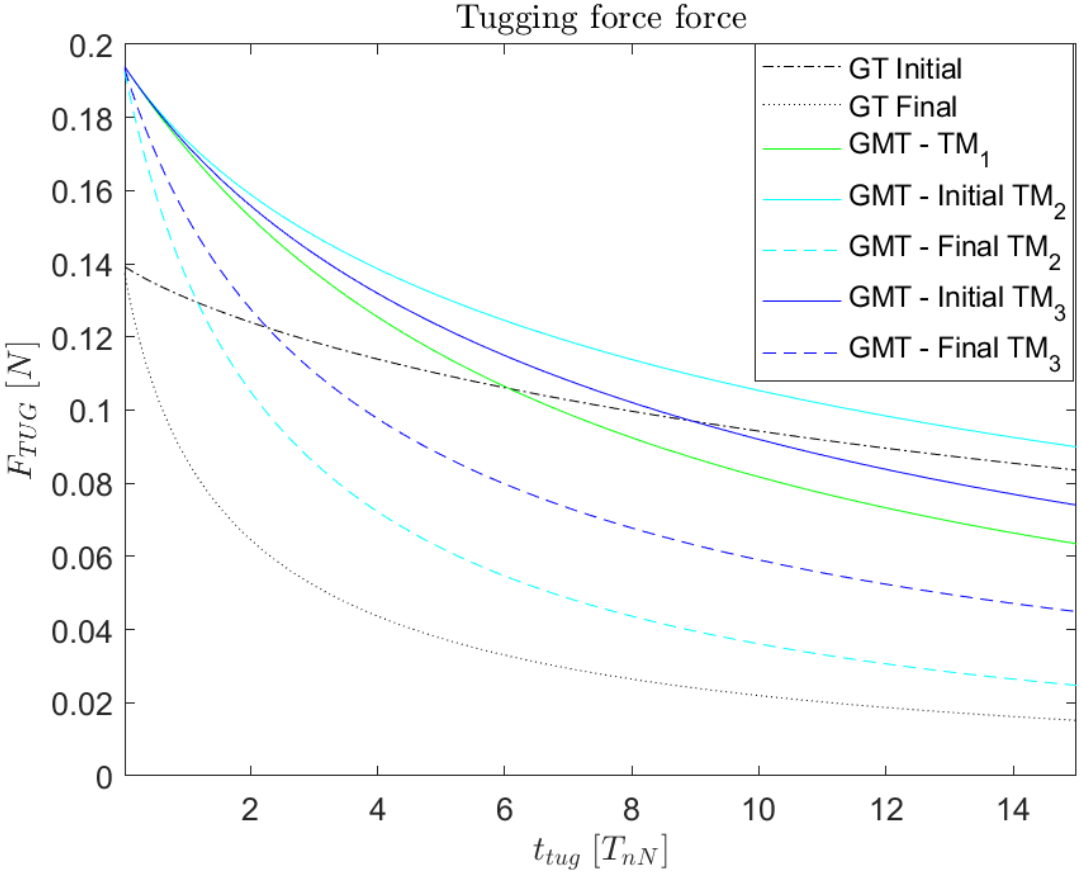
Results – Tugging Force

- Target state propagated with Gauss' equations adopting a complete thrusting arc from interception to MOID lasting

$$t_{tug} \in [7days, 15T_{nT}]$$

- Assumptions
  - $\hat{\omega}_T$ and $\hat{\mu}_{\epsilon\mu T}$ are orthogonal to the target's orbital plane
  - Interaction force at interception as if the chaser's mass is doubled (i. e., $\nu_{\epsilon\mu} = 1$)
  - Worst dipole configuration (⇒ Magnetic force pointing the target) ≡ Most demanding dipole generation on the chaser

