Demisability analysis of re-entering structures on resonant trajectories

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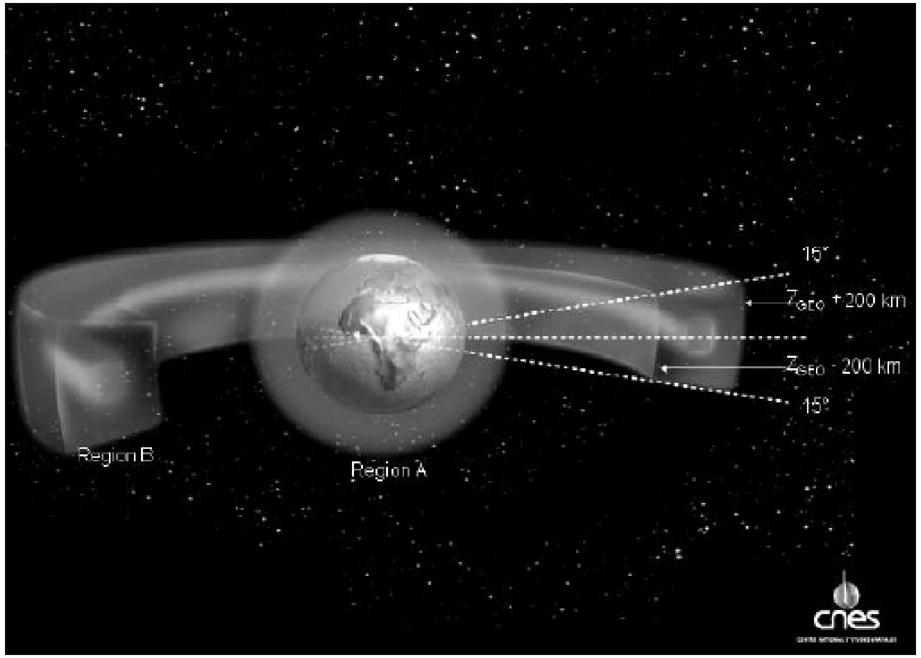
Introduction

Conformance with the GEO disposal requirement can be ensured by using a disposal orbit with the following characteristics:

- Eccentricity ≤ 0.005,
- Minimum perigee altitude above the GEO altitude

  $\Delta h_p \geq 235 + 1000 \cdot c_R \cdot A/m$ km



GEO protected region. Image by CNES

GEO protected region: segment of spherical shell

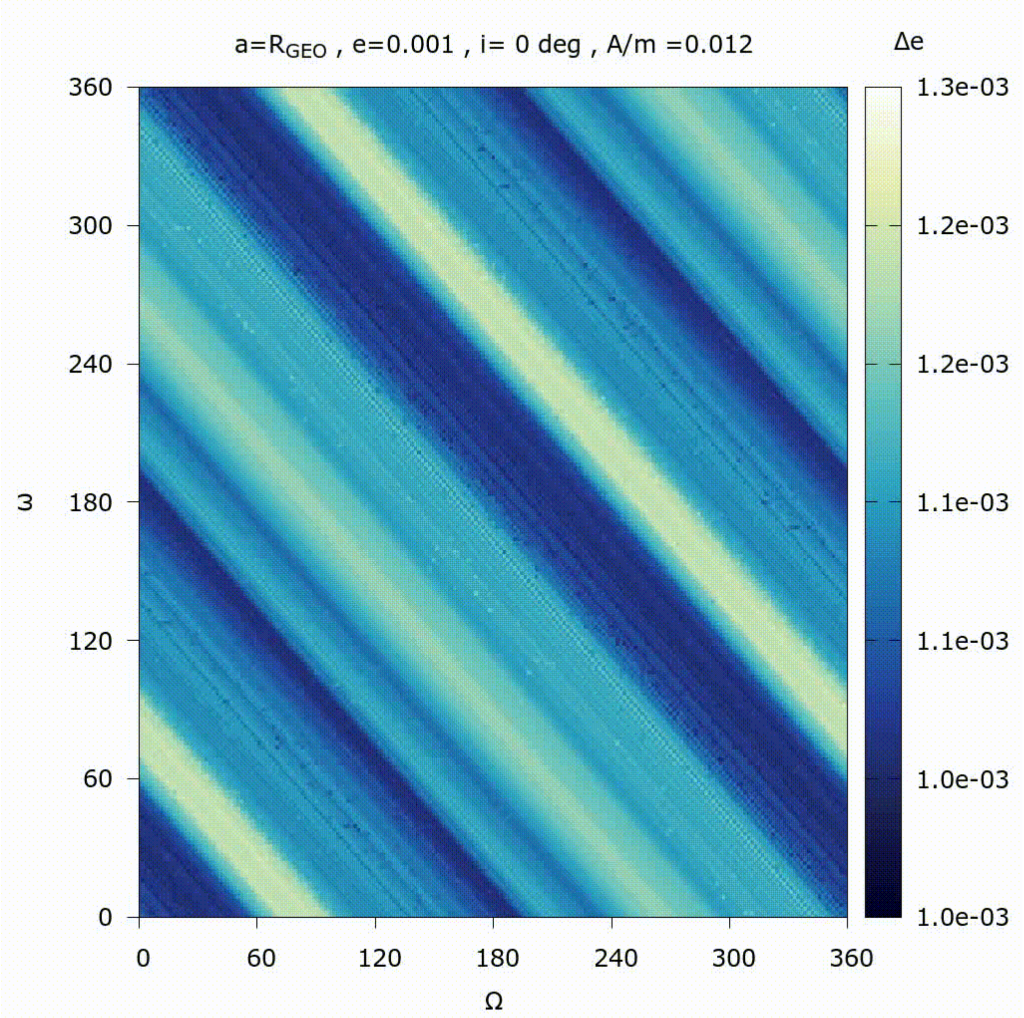
- lower altitude boundary = geostationary altitude minus 200 km,
- upper altitude boundary = geostationary altitude plus 200 km,
- latitude sector: 15 degrees South ≤ latitude ≤ 15 degrees North

