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ReFEx: Reusability Flight Experiment – A Demonstration Experiment for Technologies for Aerodynamically Controlled RLV Stages

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Abstract
The Reusability Flight Experiment (ReFEx) is a technology demonstration flight experiment to gain developmental and operational experience with a fully aerodynamically controlled reusable launch vehicle stage. It is slated to launch from Koonibba test range in South Australia in 2024 using a VSB-30 sounding rocket to inject it into a trajectory typical of returning stages. Key factor is to demonstrate the capability to autonomously initiate return flight trajectory to the launch site using only aerodynamic means and reach designated waypoints. The project is currently in the final stages of AIV and organisational activities such as applying for a launch license. This paper gives an overview of the main systems and focuses on a system level FMECA approach used to identify failure response modes for the flight safety analysis.

1 Introduction
Since the first successful landing of an orbital stage rocket in 2015, reusable launch vehicles (RLV) have transitioned from being an interesting experiment to a regular and normal event. Because of this shift many new launch vehicle developments incorporate partial (such as Electron, Neutron, Firefly Beta, Spectrum) if not full reusability (Starship, Terran R, Firefly Gamma).

The reasons for this shift have grown beyond the simplistic argument of reduced costs. Aspects such as higher reliability of flight proven systems, increased cadence while keeping the (expensive) manufacturing lines small and higher responsiveness (rockets in storage are available on short notice) and not to forget sustainability are just a few of many arguments in favour of re-use.

To realise these partial or fully RLVs there are in principle two main methods available: propulsive or aerodynamic return. Both are viable options but depend heavily on the set of requirements driving the launch vehicle design. For example, aerodynamic return is well suited for a stage, which is meant to travel between LEO and Earth. By contrast if the requirement for the same stage changes to be able to also land on multiple planetary bodies, some of which might be without a suitable atmosphere, then obviously a propulsive return is required. As such there is not one optimal RLV but rather a suitable design for the desired application and both approaches (or a mix thereof) have a place.

With this in mind DLR has embarked on the challenging task of exploring both ends of the RLV methodology spectrum, by conducting (or taking part in) two flight experiments. One being CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations) conducted in cooperation with CNES and JAXA, which is focused on vertical landing technologies, while the Reusability Flight Experiment (ReFEx) is focused on an entirely aerodynamic means of return. This puts DLR in the unique position in Europe to be able to gain design, development, manufacturing as well as operational experience in both approaches. In addition, flight data from both experiments will be invaluable to validate methods and models. The goal is to have the knowledge base available to advise other stakeholders in Europe on how to develop the right next generation RLV for Europe.

This paper will focus on ReFEx and give an overview of the project that has been in development since 2018 and will fly in 2024 from Koonibba Test Range (KTR) in Southern Australia (see section 7).

1.1 Mission

The main mission requirements for ReFEx can be summarised as follows [1]:

- "The vehicle shall perform an autonomously controlled flight from hypersonic to subsonic velocities to a predefined point in space (latitude, longitude, altitude) with a predefined terminal velocity, following the typical Mach-profile as a function of altitude of an aerodynamically controlled stage."
- "The vehicle shall perform a controlled heading change. The angle between a line connecting the apogee and the entry interface (EI) and a line connecting the EI and end of experiment (EoE) shall exceed 30°"
- "Reach a prescribed target point (EoE) within a certain accuracy (altitude, velocity and geographic position)"

