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ReFEx: Reusability Flight Experiment
A Flight Experiment to Demonstrate Controlled Aerodynamic Flight from Hypersonic to Subsonic Velocities with a Winged RLV

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Abstract

The Reusability Flight Experiment (ReFEx) aims to demonstrate the technologies necessary for a winged reusable launch vehicle (RLV) in order to drastically reduce launch costs. In a winged RLV this can be done through aerodynamic means and tailored manoeuvres, requiring much less fuel than a propulsive boostback system. The main goal of ReFEx is to demonstrate controlled flight from hypersonic velocities down to subsonic velocities and doing so while maintaining a flight corridor representative of winged RLV. In the case of ReFEx this is equivalent to a low speed, early staging event.

1. Introduction

Launch vehicles are complex and expensive systems the cost of which cannot be spread over many missions if the vehicle is expendable. Therefore, worldwide research activities at universities, research institutions and especially industrial companies are ongoing to find solutions to reduce the cost of launch systems for future missions via part or full reuse of the launch vehicle. The German Aerospace Center (DLR) has been investigating a *reusable fly back booster* LFBB concept for several years in the ASTRA-study [1]. Together with German industry and universities a large number of numerical investigations as well as dedicated wind tunnel tests were performed. Furthermore, DLR earned practical experience on national projects e.g. Shefex I & II (see for example [2] and [3] among others) as well as in international cooperation project e.g. FOTON (e.g. [4]), EXPRESS (e.g. [5]), HIFIRE (see for example [6] [7] [8] among others). Within those projects different key technologies required for reusable booster system were already developed and tested (e.g. Thermal Protection System, Hybrid Canards and special navigation systems). Furthermore, measurement data was collected und utilized for model validation.

Now, DLR is investigating the realization of a sub-scaled *fly back booster* experiment. The ReFEx (Reusability Flight Experiment) shall be launched on a Brazilian VSB-30 sounding rocket in 2021 and shall achieve a re-entry velocity of more than Mach 5. The main goal is the demonstration of a controlled autonomous re-entry flight from hypersonic down to subsonic velocity and to test key technologies required for future *reusable booster system*.

So far, two Concurrent Engineering (CE) studies were conducted to investigate the feasibility of this sophisticated project. The required subsystems, including sensors and actuators as well as their interfaces have been defined and different options were assessed regarding matters like the scientific output, complexity, risk, and cost. Figure 1 shows the current re-entry configuration of ReFEx. The re-entry vehicle has a length of 2.7 m a wingspan of 1.1 m and a mass of about 450 kg.

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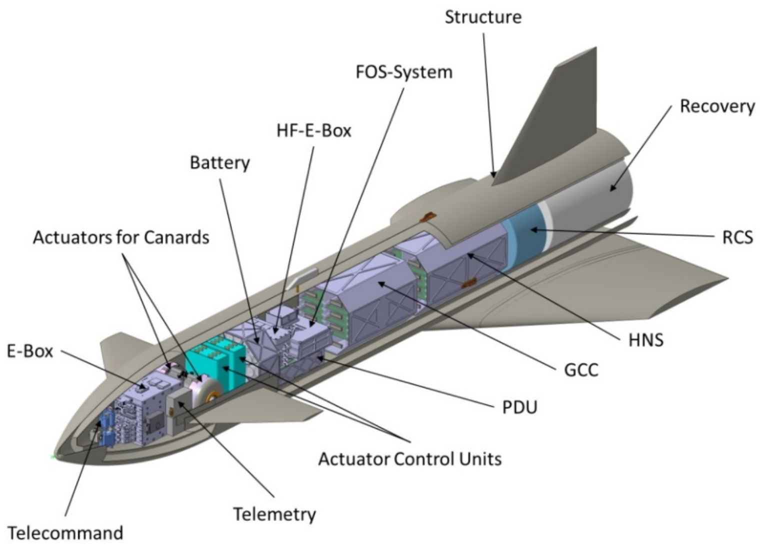

