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Multidisciplinary Design Analysis of Reusable European VTHL and VTVL Booster Stages

Jascha Wilken[1], Leonid Bussler[1], Sven Stappert[1], Martin Sippel[1], Daniel Krause[5] Sebastian Karl[2], Josef Klevanski[3], Christian Hantz[3], Lâle Evrim Briese[4], Klaus Schnepper[4], Ingrid Dietlein[1]

[1] German Aerospace Center (DLR), Institute of Space Systems, Robert-Hooke-Straße 7. 28359 Bremen, Germany
[2] German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, Bunsenstrasse 10, 37073 Göttingen, Germany
[3] German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, Linder Höhe, 51147 Köln, Germany
[4] German Aerospace Center (DLR), Institute of System Dynamics and Control, Münchener Str. 20, 82234, Oberpfaffenhofen, Germany
[5] German Aerospace Center (DLR), Institute of Composite Structures and Adaptive Systems, Lilienthalplatz 7, 38108 Brunswick, Germany

Abstract

While initially met with skepticism, launch vehicles with reusable stages are now an established and successful part of the global launch market. Thus, there is a need to analyze and assess the possibility of such a system being designed and built in Europe. Accordingly, in 2016 the German Aerospace Center (DLR) initiated a study on reusable first stages named ENTRAIN (European Next Reusable Ariane). Within this study two return method categories, respectively vertical take-off, vertical landing (VTVL) and vertical take-off, horizontal landing (VTHL) with winged stages, were investigated. First, preliminary design tools were used to identify promising configurations and in the second phase more specialized and extensive analyses were conducted for subsystems of special interest. From this second phase, the results of the evaluation of two areas are presented: Structure as well as system dynamics, guidance and control. The results of these analyses together with previously published results from other subsystems increase the confidence in the designs proposed and evaluated within the ENTRAIN study as well as in the general understanding of the technical factors driving the design of reusable stages.

Nomenclature

CFD	Computational Fluid Dynamics
CoG	Center of Gravity
DLR	German Aerospace Center
DOF	Degrees of Freedom
ELV	Expendable Launch Vehicle
ENTRAIN	European Next Reusable Ariane
FE	Fine Elements
GTO	Geostationary Transfer Orbit
IAC	In-Air Capturing
LCH4	Liquid Methane
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MEO	Medium Earth Orbit
RLV	Reusable Launch Vehicle
RTLS	Return To Launch Site
SI	Structural Index
SSO	Sun-Synchronous Orbit
TSTO	Two-Stage-To-Orbit
VTHL	Vertical Take-off, Horizontal Landing
VTVL	Vertical Take-off, Vertical Landing

1. Introduction

While initially met with skepticism, launch vehicles with reusable stages are now an established and successful part of the global launch market. However, the historical example of the Space Shuttle has also shown that simply implementing reusability into a launch vehicle does not necessarily result in a positive impact on its cost if the refurbishment costs cannot be kept low and the launch rate sufficiently high. Nonetheless, the success of SpaceX (with Falcon 9 and Falcon Heavy) and Blue Origin (New Shephard) in landing, recovering and reusing their respective booster stages by means of retro-propulsion have shown the possibility of developing, producing and operating reusable launchers at low launch service costs. This has raised the interest in introducing reusability to European launchers as a way to lower the launch costs and stay competitive on the evolving launch market.

Reusability for launch systems can be achieved through a broad range of different technologies and approaches. Understanding and evaluating the impact of the different possible return and reuse methods on a technological, operational and economic level is of essential importance for choosing a technology that is adaptable to a European launch system.

Fig 1. SpaceX Falcon 9 stage landing on a barge (Photo by SpaceX; CC BY-NC 2.0)

In order to assess these aspects of reusable launch vehicles, the DLR study ENTRAIN was initiated. In the first phase of the study, which ended in 2018, a broad range of RLV concepts were compared to each other with respect to different parameters such as performance, mass, re-entry trajectory and thermal and mechanical loads. In this phase, several design parameters such as propellant combination, upper stage Δv, engine cycle and return modes were subject to variation to identify advantages and disadvantages and optimal design points of each configuration [1], [2]. At the end, one promising vertical takeoff, vertical landing (VTVL) and one promising vertical takeoff, horizontal landing (VTHL) concept were selected to be investigated in more detail. The selected VTVL concept is propelled by LOX/LCH4 in the reusable first stage and LOX/LH2 in the second stage and is designed for downrange landings on a barge (DRL), shown in Fig 1, or return to launch site (RTLS). The VTHL launcher is propelled entirely by LOX/LH2 and is supposed to be returned to its launch site via In-Air Capturing (IAC) after its re-entry (see Fig 2 for a sketch and [8][9] for more information).

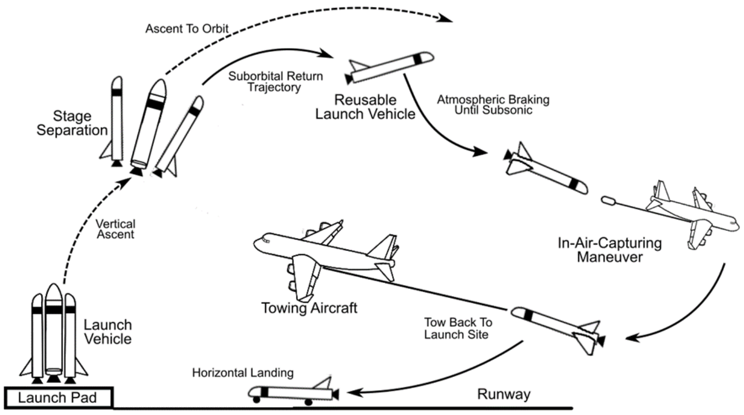

Fig 2. Sketch of an In-Air-Capturing (IAC) mission, from [8]

The goal of this second phase of the ENTRAIN study, dubbed ENTRAIN2, is the detailed investigation by using sophisticated methods and tools to achieve an in-depth understanding of the design challenges of an RLV. In previous publications the result of a detailed aerodynamic and aerothermodynamic investigation of the two launcher concepts was shown and discussed [6]. This paper focuses on the results of two other subsystems: Structure as well as system dynamics, guidance and control.

