Challenges associated with the re-entry from Sun-Earth Lagrange Points

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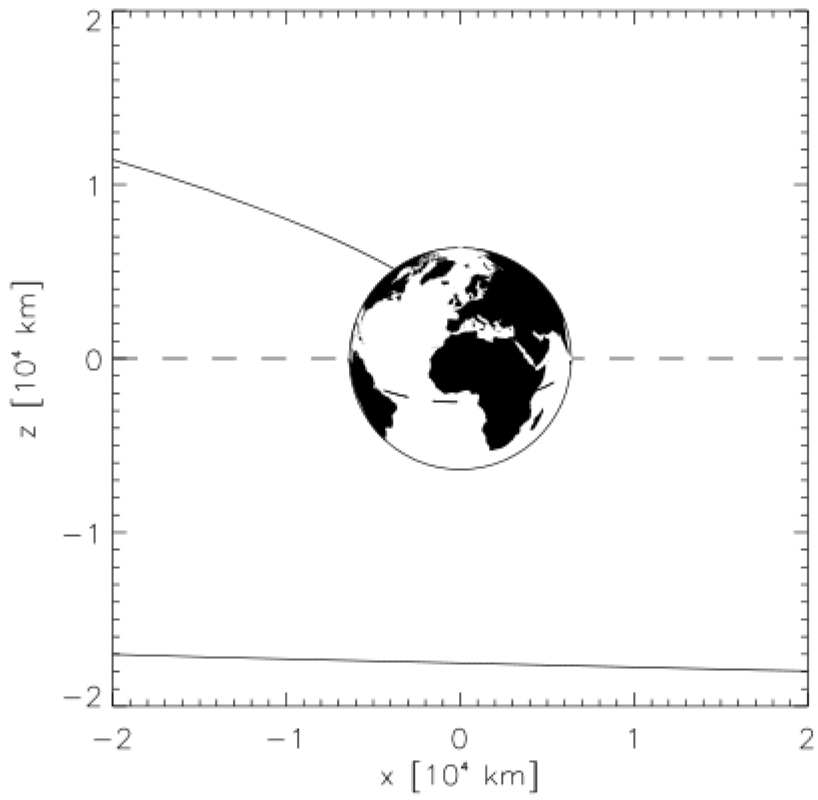
Re-entries from libration points orbits

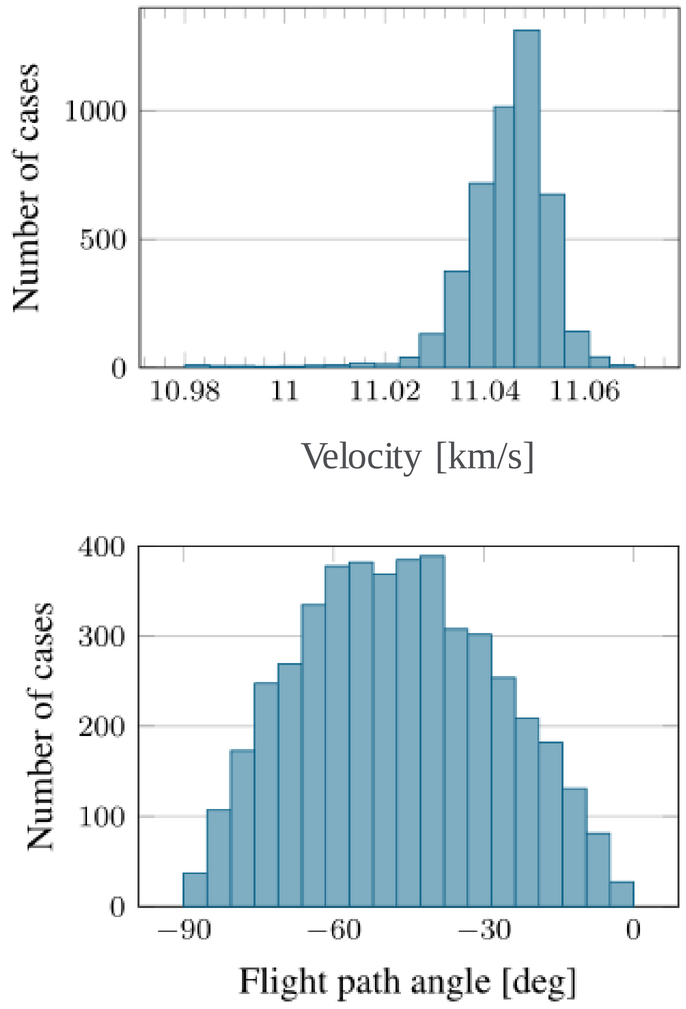
Re-entry trajectories from libration point orbits (LPO) can impact the Earth at **any latitude**

High **entry velocity**: beneficial in terms of thermal loads

…but **steep re-entry** can occur: risk of large surviving mass



Landgraf & Jehn, 2001 ▲
Representation of a re-entry trajectory



Letizia et al, 2017 ▶
Distribution of re-entry parameters from an orbit around L_2

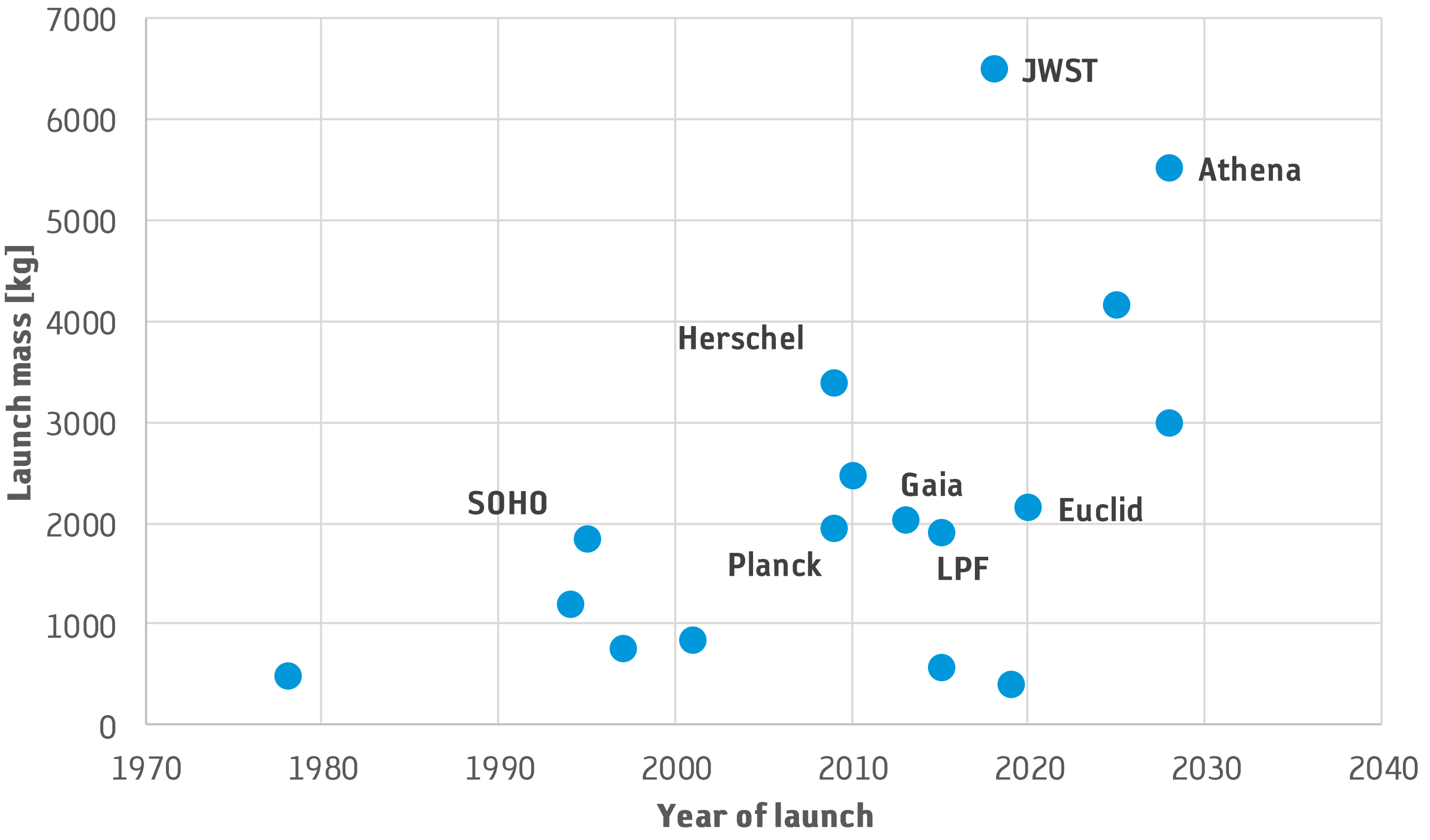
Libration point orbits & space debris mitigation

Currently, **no protected regions** but space debris **mitigation guidelines** still apply: casualty risk on ground

No standard procedure defined for libration points orbits

ESA largely involved in LPO missions: natural player in **establishing a methodology**

Distribution of past, current, and planned missions to the Sun-Earth libration points