Figure 1: ReFEx re-entry configuration

2. Return Trajectory Analysis

2.1 Assumptions

Since the main goal of ReFEx is the demonstration of a controlled fly back of a winged reusable stage, assumptions considering a representative re-entry trajectory for such stages have to be made and certain criteria have to be met by ReFEx to qualify as a winged RLV demonstrator. Therefore, based on former research on the LFBB [1], the SpaceLiner [9], and other winged RLV concepts from Airbus and CNES modelled by DLR, a RLV re-entry corridor (as shown in Figure 2) was defined which serves as reference for winged RLV trajectories. The boundaries of this corridor are defined by altitude versus Mach number and represent the range in which a winged RLV stage performs the aerodynamic deceleration and re-entry manoeuver in order to achieve a controlled transition from hypersonic to subsonic velocities. The mission goal of ReFEx is to achieve a re-entry trajectory in or close to this RLV corridor.

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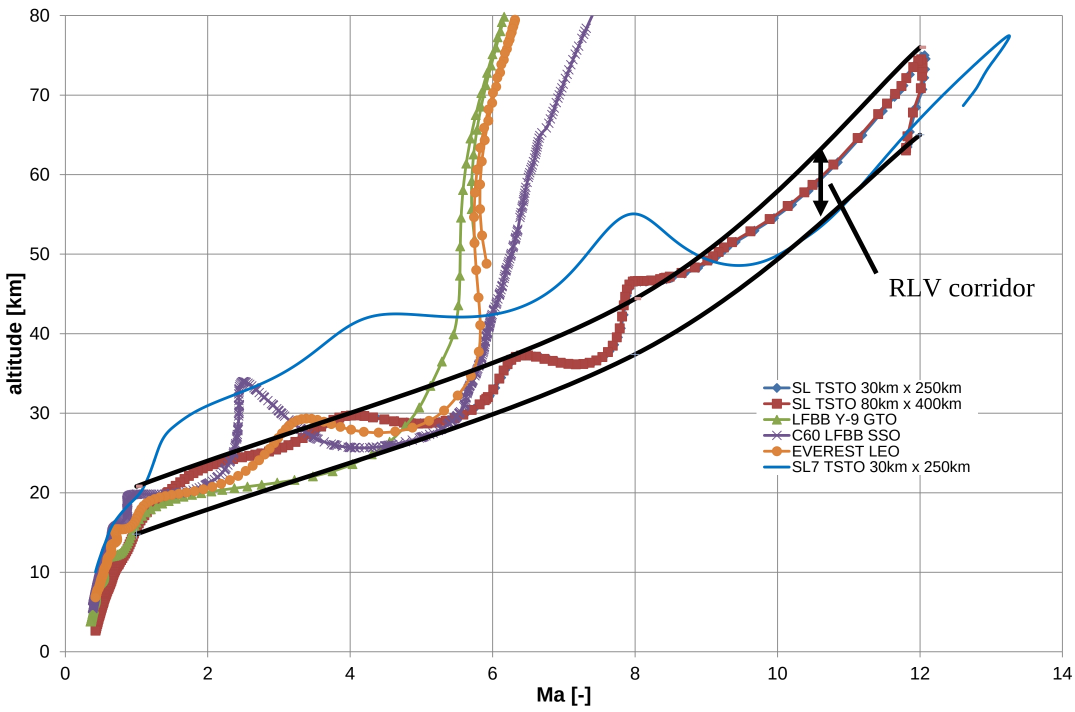

Figure 2: Re-entry trajectories and related RLV corridor for different winged RLV stages

As the flight experiment shall perform a controlled re-entry, the vehicle has to be longitudinally trimmable at every flight point of the trajectory by using the canards as trimming device. CFD calculations with the DLR in-house tool TAU were conducted for different Mach numbers and deflection angles of the canards to determine the range of trimmable AoAs of the vehicle. Since the flight dynamics and trimmability are highly dependent on the position of the CoG, calculations for three different CoG positions (61%, 62% and 63% with respect to the nose) were performed in this study to determine the optimal position of the CoG. The re-entry trajectories were calculated using the DLR-SART tool *tosca*. An overview of the main assumptions is provided in Table 1.

