PROPELLANT-INDUCED EXPLOSION RISK ASSESSMENT FOR CONTROLLED RE-ENTRIES

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ABSTRACT

The potential for spacecraft explosions during atmospheric re-entry presents a major challenge in space debris engineering. An explosion might cause fragments reaching ground with a much larger spread than without, affecting the safety area of a controlled re-entry. While significant advancements have been made in modelling re-entry dynamics, a longer standing question with limited answers remains: When does a spacecraft explode upon re-entry due to residual fuel?

This work focuses on the tank bursting extension for the DRAMA/SARA (Spacecraft Atmospheric Reentry Analysis) tool included in DRAMA 4.0, originally tested on ATV-1 (Automated Transfer Vehicle) [3]. However, this implementation simplifies the complex thermal, chemical, and structural interactions that characterise real-word re-entry explosions, leaving room for substantial refinement.

The objective of the tank bursting extension is to provide space safety and system engineers with a reliable tool for assessing controlled re-entries, where there is a potential explosion. This ensures compliance with ESA standards (ESSB-ST-U-004 and ESSB-ST-U-007). These standards emphasise the importance of controlled re-entries and accurate risk assessment, when explosive fragmentation affects impact footprints.

In this work, the sequence of events that can lead to propellant auto-ignition and explosion under extreme temperature and pressure conditions is investigated. Building on previous analyses such as the ATV-1 case [2], this work seeks to refine and validate these predictions against post-flight assessments and observational data, acknowledging the limited direct evidence for explosions during re-entry. Additionally, the novelty lies in applying the model to a component-oriented framework, allowing for realistic adjustments to the sequence of events.

Keywords: controlled re-entry; tank explosion; residual fuel; component-oriented framework.

1. TANK EXPLOSION MODEL

The SARA (Spacecraft Atmospheric Re-entry Analysis) module extension presented in this paper aims to enable users to perform tank explosion and bursting analyses and is based on the tank bursting model used in SCARAB (Spacecraft Atmospheric Re-entry and Aerothermal Breakup).

The following description and implementation of the module have been derived from the software overview in HTG's (Hypersonic Technology Göttingen) technical note [1].

1.1. Description

The logical model follows the same usual steps as the SARA modules, treating the tank shell primitive as any other primitive. It will thus receive heat during re-entry exactly the same way. Then, the temperature difference between the tank shell and its content will drive a heat transfer in either direction (shell to content or content to shell), from the item with higher temperature to the item with lower temperature.

The temperature of the tank content is considered uniform, meaning that its thermal conductivity is assumed infinite. The heat absorbed by the tank can either increase the content temperature, pressure, or evaporate the liquid content. Three phases can then be considered during the heating process of the tank (Figure 1):

1. **Liquid heating phase**: the pressure inside is given by the equation of state for an ideal pressurisation gas. During this phase, the liquid tank content volume increases due to thermal expansion. Both the tank pressure and density depend on the temperature only - pressure is calculated and density is defined in the material database.
2. **Evaporation phase**: a liquid/vapour equilibrium is assumed, meaning that the tank pressure is equal to the vapour pressure, which depends on the temperature only. All the gas constants for the pressure gas

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and the evaporated liquid are defined in the material database.

3. **Vapour heating phase**: only gaseous material forms the tank, considered a perfect gas. The tank pressure can then be calculated with the ideal gas equation.

The tank bursting pressure $p_B(T)$ is temperature-dependent and given by Equation 1:

$$p_B(T) = p_{B,0} \frac{\sigma_m(T)}{\sigma_m(T_0)} \tag{1}$$

where $p_{N,0}$ is the nominal burst pressure, T_0 the nominal temperature and $\sigma_m(T)$ the temperature-dependent maximum tensile strength.

It is then used to compare to the tank pressure p_T: if the tank pressure exceeds the burst pressure, the tank bursts. Tank bursting then either triggers an explosion or empties its contents.

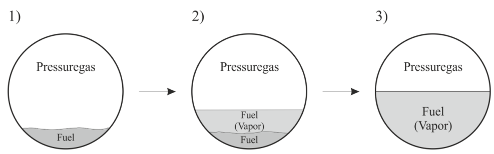

Figure 1. Tank heating phases: 1) liquid heating, 2) evaporation, 3) vapour heating. (HTG [1])

1.2. Implementation

This extension is implemented into the SARA/SESAM (Spacecraft Entry Survival Analysis Module) tool in a new `Tank` class where the thermal states of the tank content are computed and stored. Two other classes are added: `Propellant` and `PressureGas`. The module is handled inside the `Object` class, using information available in it.

