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ReFEx: Reusability Flight Experiment - Flight Safety Analysis

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Abstract
The German Aerospace Center project ReFEx aims to demonstrate autonomous GNC capabilities for aerodynamically controlled RLVs, its launch is scheduled for 2024 in Australia. This paper covers the flight safety analysis required by the Australian Space Agency (ASA). Monte Carlo campaigns results are used to assert that the flight termination system is capable of destabilizing the vehicle, to define impact probabilities for different ground areas, which are then use to calculate the risk of human injury for off-nominal trajectories of the reentry segment. The results show that the requirements of the ASA are fulfilled with margin.

1. Introduction

The complexity and cost of launch vehicles are a major cost driver for accessing space. Reusing launch vehicles, either partly or completely, can substantially reduce the total mission cost. The German Aerospace Center (DLR) is developing concepts for reusable launch vehicles, including both Vertical Take-off Vertical Landing (VTVL), such as CALLISTO [5], and Vertical Take-off Horizontal Landing (VTHL), such as ReFEx (Reusability Flight Experiment). ReFEx is part of the DLR effort to develop future winged reusable launcher stages and vehicles with reentry capabilities. The mission focuses on a vertical takeoff and horizontal landing (VTHL) strategy with autonomous navigation, online guidance, and controlled flight during each phase of the vehicle's mission. ReFEx does not use thrusters to reduce its kinetic energy during the reentry phase, but depends solely on aerodynamic maneuvering. A Reaction Control System (RCS) is used to control the attitude of the vehicle while in the outer layers of the atmosphere.

The flight experiment is expected to be launched in 2024 from the Koonibba Test Range, a launch facility in Southern Australia operated by Southern Launch, towards the Woomera Prohibited Area (WPA). In order to comply with Australian regulation a flight safety analysis needs to be provided to the Australian Space Agency (ASA). Key factors in the flight safety analysis are the maximum third-party collective risk (casualty expectancy number) and the maximum third-party individual risk per launch and risk areas, as detailed in the ASA Flight Safety Code 2019 [1]. In order to ensure that the mission complies with the ASA requirements, a Flight Termination System (FTS) is integrated into the vehicle, giving a Flight Safety Officer on the ground the capability of cutting power to the aerodynamic actuators, canards and rudder. The combination of the FTS with a spring integrated in the rudder destabilizes the vehicle, resulting in uncontrollable and unstable motion.

The paper first gives an introduction to ReFEx in Section 2, describing the vehicle and the different phases of the mission. Section 3 summarizes the regulatory aspects that are most relevant for the mission. The FTS design is covered in Section 4, which also verifies its functionality in the event of different failures. The computation of the touch-down envelope and expected casualty is shown in Section 5. The analysis of the Loss of signal (LOS) point range boundary distance in included in Section 6.

2. Mission

ReFEx is a demonstrator mission that succeeds the DLR SHEFEX II (Sharp Edge Flight Experiment), which was launched in 2012 [6]. ReFEx aims to perform an autonomously controlled and guided flight, following a trajectory

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representative of a winged RLV (Reusable Launch Vehicle) first stage. The vehicle will transition from hypersonic speeds (above Mach 5) down to the subsonic regime (below Mach 0.8). This section introduces the vehicle and the trajectory for the mission. A more comprehensive overview of the mission can be found in [11] [2].

2.1 Trajectory

Figure 1 illustrates the sequence of events for the mission, along with some preliminary details. The figure highlights several phases: 1) the launch phase, 2) the experimental phase until Entry Interface (EI), 3) the experimental phase between EI and End of Experiment (EoE), and 4) the experimental phase after EoE.

