Stochastic assessment of destructive re-entry for LEO spacecraft

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Study motivations

- Understanding the impact of uncertainties in meeting thresholds for SDM compliance
  - Threshold for casualty risk on-ground: **1 in 10 000** ($1*10^{-4}$)
  - Case study analysed: **1 in 12 500** ($8*10^{-5}$)
- What is the effect of uncertainties when aiming for **SDM compliance**?


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DOCUMENT

ESA Space Debris Mitigation Requirements

Draft in Review 1

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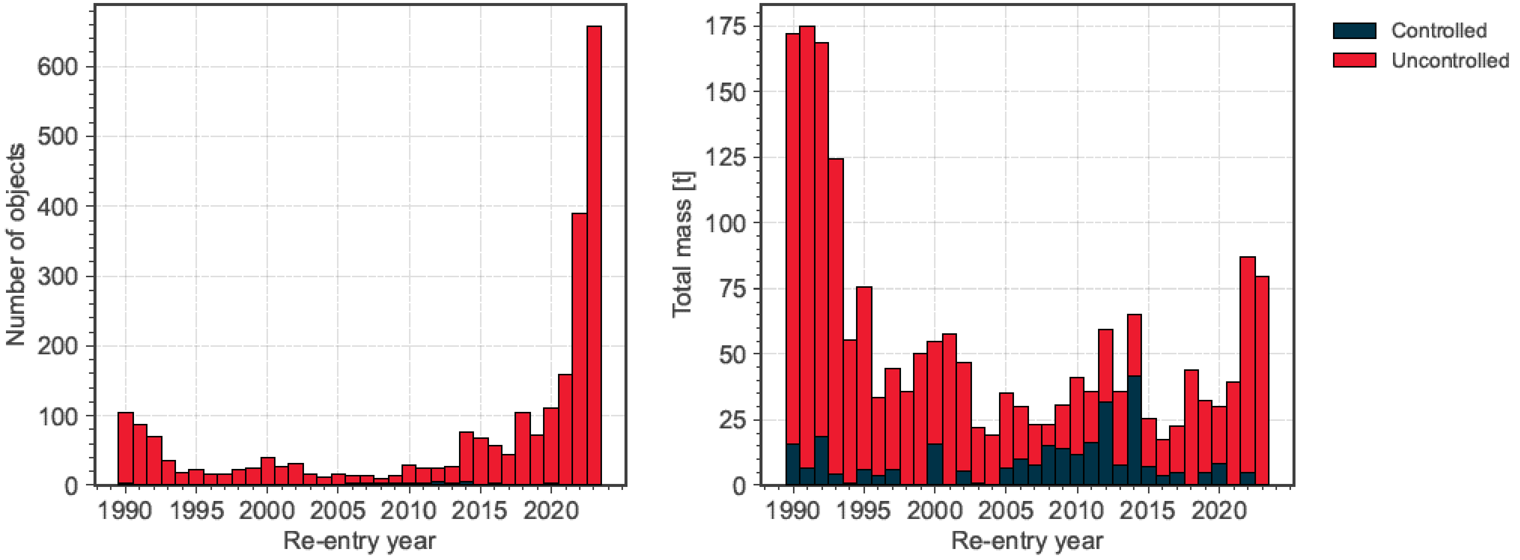
ESSB-ST-U-007
ESA Space Debris Mitigation Requirements (2023)

https://technology.esa.int/upload/media/ESA-Space-Debris-Mitigation-Requirements-ESSB-ST-U-007-Issue1.pdf



(a) Payloads: Count

(b) Payloads: Mass

ESA Space Environment Report 2024

Study objectives

- Better understand the effects of uncertainties during **uncontrolled** re-entries, with application of Monte Carlo methods
- Assess these impacts through a **case study**
- Evaluate implications with compliance to Space Debris Mitigation

Methodology (1/3) – Deterministic vs Stochastic

- Compared to deterministic models, **Monte Carlo** methods allows to:
  - Capture the **impact of uncertainties**
  - Provide a **range of possible outcomes**, and not a single result as the deterministic models
  - Scale the model for complex **multi-variable problems**
  - Identify **critical factors** affecting the outcomes through a sensitivity analysis

Methodology (2/3) – Monte Carlo key steps

- Monte Carlo approach:
  - Define input variables with associated **probability distributions**
  - Generate **random inputs** using sampling methods
  - Calculate the output for each scenario
  - Aggregate the results into **statistical distributions** (i.e. mean, standard deviation, etc.)