Libration point orbits & space debris mitigation

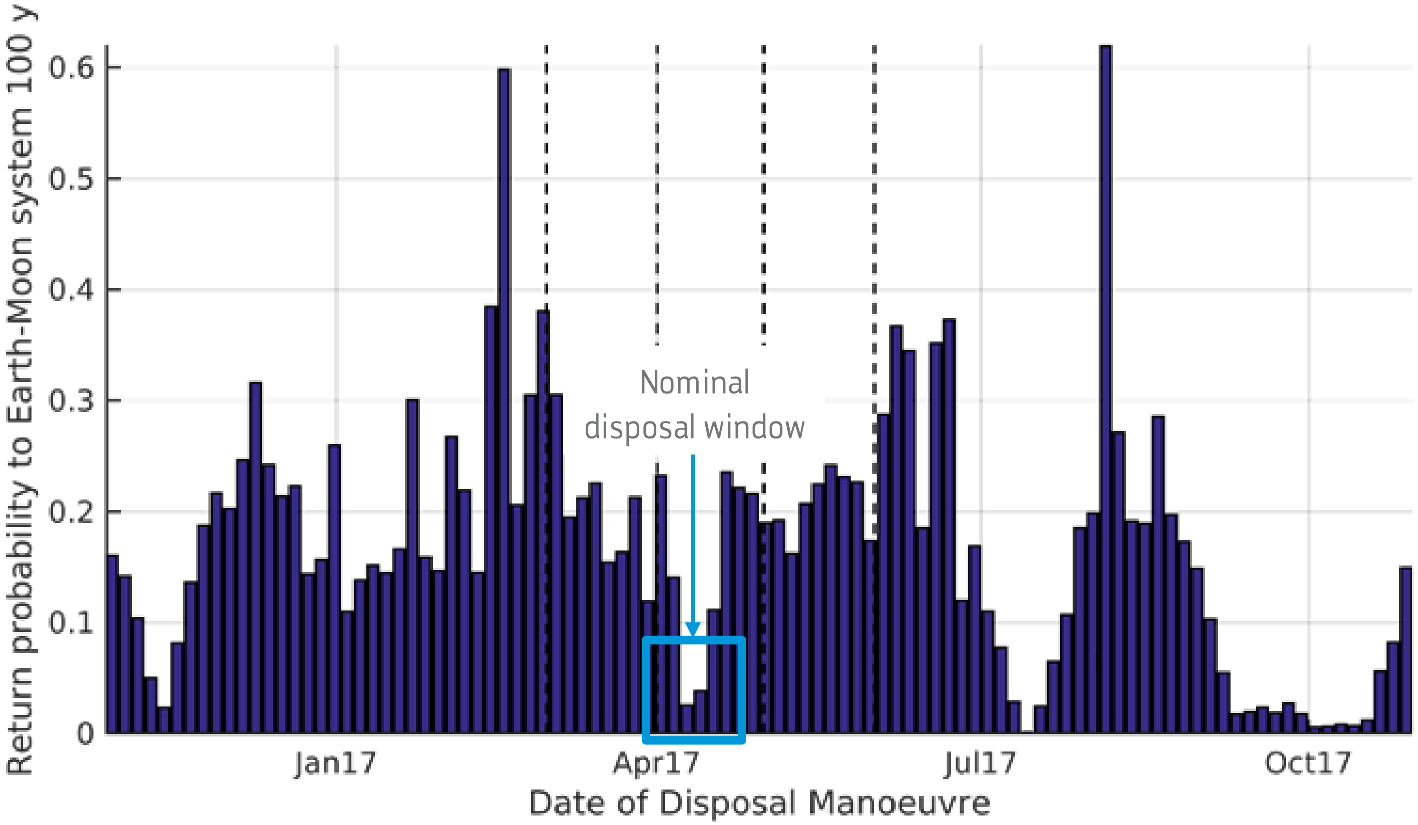
$$E_{f,i} = \sum_{i}\sum_{n}\sum_{m}(P_i)_{n,m}(\rho_p)_{n,m}(A_C)_{n,m}(\eta_f)_{n,m}$$

Example: **LISA Pathfinder**

Best-effort disposal manoeuvre to minimise return probability

Next step: **systematic analysis** of return probability and on-ground casualty risk

Return probability as a function of the epoch of the disposal manoeuvre for LISA Pathfinder (Renk & Lemmens, 2017)



Modelling challenges

- Uncertainty on **spacecraft parameters** (e.g. reflectivity coefficient, c_R)
- Different **orbit typologies** (e.g. Lissajous, Halo), different amplitudes, and chaotic dynamics
- **Radiative heat transfer** may play a significant role
- Fixed **breakup altitudes**, used in object-oriented tools, derived for re-entries with low flight path angles

Previous work

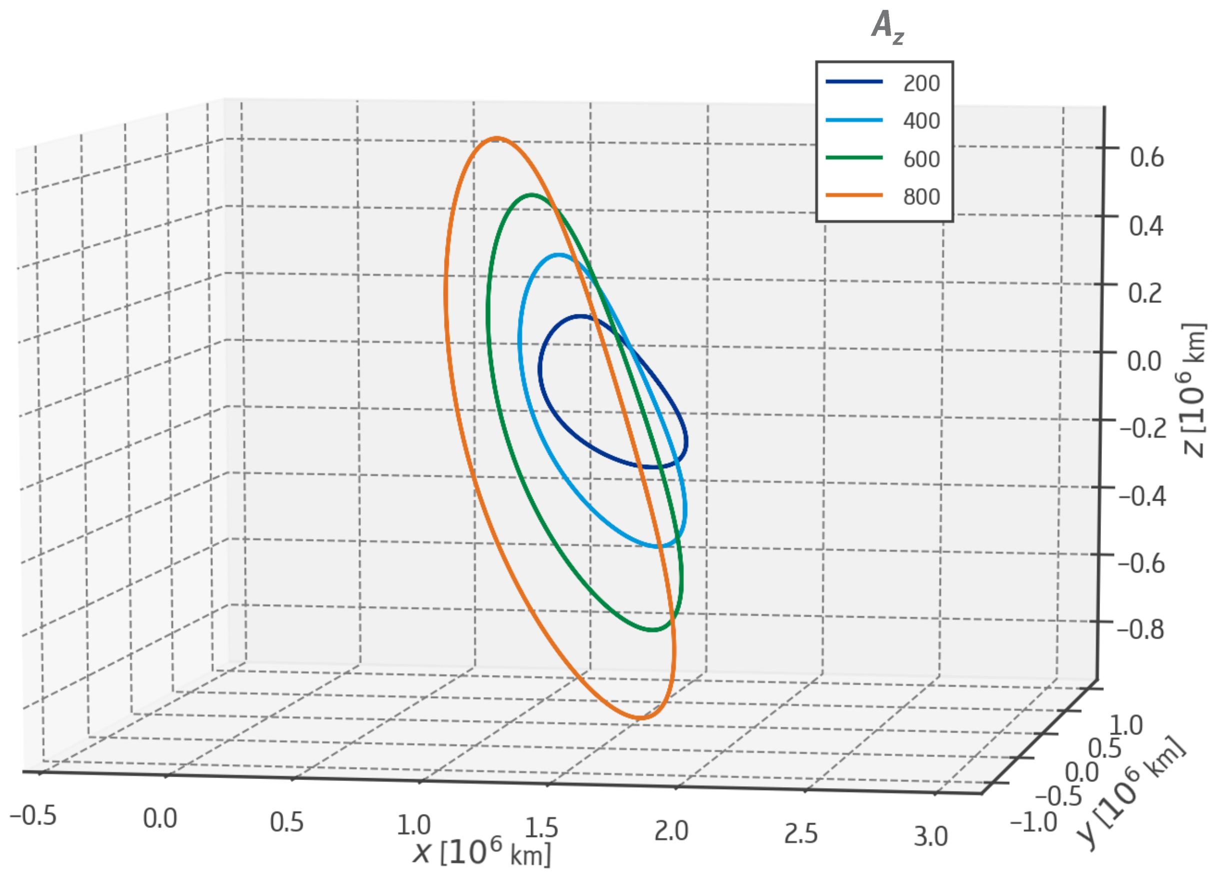
- 7th European Space Debris Conference: re-entry conditions for a spacecraft at L_1
- 31st ISTS: metric for the derivation of the break-up altitude for LPO re-entries

Trajectory generation

Analytical construction of **Halo** orbits around L_1 and L_2 (Richardson, 1979)

Orbit completely defined by the out-of-plane amplitude A_z

Trajectory sampled in **50000** points and propagated with **SNAPPshot** for 100 years. Stop criterion at **120 km** to provide re-entry conditions to **DRAMA**



Example of Halo orbits around L_2 ▲
Rotating reference frame centred in the Earth

