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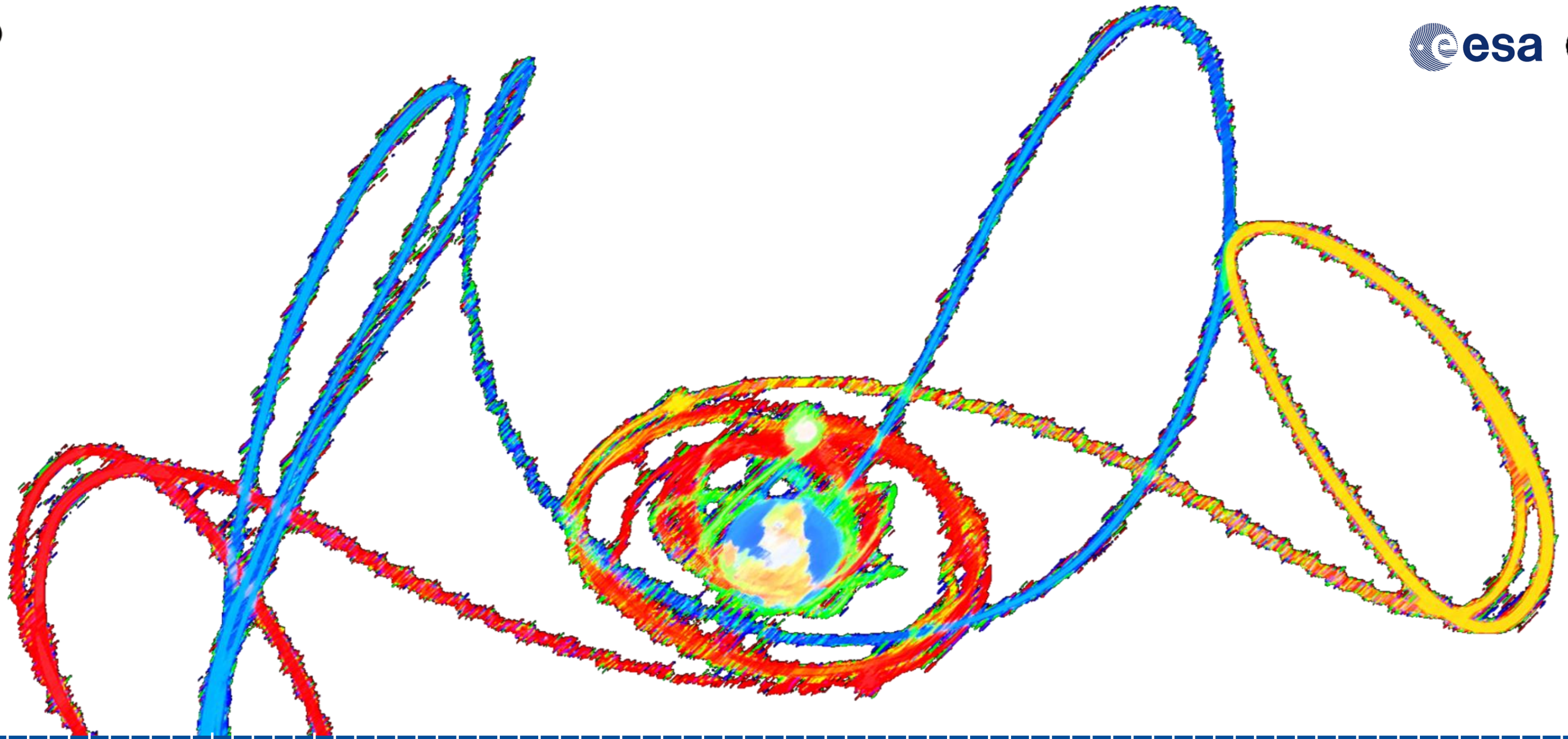

KePASSA 2019

Line Sampling procedure for extensive planetary protection analysis

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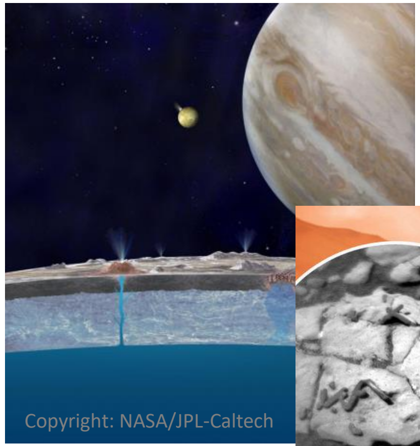
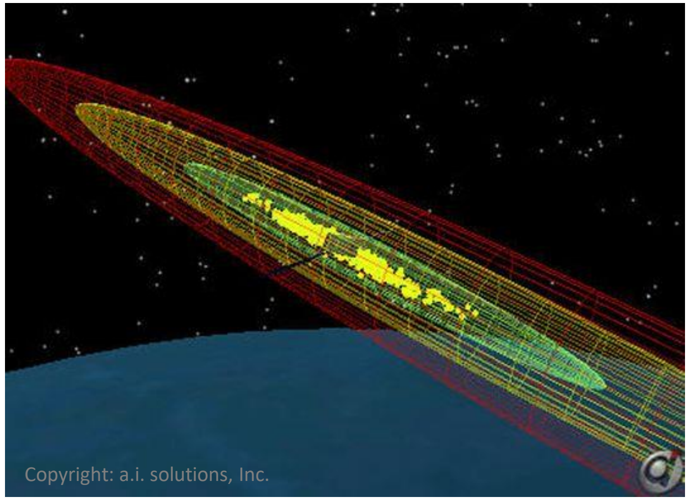
Planetary protection