2. Study Methodology and Mission Requirements

As mentioned above, the first part of the ENTRAIN study ended in 2018. Results of that part are presented in detail in [1], [2] and [3]. A sketch of some of the investigated launcher configurations is shown in Fig 3. The insights gained by this first part were used to select two promising concepts: one VTVL launcher and one VTHL launcher.

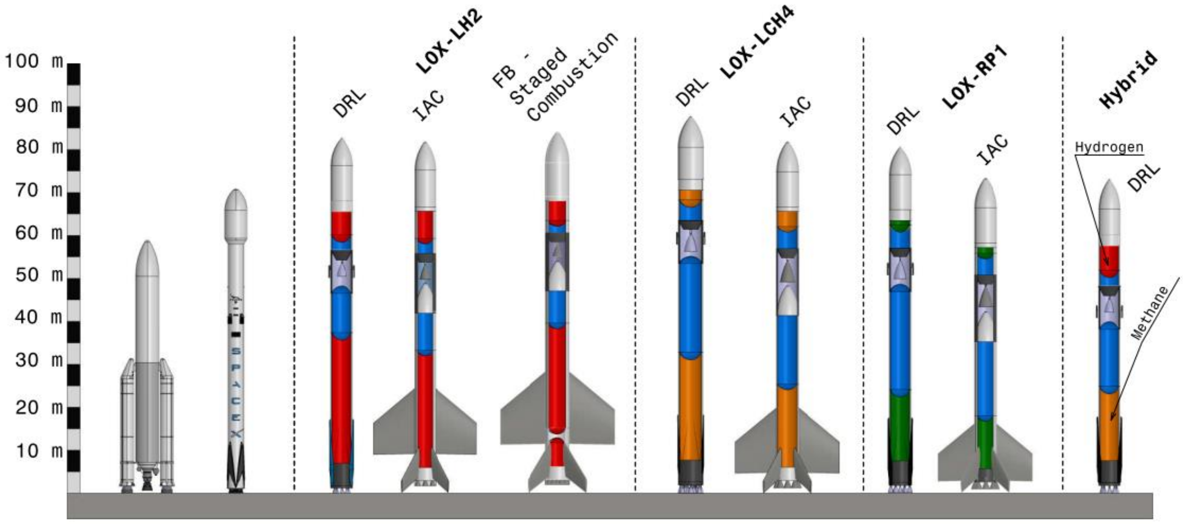

Fig 3. Geometry and layout of a selection of conceptual RLVs compared to Falcon 9 and Ariane 5, from [12]

The VTVL launcher selected by the end of this first part consists of a reusable first stage using LOX/LCH4 as propellants and an expendable second stage using LOX/LH2 as propellants. The major advantages of this design are a relatively low dry mass and the compatibility with methane engines, thus theoretically allowing the future methane engine Prometheus to be used as a first stage engine. However, in this paper the generic methane gas generator engines from the first ENTRAIN study were used [1]. A major disadvantage of this design is the resulting necessity to developing two different engines for the two propellant combinations used. The VTVL RLV is designed for a payload mass of 5.5 t into GTO with a downrange landing on a barge offshore of Kourou, similar to the strategy SpaceX is employing with its Falcon 9. Additionally, the VTVL launcher is also capable of RTLS operations for low-energy orbits such as LEO or SSO (see section 3 for details).

As VTHL reference concept, a LOX/LH2 fueled first and second stage using gas generator engines was selected. The first stage shall perform an In-Air-Capturing maneuver after re-entry, thus avoiding the need of airbreathing engines and additional propellants to perform an autonomous flyback to the landing site. The advantages of this concept are a low dry mass and the development and use of one similar engine with different expansion ratios for both stages. Furthermore, the performance losses of IAC were shown to be the lowest of all considered RLV configurations [1]. The VTHL concept was designed to deliver a payload of 7.5 t into the reference GTO.

While the VTVL configuration has a lower payload capacity in DRL-mode, as an expendable version its performance in GTO is still large enough to lift even the heaviest payloads of the launch scenario of 7.5 tons into GTO. This effectively limits the number of reuses since every heavy-lift launch has to be performed in an expendable mode. More details on the system design of the stages are given in section 3 and [6].

2.1. Target Orbits

The payload performances of both launchers into different target orbits are considered. As mentioned in the previous section, the reference target orbit is a GTO orbit with launch from Kourou. Additionally, the performances into LEO, MEO and SSO were considered. The target orbital parameters are as follows:

- GTO: 250 km × 35786 km, 6° inclination via transfer orbit of 160 km x 330 km
- LEO (ISS delivery orbit): 330 km x 330 km x 51.6° via launcher dependent transfer orbit
- SSO: 700 km x 700 km x 97.4° via launcher dependent transfer orbit
- MEO: 23200 km x 23200 km x 56° (Galileo Satellite Orbit) via transfer orbit of 200 km x 23200 km

3. System Design & Performance

The system design including the engine parameters and the initial performance estimation have been shown previously in [6] as well as the work done on the generation of the aerodynamic and aerothermodynamic databases for both vehicles. The following section only briefly describes the two launchers that were the focus of the ENTRAIN 2 study.

3.1. VTVL – System Design and Performance

The VTVL system is designed as two-stage-to-orbit (TSTO) configuration with a reusable VTVL first stage and an expendable stage in tandem configuration. The geometry and layout of the launcher in ascent configuration is shown in Fig 4 and sketch of the first stage in descent configuration in Fig 5.

The launcher's mass breakdown is provided in Table 1. The masses were calculated with preliminary sizing and mass estimation tools based on empirical correlations for each subsystem. The structural index is defined as $SI = \frac{m_{dry}}{m_{propellant}}$.

