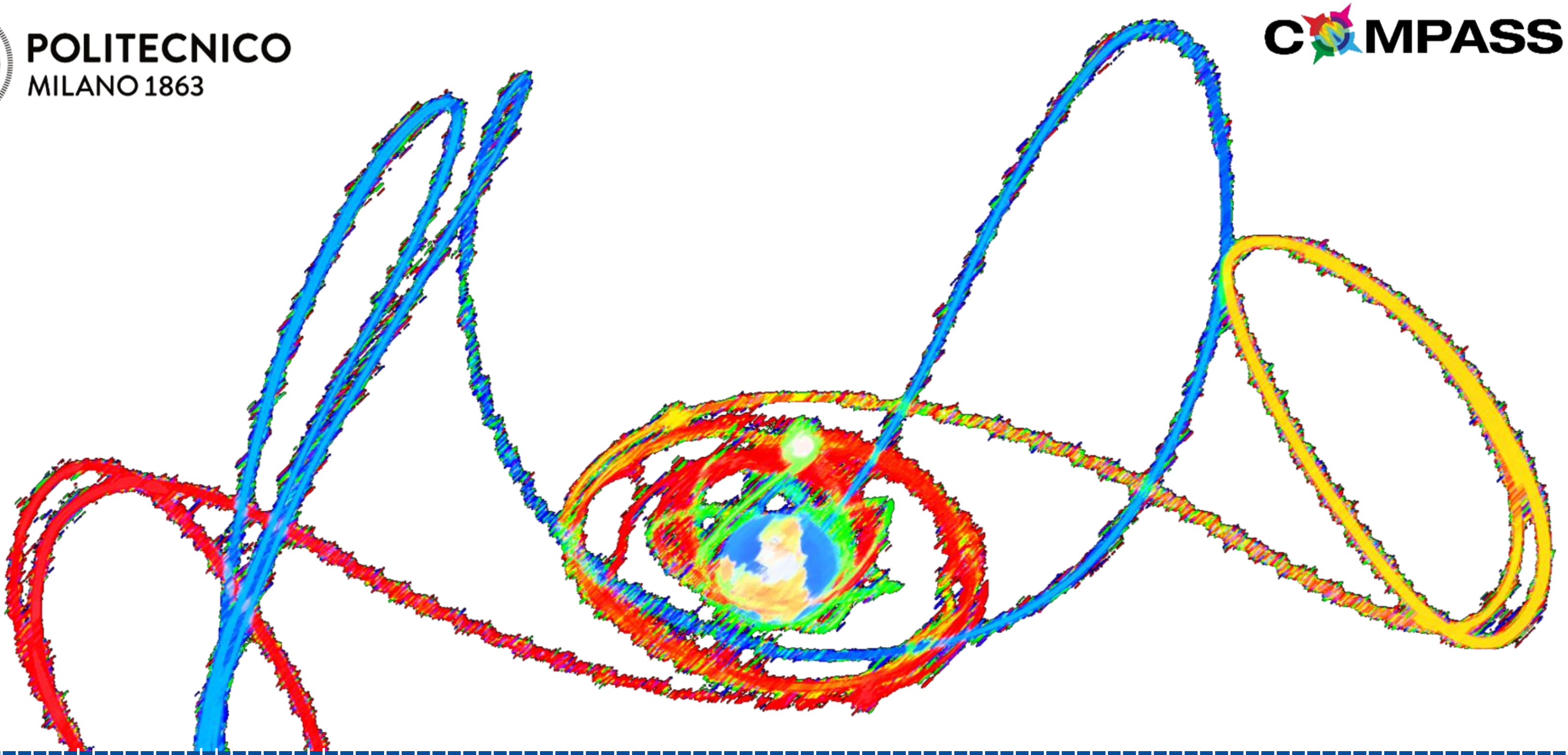


Planetary protection with SNAPPshot

Camilla Colombo, Politecnico di Milano

CCT ORB Seminar: Deep Space Missions:
End of Life and Planetary Protection

Planetary protection

INTRODUCTION

Introduction

Planetary protection framework

- Since 1958 (year after Sputnik) concern that initial exploration of the Moon and other celestial bodies might compromise future scientific exploration
- Ranger missions in 1961 first used planetary protection requirements
- Since then, all planetary missions had to implement planetary protection measures at different degrees
- Legal framework in the United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies (Outer Space Treaty)
- Spacecraft have to control
  - forward contamination
  - backward contamination

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

Introduction

Planetary protection requirements for forward contamination

For interplanetary missions and missions at Libration Point Orbit, planetary protection analysis need to be performed

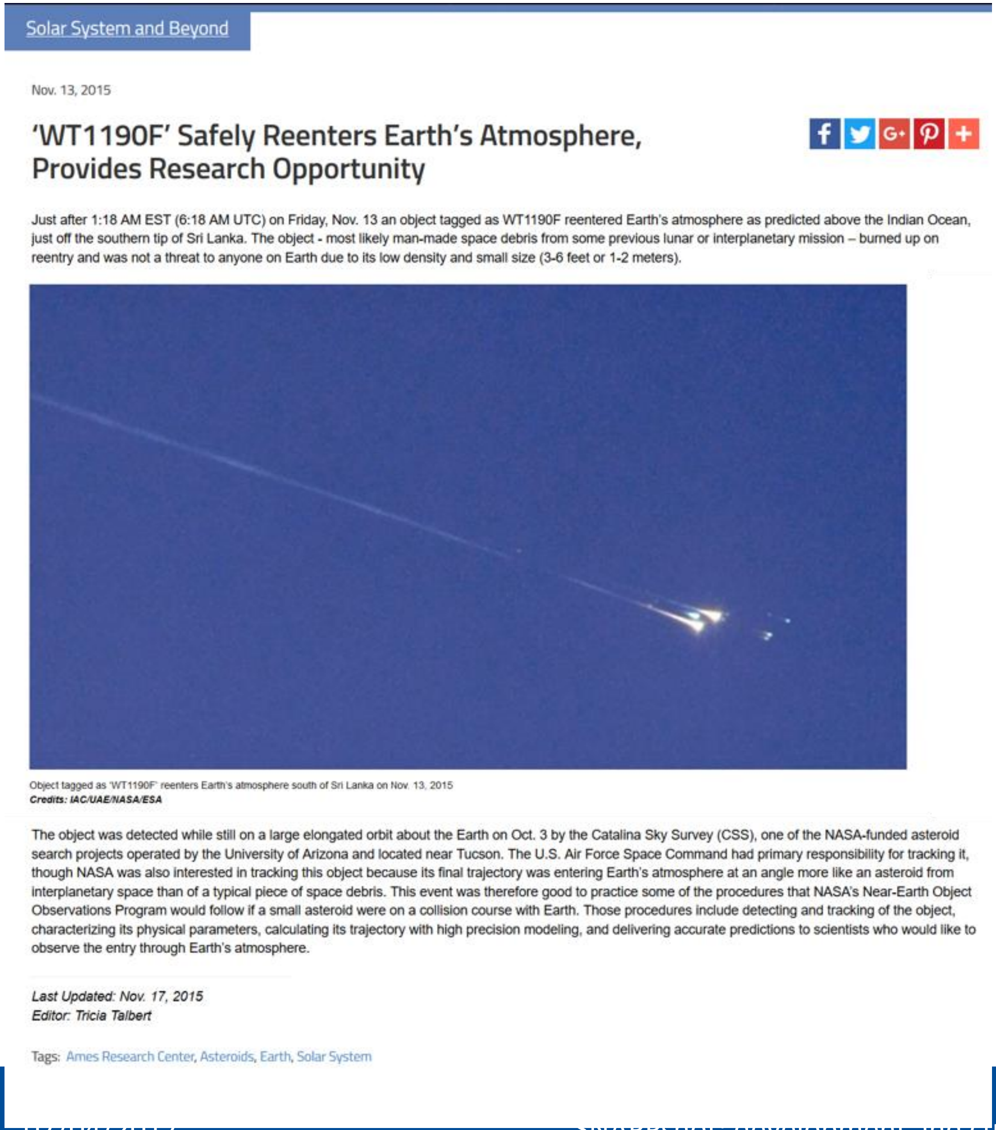
Forward contamination, contamination of celestial bodies other than the Earth by terrestrial life forms in the course of spaceflight missions