Table 1: Main assumptions for return trajectory calculation

Parameter	**Value**
Re-entry Mass	500 kg (with 50 kg margin)
Apogee	132.5 km
Velocity at Apogee	993 m/s /Ma 2.7
Intended Launch Site	RAAF Woomera Test Range
Maximum deflection angle of Canards	± 10°
CoG Position	Between 61% and 63% w.r.t. the nose
Re-entry AoA	Maximum trimmable AoA -1.5°

2.2 Results

The re-entry trajectories for the ReFEx flight demonstrator for different positions of its CoG are shown in Figure 3 and Figure 4. Furthermore, the trajectories of Shefex I&II (being ballistic re-entry experiments), the LFBB and the Space Shuttle were added (Figure 4) to illustrate the difference between the trajectories of winged and ballistic re-entry bodies. Figure 4 clearly shows the influence of the position of the CoG on the re-entry path of the flight experiment. A CoG positioned closer to the rear of the body allows a higher trimmable angle of attack during re-entry, which leads to significant aerodynamic forces in higher altitudes and therefore would be favourable to achieve a flight in the RLV corridor. However, a rear CoG leads to less longitudinal stability of the flight experiment and reduces the range of trimmable low AoAs. Therefore, the main difficulty of ReFEx is to find a configuration that fulfils the requirement of flying a winged RLV trajectory while being aerodynamically stable and trimmable in every point of the flight. In the current configuration, only a CoG position of 63% allows for flight in the RLV corridor throughout the whole mission, while the other trajectories violate the lower boundary of the corridor. Nevertheless,

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the RLV corridor was defined using full scale winged stages as reference, whereas ReFEx is a subscale flight demonstrator with a higher ballistic coefficient than its full-scaled counterparts. Taking this into account, a violation of the corridor's boundaries might be tolerable if the flight experiment still performs a controlled aerodynamic re-entry manoeuver.

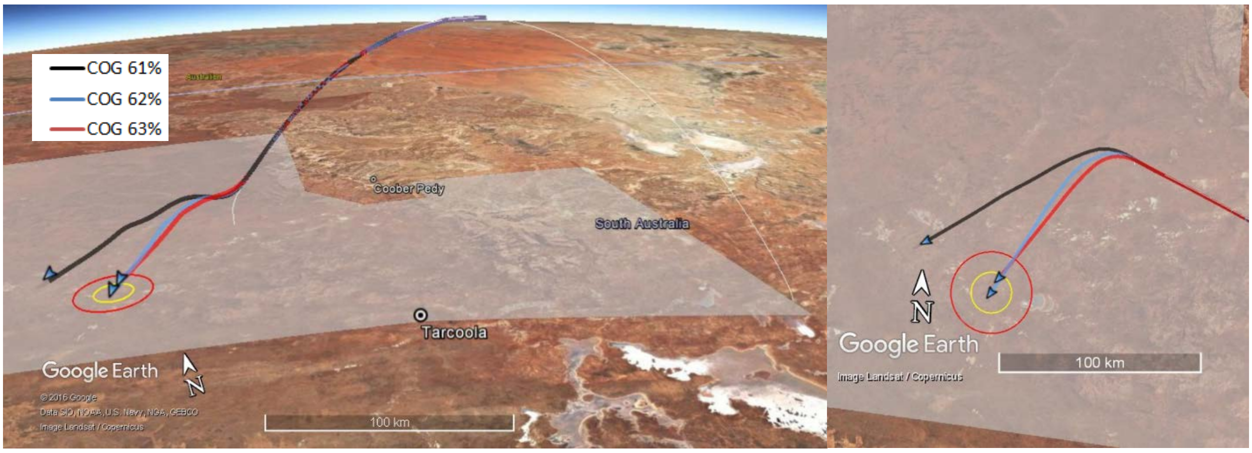

Figure 3: Re-entry trajectories for different CoG positions with 20 km circle (red) and 10 km circle (yellow) around endpoint of return trajectory for a CoG at 62%