Disposal maps

- Disposal from GEO is possible exploiting **resonances** related to Earth potential (J_2) and luni-solar perturbations
- Disposal based on **long-term eccentricity build-up**
- Dynamical evolution is determined by initial conditions:
  - Inclination, RAAN, Anomaly of the Perigee (AoP), eccentricity,
- Dynamical indicator

$$\Delta e = \frac{|e_{max} - e_0|}{|e_{re-entry} - e_0|}$$

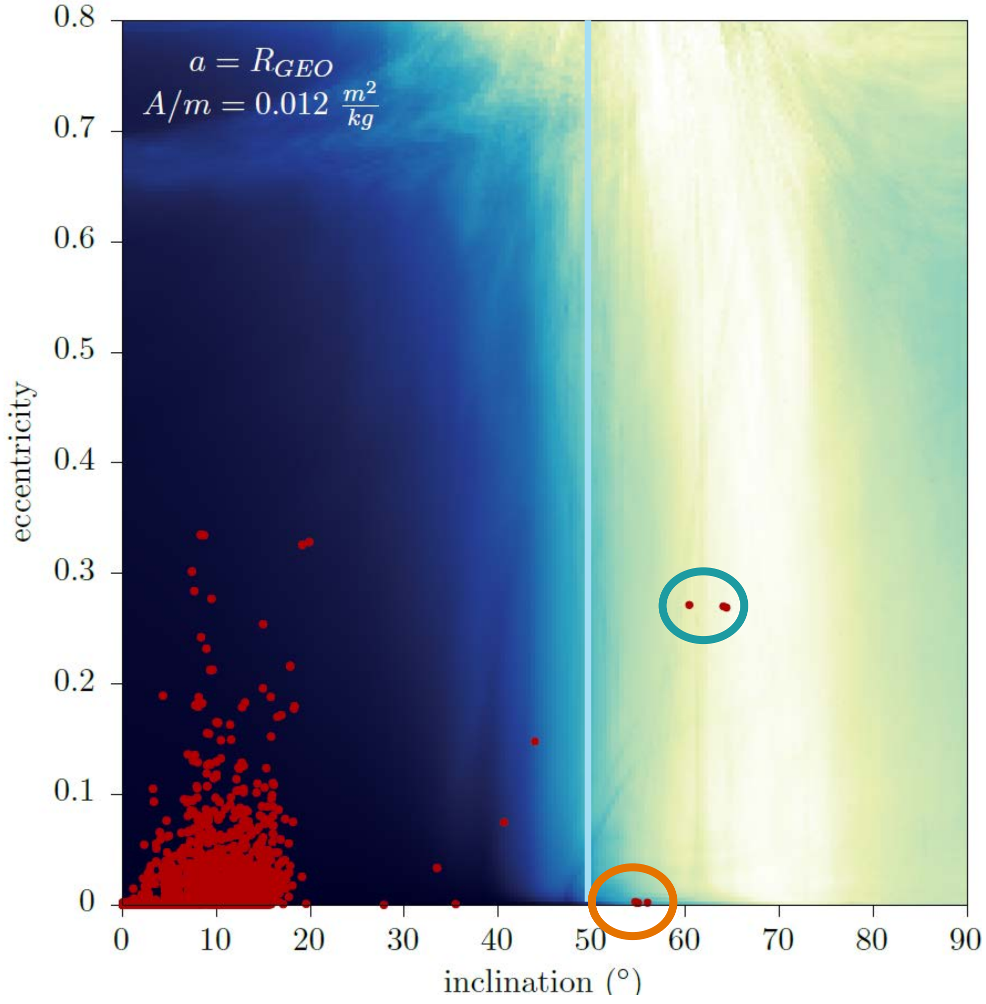
$e_0 = 0.001$ $A/m = 0.012$ m^2/kg



Angles-averaged map

- Eccentricity – inclination map averaging over RAAN and AoP
- *i* > 50 deg → high *Δe*
- Examples
  - 5 S/C of the **Sirius constellation** (3 retired)
  - 12 S/C of **BeiDou constellation** (1 retired)
- Re-entry time can be below 20 years
- LEO protected region dwell time in order of few weeks and down to days

