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Mission Analysis and Preliminary Re-entry Trajectory Design of the DLR Reusability Flight Experiment ReFEx

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Abstract

Driven by the recently increased demand for investigating reusable launchers, the German Aerospace Center (DLR) is currently developing the Reusability Flight Experiment (ReFEx). The goal is to demonstrate the capability of performing an atmospheric re-entry, representative of a possible future winged reusable stage, and to develop and test key technologies for such reusable stages. The flight demonstrator ReFEx shall perform a controlled and autonomous re-entry from hypersonic velocity of approximately Mach 5 down to subsonic velocity after separation from the VSB-30 booster. The focus of this paper is the re-entry trajectory design for the ReFEx mission.

Abbreviations

AoA	Angle of Attack
AVS	Avionics
BC	Ballistic Coefficient
BoGC	Begin of Guided Control
CALLISTO	Cooperative Action Leading to Launcher Innovation in Stage Tossback Operation
DOF	Degree of Freedom
ELV	Expendable Launch Vehicle
EoE	End Of Experiment
GNC	Guidance, Navigation and Control
L/D	Lift-to-Drag Ratio
FPA	Flight Path Angle
LFBB	Liquid Fly-Back Booster
MECO	Main Engine Cut-Off
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
TOSCA	Trajectory Optimization and Simulation of Conventional and Advanced Spacecraft
VTHL	Vertical Takeoff, Horizontal Landing
VTVL	Vertical Takeoff, Vertical Landing

1. Introduction

The recent successes of the emerging private space companies SpaceX and Blue Origin in landing, recovering and relaunching reusable first stages have demonstrated the possibility of building reliable and competitive reusable first stages. Thus, the importance for assessing whether such a reusable launch vehicle could be designed and built in Europe recently has increased. Driven by this demand for investigating reusable launchers, the German Aerospace Center (DLR) is currently studying different concepts of reusable launch vehicles (RLVs) with recoverable and reusable first stages.
There are different methods of recovering first stages after Main Engine Cut-Off (MECO) that are currently under investigation at DLR: first, vertical take-off and vertical landing (VTVL) as currently used by SpaceX with its Falcon 9 launcher [1]. As the name implies any launcher using this method will vertically land either on land or on a sea-

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going platform in the ocean by means of retropropulsion. Hence, the stage's engines have to be reignited to perform several maneuvers and finally land the stage vertically during the approach to the landing site. Therefore additional propellant is required to perform the re-entry and descent maneuvers.
Contrary to this method, the vertical take-off, horizontal landing (VTHL) approach follows a different logic; the landing is performed horizontally comparable to the Space Shuttle. Thus, the stage has to generate sufficient lift to allow for such a landing which leads to the necessity of wings and aerodynamic control surfaces. The surplus of lift compared to a VTVL stage is used to perform a non-propelled re-entry without the necessity to reignite the engines. However, such stages generally have a higher dry mass due to the required wing structure compared to VTVL launchers. Up to now, different studies focused on this method and investigated the possibility of developing VTHL stages. Figure 1 shows one of investigated concepts, the Liquid Fly-Back Booster that was studied by the DLR in the 2000s [2]. The boosters shown in the picture are equipped with wings and fins to enable aerodynamic control in all axes. Furthermore, a landing gear similar to that of a commercial aircraft is required and, in this concept, turboengines to allow an autonomous return to the landing site. Following MECO the boosters are separated from the center stage and perform an autonomous re-entry and return flight to the launch site. Other concepts using the VTHL method worth mentioning are the DLR SpaceLiner project [3] and the Hopper project with its demonstrator Phoenix [4] which has some resemblance with ReFEx.
Both approaches have their respective advantages and drawbacks. The DLR has initiated several studies to identify and quantify technical demands and requirements of both methods [5] - [7]: winged, horizontal landing stages and vertical landing stages. Thus both methods shall be compared to each other to identify the method which is favorable for an adaption as a future European RLV. Nevertheless, these theoretical and conceptual studies have to be backed up by experimental data to gather further data on re-entry conditions and their effect on RLV stage design.
Currently, the DLR is developing two flight demonstrator of which one represents the VTVL approach and the other one the VTHL approach. The former demonstrator, called CALLISTO, is developed in cooperation with CNES and JAXA [8]. The latter is the flight demonstrator ReFEx which is developed entirely at DLR. The goal of the ReFEx project is to build a flight demonstrator which is capable of performing a re-entry and return trajectory similar to that of a possible VTHL RLV stage (compare LFBB concept).
ReFEx is supposed to be launched on a VSB-30 booster in 2022 (see Figure 2) [9] - [13]. The demonstrator shall perform a controlled and autonomous re-entry flight from hypersonic velocity of Mach >5 down to subsonic velocity after separation from the VSB-30 booster. During the re-entry flight the vehicle has to be controllable while remaining within certain aerothermal and structural load limits. Additionally, the demonstrator has to reach a predefined target point while performing a heading change which imposes additional requirements on the trajectory design. The challenge in designing the re-entry trajectory and a suitable angle of attack and bank angle profile lies in the consideration of all those requirements while performing a re-entry representative of a future full-scaled winged stage.

Figure 1: Artist's impression of the Liquid Fly-Back Boosters disconnecting from the center core

In this paper, the current vehicle design and layout and the foreseen mission profile are briefly presented. Then, the aerodynamic behavior of the flight experiment is evaluated to derive an angle of attack and bank angle profile considering trimability and controllability at every flight point. Re-entry trajectories are calculated in 3 degrees of freedom from the apogee of the trajectory after separation from the VSB-30 booster. The influence of control parameters such as angle of attack or bank angle profile or the timing of roll maneuvers on the trajectory is investigated. Furthermore, the impact of the system mass on the trajectory is evaluated. The paper concludes with a summary and explanation of the major difficulties and challenges that lie within such a trajectory design.

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The design of the re-entry trajectory also has to consider local safety requirements of potential launch ranges to ensure that no violation of safety aspects occur during the re-entry flight. This paper includes a flight safety analysis based on Monte Carlo simulations. This analysis was performed for the preferred launch range, the Woomera launch facility in Southern Australia.

2. System Overview

Figure 2 shows the ReFEx Launch Configuration and a section view of the Re-Entry Segment, called ReFEx. The integrated units are grouped to the following subsystems:

- Guidance Navigation and Control (GNC)
- Avionics (AVS)
- Structure (STR)
- Flight Instrumentation (FIN)

Figure 3 illustrates the Payload (to be placed on top of the VSB-30 sounding rocket as shown in Figure 2) as well as the Re-Entry Segment as foreseen for the re-entry flight. The VSB-30 has no active vector control capabilities (passive stabilized system). Therefore, the Payload is required to have an almost rotationally symmetrical shape to enable a safe launch. However, the Re-Entry Segment needs to have an aerodynamic shape for the Experimental Phase (re-entry) which is contradicting the launch requirement. To meet both requirements the wings of the experimental vehicle were designed foldable and are covered by a fairing for the atmospheric passage. The integration of the payload on top of the VSB-30 sounding rocket will be performed at the test range, prior to the flight test. The Re-Entry Segment has a length of 2.7 m, a wingspan of 1.1 m and is a highly integrated system as can be seen in Figure 2. The total mass of the vehicle is approx. 400 kg. This leads to a larger mass to area (wing reference area) ratio by a factor of approx. 2-2.5 compared to future operational systems since those will have large empty tanks during the re-entry flight. More details can be found in [11].