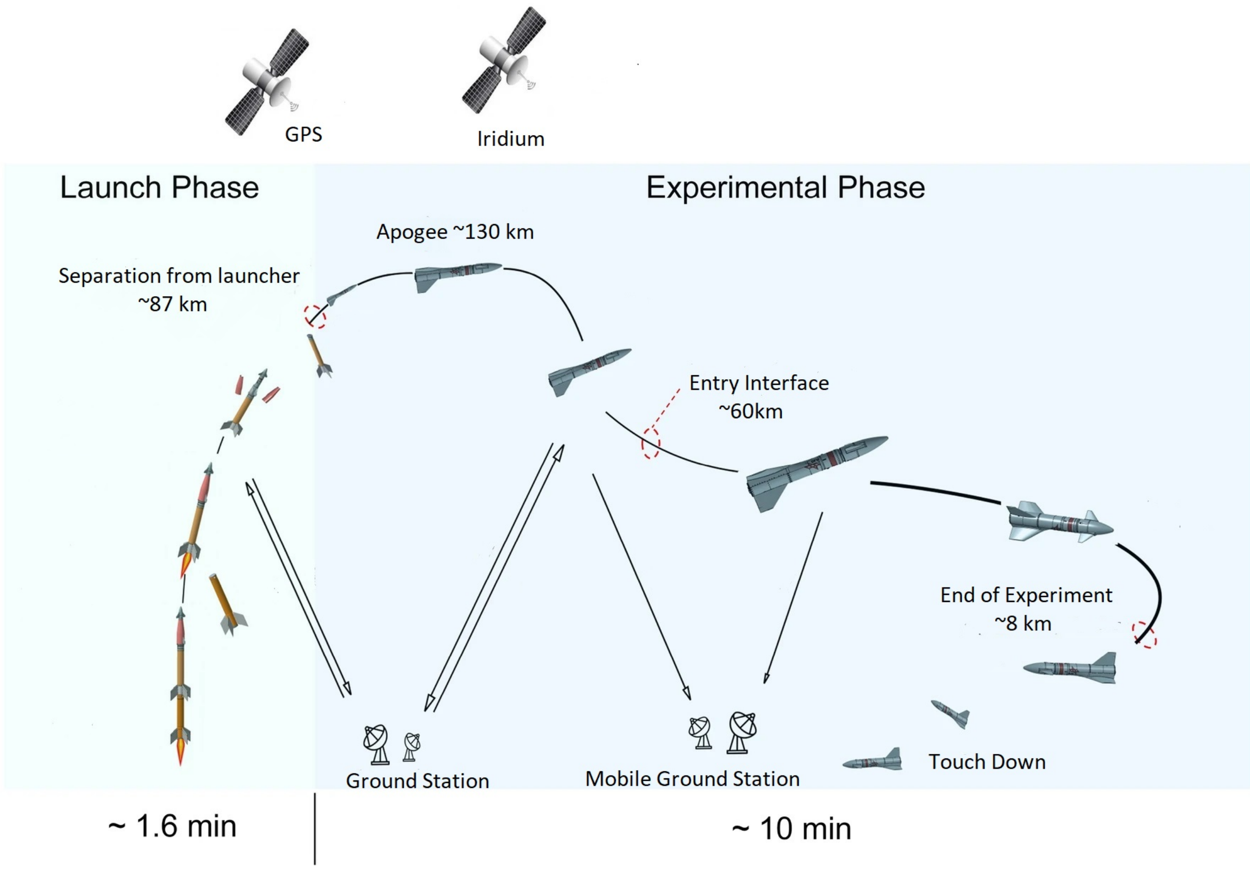

Figure 1: Mission architecture & flight events [2].

A Brazilian solid propellant two-stage rocket VSB-30 will be used during the launch phase (see Figure 2). This rocket is unguided and only passively stabilized, leading to a considerable position and velocity uncertainty at separation. During the launch phase most of the Re-Entry segment is covered using a fairing to minimize its aerodynamic effect. In addition, the wings are folded and the aerodynamic actuators are kept at a fix position by a set of pins. After the two stages are burnt out, the rocket is spun down using a Yo-Yo system and both fairing and rocket are separated.

After separation, the wings are unfolded and the aerodynamic actuators unblocked. However, until EI the atmosphere is not dense enough to aerodynamically affect the motion of the vehicle, leading to a ballistic trajectory. During this ballistic flight the aerodynamic actuators are not effective and, thus, the RCS is used to control the attitude of the vehicle. The FTS, which cuts power to the aerodynamic actuators, is not able to influence the motion of the vehicle during this phase. The EI is defined on a dynamic pressure threshold that guarantees that the vehicle attitude is aerodynamically controllable. From this point onward, the triggering of the FTS has a destabilizing effect in the vehicle.

2.2 Vehicle

The Re-Entry segment of ReFEx has approx. 400 kg of mass and a longitudinal length of 2.7 m. The wingspan is 1.1 m and the diagonal terms of the moment of inertia are approx. 15 kgm^2 for the longitudinal axis and 240 kgm^2 for the other two axes. A section view of the vehicle is shown in Figure 3.

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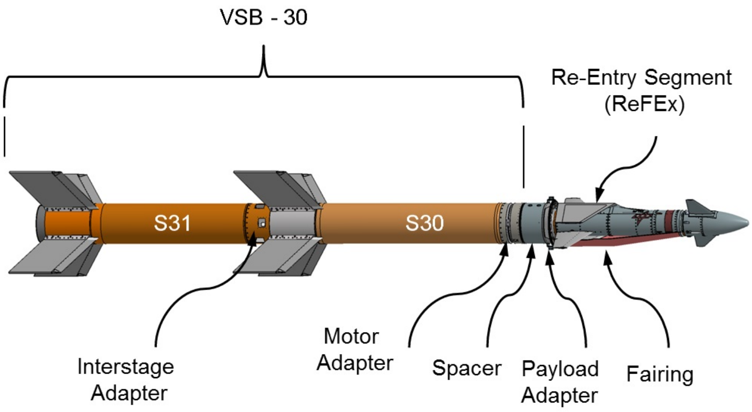

Figure 2: Launch configuration.

Several iterations on the shape of the vehicle have been undertaken through the history of the vehicle design in order to fulfill aerodynamic requirements for the planned range of velocities, i.e. from hypersonic to subsonic. The current design consists of two fixed wings located at the back of the vehicle, a fin with an attached vertical tail actuator (rudder) and two canards positioned close to the nose of the vehicle.

As the translational motion is controlled by aerodynamic forces, the actuators are used only for controlling the attitude of the vehicle. Two sets of actuators are used: 1) RCS, with 8 thrusters located at the back of the vehicle, and 2) aerodynamic actuators, with the canards and rudder previously mentioned.

3. Regulations and Considerations

Besides the main mission goals outlined in Section 2 and detailed in [10], there are several key safety requirements. These were derived from previous experiences of DLR on missions in Australia, such as support of the HIFiRE campaign, as well as existing rules from the FAA (Federal Aviation Administration). After the inception of the ASA in 2017, it published its key document concerned with flight safety: the ASA Flight Safety Code [1] in 2019. The requirements in this document apply to applicants for Australian launch permits, high power rocket permits and certain return authorizations. It describes the analysis process applicable to the flight safety analysis of launch vehicles. It now forms the basis and framework for all flight safety aspects of the ReFEx mission.

The key safety related mission goals can be summarized as follows:

1. Casualty expectancy. The maximum third-party collective risk, which is the sum of casualty risks to all individuals in the public, on a per-launch basis must not exceed 1e-04. The maximum third-party individual risk on a per-launch basis must not exceed 1e-06.

2. Range boundaries. The flight experiment shall not violate the previously agreed upon boundaries of the test range (combination of Koonibba Test Range (KTR) and Woomera Prohibited Area (WPA)), including jettisoned equipment such as fairings and spent stages.