$\Delta e \rightarrow 1$
Re−entry

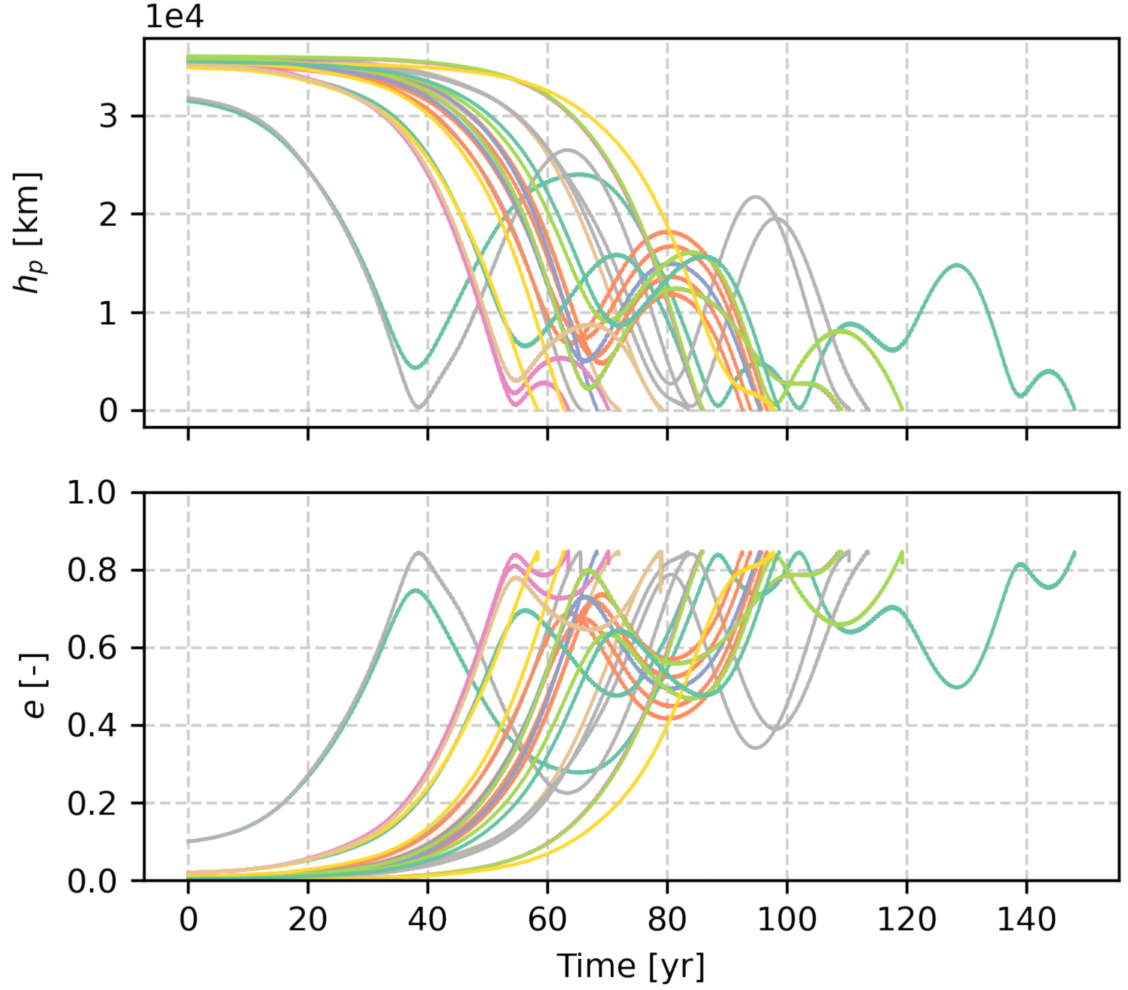


$\Delta e \rightarrow 0$
Bounded

Trajectory propagation

No drag

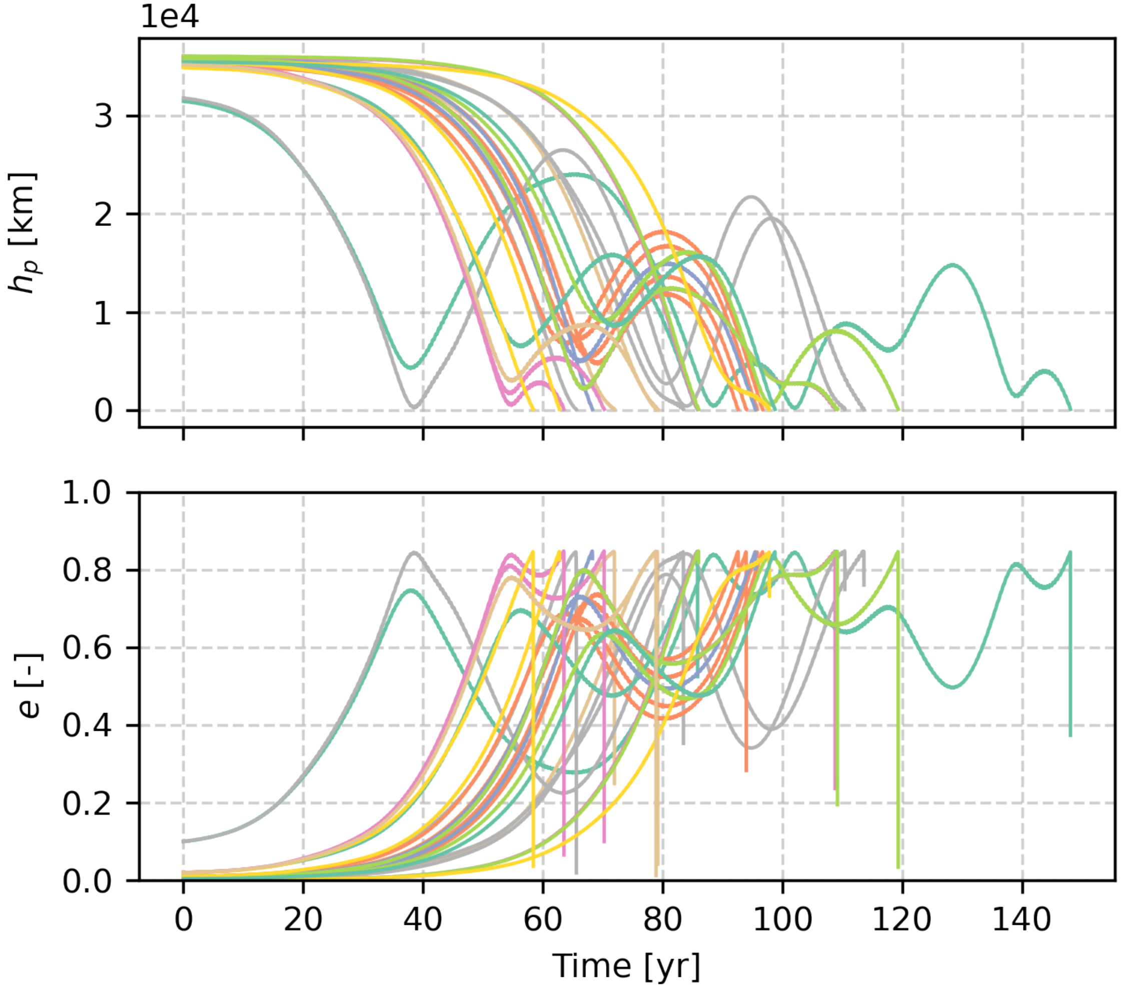
- Propagation using PlanODyn
  - Force model: 4x4 geopotential, 3rd body perturbations, solar-radiation pressure, Earth's precession
- Propagated until mean perigee altitude is 60 km



Trajectory propagation

Including drag

- Propagation using PlanODyn
  - Force model: 4x4 geopotential, 3rd body perturbations, solar-radiation pressure, Earth's precession
- Propagated until mean perigee altitude is 60 km
- Eccentricity reduction in the last few days
- *Circularisation trend* but must be verified with more suitable models
- Interface between long-term propagation and re-entry simulations