Motivations

- Interplanetary missions must satisfy **planetary protection requirements**[1]
  - Impacts from spacecraft and mission-related debris increase the **risk of biological contamination**
  - Impact probability must be limited for sensible scientific targets (Mars, Europa, Enceladus)
  - The risk of backwards contamination to Earth must also be limited



- Sources of **uncertainty** must be considered during design phase
  - Uncertainty over the initial state at the launcher injection
  - Uncertainty over spacecraft design parameters (e.g. area/mass ratio)
  - Random errors in orbital manoeuvres
  - Random failures of spacecraft propulsion system



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

Outline

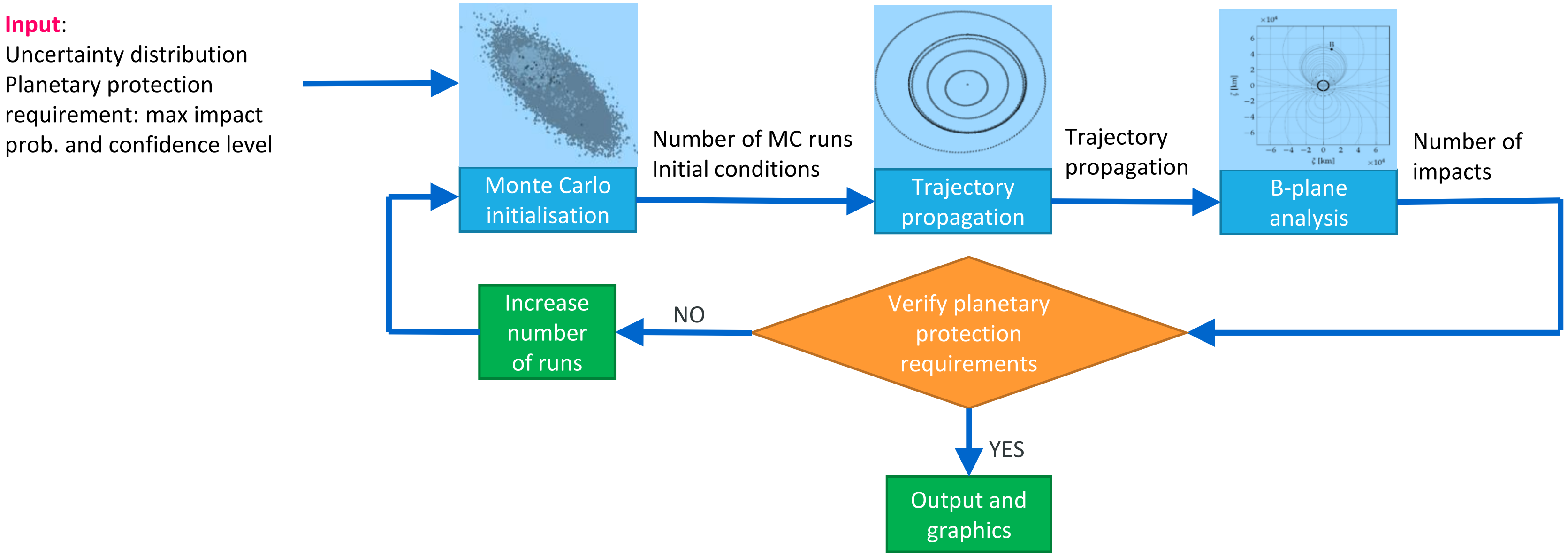
- Introduction
  - Planetary protection
  - Current state and proposed approach
- New developments
  - Line Sampling
  - Additional techniques
  - Complete algorithm
- Planetary protection analysis
  - Test cases definition
  - Results
- Conclusions

Planetary protection

SNAPPshot (Suite for the Numerical Analysis of Planetary Protection)

SNAPPshot[2,3], developed at the University of Southampton under a study for the European Space Agency and now continued at Politecnico di Milano

- **Monte Carlo approach** for sampling and propagating the initial uncertainty
- **High-order Runge-Kutta** integration methods, with time step adaptation
- Analysis of close approaches and orbital resonances in the **B-plane**