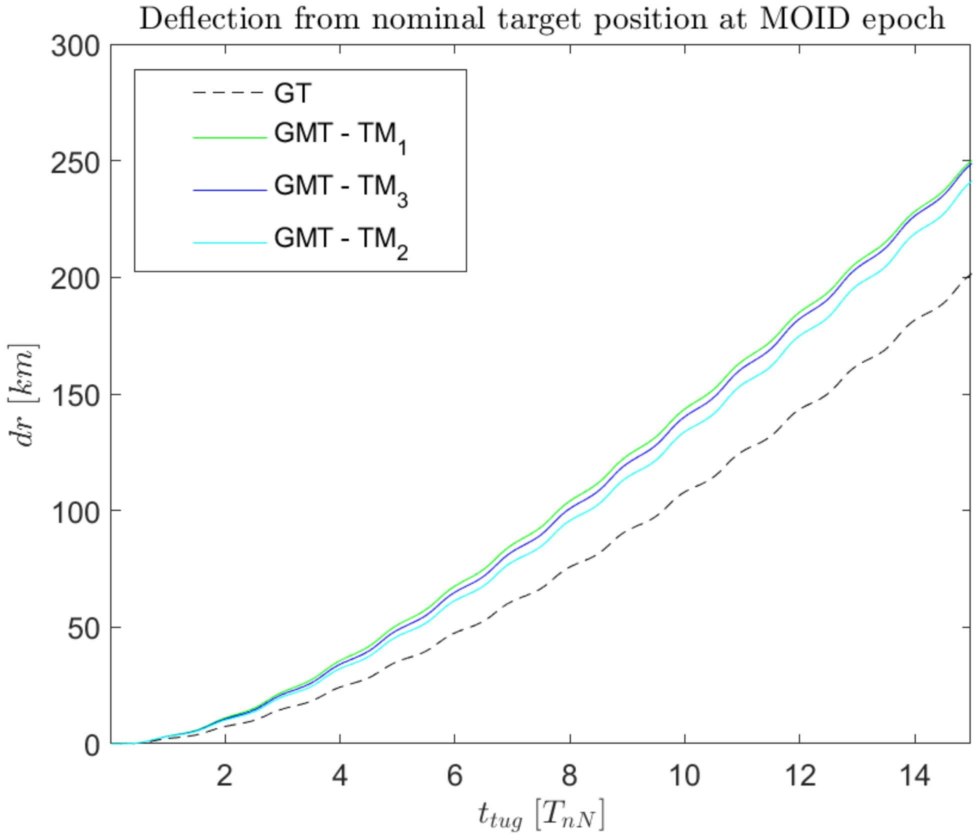


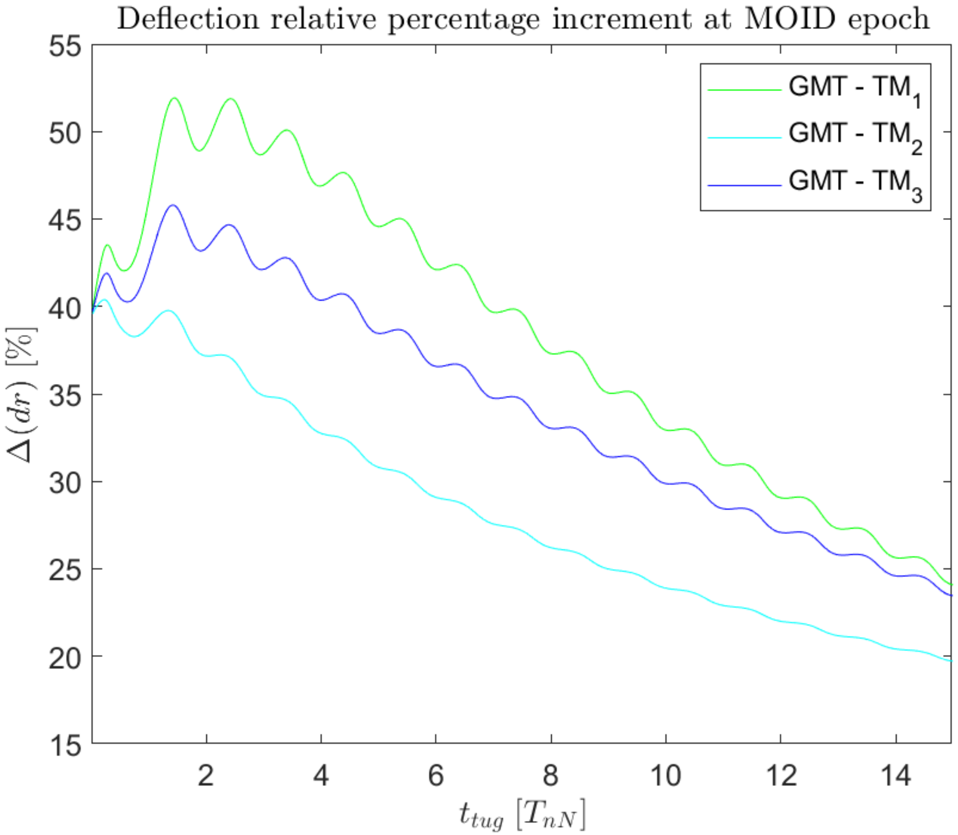


Tugging force at interception (i.e., initial) and at MOID (i.e., final) with the proposed GMT tugging modes, compared to GT.