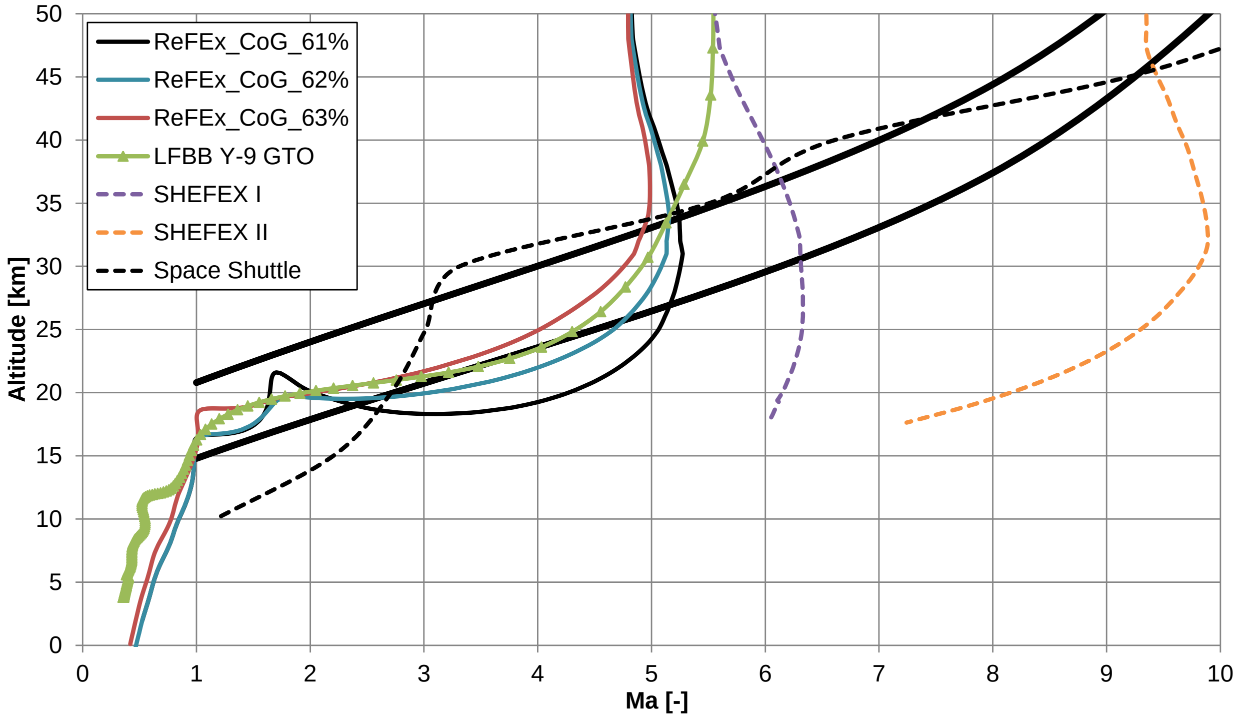

Figure 4: RLV corridor and re-entry trajectories for ReFEx (61%, 62% and 63% CoG position), the LFBB, Shefex I&II and the Space Shuttle

The AoA - and Banking Angle profiles corresponding to the respective re-entry trajectories are provided in Figure 5. The dotted lines represent the lower and upper trimmable AoAs from Mach 2 to Mach 6. The AoA profile for CoG positions of 61% and 62% are close to the upper boundaries of trimmable AoAs, yet the respective re-entry trajectories don't lie fully in the RLV corridor. It is important to note that the angle of attack is reduced to the minimum possible throughout the deceleration process in which it just takes 30 seconds to slow down the body from Mach 5 to under Mach 2. Without this reduction of AoA, the flight experiment would experience "skipping" behaviour, meaning that it would gain altitude and violate the upper boundaries of the RLV corridor after the initial phase of the re-entry (compare C60 trajectory in Figure 2). As a further measure, a banking manoeuver is performed

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that turns the lift vector sideways and thus additionally prevents skipping. This banking manoeuver is also necessary to fulfil one of the mission goals of ReFEx which is to perform a significant lateral change of the flight path (see Figure 3).

