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ReFEx: Reusability Flight Experiment – A Project Overview

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Abstract
The Reusability Flight Experiment (ReFEx) will help gain a flight and design data on, as well as operational experience with, a winged first stage of a reusable launch vehicle (RLV). It was first presented at the EUCASS 2017 and has evolved significantly since then. ReFEx will launch in late 2022 as a technology demonstrator using a VSB-30 sounding rocket as carrier. Once launched and after reaching altitudes and velocities similar to a first staging event, the goal is to conduct a return flight along a trajectory comparable to returning winged first stage RLVs, transitioning from hypersonic speeds down to subsonic flight.

1 Introduction

The Reusability Flight Experiment (ReFEx) [1] under development at DLR since 2016 will help gain a flight and design data on, as well as operational experience with, a winged first stage of a reusable launch vehicle (RLV). It was first presented at the EUCASS 2017 [1] and has evolved significantly since then [2]–[4].

ReFEx will launch in 2022 as a technology demonstrator using a VSB-30 sounding rocket as carrier. After launch and separation, which will happen at altitudes and velocities comparable to a first staging event, the goal is to conduct a return flight along a trajectory comparable to returning winged first stage RLVs, transitioning from hypersonic down to subsonic velocity.

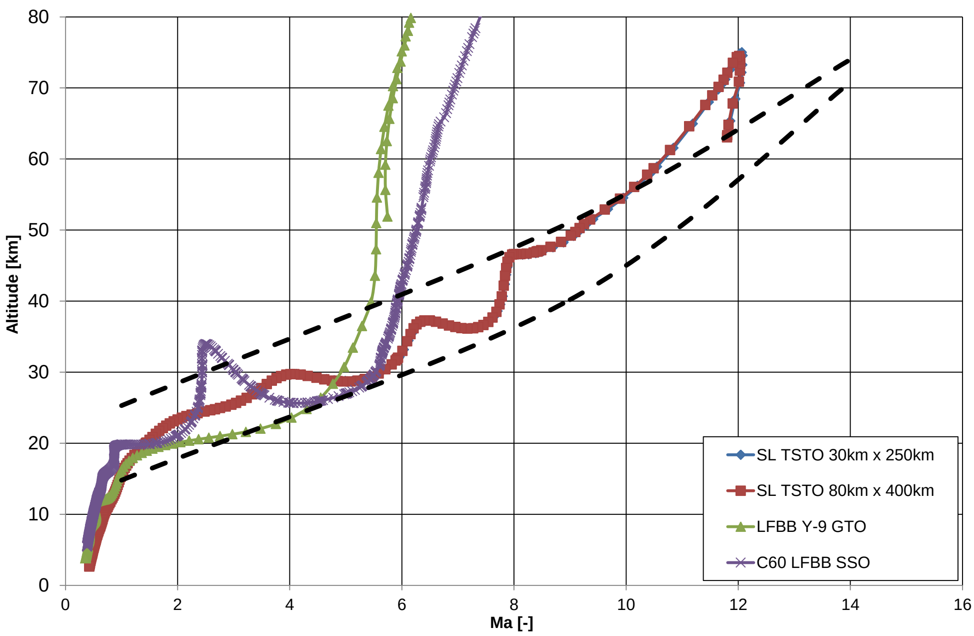

Figure 1: Re-entry trajectories and related RLV (Reusable Launch Vehicle) corridor for different winged RLV first stages including the SpaceLiner (SL), the Liquid Fly Back Booster (full-scaled final version LFBB Y-9, sub-scaled micro methane LFBB C60)

Figure 1 shows the typical trajectory of different winged RLV stages. It can be seen that these stages roughly all follow a similar altitude – Mach number profile (dashed corridor). This is not surprising, as there are two main goals

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of any return method be it aerodynamic or toss-back: one, return to the launch site with the minimal amount of propellant used and two, to do so while limiting the loads (both thermal and mechanical) on the vehicle to acceptable levels. As such the area of the lower right in Figure 1 is to be avoided for the latter reason, while the upper left area is avoided because it would be prohibitive from an energy requirement standpoint.

For flight control ReFEx (2.7 m in length, with span of 1 m and 400kg mass) will use a nitrogen cold gas reaction system (RCS) while outside the atmosphere and aerodynamic surfaces (canards and rudder) once dynamic pressure is sufficiently high. The maximum Mach number reached during the re-entry manoeuvre is about Mach 5. To reduce the thermal and mechanical loads the vehicle will fly an optimised trajectory which is generated autonomously on-board. To demonstrate the manoeuvrability required for a winged RLV first stage it will fly a turn of at least 30° with respect to the original heading measured from entry interface.

The key technologies demonstrated in this vehicle are, amongst others: aerodynamic design of a vehicle capable of stable flight through many flow regimes, guidance, navigation and control (GNC) capable of closed loop control and on-board generation of an optimised trajectory [5]–[7], the seamless transition between extra- and intra-atmospheric flight, health monitoring of the vehicle status during flight using advanced sensors such as Fibre Optic Sensors (FOS) and aerodynamic conditions measured with several sensors as well as a Flush Air Data System (FADS)[4].

ReFEx reached PDR Close-Out in May of 2019. This paper gives a system level overview of the current technological as well as the project status. In addition some focus will be put on the possible failure modes of the system, by showing a fault tree analysis (FTA). The FTA and the subsequent FDIR (Failure, Detection, Isolation and Recovery) analysis will be used for the system design, to identify critical areas, AIV (assembly integration and verification) to identify specific test sequences and mission operations to provide appropriate procedures for ground and in-flight operations.