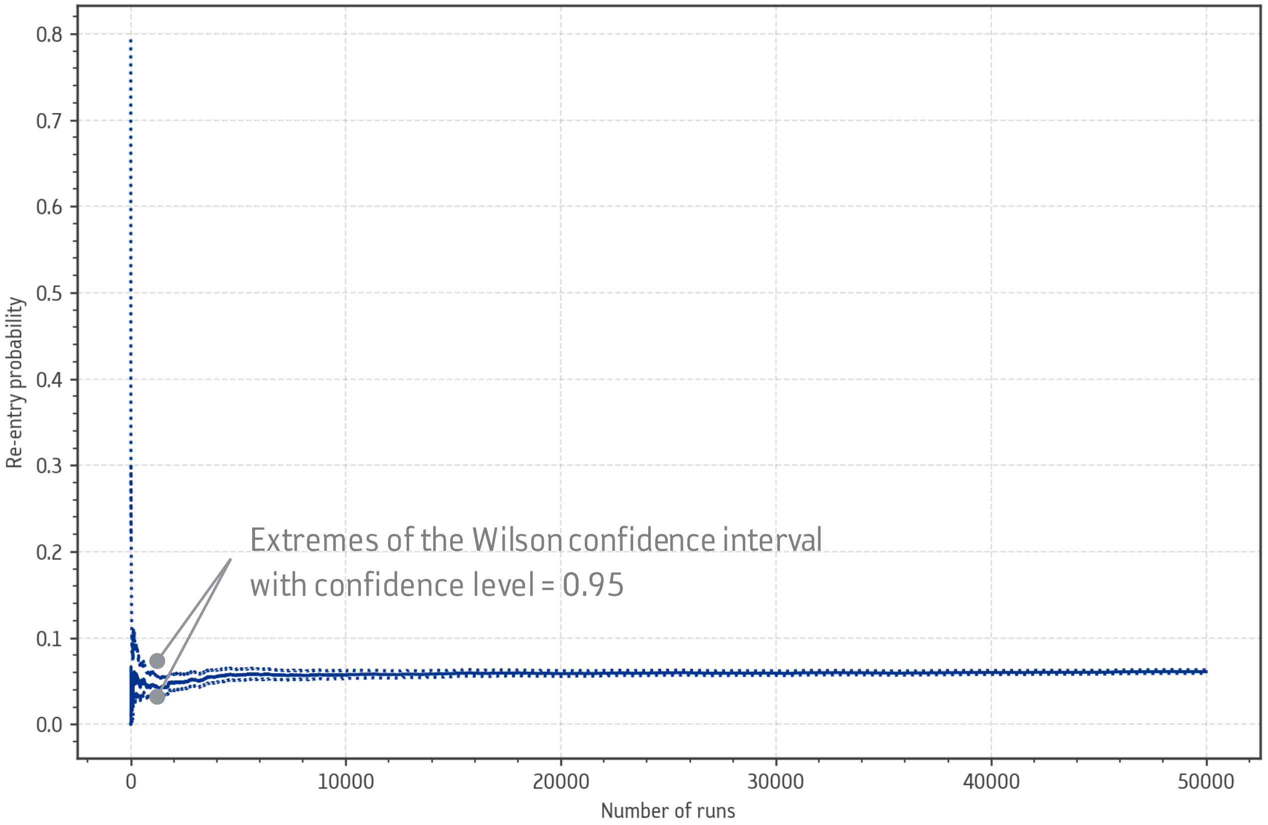
Trajectory generation

Number of runs

50000 runs

Same settings as in previous work; **stability** of **re-entry probability** checked for each scenario

▼ Results for the Halo orbit at L_2 with A_z = 400000 km



Spacecraft properties

M=2000 kg | A/M=0.01 m^2/kg | c_R= 1.08

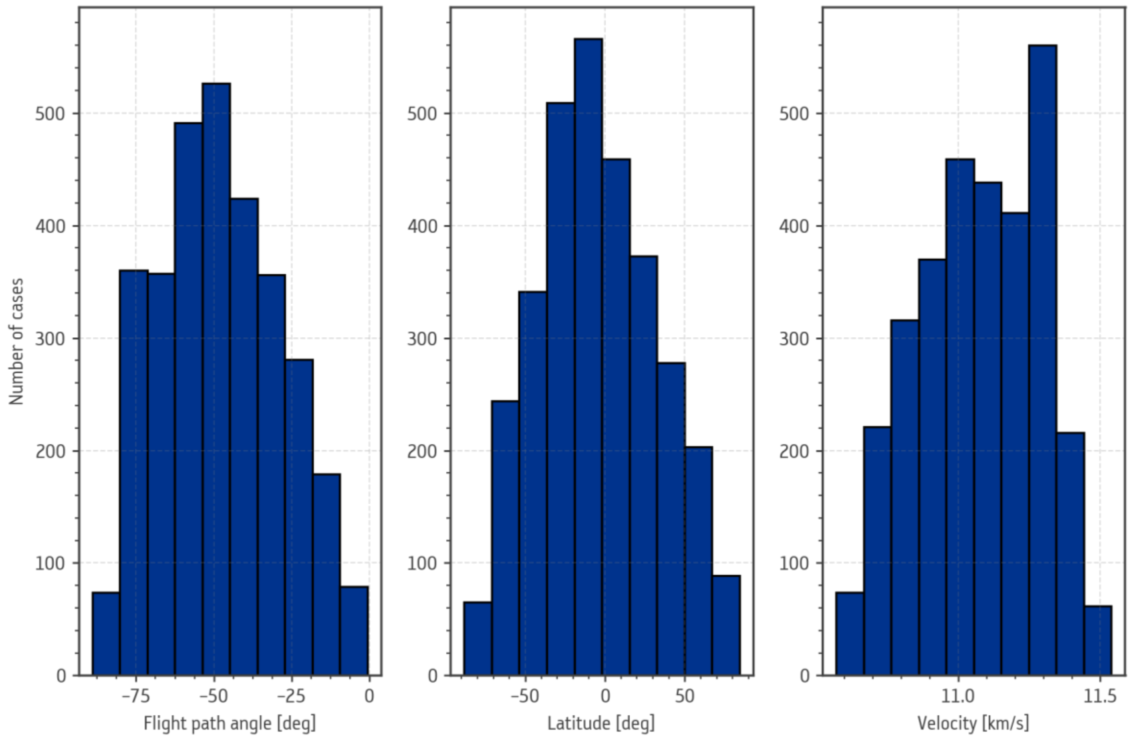
M, A/M: median values for ESA LPO missions

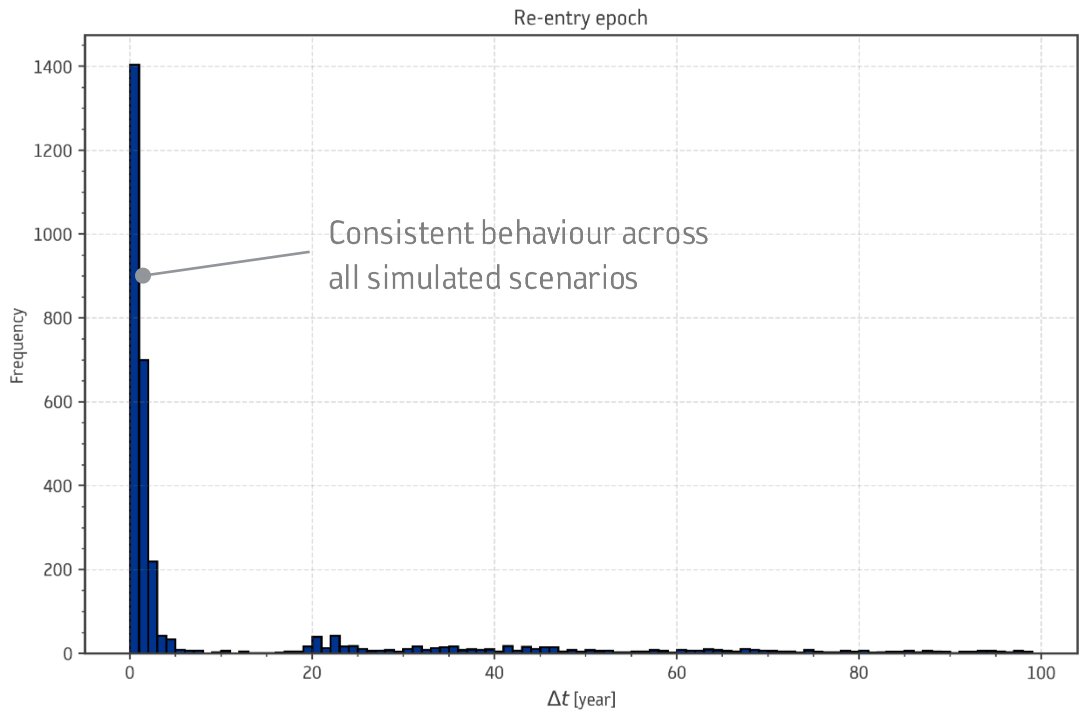
c_R: as in previous analysis

No variation of A/M and c_R

Trajectory analysis

- No uncertainty on spacecraft parameters | No manoeuvres
- One orbit type (i.e. Halo) and different out-of-plane amplitudes (A_z)
- Analysis of the distribution of the re-entry conditions as a function of A_z