Indeed, heat conduction through the tank shell depends on the shell material, thickness and inner surface area, and the temperatures of the tank shell and content. The mass of the tank content is added when the objects mass is used. The new material classes `PressureGasMaterial` and `PropellantMaterial` are added, as well as the property `strength` to the existing metal properties class.

The default XML to define a tank is the following:

```
<tank>
  <propellant>mmh</propellant>
  <propellantMass>25.0</propellantMass>
  <pressureGas>helium</pressureGas>
  <pressureGasMass>4.925</pressureGasMass>
  <contentTemperature>300</contentTemperature>
  <volume>1.694</volume>
  <nominalBurstPressure>45.0e5</nominalBurstPressure>
  <nominalBurstTemperature>293</nominalBurstTemperature>
  <explode>true</explode>
</tank>
```

Table 1. Tank XML units

Variable	Unit
`<propellantMass>`	[kg]
`<pressureGasMass>`	[kg]
`<contentTemperature>`	[K]
`<volume>`	[m^3]
`<nominalBurstPressure>`	[Pa]
`<nominalBurstTemperature>`	K

Table 2. Gas, propellant and metal materials XML units

Variable	Unit
`<weight>`	[g/mol]
`<heatOfEvaporation_c>`	[J/g]
`<heatCapacityGas>`	[J/g/K]
`<heatCapacityLiquid>`	[J/g/K]
`<coefficients>`	[–]
`<d_rho_c>`	[g/cm^3]
`<d_t_c>`	K
`<strength>`	MPa

Additionally, Tables 1 and 2 summarize all units used in the implementation of this module, where `<d_rho_c>` and `<d_t_c>` are respectfully the density and temperature at critical point, and `<coefficients>` are coefficients for the fitting functions (evolution of liquid propellant density with temperature).

2. ATV-1 STUDY

The Automated Transfer Vehicle (ATV) was a European supply spacecraft for the the ISS (International Space Station), which performed a controlled re-entry in September 2008. It broke up at an altitude of 75 km with the remaining fragments falling into the Pacific.

Before its re-entry, two studies were conducted to assess its risk of explosions during re-entry:

- The pressure and temperature conditions inside ATV's propellant tanks were monitored to quantify explosion likelihood. They found that the altitude at which the explosion happen highly impacts the ground impact: high altitude explosions strongly reduce the mass of fragments impacting the ground. [2]

- CDF (computational fluid dynamics) simulations were performed to assess the likelihood of ATV's explosion during re-entry for a propellant leakage due to structural perforation. These results showed a high risk of explosion if the propellants entered in contact with the internal flow. [3]

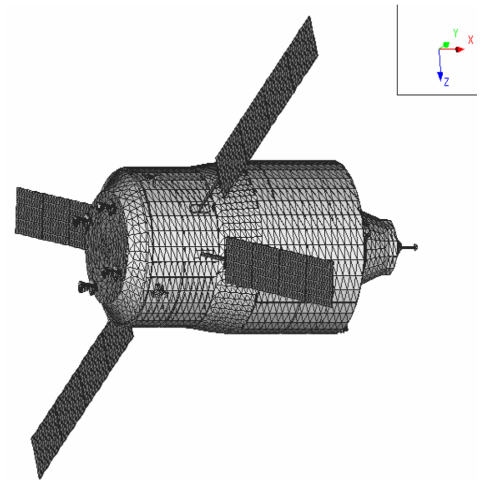

Figure 2. SCARAB model of ATV [2]

These studies allowed for the testing and validating of the SARA explosion extension, which directly benefits from their findings to ensure more realistic explosion triggers and fragmentation patterns. They highlighted the need for more accurate modelling of propellant and structural heating upon re-entry, and provided data useful to the development of the module.

3. INTEGRATION INTO SARA

3.1. Python package

With the DRAMA python package, the tank explosion extension can be used by defining a tank in the `objects.xml` file as presented in section 1.2. The `materials.xml` needs to be up to date with the tank properties previously mentioned.

