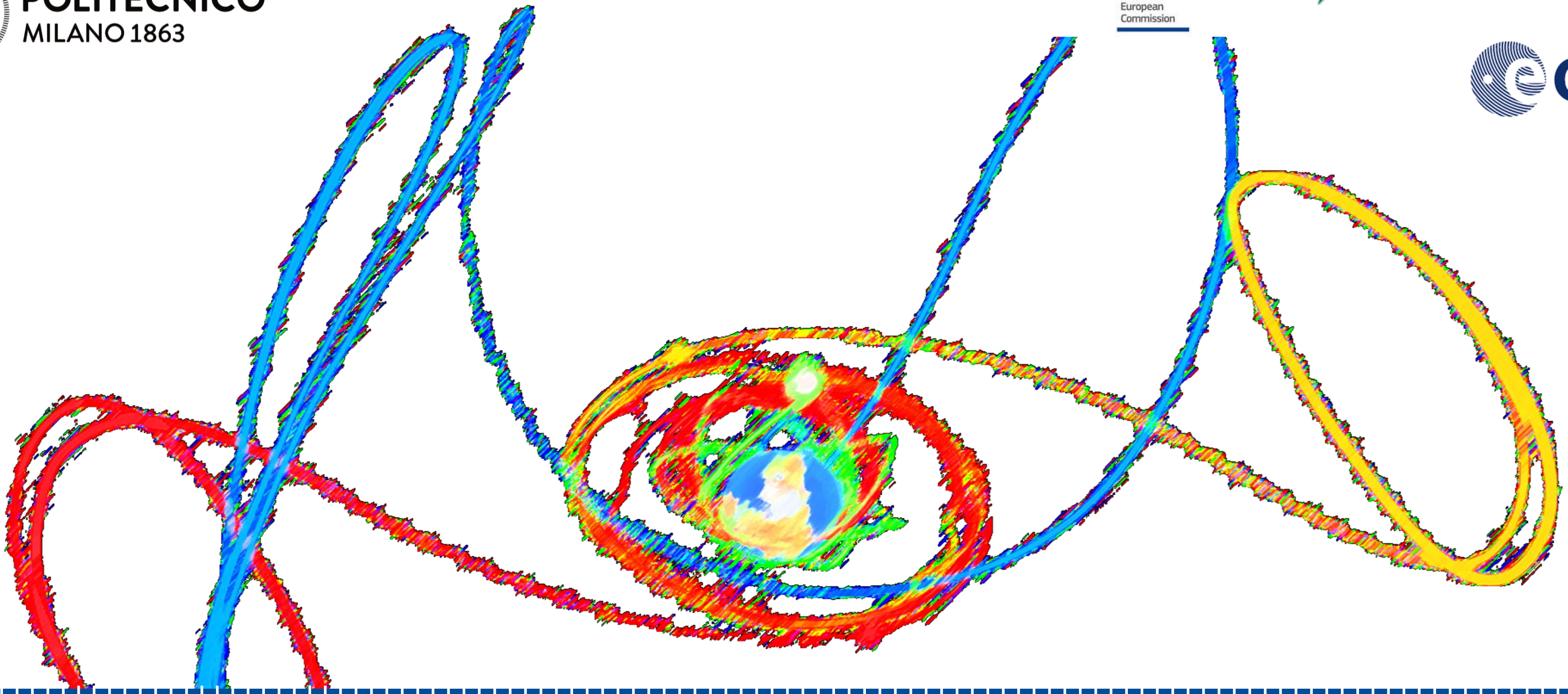


Close encounter characterisation and deflection design for planetary protection and defence

Camilla Colombo, Matteo Romano, Mathieu Petit

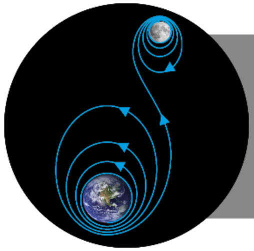
“Between Mathematics and Astronomy”
Workshop in honour of Andrea Milani 70th Birthday, Pisa 2018

INTRODUCTION

Introduction

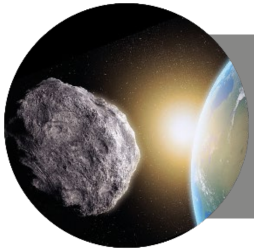
Services, technologies, science, space exploration

SPACE TRANSFER

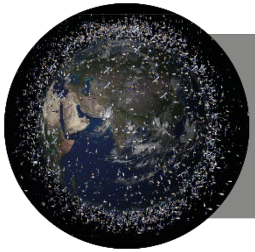


Reach, control operational orbit

SPACE SITUATION AWARENESS



Asteroids. planetary protection

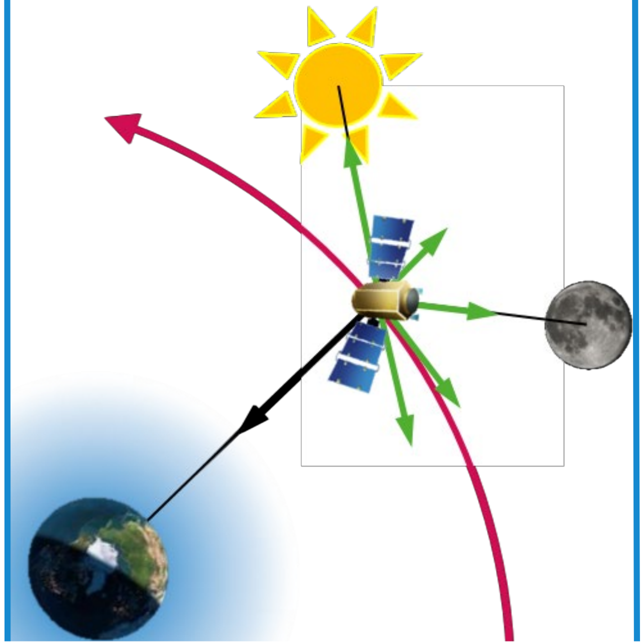


Space debris

ORBIT PERTURBATIONS

Traditional approach: counteract perturbations

- Complex orbital dynamics
- Increase fuel requirements for orbit control



APPROACH

leverage and **control** perturbations

Reduce extremely high space mission costs especially for small satellites

Create new opportunities for exploration, exploitation and planetary protection

Mitigate space debris

Develop autonomous techniques for orbit manoeuvring and control by surfing through orbit perturbations

Introduction

Asteroid missions and asteroid deflection

- On average a 10-km-sized asteroid strikes the Earth every 30-50 million years (globally catastrophic effects). Tunguska class (100 m in size) asteroid impact every 100 years (locally devastating effects)
- Near Earth Asteroids can be a **threat** but also an **opportunity** for science and material utilisation
- This is enables by mission to asteroids and demonstration mission for asteroid deflection


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

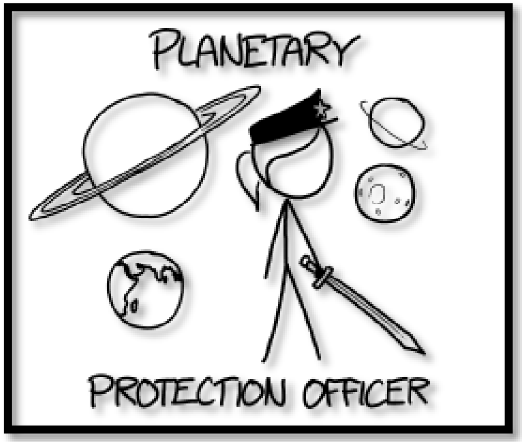

Chelyabinsk, Russia (2013), 17-30 m diameter asteroid


Asteroid manipulation

Introduction

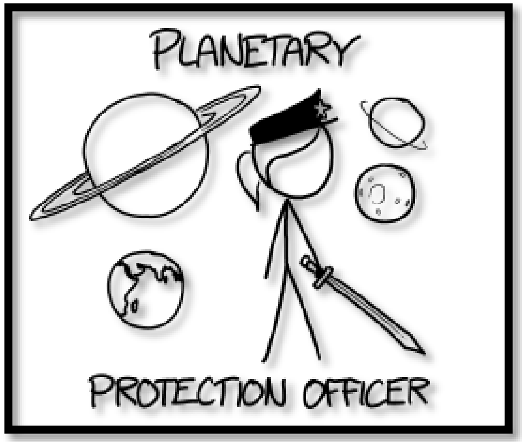
Planetary protection

- Humans now routinely venture beyond Earth and send spacecraft to explore other planets.
- With this extraordinary ability comes **great responsibility**: do not introduce terrestrial biological contamination to other planets and moons that have potential for past or present life
- For interplanetary missions and missions at Libration Point Orbit, **planetary protection analysis** need to be performed




Planetary protection verification


Breakup of the object WT110F during re-entry (November 2015)