↓

- 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 and s/c parameters

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

Introduction

SNAPPshot: Suite for Numerical Analysis of Planetary Protection

Planetary Protection Compliance Verification Software

ESA study contract: Apr 2015 – Jan 2016

Team: University of Southampton

Camilla Colombo

Francesca Letizia

Jeroen Van den Eynde

Roberto Armellin

Introduction

SNAPPshot: Suite for Numerical Analysis of Planetary Protection

Insights into planetary protection analysis and tool enhancement

Since Nov 2016

Team: Politecnico di Milano

Camilla Colombo

Matteo Romano

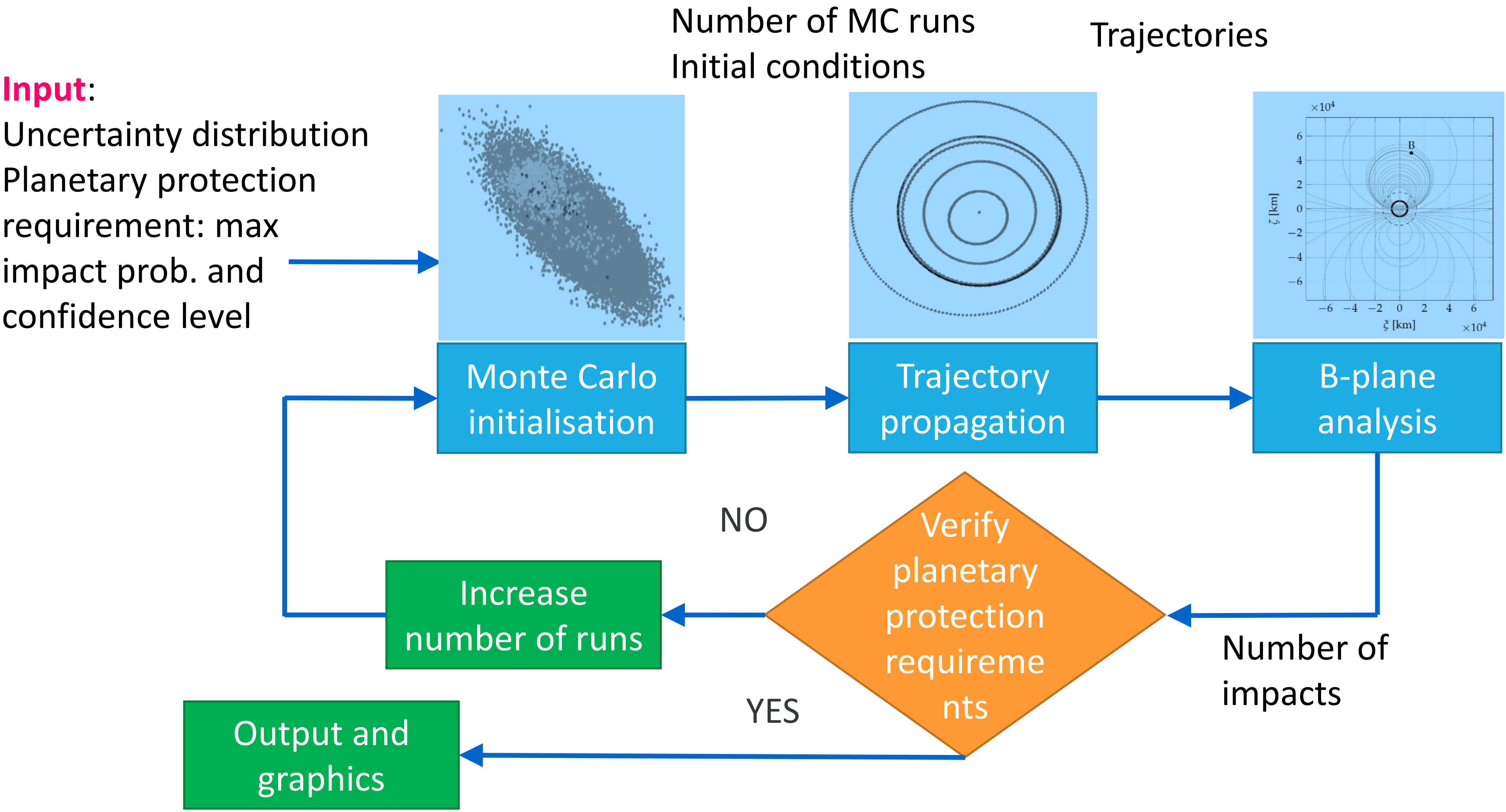
Francesca Letizia, Camilla Colombo, Jeroen Van den Eynde, Rüdiger Jehn

Original implementation and applications

SNAPPSHOT

SNAPPshot

Suite for Numerical Analysis of Planetary Protection



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

Monte Carlo initialisation

Number of MC runs
Initial conditions

Trajectory propagation

Trajectories

B-plane analysis

Number of impacts

Verify planetary protection requirements

NO

Increase number of runs

YES

Output and graphics

Monte Carlo initialisation

Defining the number of runs

- The output of the Monte Carlo (MC) run is treated as a binomial variable, with the two binary states impact/no impact

$$\boxed{X \sim \mathrm{B}(\mathrm{n}, \mathrm{p})}$$

X= number of impacts
B = Bernoulli distribution
n = number of independent trials
p = probability of impact in each trial

- Common approximation with a normal distribution with mean μ=*np* and variance $\sigma = np(1-p)$ to estimate the **confidence interval**

$$p = (\hat{p}, c)$$

$\widehat{p}$= probability of success estimated from the statistical sample
(i.e. $\hat{p} = n_I/n$)
n_I= number of impacts
c = confidence level

Not used as underestimate the error when the probability *p* tends to 1 or 0, as in the case of planetary protection

➢ Lawrence D. Brown, 2001

Monte Carlo initialisation

Defining the number of runs

- **Wilson's confidence interval** preferred: define the interval looking at the value of *p* that would put $\hat{p}$ at the **extremes** of the confidence interval

$$p \leq \left(\frac{\hat{p} + \frac{z^2}{2n} + z^2 \sqrt{\frac{\hat{p}(1-\hat{p})}{n} + \frac{z^2}{4n^2}}}{1 + \frac{z^2}{n}} \right)$$

$\hat{p} =$ probability of success estimated from the statistical sample (i.e. $\hat{p} = n_I / n$)

$z = \propto$ quantile from a standard normal distribution

- We are interested only in estimating the **minimum number of MC runs** (*n*) required to verify the compliance with the planetary protection requirements: verify the maximum level of **impact probability** (*p*), with a level of **confidence** (α)

Input: **impact probability** (*p*), **confidence** (α) → **minimum number of MC runs** (*n*)

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

Monte Carlo initialisation

Uncertainty distribution

Dispersion of the initial condition:

- 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 an **interval**

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

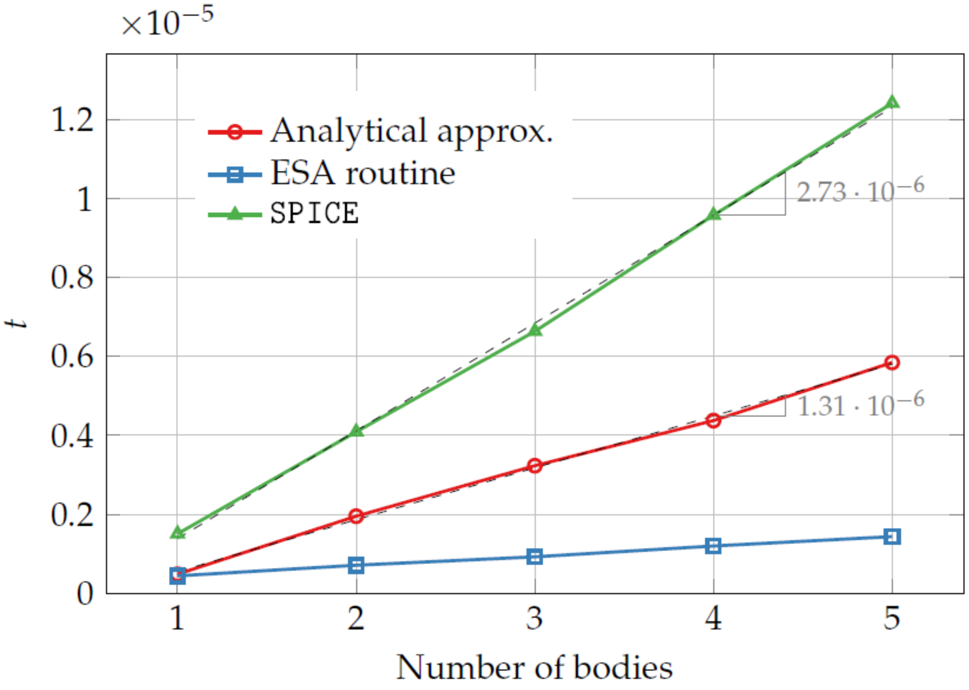
Input: Distribution can be selected (e.g., uniform, triangular) and known values

Trajectory propagation

Dynamical model

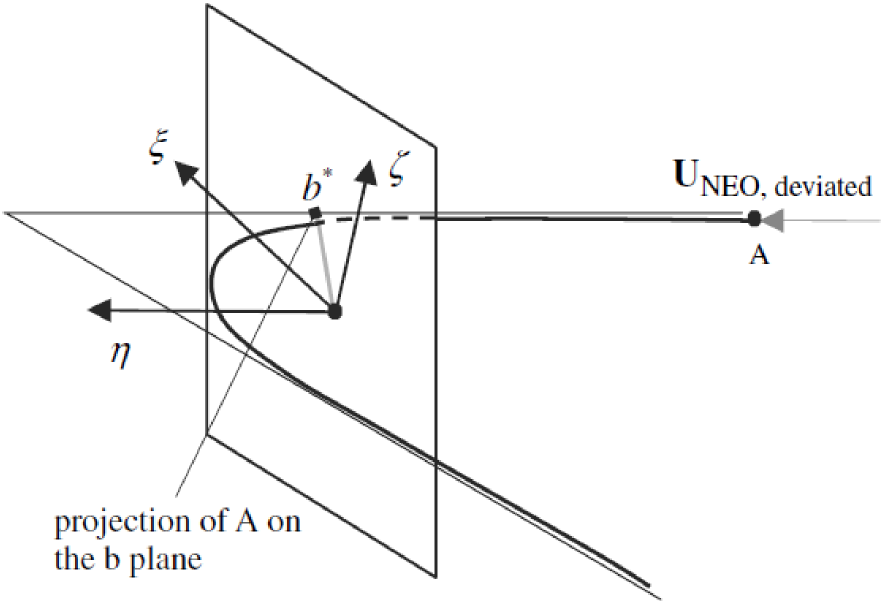
- Cartesian coordinates centred in the Solar System Barycentre J2000
- Dynamics of n planets and solar radiation pressure with cannonball model
- Ephemerides
    - Analytical ephemerides
    - ESA routine based on DE422
    - NASA SPICE
- Normalisation in dimensionless variables

$$\hat{L} = \frac{L}{AU} \qquad \hat{t} = \frac{t}{2\pi\sqrt{AU^3/\mu_{SUN}}}$$



B-plane analysis

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 planetocentric velocity
- ζ-axis: parallel to the projection on the b-plane of the planet velocity, but in the opposite direction
- ξ-axis: to complete a positively oriented reference system