3.2. DRAMA 4

DRAMA's latest version (4.1.0) directly comprises the tank explosion extension in the model definition of the satellite, as in Figure 3.

The entry parameters are the same as in the `objects.xml` of the python package (section 3.1).

4. TESTING OUTCOME

In this section, modelling recommendations emerging from a series of test are summarized.

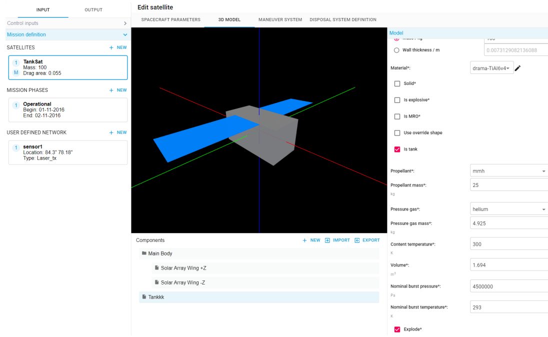

Figure 3. Tank explosion extension in DRAMA 4 GUI (see in big in Appendix: Figure 12).

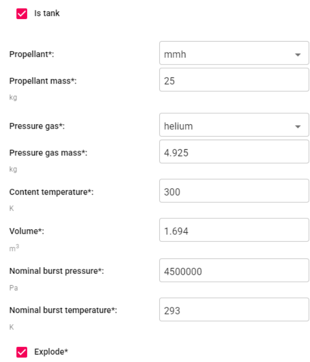

Figure 4. Tank explosion module in GUI.

For these tests, the following object was considered:

primitive	sphere
radius	0.5 m^2
mass	100 kg
material	titanium/aluminium
temperature	300 K
quantity	1

4.1. Tank material

Currently, three tank materials are suited for the analysis:

- drama-A316
- drama-TiAl6v4
- drama-CFRP

Thus, if additional materials are required, their strength properties must first be determined and added to the `materials.xml` file.

4.2. Gas/propellant combination

Different combinations of gas and propellant have been tested. Currently, modelling requires both a pressure gas and a propellant to be defined. *N.B. This should be amended in future work to allow more flexibility.*

Additionally, it has been found that a combination of nitrogen and MMH will not explode despite temperature increasing (see Figures 5, 6, 7 and 8).

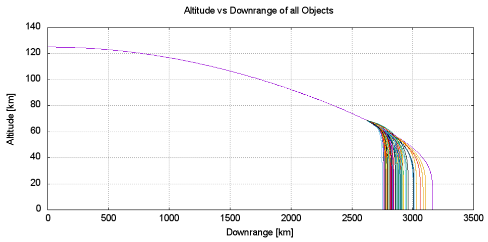

Figure 5. Altitude vs downrange of Tank for MMH-helium combination.

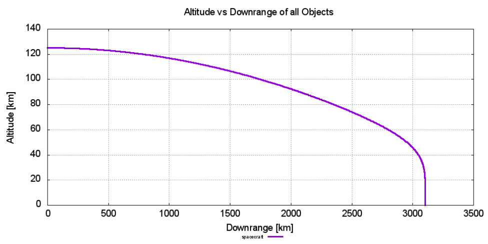

Figure 6. Altitude vs downrange of Tank for MMH-nitrogen combination.

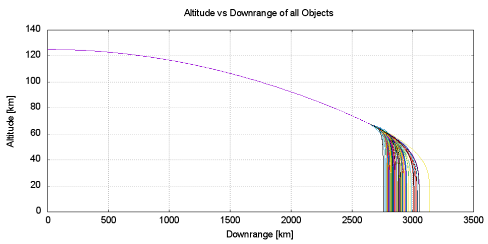

Figure 7. Altitude vs downrange of Tank for hydrazine-helium combination.

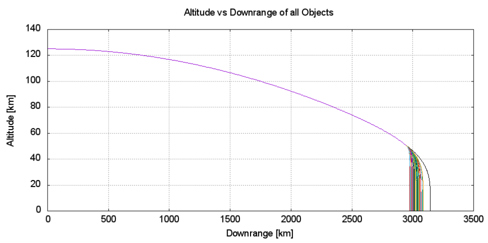

Figure 8. Altitude vs downrange of Tank for hydrazine-nitrogen combination.