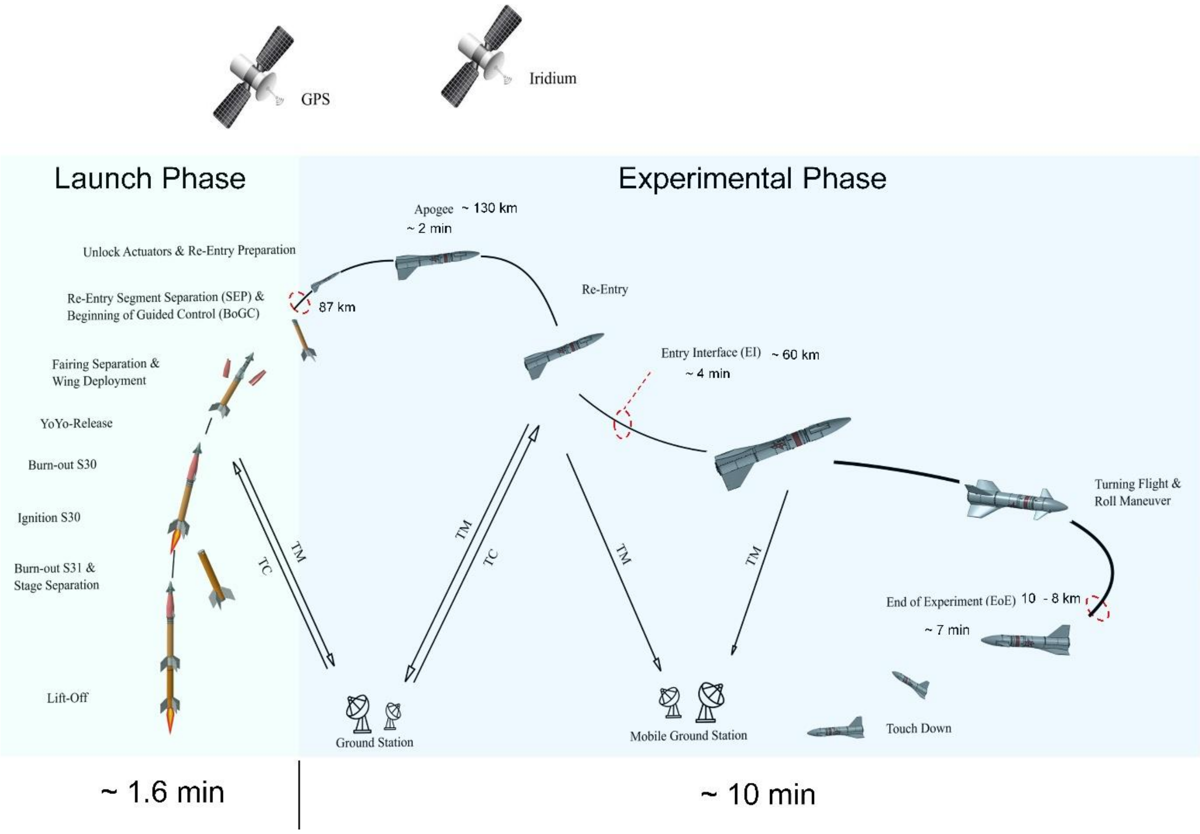

Figure 1: ReFEx mission events and timeline

These lead to flight events as shown in Figure 1. Upon launch on a VSB-30 sounding rocket (provided by MORABA) de-spin and separation from the carrier vehicle, the main flight experiment will begin. It is interesting to note that the launch vehicle had to be specially adapted to accommodate ReFEx. Since the ascent takes place on an unguided sounding rocket it naturally provides higher than usual dispersion on the returning vehicle at the beginning of guided control (BoGC). Due to this dispersion, a predefined end-point can sometimes (in certain extreme cases) not be reached. This will be compensated for by the highly adaptive GNC system and serves as a demonstration test case. Considering a future (expensive) RLV stage that is off-course but otherwise technically sound, it would be much preferable to divert to a contingency landing site than to abort the vehicle. Hence, the guidance software is capable of autonomously diverting ReFEx to previously defined contingency landing sites, demonstrating a key safety and operability feature for future RLV stages.

Returning to the events seen Figure 1, following burn-out of the second stage the stack is de-spun using a yoyo-system. This is closely followed by separation of the triple split fairing and then of the ReFEx re-entry segment itself. Once in free flight ReFEx will unfold its wings, which were stored underneath the fairing and unlock its exo- and intra-atmospheric flight controls. These were physically locked and prevented from operation during launch for safety reasons.
For control outside of the atmosphere ReFEx uses a small reaction control system (RCS) (see section 3.1), while canards and a rudder are used for aerodynamic control (see section 4).