3. Flight safety corridor. In addition to this the vehicle shall not leave a virtual safety corridor that results from MC simulations of the trajectories and a safety margin, which will have to be previously agreed upon with the flight safety authorities.

4. Control elements during powered ascent. All elements that could potentially cause a deviation in the powered ascent phase of flight (such as the canards and rudder) must be solidly locked in a fixed position which can only be unlocked through active intervention.

5. Loss of signal (LOS) point range boundary distance. The FTS system ground station is located at the range head. Since ReFEx covers a large downrange distance during its flight, at some point the primary ground station will lose track of the vehicle, since it descends below the horizon. This happens at about 10 km altitude and below. This in turn requires this point of LOS to be located so far from any range boundaries (described above), that it is physically impossible for the vehicle to reach them. Hence, even if the FTS is non-functional from this flight point onward, no harm can be done even with unintended deviations from the planned trajectory.

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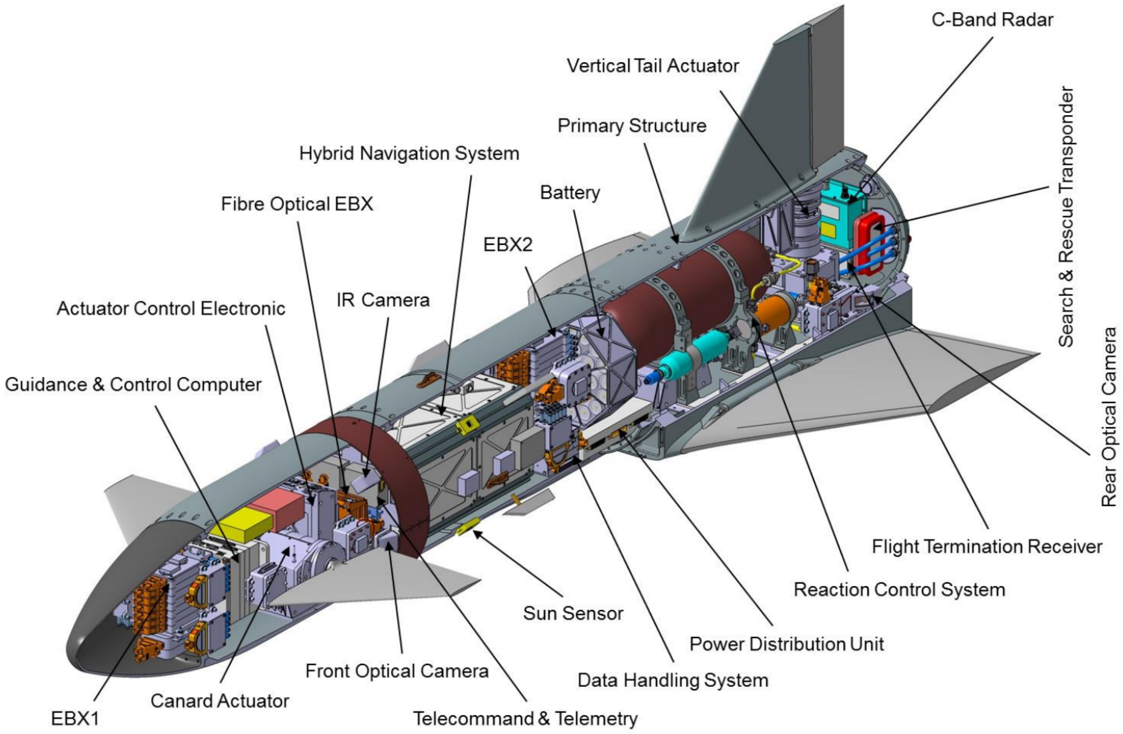

Figure 3: Section view of the Re-Entry segment of ReFEx [2].

Another key consideration is the generation of debris during nominal and off-nominal operation of the vehicle stack. During nominal operation several components of debris will be produces, such as the spent motors (S-30 & S-31), fairings (three fairing sections), ReFEx itself and yoyo-de-spin masses, all of which are inert from a debris standpoint. In off-nominal cases more debris can be produced, some of which are not inert. For example, a non-ignition of the second stage could cause such debris. In total 7 nominal debris components and 11 off-nominal ones were considered. In the latter case, a worst-case assumption was made in looking at large explosive debris components that impact at high energies.

The analyses were carried out following the ASA flight safety code [1] , which is bases on [8] amongst others. Two key critical cases were identified:

- The nominal landing of the ReFEx Re-entry segment, with a casualty area of about 2200 m^2
- The off-nominal impact produced from a failure of the second stage to ignite as well as attached payload, with a casualty area of about 12000 m^2

For the casualty calculations in the following sections, the casualty area from case 1 was used as it has the largest dispersion with the larges impact area. Case 2 leads to the stack impacting very close to the original launch site, an area that is to be previously evacuated.

4. Flight Termination System

The Flight Termination System was designed to comply with the casualty expectancy requirement explained in Section 3. It combines passive and active strategies to ensure that the Flight Safety Officer (FSO) has the capability of destabilizing the vehicle if the safety of the mission is threatened.

4.1 Functionality

During the atmospheric flight (i.e. after EI) the aerodynamic actuators, the rudder and the canards, have a extremely high influence in the motion of the vehicle. There are two main safety measures integrated in the design of the actuators:

1. The possibility of cutting power to the actuators.

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2. A spring integrated in the rudder.

The functionality of the FTS is shown in Figure 4, where the PDU is the Power Distribution Unit and the ACE states for the aerodynamic actuators. In the event the FTS is triggered by the FSO, the power lines to the aerodynamic actuators (FTS Relay Box) are cut. This effectively disables the motors of the actuators. After the motors are disabled the torque generated by the spring present in the rudder is not counteracted and drives the rudder to its end stop position (around 20°). The canards move freely and their position is not guaranteed.