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[2] Letizia F., Colombo C., Van den Eynde J., Armellin R., Jehn R., *SNAPPSHOT: Suite for the numerical analysis of planetary protection*, ICATT 2016
[3] Colombo C., Letizia F., Van den Eynde J., *SNAPPSHOT: ESA planetary protection compliance verification software, Final report*, ESA contract, Jan 2016

Planetary protection

Proposed approach

Main goal: **improve the accuracy and the efficiency** of the planetary protection analysis

- Conventional verification using Monte Carlo (MC) method is computational expensive
  - Planetary protection requirements also include high confidence levels of the probability estimates
  - Generally probabilities to be verified are small
- Line Sampling method to sample the initial uncertainty in a more **efficient** way
  - Reduce number of required samples with respect to standard MC
  - **Identifies boundaries** of impact regions inside initial uncertainty dispersion
  - Efficient for analysis of a single event
- Algorithm extended to analyse more events
  - Recognition of close approach windows
  - Repeated LS applications

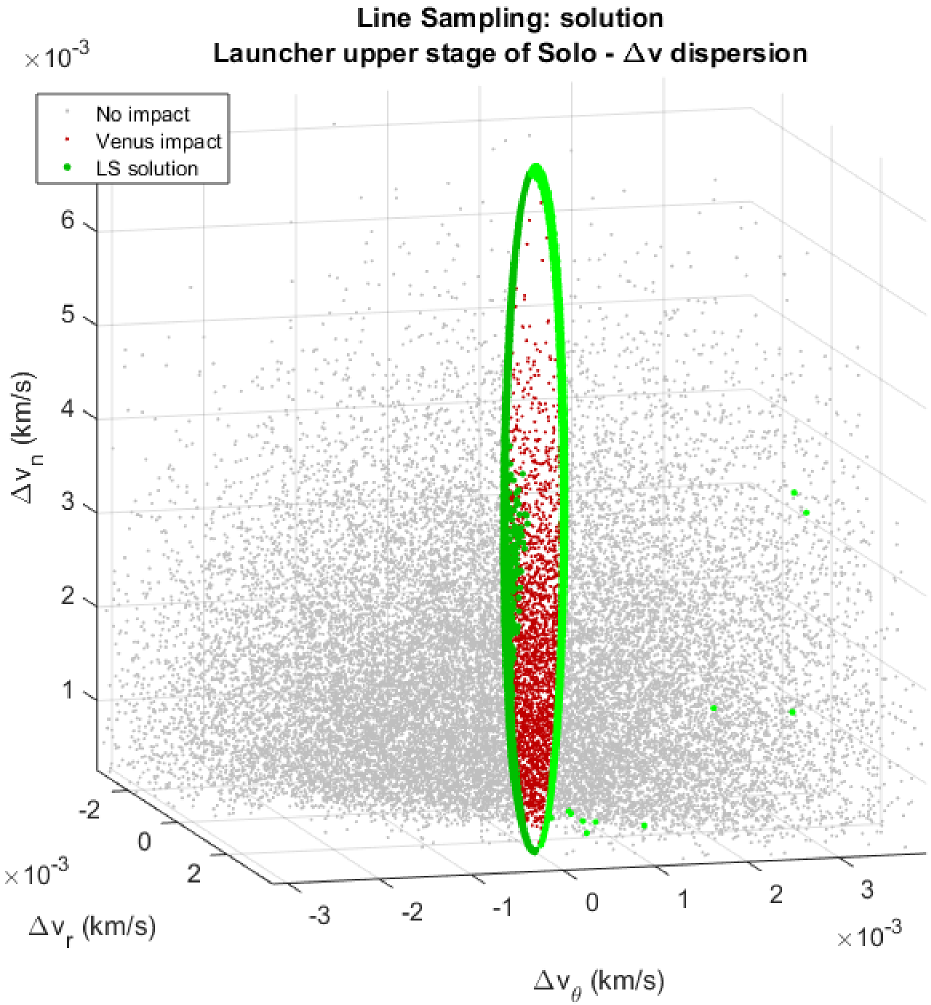
Result: a method which can be directly used in **mission design**, providing **additional information** about impact regions

Line Sampling

Working principle

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

- The lines are used to **identify the boundaries of the impact region** inside the coordinate space
  - They follow a reference direction pointing toward the impact region
  - This can be done **independently from the initial uncertainty** and the probability estimation
- The estimation of impact probability is reduced to a number of 1D integrals along each line
  - The problem is normalised to a standard normal coordinate space
  - **Analytical evaluation of integrals** increases the accuracy of the probability estimation[4]