PLANETARY PROTECTION

Introduction

Planetary protection requirements for forward contamination

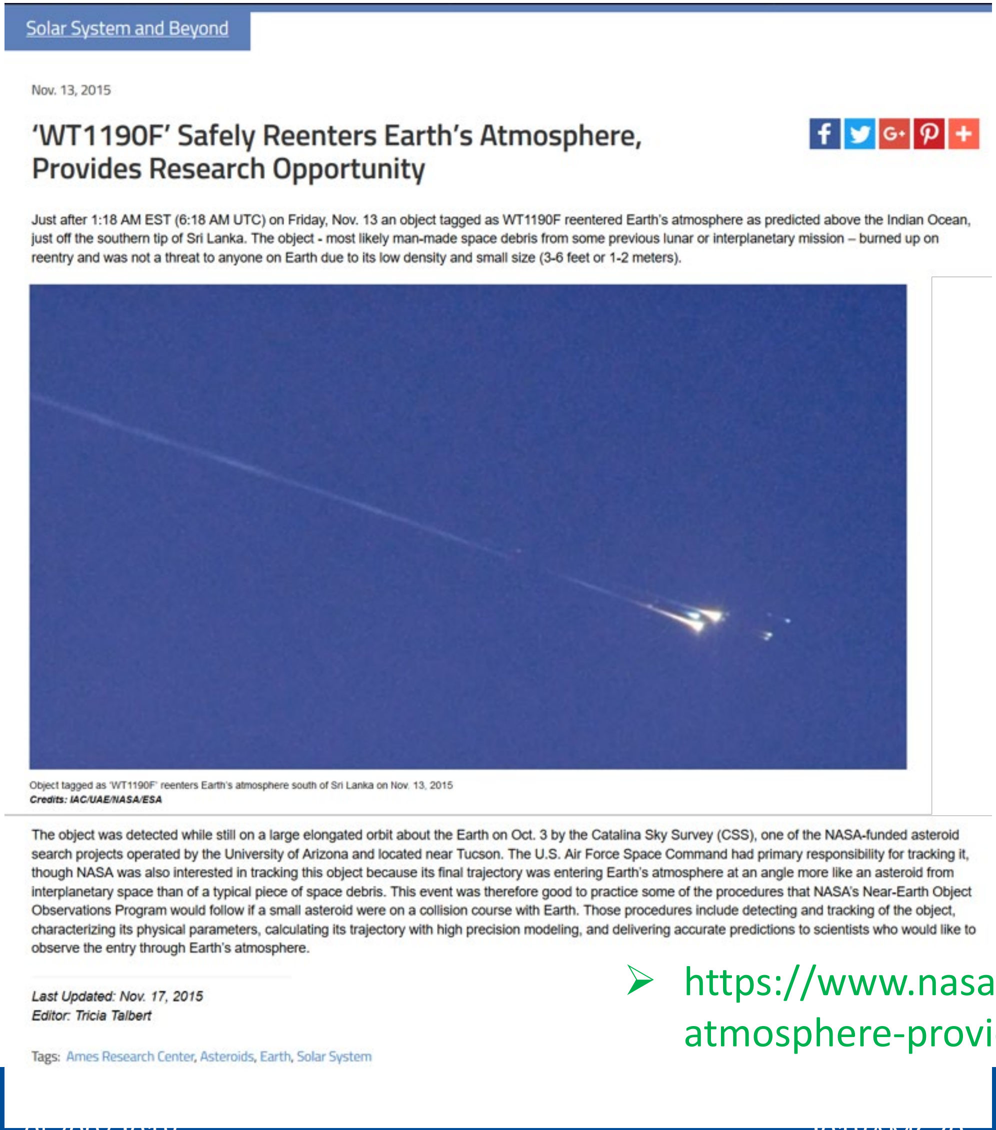
For interplanetary missions and missions at Libration Point Orbit, planetary protection analysis need to be performed (**Forward contamination**)

- Ensure that the impact probability of spacecraft and upper stages with planets and moons over 50-100 years is below the **required threshold** with a give **confidence level**.
- Compliance with requirements should be verified for
  - The nominal trajectory
  - Considering on-board failures
  - Considering uncertainties on orbit injection, s/c parameters or physical environment

➢ G. Kminek. ESA planetary protection requirements. Technical Report ESSB-ST-U-001, European Space Agency, February 2012.

Introduction

Nov. 13, 2015: “WT1190F Safely Re-enters Earth’s Atmosphere”



Solar System and Beyond

Nov. 13, 2015

‘WT1190F’ Safely Reenters Earth’s Atmosphere, Provides Research Opportunity

Just after 1:18 AM EST (6:18 AM UTC) on Friday, Nov. 13 an object tagged as WT1190F reentered Earth’s atmosphere as predicted above the Indian Ocean, just off the southern tip of Sri Lanka. The object - most likely man-made space debris from some previous lunar or interplanetary mission – burned up on reentry and was not a threat to anyone on Earth due to its low density and small size (3-6 feet or 1-2 meters).

Object tagged as ‘WT1190F’ reenters Earth’s atmosphere south of Sri Lanka on Nov. 13, 2015

Credits: IAC/UAE/NASA/ESA

The object was detected while still on a large elongated orbit about the Earth on Oct. 3 by the Catalina Sky Survey (CSS), one of the NASA-funded asteroid search projects operated by the University of Arizona and located near Tucson. The U.S. Air Force Space Command had primary responsibility for tracking it, though NASA was also interested in tracking this object because its final trajectory was entering Earth’s atmosphere at an angle more like an asteroid from interplanetary space than of a typical piece of space debris. This event was therefore good to practice some of the procedures that NASA’s Near-Earth Object Observations Program would follow if a small asteroid were on a collision course with Earth. Those procedures include detecting and tracking of the object, characterizing its physical parameters, calculating its trajectory with high precision modeling, and delivering accurate predictions to scientists who would like to observe the entry through Earth’s atmosphere.

Last Updated: Nov. 17, 2015
Editor: Tricia Talbert

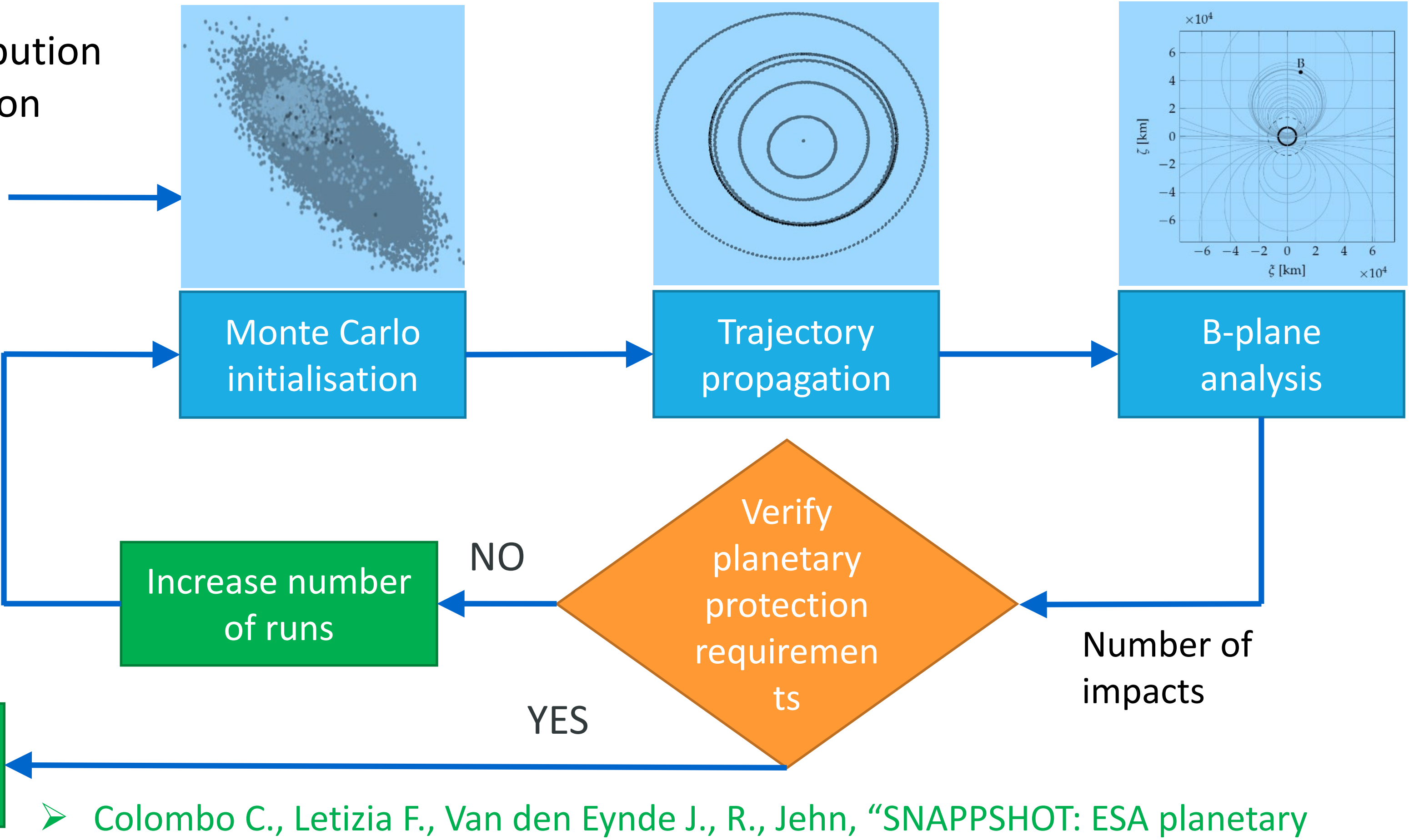
Tags: Ames Research Center, Asteroids, Earth, Solar System

- https://www.nasa.gov/feature/wt1190f-safely-reenters-earth-s-atmosphere-provides-research-opportunity

SNAPPshot

Suite for Numerical Analysis of Planetary Protection

Input:
Uncertainty distribution
Planetary protection requirement: max impact prob. and confidence level



Number of MC runs
Initial conditions

Trajectory propagation

Monte Carlo initialisation

Trajectory propagation

B-plane analysis

Number of impacts

Verify planetary protection requirements

NO

Increase number of runs

YES

Output and graphics

- Colombo C., Letizia F., Van den Eynde J., R., Jehn, “SNAPPSHOT: ESA planetary protection compliance verification software, Final report”, ESA contract, Jan 2016

Monte Carlo initialisation

Inputs

Uncertainties

- Dispersion of the initial condition due to launcher inaccuracy

  Input: 6 x 6 Covariance matrix describing the dispersion of the escape velocity and position of injection

- Failure of the propulsion system

  Input: random failure time within a time interval

- Uncertainty on spacecraft parameters (e.g. unknown area-to-mass ratio)

  Input: Distribution can be selected (e.g., uniform, triangular, etc.)