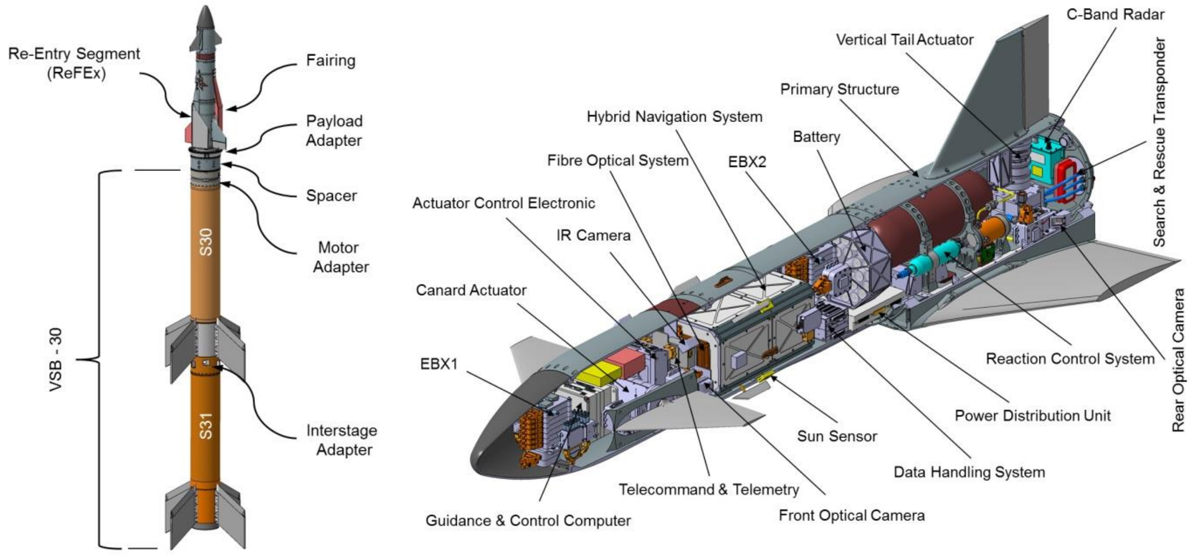

Figure 2: ReFEx Launch Configuration (left), section view of the Re-Entry Segment -ReFEx- (right) [11]

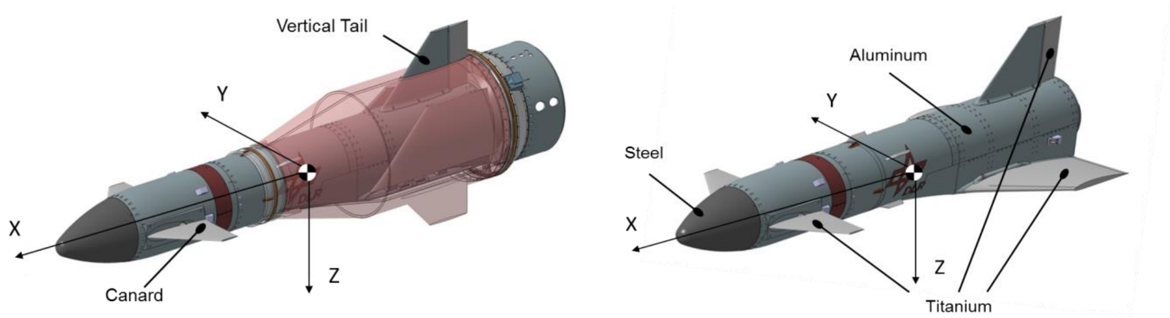

Figure 3: Configuration of the Payload (left) and the Re-Entry Segment (right) [11]

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The mission profile of the flight experiment is as follows: the launch occurs at the launch facility on the unguided VSB-30 booster. After lift-off and burnout of the first stage, there is a short coasting phase which is terminated by the ignition of the booster's second stage. Following MECO of the second stage the sounding rocket first briefly coasts and is then de-spun using a yo-yo system. Then, the fairing is jettisoned, the wings are unfolded and the experimental phase of the flight begins. This point is referred to as Begin of Guided Control (BoGC).
The vehicle follows a ballistic trajectory with attitude control by the RCS until it passes the EI in 60 km altitude in belly-up configuration with the vertical fin pointing downward. This is necessary due to the fact that the vehicle is unstable when flying with the vertical fin pointing upwards at such high AoAs. Once passing the EI the aerodynamic forces increase and allow for attitude control by the canards. The vehicle slows down until a velocity of approximately Mach 1.5 where it rolls by 180° to get the vertical fin pointing upwards. In this orientation the vehicle is stable in transonic and subsonic flight [11]. ReFEx continues to transition to subsonic velocities and flights in a stable gliding flight until it reaches its desired End of Experiment point (EoE) which is defined as the point where the vehicle reaches Mach 0.8.

3. Mission Design

3.1 Mission Requirements

The following requirements are the main drivers of the ReFEx re-entry trajectory design:

- 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 a winged first-stage reusable space transportation system (re-entry corridor).
- The vehicle shall perform a controlled heading change with an angle between downrange and cross-range of at least 30°
- Reach a prescribed target point (EoE) within a certain accuracy (altitude, velocity and geographic position)

3.2 Re-entry Corridor

The re-entry and return flight of any reusable first stage of a launch vehicle features similar events and characteristics. First, following MECO of the RLV's engines, the stage is separated from the core stage/second stage and follows a ballistic trajectory. Normally, during this ballistic flight phase negligible aerodynamic forces are present due to the high altitude at separation. The stage travels through apogee at suborbital velocity and begins falling back to earth while gaining velocity. During this phase the aerodynamic forces abruptly build up once the vehicle hits the denser parts of the atmosphere. At a certain point the stage experiences sufficient aerodynamic forces to start using the aerodynamic control surfaces to control the vehicle. Furthermore, the wing and fuselage generate sufficient lift and drag to slow down the vehicle while maintaining a desired altitude profile to ensure that the aerothermal loads are not exceeding structural limits. Following this phase, where the major part of the deceleration occurs, the re-entry vehicle transitions from supersonic to subsonic velocity and continues its flight as subsonic glider.
Since the flight profiles of said RLV stages are similar, certain thresholds and boundaries can be derived which are valid for any RLV stage. Hence, based on former research at DLR on the LFBB (Y-9) [2] and sub-scaled LFBB launchers (C60), the SpaceLiner concept [3], the Airbus EVEREST concept [14] and the ENTRAIN study [5] - [7] a so-called *re-entry corridor* was defined (see Figure 4). This corridor is defined by altitudes and Mach numbers.
It is important to note that these trajectories are all based on theoretical studies except for the Falcon 9 trajectories. However, the Falcon 9 follows a different return method of vertical landing. The trajectory shown here was derived from the SES 10 mission from 2017 using reverse engineering methods [1]. The re-entry corridor boundaries can also be defined and explained based on physical phenomena occurring during re-entry. The main point of a suborbital re-entry is to minimize the maximum heat flux and the integrated heat load during re-entry. The first requirement is driven by the fact that high heat fluxes requires an integration of a thermal protection system (TPS) which in turn increases the system mass. Since increasing the dry mass of the first stage worsens the launcher's performance, excessive loads and thus heavy TPS systems render the launcher useless from a performance and hence economic point of view. Considering the fact that the convective heat flux is calculated according to equation (2), the heat flux can be increased by reducing the velocity or the density (by flying higher). This is represented by the lower boundary of the re-entry corridor which, when violated, leads to excessive heat loads.

