MISSION ENGINEERING FOR THE RECOVERY AND VERTICAL LANDING OF AN ORBITAL LAUNCH VEHICLE

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ABSTRACT

In the last decade, the number of space-based applications increased dramatically. To cover such a demanding market, launch technologies adapted and new launch solutions were developed, to increase the efficiency and the cost effectiveness of the access to space. In particular, reusability became the focus of multiple activities devoted to the design and analysis of current and future launchers solutions. Worldwide, Space X was able to make the reusability of first stages look like a routine operation with more than 50 successful landings and recoveries, and reuse up to 6 times. ULA and Blue Origin are developing their next generation launchers to be partially reusable, and also China is testing technologies to achieve reusability for micro-launchers. In Europe, several initiatives have been started in the last years to analyse and test critical technologies and system that will enable reusability. The RETro-propulsion Assisted Landing Technologies (RETALT) project is an H2020 activity, funded by the European Union and coordinated by DLR, aiming at developing key technologies to enable the recovery of vertical take-off vertical landing launchers making use of retro-propulsion, in the field of aerodynamic and aerothermodynamics, flight dynamics and GNC, and structures and mechanisms. In this context, mission engineering is a critical process of the design-for-reusability chain, and it is a discipline of excellence of DEIMOS Space. In this paper, the mission engineering process developed and applied to RETALT is presented, as well as the results obtained.

Index Terms— atmospheric entry, launchers reusability, flight mechanics, supersonic retro-propulsion, RETALT

1. INTRODUCTION

The objective of the mission engineering in RETALT is to define a mission baseline and derive reference trajectories for all return flight phases and for all the mission scenarios selected. In this way, flight and landing loads are derived to ensure total coherence among all requirements and to support the development of the key technologies considered in the study (aerothermodynamics, structural concepts and mechanisms, TPS, GNC).

To meet the study objectives, and based on Deimos' experience in atmospheric flight and re-entry mission analysis [1][2][9], the mission engineering for RETALT at first focuses on the definition of the concept of operations (CONOPS) for the return mission and the analysis of the capability of the launcher configurations to perform such a recovery mission. In this preliminary *mission feasibility analysis*, mission needs are identified in terms of trajectory and flight mechanics, to enable reusability and guarantee a robust and reliable return mission solution. The mission constraints will limit the space of the mission solution and will contribute to the identification of mission, system and subsystems requirements, in particular for the GNC and the sizing of the actuators.

Once the flight envelope for the return mission has been identified, the *mission design* of the reference return mission can be performed in detail. The flying qualities analysis allows to evaluate the trimmability, stability, and controllability characteristics of the launcher configurations, and therefore support the consolidation of the reference mission design. The reference trajectories for the return scenarios considered are thus optimised to support the development of the different technologies necessary to enable the recovery and therefore the reusability of the launcher.

2. REFERENCE CONFIGURATIONS

The baseline configuration and main focus of the project and this paper is RETALT1, a 103 m tall two-stage to orbit (TSTO) launcher, shown in Figure 2. The vehicle operates similarly to a typical launcher until separation, after which two scenarios for the first stage recovery are considered: Downrange Landing (DRL) and Return to Launch Site (RTLS), illustrated in Figure 1. The latter differs in the use of a post-separation flip manoeuvre and boost-back burn that modifies the ballistic arc to allow a landing at or near the launch site, while the former foresees a landing at sea on a floating barge. Both scenarios employ a re-entry burn, to reduce velocity, and an active aerodynamic descent phase enabled by the use of Aerodynamic Control Surfaces (ACS). Finally, pinpoint soft vertical landing is enabled by an engine-powered descent. Different ACS configurations are considered for the RETALT1 concept, including interstage petals (IS), planar fins (PF), and grid fins (GF), see Figure 3.