Planetary protection

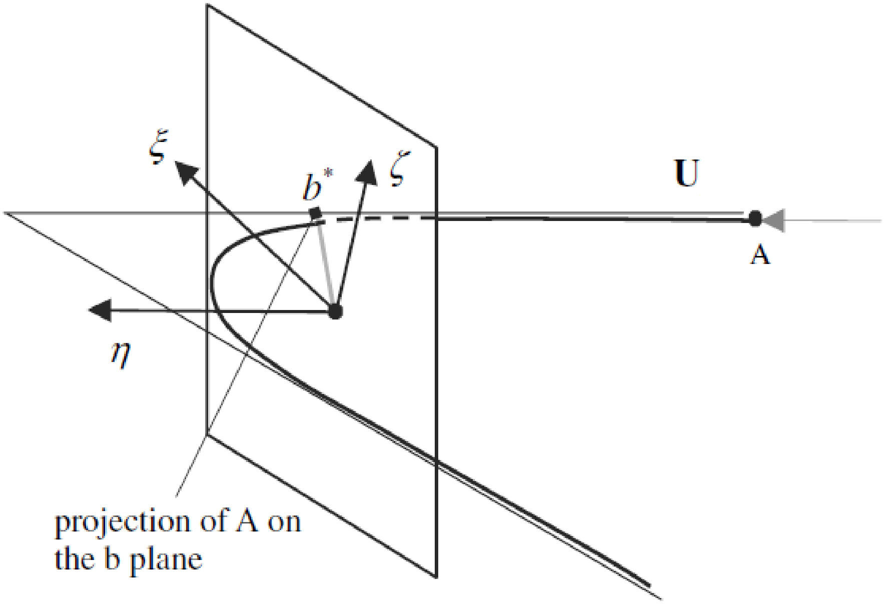
Input: impact probability (p) and confidence (α)

Output: **minimum number of required MC runs** (*n*)

➢ Wilson (1927), Jehn (2015), Wallace (2015)

B-plane

Definition



Plane **orthogonal** to the object **planetocentric velocity** when the object enters the planet’s sphere of influence

- η-axis: parallel to the relative velocity $\boldsymbol{U}$
- ζ-axis points in the opposite direction as the projection of the planet’s velocity vector on the b-plane: **time shift at close approach**
- ξ-axis completes the right-handed reference frame: **geometrical MOID**

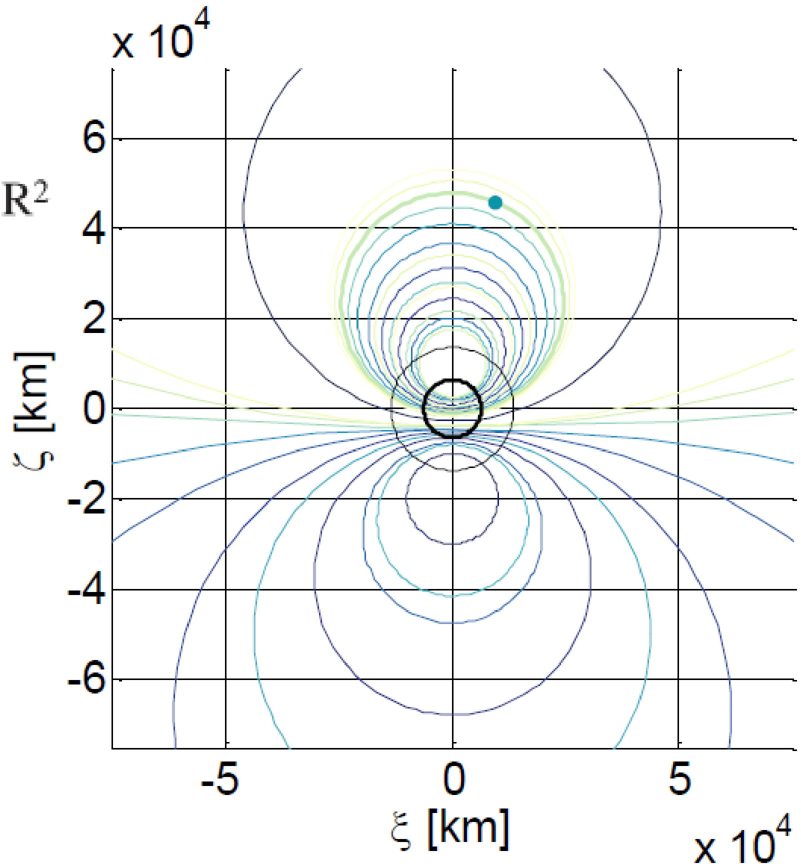
- Intersection of the **incoming asymptote** and the b-plane:
  $\boldsymbol{b} =$ impact parameter
- η = 0 on the b-plane identifies a **fly-by**

➢ (Öpik, 1976)

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. $k\mathrm{T}_P = h\mathrm{T}' \longrightarrow a'$
- A circle can be drawn on the b-plane for each couple of integers (h, k)



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

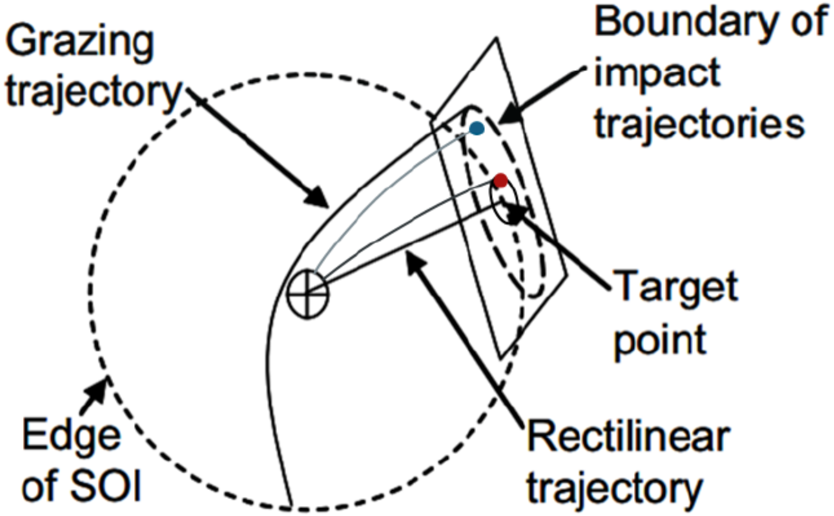
➢ Valsecchi G. B., Milani A., Gronchi G. F. and Chesley S. R., “Resonant returns to close approaches: Analytical theory”, 2003

B-plane analysis in SNAPPshot

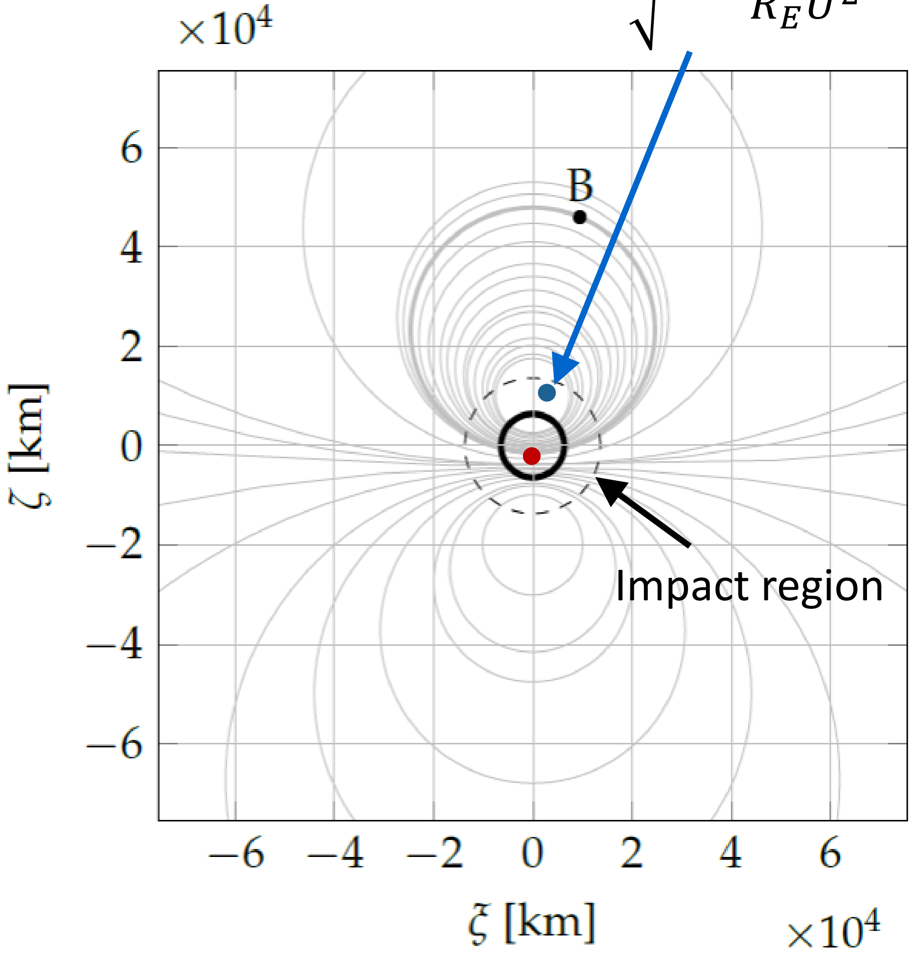
State characterisation

State characterisation:

- Impact
- Gravitational focussing



$$R_{GF} = R_E\sqrt{1+\frac{2\mu_E}{R_E U^2}}$$



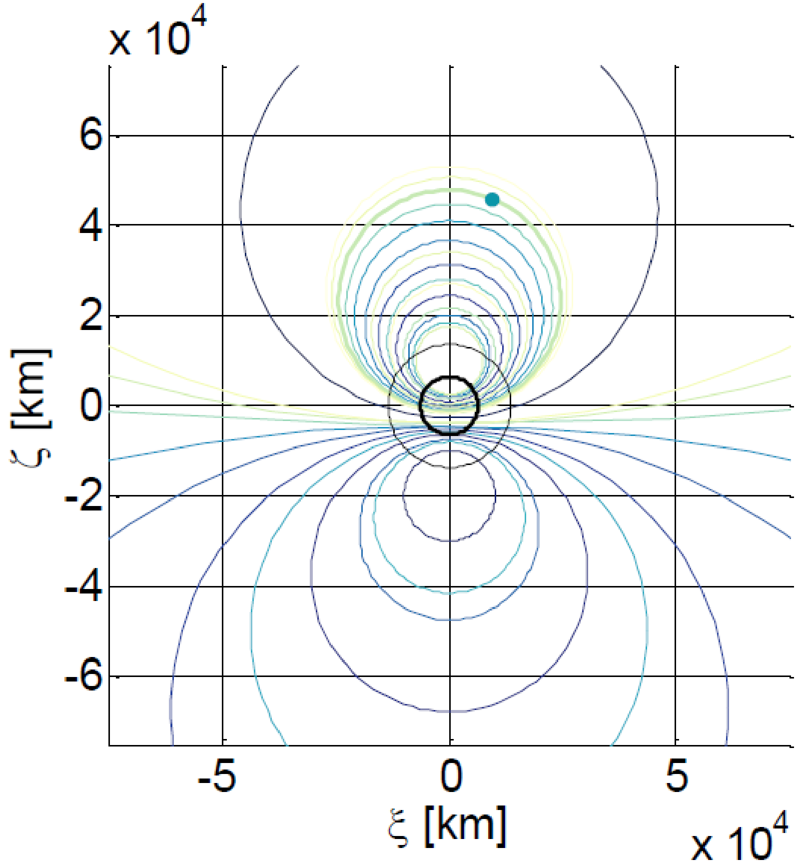
- Park and Ross

B-plane analysis in SNAPPshot

State characterisation

- Resonance:

  Severity: measured by the value of *k* (planet’s period repetitions): the lowest, the most critical.
  Resonance selection: closest resonance or resonance with the lowest *k* (and below the period threshold)



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

➢ Letizia F., Van den Eynde J., Colombo C., R., Jehn, 2016

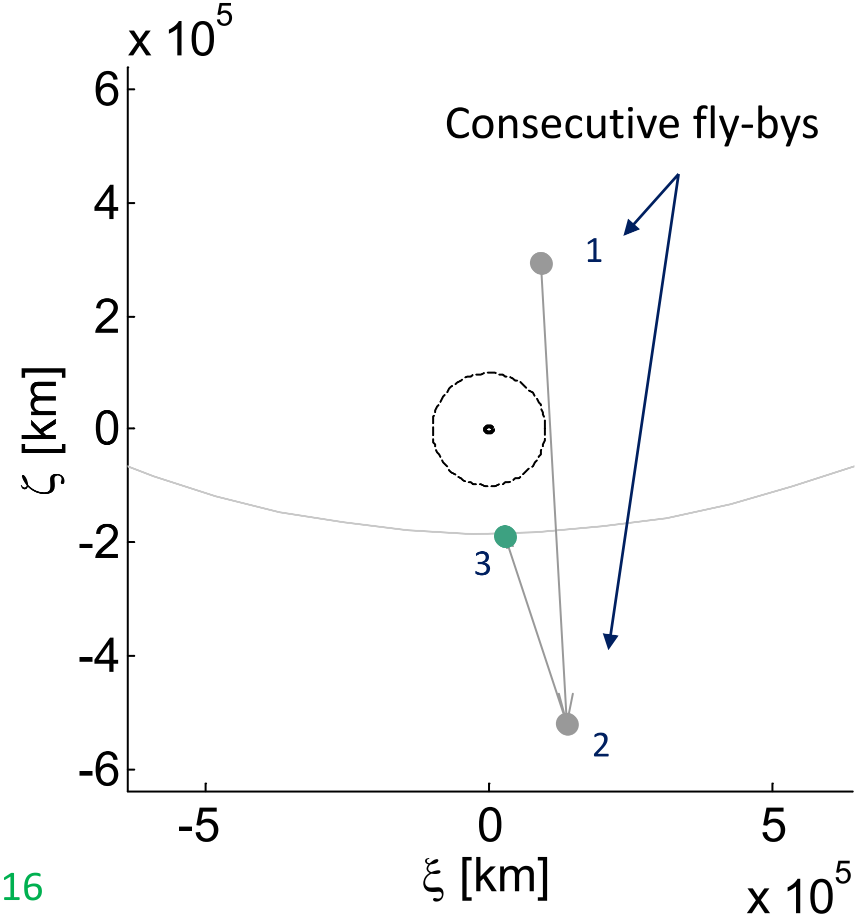
B-plane analysis in SNAPPshot

Close-encounter sorting

- When **multiple fly-bys** are recorded, for the Monte Carlo analysis **first or worst encounter** are analysed.

- **Sorting of multiple encounters:** identify the most critical ones (e.g. impact with Earth > resonance with Mars)
  - Distance-driven
  - State-driven:
    impact > resonance > simple close approach Earth > Mars > Venus

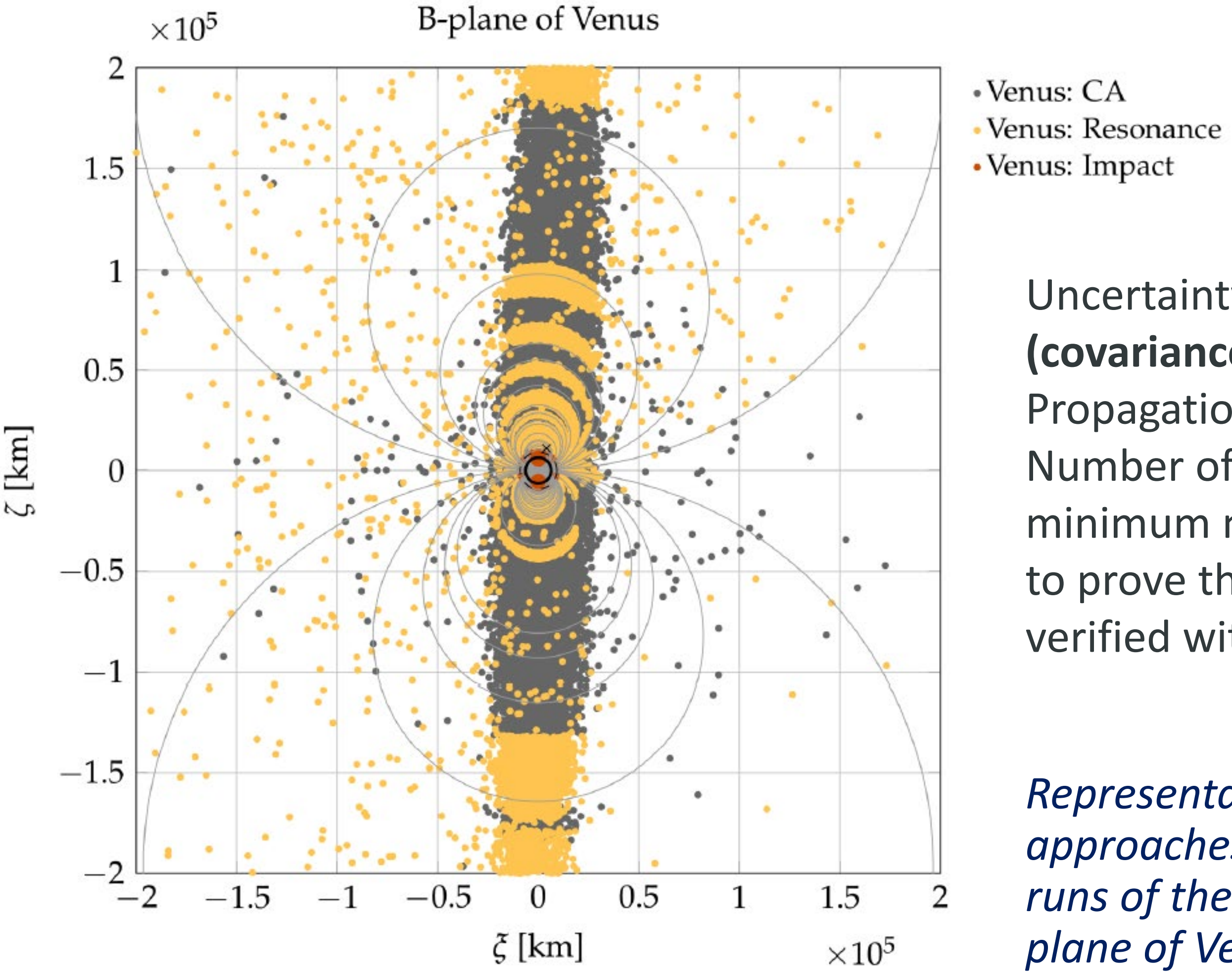
Evolution of one GAIA Fregat trajectory on the Earth's b-plane for 100 years of propagation