4.3. NBP/NBT

Both NBP (nominal burst pressure) and NBT (nominal burst temperature) are configurable. Indeed, the nominal burst pressure is assumed to be measured at some temperature (the nominal burst temperature). Therefore, the current burst pressure is calculated by scaling the measured burst pressure with the ratio of the current strength to the strength at temperature during the measurement.

Figures 9 and 10 illustrate how, respectfully, the defined NBP and NBT influence the burst pressure of the tank over time:

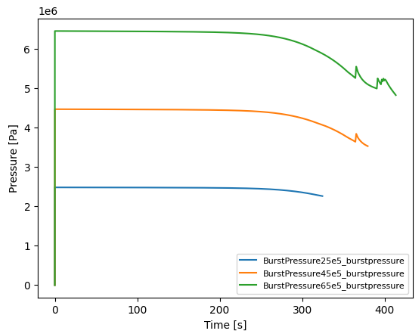

Figure 9. Burst pressure vs Time for varying nominal burst pressure.

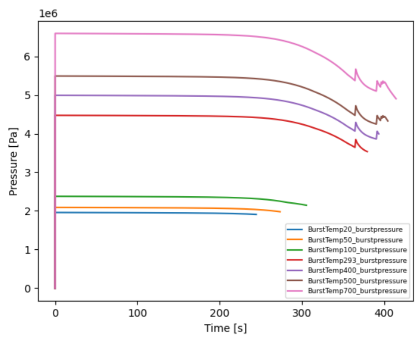

Figure 10. Burst pressure vs Time for varying nominal burst temperature.

4.4. Parent/child relations and connections

The tests have shown that in this module, a tank which is fully contained in another primitive will not heat up. Hence, it cannot explode unless its parent has already demised. In particular:

- If the tank is a child of a non-demising object, the tank will not explode.

- If the tank is a primitive, but physically inside a non-demising object in the model (like a shield), it will not explode.
- If the tank is a primitive and outside of a non-demising object, it will explode.

Additionally in these simulations, the tank explodes everything connected to it– direct connections, and connections of connections. Thus, if the tank is connected to a main body, all connections of that main body will explode too. It will not explode:

- an object that is also the child of the same parent, unless they are connected.
- objects 'near' it, unless they are connected.
- its parent, as the tank only starts to heat after the parent has demised.

In other words, if the tank explodes, it will explode all connecting parts in the same way no matter their distances from the actual explosion. For example, solar panels far away from the tank will explode into many small fragments, just as the tank shell would.

This representation doesn't seem to be entirely realistic, but presently all primitives must be connected to each other in DRAMA models. However, this is only valid for an exposed tank. To avoid this effect and enable to explode the tank only, then it must be placed inside a demisable parent object. This will ensure the connections are lost when the parent demises, and only the tank explodes.

4.5. Modelling recommendations

- Make sure all objects likely to explode near the tank are connected to it.
- Make sure the tank can receive heating (exposed primitive or inside a demisable object).
- If a tank is at particularly high risk, model it as an exposed primitive rather than as a child object (it will not heat up unless its parent, or primitive, has demised).
- To explode a tank only, and no surrounding objects, place it inside a demisable parent object.
- Presently, both a pressure gas and propellant must be defined. Do not combine nitrogen and MMH.
- Presently, tanks must be made out of drama-A316, drama-TiAl6v4 or drama-CFRP.

5. COMPLIANCE WITH ESA STANDARDS

Ensuring compliance with ESA standards for space debris mitigation (ESSB-ST-U-007 [5]), as well as re-entry safety (ESSB-ST-U-004 [6]), is a critical aspect for responsible spacecraft design and operations. The ESA SDM (Space Debris Mitigation) handbook (ESSB-HB-U-002 [7]) provides guidance in assessing compliance with these requirements via structured methods.

The SARA tank explosion extension consists another tool to help space safety and system engineers assess compliance with SDM requirements, especially those related to on-orbit break-ups and fragmentation. This explosion module can be used to:

- **ESSB-ST-U-007** – Space Debris Mitigation requirements
  - ➔ support accidental break-up probability assessment (req. 5.3.2.1), in the case where it is due to residual fuel.
  - ➔ analyse failure scenarios of spacecraft passivation (req. 5.3.2.2).
  - ➔ contribute to validation of design for demise through modelling of tank bursting effects.
- **ESSB-ST-U-004** – Re-entry requirements
  - ➔ ensure pressurised or explosive substances are accounted for and mitigated (req. 5.2.4).
  - ➔ evaluate the probability of tank explosion and resulting fragmentation, impacting casualty risk assessments (req. 5.1).
  - ➔ support simulation scenarios of controlled versus uncontrolled re-entry.