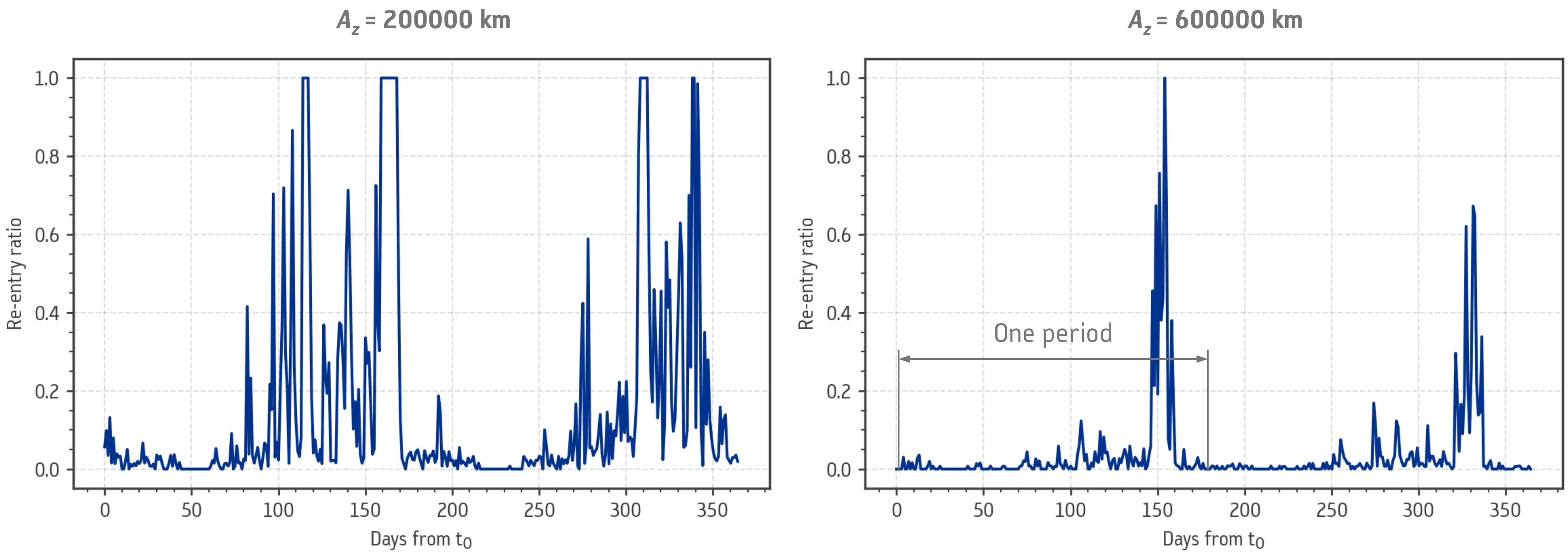




▲ Results for a Halo orbit at L_2 with A_z = 400000 km ▲

Re-entry probability & epoch

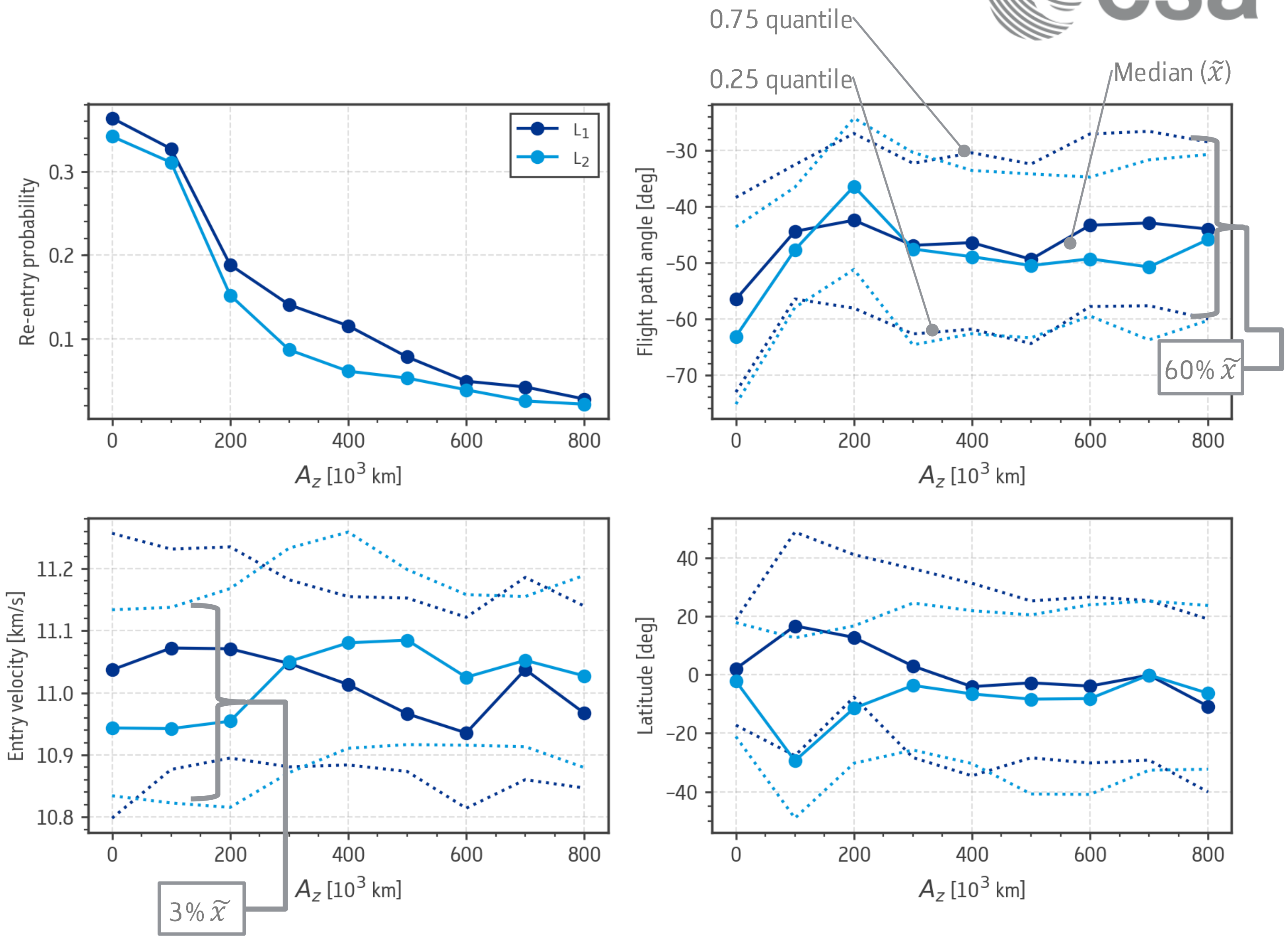
- All trajectories are generated using the same reference epochs
- The re-entry probability value is the total one, even if a strong dependence on the position along the LPO is present



Re-entry trends

Most parameters: limited dependence on the amplitude when $A_z \geq 300000$ km

Limited variation in the entry **velocity**, but large **spread** in the **flight path angle**

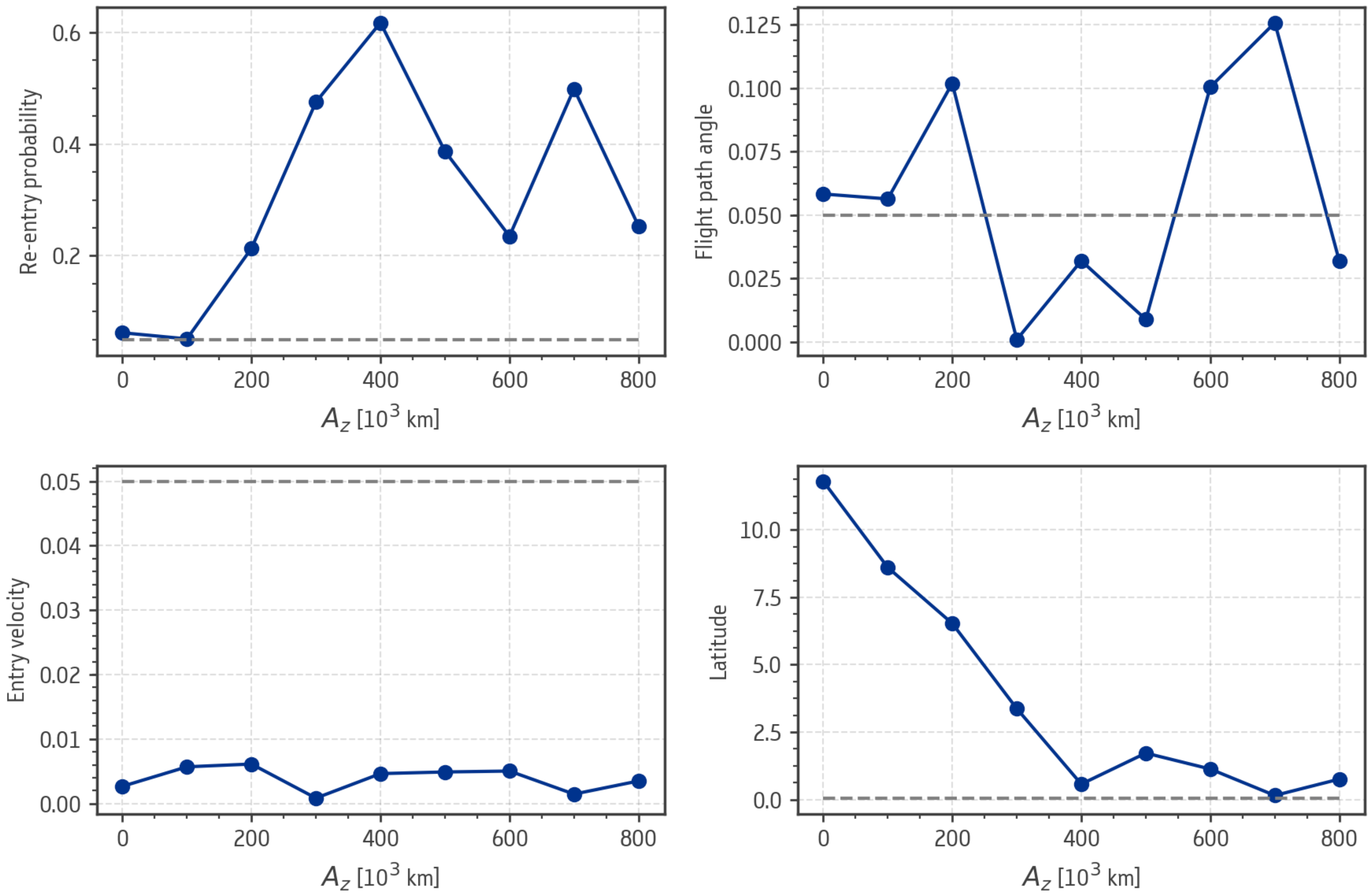


Re-entry trends: same distribution?