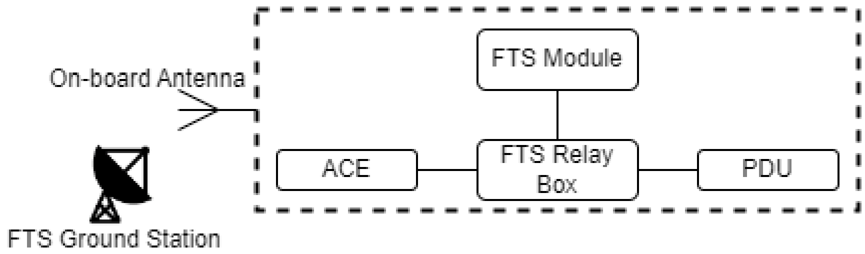

Figure 4: Functionality of Flight Termination System.

This process does not depend on a proper functioning of the actuators components, i.e. the actuator control electronics, motors or sensors, and is therefore valid even if a failure in the mentioned actuator components or a power loss occurs.

4.2 Verification

This section verifies that the FTS is able to destabilize the vehicle in any failure event. The requirement (see Section 3) that control elements during powered ascent need to be fixed, applies for the aerodynamic actuators. This adds a potential failure (failure to unlock one or more aerodynamic actuators) that can influence with the performance of the FTS. The following cases are investigated:

1. Flight Termination System (FTS) triggered
2. Known failure to unlock one aerodynamic actuator (rudder or canard)
3. Unknown failure to unlock one aerodynamic actuator (rudder or canard)
4. Failure to unlock all aerodynamic actuators

The first failure mode is assumed to cover all potential failure modes, excluding the other three presented here. These three are added due to their potential interference with the behavior of the vehicle once the FTS has been triggered. The effect of each of these failure modes is studied with Monte Carlo analysis using the end-to-end model in the loop (MIL) simulator developed by the DLR [9].

4.2.1 FTS triggered

The Monte Carlo campaign used for this analysis contains 400 runs, with a nominal mass of the reentry segment of 375 kg. The FTS is triggered at a random time (uniform distribution) between 150 and 500 s after launch. Triggering the FTS before 150 s would have an equivalent effect as triggering it at 150 s, as the vehicle is still outside the atmosphere and, thus, the aerodynamic actuator do not generate meaningful torques. After 500 s the vehicle is already at a low altitude and the vehicle would not have enough energy to leave the Woomera Prohibited Area.

Figure 5 compares the time at which the FTS is triggered with the time at which the vehicle becomes unstable. The vehicle is considered unstable when it starts spinning at more that 360 °/s.

Two regions are observed in Figure 5:

- The FTS is triggered between 150 and 300 s after launch. As the vehicle is still outside the atmosphere it does not immediately become unstable. It becomes unstable once EI is reached (between 300 and 360 s).
- The FTS is triggered after 360 s after separation. The vehicle quickly becomes unstable.

Additionally, there are 3 out-layers where the vehicle becomes unstable before the FTS is triggered. In these cases the mission would have failed even without triggering the FTS, as the flight control would not have been able to

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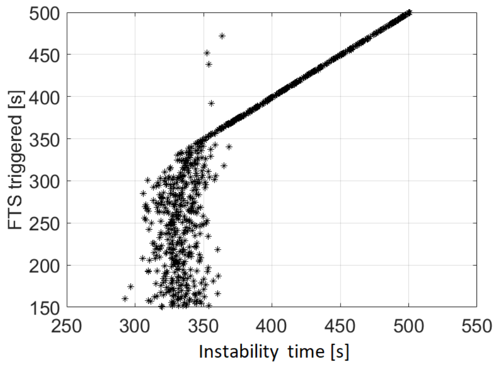
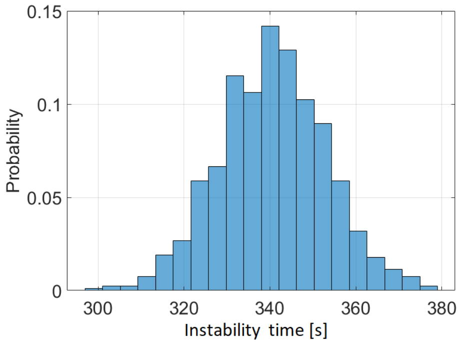


Figure 5: Destabilizing effect of the FTS

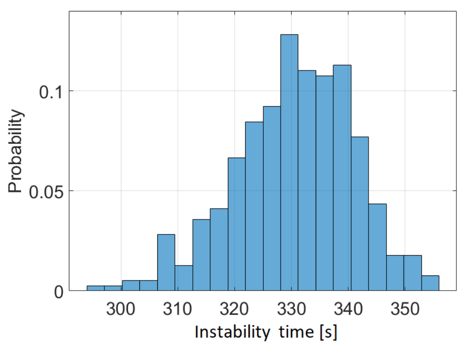
stabilize the vehicle through the initial contact with the atmosphere. These cases are expected to be removed by further improvements of the navigation control subsystem (see [9]).

4.2.2 Known partial failure to unlock aerodynamic actuators

This analysis studies the performance of the FTS in case there is a failure when unlocking one aerodynamic actuator, and this failure is detected before EI. As the failure to unlock is known, the FTS is triggered during the exoatmospheric phase. Due to vehicle symmetry, the failures to unlock right and left canard are considered equivalent. The results are shown in Figure 6. It can be observed that in both cases the vehicle becomes unstable between 300 and 360 s after launch, which is precisely when the reentry phase is starting. This confirms that the FTS retain its effectiveness in the event of one of the aerodynamic actuators failing to unlock.