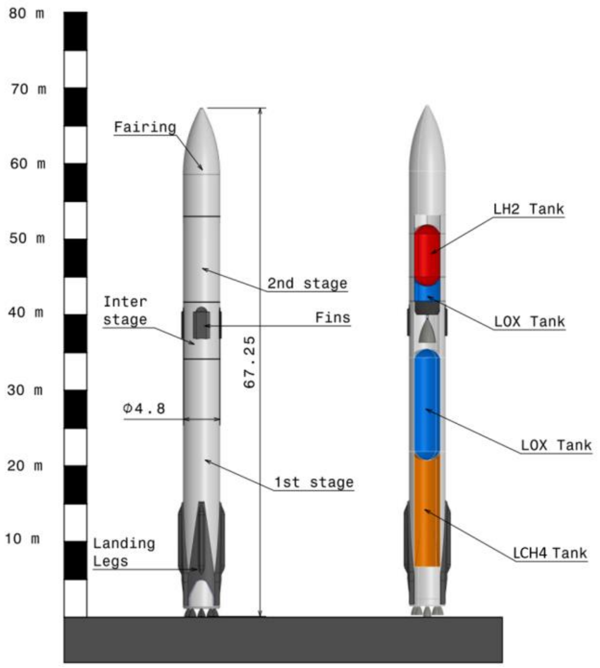

Fig 4. VTVL launcher dimensions and internal layout

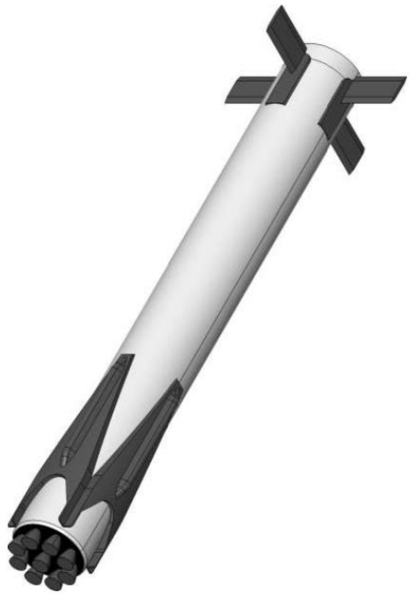

Fig 5. VTVL reusable first stage in descent configuration with fins extended

The total GLOM of the launcher is 479 tons and the total length is 67.25 m with a diameter of 4.8 m. In comparison, a Falcon 9 with a payload capability of 5.5 t into GTO has a GLOM of around 550 t. Fig 6 shows the payload performance of the VTVL launcher into different target orbits as either expendable or reusable launch vehicle with downrange landing (DRL) or RTLS landing.

Table 1. Mass breakdown, VTVL concept

Stage	Parameter	Value
1st stage	Dry Mass	33.8 t
	Propellant Mass	378.0 t
	SI	8.95 %
2nd stage	Dry Mass	5.7 t
	Propellant Mass	60.2 t
	SI	9.5 %
Complete Launcher	GLOM	479.0 t

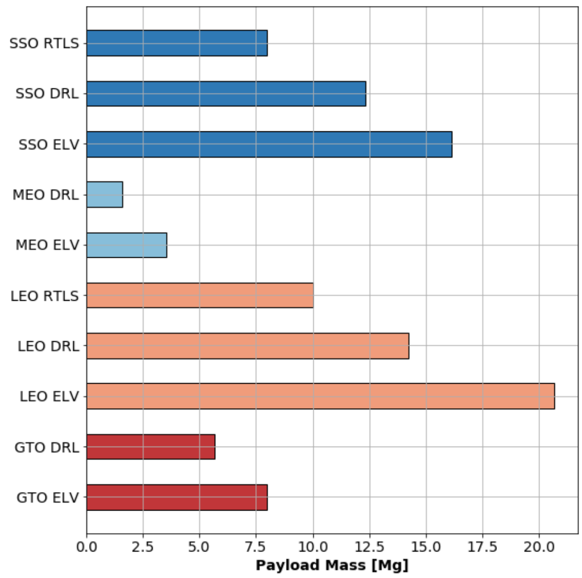

Fig 6. Payload performance of the VTVL launcher concept in different target orbits

A major advantage of the VTVL strategy is the high flexibility, which is highlighted by the various different possibilities to service any specified orbit. The payload masses are 7.5 t to GTO as ELV, respectively 5.5 t to GTO as RLV, comparable to the Falcon 9, but with a lower GLOM. LEO payloads range from 10 t to 20.5 t, thus serving roughly the same payload range as the Ariane 5. SSO payloads range from 7.5 t to 16 t, thus enabling either the launch of heavy SSO satellites or providing rideshare options for small to medium satellites. The payload into a MEO orbit typical for the Galileo satellites is between 1.7 t to 2.8 t, thus enabling the launcher to transport up to 4 Galileo satellites per launch.

3.2. VTHL – System Design and Performance

Similar to the VTVL system, the VTHL system is designed as TSTO configuration with a reusable winged first stage and an expendable upper stage in tandem configuration. The geometry and layout of the launcher is shown in Fig 7.

The VTHL launcher is to be recovered by IAC after re-entry. This method is based on the idea that a towing aircraft (e.g. modified Boeing 747) captures the returning RLV stage after reentry and tows it to the respective landing site, where the stage is released and performs an automatic and autonomous landing. A more detailed description of this return method and the current technological status can be found in [9].

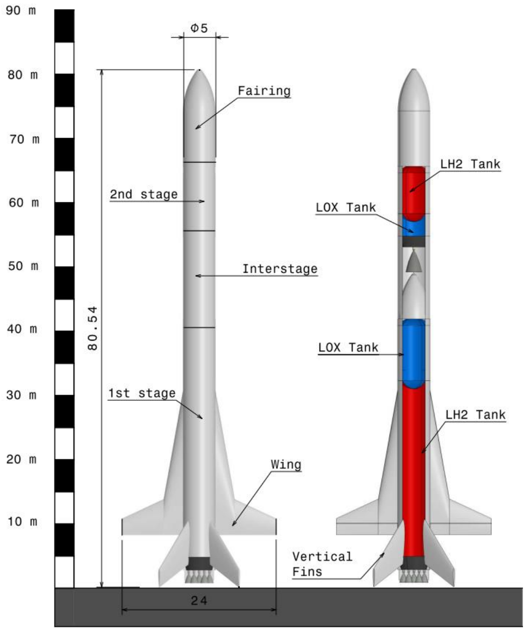

Fig 7. VTHL launcher dimensions and internal layout

Fig 8. VTHL reusable first stage in descent configuration

Table 2. Mass breakdown of the VTHL launcher

Stage	Parameter	Value
1st stage	Dry Mass	49.3 t
	Propellant Mass	248.3 t
	SI	19.9 %
2nd stage	Dry Mass	6.4 t
	Propellant Mass	60.3 t
	SI	10.6 %
Complete Launcher	GLOM	377.8 t