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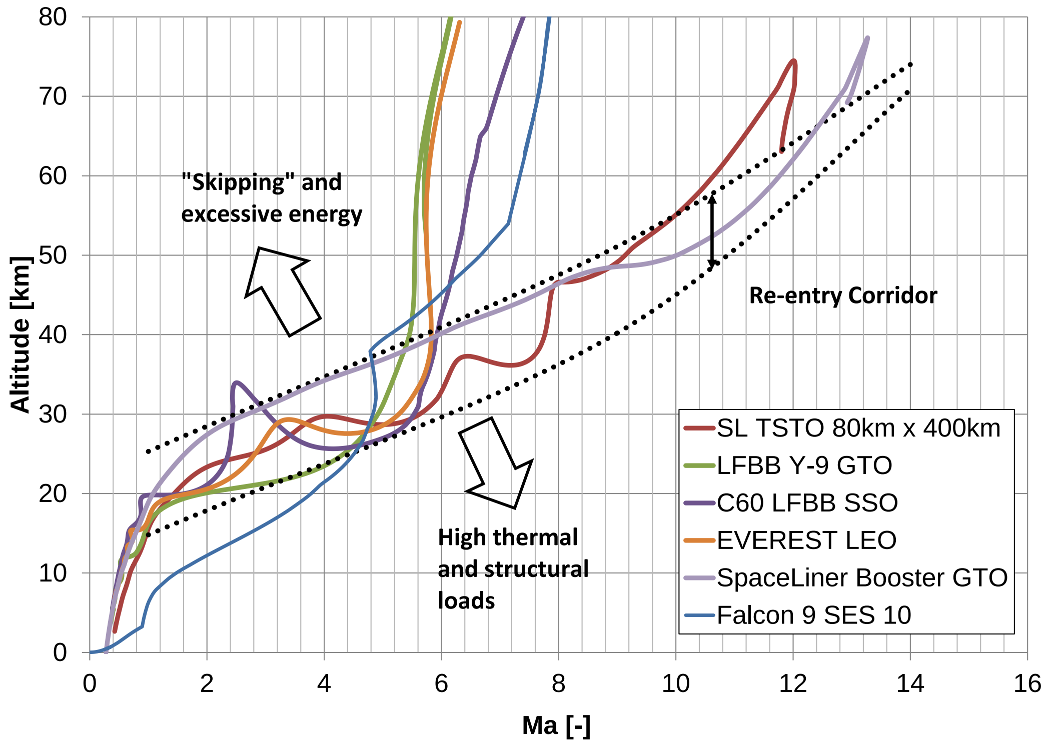

Figure 4: Re-entry corridor and examples of re-entry trajectories of different winged RLV stages including the SpaceLiner (SL), the LFBB and micro-LFFB concepts (Y-9, C60), the Airbus EVEREST concept and the Falcon 9 trajectory of the SES 10 mission

The upper boundary of the re-entry corridor addresses the requirement considering integrated heat load and excessive energy throughout the whole trajectory. When entering to shallow or with too much lift, the stage might “bounce off” the thicker parts of the atmosphere, thus experiencing so-called “skipping” off the atmosphere. If this occurs during flight, the integrated heat load over the re-entry trajectory will increase since the flight time increases and several “dips” into the atmosphere occur which lead to increased heat flux during each re-entry. Thus, the vehicle’s energy is not sufficiently reduced.
Another important parameter for re-entry vehicles is the ballistic coefficient as defined in equation (1) where m is the vehicle mass, c_d is the drag coefficient and A the area of the vehicle. A high ballistic coefficient leads to higher peak heat flux and loading. Hence, higher ballistic coefficients lead to a re-entry trajectory further toward the lower boundary of the re-entry corridor. The ballistic coefficient of ReFEx is around 7900 kg/m² (reference vehicle mass of 400 kg) whereas the BC of the LFBB is around 2900 kg/m² at Mach 5 and 0° angle of attack. The BC at 40° AoA (roughly re-entry orientation) is approximately 550 kg/m² for ReFEx and 215 kg/m² for the LFBB, showing that the relative difference between both values stays roughly constant regardless of the AoA. Due to the higher BC it is acutally more demanding to keep the re-entry trajectory of ReFEx within the corridor boundaries compared to the full-scale vehicles.

$$\boldsymbol{BC} = \frac{\boldsymbol{m}}{\boldsymbol{C_d * A}} \qquad (1)$$

3.3 Re-entry Trajectory

The ReFEx flight demonstrator features some unique peculiarities compared to full-scale winged stages. Since the stage re-enters with the vertical tail pointing downward (*belly-up* configuration), at a suitable point of the trajectory the vehicle has to perform a roll maneuver to get the vertical tail pointing upwards. From a trajectory point-of-view, the following events occur during the re-entry of the ReFEx vehicle:

- Ballistic flight from separation until re-entry, preferably in re-entry configuration (belly-up)
- Re-entry with high angle of attack to produce sufficient lift and drag to stay within the re-entry corridor (typically around 40°-50° AoA)
- Rapid reduction of angle of attack during abrupt build-up of aerodynamic forces, simultaneous banking to enable heading change

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- Roll maneuver to change to belly-down configuration at around Mach 1.5
- Transition to subsonic velocities and subsonic gliding until End of Experiment at Mach ~ 0.8

The trajectories presented herein were calculated in 3 degrees of freedom using the DLR in-house tool tosca.

Aerodynamics

The initial phase of the re-entry, during the abrupt build-up of aerodynamic forces, the vehicle has a high AoA to produce sufficient lift and drag forces to slow down the vehicle. Therefore, the vehicle has to be trimable at high AoAs. Furthermore, the vehicle should be laterally and longitudinally stable. During the later phase of the re-entry, once the major part of velocity has been shed, the AoA has to be significantly reduced. Hence, the range of trimmable AoAs for ReFEx is quite demanding.

During the trajectory design only trimmable and stable flight points are used. The respective CFD analysis was performed by the Institute of Aerodynamics and Flow Technology of the DLR Braunschweig and is presented in detail in [15]. The CL/CD ratio is shown in Figure 5. The maximum CL/CD ratio is approximately 1.8 at Mach number 5-6 to 2.2 at Mach number 2. Hence, it is slightly lower than the CL/CD ratio of the LFBB of 4 – 4.5 at subsonic velocities. This is caused by the relatively smaller wing area of the experimental vehicle.

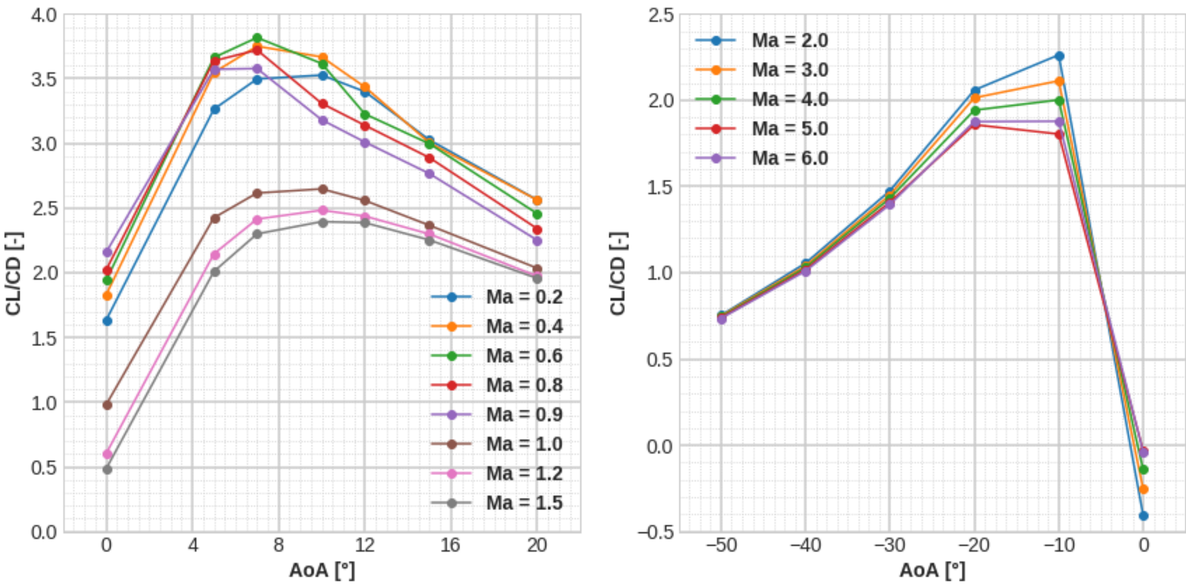

Figure 5: Lift-to-Drag-Ratio of ReFEx at super-/subsonic (left) and hypersonic (right) velocities