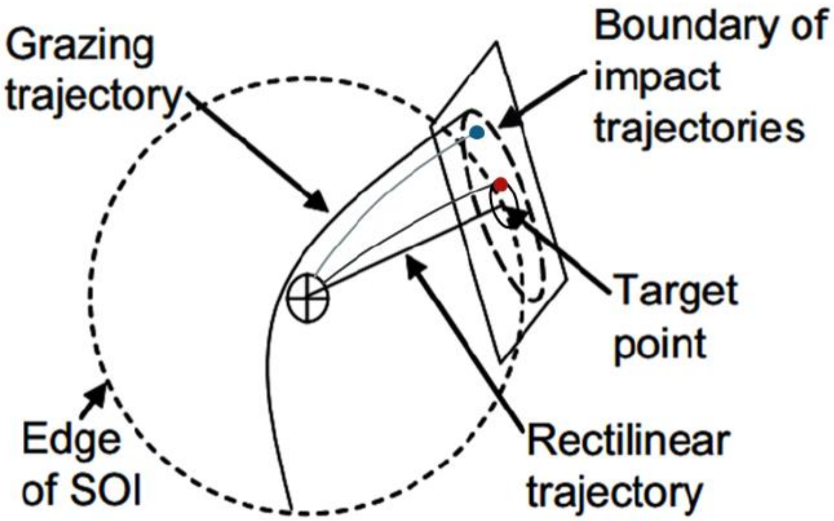
- Intersection of the **incoming asymptote** and the b-plane:
  $\boldsymbol{b}^* =$ impact parameter
- η = 0 on the b-plane identifies a **fly-by**

- (Öpik, 1976)
- Vasile and Colombo, 2008

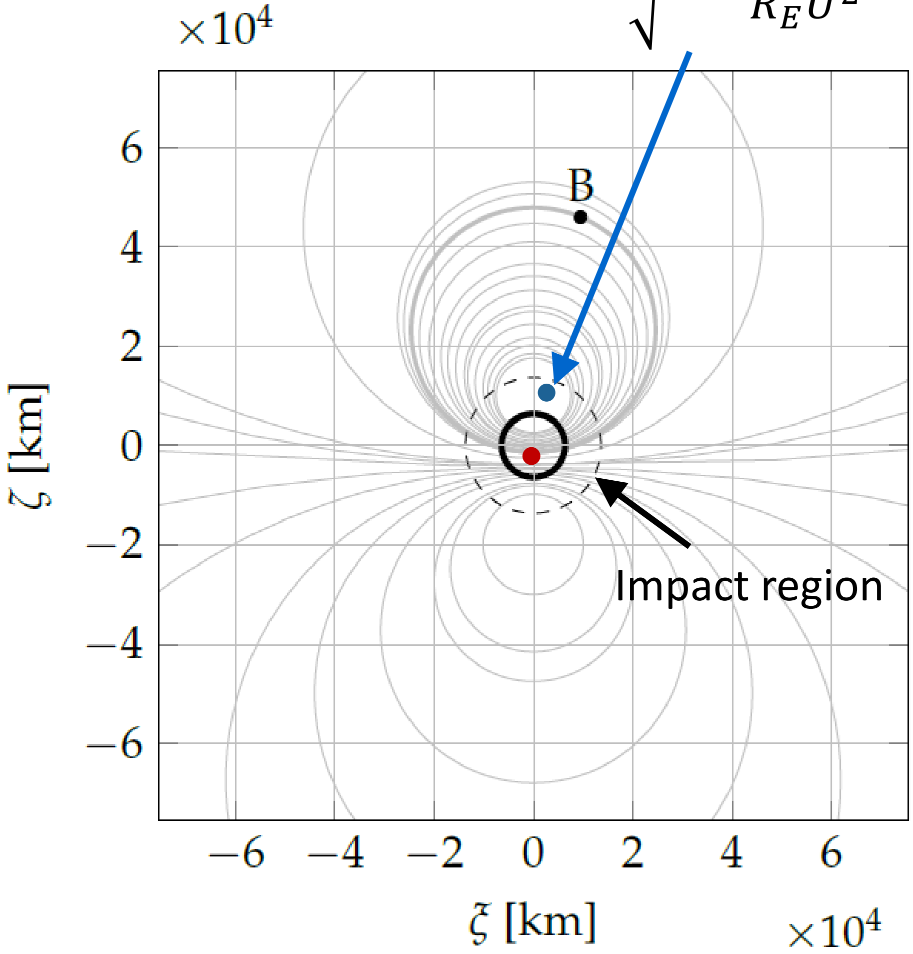
B-plane analysis

State characterisation

- Impact
- Gravitational focussing



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



B-plane analysis

State characterisation

- Resonance:

Circle on the b-plane $\xi^2 + \zeta^2 - 2D\zeta + D^2 = R^2$

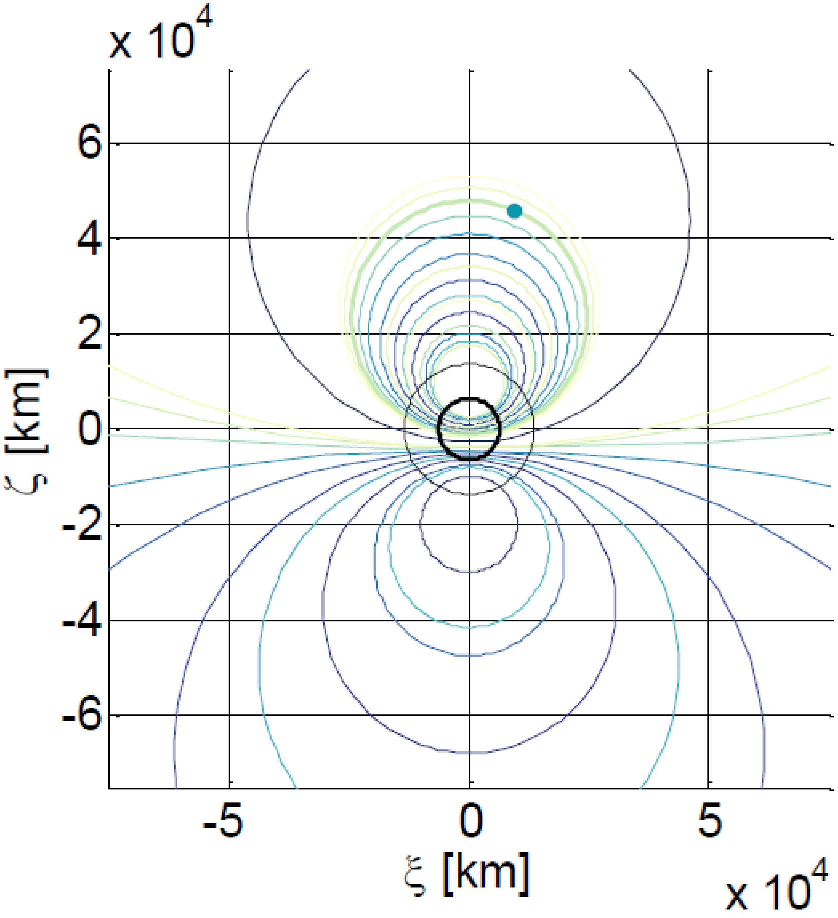
Requirement: Tisserand criterion < 3

➢ Valsecchi et al. (2003)

For a given close encounter, the **post-encounter semi-major axis** is computed. The resulting period is compared to the ones of **possible** resonances.

The **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

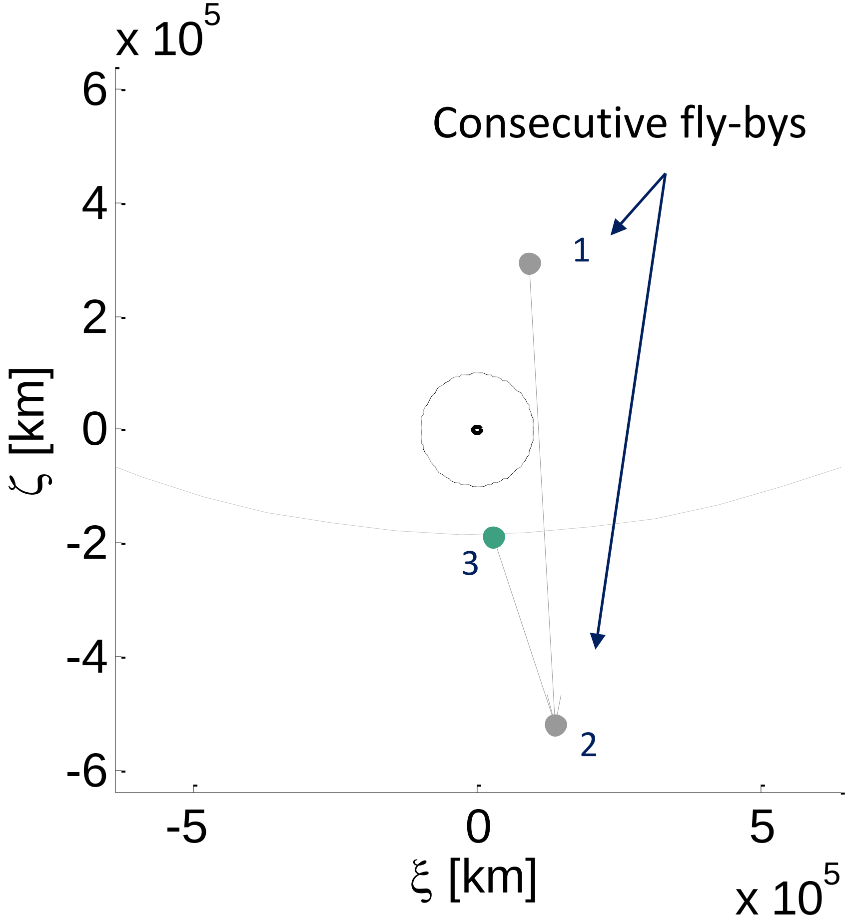


B-plane analysis

Close-encounter sorting

- When **multiple fly-bys** are recorded, for the Monte Carlo analysis only one state should be selected to characterise the trajectory. Two implemented options:
  - first encounter
  - worst encounter.
- Multiple encounters are **sorted** sorting = identify the most critical ones (e.g. impact with Earth > resonance with Mars
  - Distance-driven: worst case is the one with the minimum distance from the Earth
  - 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