Initially during the early phases of flight, ReFEx uses an inverted flight orientation to control its trajectory (see also Section 2) Upon reaching Mach 1.5 in the lower atmosphere it performs a roll manoeuvre to the “normal” belly-down position (which henceforth is the preferred flight orientation) and continue the flight to EoE.

The main demonstration goal for ReFEx is to reach the end of experiment (EoE) target conditions, which are a set of coordinates associated with a specified volume in space, as well as a velocity of Mach 0.8 or below. Automated landings in this subsonic flight regime are well demonstrated and ordinary daily occurrences.
However, the flight will continue to be guided to minimize impact energy and avoid certain no-go areas, where the vehicle could be very difficult to recover in order to preserve the on-board data recorders, which provide a wealth of additional information over the pure telemetry.

2 Trajectory Design

As ReFEx is a flight experiment to demonstrate the technologies required for a fully aerodynamically controlled return flight of a RLV stage, the appropriate trajectory design is a key feature of the flight experiment. When looking at returning RLV stages of different type one can notice that these stages always try to follow a certain corridor. Figure 2 shows the typical flight paths of different RLV concepts and also operational RLV stages.

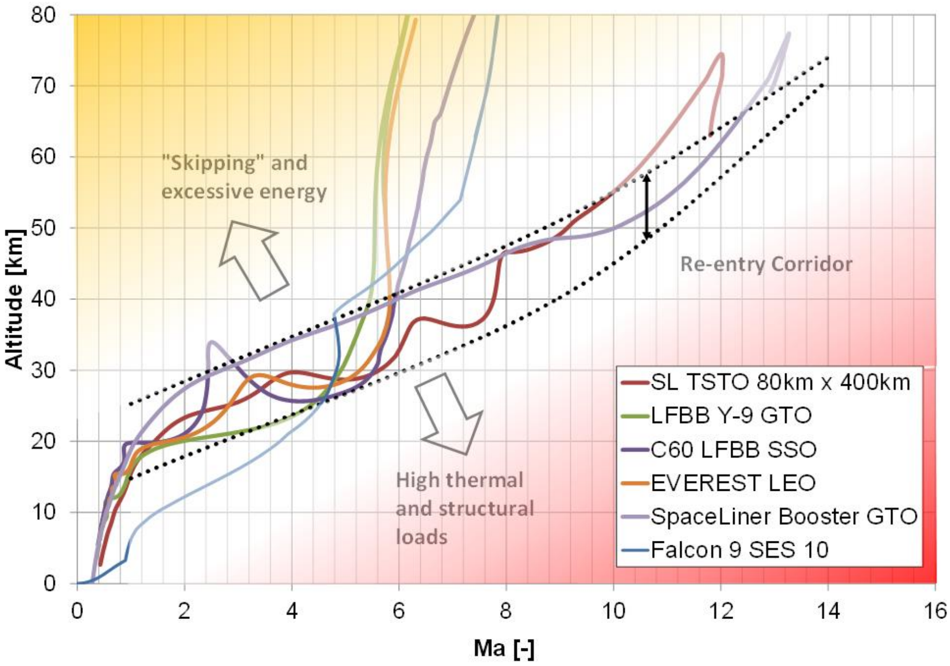

Figure 2: The RLV corridor

It is clearly visible that all of the concepts as well as operational vehicles, even the ones with propulsive return (F9 SES 10) fall into a typical corridor of altitude vs. Mach number. This corridor was dubbed the RVL corridor and it is the region of flight, where a returning stage neither experiences undue thermal and mechanical loads, nor wastes energy due to skipping in a too shallow trajectory.