➢ Letizia F., Van den Eynde J., Colombo C., R., Jehn, 2016

Results

Effect of launcher dispersion: Solo launcher



- Letizia F., Van den Eynde J., Colombo C., R., Jehn, 2016

Uncertainty: **state dispersion (covariance matrix)**
Propagation: time 100 years,
Number of runs: 54114 (the minimum number of runs required to prove that planetary protection verified with 99% confidence)

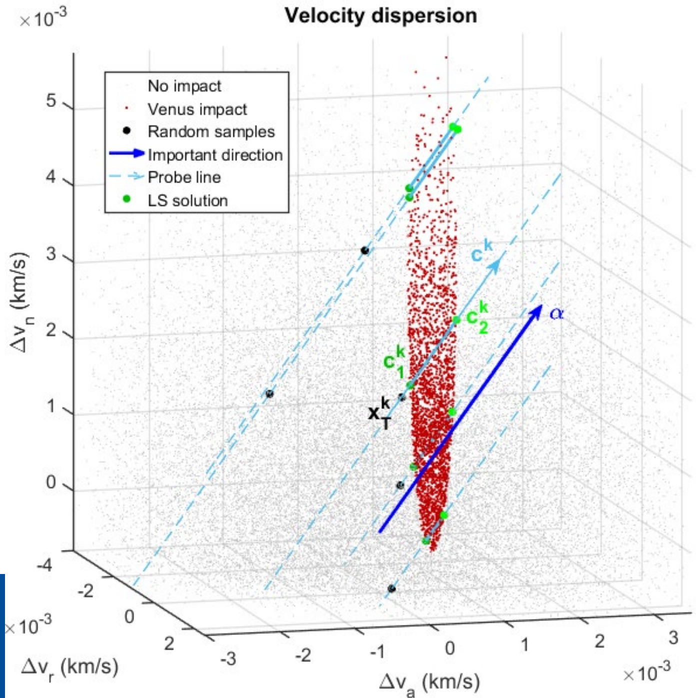
Representation of the worst close approaches for the 1000 Monte Carlo runs of the launcher of Solo on the b-plane of Venus.

Sampling techniques

Line Sampling

The Line Sampling (LS) is a **Monte Carlo sampling** method that probes the uncertainty domain by using **lines** instead of random points

- Line used to **identify the boundaries of the impact region** inside the domain
  - The lines follow a reference direction pointing toward the impact subdomain
  - Can be done **independently from initial uncertainty** and probability estimation
- The estimation of impact probability is reduced to a number of 1D problems along each line
  - **Analytical evaluation** increases the accuracy of the solution
- This generally improves the estimation of impact probability and reduces the amount of random samples required



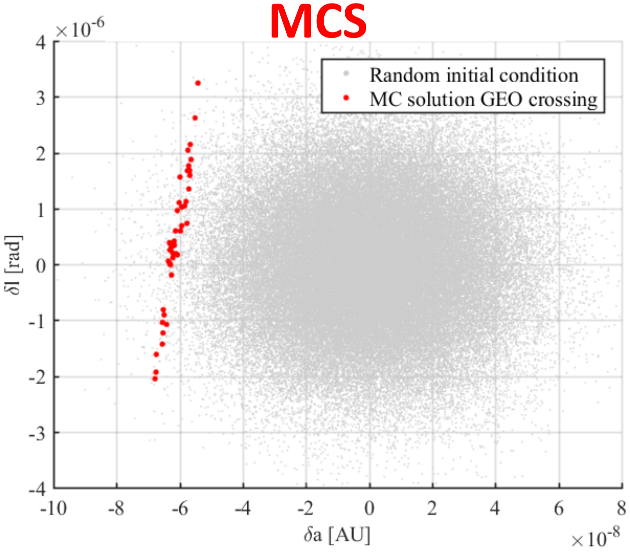
- ➢ Zio E., Pedroni N., Subset Simulation and Line Sampling for Advanced Monte Carlo Reliability Analysis, 2009

Sampling techniques

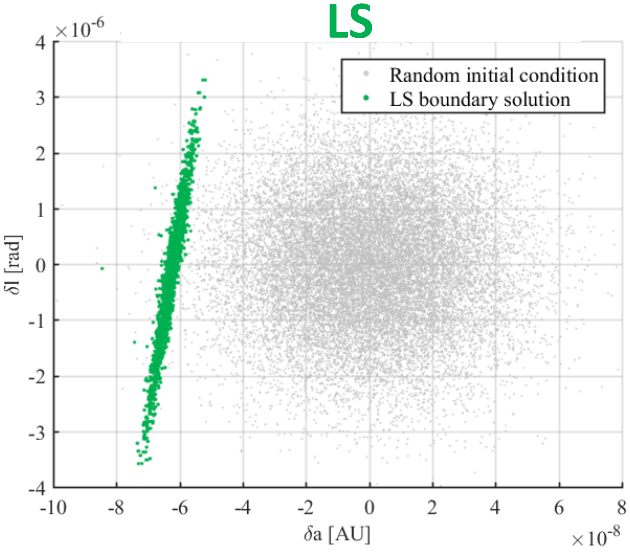
Results: asteroid Apophis

Analysed event: expected return in 2036 (according to observations in 2009)[2]

MCS



LS



Small expected probability

Distributed impact region

	$N_{Samples}$	N_{Prop}	$\hat{P}(I)$	$\hat{\sigma}$
MCS	1e6	1e6	5.00e-5	6.86e-6
LS	1e4	~1e5 ↓	5.38e-5	1.18e-6
	1e5	~1e6	5.32e-5	3.45e-7 ↓

Similar confidence level as MC

Similar number of orbital propagations as MC

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[2] http://newton.dm.unipi.it/neodys

* propagations performed with RK8(7) with relative tolerance 10^{-12}

Statistical analysis

Effect of numerical integrators

Two integration methods were considered:

- RK78, **explicit** Runge-Kutta of 8th order with adaptive step (Dormand-Prince), already implemented in SNAPPshot
- GLRK8, **implicit** Runge-Kutta of 8th order, **symplectic**, with fixed-point non-linear solver, newly implemented in SNAPPshot

The results of the test cases confirmed that, even though the propagation of a single initial condition present differences between integrators, these differences are not relevant on a statistical level (thousands of initial conditions)

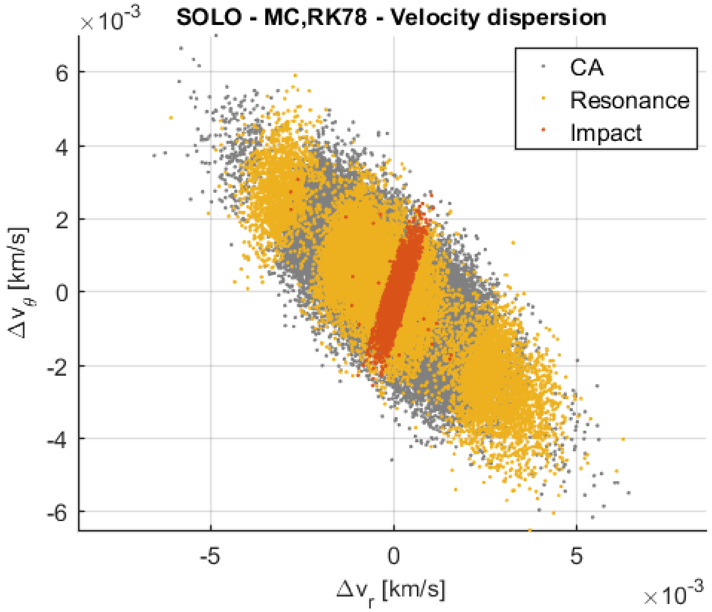
- **Planetary protection** analysis returns the **same results**