Interface

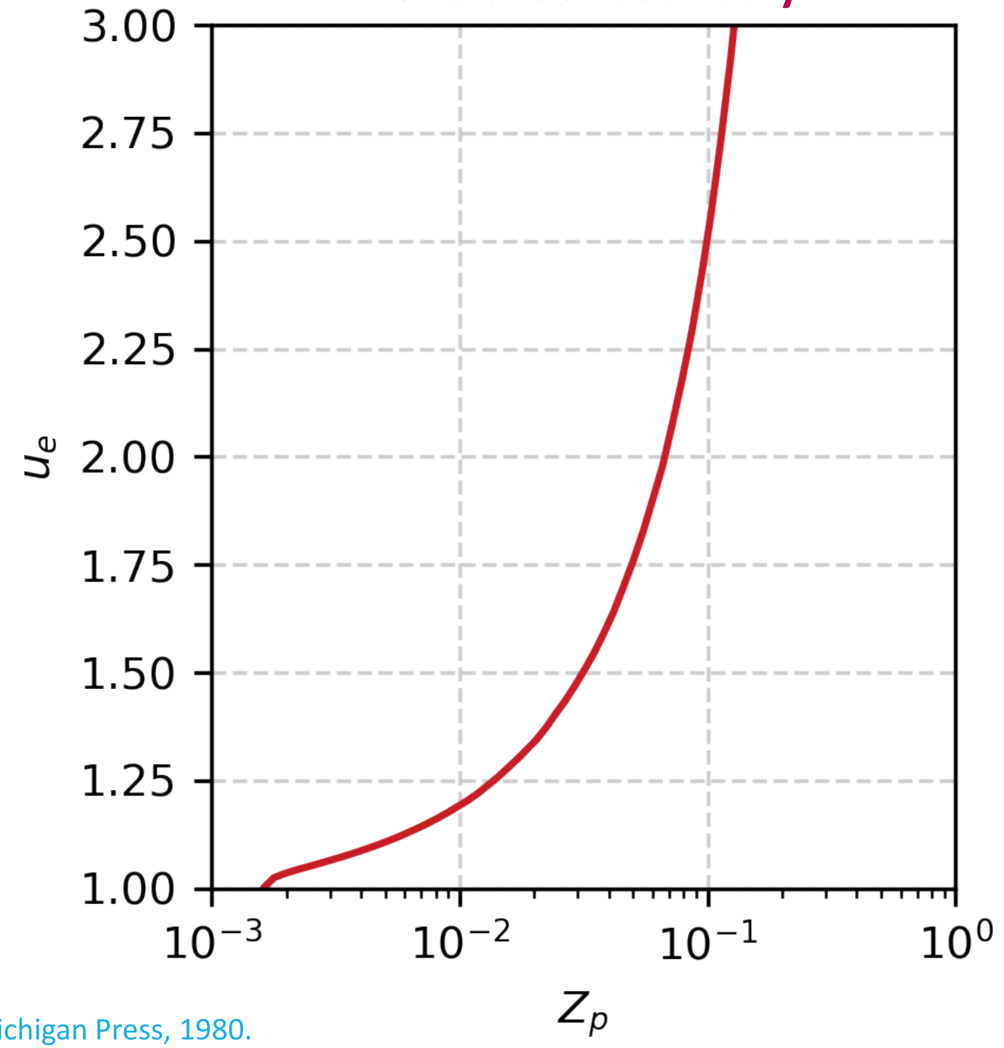
Overshoot boundary

- Link between the Keplerian perigee altitude and entry conditions
- Simplified description by Vinh[1], using modified Chapman's variables

$$u_e = \frac{v_e^2 \cdot \cos\gamma_e}{g \cdot r} \qquad Z_p = \rho \cdot \frac{C_D S}{2m}\sqrt{\frac{r_p}{\bar{\beta}}}$$

- Conditions **below the boundary** are ***predicted* to re-enter**
- In the final part of the trajectory can be used to verify if entry conditions are met

Overshoot boundary

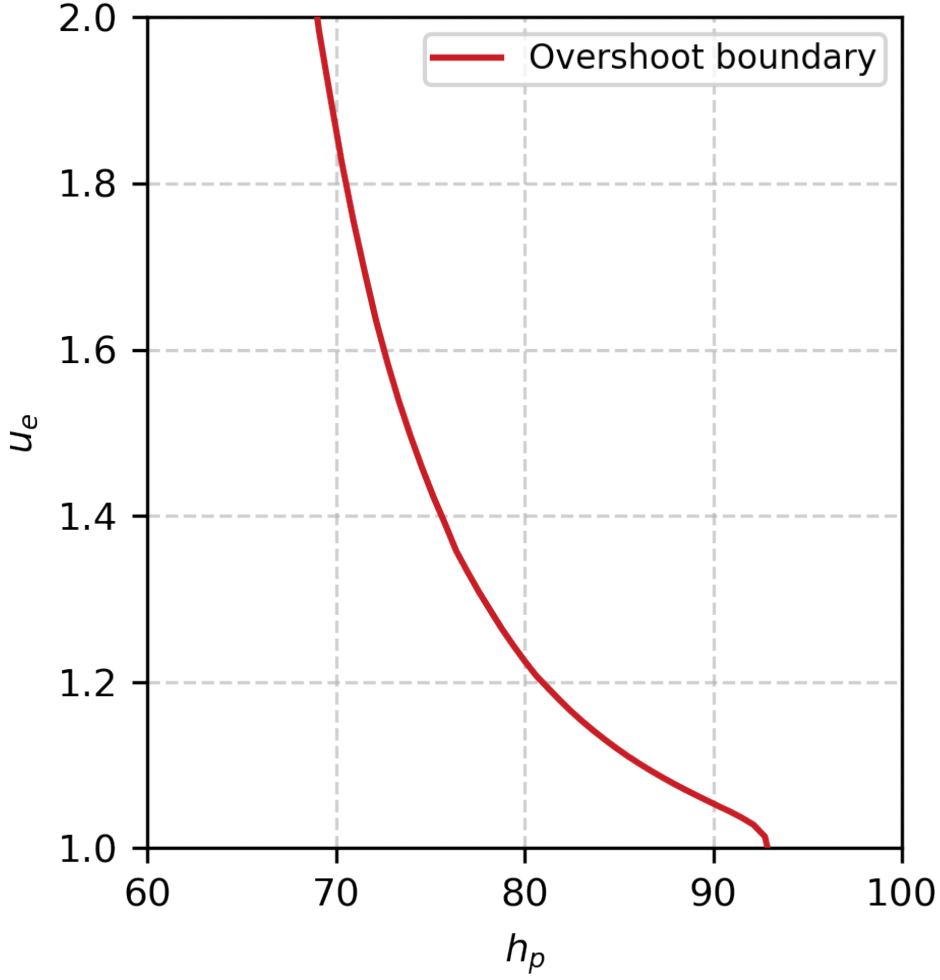


[1] Vinh, Nguyen X., et al. Hypersonic and Planetary Entry Flight Mechanics. Ann Arbor: The University of Michigan Press, 1980.