The module simulates potential explosions within spacecraft propellant tanks during re-entry. By modelling these scenarios, engineers can assess the consequences of such explosions, influencing design choices to reduce break-up risks. Integrating this extension within DRAMA 4 will enable engineers to improve the quality of their compliance assessments.

6. STEP-BY-STEP GUIDE

In this section, a step-by-step guide to configure and run a simulation of the SARA tank explosion module is provided, for a simple satellite with a basic trajectory.

6.1. Update the materials database

Update the `materials.xml` file or check the materials database on DRAMA to ensure that all tank material properties are included. If a new material is to be used, define its strength, heat capacity and conductivity, emissivity and melting properties.

Likewise, is a new propellant or gas is to be used, make sure that their thermal properties are included in the database.

6.2. Define the satellite

This can be edited in the `objects.xml` file or directly in the DRAMA 4 GUI model section (Mission definition / SATELLITES / 3D MODEL). Beside the rest of the satellite, one tank should be modelled with:

- a shape: sphere (therefore a radius) or cylinder (therefore a radius and height)
- a mass
- a material: drama-A316, drama-TiAl6v4 or drama-CFRP
- a relative position
- scaling factors
- a temperature
- tank features, as described in section 1.2.

Make sure that the `<explode>true</explode>` is set to true in the python package, or that the '**Is tank**' is ticked in DRAMA (see Figure 4).

6.3. Define the mission

This can be edited in the `sara.xml` file while using the python package, or inside the "Mission phases" section of DRAMA 4 (Mission definition / MISSION PHASES). Here, the spacecraft's initial conditions need to be specified:

- mission initial date (BASIC SETTINGS)
- initial coordinates in appropriate coordinate system (ORBIT DEFINITION)
- initial state (SPACECRAFT ATTITUDE)
- fragments attitude after break-up (SPACECRAFT SETTINGS)
- re-entry type and inclination angle (SPACECRAFT SETTINGS)
- global spacecraft temperature (Mission definition / SATELLITES / SPACECRAFT PARAMETERS)
- environment (Environment definition / REENTRY)

6.4. Run the simulation and export results

By default, the python package will plot for each simulation, the altitude of fragments versus time and versus downrange. Many other plots can be produced with the `PySara.spacecraft_TankHistory.txt` file after running SARA. This file provides data history of the tank over time: its temperature, pressure, wall temperature, burst pressure and heat.

In DRAMA 4, several plots can be viewed too: again, the altitude of fragments versus time and versus downrange, but also the trajectory of each single fragment, and 2D and 3D impact maps (see example Figure 11 below, and Figure 13 in Appendix).

Figure 11. Example of a 3D impact map.

7. CONCLUSION

This study presents a DRAMA/SARA extension aimed to enable a better assessment of propellant-induced explosions during re-entry. Initially validated using ATV-1 data, the module improves predictions of explosion likelihood and fragment dispersion, supporting assessments of compliance with ESA SDM standards. Future improvements will focus on material properties, propellant behaviour, and validation through post-flight data.