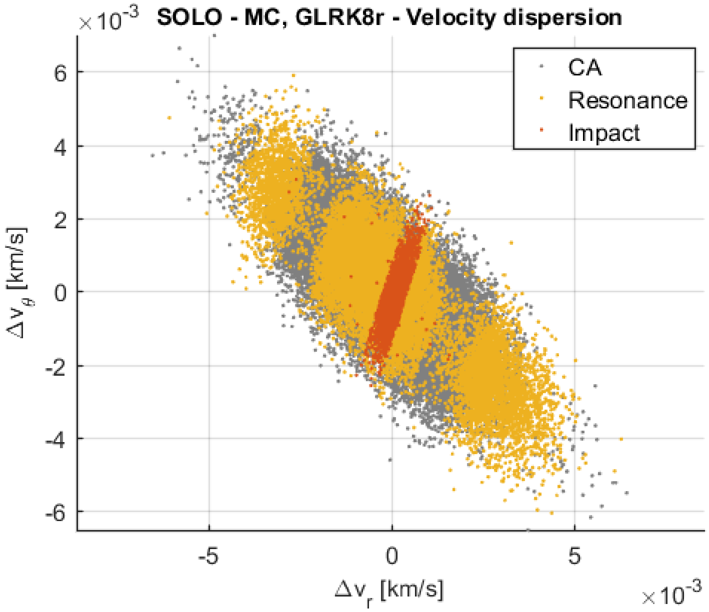
➢ Prince P. and Dormand J., High order embedded Runge-Kutta formulae, Journal of Computational and Applied Mathematics, 7(1):67–75, 1981. ISSN 03770427

➢ Aristoff, J.M., Poore, A.B, Implicit Runge–Kutta methods for orbit propagation, Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, Minneapolis, MN, August. Paper AIAA 2012–4880 (2012)

Statistical analysis

Effect of launcher dispersion: Solo launcher





	RK78	GLRK8r
Number of Impacts	2347 (Venus), 1 (Earth)	2348 (Venus), 1 (Earth)
Impact probability (Venus)	4.34e-2	4.34e-2
Confidence level (σ)	8.76e-4	8.76e-4
Computational time	6.5 h	81.5 h

Image credits: ESA Space in Images – AIM at Didymos

OPTIMAL DEFLECTION OF NEAR-EARTH OBJECTS USING THE B-PLANE

Introduction

B-plane in asteroid deflection

- Kinetic impactor as the most mature technology
- Determine the optimal deflection direction to maximise the displacement on the b-plane
- Design an optimal deflection strategy aimed at avoiding resonant returns of the asteroid following the deflection manoeuvre

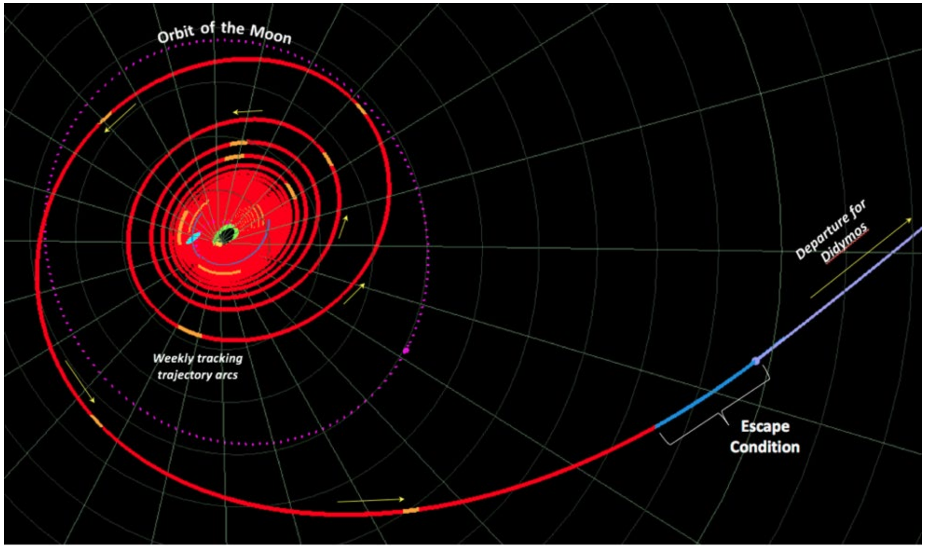
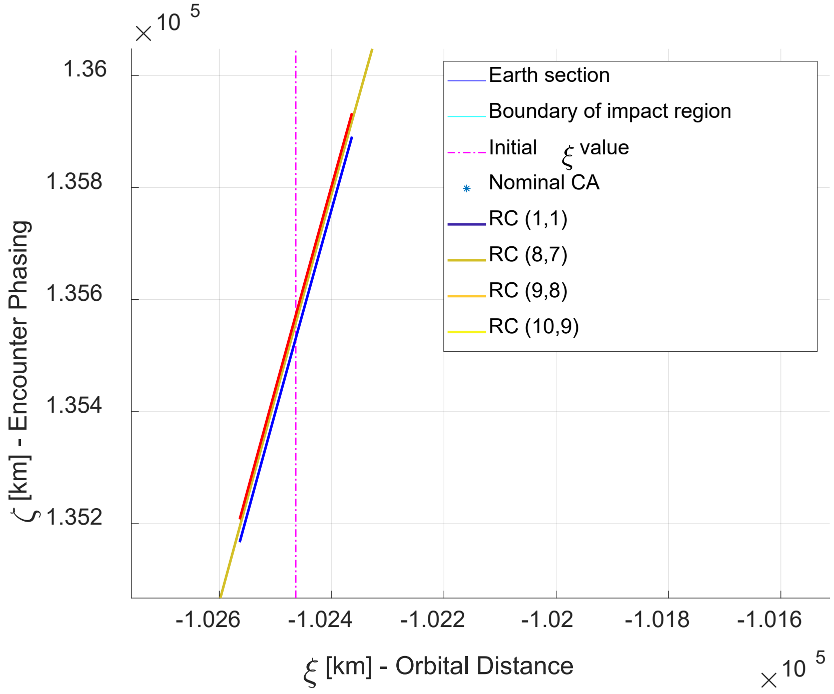


Image credits: NASA Planetary Defense - DART

B-plane analysis

Resonances and Keyholes

- Resonant circles are regions of the b-plane corresponding to returns to Earth
- Keyholes are the regions of the b-plane leading to a subsequent encounter
  - Hit: pre-image of the Earth's cross-section
  - Return: pre-image of the Sphere of Influence (SOI)'s cross-section
- Close to the resonant circles

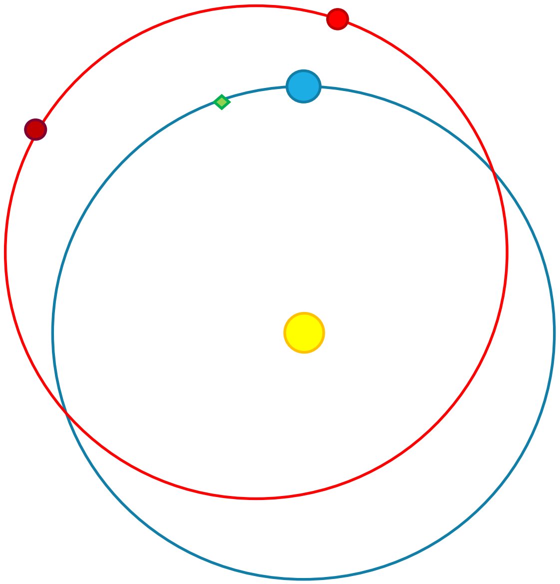


➢ Valsecchi G. B., Milani A., Gronchi G. F. and Chesley S. R., "Resonant returns to close approaches: Analytical theory", 2003

Deflection mission

Introduction

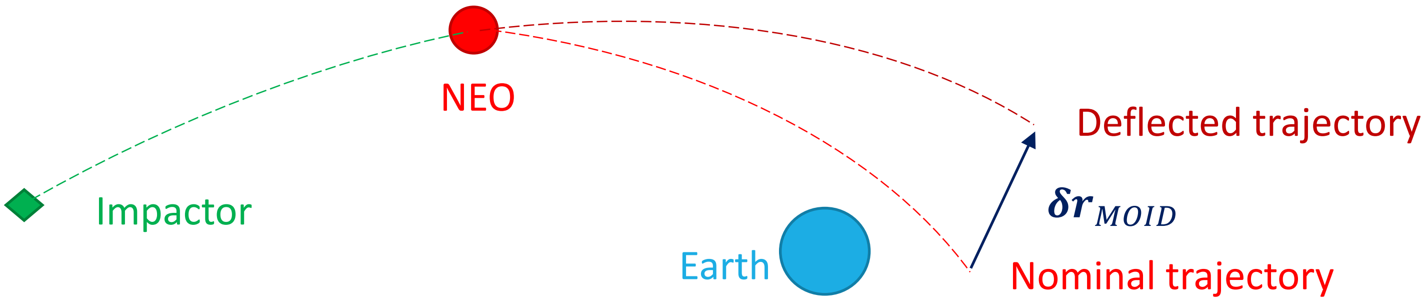
- Deflection mission
  - Departure from Earth
  - Asteroid hit
  - Deflected NEO fly-by of the Earth
- Modeling
  - Deflection a certain amount of time before the close approach
  - Study the effect at the close approach



Earth orbit
NEO original orbit
Impactor
NEO modified

Deflection manoeuvre

Fully analytical modelling



Relative motion equations

Gauss planetary equations

$$\begin{cases} \boldsymbol{\delta r}_{MOID} = \boldsymbol{A}_{MOID}\boldsymbol{\delta\alpha}_d \\ \boldsymbol{\delta\alpha}_d = \boldsymbol{G}_d\boldsymbol{\delta v}_d \end{cases} \Longrightarrow \boldsymbol{\delta r}_{MOID} = \overset{\boldsymbol{T}}{\boldsymbol{A}_{MOID}\boldsymbol{G}_d}\boldsymbol{\delta v}_d$$