Comparison of the distributions with the same out-of-plane amplitude

Preliminary test by comparing the **mean values** only for each quantity *x*

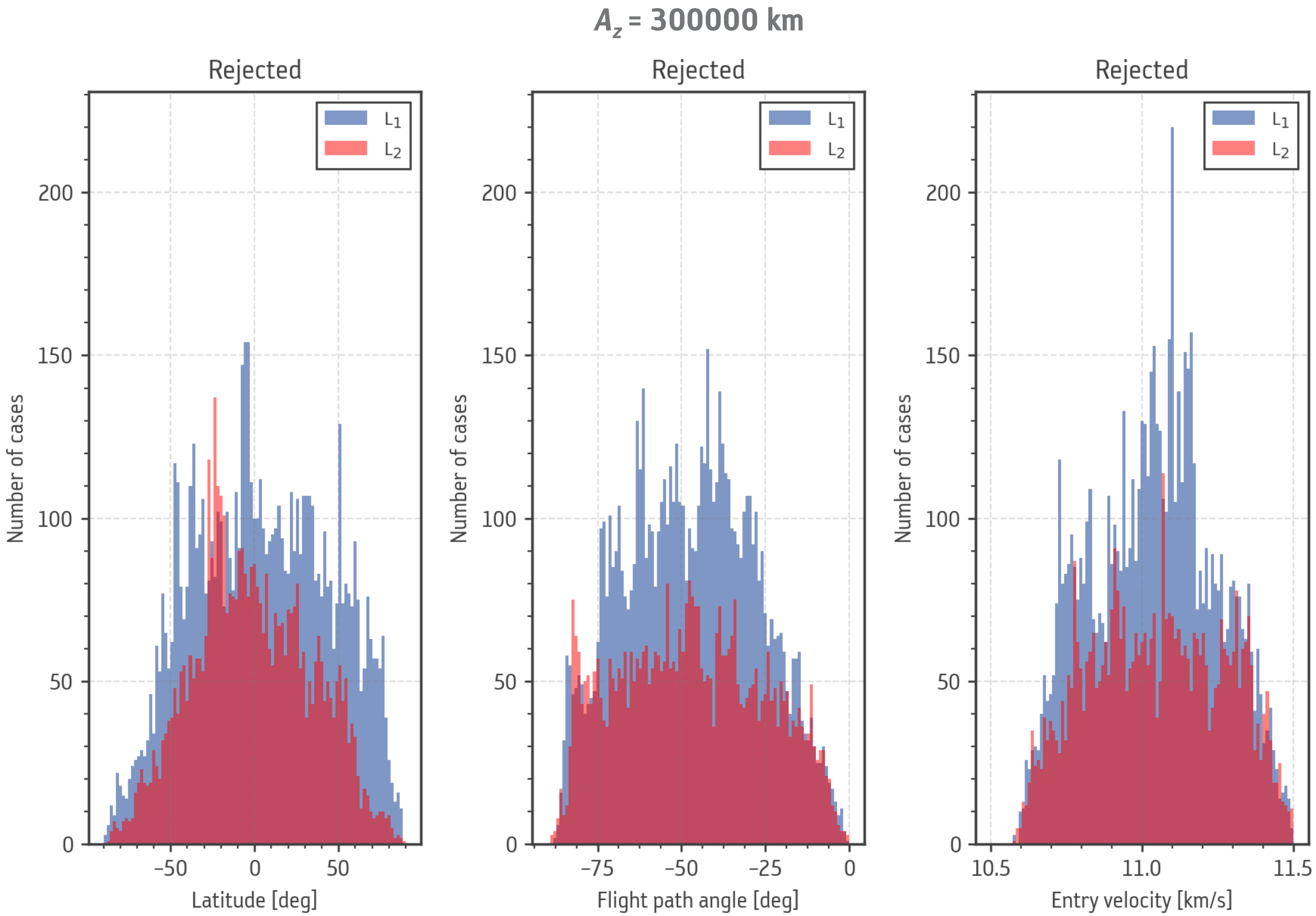
$$y = \frac{|\bar{x}_{L1} - \bar{x}_{L2}|}{\bar{x}_{L1} + \bar{x}_{L2}}$$



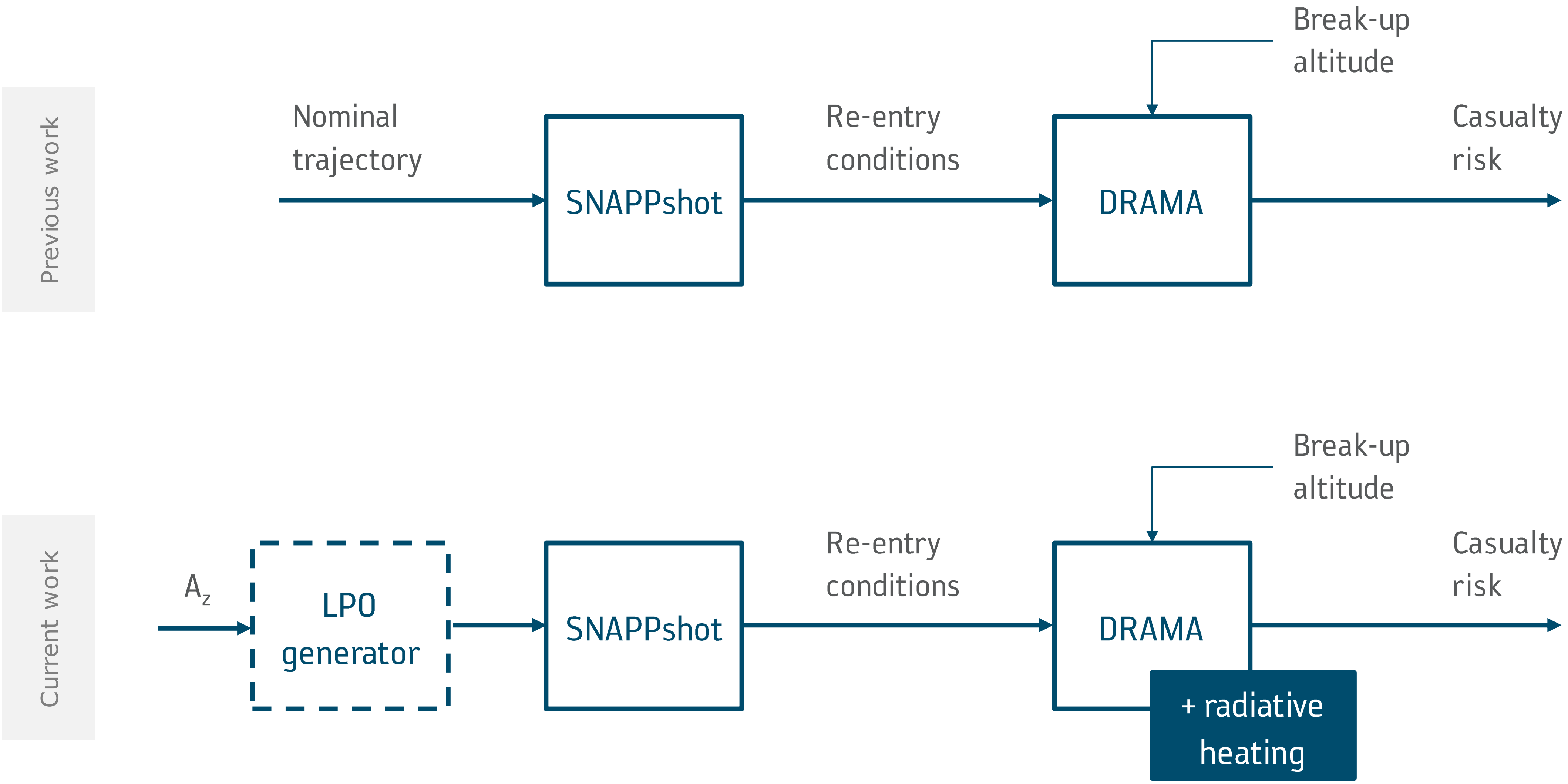
Re-entry trends: same distribution?

Statistical tests (Mann-Whitney & Kolmogorov-Smirnov) to evaluate the **hypothesis** that the two samples come from the **same population**

The hypothesis is always **rejected**: the two scenarios need to be analysed separately