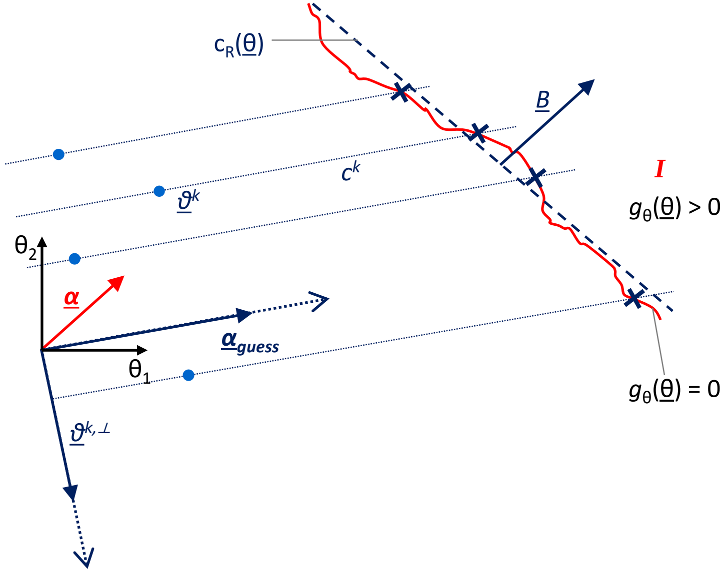
[4] Zio E., *The Monte Carlo Simulation Method for System Reliability and Risk Analysis, 1st edn., Springer Series in Reliability Engineering*, Springer-Verlag London (2013)

Extended algorithm

Correction of sampling direction

- Performance of LS depends on the sampling direction
  - Information on the impact region is available only after some pre-processing
  - Accuracy is highest when the sampling direction is (almost) orthogonal to the border of the impact region
  - Hypothesis: impact region with **nearly rectilinear boundary**

- Algorithm
  1. A preliminary sampling direction $\boldsymbol{\alpha}_{guess}$ is found from the Markov Chain
  2. A short Line Sampling is performed using a few initial samples
  3. The reference axes are rotated to an orthonormal bases aligned with $\boldsymbol{\alpha}_{guess}$
  4. Impact region (c^k values) is approximated with a hyperplane using multilinear regression as
     $$c_R = b_1 + b_2\theta_2^{k,\perp} + b_3\theta_3^{k,\perp} + b_4\theta_4^{k,\perp} + \cdots = [1\ \boldsymbol{\theta}^{k,\perp}] \cdot B$$
  5. The vector ***B*** orthogonal to hyperplane is set as new sampling direction
  6. The main sampling is performed following the new direction



Extended algorithm

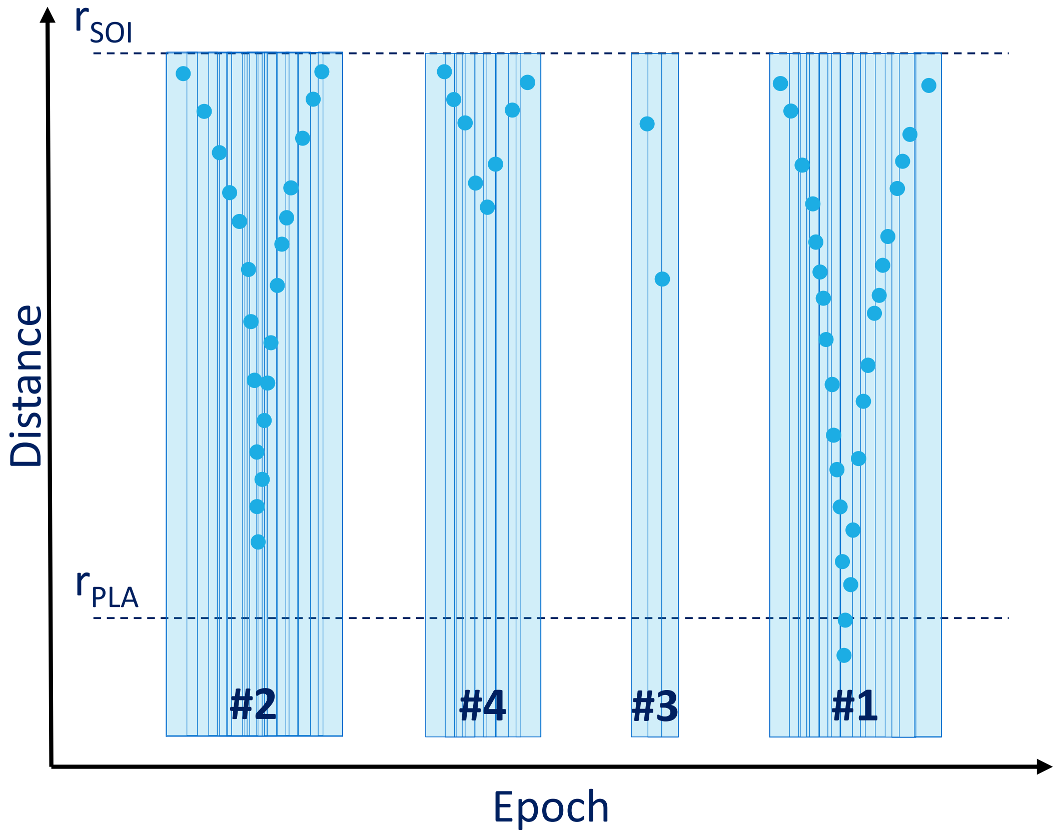
Close approach windows identification

Problem: identify **groups of close approaches** (CA windows) distributed in time