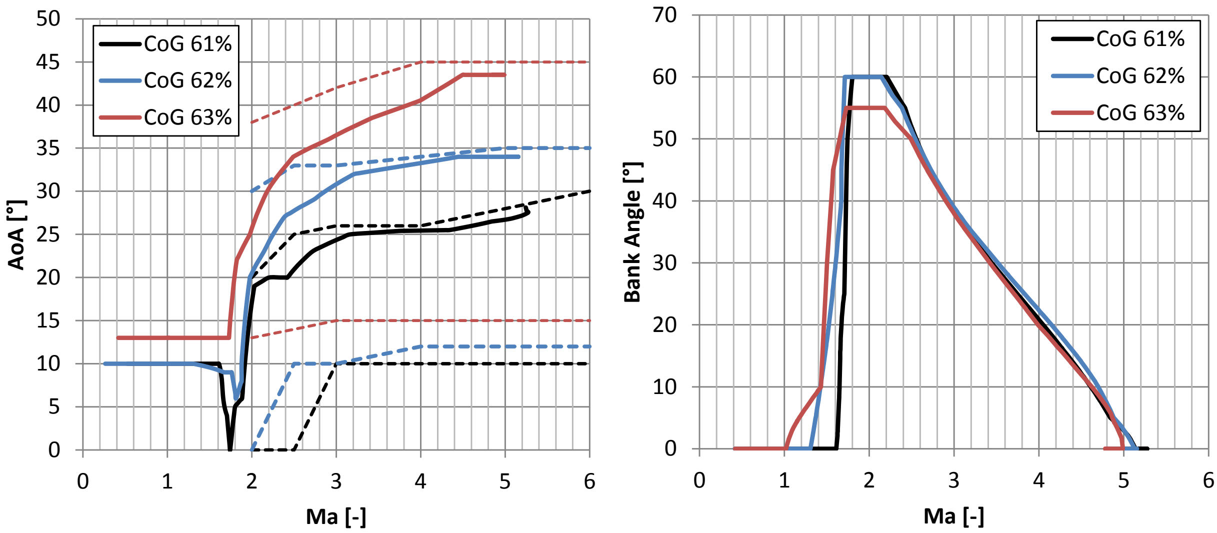

Figure 5: Angle of Attack (left) and Bank Angle (right) with respect to the Mach number for different CoG positions

The AoA at re-entry greatly influences the loads experienced by the vehicle (Figure 6). It is visible that a higher AoA at re-entry leads to less lateral forces experienced by the flight experiment, meaning that rear CoG positions are favourable for reducing loads. It might seem counterintuitive that higher AoAs lead to lower aerodynamic forces. This can be explained by the fact that a higher AoA leads to the generation of significant lift forces in higher altitudes compared to lower AoAs. By generating lift earlier, the deceleration of the vehicle starts in higher altitudes, allowing for the AoA to be reduced earlier. Hence, the total aerodynamic forces encountered are smaller with higher AoAs at re-entry.