Re-entry modelling



Radiative heating contribution

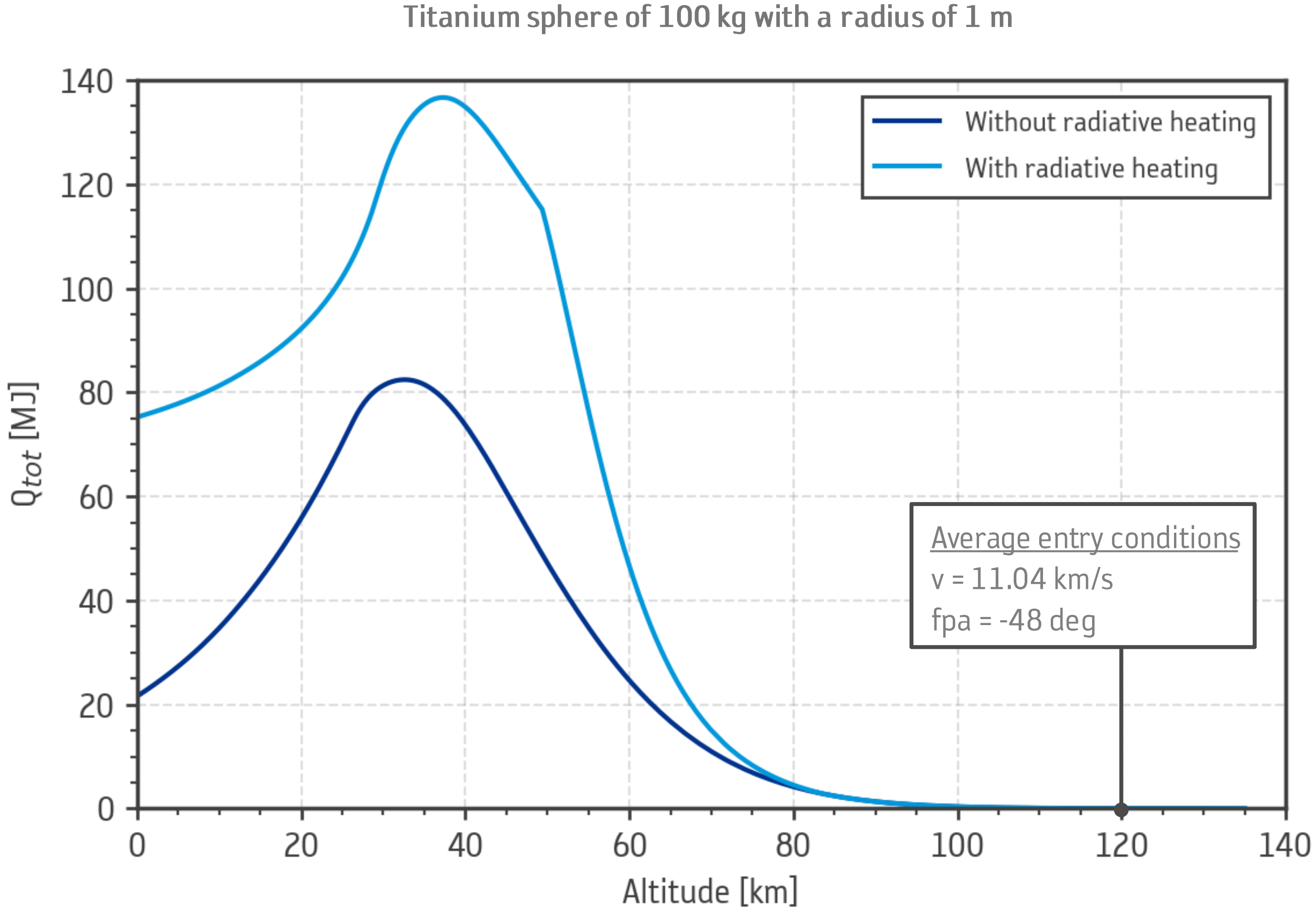
Standard re-entry break-up models consider **convective** heating and thermal **re-radiation**

$$Q_c \sim v^3 \left(\frac{\rho}{R}\right)^{1/2} \qquad Q_t \sim \varepsilon\sigma T^4$$

At high velocities (v≥10 km/s) **radiative heating** can't be omitted

$$Q_r \sim R^{>0}\rho^{>1}f(v)$$

(Brandis & Johnston, 2014)



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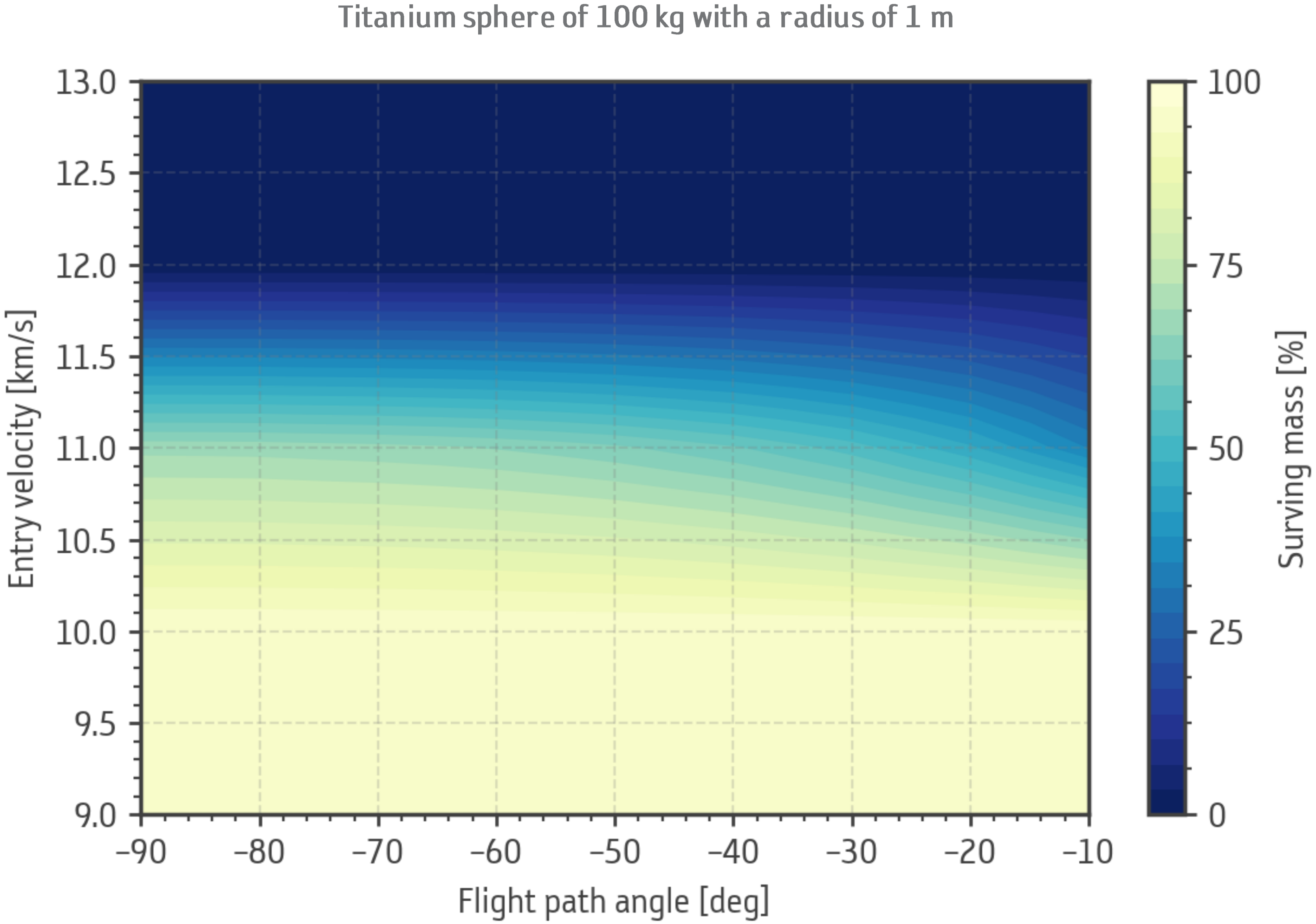
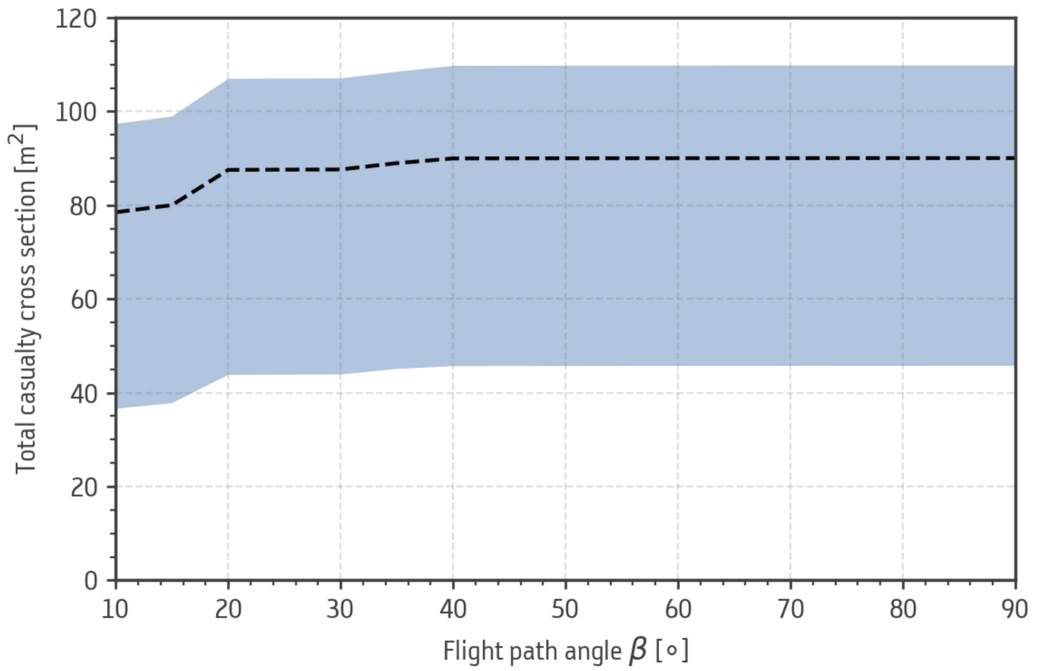