- Most of CAs appear to occur in groups clustered around the same epochs
- These groups are good candidates to look for impact regions with Markov Chains
- Identification method should be independent from body

Implemented solution: use information from recorded CAs

1. Each CA is recorded with associated SOI entry and exit epochs
2. Overlapping CA intervals are merged to identify larger intervals
3. CA windows are sorted according to the minimum distance from a planet to give priority to the most narrow CAs



Extended algorithm

Multi-event analysis

- Problem:
  identify different impact regions at different positions in the distribution and compute the overall impact probability
- Implemented approach:
  use information about close approaches obtained during **preliminary analysis**
  1. Preliminary MC sampling
     - Storing of close approach (CA) info (time, body, distance)
  2. Identification of close approach windows based on epoch and body, sorted by minimum distance
  3. Markov Chain for the selected close approach window
     - If impacts are detected, determination of sampling direction
  4. Line Sampling
     - Optional: correction of sampling direction
  5. Go back to 2. until all windows have been analysed
  6. Compute total probability

- Pros: **ideally complete sampling** of the uncertainty over the whole time interval
- Cons: **computationally heavy**, not memory efficient

Extended algorithm

Multi-event analysis

Test cases

Definition

SOLO (launcher upper stage)

- Trajectory of launcher upper stage following injection into transfer orbit and separation
- Initial state from old launch option in October 2018
- Uncertainty expressed as covariance matrix over initial position and velocity

Mars Sample Return

- Return trajectory after Earth-avoidance manoeuvre
- Uncertainty expressed as covariance matrix over initial position and velocity