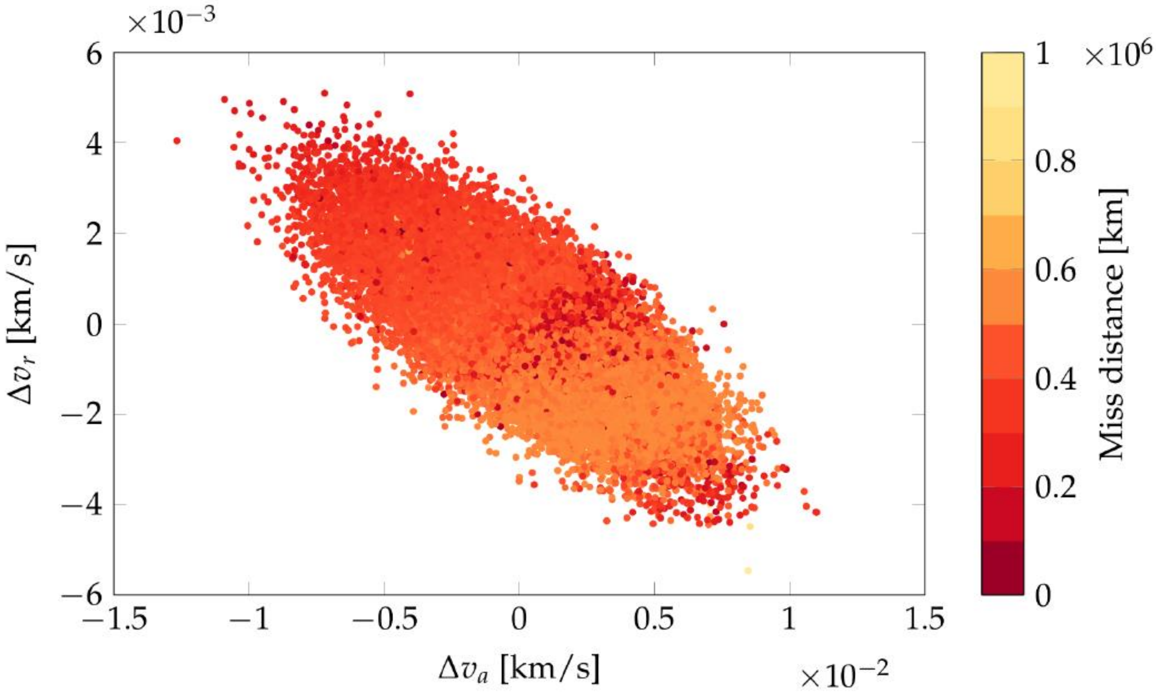


Results

Effect of launcher dispersion: Ariane launcher of BepiColombo

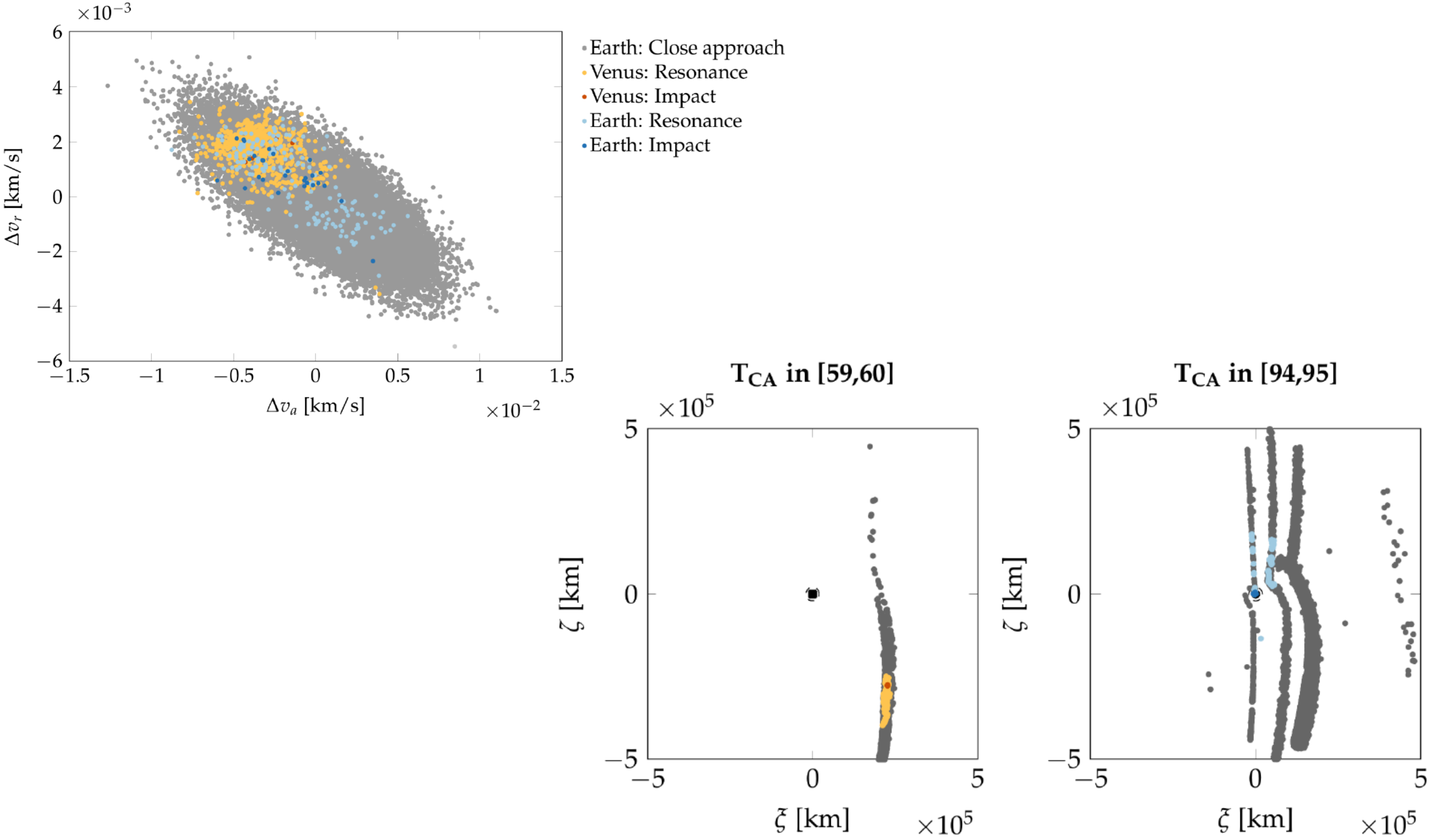
- Uncertainty: **state dispersion (covariance matrix)** and **area-to-mass** ratio distribution (triangular distribution)
- Propagation: time 100 years, RK8(7)

- Number of runs: 54114 (the minimum amount of runs required to prove that the object does not impact with a selected planet, with a confidence level of 99%)
- Number of impacts: **4 Venus, 28 Earth**