2 System Design

ReFEx is meant to demonstrate technologies necessary for a winged reusable first stage. This means that the vehicle has to be shaped aerodynamically to be stable or at least controllable within a wide flight envelope. In order to perform the experiment the unpowered ReFEx experiment is launched on a VSB-30 sounding rocket to altitudes and velocities comparable to a first staging event. The use of an unguided sounding rocket (VSB-30) complicates the aerodynamic design (see also [8]). As a result the shape has to be symmetric and the centre of pressure has to be kept behind the centre of gravity during the launch phase, to ensure static stability. This means that any aerodynamic surface, especially asymmetric ones such as the wings have to be covered by a fairing, or in case of the vertical tail a dummy fin has to be added to preserve symmetry. More details about the aerodynamic design can be found in [9].

A detailed view of the payload (defined as anything above the motor adapter– see Figure 2) can be seen in

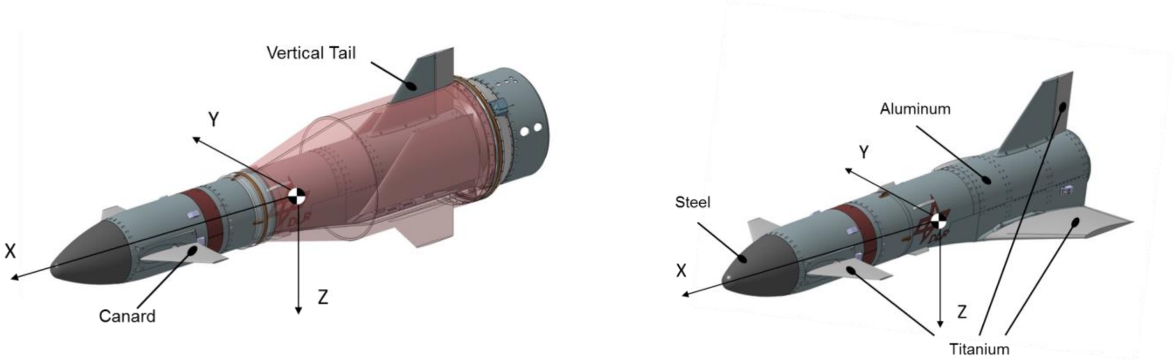

Figure 3. ReFEx is stowed underneath a triple shell fairing with the wings folded. The antennas for GPS (wrap-around) and telecommunication are all located outside of the fairing. This allows the fairing to be fabricated of carbon fibre, which is opaque to RF transmissions, saving mass and improving rigidity over a glass-fibre variant.

All active control surfaces protruding into the oncoming flow a physically locked during this phase of flight as any inadvertent deflection might cause the vehicle to become unstable.

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Once the fairings are jettisoned and ReFEx is separated from the launch vehicle it will assume its re-entry configuration (see Figure 3, right). In its re-entry configuration ReFEx has a length of 2.7m, a span of about 1m, a height of 0.6m and a mass of about 400kg [10].

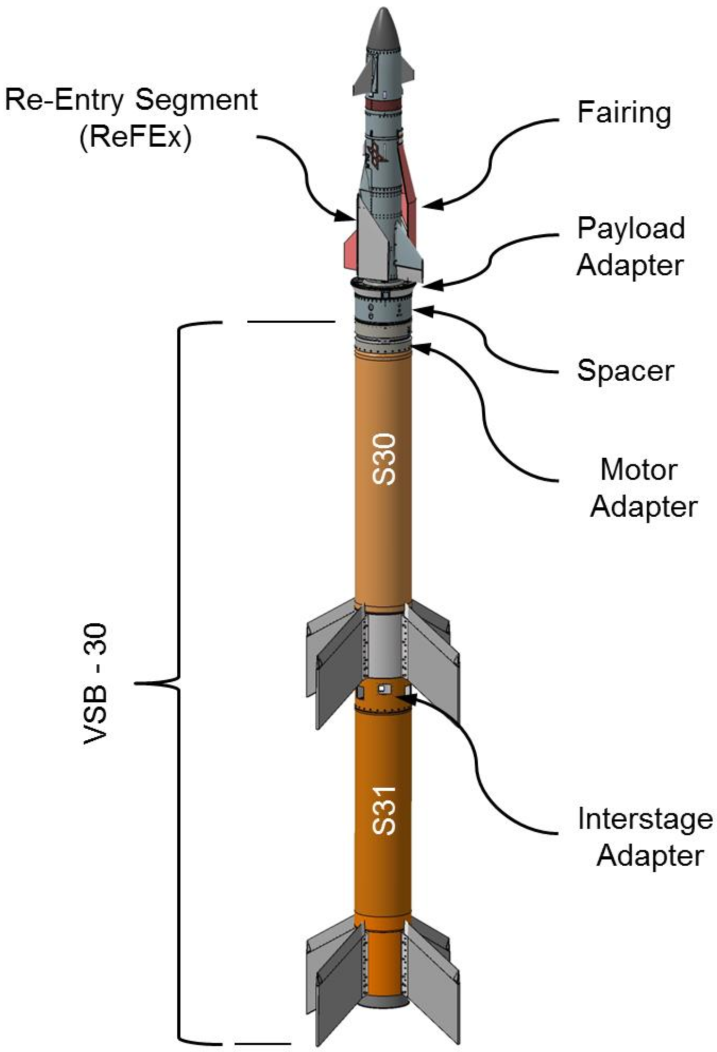

Figure 2: ReFEx in its launch configuration atop the VSB – 30 (one fairing half omitted for illustration purposes) [10]