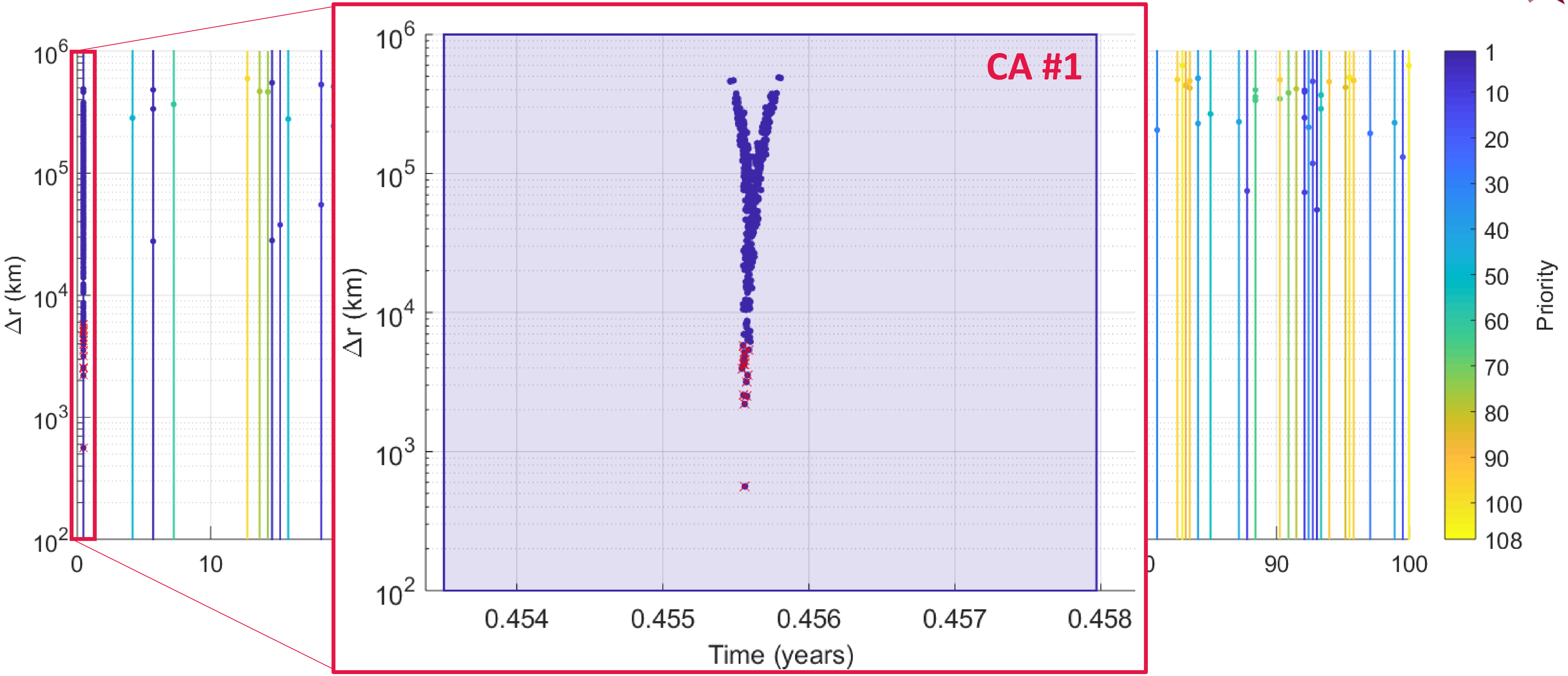
Test cases

The results are analysed and compared in terms of

- Preliminary analysis
  - Number of initial samples
  - Number of recorded CAs
  - Number of CA windows
  - Number of impact regions found
- Line sampling phases vs. Monte Carlo
  - Number of sampling lines per LS phase N_{lines}
    or
    Number of initial samples for MC $N_{samples}$
  - Number of propagations per LS phase N_{prop}
  - Probability estimate and variance $\hat{P}(I), \hat{\sigma}$
  - Total number of propagations
  - Total CPU time
  - Comparison with MC