Overshoot boundary application

Overshoot boundary for selected re-entry trajectories

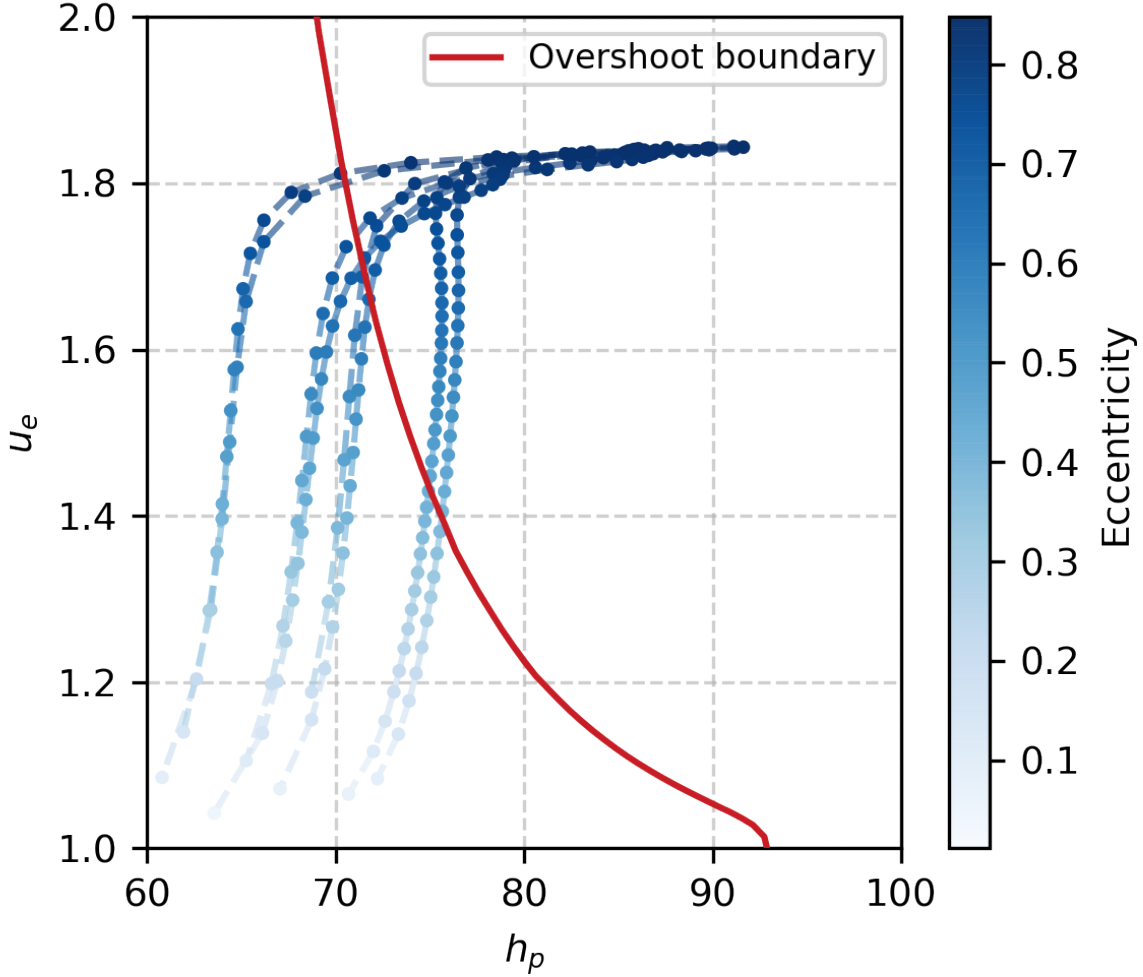
- Area-to-mass ratio of 0.012 m^2/kg
- Avg. scale height between 60 km and 120 km of altitude



Overshoot boundary application

Overshoot boundary for selected re-entry trajectories

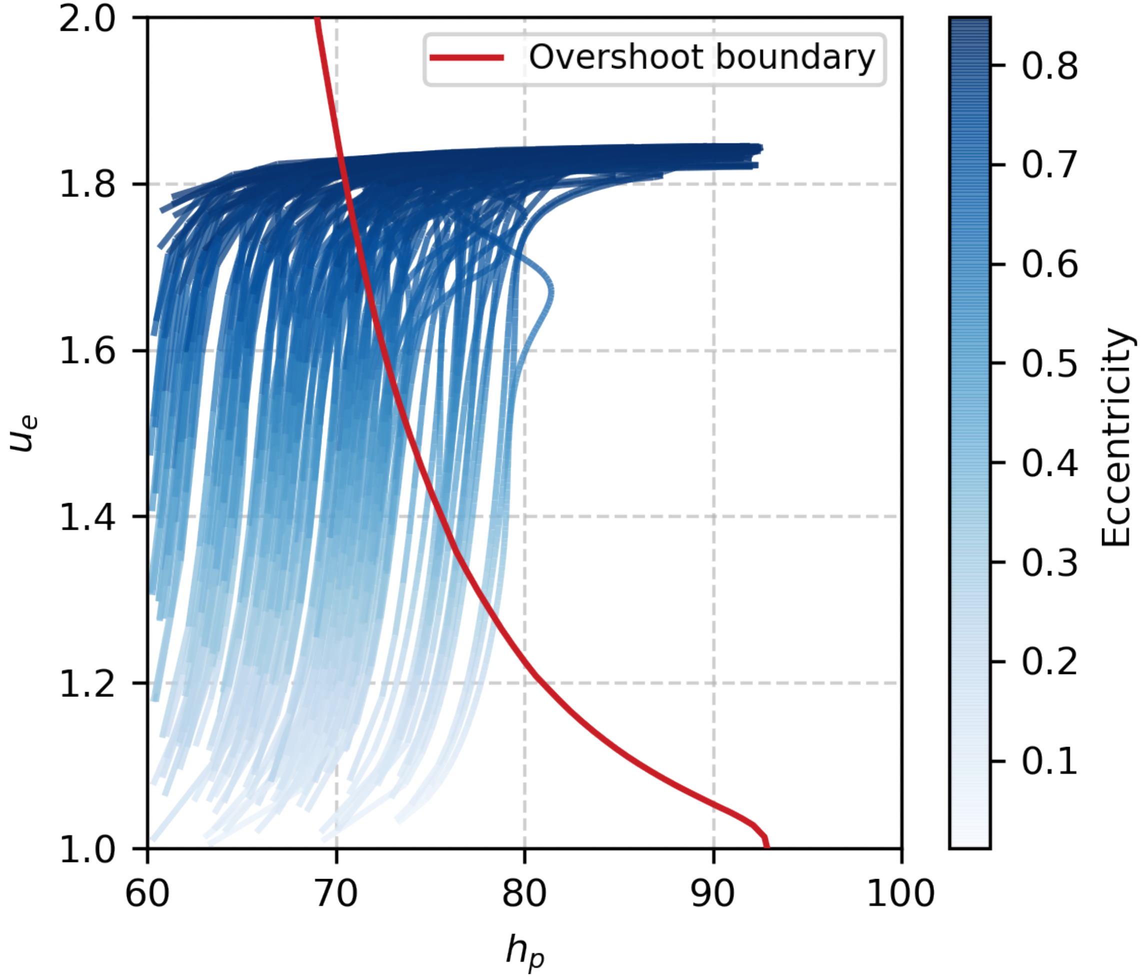
- Area-to-mass ratio of 0.012 m^2/kg
- Avg. scale height between 60 km and 120 km of altitude
- Evolution of entry conditions w.r.t. the overshoot boundary
- Every point corresponds to a revolution