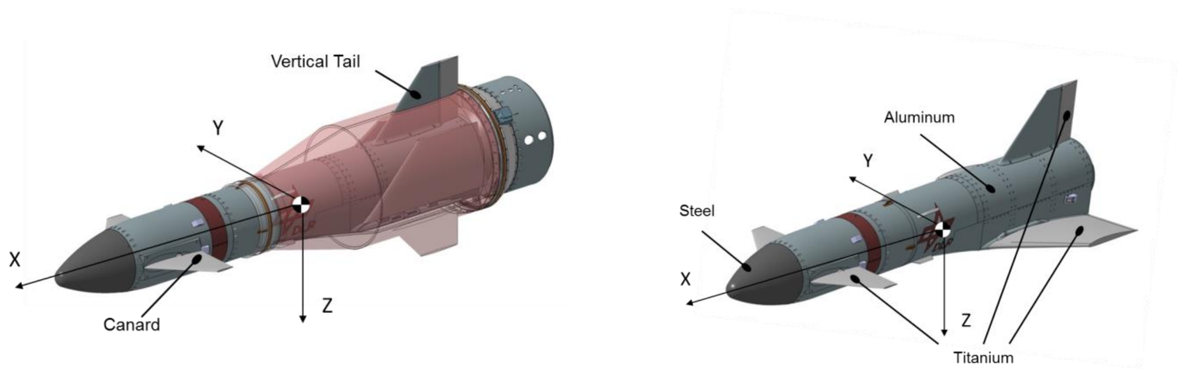

Figure 3: Detailed view of ReFEx in stowed/launch configuration (left) & re-entry configuration (right) [10]

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In contrast to operational RLV stages ReFEx has a significantly higher bulk density. This becomes especially apparent when looking at the internal layout (see Figure 4 below). While typical operational RLV stages have large (and during the return leg) mostly empty tanks, ReFEx is equipped with the required control electronics, several secondary experiments and la large suite of sensors [10].

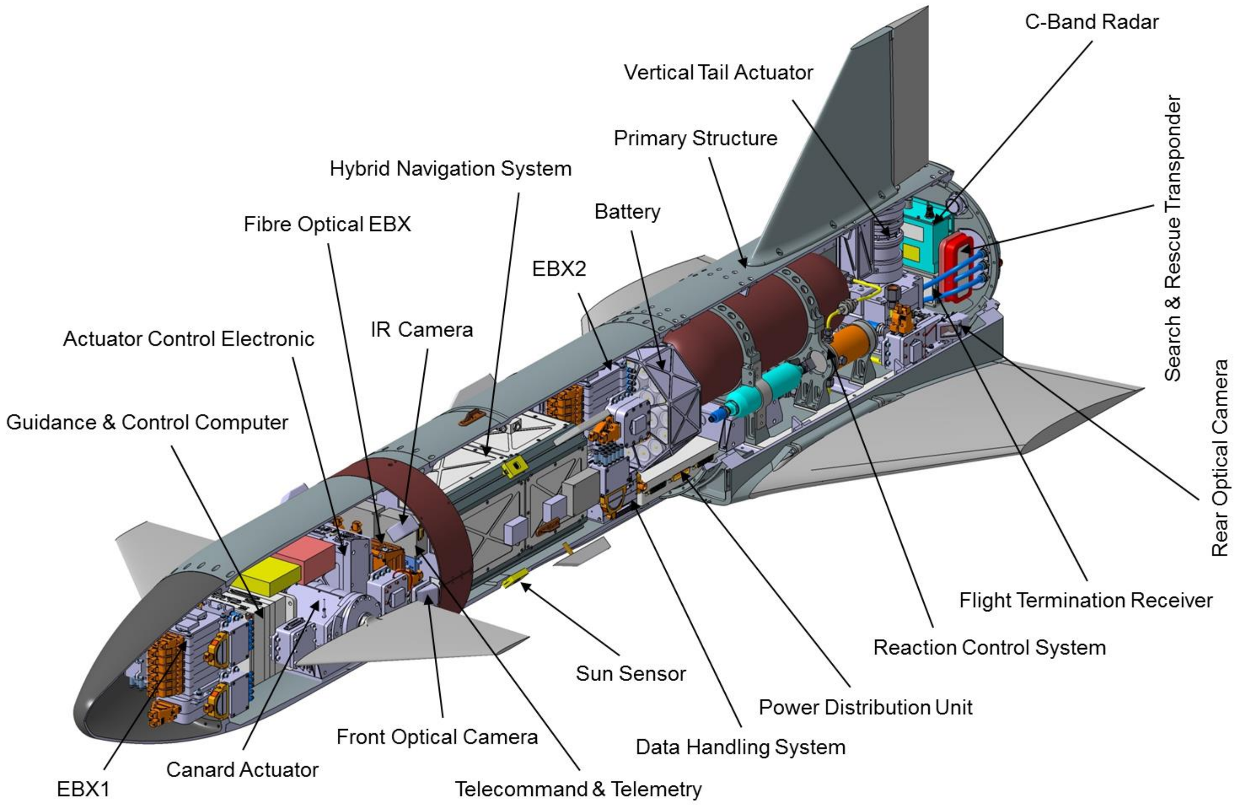

Figure 4: ReFEx internal layout [10]

This higher bulk density leads to increased wing loading and makes it challenging to control ReFEx through the altitude – Mach number profile indicated in Figure 1. In addition ReFEx is much smaller and more nimble than a large operational RLV, increasing the response requirements by the GNC system especially during dynamically unstable flight. As such, the lessons learned for the GNC system during this experiment will be very much applicable to a larger winged RLV and will be very valuable for the future development of such a system.

2.1 Mission Design

The main mission goals for ReFEx are as follows:

- Perform a controlled flight following a re-entry trajectory representative for a winged RLV first stage in the velocity range hypersonic down to subsonic (see Figure 1)
- Perform a controlled heading change (capability required for returning to the launch site)
- Test of the autonomous Guidance Navigation and Control (GNC) system
- Perform in flight data acquisition using advanced sensors
- Recovery of ReFEx (see Figure 3 right) for Post Flight Analysis (PFA)

To fulfil all of these goals a mission profile has been designed and is depicted in Figure 5.
The mission begins by launching ReFEx on a VSB – 30 sounding rocket. The preferred launch site is Woomera Test Range, Australia as it is one of the few land ranges large enough for the flight experiment. After lift-off and burnout of the first stage there is a small delay before the second stage is ignited. This helps to produce a shallower trajectory, which in this case is desirable to achieve conditions similar to a RLV first stage at separation of ReFEx.