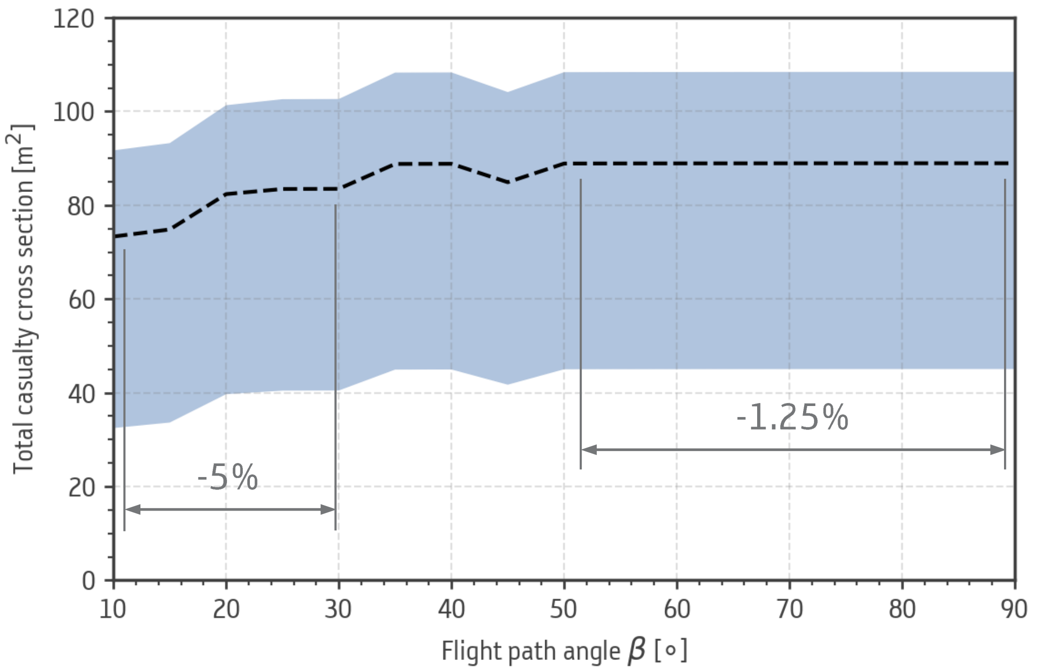
Effect on the casualty risk

- Definition of a **reference case**: v = 11.04 km/s
- Parametric analysis in DRAMA with a fictitious spacecraft configuration
- **Fixed breakup altitude** (60 km)

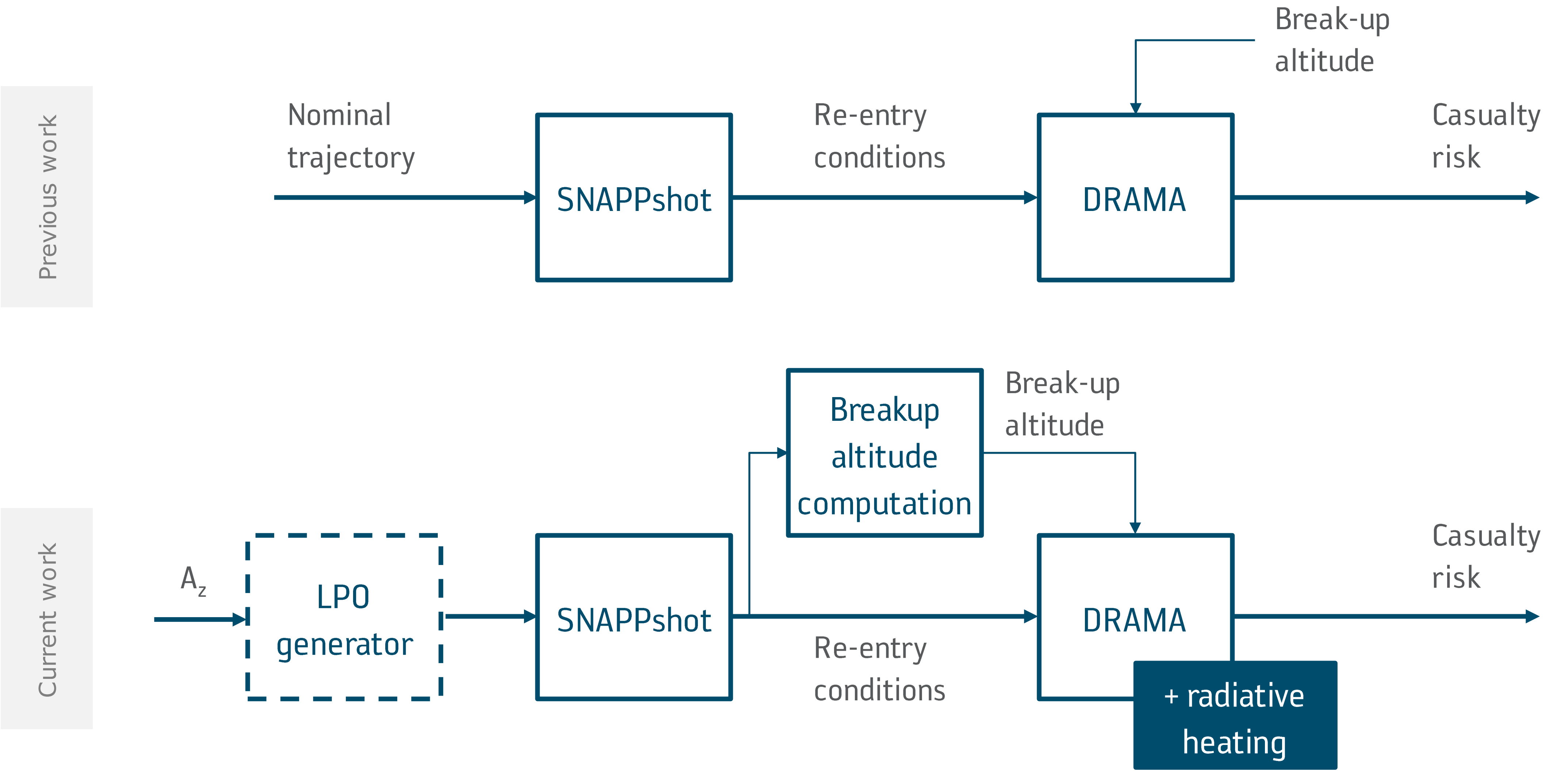
Without radiative heating



With radiative heating



Re-entry modelling



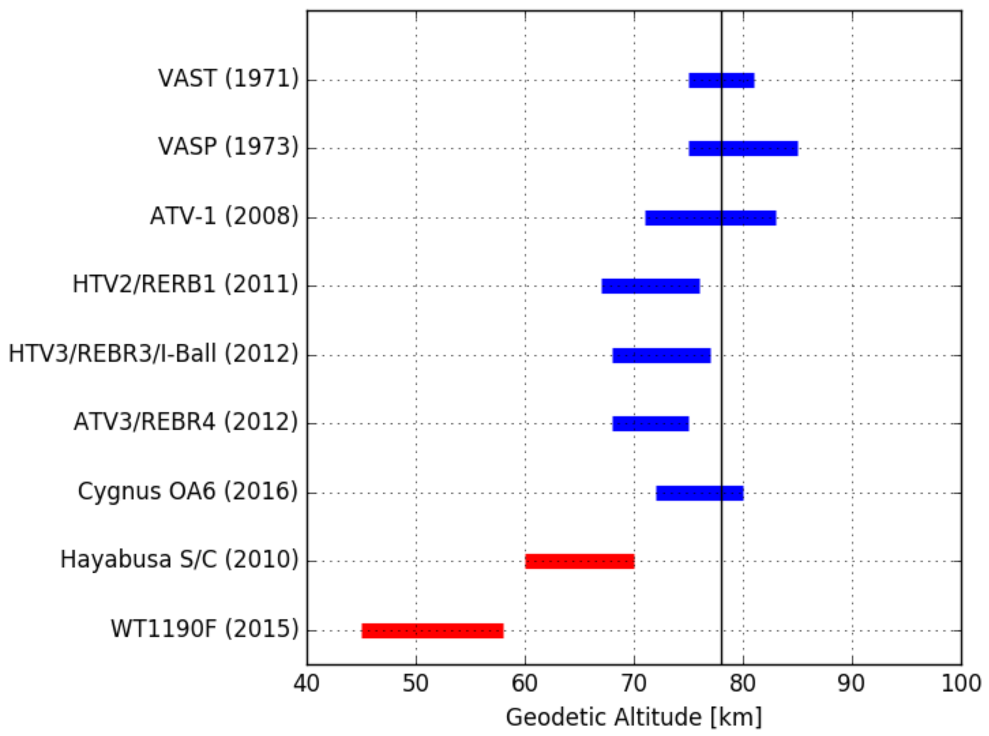
Break-up observations

Scientific observations to determine break-up altitudes were based on **controlled re-entries** with **low**, but non-zero, **eccentricity** (blue).