Guidance

The goal of the ReFEx mission is to reach a prescribed End of Experiment (EoE) point within a certain accuracy. Due to the fact that the VSB-30 sounding booster is an unguided missile, the expected dispersion at the separation point is rather large compared to an orbital launch vehicle's conditions at MECO. Therefore, a sophisticated guidance and control system is required that is able to compensate inaccuracies during re-entry flight to enable the vehicle to reach the EoE point.

Within the ReFEx project certain guidance logic is implemented: the so-called bank-reversal strategy. This strategy is a common approach used for re-entry vehicles to control the magnitude and orientation of the vehicle's lift vector. The method was used for the Space Shuttle re-entry flight as well and is based on the fact that by banking the vehicle the lift vector can be rotated out of the vertical plane (compare Figure 6). The magnitude of lift is then controlled via the angle of attack while the bank angle is used to match the actual vertical lift component with the required one. Hence, offsets of the nominal trajectory can be compensated by changing the bank angle. However, a bank angle also produces a lateral force which in turn compels the vehicle into flying a curve. Thus, when reaching a certain predefined threshold the bank angle has to be reversed and turned into the opposite direction.

In this paper, re-entry trajectories with bank-reversal maneuvers are presented. The details of the guidance logic are part of another paper and are described in more detail in [16].

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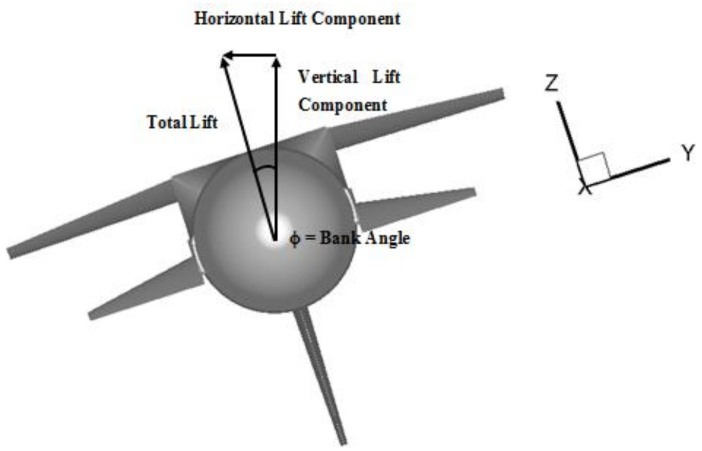

Figure 6: Effects of the bank angle on the orientation of the lift vector (right-hand coordinate system)

Results

The launch site for the calculated trajectories is the Woomera Range Complex in Southern Australia. The launch trajectories were calculated by MORABA [17]. The re-entry trajectories are calculated from apogee until the flight demonstrator reaches ground level (note that the actual EoE is at Mach 0.8).

Different masses were considered in this paper, respectively 300 kg – 500 kg in 50 kg steps to determine the impact of the ballistic coefficient on the re-entry trajectory and its position with respect to the re-entry corridor. Figure 7 shows the trajectory path of the 400 kg version. The approximate range boundaries are highlighted in grey color. It is visible that ReFEx performs a heading change once reaching denser parts of the atmosphere and continues to perform bank-reversals when traveling through the EoE target ellipse. The phase where the vehicle enters with a high AoA is clearly visible in the trajectory profile where the trajectory flattens and the flight path angle increases. In order to achieve the desired mission goal of demonstrating a heading change of the vehicle with a specified angular value, the vehicle banks almost throughout the whole trajectory until it reaches subsonic velocity.

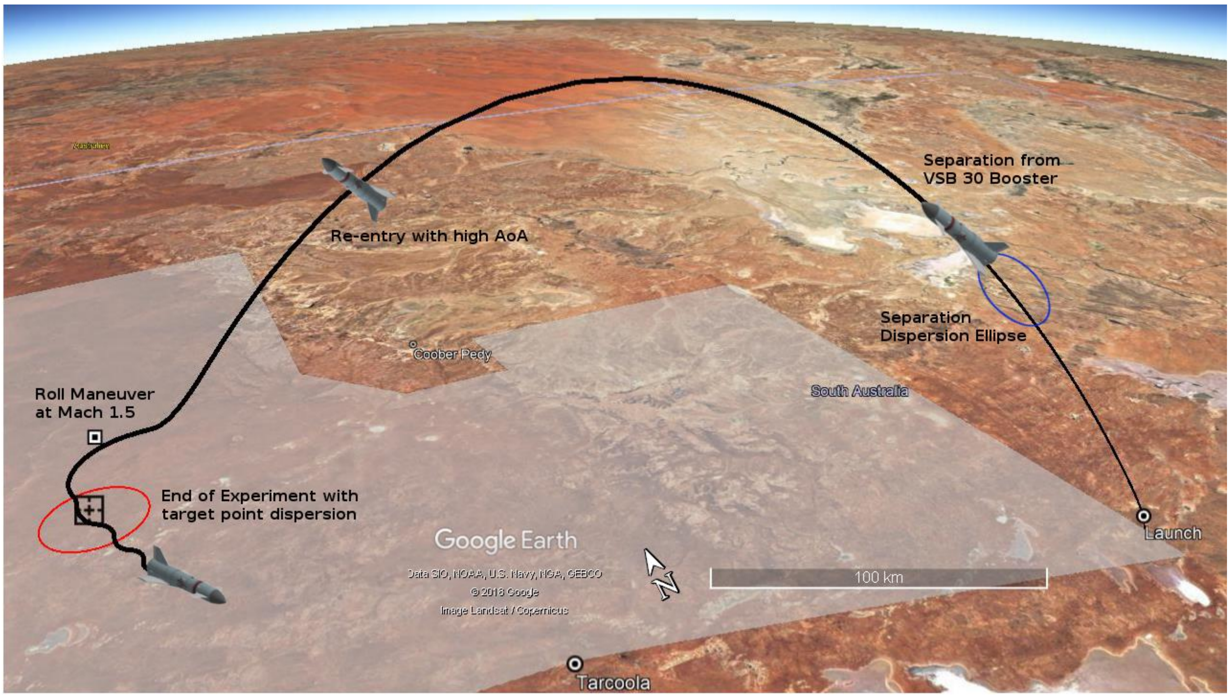

Figure 7: Trajectory with launch from Woomera for a system mass of 400 kg with bank-reversal maneuvers

Figure 8 shows the re-entry trajectories in the Altitude-Mach-diagram and the two boundaries of the re-entry corridor (compare Figure 4). Furthermore, isolines of dynamic pressure and heat flux were added. The convective stagnation point heat flux was calculated with a modified Chapman formula according to equation (2). Here, ρ is the local density at the respective altitude according to the US standard atmosphere 1976, ρ_R is a reference density value of