The mass breakdown of the VTHL launcher is presented in Table 2. The dry mass of the first stage is around 49.3 t with a propellant loading of 248.3 t. The SI is around 20% and thus around twice as high as the respective SI of the VTVL launcher. This is as expected and can be explained by the

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added dry mass by wings, aerodynamic control surfaces, TPS and landing gear. Furthermore, the use of LOX/LH2 leads to high SIs due to the low bulk density of the propellant combination. The second stage SI is 10.6% and thus at a value similar to the VTVL, although slightly higher due to a more powerful and heavy second stage engine.

The performances for the different target orbits as described in section 2.1 are shown in Fig 9. The VTHL is able to deliver more payload in RLV mode compared to the VTVL. The performances are in the heavy-lift segment and it is assumed that all typical commercial payload masses and target orbits can be served. Comparing Fig 6 and Fig 9 highlights a difference from the VTHL to the VTVL, which is the reduced flexibility. Since the re-entry is controlled via aerodynamic forces without using the engines, the impact on payload performance of operating as an ELV is minimal.

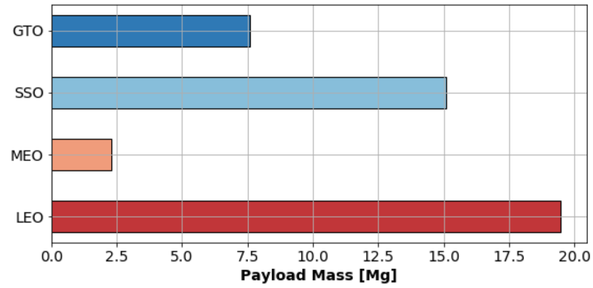

Fig 9. Payload Performance of VTHL launcher concept in different target orbits

4. System Dynamics, Guidance and Control

For systematic assessment of the chosen reference configurations in terms of system dynamics, guidance and control, various multi-disciplinary and multi-fidelity studies have to be performed. For this purpose, consistent multibody models with dedicated levels of detail have been implemented for both concepts at the Institute of System Dynamics and Control (see [13]-[15]).

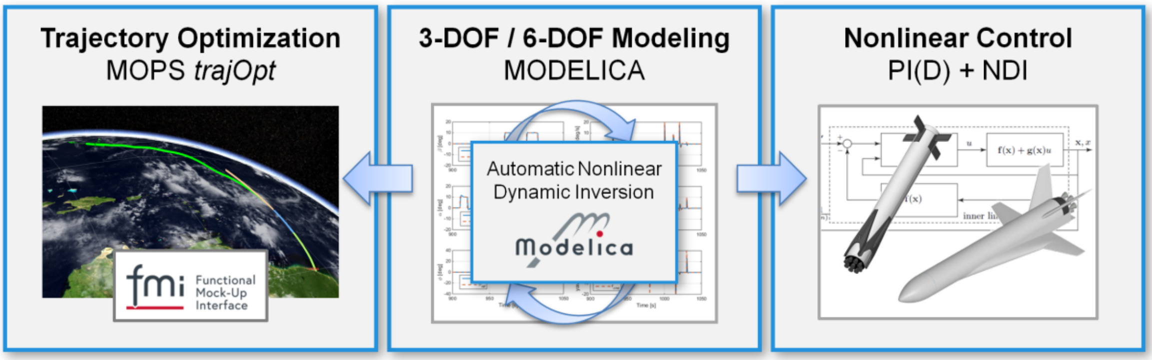

Fig 10. Modeling and Simulation Framework for System Dynamics and Control.

For the VTVL configuration, the multi-disciplinary and multi-fidelity modeling approach depicted in Fig 10 is used to evaluate the launch vehicle's performance described in [11] and [16]. First, 3-DOF flight dynamics models are generated using the object-oriented modeling language MODELICA. These models are then translated into so-called Functional Mock-up Units, which can be integrated into the Matlab-based multi-objective and multi-phase trajectory optimization package MOPS trajOpt introduced in [13]. In this context, these flight dynamics models can be upgraded and extended individually in order to address dedicated analysis requirements; for example, when the in-air-capturing maneuver is evaluated as a return option for VTHL configurations using multiple flight vehicles and flexible multibody dynamics as described in [17].

The resulting reference trajectory provides optimal guidance commands (e.g. aerodynamic angles), which are used to compute the corresponding angular velocities with consistent 6-DOF flight dynamics models by capitalizing on the automatic nonlinear dynamic inversion capabilities of MODELICA. If required, the nonlinear inverse model can also be replaced by a range of 1-DOF to 6-DOF models by exchanging the underlying kinematics formulation. Finally, the required moments to perform a desired maneuver in terms of attitude dynamics can be obtained from the nonlinear inverse model (see [11] and [14]-[16]).

In this paper, we focus on the ENTRAIN2 VTVL concept from section 3.1. The VTVL configuration was incorporated into DLR-SR's modeling environment to generate 3-DOF models suitable for computation of optimal ascent and descent trajectories. In particular, the scope of the performed study was the computation of optimal trajectories for the combined problem of the ascent of the second stage into a suitable orbit and at the same time the return of the first stage based on the downrange landing approach. The overall problem is described by a total of nine phases shown in Table 3.

Table 3. Flight phases of the VTVL configuration (for ascent and descent).