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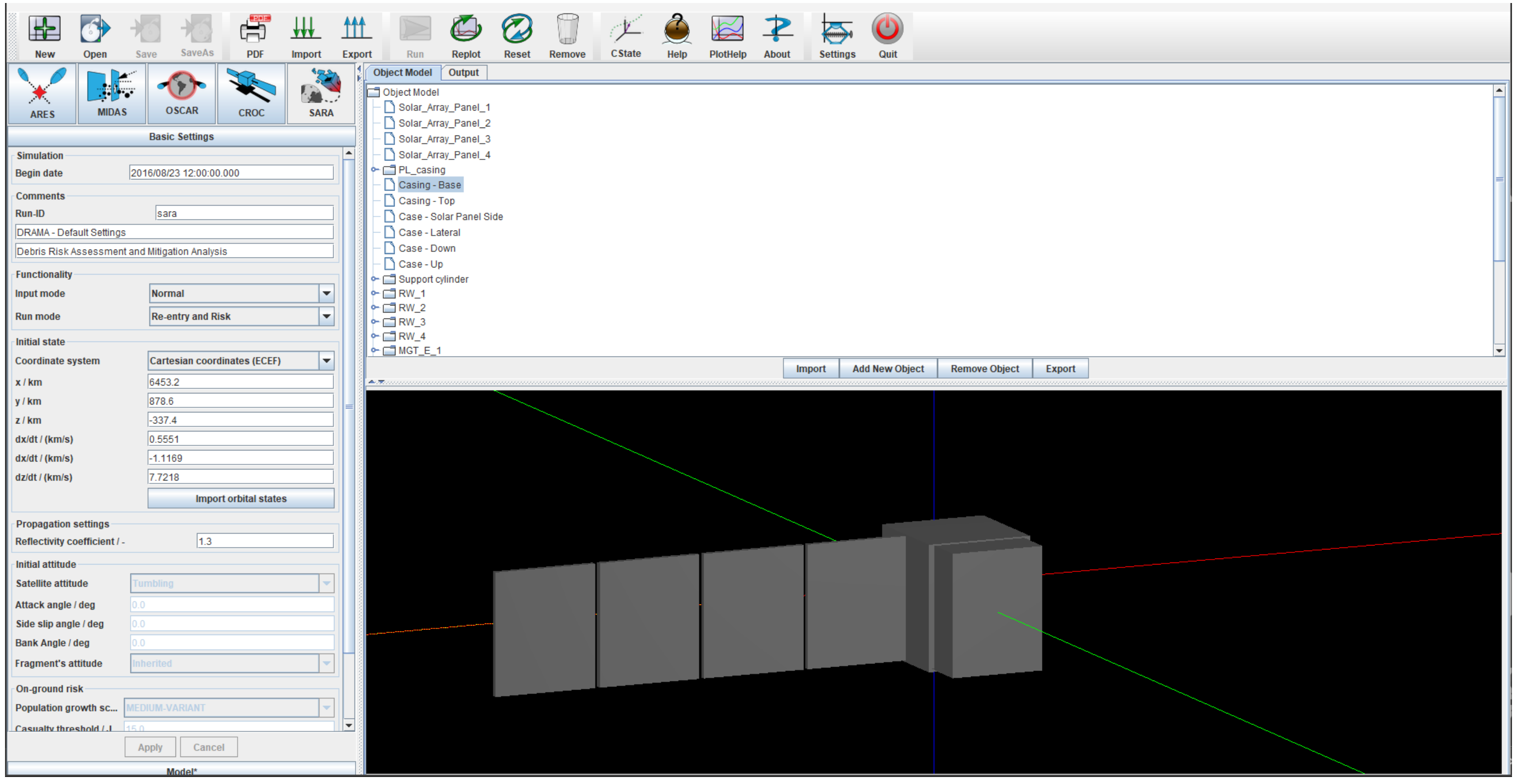
Methodology (3/3) – The uncertainties