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1.225 kg/m³, $R_{N,r}$ is reference nose radius (here 1 m), R_N is the vehicle nose radius (here 0.05 m for the ReFEx vehicle), v is the vehicle's velocity and v_R is a reference velocity of 10000 m/s.

$$\dot{q} = 20254.4\, W/cm^2 \cdot \sqrt{\frac{\rho}{\rho_R}\frac{R_{N,r}}{R_{,N}}}\left(\frac{v}{v_r}\right)^{3.05} \tag{2}$$

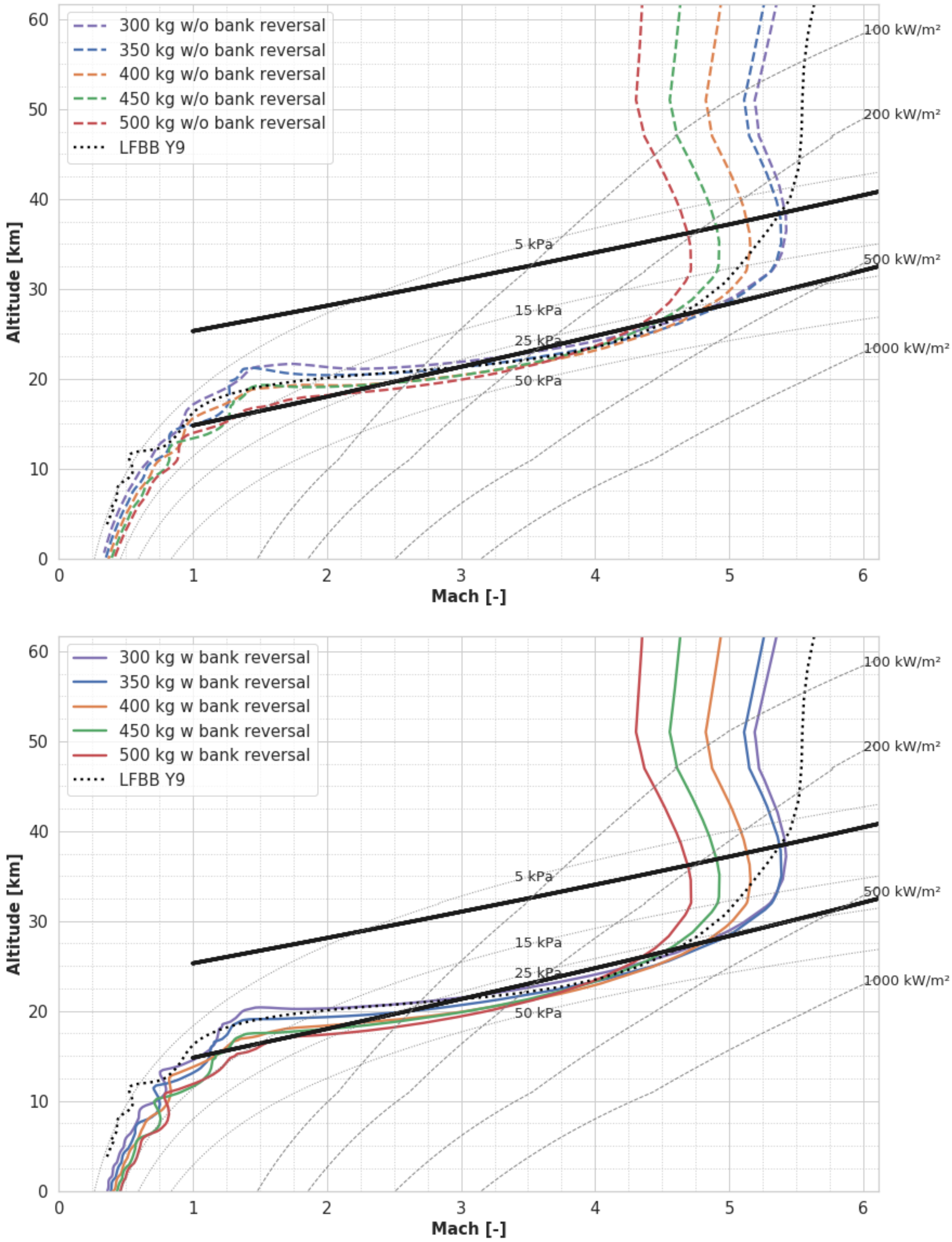

Figure 8: Re-entry trajectories for different re-entry masses without bank-reversal (top) and with bank-reversal with a bank angle of 36° (bottom)

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Higher re-entry masses and thus ballistic coefficients during re-entry shift the trajectory slightly towards the lower boundary of the corridor. The achievable re-entry velocity using the VSB-30 launch system is higher for lower experimental vehicle masses. However, all trajectories undershoot the lower boundary of the corridor. Nevertheless, comparing the trajectories to that of the LFBB Y-9 version the accordance is quite good, although the BC of ReFEx is higher and there are more restricting requirements (foldable wings, lower wing area).
It is important to highlight that all trajectories end up within the re-entry corridor around Mach 2 thus fulfilling the mission requirements. The effect on vertical lift reduction by banking is visible in the trajectories in the lower plot of Figure 8. The bank angle for the trajectories on the right-hand side is around 36° which is equivalent to a reduction in vertical lift of 20%. Within a range from Mach 3 to Mach 5 the differences between banking and non-banking trajectories are negligible. Only from Mach 2 downwards the non-banking vehicles traverse at higher altitudes.
While the plots in Figure 8 might indicate that most of the re-entry flight is occurring at supersonic velocities, the picture changes once the timeline of the re-entry is considered (see Figure 9). It is noticeable that the velocity is reduced in quite a small amount of time, namely around 50 s to 60 seconds from re-entry velocity to around 400 m/s. This distinguishes the ReFEx re-entry trajectories compared to the full-scale winged vehicles (compare Y-9), where the velocity is not as abruptly reduced. The deceleration loads on ReFEx are a result of the aerodynamic forces acting upon the vehicle which scale with the dynamic pressure (see Figure 9). The maximum dynamic pressure is in the same range of 37 kPa – 40 kPa for all re-entry masses. This similarity can be explained by the fact that although heavy vehicles with a high BC require higher aerodynamic forces and “dip” deeper into the atmosphere, the re-entry of the heavy vehicles occurs with a lower velocity. It is important to highlight the similarity in dynamic pressure between the ReFEx re-entries and the LFBB re-entry, once again showing that ReFEx performs a sufficiently representative re-entry.

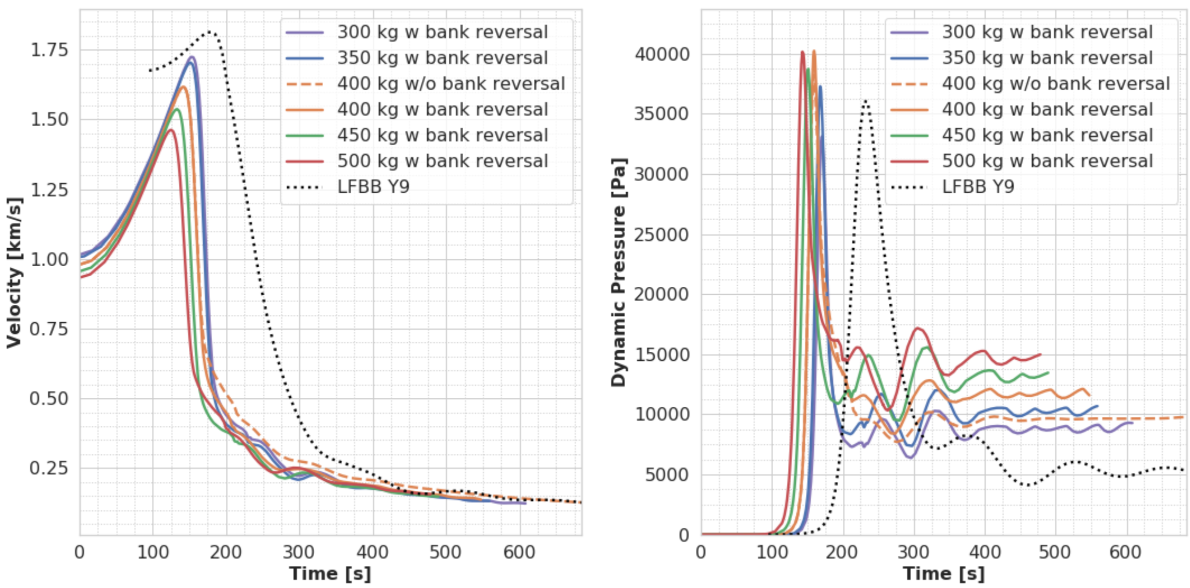

Figure 9: Velocity over ground (left) and dynamic pressure (right) for different vehicle masses with (w) and without (w/o) bank reversal