Overshoot boundary application

Overshoot boundary for selected re-entry trajectories

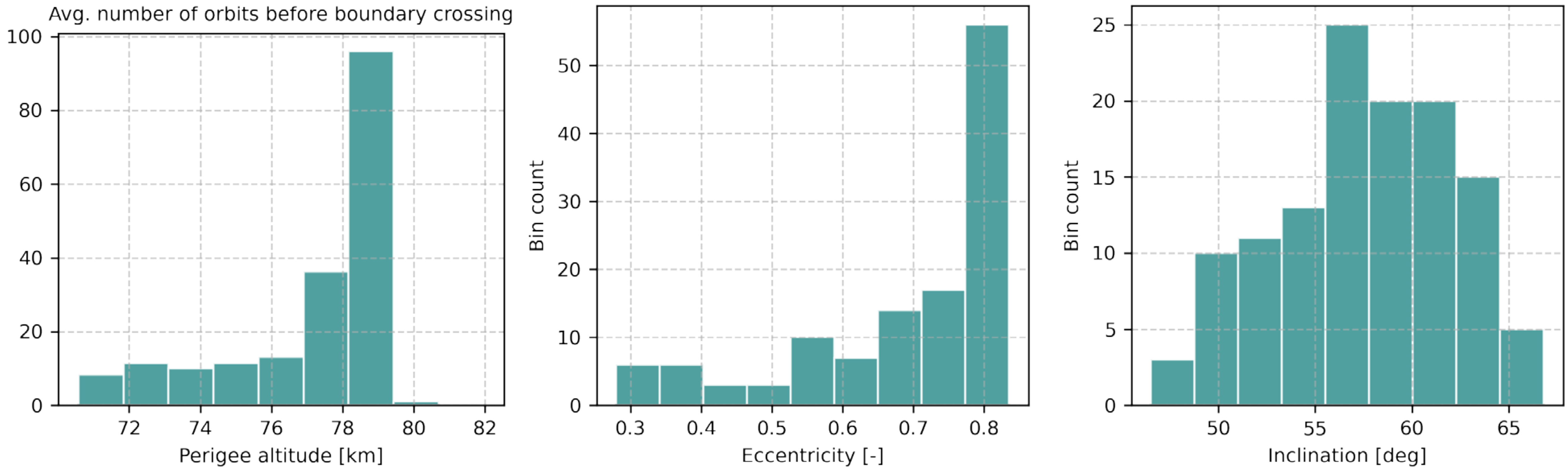
- Area-to-mass ratio of 0.012 m^2/kg
- Avg. scale height between 60 km and 120 km of altitude
- Evolution of entry conditions w.r.t. the overshoot boundary
- Every point corresponds to a revolution
- Intersection occurs at different eccentricities



Overshoot boundary application

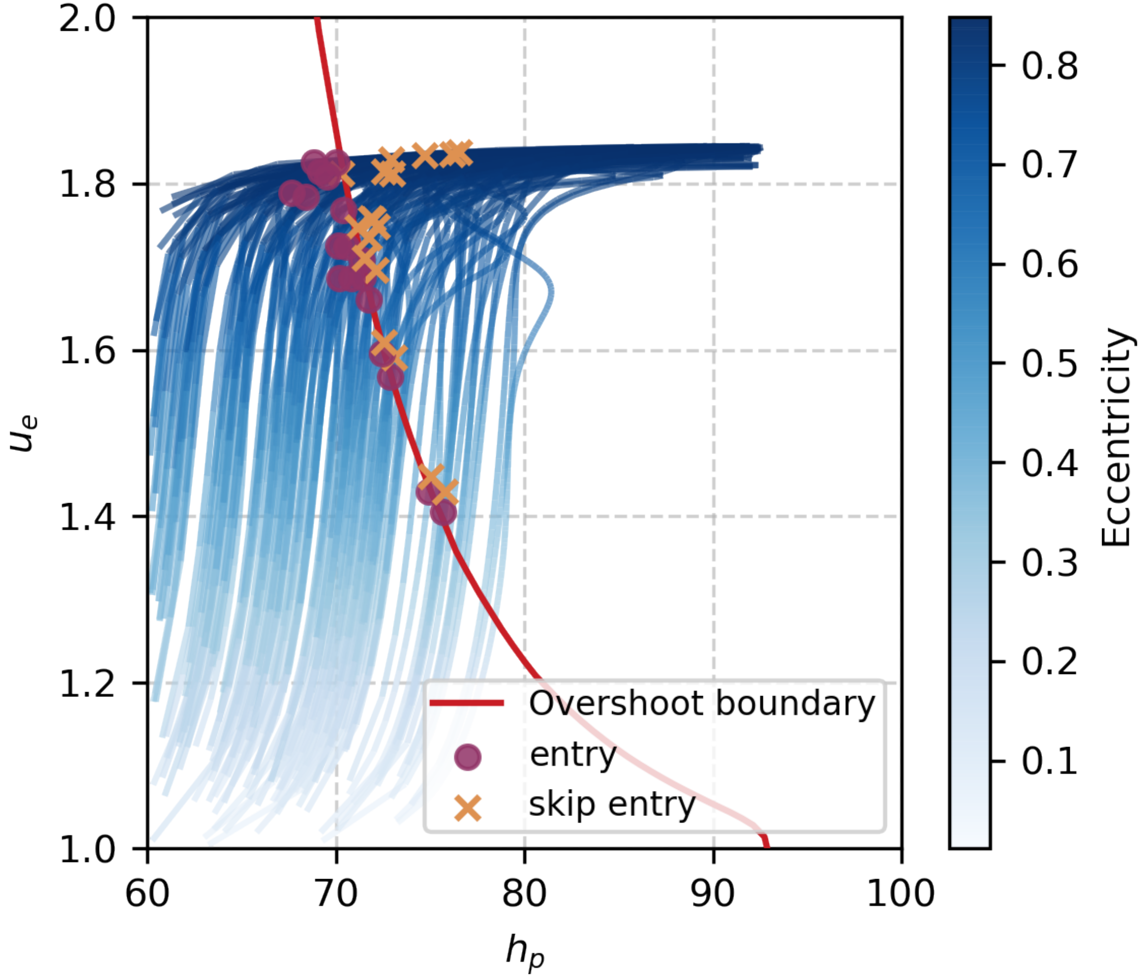
Statistics

- Orbit characteristics at overshoot boundary crossing
- Showing orbit passages before entry, eccentricity and inclination at entry