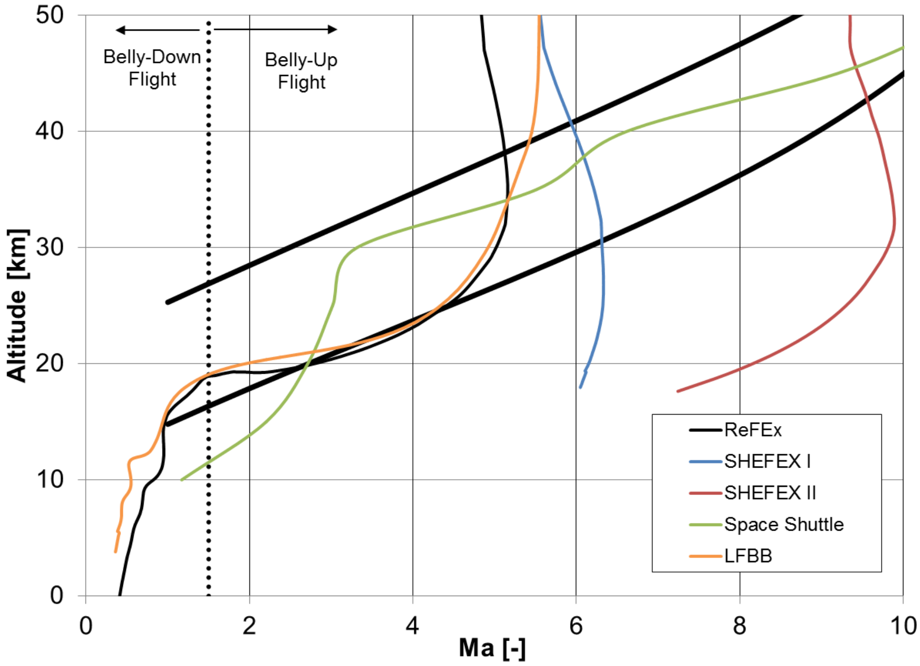

Figure 3: Re-entry corridor with ReFEx and previous flight experiments (SHEFEX), Shuttle and the Liquid Fly Back Booster Study

ReFEx will also follow this RLV corridor, as can be seen in Figure 3, while being slightly on the lower end of the corridor one should keep in mind, that the corridor is not a hard border and that ReFEx as opposed to an operational returning stage is much more dense (higher ballistic coefficient), since it does not contain any empty fuel tanks [1]. In addition, ReFEx performs a turn manoeuvre to return toward the launch site in order to demonstrate the capability of return, necessary for a RLV and as stipulated in the main mission requirements set out in Section 1.1.

ReFEx performs a roll manoeuvre during its return flight, which would also not be the case for an operational stage. The main reason for this is the stability along the longitudinal roll axis. Due to its high angle of attack (AoA) during early phases of the return the rudder would be in the wake of the main fuselage, would the vehicle fly the "right way up". This would render it ineffective. The Space Shuttle faced a similar situation and compensated by using a powerful hot-gas RCS, which is not an option for the small and compact ReFEx, leaving the inversion as the only viable option. The argument here is, that if the flight controller is capable of performing such a manoeuvre reliably in the experiment, it would be easily able to control a more benign operational stage. One always has to keep in mind that ReFEx was specifically chosen to test the limits of full aerodynamic control of returning RLV stages. More details on the trajectory design of ReFEx can be found in [2].

3 GNC Subsystem

To realise the flight performances described above a sophisticated guidance, navigation and control (GNC) system is required. The goal for the GNC system is to reach the target ellipsoide which was previously specified at EoE. This system takes over control after separation from the passively controlled launch vehicle and initially conducts a onetime overall trajectory planning and updating step, to confirm the main target location. This is necessary since the dispersion at handover is much larger than would ordinarily be the case with a guided ascent [2]. As such the main target location is not always reachable from these states, necessitating a diversion to previously specified contingency landing sites. For an operational RLV this is a desirable situation, as a diversion and landing are much preferable to the current practice of flight termination.

Once the final trajectory has been generated toward the final EoE, a guidance algorithm takes over, which runs at a lower frequency and compares the desired with the measured state, updating the trajectory to compensate for control, navigation and modelling errors. The measured state is provided by the hybrid navigation system (HNS), which uses a suite of sensors to determine the location and attitude of ReFEx. These include an inertial measurement unit (IMU), global positioning systems (GPS) and flush air data system (FADS) as well as sun sensors. The sun sensors are used during exoatmospheric flight to refine the navigation solution, which might have degraded due to the spin stabilised launch. FADS allows to measure the attitude of the vehicle relative to the local atmosphere, which is critical to compensate for the effect of wind. The data from all these sensors is then fused to provide the measured state.