Results

Solo, launcher upper stage

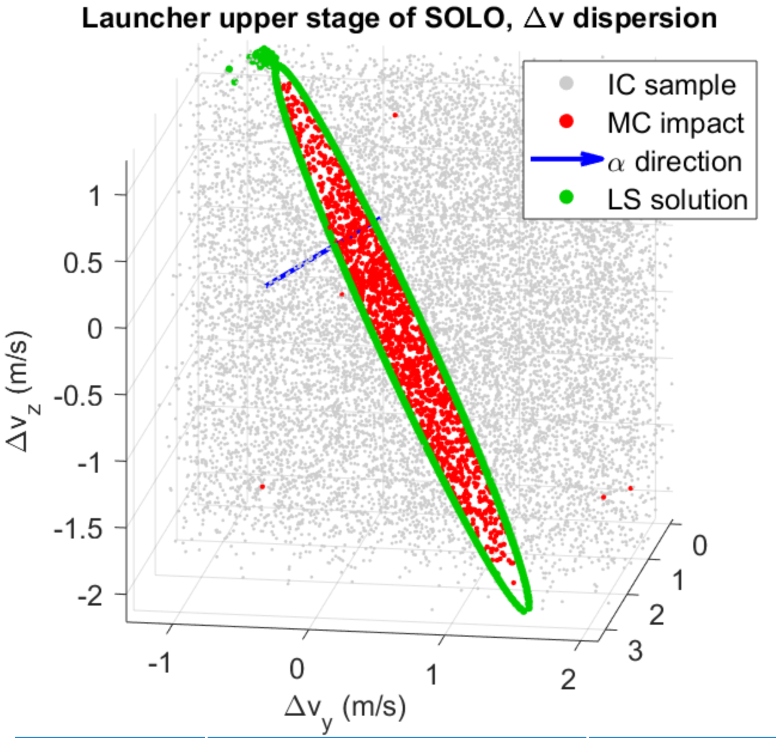


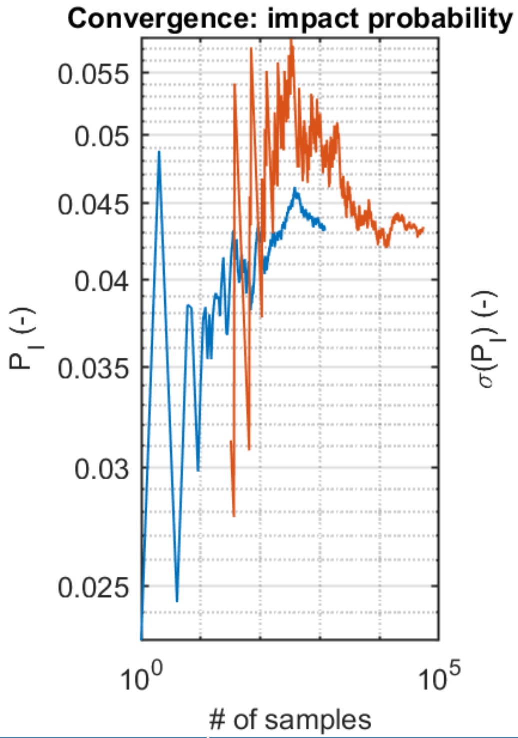
Results

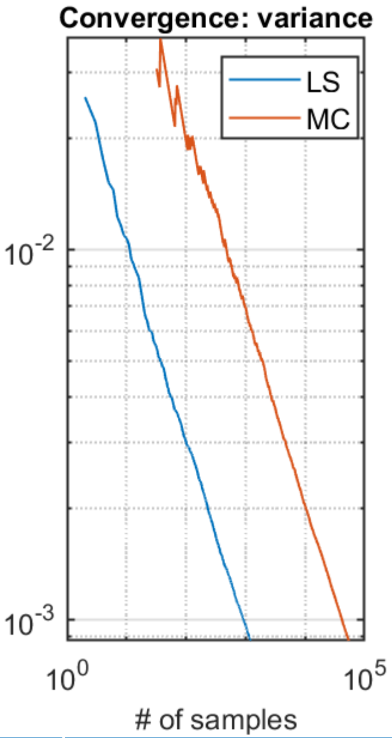
Solo, launcher upper stage

Line Sampling

- Markov chains: 108 (max length: 200 samples)
- Impact regions: 1
- Tot. propagations: 32490
- Tot. CPU time: 0.79 h





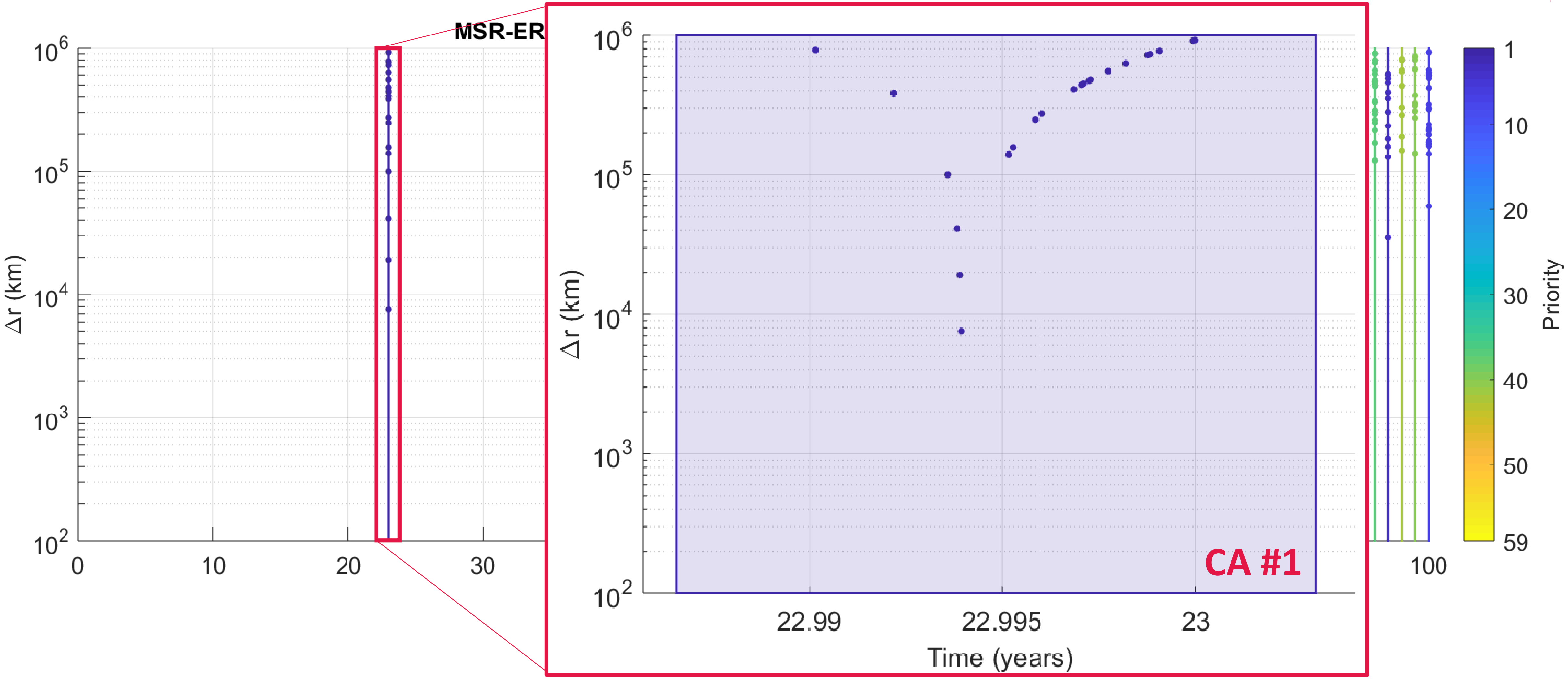


	N_{lines}	$N_{samples}$	N_{prop}	$\hat{P}(I)$	$\hat{\sigma}$
LS	1212		9896*	4.31e-2	8.74e-4
MC		54114	54114	4.34e-2	8.76e-4