Phases	S1	S2	Payload	Fairing	Description
P1	x	x	x	x	Vertical liftoff, pitch over
P2	x	x	x	x	Gravity turn, ascent phase
P3	x	x	x	x	Ballistic flight after separation
P4		x	x	x	Powered ascent of upper stage
P5		x	x		Powered ascent (after fairing sep.)
P6	x				Unpowered descent phase, flip-over maneuver
P7	x				Reentry burn
P8	x				Unpowered descent phase
P9	x				Final burn for downrange landing

In addition to the requirements presented in previous sections, the following aspects were considered for the combined trajectory optimization of the ascent and descent phases:

- The payload mass shall be maximized.
- The propellant used for the return flight of the first stage shall be minimized while allowing free exchange between the first stage ascent and descent propellant.
- In the upper stage, the propellant mass may be traded for the payload mass.
- A circular geostationary transfer orbit has to be reached with an apogee and perigee of 250 km × 250 km and an inclination of 6°. The remaining mission to the geostationary orbit is approximated by impulsive maneuvers.
- The heat flux at fairing separation shall be lower than 1540 W/m².
- The maximum dynamic pressure shall be lower than 60 kPa.
- The final descent phase has to conclude at an altitude of approximately 35 m to 60 m and a final velocity below 8 m/s.
- The remaining descent propellant at the end of phase 9 has to be at least 900 kg for the final landing maneuver considering 3 s to 5 s for the soft landing final burn before touch down.

The usual launch sequence to place a satellite into a geostationary orbit is to launch the upper stage into an intermediate low to medium earth orbit and to reignite the upper stage engine for insertion into a Hohmann transfer orbit with the apogee of the geostationary orbit. Then, the satellite's apogee motor is used to obtain the final geostationary orbit. Within the ENTRAIN2 study, one task was to study the effect of different launch sequences on the maximum achievable payload mass. For this purpose, the direct injection into the geostationary transfer orbit with an argument of perigee ω of 0° or 180°, as well as a circular parking orbit and subsequent injection into the Hohmann transfer orbit were studied. The resulting ascent trajectories of the VTVL configuration are shown in Fig 11. As expected, the payload is maximized for the launch sequence using a circular parking orbit and a conventional Hohmann transfer, while the maximum achievable payload mass to GTO is reduced significantly for direct injection into orbit with a required argument of perigee of 0° or 180°.

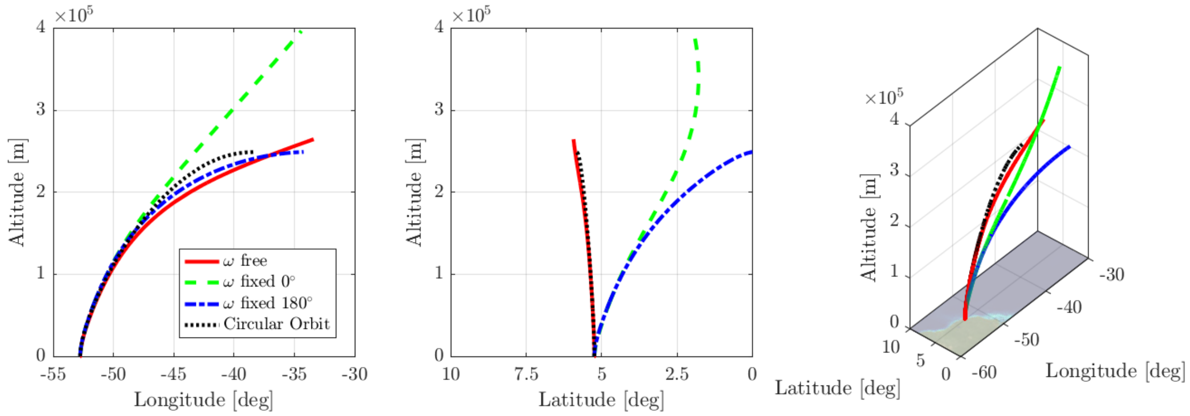

Fig 11. Ascent trajectories of the VTVL configuration for different arguments of perigee.

According to the reference mission, the final burn at the beginning of phase 9 is performed with three engines and then reduced to only one engine at the end of phase 9. Within the ENTRAIN2 study, the trajectory optimization was performed for the reference mission and additionally for the case where only one engine is used for the phase 9. The results of the trajectory optimization for the ascent and descent phases of the VTVL configuration are shown in Fig 12. The red line represents the reference case when three engines are used during phase 9 and the blue line shows the trajectory for the case when only one engine is active. In general, the flight path angle highlights the vertical take-off (90°) and vertical landing (-90°).