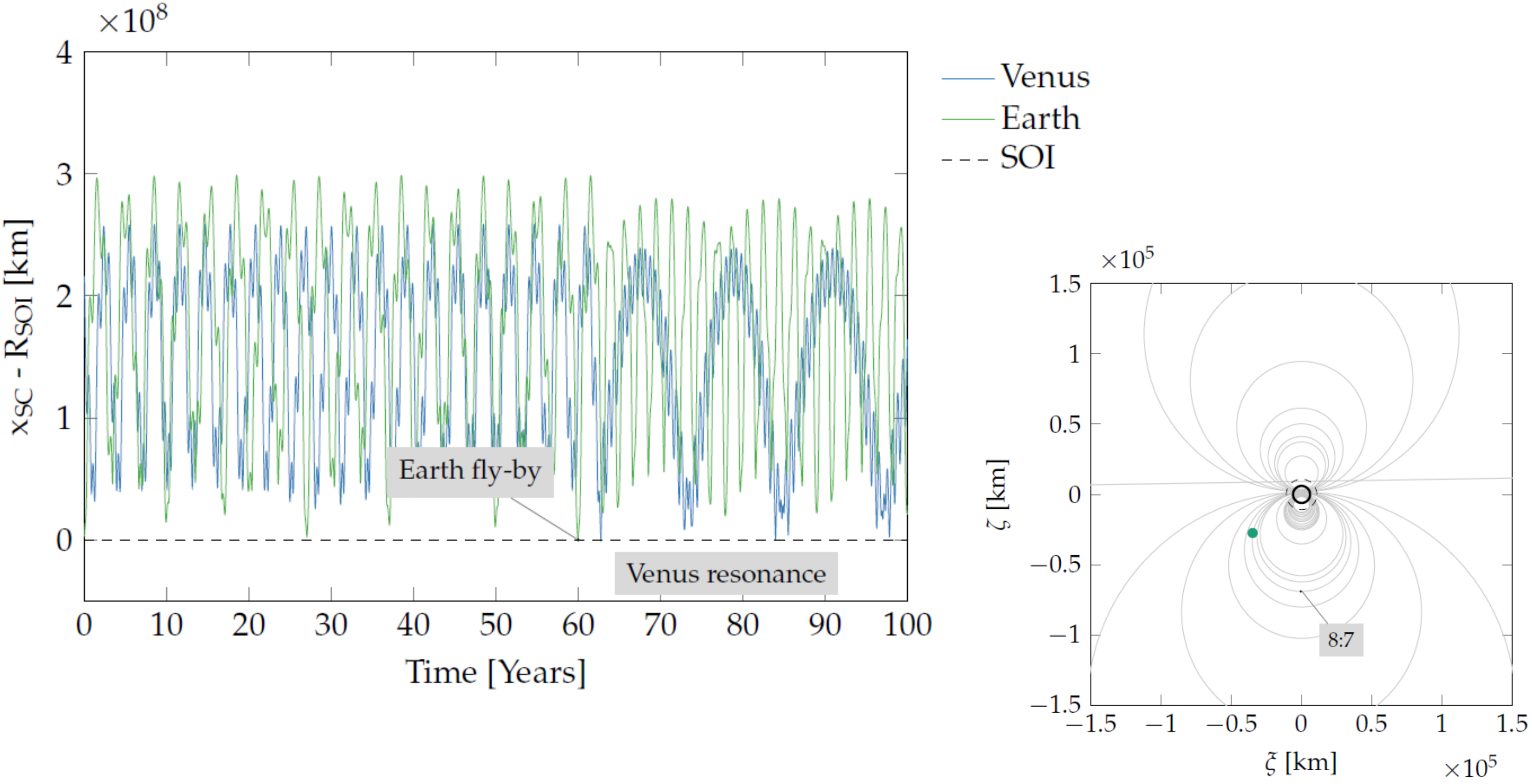
Results

Effect of launcher dispersion: Ariane launcher of BepiColombo



Results

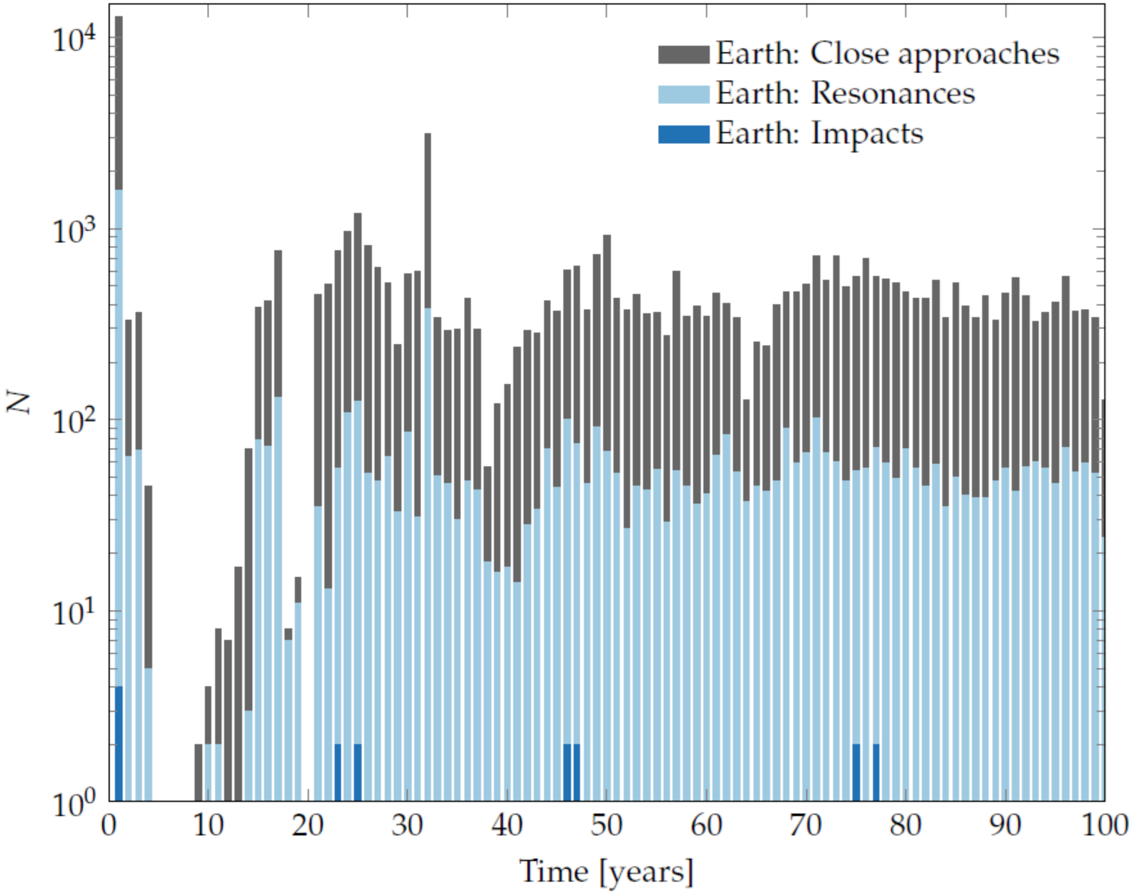
Effect of launcher dispersion: Ariane launcher of BepiColombo



Results

Effect of Failure of propulsion system: BepiColombo

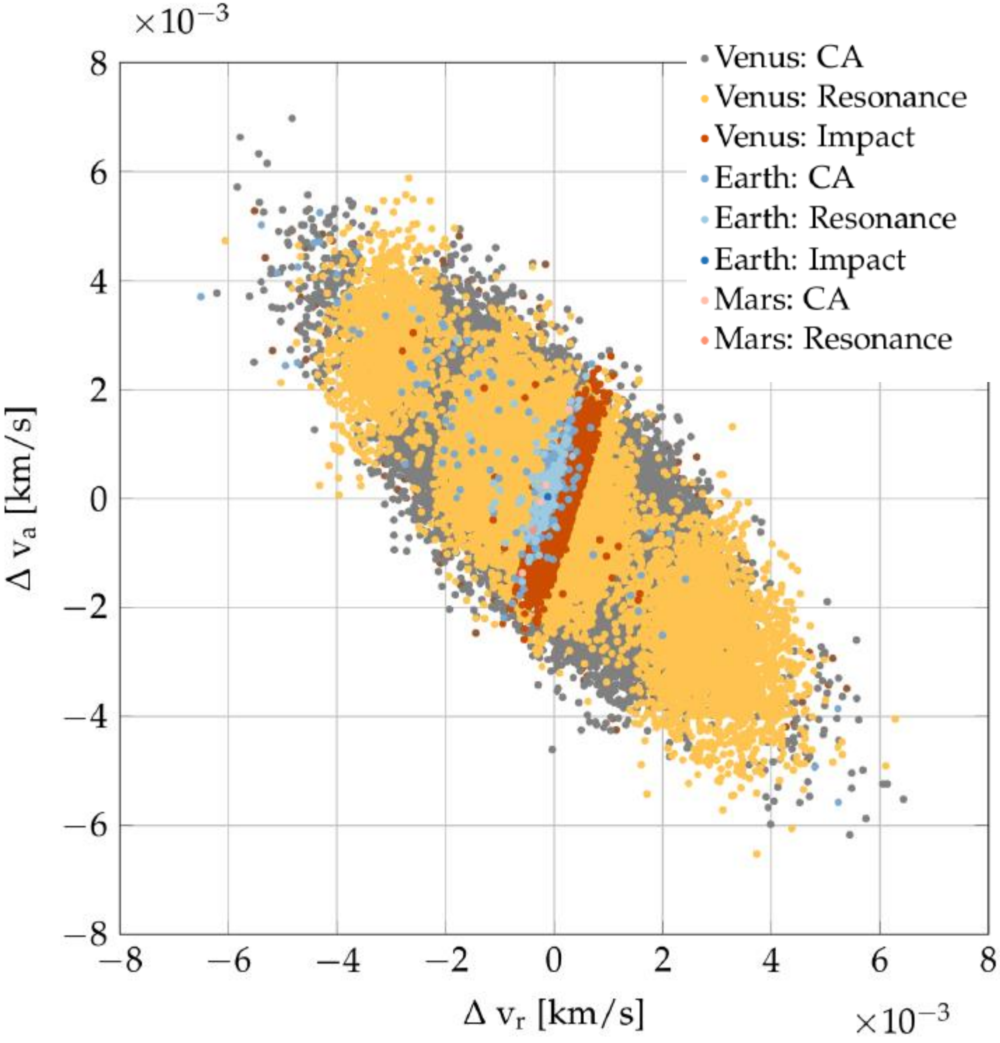
- Uncertainty: **state dispersion** following failure of propulsion system
- Propagation: time 100 years, RK8(7)
- Number of runs: 54114 (the minimum amount of runs required to prove that the object does not impact with Mars of 10^{-4}, with a confidence level of 99%)
- Number of impacts: **28 Earth**