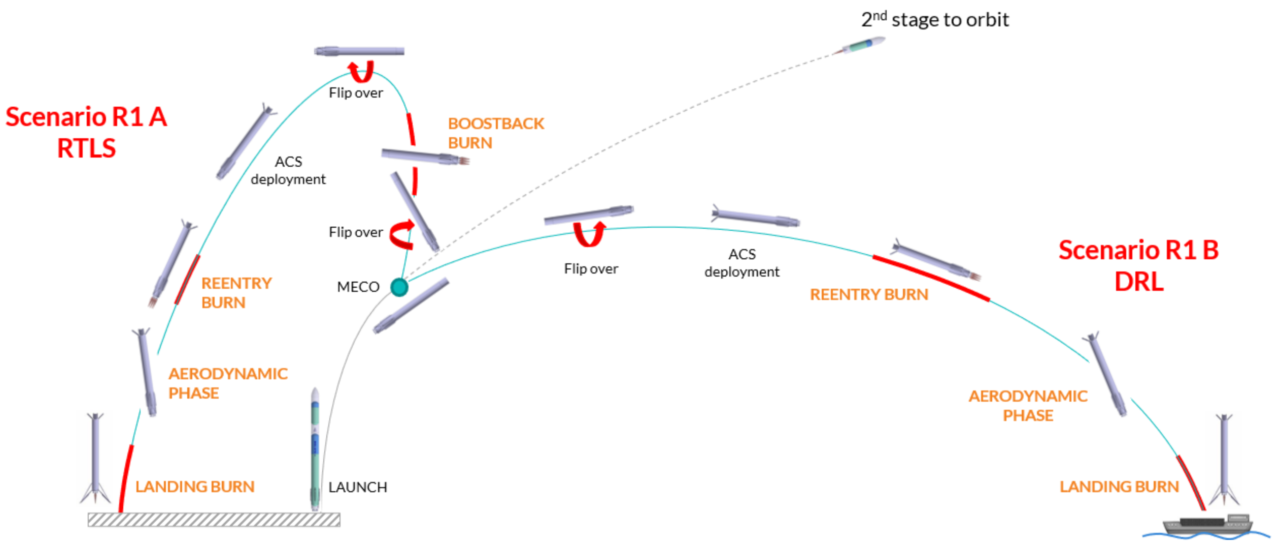

Figure 1 RETALT1 return mission concept

The concept configuration of the RETALT1 first stage was designed assuming the use of Vulcain-like engines [3], and has a dry mass of 59.3 tons and 57 tons of propellant available for the return manoeuvres (50 tons plus 7 reserve).

As an alternative, a 17.9 m tall single-stage to orbit (SSTO) launcher similar to the DC-X, RETALT2, was also taken into account to assess the possibility of performing a recovery mission directly from orbit with such a configuration: after a de-orbit burn, a long aerodynamic re-entry phase follows taking advantage of the aerodynamic performance of this configuration. Soft landing is still performed with retro-propulsion. This configuration, however, is considered only as a possible alternative, while the main focus of the study is RETALT1.

Dedicated supersonic Wind Tunnel tests campaigns, and CFD analyses were carried out to deliver dedicated aerodynamic databases for all RETALT configurations. Aerodynamic performance was inputted to compute preliminary concept trajectories, to assess the flight envelope before the consolidation of the mission design [4][5].

Figure 2 . RETALT1 and RETALT2 concepts (not to scale)

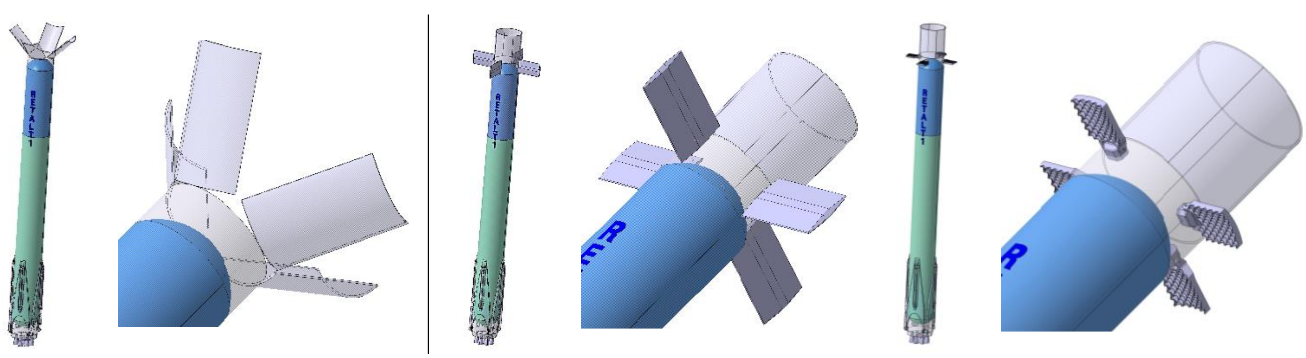

Figure 3 RETALT1 ACS configurations: interstage petals (left), planar fins (center), and grid fins (right) [3]

3. MISSION FEASIBILITY ANALYSIS

The mission feasibility analysis of RETALT1 focuses on the assessment of the capabilities of the proposed configurations to perform a return mission. The exploration of the flight envelope identifies the conditions that the launchers will face during the return.

At first, the analysis of the recovery capability is carried out studying the different recovery manoeuvres to identify design drivers for the recovery mission and to contribute to the consolidation of the propellant budget and the flight and landing loads, which contribute to the sizing of the aerodynamic actuators.

Then, based on the results of the recovery capability analysis, the mission needs are identified in terms of performance required to achieve the mission objectives and enable recovery and thus reusability.