Break-up altitude is hard to predict due to the superposition of various phenomena

Only two objects were in the **radiative regime** (red)

Main break-up altitudes for observed re-entries



Break-up observations

Define a **break-up metric H** based on:

- Absorbed thermal energy $\frac{Q}{m}$
- Approximate spacecraft with intact outer shell
- Random tumbling A
- Aerodynamic pressure P

$$H = PA\frac{Q}{m},$$

$$[H] = \left[\frac{\mathrm{N}}{\mathrm{m}^2} \cdot \mathrm{m}^2 \cdot \frac{\mathrm{J}}{\mathrm{kg}}\right] = [\mathrm{NGy}]$$

Case	Shape	Mass [kg]	Length [m]	Diam. [m]	Ecc [-]	H(60 km) [N 10^6Gy]	H(71 km) [N 10^6Gy]	H(75 km) [N 10^6Gy]	H(82 km) [N 10^6Gy]
KH8G3	Cylinder	1500	7.22	1.52	0.0035			6.597	1.257
Agenda-D	Cylinder	673	6.7	1.52	0.0035			10.901	2.195
VASP	Cylinder	5300	16.2	3	0.0035			25.173	4.925
Cygnus	Cylinder	1800	6.3	3.07	0.0035			15.508	3.095
HTV	Cylinder	10500	9.6	4.4	0.02		9.526	6.917	
ATV	Cylinder	13000	10.3	4.5	0.02		9.053	6.579	

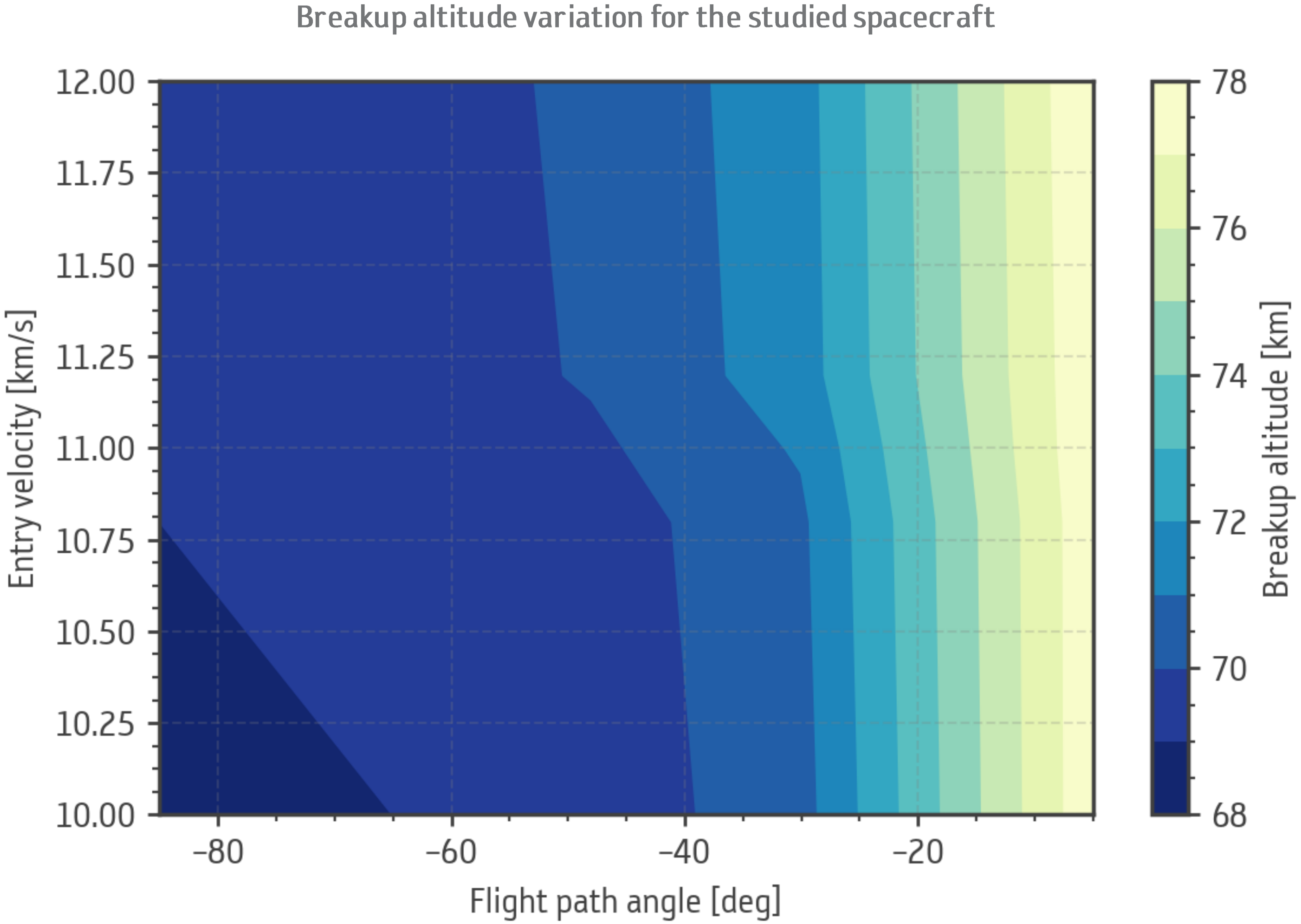
Case	Shape	Mass [kg]	Length [m]	HxW [m]	FPA [deg]	Vel [km/s]	H(60 km) [N 10^6Gy]	H(70 km) [N 10^6Gy]	H(75 km) [N 10^6Gy]	H(82 km) [N 10^6Gy]
Hayabusa	Box	380	1.6	1.1x1.0	-12.35	12.03	27.256	2.158		

Altitude break-up definition

$H = PA\frac{Q}{m}$ computed on a **grid** of values of **entry velocity** and **flight path angle**

Breakup altitude defined where **H=5**

Each trajectory analysed with the **corresponding break-up altitude**



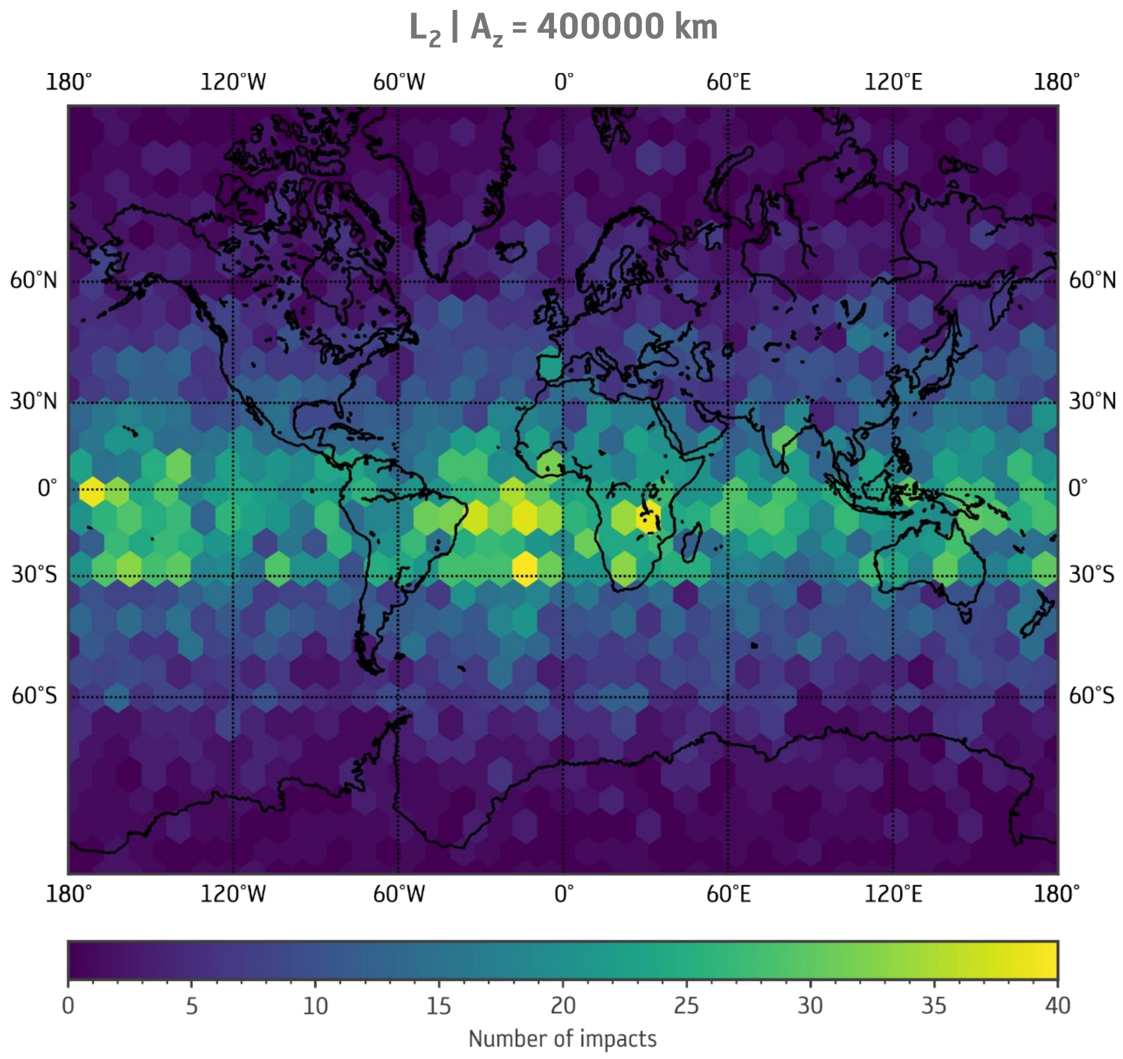
Example of casualty risk computation

Re-entry probability: **6%**

76% re-entry trajectories ends into the **ocean** (casualty risk = 0)

Average casualty risk (over all samples): **$1.237 \cdot 10^{-3}$** (+4% case wrt case with breakup altitude = 78 km)

Final casualty risk: **$7.5 \cdot 10^{-5}$**



Conclusions

- **Space debris mitigation guidelines** apply to spacecraft at the libration points
- The **challenges** associated with performing casualty risk analysis (especially in the early phases of a mission) is the dependence on **evolving parameters** (e.g. orbit amplitude, reflectivity coefficient) and the limited availability of **tools** for high-velocity & steep trajectories
- In this work, we studied the dependence of **entry conditions** on the **out-of-plane amplitude** for Halo orbits: **limited variation** in the entry **velocity**, but large **spread** in the **flight path angle**
- The resulting casualty area was computed by including a model of the **radiative heating** and computing an equivalent **break-up altitude** for each scenario

Open points

- Generalisation to **all LPO families**
- Investigation of the dependence on the **departure epoch**
- **Radiative** models for **non-spherical** objects
- Verification of simplified **breakup altitude** models
- More **experimental data** for better understanding of the phenomenology
- Similar analysis for objects on **high-elliptical orbits**

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