Design of electromagnetic tag mission

Results – Deflection at MOID





- Deflection at MOID increased in respect the reference GT

- Best deflection relative percentage increment achieved with TM1
- GMT improvement decreases with increasing total tugging time

Alessandra Bassani, Gabriella Gaias, Ioannis Gkolias, Camilla Colombo

RECOVERY OF THE GRAVITY FIELD THROUGH RELATIVE NAVIGATION BETWEEN TWO S/C

Support scientific mission

Gravity field recovery

Recovery the gravity field of a Near Earth Asteroid

Two satellites

Mean elements

Analytical conversion from mean to osculating elements and vice-versa.

LSM ** + EKF ***

Estimation process works **indipendently** of the level of confidence and knowledge of the **initial guess**

Selection of the orbits

To guarantee **a uniform coverage** and **stable orbits** respecting requirements of the theory in use

ROE *

Propagation of the **ROEs without integration**

* ROE: Relative Orbital Elements

** LSM: Least Square Method

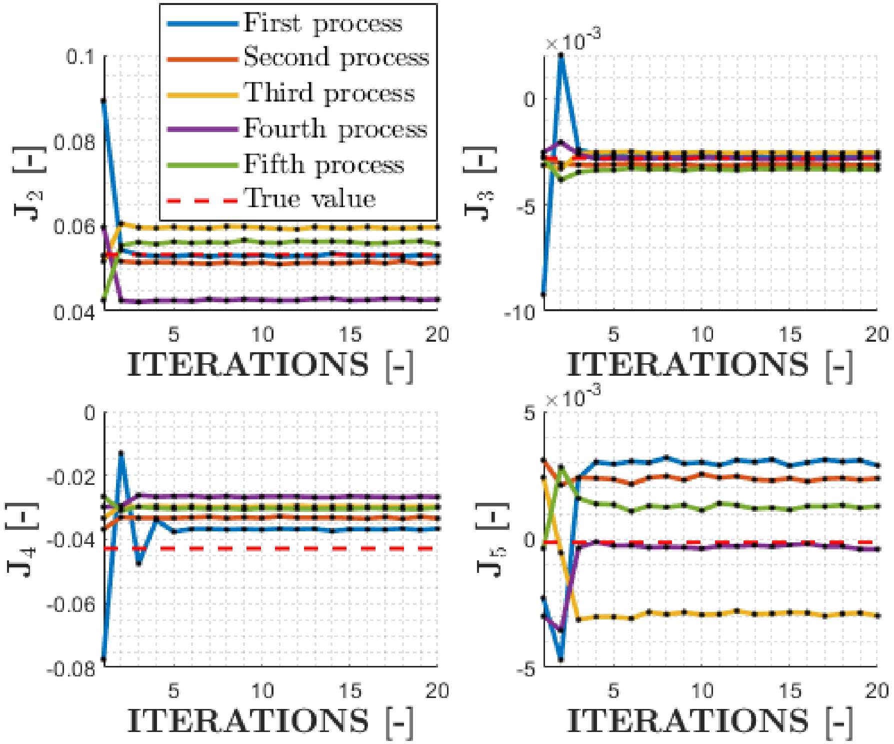
*** EKF: Extended Kalman Filter

Support scientific mission

Gravity field recovery

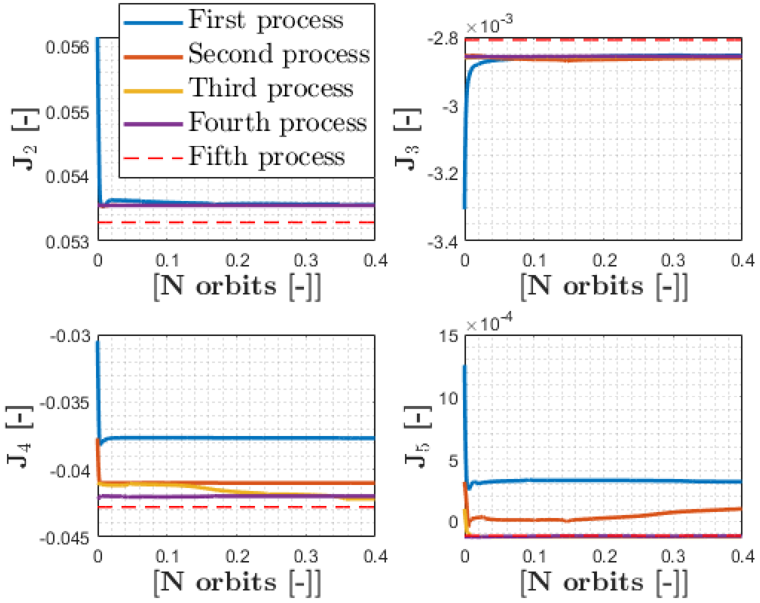
Batch least square method

- J_4 is the state variable with the higher absolute errors



Extended Kalman filter