Overshoot boundary verification

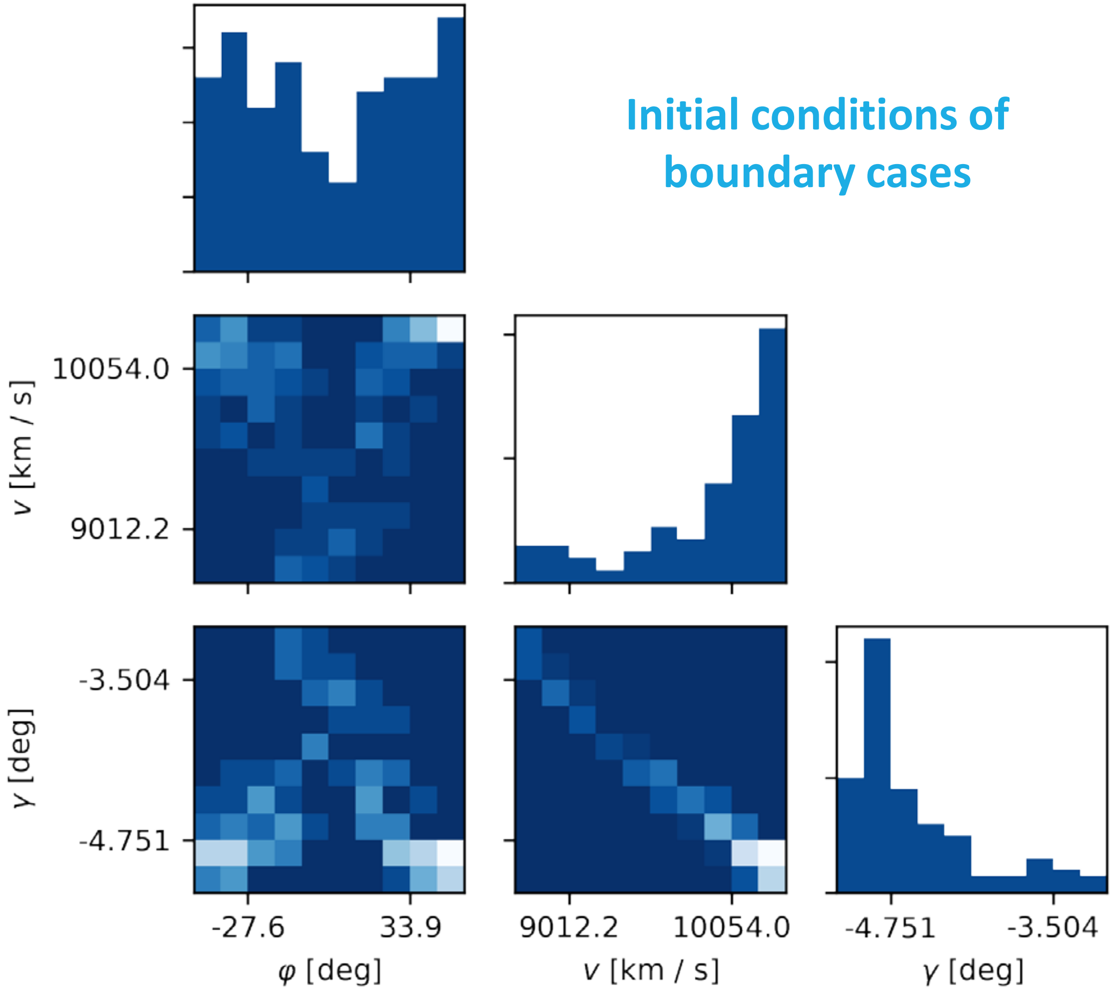
- **Verification** with in-house **object-oriented re-entry code**
- Check quality of predictions of the overshoot boundary
- For every orbit revolution a re-entry simulation has been performed
  - Skip and entry conditions are in accordance with the overshoot boundary prediction
- Care must be taken as **major break-ups may occur before the boundary**



Re-entry case

Selected example

- Initial conditions selected from overshoot boundary:
  - h = 120 km; v = 9.923 km / s; γ = -4.618 deg
- Spacecraft characteristics
  - Dry mass: 1200 kg
  - Size: 3 x 1.7 x 1.7 m
  - Array area: 25 m^2
- Modelled mass: 520 kg (including most critical components)