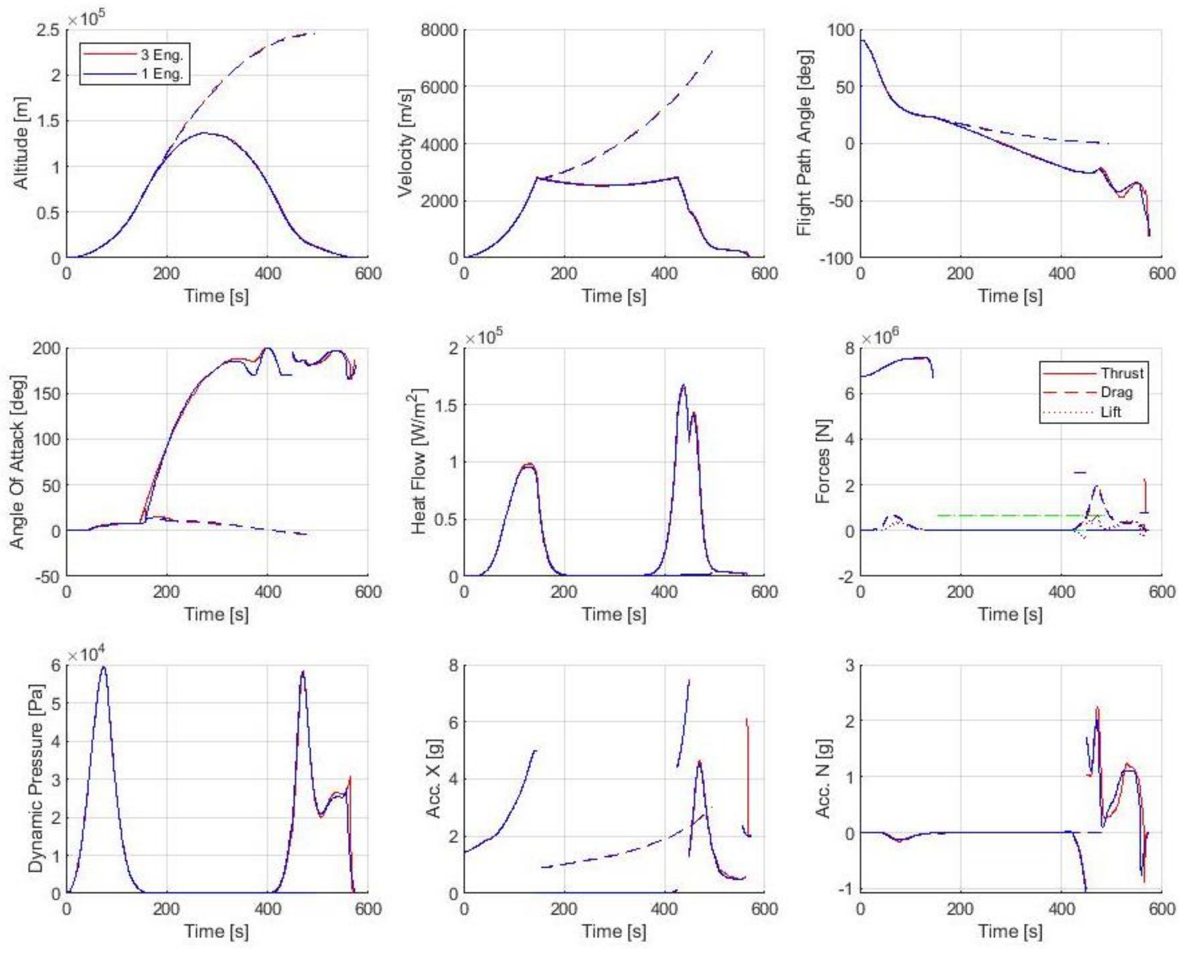

Fig 12. Optimized VTVL trajectories (Comparison: three engines / one engine at phase 9).

The results in Fig 12 clearly indicate that a return using only one engine for the final burn in phase 9 is feasible. In fact, for both cases similar payload masses are delivered into the geostationary orbit.

However, the consumption of return propellant for one engine is slightly increased compared to the case where three engines may be used during final burn. Nonetheless, the controllability of the case with one engine is potentially better because issues that may arise from shutting down two engines at a critical point during descent can be avoided.

Based on these results, the effect of the dynamic pressure constraint on the performance of the first stage during descent were studied. This was done by computing another optimal trajectory for a dynamic pressure limit of 50 kPa (instead of 60 kPa). In this case, the final burn in phase 9 is initiated with three engines and finished with just one engine (see Fig 13).

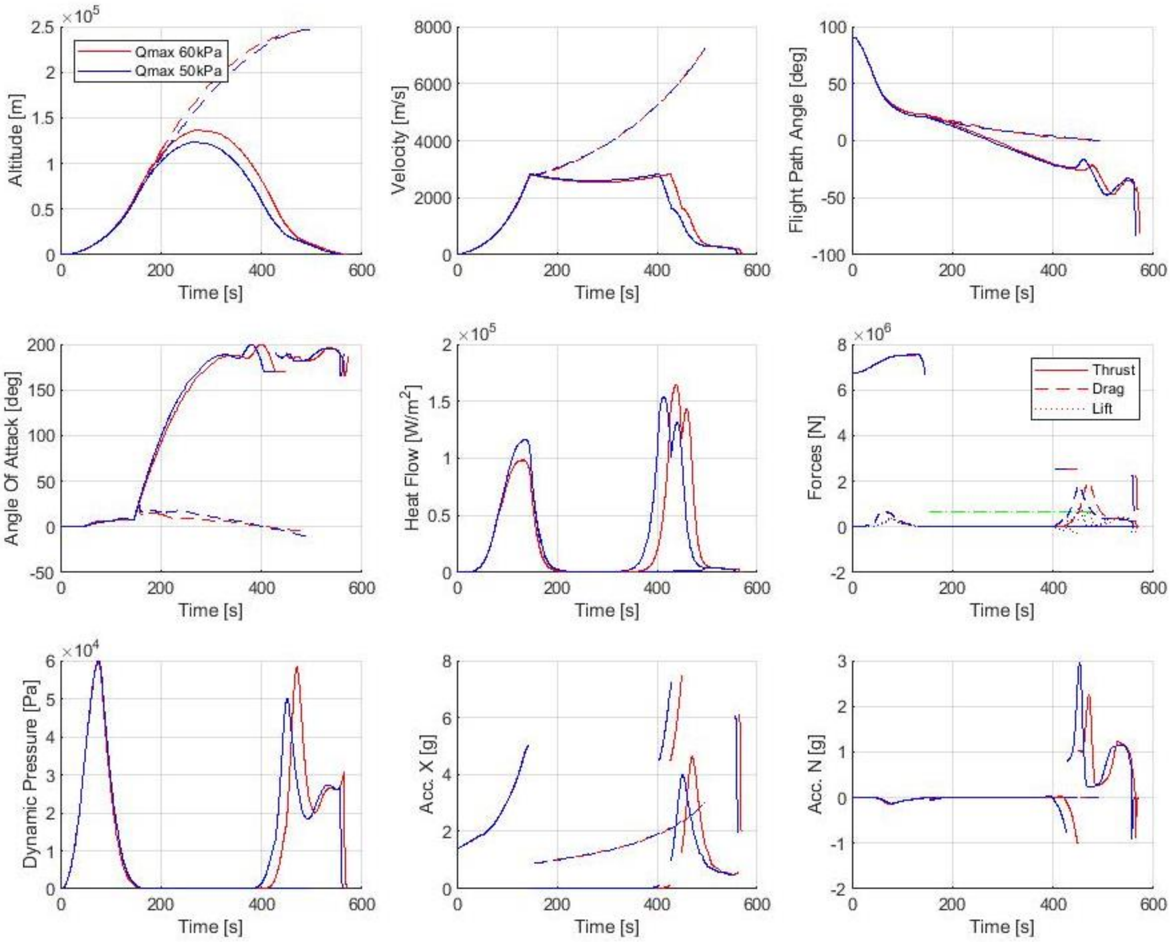

Fig 13. Optimized VTVL trajectories (Comparison: dynamic pressure of 50 kPa / 60 kPa).