Parameter	Uncertainty	Uncertainty reduction methods
Aerodynamic drag, continuum	± 10% uniform	Delivery of a dedicated CFD, panel based, or test analysis for a specific shape
Heat flux, continuum	± 30% uniform	Delivery of a dedicated CFD, or test analysis for a specific shape
Oxidised emissivity	± 25% triangular	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE
Specific heat capacity	± 5% normal three sigma unit	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE
Latent heat of melt	± 5% normal three sigma unit	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE
Alloys melt temperature	±30K uniform	Delivery of a dedicated test analysis for a specific material for inclusion in ESTIMATE

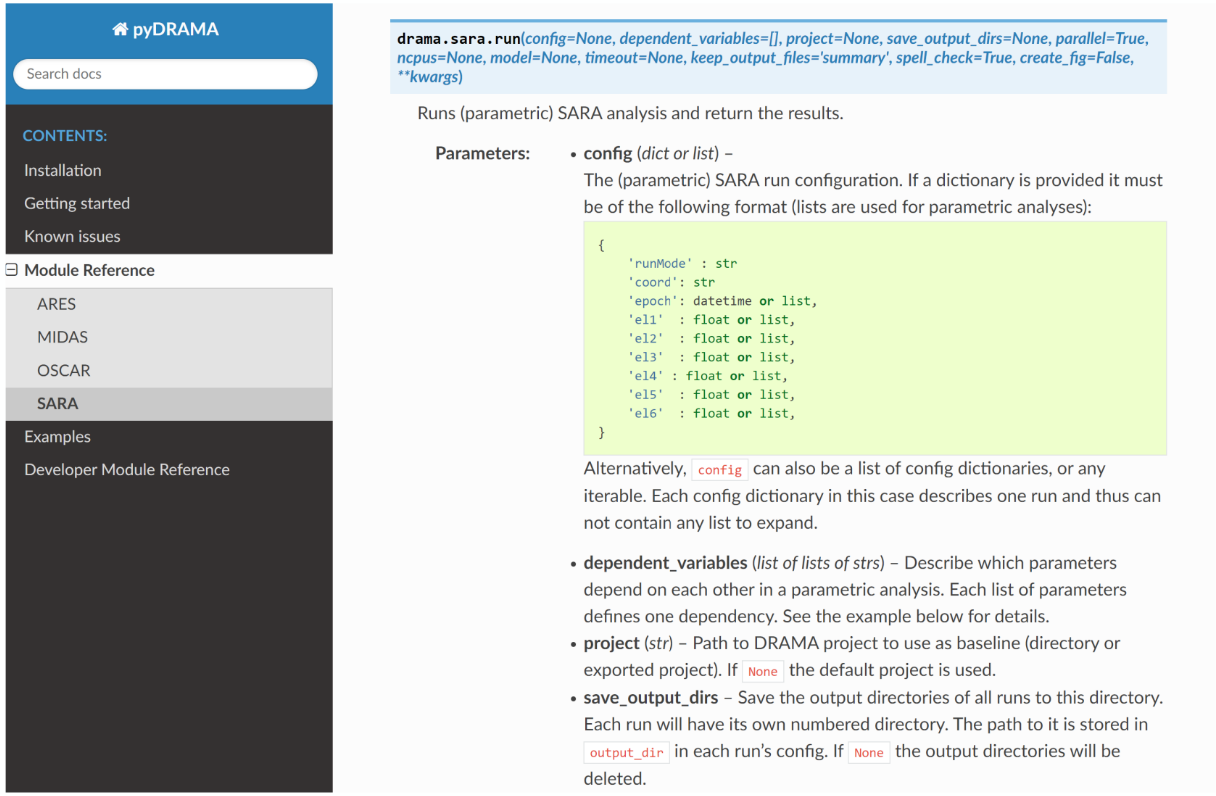
Case study – LEO spacecraft

- Small Sat with mass of **600 kg**
- Optical payload not analysed
- Critical elements equipped:
  - **3 magnetorquers**
  - **4 reaction wheels**
  - Titanium **tank**
  - **2 electronic** units
  - **Battery** module