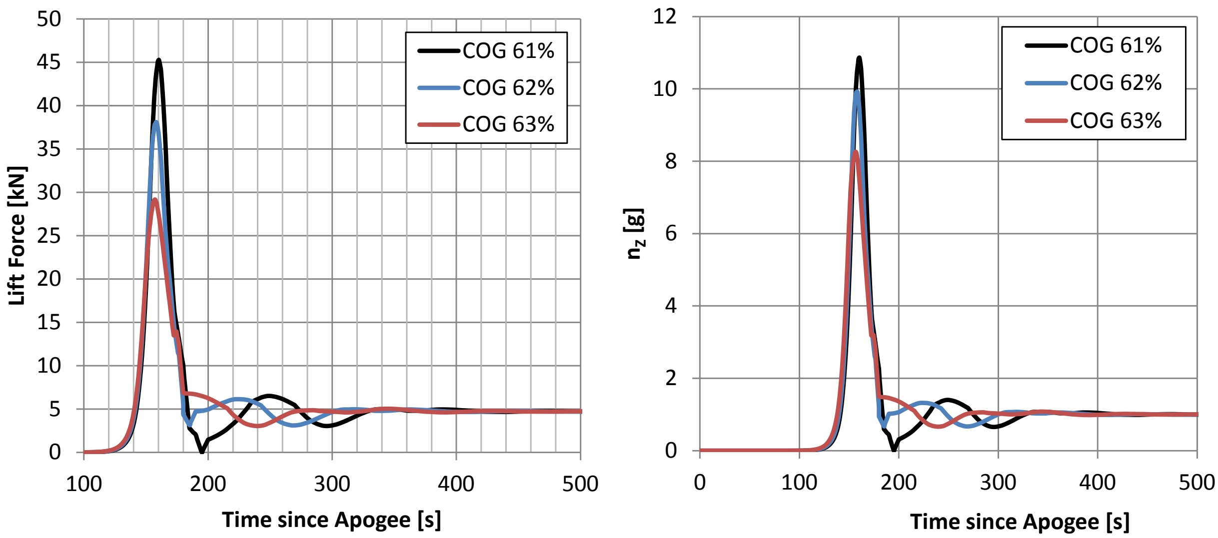

Figure 6: Lift Force (left) and lateral load factor (right) for different CoG positions

In summary, a rear-lying CoG allows a higher re-entry AoA leading to a flight in the RLV corridor and lower loads experienced by the vehicle. However, there are limitations to the range in which the CoG may be positioned, since the vehicle's subsystems can't be placed at random positions. Furthermore, a rear-lying CoG reduces static stability of the vehicle, so effects on controllability have to be further investigated and understood. The main challenge of this flight experiment is to find a configuration which is able to fly a return trajectory representative of winged RLVs while being controllable and stable at every point of the trajectory.

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3. Project

3.1 Goals

The main goal of the project is to demonstrate a controlled flight from hypersonic velocities down to subsonic range. As such the main focus lies on the necessary capabilities of the control algorithms and actual control devices (in this case canards and RCS – reaction control system). One of the central challenges is to design a vehicle that is stable a high angles of attack (AoA) in the hypersonic flight regime to be able to fly the trajectory displayed in (Figure 4) but agile enough to change its attitude quickly to follow the required AoA profile. In addition, the aerodynamic configuration and GNC (guidance navigation and control) also need to be able to cope with the flight through the transonic region, where there are rapid large shifts in the location of the aerodynamic centre.

In order to be useful as a winged RLV stage it is necessary that the on-board algorithms can generate the required trajectory from the entry interface (EI) down to the landing location autonomously also accounting for external factors such as wind and limited inaccuracies in reaching the exact EI in the initial unguided boost by the sounding rocket booster. As such this is also a central demonstration goal. All control surfaces and actuators have to work in unison to manage the altitude and range, as only non-powered flight is possible, limiting the actions that can be taken to correct the trajectory.

In addition to these basic goals which are necessary to perform the mission in the first place, there are several additional experiments that also fly on ReFEx, which cover topics ranging from aerodynamics to health monitoring systems.

The data from the experiment, which is both engineering housekeeping data as well as high speed data, will be stored in a special ruggedized data recorder on board the vehicle. In addition the most critical data will also be downlinked live to tracking stations.