Results

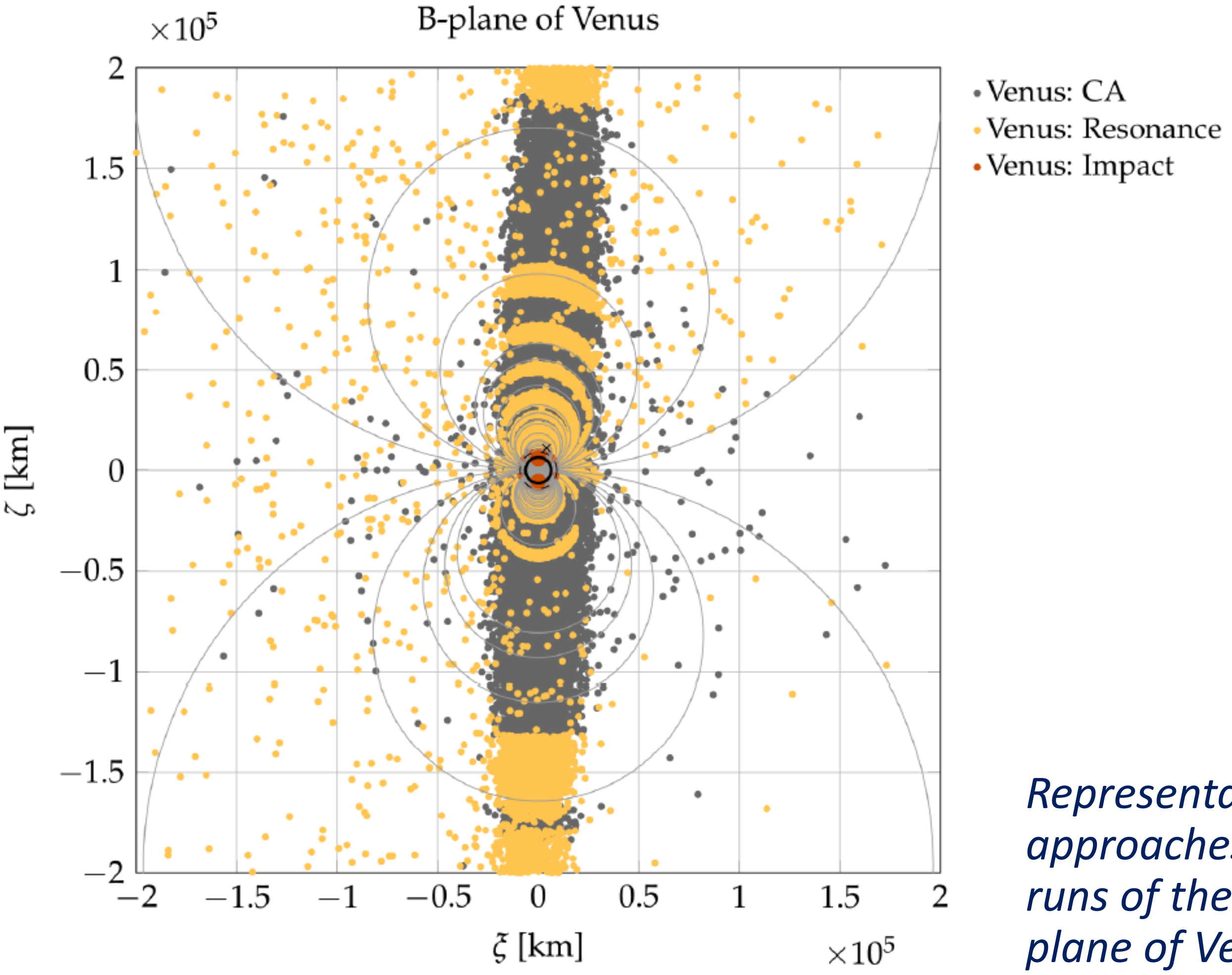
Effect of launcher dispersion: Solo launcher

- Uncertainty: **state dispersion (covariance matrix)**
- Propagation: time 100 years, RK8(7)
- Number of runs: 54114 (the minimum amount of runs required to prove that the object does not impact with a selected planet, with a confidence level of 99%)
- Number of impacts: **4 Venus**, **2348 Earth**



Results

Effect of launcher dispersion: Solo launcher



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

Matteo Romano, Camilla Colombo, Jose Manuel Sánchez Pérez

Insights into planetary protection analysis and tool enhancement

SNAPPSHOT EXTENSION

Integration methods

Symplectic methods

- Planetary protection analysis involves long-term orbital propagations (up to 100 years)
- Numerical methods accumulate errors during the integration
  - This may cause the constants of motion (e.g. energy) to change in time, obtaining a bad estimate of the spacecraft state
- Alternative numerical approaches may be beneficial to the accuracy of the orbital propagation
  - **Symplectic schemes** ensure that the constants of motion are conserved exactly or have a variation bounded in time
  - Additional methods can **“force” the conservation of those quantities**

Integrations methods

Symplectic schemes

Different methods to obtain symplectic schemes

1. RK derived methods, which are not symplectic but they **behave as symplectic** when applied to Hamiltonian dynamics (and with special choice of coefficients)

2. Methods **derived from Hamiltonian formulation** of the dynamics using multiple canonical transformations

3. **Projection methods:** methods which enforce conservation of first integrals (e.g. total energy) without being symplectic

Integrations methods

Projection methods

The conservation of the Hamiltonian or other constants of the motion can be enforced even if the integrator is not symplectic

Projection methods correct the numerical solution obtained with an arbitrary method in order to minimise the error between the chosen integral(s) of motion and the correct value

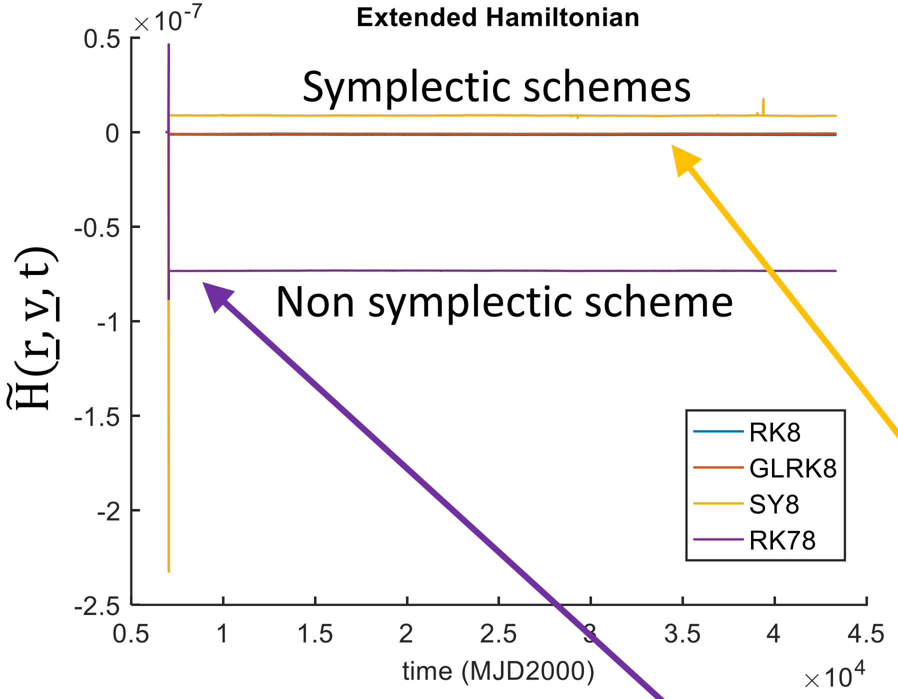
Numerical solution x_{n+1} (arbitrary method) is projected onto the integral manifold to obtain a corrected solution $\bar{x}_{n+1}$ minimising

$$\mathcal{L}(\bar{x}_{n+1}, \lambda) = \frac{1}{2} \|\bar{x}_{n+1} - x_{n+1}\| - g(\bar{x}_{n+1})^T \lambda$$

where $g(x_{n+1})$ can be a combination of different first integrals

Results RNBP

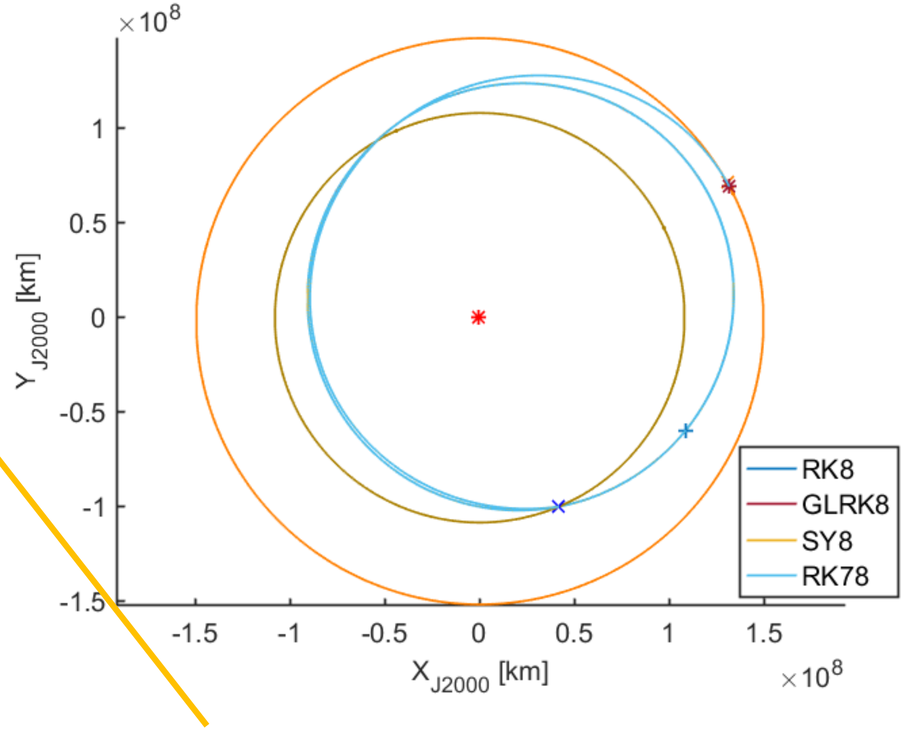
Step regularisation, no projection



Symplectic schemes

Non symplectic scheme

Integration through a Venus fly by



The step regularisation alone (non symplectic integrator) is not sufficient to prevent the error on the Hamiltonian to “jump” during the fly-by