(a) Right canard



(b) Rudder

Figure 6: Instability time with known failures

4.2.3 Unknown partial failure to unlock aerodynamic actuators

This analysis studies the performance of the FTS in case there is a failure when unlocking one aerodynamic actuators, and this failure is not detected. As the failure to unlock is unknown, the FTS is not triggered during the exoatmospheric phase. Due to vehicle symmetry, the failures to unlock right and left canard are considered equivalent. The results are shown in Figure 7. It can be observed that in both cases the vehicle becomes unstable between 310 and 370 s after launch, which is consistent with when the reentry phase is starting. This confirms that: 1) the failure to unlock one of the aerodynamic actuators would lead to an unstable vehicle even if it is not detected, and 2) the vehicle would become unstable at a later point than if the failure would have been detected and the FTS activated.

4.2.4 Complete failure to unlock aerodynamic actuators

This analysis studies the failure event in which all aerodynamic actuators remain locked. In this case, the knowledge about the failure is irrelevant, as the FTS does not unlocked the actuators. The results are shown in Figure 8. It can be confirmed that all cases become unstable not long after the reentry phase begins.

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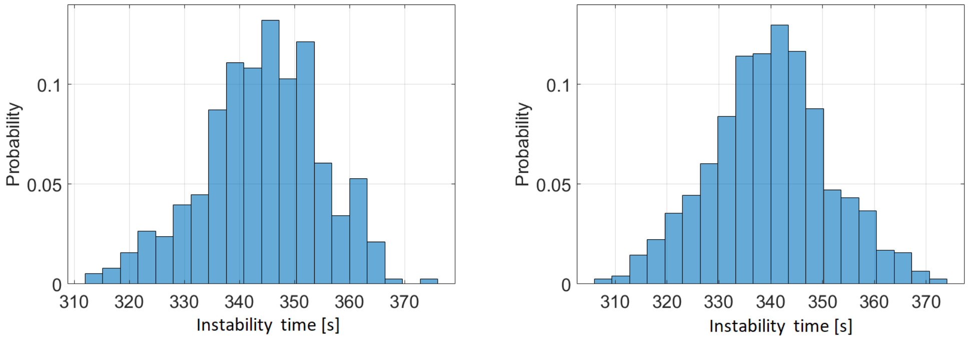

(a) Right canard (b) Rudder

Figure 7: Instability time with unknown failures

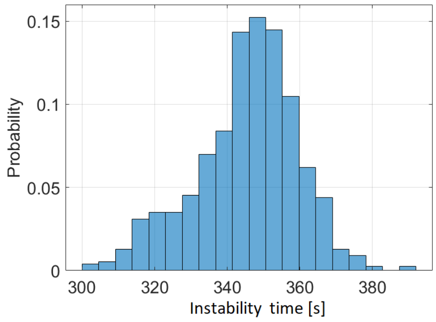

Figure 8: Instability time with all actuators locked

Figure 9 shows a comparison of the instability times for the different cases studied. It confirms that known failures (which lead to triggering the FTS) lead to the vehicle becoming unstable sooner. It also shows that the worst case scenario is when all actuators are locked.

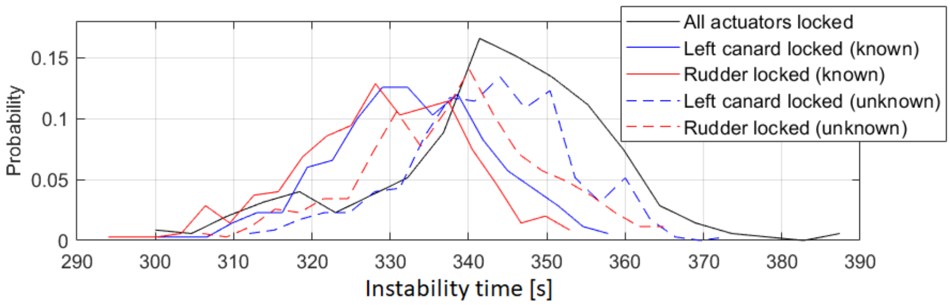

Figure 9: Comparison of instability times.

5. Casualty Expectation

The aim of this section is to verify that the mission complies with the casualty expectation requirement imposed by ASA (see Section 3). The casualty expectation E_c is the statistical number of casualties of third-party members per launch and includes all population within the considered area. Third party members are defined as all public persons except those participating in the flight experiment. The requirement can be represented by individual risk isopleths which reflect the statistical risk of casualty to an individual during launch. To show compliance with the above-mentioned Australian flight safety code and in particular to calculate the casualty expectation, extensive Monte-Carlo analyses were performed. The approaches used, assumptions and results are described in this section.

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5.1 Touch-down Envelope

The focus of the performed flight safety analysis is the experimental payload of the ReFEx mission. Thus, the state of ReFEx at separation from the launch vehicle, the tools used to calculate the trajectory as well as the logic and assumptions concerning failure during reentry are presented.

5.1.1 State at separation

The initial conditions for the calculation of the reentry trajectory are based on a dispersed dataset coming from VSB 30 ascent trajectory calculations. This set was calculated using a 6-DoF model of the ascent vehicle while imposing a range of possible disturbances on the vehicle as e.g. thrust misalignment, elevation inaccuracy and variation in aerodynamic drag. For the nominal ReFEx vehicle mass of 375 kg around 10000 ascent trajectories have been calculated. The dispersion of velocity, altitude and flight path angle is shown in Figure 10. The distribution of the state variables at separation follows a normal distribution around the nominal conditions.