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After burnout of the second stage and a brief drifting phase, the sounding rocket is de-spun using a yo-yo system. Once this is completed the fairing is jettisoned, the wings are deployed and shortly after ReFEx is separated from the second stage. This point is also known as Re-Entry Segment Separation (SEP) and Beginning of Guided Control (BoGC). It marks the beginning of the experimental phase and coincides with the unlocking of all actuators (RCS and aerodynamic). For more information about the launch phase please also see [8].

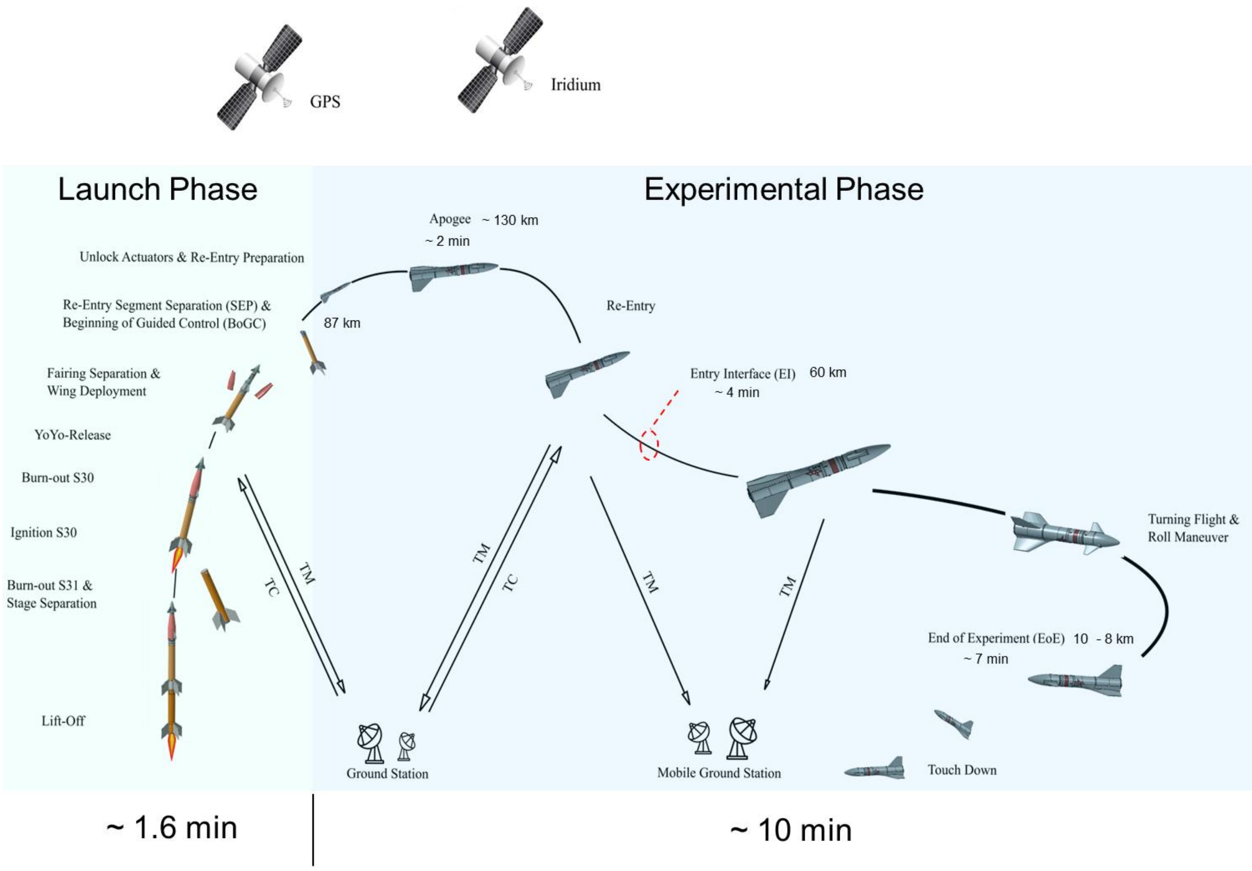

Figure 5: Mission Architecture & Flight Events

The experimental phase of flight begins with exo-atmospheric flight, controlled by the reaction control system (RCS). Its task is to reduce any residual rotations left over from the launch phase and re-orient ReFEx in the correct orientation for re-entry. This orientation might seem unusual, as ReFEx will re-enter in an inverted orientation (belly-up). This is done due to stability considerations during hypersonic flight. It allows the fin to remain in the flow, as opposed to the leeward side of the vehicle, where it would be shielded from the oncoming flow and of little use. More details on this strategy can also be found in [7], [9], [11]. This is not an entirely new concept as the Baikal reusable first stage booster employs a similar approach [12].

The entry interface (EI) for ReFEx was defined to be at 60 km. This is about half the altitude of the entry interface for objects returning from orbit. The reason for this is the much lower velocity of ReFEx, which results in a significant rise in dynamic pressure only at 60 km and below. The definition of the EI is important since it is the point of reference for the return manoeuvre. As stated in the mission goals a controlled heading change is to be performed. This change must result in at least 30° angle between downrange and cross-range as measured from the EI.

Consequently, after passing through the EI and the aerodynamic surfaces gaining control authority ReFEx will initiate a turn to achieve this heading change.
In addition ReFEx will have to roll to the normal belly down position at approximately Mach 1.5. since this orientation is preferred for tans- and subsonic flight.

ReFEx will then continue to fly towards its target volume, which is an arrival ellipse located at about 8 – 10 km altitude and after the vehicle has traversed the transonic phase. This point the marks the end of experiment (EoE).

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Notably Figure 4 shows that ReFEx does not possess a recovery system such as parachutes or landing gears. This was decided due to volume considerations and since all flight mission goals will be met at that time. However, an additional goal is to recover ReFEx after landing for post flight analysis. Of special interest is the high speed data recorded during the experiment (see [13] for details). It is stored in several impact resistant memory units on board the vehicle, since its transmission exceeds the telemetry bandwidth limitations.
As such ReFEx will continue to be actively controlled after EoE and attempt a crash landing, with the goal of minimizing impact velocity.