- J_2 and J_4 estimated with a relative error lower than 1%
- The lower is the orbit the less is the required time



Mattia Pugliatti, Michele Maestrini, Pierluigi Di Lizia, Francesco Topputo

ONBOARD SMALL-BODY SEMANTIC SEGMENTATION BASED ON MORPHOLOGICAL FEATURES WITH U-NET

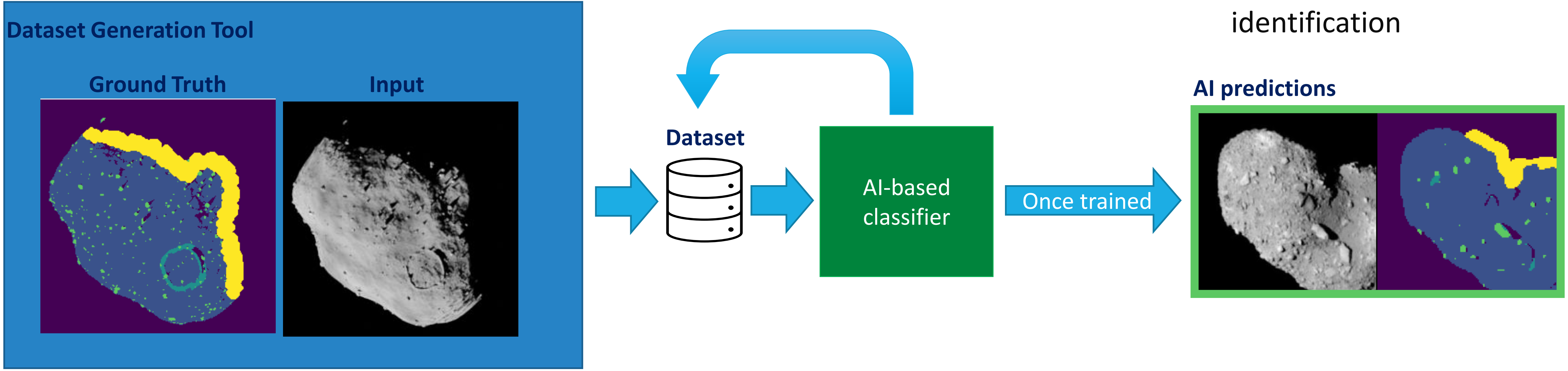
Onboard Small-Body semantic segmentation based on morphological features with U-Net

Application and purpose

1. **Procedurally generated asteroid 3D models**
2. Production of large amount of **automatically and robustly labelled data**
3. Labels identify **surface morphological features** (e.g. Craters and boulders)
4. Dataset is used to train a **AI-based classifier**

Many Applications readily available for these pixel masks:

- Navigation (AI based)
- Scientific planning of optimal observations
- Safe landing location identification



Pugliatti, M., Maestrini, M., Di Lizia, P. and Topputo, F., 2021. On-board Small-Body Semantic Segmentation Based on Morphological Features with U-Net. In *31st AAS/AIAA Space Flight Mechanics Meeting* (pp. 1-20).

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

Mission analysis for potential threat scenarios: kinetic impactor

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