The assessment is based on the reference system configurations and the concept trajectories identified, but not limited to these trajectory conditions. Actually, the capability of recovering the launcher's first stage from a wide range of launch mission scenarios is key in enabling a broad combination of payloads and injection orbits, providing the launcher with the flexibility to meet the needs of different customers. For given conditions at MECO, a specific recovery strategy is possible (RTLS or DRL). The variability of conditions at MECO (velocity and FPA) expected for the RETALT launcher has been identified mapping characteristic conditions for typical LEO and GTO launch missions, which are the mission scenarios envisaged for RETALT1.

3.1. Analysis of the recovery capability

For the analysis of the recovery capability of RETALT, a bottom-up approach is implemented. The analysis starts focusing on the landing phase, then it addresses the aerodynamic phase, and finally the propulsive phases (re-entry and boost-back burns). The analysis of the landing and aerodynamic phases is common for all scenarios, while the analysis of the re-entry and boost-back burns depends on the mission scenarios considered.

The primary objective of the landing phase is to successfully land the vehicle (reaching zero velocity at touchdown), and target a precise landing site by compensating the residual trajectory dispersions and achieving pinpoint landing. The capability of providing lateral manoeuvring is therefore necessary, and it is obtained by changing the attitude of the thrust vector during the landing phase. The timing for the start of the landing manoeuvre is also important. The best timing is the one that combines effectively the use of the aerodynamic braking capabilities and the retro-propulsion manoeuvre. If the landing burn starts too late, there is not enough time to land with zero velocity. On the other hand, if the landing burn is started too early the propellant required to land increases. The configuration with the interstage petals maximizes the braking capability during the aerodynamic phase allowing to decelerate down to Mach 0.3. In this case, the range capability during the landing phase is about 300 m for pitch angles up to 10º. Pitch angles above 10º significantly reduce the landing success region. The different launcher configurations mainly affect the variability of the trajectory conditions at the end of the aerodynamic phase, and the capability to carry out a successful landing depends on the trajectory conditions, as well as the propellant required to land. With the planar fins and grid fins configurations the aerodynamic braking capability is reduced, with terminal velocities in the range of Mach 0.5/0.6, respectively. Due to the earlier activation, the range capability increases up to ±450 / 500 m approximately. The design of the landing manoeuvre is therefore a trade-off between the range capability that shall be guaranteed, driven by the capability of the GNC system to bring the launcher to the start of the landing phase within a certain accuracy, and the propellant that is required for a successful landing. For the RETALT1 return scenario considered, a promising design point has been found depending on the configuration [6]: the interstage petals configuration requires about 9 tons of propellant, while the other configurations require about 2 tons of additional propellant, bringing the total propellant consumption for the landing phase up to 11 tons. This total consumption is computed on top of the reserve/margin propellant. A propellant mass above this value is not recommended to be allocated to the landing phase: it is not necessary to perform the landing and would affect the payload capability.

The objective of the aerodynamic entry phase is to successfully slow the vehicle down to the desired initial conditions for the landing phase, while maintaining the thermomechanical loads within the required limits. In addition, it has to contribute to the trajectory control compensating the residual trajectory dispersions after the re-entry burn and the trajectory dispersions that could be accumulated during the aerodynamic flight due to uncertainties. The orientation of the vehicle with respect to the velocity vector during the aerodynamic phase (i.e., the aerodynamic trim angle) determines the aerodynamic performance of the vehicle. In case of a ballistic flight, lift is zero, and the capability to control the position is neglected. Deployable surfaces could be used to directly increase the drag coefficient, but they are also required to provide the capability to trim the vehicle at AoA different than 180º to enable trajectory control. The aero-thermo-mechanical loads during the aerodynamic phase depend on the drag characteristics of the vehicle and on the velocity conditions at the beginning of the aerodynamic phase. For example, see Figure 4, where the drag coefficient range covers the expected variability from a clean vehicle configuration to the configuration with the interstage petals deployed; the performance of grid fins and planar fins configurations are in between [5]. From the point of view of the aerobraking needs, Figure 4 shows that deploying the interstage petals will decrease the peak dynamic pressure during the flight, and in general decrease the loads. Anyhow, it is possible to maintain the dynamic pressure under the 100 kPa limit even with the clean configuration by either decreasing the initial velocity – i.e. performing a more aggressive re-entry burn - or by increasing the drag coefficient flying the vehicle with a trim angle different than 180º. Clearly, a stronger re-entry burn would imply a higher propellant consumption. An analysis of the trim flight characteristics was carried out for the different configurations, considering variable initial conditions and AoA during the aerodynamic flight [6]. The conclusion was that flying with trim angles up to ΔAoA of 10º would be compatible with the set of path constraints defined in the study (with the goal to limit as much as possible the impact of the recovery needs on the launcher structure) and should allow compensating the trajectory dispersions accumulated.