During the entire flight, telemetry will be downloaded from the vehicle and there are two ground stations to accomplish this. One stationary located at the launch site and one mobile ground station located nearer to the predicted EoE zone. This is done to allow for maximum coverage of all flight phases as the station located at the launch site will lose the link below 10km altitude (varying with downrange) since ReFEx will fly below the local horizon. In addition this allows for redundancy the in telemetry downlink as there will be overlap between the two telemetry stations coverage.

3 Fault Tree Analysis

A system-level qualitative Fault Tree Analysis has been established for the ReFEx project which supports the FMECA (Failure Modes, Effects and Criticality Analysis) process as well as the identification of flight safety critical failure modes.
FTA is an analytical, graphical, top-down failure analysis method which starts on top-level with an unwanted failure mode and using Boolean logic to combine a series of lower-level events [14]. From this top-level gate sub-branches and -gates are elaborated that will result in the occurrence of the predefined undesired event.
At this current project phase system-level fault trees have been developed which are broken down to unit-level but not beyond that.

As Figure 6 shows, the top-level failure mode *ReFEx mission failed* has been investigated which can be caused by not accomplished mission goals (chapter 2.1) and/or safety relevant failure modes. The mission success goals are output events of sub-trees which then merge together in the top-level tree and serve there as input events.
If e.g. one of the sub-tree failure modes *Autonomous on-board trajectory generation failed* (Gate MR-3) or *ReFEx leaves the acceptable flight range* occur, the top-level failure mode would be true as well. Both failure modes have also been identified as flight safety critical (description fields are marked with red safety indicator).

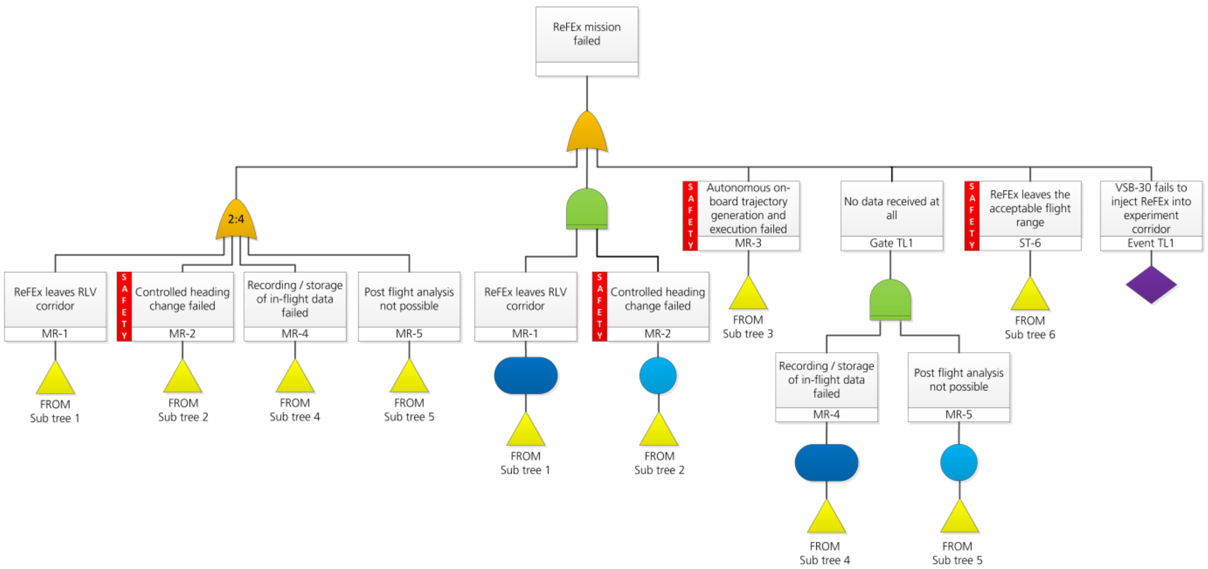

Figure 6: ReFEx top-level fault tree

Figure 7 shows that ReFEx can leave the RLV corridor if it is uncontrollable (Gate 101) or the separation from the S30 motor failed (Gate 102).

Gate 101 summarizes the OR connection of failure events of ReFEx major/critical units which are: Folded wings system, Hybrid Navigation System (HNS), Guidance & Control Computer (GCC), RCS, power system and control elements (canards, side rudder).