The peak dynamic pressure builds up rapidly and decelerates the vehicle but converges towards an almost constant value for the steady gliding phase of the trajectory. In case of the LFBB the dynamic pressure gradient in the critical deceleration phase of re-entry is not as high. This can be explained by the much lower re-entry flight path angle (compare Figure 10). A small re-entry flight path angle decreases the gradient of atmospheric density increase and leads to a mellower build-up of aerodynamic forces and loads (compare Figure 10).
The AoA during transonic and subsonic flight is reduced to a constant value of 7° which allows a flight at almost maximum L/D. The wing loading determines the steady gliding velocity at a given altitude for the subsonic flight, hence explaining the higher dynamic pressure values for higher masses beyond 400 seconds after apogee.
The loads experienced by the vehicle during re-entry are directly linked to the dynamic pressure since only aerodynamic forces decelerate the vehicle. The maximum loads are experienced in the z-body-axis of the flight vehicle due to the fact that the re-entry occurs with a high AoA (see Figure 10). Depending on the re-entry mass the maximum static loads range from ~8 g_0 to ~11.5 g_0 (g_0 = 9.80655 m/s²). Compared to the full-scale vehicle LFBB those loads are significantly higher (~3.5 g_0). Once again, the reasons behind the high values for the ReFEx re-entry are a high BC and a very steep entry with a high negative FPA (see Figure 10). Nevertheless, whereas up to 12 g would be unbearable by a full-scale stage, the ReFEx demonstrator with its smaller dimensions is designed to

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withstand those loads. Another highly important parameter regarding re-entry loads is the heat flux. Within the herein simulated trajectories, a heat flux is calculated based on the equation (2). The thus calculated maximum stagnation point heat flux for a nose radius of 0.05 m is approximately 300 kW/m² in all cases. However, due to the fact that sophisticated calculations were performed by the Institute of Aerodynamics and Flow Technology, the detailed information about heat flux is not presented here, but in the respective paper [15].

Considering the AoA and bank angle control profile, the differences and similarities between ReFEx and the LFBB get obvious. Both re-enter at initially high AoAs of around 35° (LFBB), respectively -39° (ReFEx). The AoA sign is negative for ReFEx because the re-entry occurs in belly-up configuration which is equivalent to a bank angle of 180°. Thus, negative AoAs produce positive lift (see [15], [16] for detail). Once the maximum dynamic pressure is reached, the AoA is significantly reduced to avoid skipping of the vehicle off the atmosphere. The ReFEx vehicle then executes the roll maneuver bringing it to a belly-down attitude which is visible in the switch of sign in the AoA angle. After transition to subsonic speed the AoA is kept almost constant to enable a constant and steady gliding flight.

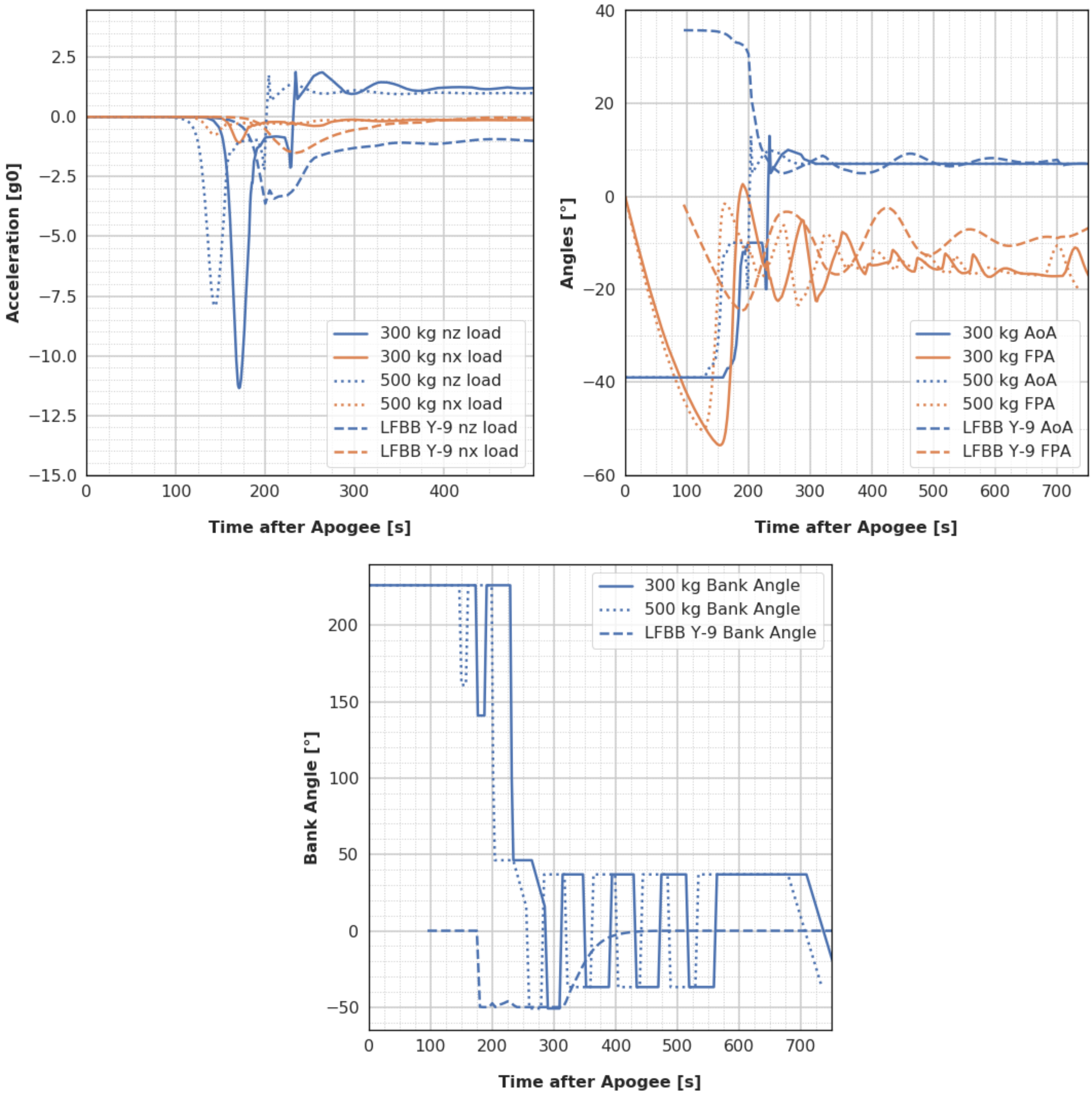

Figure 10: Total Acceleration and loads in x- and z-body-axis (left) and AoA, bank angle and flight path angle (right) for 300 kg and 500 kg vehicle mass with bank reversals

The bank angle is needed for both ReFEx such as LFBB to fly a curve. In case of the LFBB this maneuver is essential to position the stage closer to the landing site. While the LFBB enters without any banking, the ReFEx vehicle is banked about 216°, 180° for belly-up flight plus 36° of additional banking for the bank-reversal strategy. Once the maximum dynamic pressure is experienced and the AoA is reduced, the LFBB initiates the banking

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maneuver which brings it to a bank angle of 50°. At the same point in the re-entry flight ReFEx has to perform a bank-reversal and later on rolls 180° around its x-body axis to get to a belly-down orientation. The bank angle of the LFBB is reduced once the curve is finished. ReFEx on the other hand starts flying several bank-reversals to bank around a straight line.
In summary, both ReFEx as well as the LFBB have a quite similar control profile. The differences that arise between both vehicles are due to the control strategy of ReFEx (bank-reversal), the lower velocity, the difference in BC and the steeper re-entry.