To maximise $\|\boldsymbol{\delta r}_{MOID}\|$ maximise the quadratic form $\boldsymbol{T}^T\boldsymbol{T}$ by choosing $\boldsymbol{\delta v}_d$ parallel to the direction of the eigenvector of $\boldsymbol{T}^T\boldsymbol{T}$ conjugated to its maximum eigenvalue

- Vasile and Colombo, “Optimal Impact Strategies for Asteroid Deflection”, 2008
- Conway 2005

Deflection manoeuvre

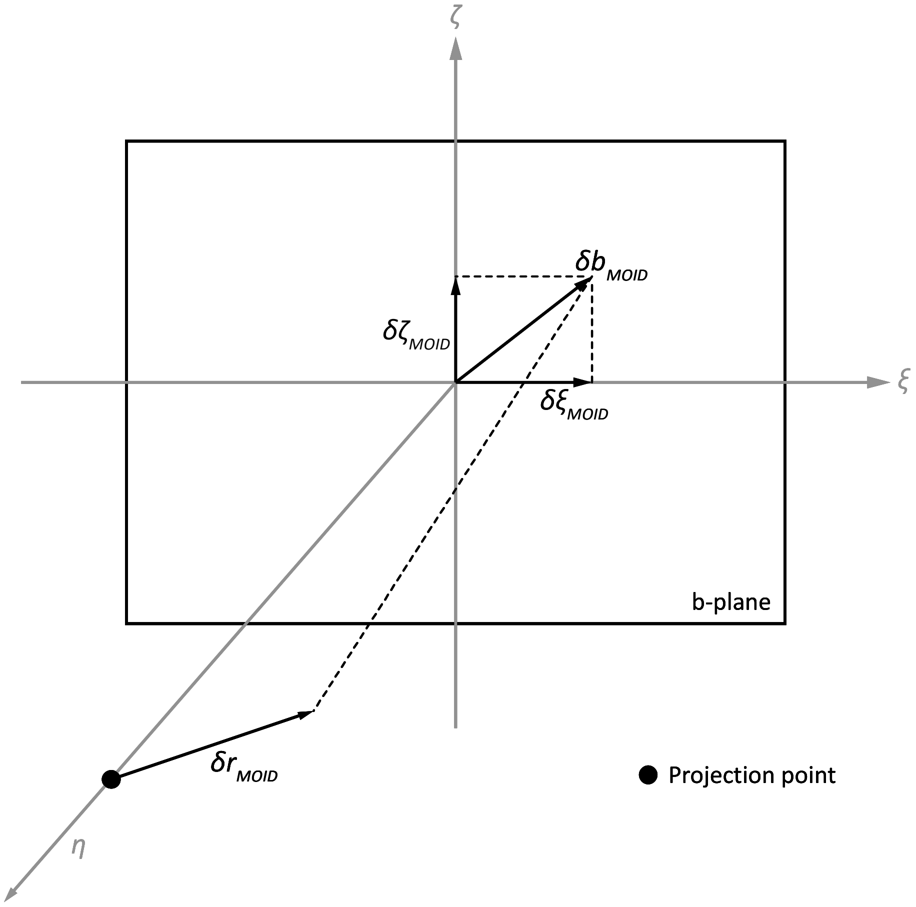
Extension to the b-plane

- Analytical formulation extended to compute the deviation projection on the b-plane

$$\begin{aligned}\boldsymbol{\delta b}_{MOID} &= \boldsymbol{\delta r}_{MOID} - (\boldsymbol{\delta r}_{MOID} \cdot \boldsymbol{e}_{\boldsymbol{\eta}})\boldsymbol{e}_{\boldsymbol{\eta}} \\ &= \boldsymbol{e}_{\boldsymbol{\eta}} \times (\boldsymbol{\delta r}_{MOID} \times \boldsymbol{e}_{\boldsymbol{\eta}}) = \boldsymbol{M}_{\boldsymbol{\delta b}}\boldsymbol{\delta r}_{MOID}\end{aligned}$$

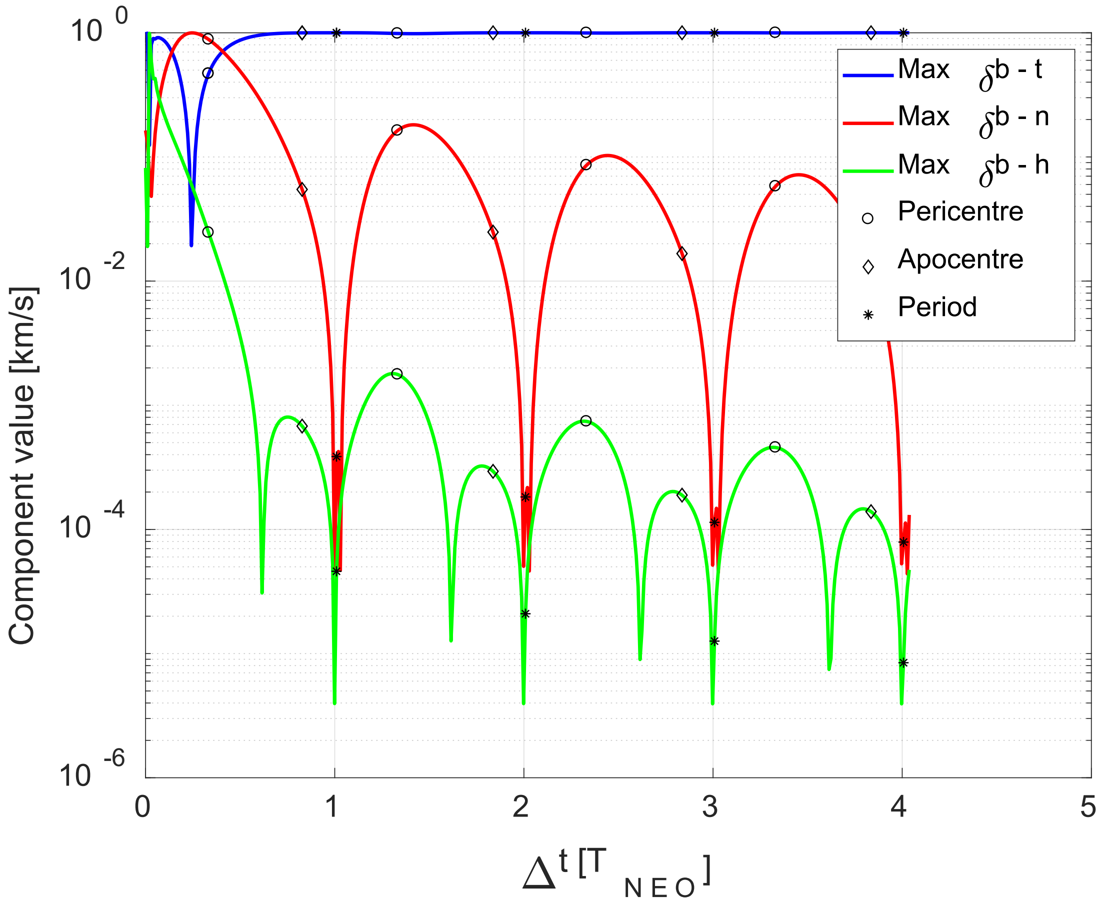
$$\boldsymbol{\delta b}_{MOID} = \boldsymbol{M}_{\boldsymbol{\delta b}}\boldsymbol{T}\boldsymbol{\delta v}_{d} = \boldsymbol{T}_{\boldsymbol{\delta b}}\boldsymbol{\delta v}_{d}$$

- Same eigenvector-based maximisation can be applied



Deflection manoeuvre

Optimal deflection direction for maximising *b*

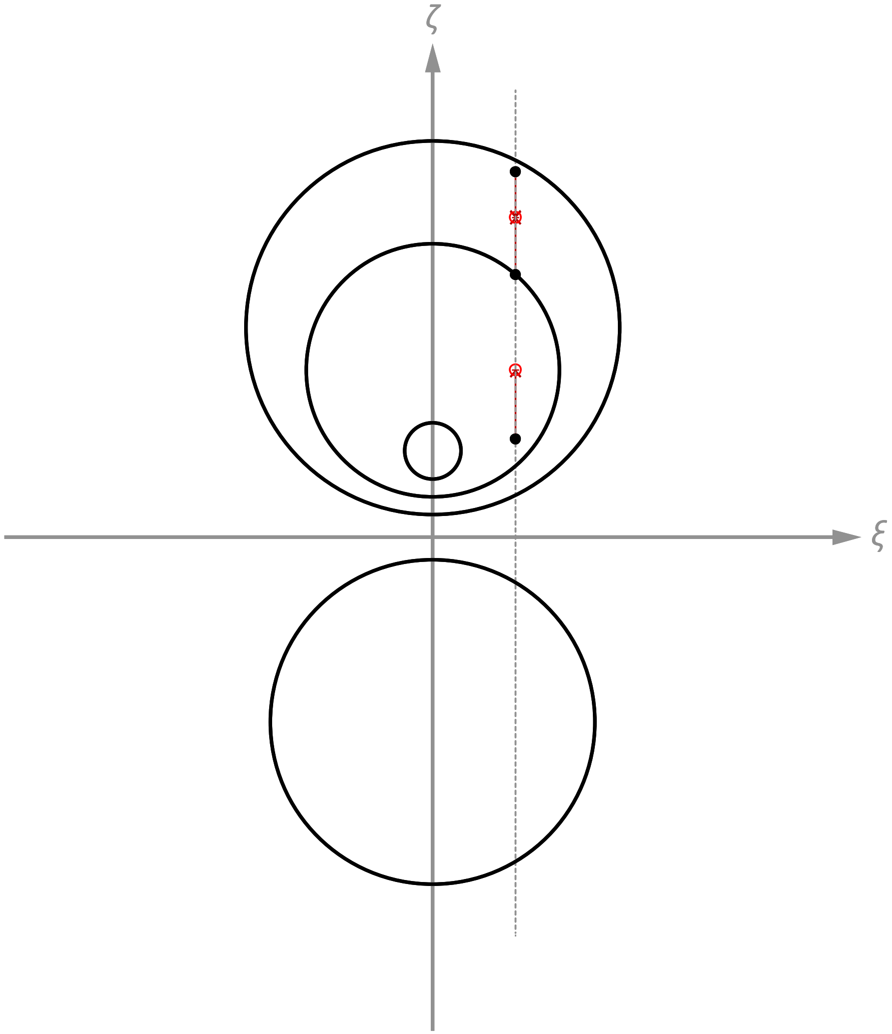


Deflection manoeuvre

Optimal deflection strategy to avoid keyholes

- A deviation along ζ is considered (early deflections)