The results in Fig 13 showcase that for the maximum deliverable payload mass into the geostationary orbit the dynamic pressure constraint for the first stage during descent does not matter much. But constraints such as the flight path angle at stage separation and the actual overall trajectory are affected quite drastically. In particular, the flight path angle at stage separation needs to be significantly lower for the 50 kPa dynamic pressure limit. Consequently, the trajectory for the lower dynamic pressure limit has a shorter duration. However, the necessary return propellant mass is practically unaffected by the lower dynamic pressure limit. The optimized trajectory is shown in Fig 14 using DLR-SR's in-house visualization tools.

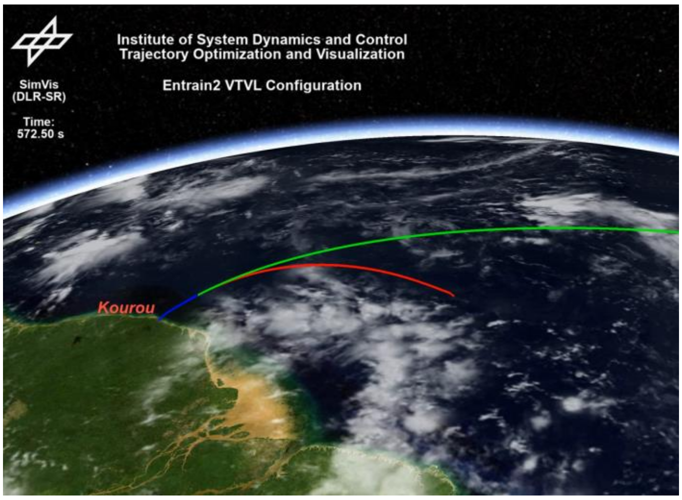

Fig 14. Visualization of the optimized VTVL trajectory.

For preliminary design studies, an accurate estimation of the overall moment budgeting is required. Since a full aerodynamic coefficient matrix is often not available during preliminary design studies, the fidelity level of the flight dynamics models can be adapted to the availability of the aerodynamic coefficients. For this purpose, multi-fidelity flight dynamics models (1-DOF to 6-DOF) were used for the moment estimation and angular impulse computation of the flip-over maneuver during phase 6, during which the first stage is reoriented for the reentry with the engines ahead. In this case, the reference flight trajectory indicated in [6] was used, while considering a simplified assumption of the moment of inertia and by using aerodynamic axial, normal and pitch moment coefficients. As shown in Fig 15, the computation of the required moments for the flip-over maneuver for each multi-fidelity flight dynamics model provides similar values as depicted by the normalized angular impulse. Consequently, these multi-fidelity models can be used within preliminary design studies even if the full aerodynamic coefficient matrix is not available yet.

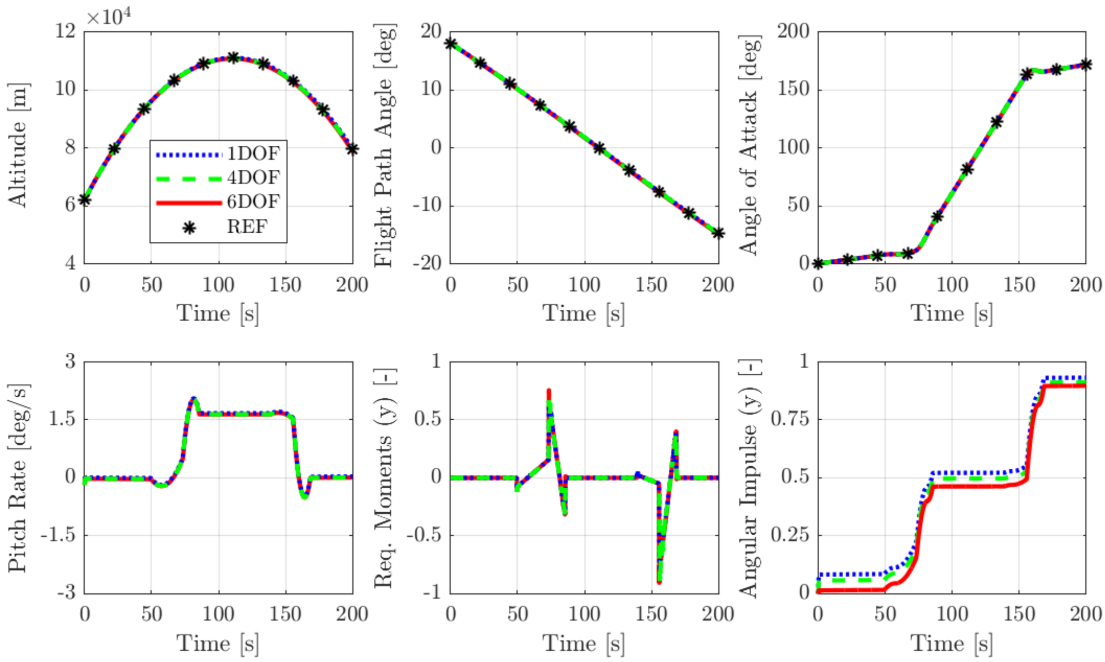

Fig 15. Computation of Required Moments to perform the Flip-Over Maneuver in Phase 6.

5. Structures

5.1. VTVL

For both the VTHL and VTVL structural analysis, the same general procedure is utilized. As the launcher is in an accelerated state at all times, the sum of all acting forces (thrust, weights, aerodynamic forces) leads to a non-zero resulting force that needs to be compensated for. To this end, a quasi-static surrogate model is set up introducing artificial inertial loads so that the sum of all inertial loads and all acting loads is zero. The finite element analysis including the model setup is done in the commercial software suite ABAQUS. This model is then imported in the commercial sizing tool HYPERSIZER for estimating structural masses based on advanced analytical buckling and stress criteria. Regarding the modelling, the launcher structure is idealized as a 2D shell with smeared stiffeners. Major masses are included via continuum distributed coupling constraints (aka Rigid Body Elements (RBE3) in other FE software). Aerodynamic forces are mapped from the results of the according CFD analysis [6] via the "Analytical Field" → "Mapped Field" feature in ABAQUS. Regarding the sizing, the predefined design is an orthogrid stiffened structure with 0°/90° I-shaped stiffeners of same thickness and height. The material choice for both skin and stiffeners is AL2219-T87. Since changing the load carrying cross sections also changes the stress distribution in the model, the sizing process has to be iterative until the solution is considered converged (load update).