The objective of the re-entry burn is to decrease the velocity of the vehicle making use of the propulsion system and thus maintain the aero-thermo-mechanical loads under control during the following aerodynamic phase. Also, the control of the thrust vector attitude would enable trajectory control, contributing to the compensation of trajectory dispersions accumulated during the high-altitude aerodynamic flight due to uncertainties or errors with respect to the reference conditions. The performance during the re-entry burn depends on the starting point of the burn, its duration, and the initial conditions at the start of the burn. In case a downrange landing (DRL) is performed, the re-entry burn is the only active manoeuvre occurring between MECO and the aerodynamic phase, and the initial conditions of the re-entry burn only depend on the conditions at MECO. The propellant consumption during the re-entry burn is comparable for the different aerodynamic configurations explored due to the low influence of aerodynamics on the trajectory during this phase.

In case a RTLS is targeted, a boost-back burn is required to change the direction of the velocity and correctly target the desired landing site: the launch pad, or an alternative landing pad close to the launch pad. The analysis of the recovery capability for the boost-back burn focuses on the identification of the propellant required to achieve the inversion of the velocity and the targeting of the landing site. As for the analysis of the re-entry burn in the DRL scenario, the recovery capability analysis of the boost-back burn is carried out considering the same variability in terms of conditions at MECO, but the distance from the launch site at MECO was also added as a mission design variable.

3.2. Identification of the performance needs

Based on the results of the recovery capability analysis, the performance needs are identified for the two proposed recovery strategies (DRL and RTLS) to enable the re-entry and landing of the RETALT1 first stage.

The overall propellant budget for each scenario and for each configuration is computed as function of the conditions at MECO building end-2-end performance maps taking into account the propellant consumption required for each phase where the retro-propulsion is active [6]. The region of FPA/velocity at MECO for which a recovery mission is compatible with the available propellant and the structural constraints is defined as the *feasible domain* for the return mission. For example, for the planar fins' configuration (Figure 5), the maximum dynamic pressure limit prevents to perform a DRL recovery of the first stage for those launch missions that have very steep FPA and very high-speed conditions at MECO. The maximum propellant available of 50 tons limits the duration of the re-entry burn for very high speed and shallow conditions at MECO, characteristics of launch missions to GTO.

Moreover, propellant available limits the feasible domain for the RTLS mission to low speed and steep conditions at MECO (Figure 6). Also, if the MECO occurs more than 60 km downrange from the LS, RTLS is not possible for the range of conditions at MECO considered.

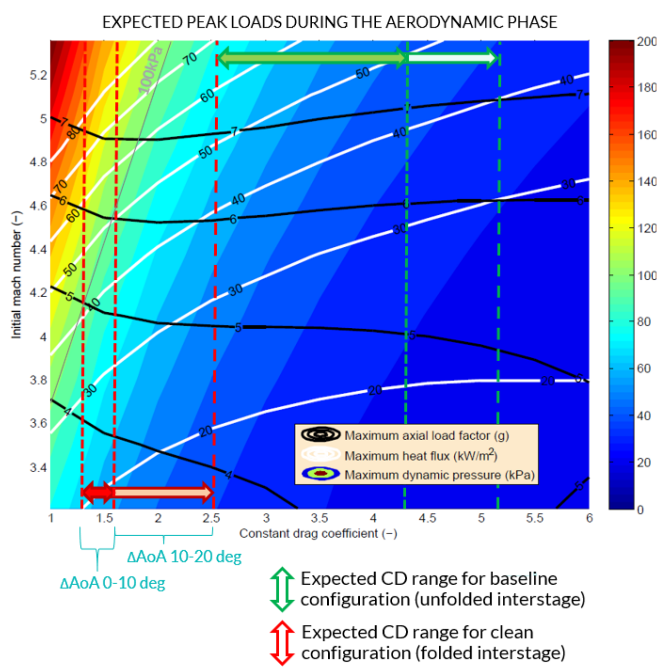

Figure 4 Expected peak loads during the aerodynamic entry, RETALT1 aerodynamic phase

The use of grid fins allows saving on average up to about 5% of the total propellant budget for the same mission (any given set of conditions at MECO), but this gain in the propellant consumption is not enough to significantly change the feasible domain. The use of the interstage petals as aerobraking devices has a similar yet much stronger impact with a 13% saving on average for the same mission [6].

Also, a dispersion budget could be computed to define the characteristics of the trajectory control that shall allow a precise landing [6]. This dispersions budget can used to derive preliminary requirements for the GNC.