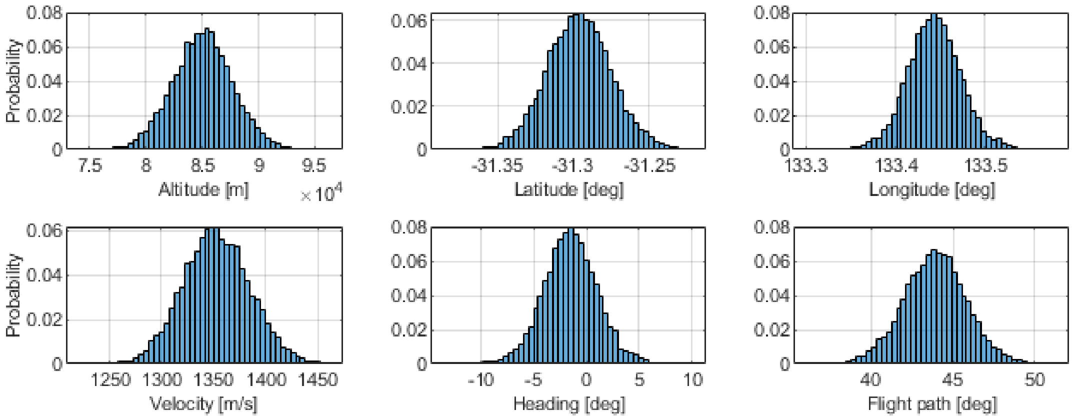

Figure 10: State dispersion after separation.

5.1.2 Failure assumptions

The performed flight safety analysis is based upon a failure probability calculation and includes a failure modelling logic. The failure probability calculation is made possible through Fault Tree and Failure Modes analysis (see [10]). The resulting value of the failure probability of ReFEx that was used in the presented flight safety analysis is 23.2%. This means that out of the entire set of trajectories performed within the Monte-Carlo analysis only 23.2% are containing a failure at some point in time. The remaining 76.8% do not contain a failure.

For those trajectories that failed, it is assumed that the FTS is triggered at the time of failure and that,based in results from Section 4, the vehicle becomes unstable soon after. The aerodynamic knowledge of the vehicle is limited, i.e. the aerodynamic coefficients are only known for a predefined envelope in angle of attack (α), Mach (Ma), angle of sideslip (β), angular rates and several other variables. When the vehicle becomes unstable the vehicle leaves this envelope and, therefore, it is necessary to define some assumptions in order to be able to model its dynamics. Predetermined distributions of α, bank angle (μ) and β are assumed (see Equation 1), aiming at providing a more conservative impact envelope than a purely ballistic flight.

$$\alpha = \begin{cases} -5^\circ & \text{if Ma} \geq 1.5 \\ 5^\circ & \text{if Ma} < 1.5 \end{cases} ; \quad \mu = \begin{cases} 180^\circ & \text{if Ma} \geq 1.5 \\ 0^\circ & \text{if Ma} < 1.5 \end{cases} ; \quad \beta = 0; \tag{1}$$

5.1.3 Simulation tools and results

Two different simulation tools have been used to propagate the trajectory until reaching the ground:

1. The ReFEx Closed-Loop Simulator.
2. TOSCA.

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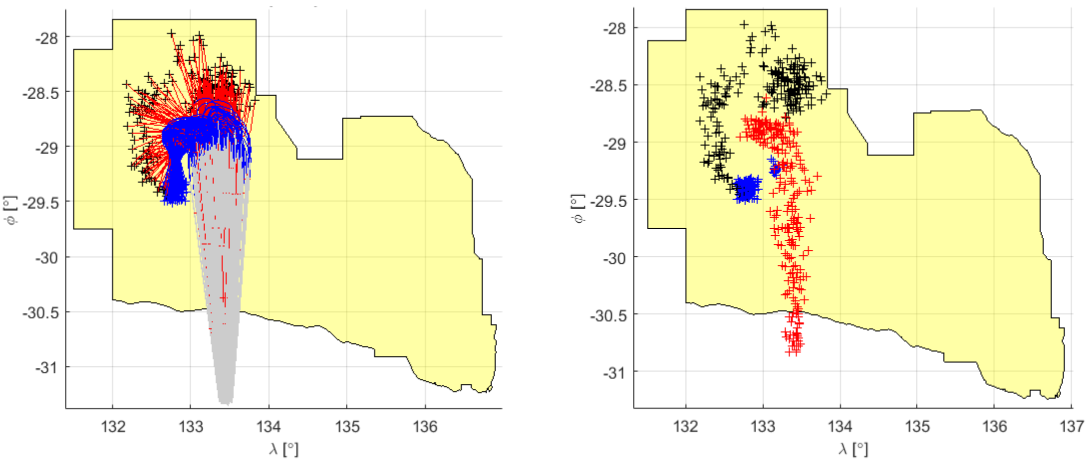
The ReFEx Closed-Loop Simulator is an internal tool developed by DLR, using heritage from several other projects. More information can be found at [9]. For this particular analysis, only the position and velocity are propagated, while the attitude is exactly the reference commanded by the Guidance module. The Guidance module updates the profiles of α and μ correction for deviations from the nominal trajectory with the objective of reaching the targets at EoE.

After the FTS is triggered, the vehicle follows the angular profiles defined in equation (1). The FTS time is selected from a random uniform distribution between 150 and 500 seconds after launch. The Monte Carlo campaign conducted for this analysis contains 1000 runs with nominal reentry mass of 375 kg. Figure 11a shows the latitude (ϕ), longitude (λ) and altitude (h) of the vehicle from separation to the touch-down. The trajectory is gray until the dynamic pressure reaches 1000 Pa or the FTS is triggered. The yellow area in the figure is the Woomera Prohibited Area. The blue trajectories are those in which the FTS is not triggered. Figure 11b shows ϕ, λ and h at which the FTS is triggered (red) and at touch-down, both for the successful trajectories (blue) and for the FTS-triggered ones (black).