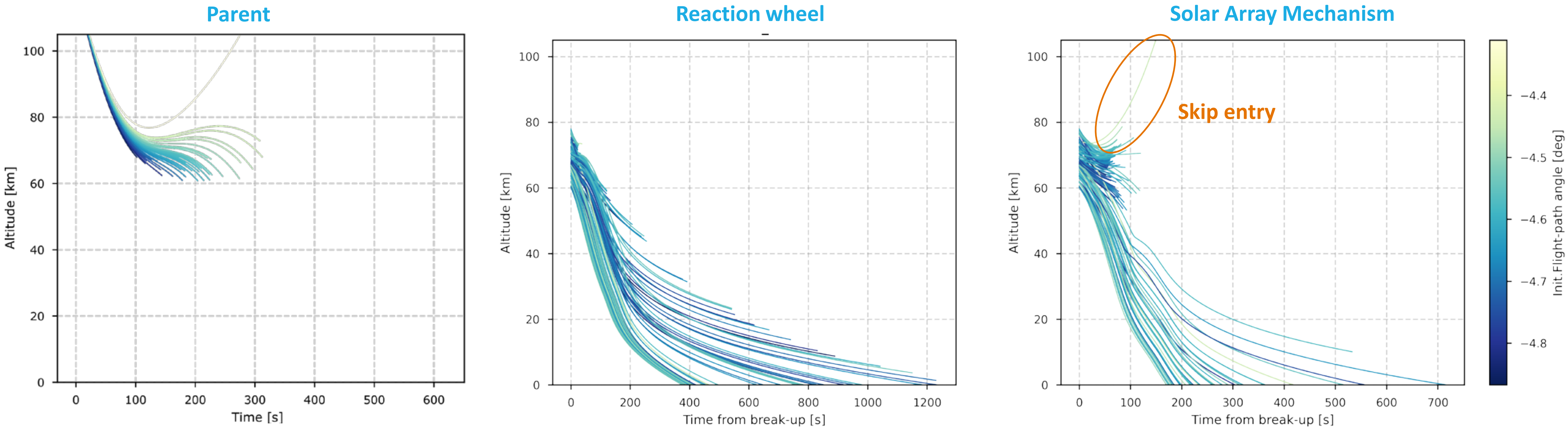


Initial conditions of boundary cases

Re-entry case

Including uncertainties

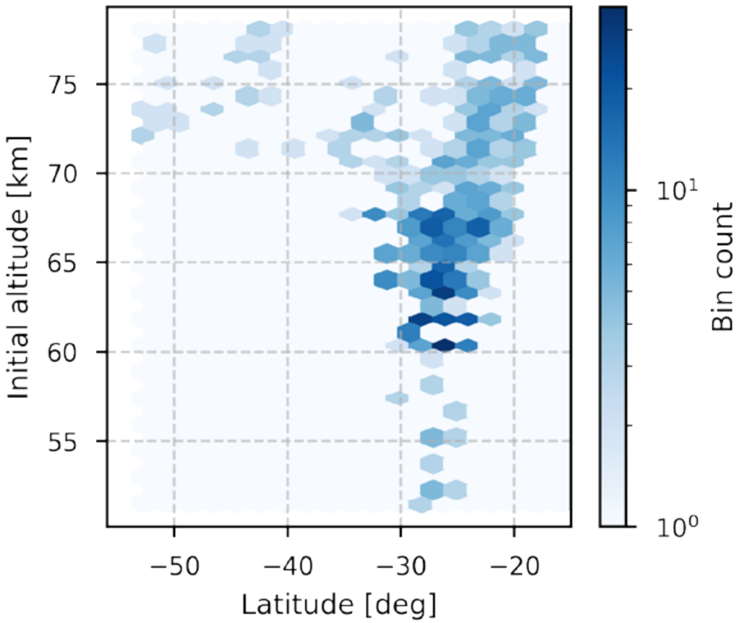
- Included uncertainties in initial conditions: (10 m/s, 0.05 deg) σ
- Included uncertainties in break-up altitude:
  - Uniform distribution between 78 km and 60 km

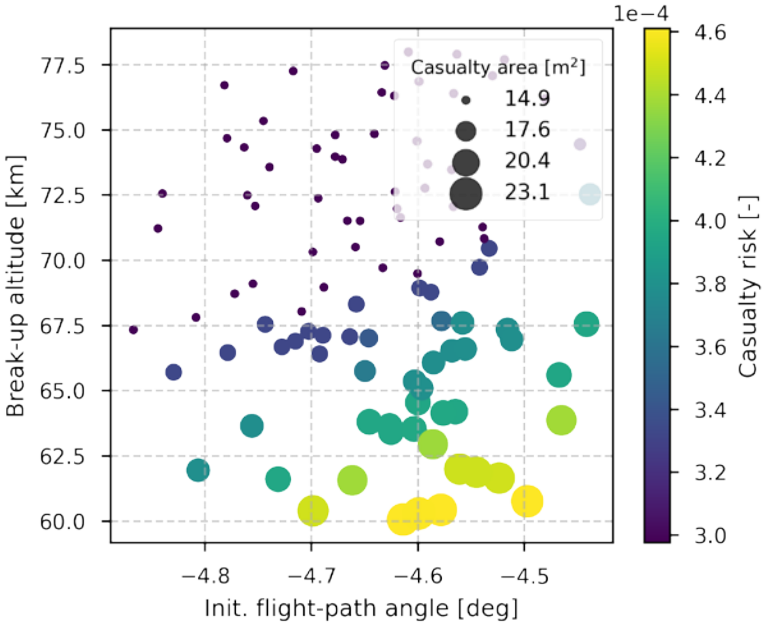


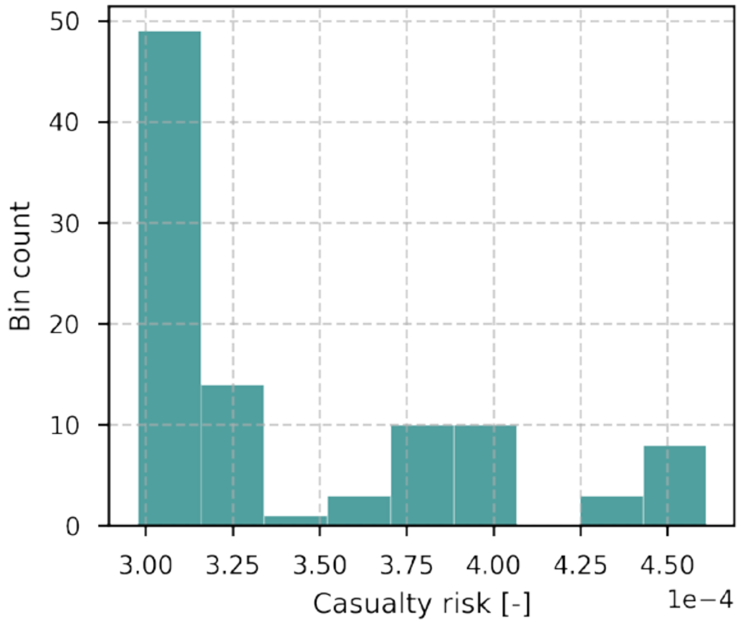
Re-entry case

Footprint and casualty risk

- Preliminary risk assessment
  - Casualty risk greater than 10^{-4}
  - Most of the drawn samples belong to the low-end of the casualty risk range
- As expected, break-up altitude and flight-path angle influence the latitude band covered and the demisability







Conclusions and discussion

- Disposal through re-entry from GEO is possible for high-inclination orbits exploiting luni-solar perturbations
  - Re-entry in less than 20 years can be achieved
- These orbits are compliant with regulations on protected regions
- The contribution of drag has been investigated
  - Can change significantly the evolution in the last part of the trajectory
- An interface between long-term propagation and destructive re-entry codes has been proposed using the concept of overshoot boundary
  - Prediction of suitable re-entry interface
  - Re-entry for most of the tested orbits remains > 0.7
  - Validity of the overshoot boundary checked with object-oriented code
- Casualty risk for a selected test case > 10^{-4}

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Credit: NASA

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