The ACS design and sizing activities showed that the use of the interstage petals as the main ACS for the current RETALT1 configuration is considered not feasible due to current structural and mechanisms design limitations [7]. Hence, the configuration with the planar fins was selected as the baseline configuration for RETALT1. Although deemed unfeasible for the RETALT1 vehicle, the impact of having the interstage petals on the overall propellant budget is significant in comparison to the planar fins. The use of such aerobraking devices is recommended for smaller launchers, when actuation loads are limited and feasible solutions could be designed.

For the baseline planar fins configuration, an overall *feasibility map* is identified considering both the DRL and RTLS recovery strategies and as function of the velocity and FPA conditions at MECO. Figure 7 shows the RETALT1 recovery feasibility map for the range of MECO velocity and FPA considered in this mission feasibility analysis. For the sake of comparison, the recovery map inferred for SpaceX's Falcon 9 [8] is also reported

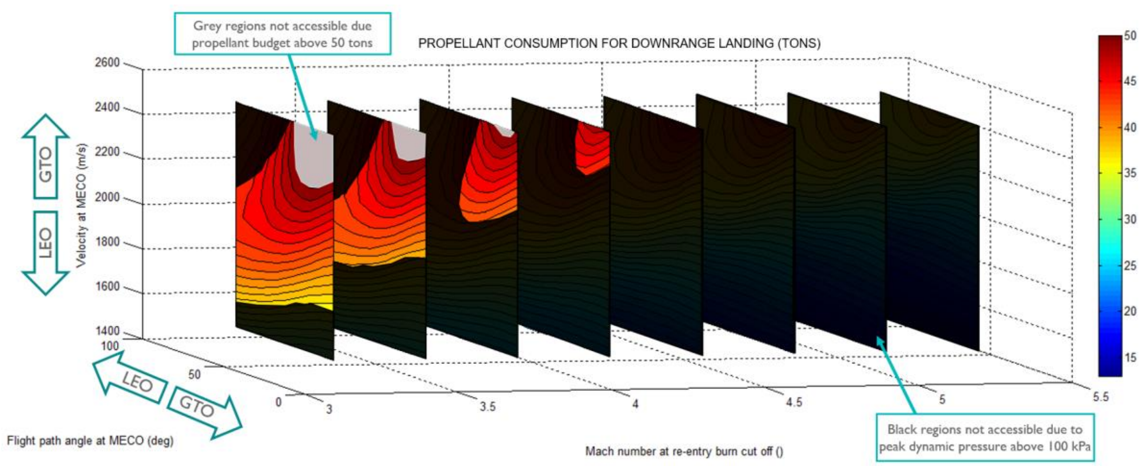

Figure 5 End-2-end propellant budget as function of conditions at MECO, RETALT1 PF configuration, DRL

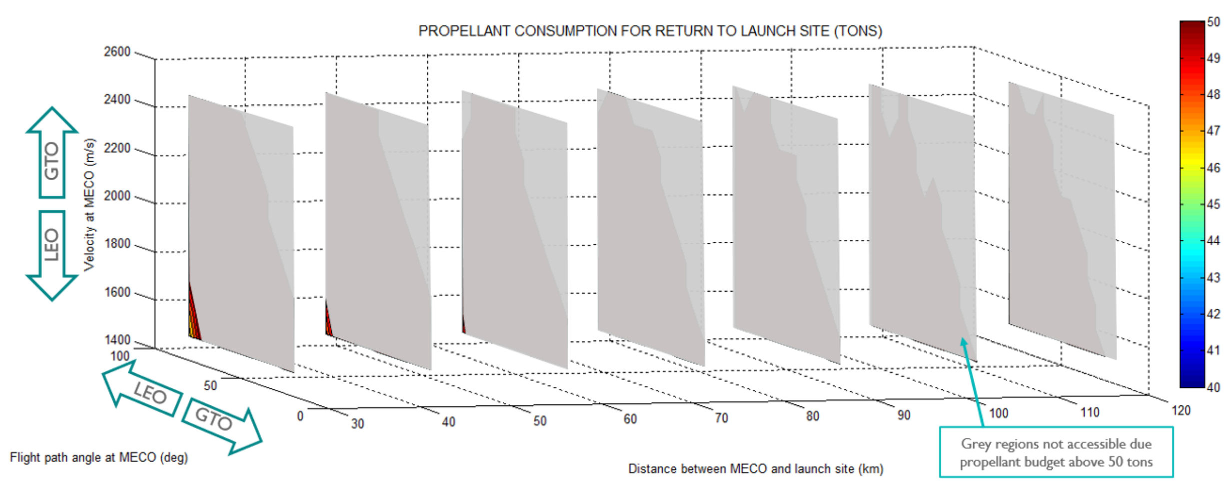

Figure 6 End-2-end propellant budget as function of conditions at MECO, RETALT1 PF configuration, RTLS