The symplectic methods (all other three) reduce this jump

Physical model update

Fly-by detection through Jacobian

Aim: use projection only in correspondence of a fly by to save computational time → **Fly by detection with Jacobian**

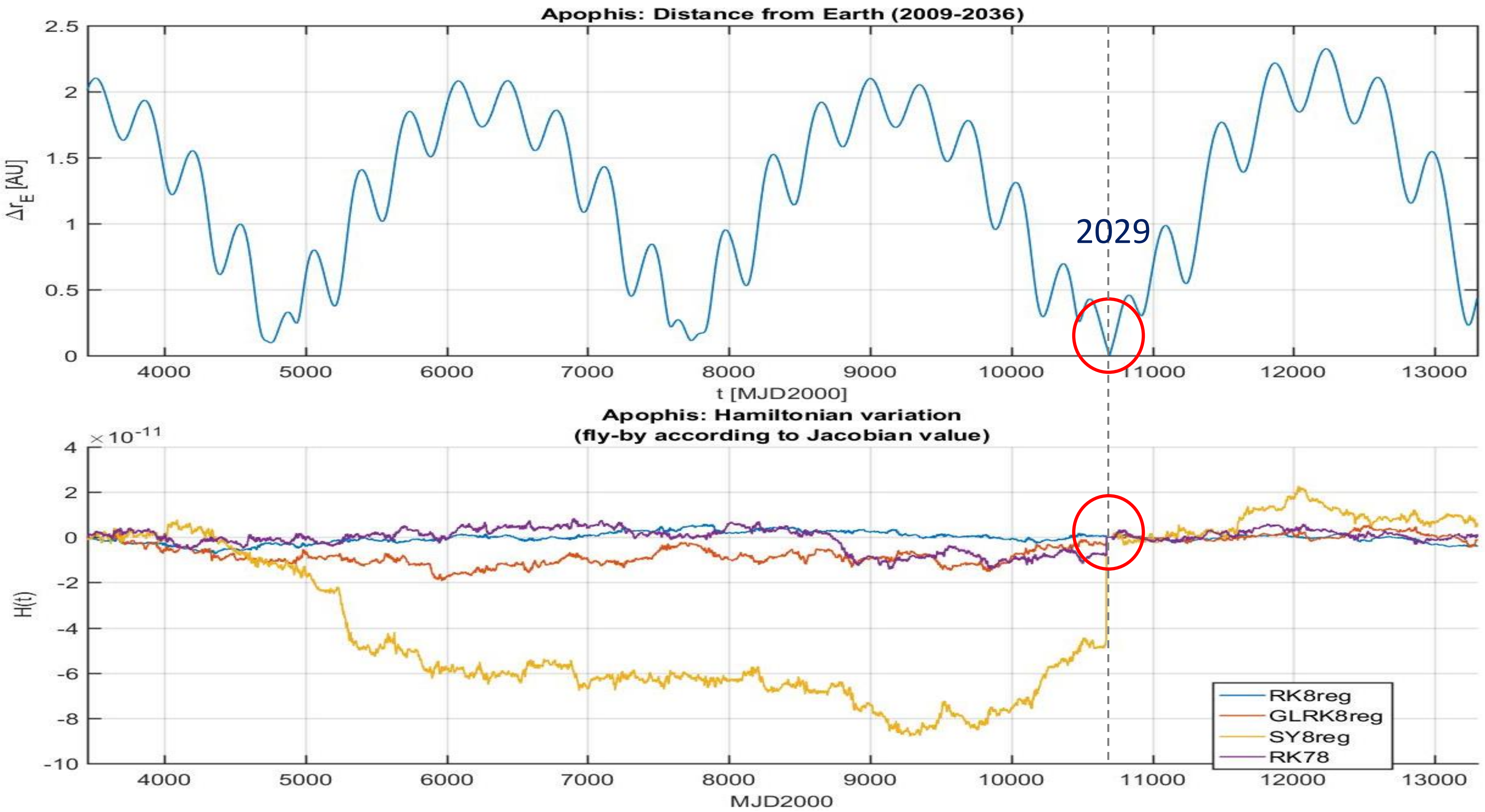
- Eigenvalues of the whole Jacobian: $\lambda^2 = eigs(GI) = eigs(G), \quad \Lambda = \max(\lambda)$
- Body alone contribution: $\lambda_j^2 = eigs\left(G_j\right), \quad \Lambda_\mathrm{j} = \max\left(\lambda_j\right) \qquad \lambda^2 \neq \sum\left(\lambda_j^2\right)$
- Value of planet contribution (grows approaching to the planet) $$\Lambda_\mathrm{j} = \frac{2\mu_j}{\left|\underline{r} - \underline{r}_j\right|^3}$$
- Time variation of planet contribution (grows approaching to the planet) $$\dot{\Lambda}_\mathrm{j} = 2\mu_j \frac{3(\underline{r} - \underline{r}_j)(\underline{v} - \underline{v}_j)}{\left|\underline{r} - \underline{r}_j\right|^5}$$
- Fly-by detection criteria (approximation)

Relative value w.r.t. main attractor: $\Lambda_j/\Lambda_{Sun} \geq Tol\ e.g.\ 10^{-1}$

Relative variation w.r.t. main attractor: $\dot{\Lambda}_\mathrm{j}/\dot{\Lambda}_\mathrm{Sun} \geq Tol\ e.g.\ 10^{-1}$

Physical model update

Fly-by detection through Jacobian



Advanced sampling techniques

Monte Carlo approach

- Verification that planetary protection requirements are satisfied implies a **large number of long-term orbital propagations** with standard Monte Carlo Simulations

- More efficient sampling methods may reduce the amount of propagations and the computational cost
- The **Line Sampling** method probes the impact region of the uncertainty domain by using lines instead of random points
  - This generally improves the estimation of impact probability and reduces the amount of random samples required

Advanced sampling techniques

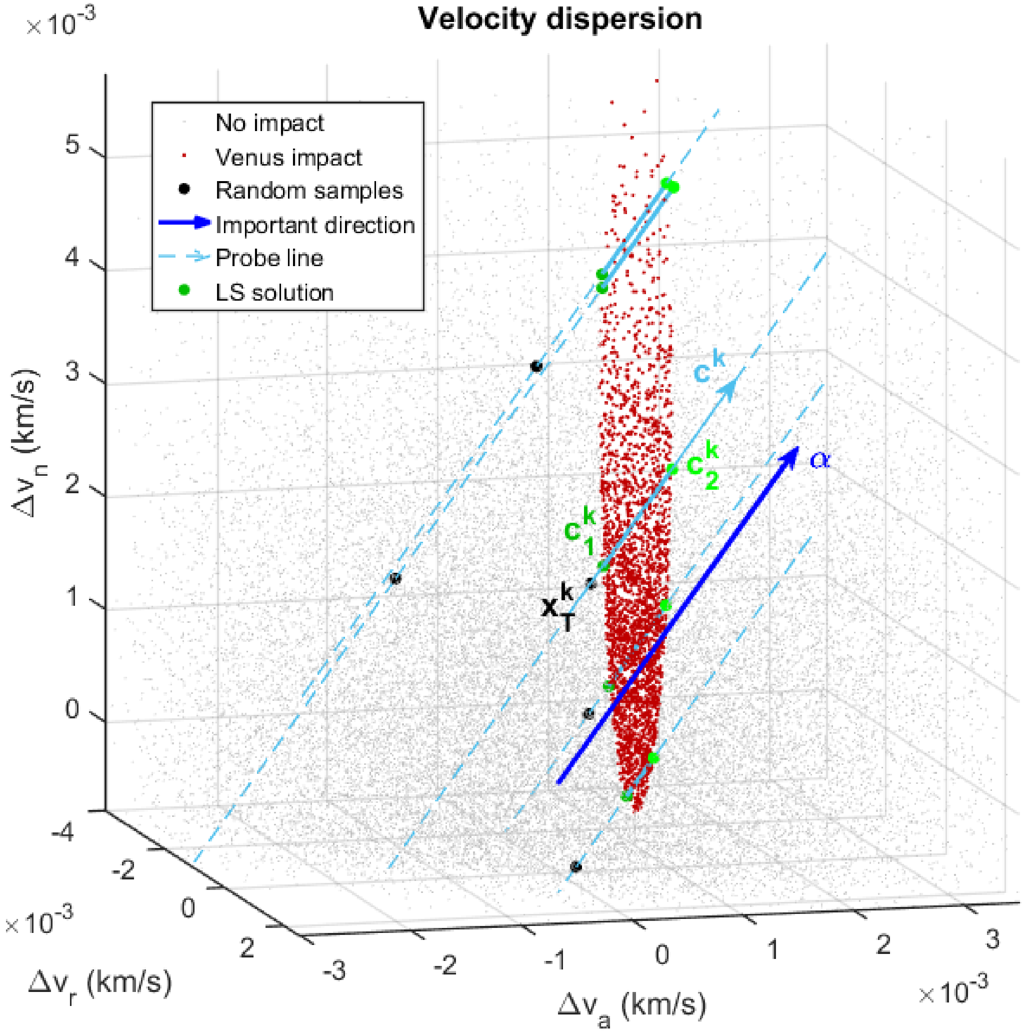
Line Sampling

The method is made of 4 phases

1. **Determination of the “reference direction”**
   Through a Markov Chain a direction pointing toward the impact region of the domain is found
2. **Mapping onto the standard normal space**
   Each sample is mapped from the physical coordinates to normalised ones, in order to associate a normal distribution to each line
3. **Line Sampling**
   For each sample, a line following the important direction is probed to identify the limits of the impact region
4. **Estimation of impact probability**
   Probability is estimated as the average of integrals of unit normal distribution obtained along each line