Results (1/3)

- **2000 simulations** performed using random input variables
- Simulation tools: **pyDRAMA** and **SARA** used for modelling and analysis
- Analysed outputs:
  - **Total casualty area**
  - **Break-up altitude** of key components (e.g., ball bearings, tanks, electronics)
  - **Total casualty risk** assessment



pyDRAMA

Search docs

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Installation

Getting started

Known issues

⊟ Module Reference

ARES

MIDAS

OSCAR

SARA

Examples

Developer Module Reference

drama.sara.run(*config=None, dependent_variables=[], project=None, save_output_dirs=None, parallel=True, ncpus=None, model=None, timeout=None, keep_output_files='summary', spell_check=True, create_fig=False, **kwargs*)

Runs (parametric) SARA analysis and return the results.

Parameters:

- **config** (*dict or list*) – The (parametric) SARA run configuration. If a dictionary is provided it must be of the following format (lists are used for parametric analyses):

```
{
    'runMode' : str
    'coord': str
    'epoch': datetime or list,
    'el1'  : float or list,
    'el2'  : float or list,
    'el3'  : float or list,
    'el4' : float or list,
    'el5'  : float or list,
    'el6'  : float or list,
}
```

Alternatively, `config` can also be a list of config dictionaries, or any iterable. Each config dictionary in this case describes one run and thus can not contain any list to expand.

- **dependent_variables** (*list of lists of strs*) – Describe which parameters depend on each other in a parametric analysis. Each list of parameters defines one dependency. See the example below for details.
- **project** (*str*) – Path to DRAMA project to use as baseline (directory or exported project). If `None` the default project is used.
- **save_output_dirs** – Save the output directories of all runs to this directory. Each run will have its own numbered directory. The path to it is stored in `output_dir` in each run's config. If `None` the output directories will be deleted.