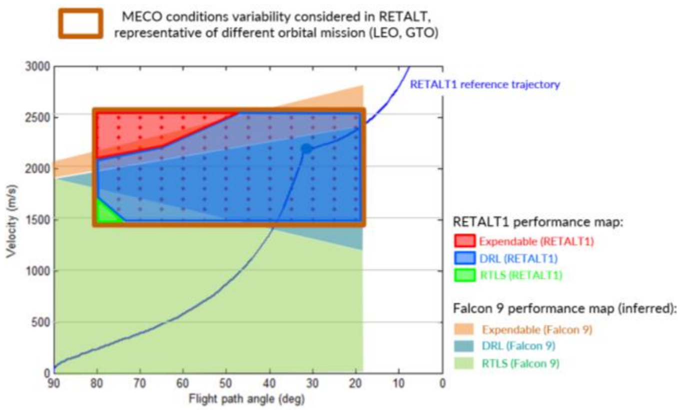

Figure 7 Feasibility map for the recovery of RETALT1 (and comparison with reconstructed Falcon 9 performance [8])

4. MISSION DESIGN

4.1. Entry Corridor analysis

The trimmability and stability of the system - Flying Qualities Analysis (FQA) - are evaluated to support the definition of a trim strategy and a trim solution based on the mission needs. This is done through the identification of the AoA Entry Corridor (EC), defined as the region of the Mach-AoA plane compatible with the set of flight mechanics constraints considered, that identifies the region within which a trim solution can be identified. When the influence of the CoG location is brought into the equation with the objective of looking to define defining boundaries in terms of CoG position that guarantee the existence of an EC, a feasible domain (FD) analysis is carried out.

The trim design and the FQA are carried out for all phases of the return mission of RETALT1 when the aerodynamics is non-negligible: the landing burn and, most importantly, the aerodynamic phase. The FQA tool available in DEIMOS is used [1] for this analysis. So far, in RETALT the FQA are limited to the longitudinal plane. A neutral trim in the lateral plane is targeted for the mission design in reference conditions. However, extension to 6DoF is planned before the end of the project with the latest version of the dataset [4]. Figure 8 shows the entry corridor during the aerodynamic phase for the planar fins' configuration for a CoG correspondent to the reference propellant consumption as obtained by the consolidated DRL reference trajectory. The corridor is obtained considering dispersions in the atmosphere, aerodynamics, and MCI. The result shows that a valid entry corridor (green region in the figure) can be identified for the region of interest in terms of Mach-AoA. In particular, the aerodynamic flight is expected to be fully trimmable and stable up to ΔAoA of 10º, in line with the mission needs. The fins deflection required to trim the vehicle is also reported.

Similar results are obtained for the RTLS scenario, that has a lower mass during the aerodynamic phase, and therefore a slightly forward CoG.

With respect to preliminary results obtained with initial versions of the dataset [6], the consolidated aerodynamic database shows better stability performance of the vehicle during the aerodynamic phase, assuring full flyability of the first stage for all the mass range including with a full tank loading.

A similar analysis has been made for the landing phase. In this case, the central engine is active and when the TVC is actuating the vehicle shall be trimmed taking into account the contribution of the thrust. Based on the models available, the planar fins are able to fully trim the vehicle during the landing phase [6]. Therefore, the FQA confirms the return mission to be feasible from a flight mechanics point of view, and the performance required to guarantee the recovery of the RETALT1 first stage could be met. These results have been used as input to consolidate the reference return scenario of RETALT1.

4.2. Mission consolidation

The mission design consolidation for the RETALT1 return scenarios has been carried out focusing on the baseline configuration with planar fins. Consolidated reference trajectories have been optimized considering the flight envelope and mission requirement derived from the mission feasibility analysis. Different initial conditions for the two scenarios have been assumed in line with the feasibility domain reported in Figure 5 and Figure 6. Trajectory optimization is performed with an optimisation tool available in DEIMOS' proprietary Planetary Entry Toolbox (PETbox) [1]. The objective is to define the reference mission minimizing the mass consumption during re-entry and landing burn that is compatible with the performance needs and the mission requirements. The optimisation variables are the timing of the different burns (landing, re-entry, and boost-back for RTLS), the attitude during the aerodynamic phase, and the attitude profile during the boost-back phase for RTLS.

The consolidated trajectories respect all the mission constraints, with margins to compensate for uncertainties and dispersions. The angle of attack during the aerodynamic phase is optimized in order to have a different value to 180º and therefore obtaining two main benefits: increased drag acceleration which contributes to the braking allowing propellant saving, and creation of positive lift acceleration that can be used to control the trajectory and generate enough crossrange capability to steer the vehicle toward the landing site (Figure 10). The consolidation of the reference trajectories with more detailed aerodynamic datasets confirms the feasibility of the mission solution, showing similar performance in terms of trajectory characteristics (Figure 9). The consolidated propellant consumption for the DRL scenario is lower than 45 tons (Figure 9), while for the RTLS scenario it is slightly lower than 50 tons as a result of the additional boost-back manoeuvre, and in line with the preliminary needs estimated in Section 3. However, the boost-back manoeuvre partially contributes to slow the 1st stage down reducing the propellant budget for the re-entry burn in case of RTLS by about 30% with respect to the DRL scenario. The trim AoA solution for the aerodynamic phase is within the corridor avoiding instability regions.