Advanced sampling techniques

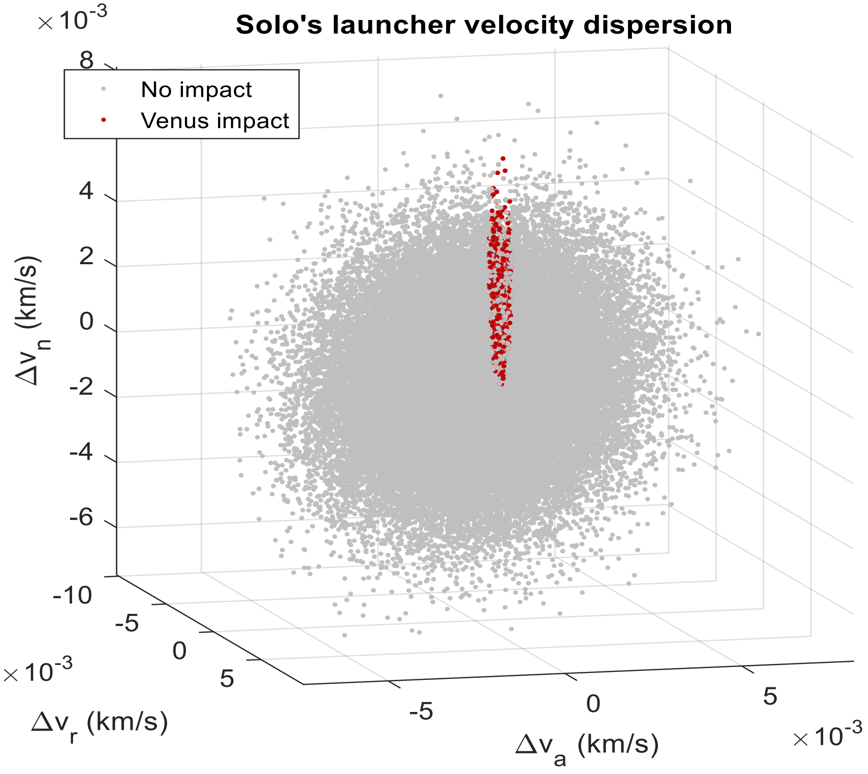
Line sampling



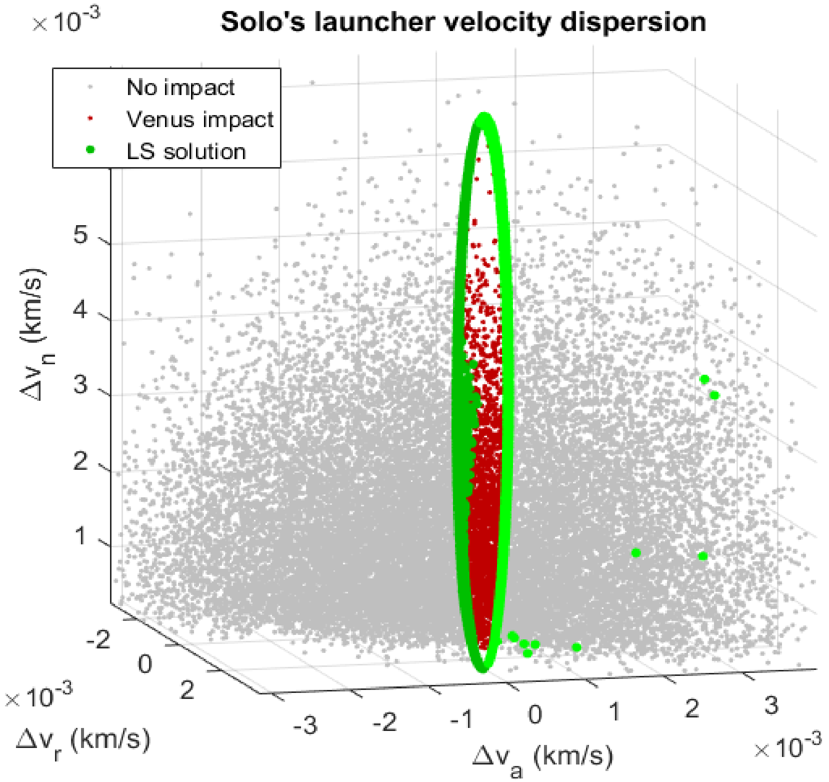
Example:
visualization of probe lines
crossing a generic impact region

Advanced sampling techniques

Results



Solution with **standard MCS**



Boundaries of impact region computed with **LS**

Advanced sampling techniques

Results

- Results from a **preliminary application** of LS method to the test case

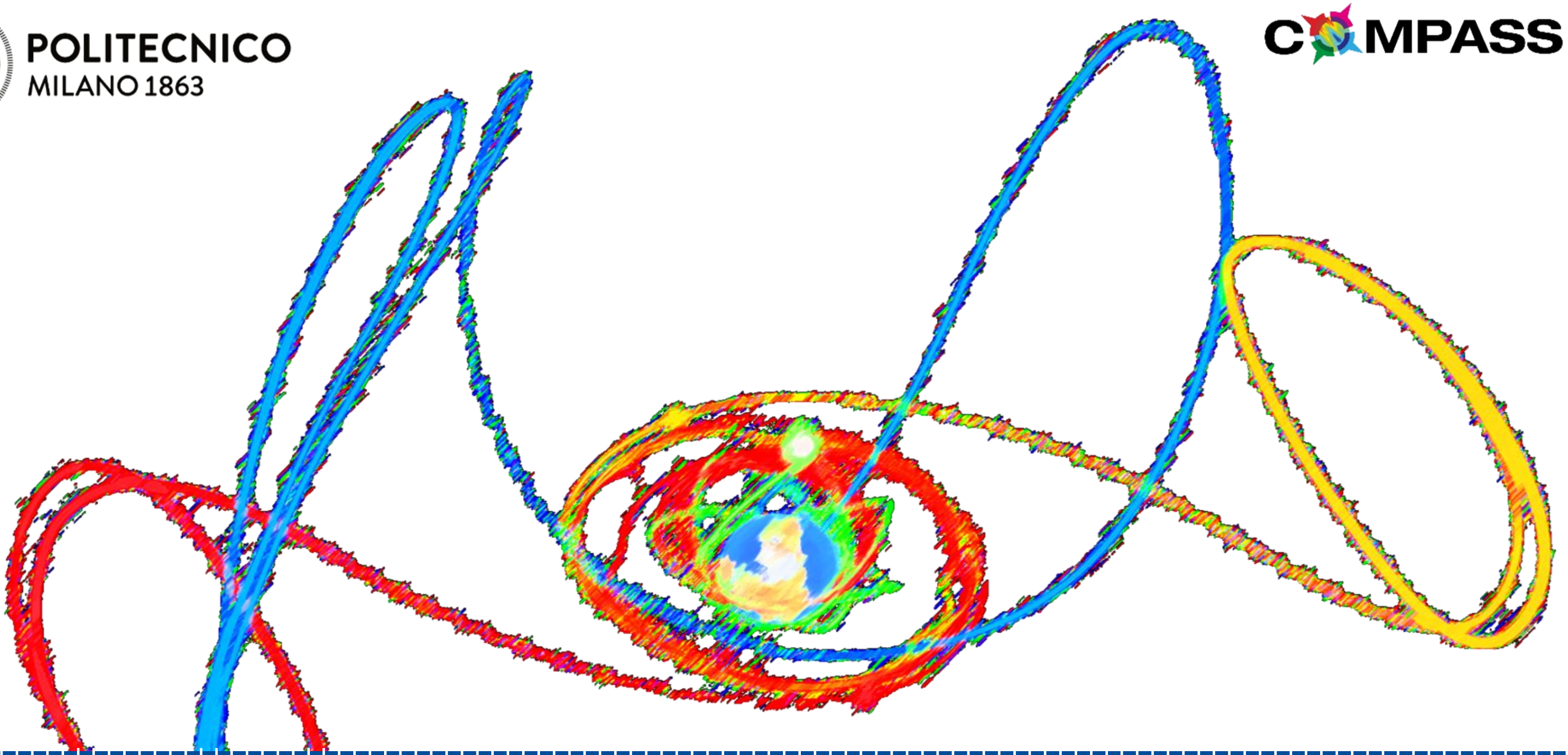
	$\widehat{\mathbf{P}}(\mathbf{F})$	$\widehat{\boldsymbol{\sigma}}$	$\mathbf{N_T}$	$\mathbf{N_{sims}}$
MCS	$5.20\cdot10^{-2}$	$9.93\cdot10^{-4}$	50000	50000
LS	$5.26\cdot10^{-2}$	$4.96\cdot10^{-4}$	50000	250133

- Impact probability is estimated with a **good level of approximation** even with much lower amount of samples (because it is computed analytically and continuously on each interval)
  - A choice of an alternative method to estimate the limits of the impact region may improve efficiency of the LS

Conclusions

Current and future work

- Propagation
  - Symplectic integration techniques and projection methods
  - Regularisation and fly-by detection through Jacobian
  - Analytical and semi-analytical techniques
- Dynamics
  - Relativity
  - Moon system for JUICE mission
- Fly by characterisation
  - B-plane
  - Representation of tree of solutions
- Simulation
  - Parallel programming
  - Machine learning



Planetary protection with SNAPPshot

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CCT ORB Seminar: Deep Space Missions:
End of Life and Planetary Protection