4. Flight Safety

Since ReFEx is a winged flight vehicle with a significantly higher L/D ratio and thus achievable range than a ballistic missile, it is of high importance to consider the aspect of flight safety in the design process. Based on the trajectories presented in the previous section 3-DOF Monte Carlo simulations were conducted to determine flight safety hazards. The Woomera test range as preferred launch site was selected as range for the following flight safety considerations.
The basic idea behind the approach to the flight safety analysis is to determine possible impact sites in case of off-nominal flight conditions. Hence, the reference trajectory of ReFEx with 400 kg re-entry mass was selected as reference. Based upon this trajectory, the nominal apogee conditions were distorted by randomly imposed apogee conditions within the 3σ limits:

- Reference altitude ± 20 km
- Reference velocity ± 70 m/s
- Reference Position ± 24 km cross range and ± 22 km downrange

Furthermore, the vehicle is assumed to stay within trimmable AoAs and the bank angle is set to 0° after a random amount of time. This is a conservative approach since it assumes that the vehicle stays within a stable flight condition throughout the whole mission time. However, this approach is adequate to determine the possible range of the flight experiment under worst-case conditions and, based on the results of this analysis to derive active in-flight measurements to ensure that ReFEx under no conditions is able to leave the Woomera range.
The determination of impact probability was performed by selecting a rectangular target area which stretches from a latitude of 27.5° S to 31° S and from a longitude of 131° E until 135.25° E (see Figure 11). This target area was further divided into 22500 smaller squares with a mean surface area of 7.12 km². Then, 20000 trajectory calculations using the Monte-Carlo approach described previously were performed and the number of ground impacts in each square was counted.
Thus, the impact map shown in Figure 11 was derived. Here, the different colors represent the number of impacts per square (not to be confused with number of impacts per km²). It is clearly visible that there is a “hot spot” with a high probability of impact in the downrange direction of the launch azimuth. The highest number of impacts per square is 69 which corresponds to an impact number of ~10 impacts/km². The major number of impacts (~90% of impacts) occurs within an area of around 11300 km², roughly within a circle with a diameter of 120 km. All of these points in the 90% impact probability area lie within the range.
Some impacts occur outside of the range, respectively 1% of all calculated trajectories. All of the observed range violations occur at the northern end of the range. In this region lies the settlement of Coober Pedy with a population of around 1695, hence any impact in the vicinity of this settlement has to be avoided. However, ReFEx’ nominal trajectory features banking to the left, which drives the vehicle away of the settlement to the southern boundaries of the range. The impacts in the Coober Pedy region only occur if the vehicle, for some reason, uncontrollably banks to the right and then continues flying in a straight line.
However, this first preliminary safety analysis has shown that ReFEx is physically able to leave the range boundaries, hence counter measurements in case of off-nominal behavior have to be foreseen in the whole flight safety approach. This is foreseen in the current design phase of the vehicle by deflecting the canards to their maximum possible deflection angle but into opposite directions once the system gets passive (for details refer to [11]). This introduces a roll moment which leads to uncontrollable movement and thus a reduction of the lift which shall shorten the range that the vehicle can fly.
Nevertheless, 6-DOF simulations of this approach are actually necessary to determine if ReFEx, under tightened assumptions and considering the movement once the canards are deflected, is still able to violate the range boundaries. These simulations are set to begin in the near future with results still pending.

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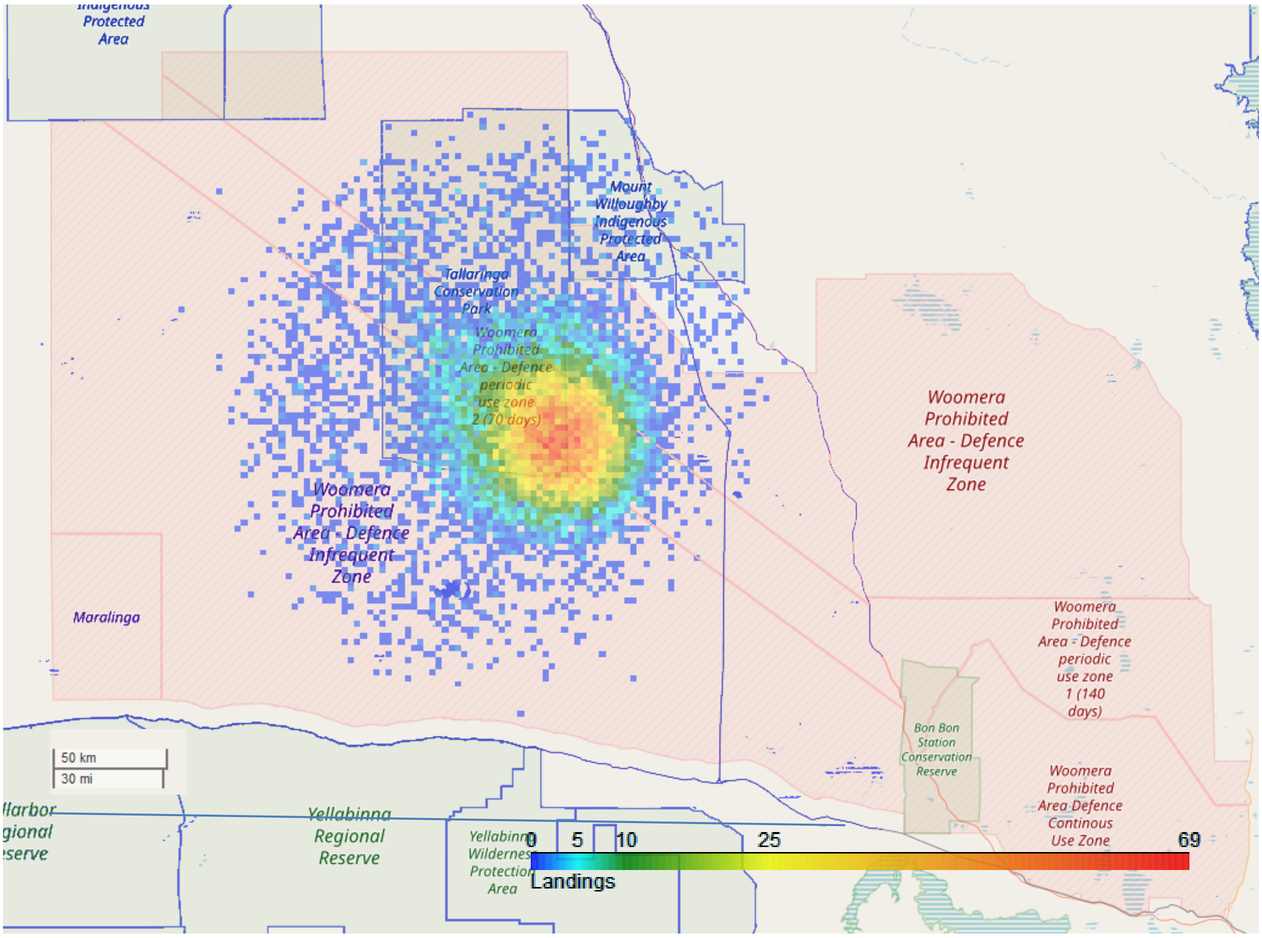