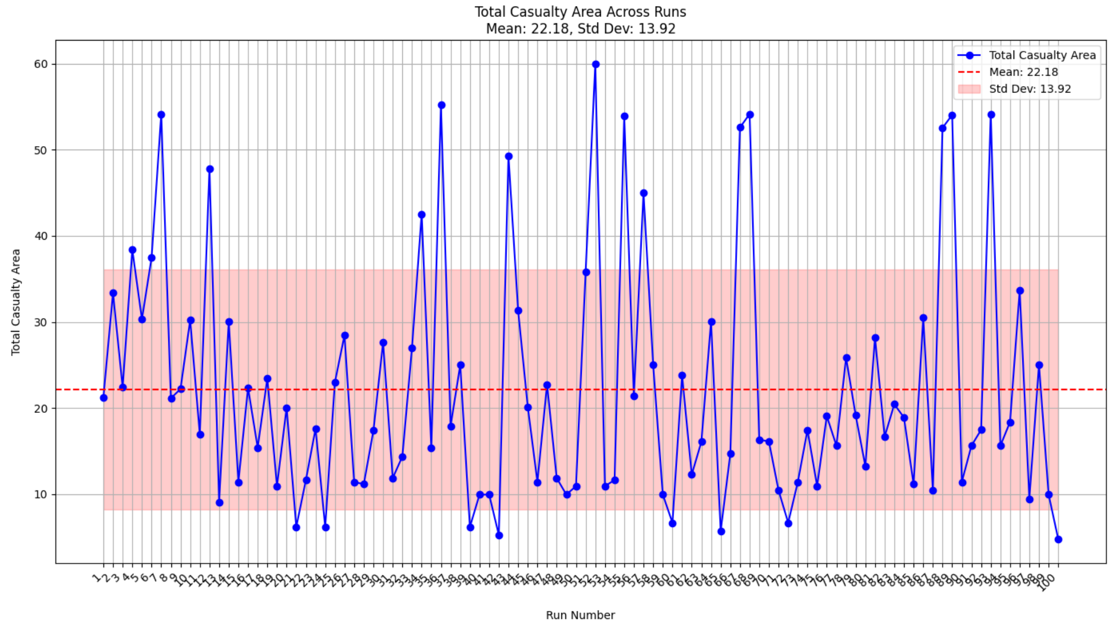
Results (2/3) – Total casualty area

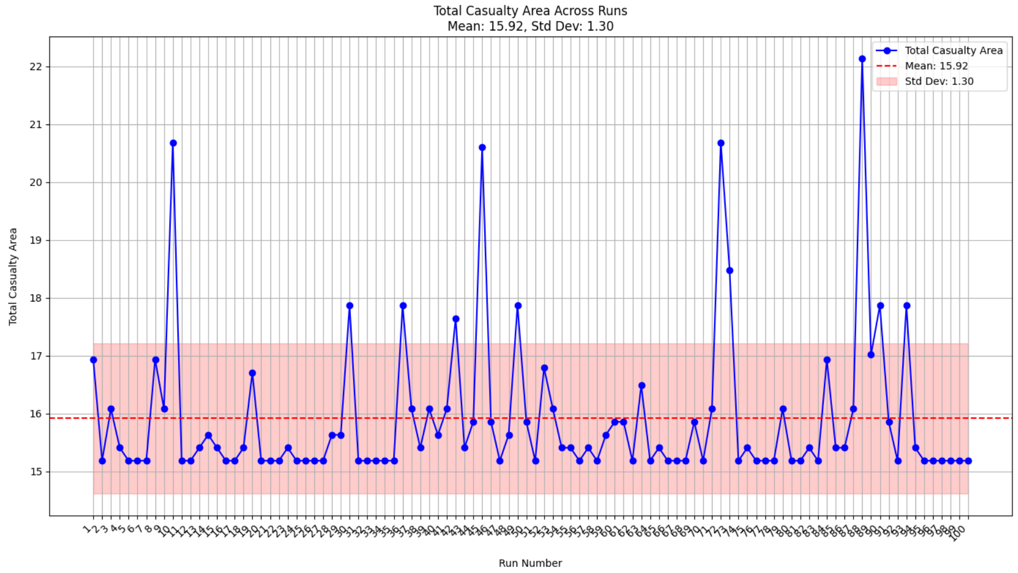
Most Impacting Uncertainty:

- **Heat Flux**: Significant influence on the casualty risk outcomes

Less Influential Uncertainties:

- **Material Properties**: Does not significantly affect the simulations
- **Atmospheric Drag**: Minimal impact on the overall