(a) Trajectory

(b) FTS (red) and Touch-down (blue/black) events

Figure 11: Results of ReFEx Closed-Loop Simulator Monte Carlo campaign

TOSCA is a DLR in-house trajectory simulation and optimization program using a formulation of the full 3-DoF point mass equations of motion in the planet fixed frame. The trajectory states are propagated with a Runge-Kutta 78 method. An ellipsoidal earth with gravity coefficients J2 to J4 is used. The atmosphere is a NRLMSISE model for a specific date and time (assumed launch date and time). Wind is not considered. Tabulated aerodynamic coefficients are provided depending on angle of attack and Mach number. A pre-trimmed aerodynamic data set is used. Furthermore, profiles of angle of attack and bank angle need to be provided as an input to the trajectory calculation tool. Further details can be found in [7].

The total number of trajectories investigated in this analysis is approximately 50000. The profiles of angle of attack and bank angle are defined within the nominal trajectory design of ReFEx and are used independently of the varying initial conditions as long as the FTS is not triggered. The process of defining the nominal trajectory is explained in [3]. It is important to highlight that this tool is expected to lead to a higher touch-down dispersion compared to the first one, due to not including the guidance in the loop.

Figure 12 overlays the impact points resulting of a 1000-run Monte Carlo campaign with the ReFEx Closed-Loop Simulator and a 50000-run Monte Carlo campaign with TOSCA. The failures before or during the exoatmospheric phase lead to similar touch-down locations, at around $-28.5°$ latitude and $133.5°$ longitude. This is caused by the ineffectiveness of the guidance during this phase, due to low dynamic pressure. For the successful trajectories and those in which the failure occurs at a later time, the effect of the guidance in-the-loop is noticeable in the lower dispersion of the impact points.

5.2 Expected Casualty

The objective of these Monte-Carlo analyses is the calculation of the casualty expectation E_c. The casualty expectation can be expressed as the product of impact probability p_k, casualty area A_c and population density D_k summed over the population centers k:

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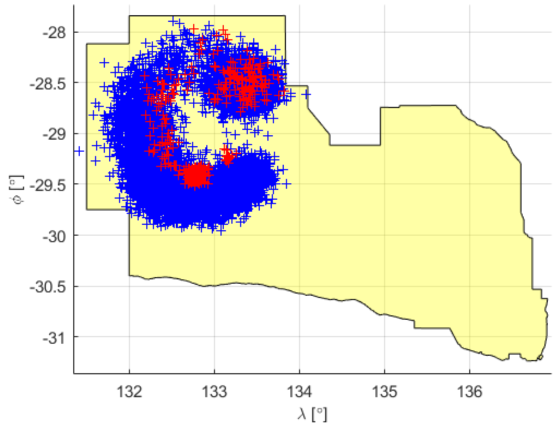

Figure 12: Comparison of impact points for Tosca (blue) and ReFEx Closed-Loop Simulator (red). Woomera Prohibited Area in yellow.

$$E_c = \sum_k p_k A_c D_k \tag{2}$$

Information on the population density in the area of the ReFEx flight experiment is taken from the Australian Bureau of Statistics and the local government of South Australia [4]. The casualty area was calculated within a fragmentation and casualty area analysis to be approximately 2200 m^2. That said, what remains to be determined for the casualty expectation calculation are the impact probabilities. This is an output of the Monte Carlo campaigns described in Section 5.1.

Once the impact points are determined, a probability density function (PDF) is derived based on Kernel Density Estimation (KDE). This allows to calculate an impact probability for every incremental area within the larger area of interest. The purpose of a KDE analysis is to derive a continuous PDF which is the sum of smaller kernels. These kernels or local PDFs are calculated based on the number of impacts per incremental area. A local probability density distribution which is Gaussian is assumed. The sum of all local PDFs then renders us the total PDF for our considered area of interest. The determination of impact probabilities allows the calculation of the casualty expectation based on equation 2. A summary of the results is shown in Table 1. The shown results are for a mass of the ReFEx vehicle of 375 kg and include the impact envelope (i.e. the area containing all impact points), the probability of range violation and the resulting casualty expectation.

Table 1: Summary of Touch-down Analysis

Simulator	**ReFEx Closed-Loop Simulator**	**TOSCA**
Impact Envelope Area [km]	24047	57629
Probability of Range Violation [%]	0.1	0.04
Casualty expectation	4.7e-07	1.6e-07

For both analyses, the resulting casualty expectation several orders of magnitude below the required threshold of 1e-04. The impact envelope area is considerably higher for TOSCA, as expected from the open-loop character of this tool. On the other hand, both the probability of range violation and the casualty expectation are higher when running the closed-loop analysis. In order to study more in detail the results of both analysis, the the impact probability including the 1e-06 risk isopleth is shown in Figure 13. The aforementioned area of interest is highlighted as light square between 131° and 134.9° eastern longitude and 27° and 30.5° southern latitude. It is including the town of Coober Pedy - as largest population center of special interest within the presented analysis. The incremental area used for the analysis is 5 km^2. The colors shown represent ranges of impact probabilities determined through KDE. The dashed black line represents the 1e-06 risk isopleth.