Four major load cases are considered within the analysis, of which LC2 has been found to be dimensioning for most components:

- Launch pad: Crosswind load at empty and unpressurized launcher
- Maximum dynamic pressure times angle of attack (q*alpha)
- Maximum axial acceleration
- (Simplified) 3g landing shock

Table 4. Mass results of the VTHL launcher structure sizing

Component		Mass [kg]
Upper stage	Fairing	2290
	LH2 tank	500
	LOX tank	290
	Domes	710
Interstage		1487
	LOX tank	1200
	LCH4 tank	1680
	Domes	680
	Rear skirt	710
Total		9540

Table 4 shows the resulting masses of the launcher structure. The following assumptions and limitations apply:

- There is a safety factor of 1.25 for both limit (local buckling, yield) and ultimate load (global buckling, strength) criteria.
- No flanges or overlaps are considered in the model, which are crucial for manufacturing.
- There is no margin for additional masses due to bolts or weld lines.
- The masses given are for the load carrying structure only. It is not to be confused with the dry mass of other "structural masses" that might include insulation etc.
- No dynamic loads were considered, this estimation is purely statically driven (strength and stability). There are no dynamic/modal or damage tolerance requirements. While the latter is even applicable to expendable launch vehicles, for the herein considered reusable launch vehicle this is a major shortcoming, which is likely to be a driver for the structural design.
- This is a purely stress driven design. There are no manufacturing or economical limits like minimum skin thicknesses for bolting or cost advantages for common skin thicknesses, etc.

5.2. VTHL

Due to the wings, the VTHL model is much more complex, which requires a two-stage analysis approach: The wing and the stage (rf. Fig 16) are analyzed in two uncoupled sizing processes. First, a wing model is sized and the resulting reaction forces of the model are then applied to the stage model for sizing. Overall, the modeling and sizing procedure is identical to the one described above. In contrast to this, only the following critical load cases are used for sizing:

- Maximum dynamic pressures times angle of attack (q*alpha)
- Re-entry

While CFD aerodynamical data exists for the re-entry load case, only discrete aerodynamic loads based on the slender body theory are available for the max. q*alpha load case. These loads are introduced at the very tip of the structure to represent a worst case in terms of introduced bending moments. For the wing model, the same aerodynamic load distribution as for the descent load case is used and scaled to meet the provided discrete lift loads from the preliminary systems analysis.

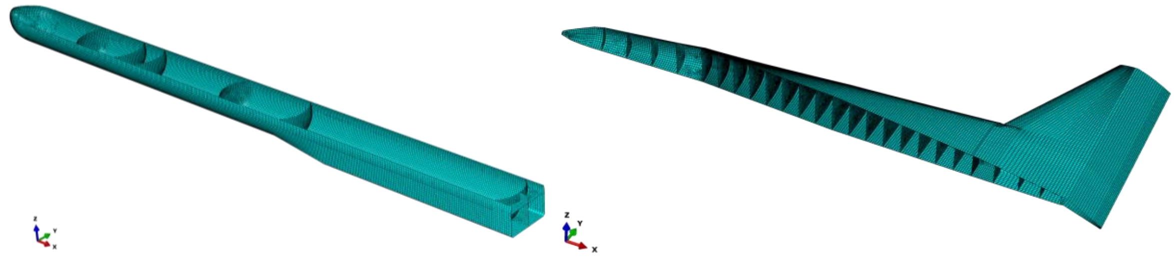

Fig 16. FE models of the stage and the wing, respectively.

Table 5. Mass results of the VTHL launcher structure sizing

Component		Mass [kg]
Upper stage	Fairing	1480
	Front skirt	460
	LH2 tank	3880
	LOX tank	2110
	Domes	2080
Interstage		8470
Lower stage	Nose	501
	LOX tank	5270
	LH2 tank	10900
	Domes	2230
	Rear skirt	1510
	Belly fairing + Body flap	7980
	Wing	3090
Total		49970

Table 2 shows the results of the structural sizing process. The limitations of the VTVL structural analysis apply here as well. Additionally, previous studies have revealed that a detailed design of the wing attachment region increases the mass of these components, i.e. the LH2 tank in this case, by a factor of roughly 1.4 since the stresses are artificially reduced by the coupling constraints in the global model which results in systematically lower structural masses.

6. Conclusion

Within the ENTRAIN2 study, potential future European reusable launchers have been investigated to determine and understand technical challenges and their impact on RLV design. Hence, two different promising concepts of reusing first stages, namely VTVL and VTHL, were applied to a launcher design according to common requirements and preliminary design and mission assumptions. The goal was to enhance the know-how about RLV launcher design and the necessary technologies.

The ENTRAIN2 study was not continued after 2019. While the planned design iterations were not completed to the extent originally envisioned, the results of the more detailed analysis at subsystem level agreed reasonably well with the simplified approaches used for the initial sizing. Thus, the options evaluated in both ENTRAIN studies appear to be viable for a future European launch vehicle with a reusable first stage. This also represents a validation of the methods used for the comparison of the various options in the initial ENTRAIN study.

For the information of design decisions for future launch vehicles these type of system studies remain highly relevant. They can also show promising design spaces to be explored by more detailed design studies or dedicated demonstrators. The design space for new ideas and methods of returning and reusing a first stage is large and not fully explored, especially when tailored to the technological background of the European launch sector.

A major uncertainty remains when evaluating and comparing these types of vehicles: A reliable assessment of cost. The principal goal of any RLV development is the reduction of cost. In order to achieve this goal, the launcher has to be designed in a cost-efficient manner. Given the very large uncertainties in cost estimation, especially for RLV, this is currently unfeasible. Preliminary assessment of cost and improvement of existing models is being conducted at DLR [12][18]. There is a large need for reliable and accurate cost estimations methodologies in order to evaluate different design options beyond the technical level.

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