Finally, a fast running control algorithm runs underneath the guidance algorithm and provides short term actions for the actuators to achieve the desired flight attitude and follow the prescribed trajectory despite various disturbances and uncertainties. Details of the GNC algorithms can be found in [3].

3.1 Exoatmospheric Control

In order to re-orient ReFEx during exoatmospheric flight a RCS is used. Its main task is to reduce any residual rotational rates after yoyo deployment and re-orient ReFEx into the correct attitude for the entry interface. Since the RCS is limited in thrust it is crucial to achieve a smooth transition from RCS to aerodynamic actuator control. In addition to this the RCS can perform a special manoeuvre to orient the sun sensors toward the sun to aid in the refinement of the navigation solution after separation from the launch vehicle. Details of the RCS can be found in [4].

In addition, the control algorithms described in section 3 is only applicable for the flight inside the atmosphere. For exoatmospheric flight a specialised controller is used, which is based on a PD-controller with a deadband, to also account for fuel limitations as well the discreet behaviour of the thrusters. Details on the exoatmospheric control system can be found in [5].

4 Aerodynamic Design

Another key feature to enable aerodynamically controlled RLV is the aerodynamic design. Especially in the early design phases this poses a challenge as the establishment of an aerodynamic database is very resource intensive, requiring many CFD (computational fluid dynamics) calculations. As a consequence, early design relies heavily on first order approaches and simplifying assumptions. However, since these sometimes miss critical aspects of the aerodynamic coefficients, which have a large impact on the overall feasibility of the design a design initially thought feasible, might turn out to not be controllable at a later stage, when more details are available. This in turn requires revisiting and sometimes re-doing large portions of the previous database. This iterative process is time consuming and not completely avoidable.

For ReFEx a large aerodynamic database was established using DLRs TAU code [6], which forms the basis for the flight control algorithms described in the previous section. In addition, several wind tunnel experiments were performed at specific critical points [7] and one such investigation were experiments on the heatflux and shock interactions on the forward section of ReFEx, conducted at the HEG in Göttingen on a ¼ scale model. Details of this can be found in [8].

5 Vehicle System Design AIV

Finally, to bring the flight experiment to fruition all the components and subsystems have to be brought together and their intended function has to be verified. This is the task of assembly, integration and verification (AIV), which is performed at the DLR Institute of Space Systems in Bremen. Here, the processes of AIV themselves are also a topic of research and constant improvement. Current focus lies on using robotic assistance as well as supplemental databases and augmented reality to assist the AIV process. Since the Institute only assembles prototypes and experimental vehicles, the processes have to be flexible enough to handle systems from RLV, to satellites, to even planetary exploration surface vehicles [9].

In order to evaluate the reliability and safety of the vehicle, a FMECA process tailored to the specific missions is implemented. For ReFEx this process was key in identifying critical functions and their failure modes and is described throughout the next section.

6 Failure Modes, Effects and Criticality Analysis (FMECA)

The ReFEx system-level FMECA has been developed according to the definitions of the ReFEx Product Assurance Plan which are based on ECSS-Q-ST-30-02C [10]. This analysis has been prepared on hardware level and covers the *ReFEx payload* which consists of the *re-entry segment* and the *launch support structure*. It identifies for each equipment failure modes, causes and their resulting effects. Additionally, recovery or compensation means (FDIR) for each failure mode are given within the analysis. The FMECA includes a criticality analysis by determining a Criticality Number (CN) for each failure mode and a summarization of Single Point Failures (SPF) and critical items.
It also aims for the identification of Failure Response Modes (FRM) in order to support the ReFEx flight safety and risk hazard analysis (see [11]).
A short summary of relevant FMECA definitions will be given in the following.