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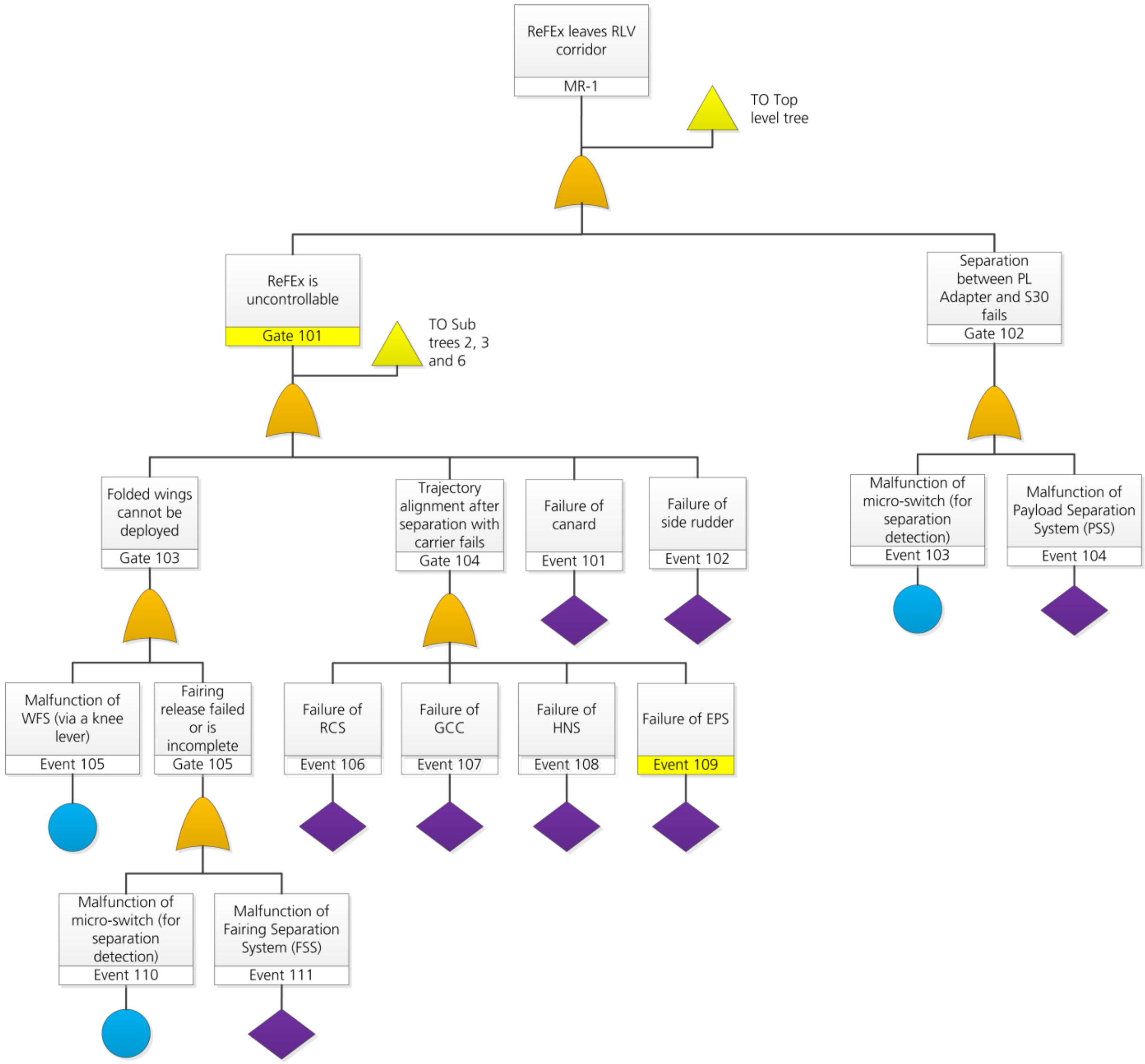

Figure 7: Sub-tree 1 - *ReFEx leaves RLV corridor*

Sub-tree *ReFEx leaves the acceptable flight range* is depicted in Figure 8. It shows that ReFEx violates the defined flight safety geo-fence corridor if the vehicle is uncontrollable/the trajectory generation failed and the unlikely event occurs that both flight termination systems fail. At the current project progress two independent flight safety/termination concepts are foreseen.

If then the vehicle additionally leaves the nominal trajectory and is heading to range boundaries it can violate the flight range in worst case. The same is valid for events which can lead to the disintegration of ReFEx.

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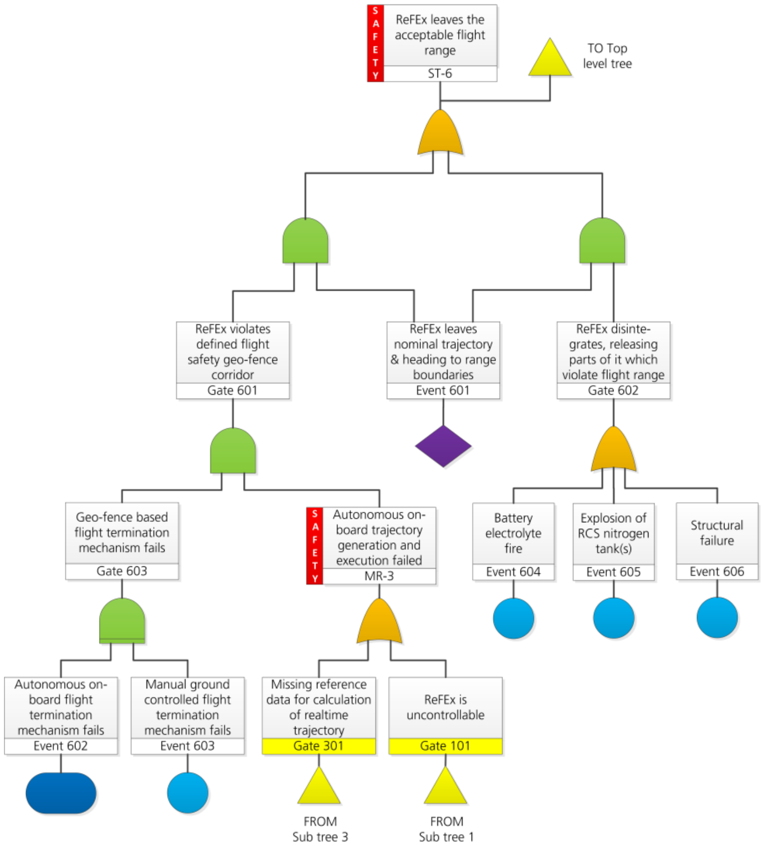

Figure 8: Sub-tree 6 - *ReFEx leaves the acceptable flight range*

As a first result Gate 101 of sub-tree *ReFEx leaves RLV corridor* (Figure 7) has been identified as critical path of the ReFEx fault tree. Gate 101 summarizes the OR connection of complete failures of major ReFEx units and is repeated in different sub-trees. These sub-trees are furthermore identified as flight safety relevant for the ReFEx mission as well. Since the HNS is the central element of the GNC system it will be designed one fault tolerant.

In the further course of the FTA sub-trees will be elaborated in more detail and failure modes on unit level will be analysed. Those unit failures which can cause safety relevant system-level failure modes have to be investigated more deeply and mitigation strategies to prevent respectively to recover from these failure modes have to be defined if possible (FDIR). This can be autonomous on-board recovery or manual recovery per telecommand.