Figure 11: Impact Map of the Flight Safety Analysis on the Woomera range

5. Conclusion and Summary

The goal of the ReFEx flight vehicle is to demonstrate the capability to autonomously re-enter and preferably land an unmanned winged vehicle. The demonstrator is supposed to lift the TRL of winged reusable stages and create knowledge which shall be used in the further development of reusable launch systems in Europe. Therefore, the mission parameters and goals of ReFEx have to be similar to that of a full-scale winged RLV stage.
First, the re-entry trajectories of ReFEx all lie within close distance to the re-entry corridor, more or less regardless of the mass which is a good result. It also shows that the mass is not the major driver of achieving a trajectory close to the corridor. However, as already noted in the previous section, the BC of ReFEx is much higher, the re-entry velocity is slightly lower and the re-entry flight path angle is higher compared to the LFBB trajectory. This leads to higher loads experienced and higher dynamic pressure and its gradient during re-entry and demands for sophisticated control and guidance algorithms, since the vehicle reacts much faster to the flowfield. All of these points render the re-entry of ReFEx actually more challenging compared to a full-scale vehicle. Considering these difficulties it is a very good result to see a good accordance between the ReFEx and the LFBB trajectories in the H-Ma-diagram.
Another question to be answered when considering level of representation is the question if ReFEx uses a control profile similar to that of the LFBB. Considering that the vehicle shall use bank-reversals to control its energy and reach the predefined target point and the difference in re-entry conditions, the control profile is quite similar. The re-entry occurs with a high AoA, followed by sudden decrease of the AoA to avoid skipping after an adequate amount of time. The vehicle then transitions through the transonic flight regime until it reaches a steady gliding flight. The mission requirement to successfully demonstrate a heading change can be fulfilled in all cases.
In summary, any winged re-entry vehicle entering the atmosphere from suborbital velocities will experience a mellower re-entry if:

- The ballistic coefficient is low (either by low mass or high L/D by high wing area)

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- The flight path angle is sufficiently low
- The angle of attack is as high as possible during re-entry

Considering the aspect of flight safety ReFEx has to meet the safety requirements of the launch range. Therefore, the desired launch range Woomera was subjected to a Monte-Carlo analysis to determine, under conservative assumptions, the probability of range violations of the flight experiment. This analysis has shown that ReFEx is physically able to leave the range over the northern range boundaries into the direction of Coober Pedy. Hence, a safety strategy was established by deflecting the canards to their fullest in case of off-nominal conditions or a loss of power. However, this approach has to be verified by 6-DOF Monte-Carlo simulations in the next step.

References

[1] Stappert, S., Sippel, M. 2017. Critical Analysis of SpaceX Falcon 9 v1.2 Launcher and Missions. DLR SART TN-009/2017

[2] Sippel, M., Manfletti, C., Burkhardt, H.: Long-term/Strategic Scenario for Reusable Booster Stages In: *Acta Astronautica, vol. 58, no. 4, pp. 209–22,* 2003

[3] Sippel, M. et al. 2017. SpaceLiner Concept as Catalyst for Advanced Hypersonic Vehicles Research. In: *7th European Conference for Aeronautics and Space Sciences (EUCASS),* Milan, Italy

[4] J. Spies and H. Kuczera, "The sub-orbital hopper - One of FESTIP's preferred concepts," in *9th International Space Planes and Hypersonic Systems and Technologies Conference, Norfolk, UK*, 1999.

[5] Wilken, J., Stappert, S., Bussler, L., Sippel, M., Dumont, E. 2018. FUTURE EUROPEAN REUSABLE BOOSTER STAGES: EVALUATION OF VTHL AND VTVL RETURN METHODS. In: *69th International Astronautical Congress (IAC), 01.-05. Oktober 2018.* Bremen. https://elib.dlr.de/122188/

[6] Bussler, L., et al. 2018. Assessment of VTVL and VTHL Reusable First Stages. In: *HiSST: International Conference on High-Speed Vehicle Science Technology*. Moscow. https://elib.dlr.de/125063/

[7] Stappert, S., Wilken, J., Sippel, M., Dietlein, I. 2018. Evaluation of European Reusable VTVL Booster Stages. In: *2018 AIAA SPACE and Astronautics Forum and Exposition.* Orlando, Florida, USA. https://elib.dlr.de/121912/

[8] Dumont, E. et al.: CALLISTO – Reuable VTVL launcher first stage demonstrator. In: *Space Propulsion Conference, 14th to 18th May 2018*. 2018

[9] Rickmers, P., Bauer, W., Stappert, S., Kiehn, D., Sippel, M. 2018. Current Status of the DLR Reusability Flight Experiment. In: *HiSST: International Conference on High-Speed Vehicle Science Technology*. Moscow. https://elib.dlr.de/126516/

[10] Rickmers ,P. et. al. 2018. An Update of the Upcoming DLR Reusability Flight Experiment - ReFEx. In: *69th International Astronautical Congress (IAC), 01.-05. Oktober 2018.* Bremen. https://elib.dlr.de/126514/

[11] Rickmers, P., Bauer, W., Wübbels, G. 2019. ReFEx: Reusability Flight Experiment – A System Overview. In: *8th European Conference For Aeronautics and Space Sciences (EUCASS).* 01.07.-04.07.2019. Madrid, Spain

[12] Bauer, W. et al. 2017. Upcoming DLR Reusability Flight Experiment. In: *Proceedings of the International Astronautical Congress, IAC*, 25th – 29th September 2017. Adelaide, Australia. https://elib.dlr.de/116879/

[13] Bauer, W., Rickmers, P., Kallenbach, A., Stappert, S., Wartemann, V., Merrem, C. H-J., Schwarz, R., Sagliano, M., Grundmann, J. T., Flock, A., Thiele, T., Kiehn, D., Bierig, A., Windelberg, J., Ksenik, E., Bruns, T., Ruhe, T., Elsäßer, H., "DLR Reusability Flight Experiment ReFEx," *Acta Astronautica (under review)*, 2019

[14] Iranzo-Greus, D. et al. 2003. Selection and Design Process of TSTO Configurations. In: *54th International Astronautical Congress, Bremen, Germany*

[15] Merrem, C. et al. 2019. Aerodynamic Design of a Reusable Booster Stage Flight Experiment. In: *8th European Conference For Aeronautics and Space Sciences (EUCASS).* 01.07.-04.07.2019. Madrid, Spain

[16] Schwarz, R. et al. 2019. Overview of Flight Guidance, Navigation, and Control for the DLR Reusability Flight Experiment (ReFEx). In: *8th European Conference For Aeronautics and Space Sciences (EUCASS).* 01.07.-04.07.2019. Madrid, Spain

[17] Schmidt, A.: ReFEx Launch with a Sounding Rocket – A Challenging Mission on A Reliable Carrier, In: *8th European Conference For Aeronautics and Space Sciences (EUCASS).* 01.07.-04.07.2019. Madrid, Spain