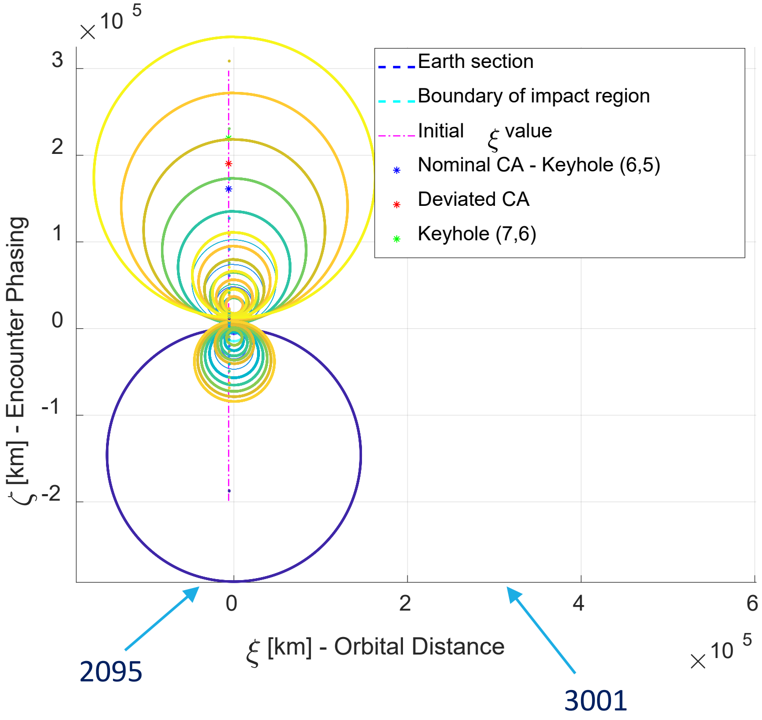
- Target ζ value: The middle point between the considered keyholes
- $\boldsymbol{\delta v}$ vector direction through eigenvector problem
- Not a pure maximisation when trying to avoid a keyhole



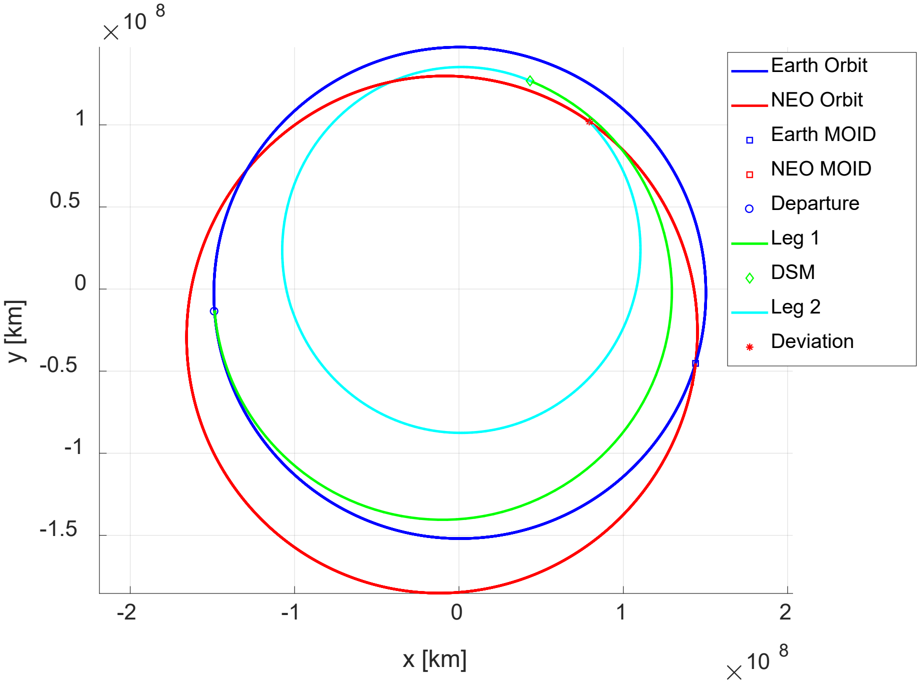
Results

Preliminary Deflection Mission Design

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



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



Conclusions

NEO deflection and planetary protection

- An analytical correlation between the deflection and the displacement on the b-plane is obtained
- It allows analytic optimization of impulsive deflection direction
- Impulsive deflection technique to avoid the keyholes as preliminary design for n-body propagation

- Uncertainty in initial conditions, spacecraft parameters, engine failures effect on 100 propagation for interplanetary space mission
- Minimum numbers of MC or line sampling runs for ensuring compliance to planetary protection requirements

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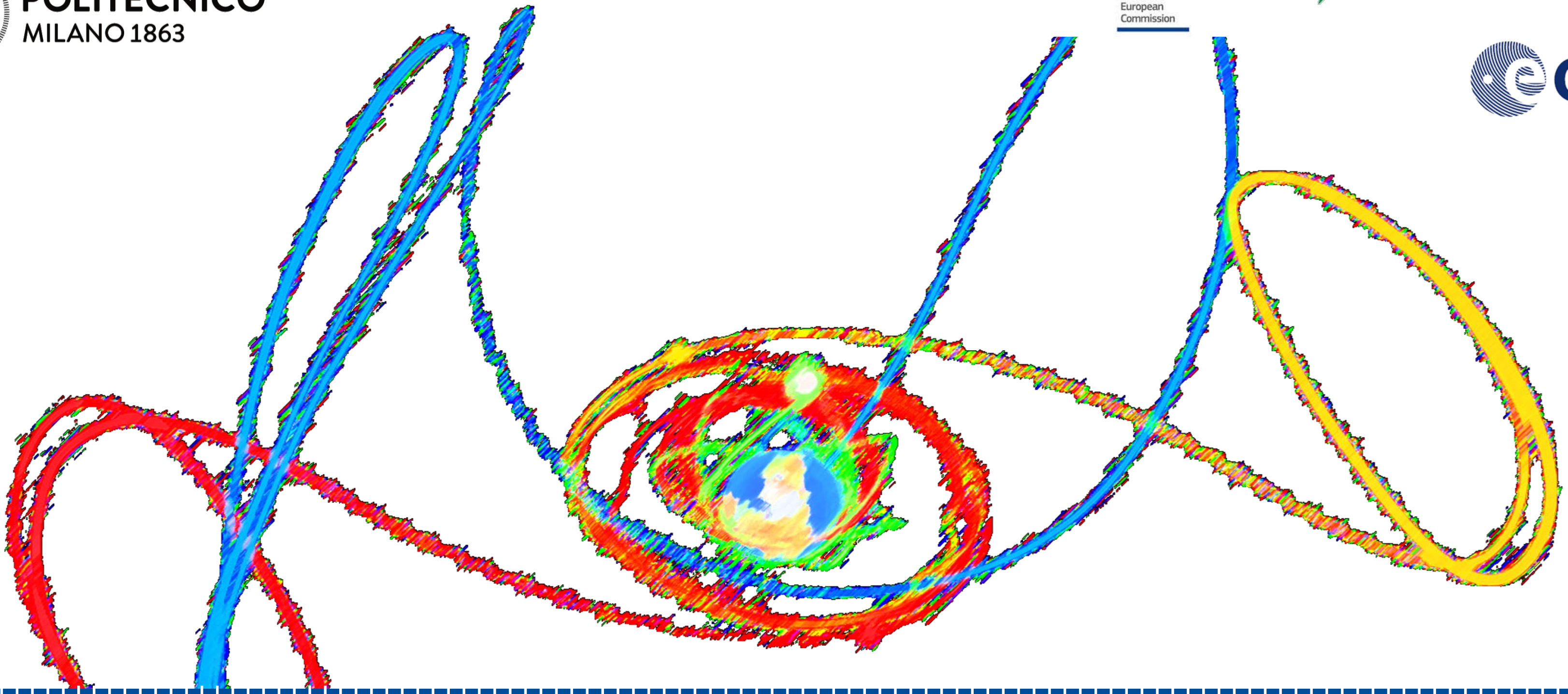

Close encounter characterisation and deflection design for planetary protection and defence

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