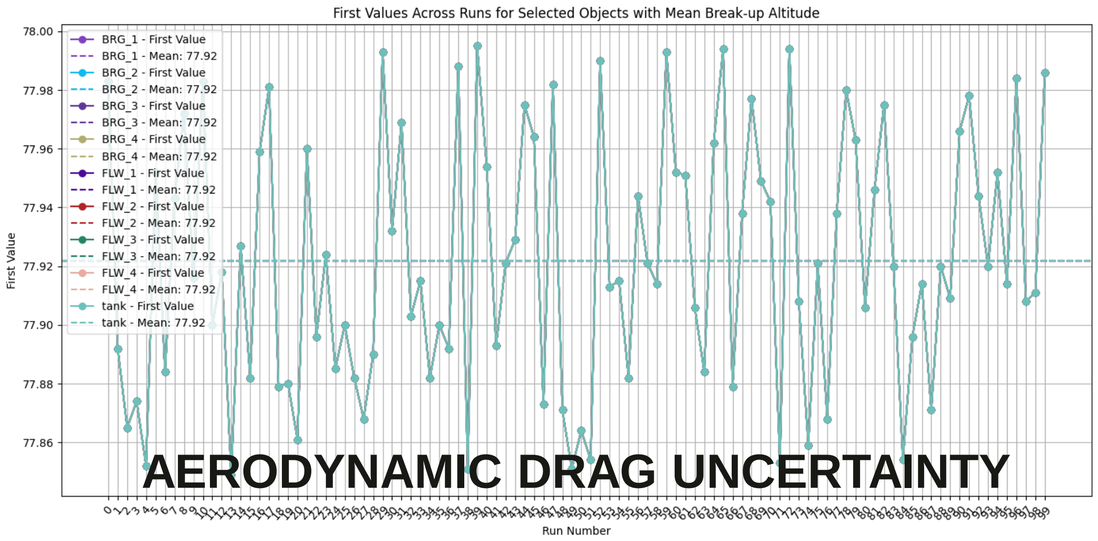


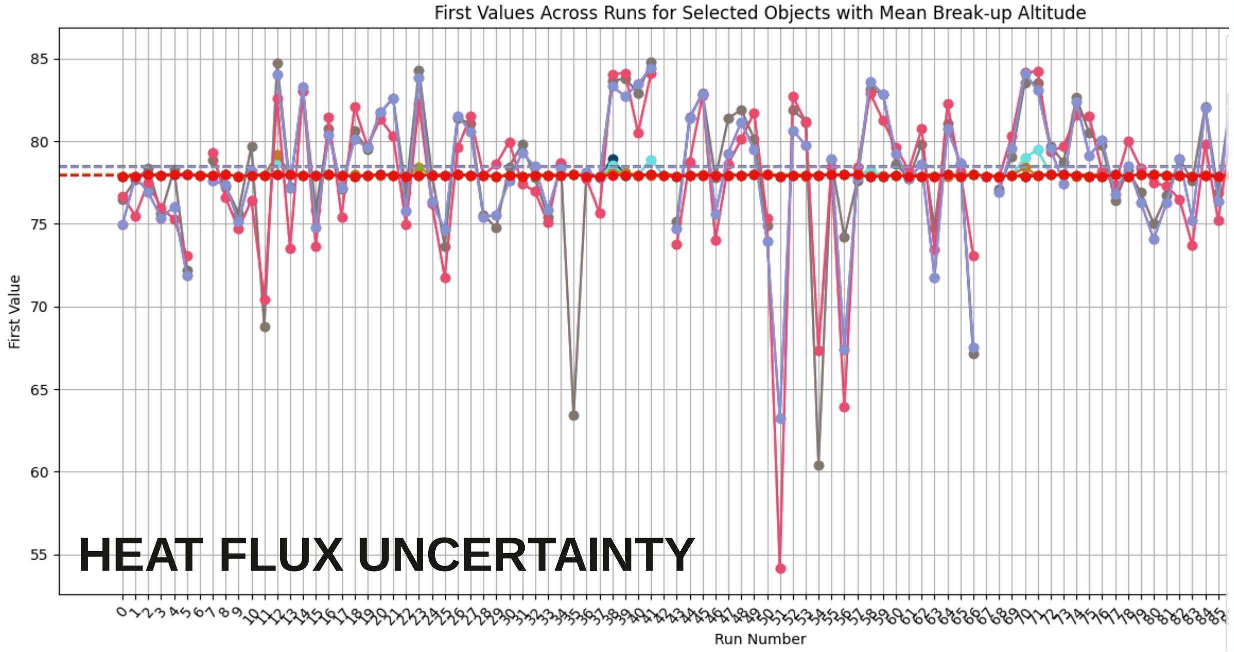
Heat flux effects

Aerodynamic drag effects

Results (3/3) – Break-up altitude

- Similar variability when analysing the break-up altitude → results affected in the same way
- Variability changes when considering different uncertainties





Conclusions

- At the spacecraft level, **heat flux** has very high impacts → High deviations from nominal values
- The **physical properties** of materials and **aerodynamic drag** have a minimal effect at the spacecraft level
- Compliance to space debris mitigation **could be compromised** due to the high variability in the results

Thank you for your attention!