The following table summarizes the main experimental goals:

Table 2: ReFEx goals

Category	Details
Mission	• Demonstrate a trajectory representative of a winged first stage RLV • Demonstrate altitude und range management • Demonstrate smooth interaction and handover between RCS and aerodynamic control surfaces • Demonstrate ability to fly the required AoA profile
Aerodynamics	• Achieve an aerodynamically stable configuration in all flight regimes (hypersonic to subsonic) • Demonstrate effective aerodynamic control surfaces • Provide an exact aerodynamic database • Demonstrate the ability to actively control possibly unstable flight events
GNC	• Demonstrate high fidelity navigation • Demonstrate the ability to autonomously generate optimized trajectories to reach the landing zone from a given set of starting conditions
Experiments	• Gain data on flow-structure interaction • Health monitoring systems using advanced sensors • Flush Air Data System (FADS) • Positioning using different global localization/navigation systems

3.2 Roadmap

The project currently is in phase A planning. Two CE studies have been performed to run through several trade-offs concerning the experiment, its subsystems and the launcher options. These extensive studies have led to the current configuration, which is planned for flight in the second half of 2021.

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The experiment in general ties into a larger roadmap to investigate the technical feasibility of winged RLV first stages. The following roadmap shows a possible future development path for winged RLVs (see Figure 7). ReFEx is the first risk-reducing step on the path to a full scale winged RLV. As such the flight experiment can also be repeated with different goals in mind, depending on the availability of appropriate boosters. For instance currently ReFEx, launching on a VSB – 30 is limited in terms of maximum flight velocity. This allows for a suitable trajectory to test GNC algorithms but is not challenging from a TPS (thermal protection system) standpoint. A later flight on a more capable booster would allow re-using the developed and validated flight control algorithms while extending the flight envelope to also include TPS aspects for study. This in turn allows a stepwise approach to a much larger powered flight experiment, while reducing the risk involved.