ACKNOWLEDGMENTS

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APPENDIX

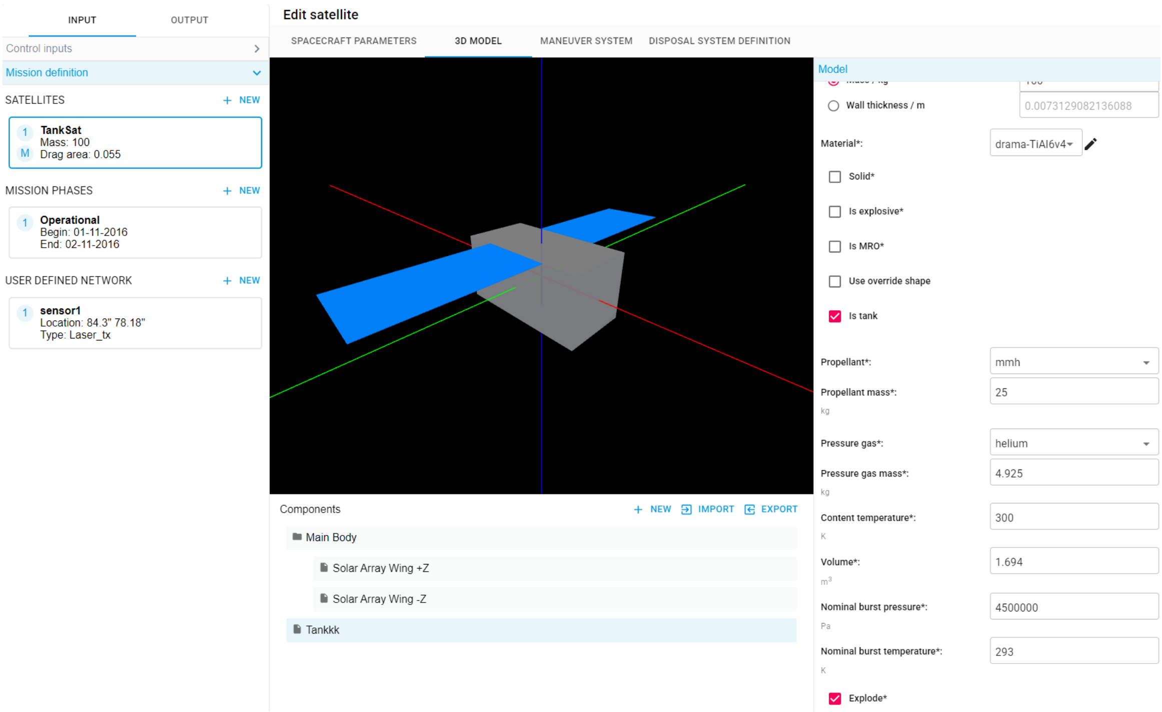

Figure 12. Tank explosion extension in DRAMA 4 GUI.

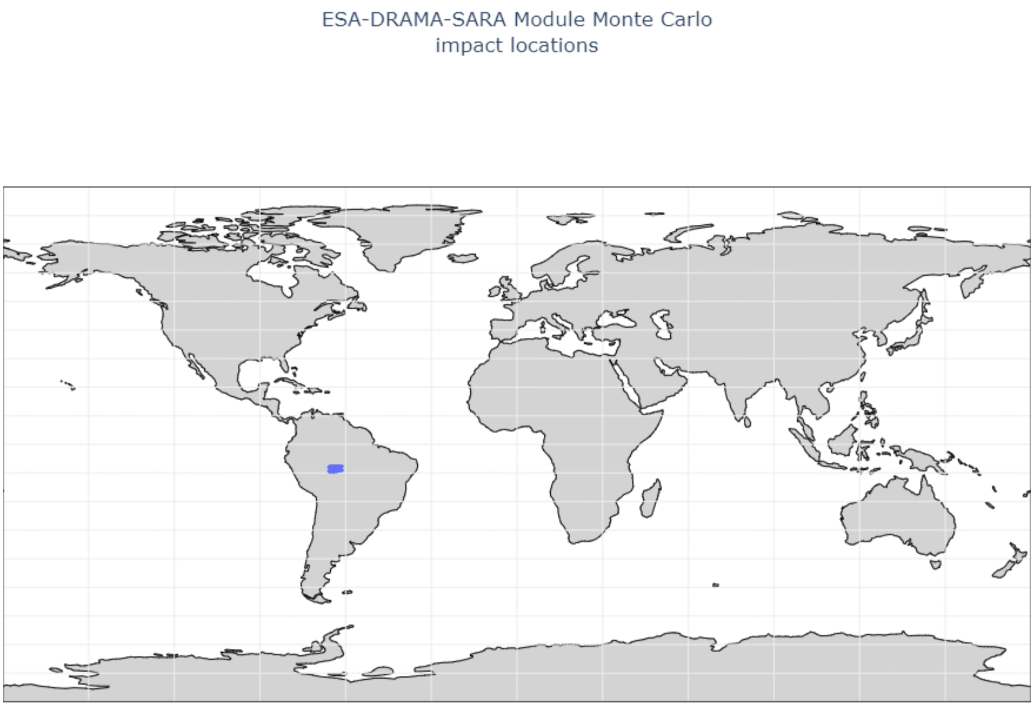

Figure 13. Example of a 2D impact map.