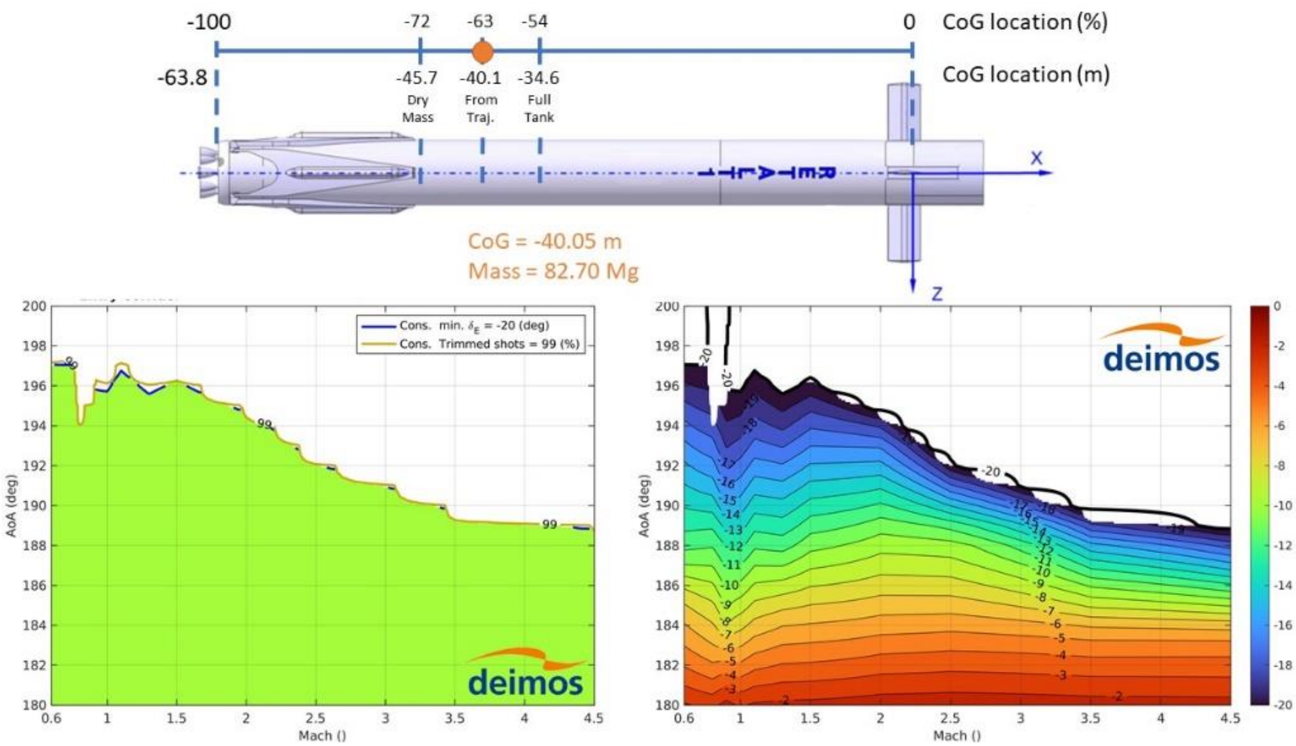

Figure 8 Dispersed (Monte Carlo) AoA entry corridor for the reference propellant loading, planar fins configuration, aerodynamic phase