* preliminary MC + Markov chain + LS

Results

Mars Sample Return, post-Earth encounter trajectory

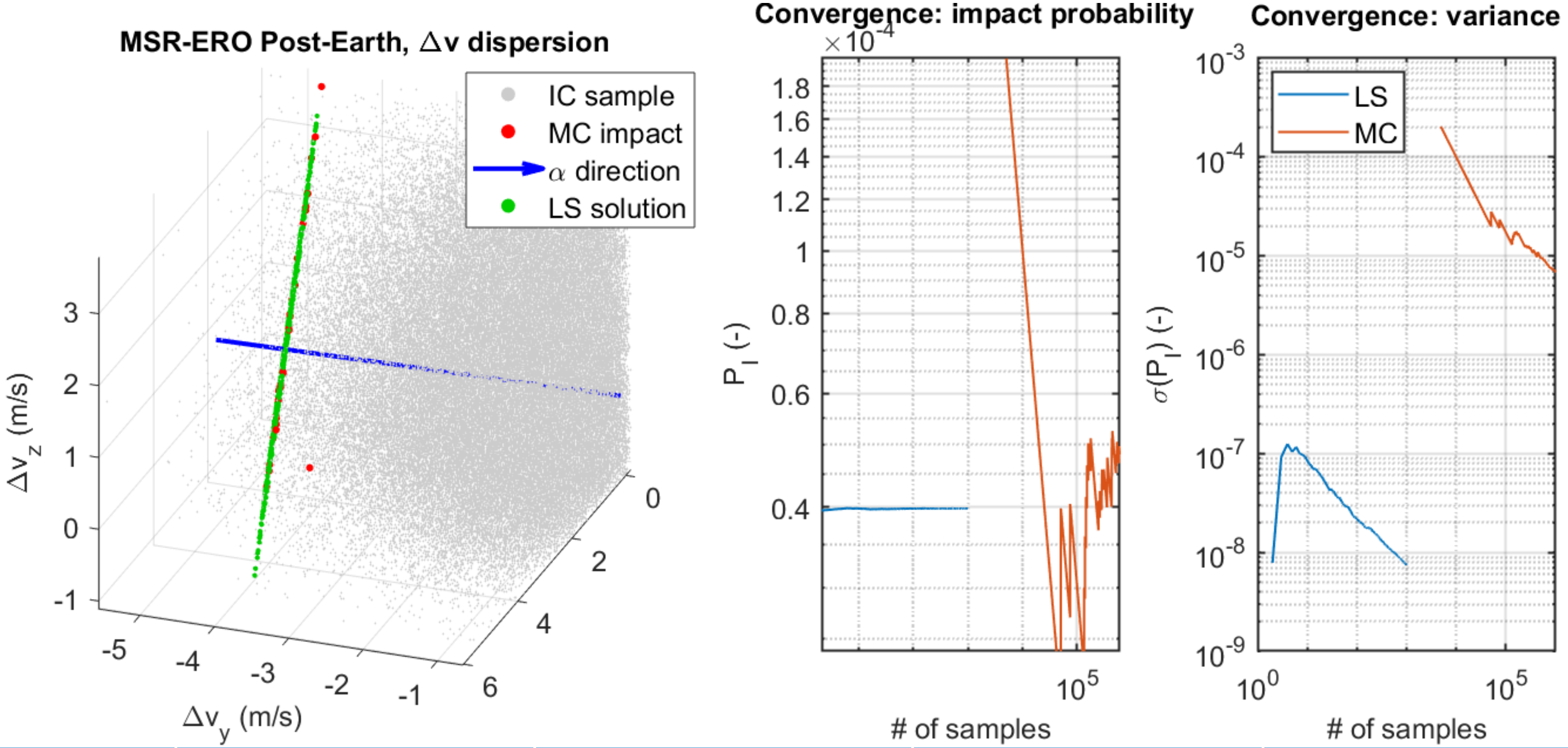


Results

Mars Sample Return, post-Earth encounter trajectory

Line Sampling

- Markov chains: 59
  (max length: 1000 samples)
- Impact regions: 1
- Tot. propagations: 42897
- Tot. CPU time: 4.44 h



	N_{lines} $N_{samples}$	N_{prop}	$\hat{P}(I)$	$\hat{\sigma}$
LS	707	5943*	3.99e-5	1.62e-7
MC	1e6	1e6	4.70e-5**	6.85e-4

* preliminary MC + Markov chain + LS, ** all impact regions

Conclusions

Goals reached

- Identification of close approach windows
  - Independent from celestial body
  - Requires preliminary data
- Line Sampling applications in interesting regions
  - More efficient/accurate than standard MC
- Tool to obtain overall overview of the uncertainty distribution in interesting regions

Open points

- Computational efficiency and accuracy, depending on
  - confidence level for LS and preliminary MC
  - max length of Markov Chains
  - iterations and tolerances
- Computational time and memory management
  - Possible improvement: parallelisation
- Identification of CA windows depending on number of preliminary MC runs
- Generalisation of the algorithm

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