For the analysis based in the ReFEx Closed-Loop Simulator, several areas of interest can be identified. There is a northern down range impact area in direction of the VSB-30 ascent trajectory heading with increased impact probability. This area contains the touch-down locations of the trajectories where a failure occurs before EI. In this case, the

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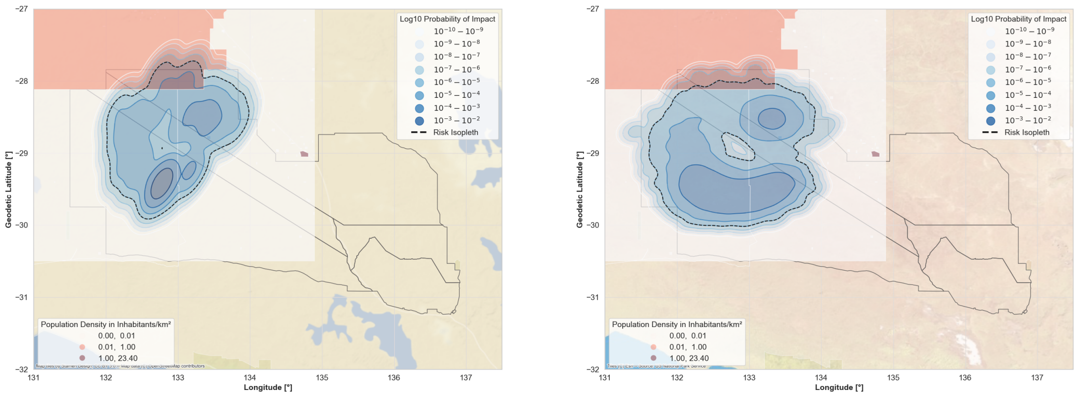

(a) ReFEx Closed-Loop Simulator

(b) TOSCA

Figure 13: Impact probability analyis.

vehicle follows an almost ballistic trajectory without any heading change. The second area of interest is the extensive area of low impact probability northwest from the target, containing the touch-down locations of trajectories in which a failure occurs after EI. Finally, there are two small areas of high impact probability, located in the southern part of the envelope. These areas contain the impact points of the successful trajectories, and they can be linked to the nominal and alternative targets. These areas show the highest impact probability, as only 23.2% of the trajectories contain a failure during the reentry flight. Figure 11b can be used to identify trajectories with and without failure.

Regarding the analysis based in TOSCA, two distinct areas of increased impact probabilities higher than 1e-04 can be seen. Similarly as with the previous analysis, there is a northern area that contains the impact points for the trajectories in which there is a failure before EI. The higher level of smoothness in the dispersion is caused by the increased number of trajectories (x50). A southern area of increased impact probability can also be identified. This area contains the impact points of the successful trajectories and of those in which the FTS was triggered at a later point in the trajectory. As expected from the comparison shown in Figure 12, the absence of the guidance corrections results in a high impact dispersion for the successful trajectories, due to the dispersion of the initial conditions and the fixed angle of attack and bank angle profiles.

The presented analyses constitute conservative approaches w.r.t. to the casualty expectation calculation. The defined failure modelling logic considers an angle of attack magnitude of 5°, which especially in the subsonic regime is close to the maximum of the lift-to-drag ratio and extends the flown range of the ReFEx vehicle. In addition, in the analysis performed with TOSCA, no guidance is applied for the reentry trajectory simulations and no adaptation of the angle of attack and bank angle profiles takes place in the presence of changing initial conditions. All that leads to a greater spread of impact points and a larger impact area envelope. Even in the presence of these conservative approaches, the casualty expectation is clearly below the threshold of 1e-04 and the 1e-06 risk isopleth is shown to be almost entirely within the WPA boundaries.

6. Loss of Signal point range boundary distance

The aim of this section is to verify that the mission complies with the LOS point range boundary distance requirement imposed by ASA (see Section 3). Approximately at 10 km altitude, the primary ground station is expected to lose the signal of the vehicle. From this point the activation of the FTS is not feasible. Therefore, it needs to be ensured that, for trajectories that are successful until this altitude, the vehicle is no longer able to leave the WPA. This requirement is converted into a minimum distance of 51 km between the vehicle and the boundaries of the WPA, when the vehicle reaches an altitude of 10 km. Figure 14, uses the same Monte Carlo analysis shown in Figure 11a, excluding the failure cases. It shows the latitude and longitude of the vehicle when reaching 10 km altitude (in blue), in red the region of the WPA within a 51 km distance from the boundary and in yellow the red of the WPA. It can be observed that the distance to the boundary is respected with margin.

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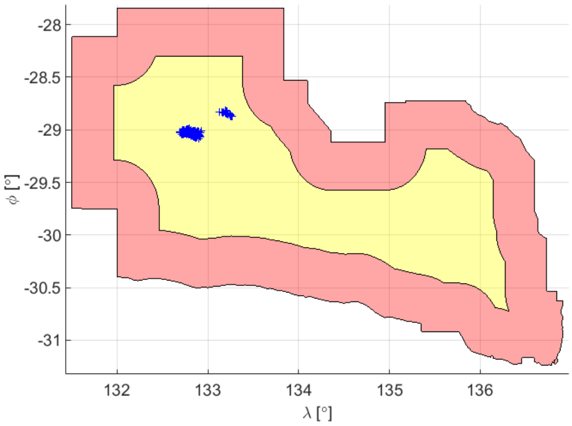

Figure 14: Vehicle position at 10 km altitude. In yellow WPA with more than 51 km distance to boundary.

7. Conclusions

There are safety measures in place to ensure that the expected casualties are within the regulatory limits. The FSO has the capability of cutting the power to the aerodynamic actuators via an independent FTS. It is confirmed that the triggering of the FTS would destabilize the vehicle, also after accounting for other failure modes. A conservative model of the dynamics of the unstable vehicle is implement to study the impact region of the vehicle in case of failure. Both open-loop and closed-loop Monte Carlo campaigns are performed to investigate the distribution of touch-down locations. These are then used to compute the casualty expectation, confirming that it is within the safety requirements. The LOS point range boundary distance requirement is also verified.

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