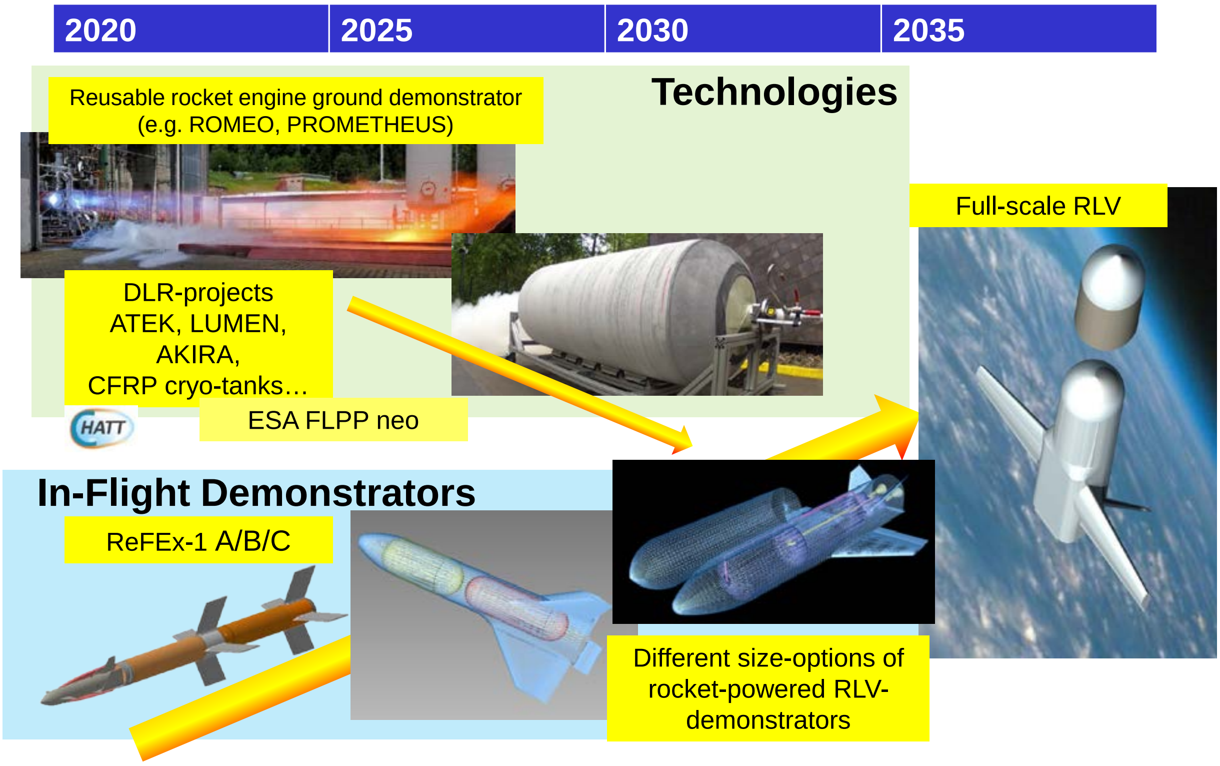

Figure 7: ReFEx-flight experiment in context with other European space research programs and potential roadmap to operational RLV

4. Conclusion

The ReFEx is a sub-scaled flight experiment utilized to demonstrate *key technologies* needed for winged *RLV first stages*. These include among others autonomous GNC algorithms, complex aerodynamic layout, specialised control surfaces and sensors for health monitoring. The flight experiment will be launched on a small sounding rocket in the second half of 2021 and will help to establish a knowledge base for such systems.

This paper gives a short overview of the experiment and its main goals and focuses on the relevant return trajectories and their impact on the flight experiment design. In addition the paper provides a tentative roadmap showing the path from ReFEx toward a full scale RLV, with the associated technologies.

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References

[1] M. Sippel, C. Manfletti and H. Burkhardt, “Long-Term / Strategic Scenario for Reusable Booster Stages,” *Acta Astronautica* , p. 209 – 221, 2006.

[2] T. Barth and J. M. Longo, “Advanced aerothermodynamic analysis of SHEFEX I,” *Aerospace Science and Technology,* pp. 587-593, Volume 14, Issue 8 December 2010.

[3] H. Weihs, J. Turner and J. M. Longo, “The Sharp Edge Flight Experiment SHEFEX II, a Mission Overview and Status,” in *AIAA International Space Planes and Hypersonic Systems nad Technologies Conference*, Dayton, OH (USA, 2008.

[4] T. Reimer, *The KERAMIK Thermal Protection System Experiment on the FOTON-M2 Mission,* Noordwijk, NL: 5th European Workshop on Thermal Protection Systems and Hot Structures. Thermal Protection Systems and Hot Structures (5th Workshop), 2006.

[5] H. Hald and T. Ullmann, *Reentry Flight and Ground Testing Experience with Hot Structures of C/C-SiC Material,* Norfolk, VA (USA): 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Material Conference, April 2003.

[6] C. Bode and T. Eggers, “Numerical generation of a Flush Air Data System for the Hypersonic Flight Experimental HIFiRE 7,” in *17. DGLR / STAB Fachsymposium*, Berlin, Germany, 9.-10. Nov. 2010.

[7] H. Böhrk, S. Löhle, U. Fuchs, H. Elsäßer and H. Weihs, “FinEx – Fin Experiment on HIFiRE-5,” in *7th Symposium on Aerothermodynamics for Space Vehicles*, Brügge, Belgium, 9-12 May 2011.

[8] D. E. Glass, D. P. Capriotti, T. Reimer, M. Kütemeyer and M. K. Smart, “ Testing of DLR C/C-SiC for HIFiRE 8 Scramjet Combustor,” in *7th European Workshop on Thermal Protection Systems and Hot Structures. 7th European Workshop on Thermal Protection Systems and Hot Structures*, Noordwijk, Netherlands, 8.-10. April 2013.

[9] M. Sippel, C. Valluchi, L. Bussler, A. Kopp, N. Garbers, S. Stappert and S. Krummen, “SpaceLiner Concept as Catalyst for Advanced Hypersonic Vehicles Research,” in *7th European Conference for Aeronautics and Space Sciences (EUCASS)*, Milan, 2017.