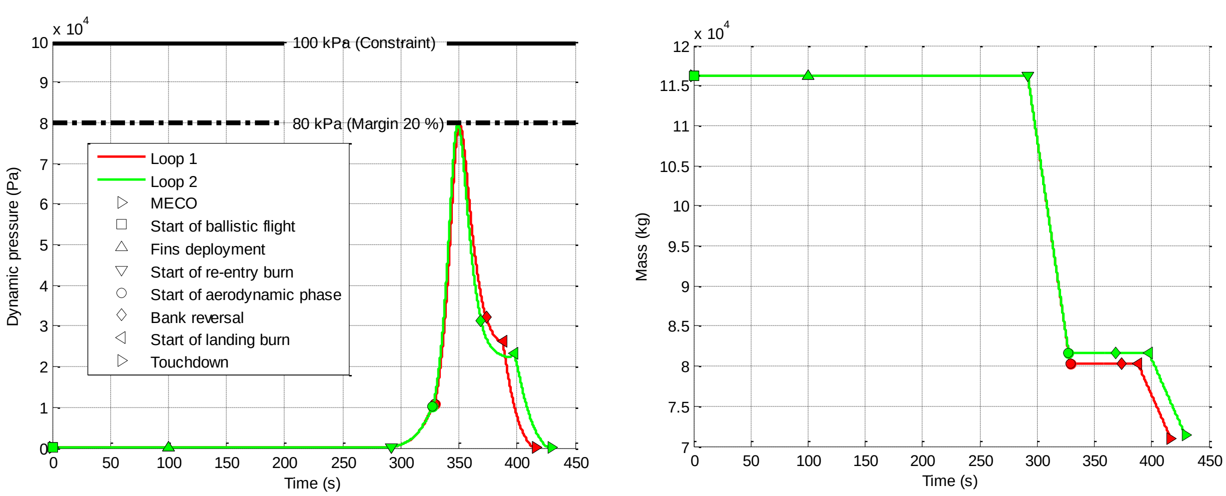

Figure 9 Dynamic pressure (left) and total mass profile for the DRL (R1 B) scenario

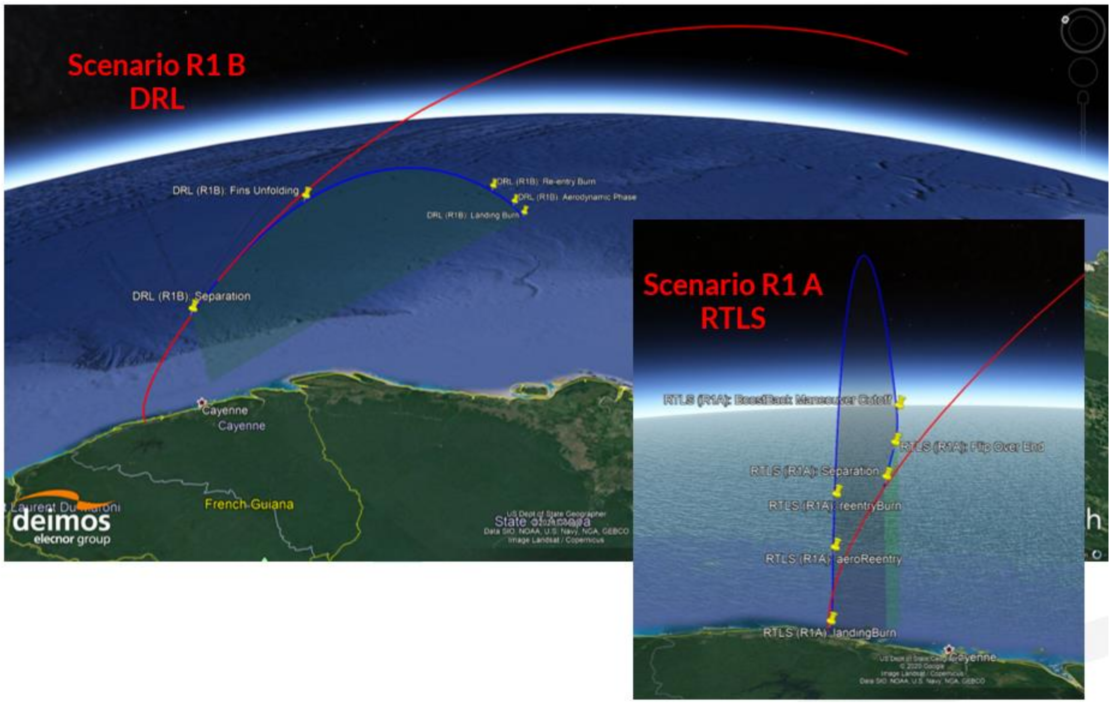

Figure 10. **Google Earth representation of the consolidated return trajectories: RTLS (R1 A) and DRL (R1-B) scenarios**.

5. CONCLUSIONS

The mission engineering activities demonstrated that the recovery of the first stage of RETALT1 is feasible for a recovery strategy based on the use of retro-propulsion. The propellant budget assigned for the return mission enable the recovery of the RETALT1 booster for a wide range of launch missions, that can be performed either with a Downrange Landing on a barge, or with a Return To Launch Site depending on the conditions at MECO.

Needs for the vehicle recovery were identified and allowed the definition of preliminary mission requirements that drove the consolidation of the return mission design. The baseline mission identified were consolidated and verified in full alignment with the most detailed vehicles models made available during the activity.

Also, the assessment of the capabilities of the proposed configurations to perform a return mission enabled the identification of preliminary flight and landing loads to support the sizing of the aerodynamic actuators, and the design of the GNC solution.

6. ACKNOWLEDGMENTS

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