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

Francesca Letizia, Stijn Lemmens
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.

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Landgraf & Jehn, 2001
Representation of a re-entry trajectory
Letizia et al, 2017
Distribution of re-entry parameters from an orbit around L_2

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Letizia, Lemmens | 01/03/2018 | Slide 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
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
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 L₁ and L₂ (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 L₂

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

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 $A_z \geq 300000 \text{ km}$

**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

Previous work
Nominal trajectory
SNAPShot
Re-entry conditions
DRAMA
Break-up altitude
Casualty risk

Current work

$A_z$
LPO generator
SNAPShot
Re-entry conditions
DRAMA
Break-up altitude
Casualty risk
+ radiative heating
Radiative heating contribution

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

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

At high velocities \((v \geq 10 \text{ km/s})\) **radiative heating** can’t be omitted

\[ Q_r \sim R^0 \rho^1 f(v) \]

(Brandis & Johnston, 2014)
Radiative heating contribution

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(Brandis & Johnston, 2014)
Effect on the casualty risk

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

![Diagram showing the effect on casualty risk with and without radiative heating.](image_url)
Re-entry modelling

Previous work

Nominal trajectory → SNAPPshot → Re-entry conditions → DRAMA → Break-up altitude → Casualty risk

Current work

$A_z$ → LPO generator → SNAPPshot → Breakup altitude computation → Break-up altitude → DRAMA + radiative heating → Casualty risk
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)
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 $P$

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

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

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Altitude break-up definition

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

**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): $1.237 \times 10^{-3}$ (+4% case wrt case with breakup altitude = 78 km)

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