4 Assembly Integration and Verification

The realization and validation phase of a highly integrated and highly autonomous flight experiment comprises several interacting challenges within the assembly, integration and verification planning, such general project constraints (resources), as well as performance verification. This chapter gives an overview over the applied model philosophy, the manufacturing and integration sequence and the verification approach.

4.1 Model Philosophy

For the ReFEx flight experiment model philosophy, a trade-off had to be made between a low risk – high cost prototype approach, as seen in orbital spacecraft missions, and a high risk – low cost approach as used in sounding rocket programs. The program chose a hybrid model philosophy, which distinguished between a Protoflight Model approach (PFM) on subsystem level and a Prototype Model approach on system level (Flight Model - FM). The vehicle will make use of three standalone builds, including:

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- One System Structural Model (SM)
- One System Engineering Model in a Core Avionics Testbed (EM / CAT)
- One System Proto Flight Model (PFM)

The system verification approach splits between mechanical / process verification and electrical / software verification. For mechanical and process verification a full scale Structural Model (SM) of the vehicle is set up to evaluate the integration processes, Ground Support Equipment (GSE), mechanisms, harness routing, mission loads and handling. On functional side a testbed approach is used for functional verification of the subsystem architecture, such as interfaces and the associated protocols and control algorithms. The functional verification makes use of a testbed engineering model (EM) in a Core Avionics Testbed (CAT) environment, which is a pallet setup of all subsystem components, harness and an Electrical Ground Support Equipment (EGSE). The EM CAT is also used for functional checkouts of the subsystem PFMs prior to the integration into the spacecraft system, an approach that has gained heritage from to the DLR Compact Satellite Program [15].

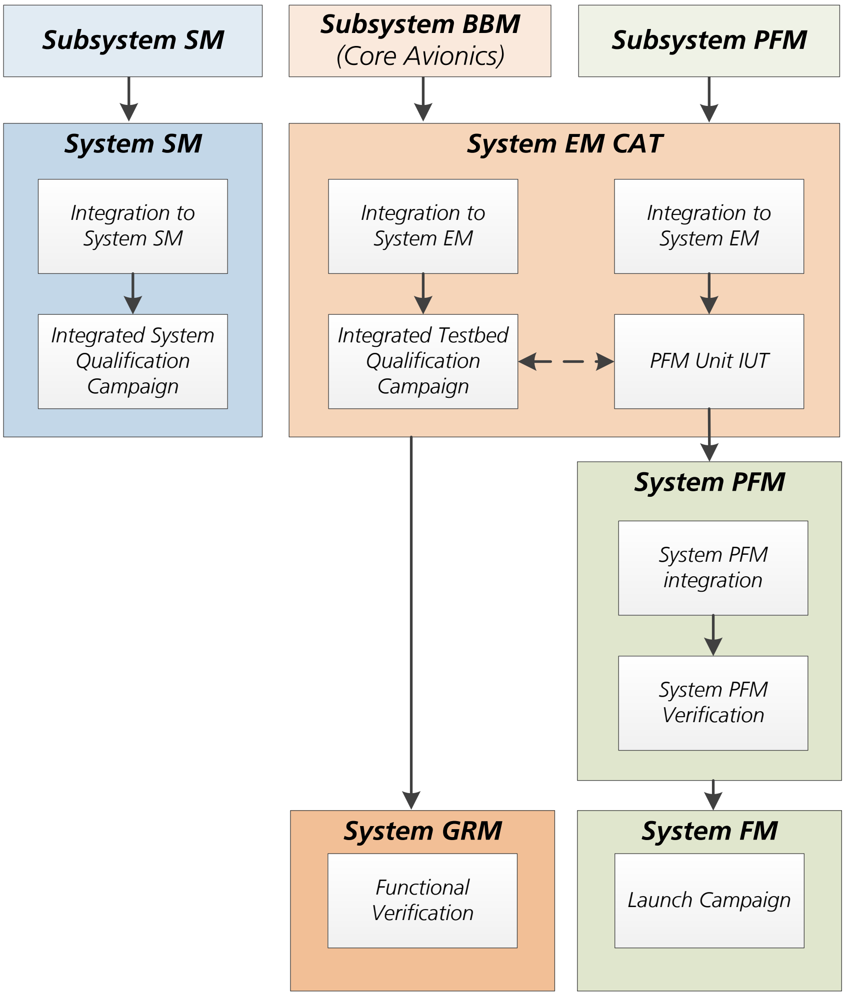

Figure 9: ReFEx AIV model philosophy

The only full scale functional model is the System Protoflight Model, which is integrated and verified after close-out of both SM and EM campaigns. Once the System PFM verification campaign is closed out, the system PFM will become the system Flight Model (FM) while the system EM CAT will be used as Ground Reference Model (GRM) for software validation and functional verification.

On subsystem level a different approach is used. The subsystems will deliver a Structural Model and a fully qualified Protoflight Model of all included units. For functional verification of the system architecture, the EM CAT will be gradually assembled from unit Breadboard Models (BBM). Once the setup has proven its functional performance, the BBMs will be replaced by the unit PFMs for testing prior to the integration into the vehicle PFM. The described test approach has been investigated within the DLR Compact Satellite Program and has proven feasible [16].