Table 1: Definition of severity categories and Severity Number (SN)

Severity category	Dependability effects	Safety effects	SN
Catastrophic	Failure propagation	- Loss of life, life-threatening or permanently disabling injury or occupational illness - Severe detrimental environmental effects - Loss of launch site facilities	4
Critical	Loss of mission	- Temporarily disabling but not life-threatening injury, or temporary occupational illness - Major detrimental environmental effects - Major damage to public or private properties - Major damage to interfacing flight systems - Major damage to ground facilities	3
Major	Major mission degradation	-	2
Minor / Negligible	Minor mission degradation or any other effect	-	1

Table 2: Probability levels, limits and Probability Number (PN)

Level	Limits	PN
Probable	$P > 0{,}1$	4
Occasional	$0{,}001 < P \leq 0{,}1$	3
Remote	$1E^{-5} < P \leq 0{,}001$	2
Extremely remote	$P \leq 1E^{-5}$	1

The Criticality Number (CN) shall be calculated as the product of the ranking assigned to each factor: $CN = SN \cdot PN$. As a result of this equation, CN is defined in the criticality matrix as follows in Table 3:

Table 3: Criticality matrix

		Probability level			
		10^{-5}	10^{-3}	10^{-1}	1
		PNs			
Severity category	**SNs**	**1**	**2**	**3**	**4**
Catastrophic	**4**	4	8	12	16
Critical	**3**	3	6	9	12
Major	**2**	2	4	6	8
Minor/Negligible	**1**	1	2	3	4

6.1 Failure Response Modes and Mission Reliability Prediction based on FMECA

In the further course of the FMECA the Failure Response Mode (FRM) concept has been applied which takes into consideration that many failure modes often result in the same overall system behaviour respectively FMECA end effect. In an FRM group, all failure modes with the same failure response respectively end effect are aggregated. FRMs identify the response of the vehicle to a given failure or group of failures ([12] and [13]).
Following the FRM concept, all Critical Items of the ReFEx FMECA with a SN of 3 and 4 are summarized according to the failure *end effect* in the following table. Only launch (ascent) and experimental (descent) phase failure modes were considered (see Figure 1).
In the following table FRM-R denotes *Rocket* and FRM-P *Payload* (i.e. *launch support structure and* ReFEx *re-entry segment*) related FRMs.
$\mathbf{P_{max}}$ denotes the summed Probability of occurrence worst case (i.e. maximum) limits as defined in Table 2 for all in each FRM grouped failure modes [12]. The arithmetic average of all $\mathbf{P_{max}}$ values in each FRM has been calculated in column $\mathbf{P_{max,\ mean}}$ in order to compensate the unequal distributed number of identified Failure modes in each FRM and additionally discrepancies in the qualitative PN selection which is predominantly based on expert's judgement.
Hence, the overall Probability of Failure Occurrence is 23.2% and consequently the Probability of Mission Success is 76.8%.

Table 4: Failure Response Modes and probability numbers

FRM Id.	FMECA Id.	Item / block	Failure mode(s)	Failure response / end effect	Mission phase	PN	P_{max}	$P_{max,\ mean}$
FRM-P #1	Nominal mode/trajectory							
FRM-P #2	02, 03	PDU, Battery	Complete functional failure of PDU / Battery	Single units or all units of re-entry segment not supplied with power. Loss of mission. Complete power loss of re-entry segment during ascent phase before separation from second stage will result in locked actuators (both canards and rudder) and vehicle is unable to re-orient using RCS.	Launch phase	2	2,00E-03	1,00E-03
FRM-P #3	02, 03	PDU, Battery	Complete functional failure of PDU / Battery	Single units or all units of re-entry segment not supplied with power. Loss of mission. Vehicle aerodynamic control surfaces become unpowered: Canards freewheeling, rudder goes into full lock max deflection (compare FTS activation).	Experimental phase	2	2,00E-03	1,00E-03
FRM-P #4	06, 07	Wing folding mechanism +/-Y	Deployment failure	Impossible unfolding of +/-Y wing. Loss of mission. Aerodynamically unstable - ballistic trajectory.	Launch phase	2	2,00E-03	1,00E-03
FRM-P #5	15, 23, 24, 28, 96	RCS / GCC to RCS CANopen interface	Various RCS internal failure or GCC Interface failure	Loss of RCS. Planned Entry Interface won't be met. Mission loss.	Launch phase / RCS phase	2 to 3	1,04E-01	2,08E-02
FRM-P #6	37, 41, 43, 50, 56, 58, 59, 60, 63	Aerod. actuators - left / right Canard	Various	Left or right canard freewheeling. Included in simulation of FTS activation.	Experimental phase	2 to 3	4,05E-01	4,50E-02