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4.2 Assembly and Integration Approach / Production Methodology

The integration strategy of the presented project is driven by the limited project resources, which contrasts the very high reliability requirements of a fully autonomous reentry experiment and the necessary manufacturing flexibility for a prototype mission. Listed below are the identified major drivers for AIV in terms of project, technology and mission specifics:

Project
1. Tight schedule for implementation after phase B
2. Budget limited
3. Small integrated team

Technology
1. Combination of heritage between aerospace, sounding rockets and small spacecraft
2. Distributed data handling architecture of core avionics
3. Prototype spacecraft: flexible verification methods
4. Model philosophy (only a limited number of models possible)

Mission Specifics
1. Fully autonomous flight
2. Mission time approx. 10 minutes
3. Limited telecommand capabilities

Since several of the described aspects are recurring parameters in all institutional projects, the ReFEx project will make use of the AIV methodology developed and introduced for the DLR asteroid landing mission MASCOT and the DLR Compact Satellite Program, as described in [17]. For both projects, it was decided to implement a lean production approach (Toyota Production System - TPS) to optimize the processes and logistics as well as harmonize the usage of infrastructure between projects. Since the implemented philosophy has been primarily developed for supplier dependent, large scale production processes, several adaptions had to be made to tailor it to a space related context. The goals are to generate a work environment that allows maximum quality, productivity and adherence to schedule. The identified assets of the DLR organizational structure are used to boost production effectivity and cross-project synergies:

- *Flat project hierarchies*
- *Small Teams with high dedication and expertise in diversified in-house department structure*
- *In-house manufacturing and production / AIV (Clean room, electronics lab)*
- *In-house testing (Vibration, shock, thermal/ vacuum)*
- *Dedicated Launch: In-House Launch Provider / Ground Segment (MORABA)*

To avoid communication problems between subsystems, system engineering and AIV and enable direct communication and feedback loops, a mixed team of AIV- and subsystem engineers is set up for the integration campaigns. To optimize production logistics during integration, a just-in-sequence method is used in combination with a structured cell production, projecting a Pull-Kanban method to the three model system as applied for ReFEx. The integration sequence is segmented into three autonomous cells with interchangeable tool and GSE sets. One cell is used solitarily for the EM CAT, while the remaining cells will hold the wingbox and fuselage elements of the vehicle structure, what fosters the necessary flexibility. The parallel integration and test of two models at any given time, the flexibility in the order of operations due to the pull-approach, and the interchangeability of tools and GSE, all help to compensate for delays caused by the supply chain and, in the end, will speed up the integration process. In addition, the PA driven process philosophy of the DLR Compact Satellite Program, which is tailored from the ECSS standards, will be fully applied to the integration campaigns. The approach is optimized to allow quick and effective reaction to occurring problems, a key capability of small, highly integrated AIV teams. Furthermore is investigated, how the methodology can adapt processes from sounding rocket programs to improve the integration campaigns of future spacecraft projects. Each campaign is estimated to last 30 work days. The EM CAT will be operated throughout the project phases C and D.

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4.3 Verification Approach

The overall verification strategy of the ReFEx project is based on an ECSS approach, tailored to the hybrid PFM model philosophy. The verification methods used are Review of Design, Analysis, Inspection and Test, applied on the system domains Structure, EMC, Thermal and the corresponding models employed. This includes the usage of the three described spacecraft models and the verification stages qualification and protoflight for system functional testing. All Review of Design aspects are treated within the project milestone reviews (PDR, CDR, AR), while analyses are in the field of the respective subsystem or system domain (thermal, mechanical). Verification by Test is used both on system and subsystem level.

The hardware verification approach on system level is composed of the three steps described in the model philosophy and splits up into three verification campaigns, one for each model:

- System Structural Model campaign
    - Validation of integration processes
    - Mechanical verification
    - Integrated System Verification (Analysis, Test)
    - Thermal Verification (Analysis, Test)
    - Venting (Analysis, Test)
    - Mechanical functional chain (Test)
- Engineering Model campaign
    - Validation of integration processes
    - Interface Verification (Analysis, Test)
    - Electrical functional chain
    - Integrated System Qualification (Analysis, Test)
    - End-to-End Verification (Test)
- Proto Flight Model campaign
    - Electro-magnetic Compatibility (EMC)
    - Mechanical Verification of Workmanship (Test)
    - Thermal Balance (Analysis, Test)
    - Venting (Analysis, Test)
    - Mechanical functional chain (Test)
    - Electrical functional chain (Analysis, Test)
    - End-to-End Verification (Test)

To reduce the workload and verification effort on subsystem level and to reduce phases of unnecessary over-testing, mechanical development and necessary qualification tests will be conducted on system level as Integrated System Qualification (ISQ). This test mode allows the subsystem to deliver non-qualified Structural Models (SM) of the respective units, which are integrated into the vehicle structure and tested with the actual coupled loads (mechanical and thermal (except aerodynamic heating)) in the frame of the system SM campaign. During the tests the specific load environments are recorded at defined mechanical reference points close to the unit footprints and serve as input for the subsystem PFM tests.

Since the systems such as GNC as well as Data Handling and Flight Instrumentation are distributed within the vehicle and the mission duration of approximately twelve minutes for launch, re-entry and landing is short the thorough validation of the functional chains is absolutely vital for the success of the project. Therefore the focus during the PFM verification campaign is set on the use of end-to-end test scenarios as early as possible to gain experience with the vehicle behavior and to identify possible design flaws. Since the simulation of both ballistic flight and aerodynamic flight of the Re-Entry Segment encounters many uncertainties towards sensory inputs, test definition may lead to highly over-engineered test setup designs. Therefore the Pareto principle is strictly enforced throughout the project, stating that most of all critical malfunctions to be encountered during the mission can be detected even with a test setup which is only 80% representative.

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5 Conclusion

This paper gives an overview of the Reusability Flight Experiment, ReFEx, which will be launched on a VSB – 30 sounding rocket in 2022 at the preferred range of Woomera. The flight experiment is conducted by DLR to gain more experience and know – how for winged reusable first stage vehicles. Special emphasis in this experiment is the GNC chain as well as instrumentation and aerodynamics of such a vehicle.

In order to conduct such an experiment safely an exhaustive failure tree analysis is conducted on a system level to identify critical events during flight and support FMECA efforts in the project.

In addition such a complex vehicle requires an adapted AIV strategy that also takes into account the project framework and available resources. The employed methods are highlighted in this paper.

Detailed further information on the specific subsystems, especially the GNC chain can be found in the referenced papers.

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