FRM Id.	FMECA Id.	Item / block	Failure mode(s)	Failure response / end effect	Mission phase	PN	P_{max}	$P_{max, mean}$
FRM-P #7	54, 55	Aerod. actuators - left / right Canard	Various	Left or right canard stuck at 0°	Experimental phase	1 to 3	1,00E-01	5,00E-02
FRM-P #8	66, 70, 72, 79, 85, 87, 88, 89, 92	Aerod. actuators - rudder	Various	Loss of Rudder actuation with Rudder pushed against aeroloads by spring	Experimental phase	2 to 3	4,05E-01	4,50E-02
FRM-P #9	83, 84	Aerod. actuators - rudder	Various	Rudder stuck at 0°	Experimental phase	1 to 3	1,00E-01	5,00E-02
FRM-P #10	93, 94, 97, 99, 100, 101, 107 to 110, 118, 119	GCC / HNS	Various	Vehicle cannot be controlled. Position and Velocity estimation performance degrades. Mission loss.	Experimental phase	1 to 3	2,06E-01	1,72E-02
FRM-R #1	09	Payload adapter	Separation failure	Prohibits 2nd Stage Motor Separation from Payload. Possible disintegration. Loss of mission.	Launch phase	2	1,00E-03	1,00E-03
FRM-R #2	52, 53	Aerod. actuators - left / right Canard	Various	Unlocking during ascent and left or right canard freewheeling	Launch phase	1	2,00E-05	1,00E-05
FRM-R #3	81, 82	Aerod. actuators - rudder	Various	Loss of Rudder actuation with Rudder pushed against fairing / aeroloads by spring	Launch phase	1	2,00E-05	1,00E-05
							Probability of Failure Occurrence	0,232
							Probability of Mission Success	0,768

7 Campaign

ReFEx is slated to launch from Koonibba Test Range (KTR) in the summer of 2024, where the launch range is provided by Southern Launch and the launch service provided by DLR Mobile Rocket Base (MORABA). Since a lot of infrastructure is slated to be brought and set up a large campaign of about a month is foreseen for the launch. Infrastructure includes a main and a down-range telemetry station, as well as a radar, launcher and temporary integration facilities at the launch site.

ReFEx would launch on a northerly trajectory and reach down-range distances of more than 300 km. This was also the reason for the choice of Southern Australia as the launch site, since it is the only available one allowing for such down-ranges and land recovery. Land Recovery was a key requirement to preserve the on-board data recorders, without the added complexity and risk of an ocean splashdown.

Details of the campaign planning can be found in [14].

7.1 Flight Safety

A key factor for the successful conduction of the flight experiment is flight safety. Even though this is an experimental vehicle and it is launched in an area with very low population density, the utmost care must be taken to conduct the experiment in as safe a manner as possible. One key factor here was the FMECA described in section 6, which provides the basis for failure response modes of the vehicles, which have to be individually modelled to provide a casualty expectancy. This is a number specified by the Australian Space Agency Flight Safety Code [12] and has to be lower than about 10^{-6}, i.e. a likelihood of causing a casualty of less than one in a million. Details of how this was modelled from a trajectory simulation point of view can be found in [11].

8 Conclusion

This paper gives an overview of the Reusability Flight Experiment (ReFEx), which is aimed at gaining, design, flight and operational experience with a fully aerodynamically controlled RLV. Several subsystems and components necessary for the mission were highlighted and further details were referenced in specific papers. In this paper a special focus was put on the FMECA analysis and how it impacts flight safety, by providing the basis for failure response modes.

ReFEx is slated to launch in the summer of 2024 from the South Australian Koonibba Test Range, to verify the developed design tools for aerodynamically controlled RLV stages and provide valuable input for future decisions on European RLV systems.

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