FALCon

Formation flight for in-Air Launcher 1st stage
Capturing demonstration

In-Air-Capturing Development Roadmap (Update)

Deliverable D2.4

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FALCon
Formation flight for in-Air Launcher 1st stage Capturing demonstration

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(Update)

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Author(s)	date
Martin Sippel Sven Stappert Sunayna Singh	13.01.2023

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Nomenclature

a	acceleration	m/s^2
C_D	Drag coefficient	-
C_L	Lift coefficient	-
F	Thrust	N
H	Altitude	km
m	Mass	kg
m_T	Propellant mass	kg
n_x	Load factor along the main axis of the vehicle	-
n_z	Load factor normal to the main axis of the vehicle	-
t	Time	s
α	Angle of attack	°
γ	Flight path angle	°

Abbreviations

AoA	Angle of Attack
ACCD	Aerodynamically Controlled Capturing Device
ATM	Air Traffic Management
CFD	Computational Fluid Dynamics
COTS	Commercial Off the Shelf
DARPA	Defense Advanced Research Projects Agency
DRL	Downrange Landing
e.c.	economic condition
ELV	Expendable Launch Vehicle
FEM	Finite Element Method
GLOM	Gross Liftoff Mass
GNC	Guidance Navigation Control
HL	Horizontal Landing
IMR	Inert Mass Ratio
IRL	Integration Readiness Level
IT	Information Technology
JP	Jet Propellant
L/D	Lift/drag ratio
LFBB	Liquid Fly-Back Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MAR	mid-air retrieval
MECO	Main Engine Cut-off
MoM	Minutes of Meeting
NRC	N*on*-Recurring Cost
RANS	Reynolds-Averaged Navier-Stokes
RC	Recurring Cost
RLV	Reusable Launch Vehicle
ROM	Rough Order of Magnitude
SI	Structural Index
TET	Turbine Entry Temperature
TN	Technical Note
TRL	Technology Readiness Level
TSTO	Two Stage To Orbit
UAV	Unmanned Aerial Vehicle
VL	Vertical Landing
VTHL	Vertical Takeoff, Horizontal Landing
VTVL	Vertical Takeoff, Vertical Landing
WP	Workpackage

1 Executive Summary

1.1 Scope of the deliverable

According to the FALCon GA [1][2] the WP 2.2 is about the “Definition of Technology Development Roadmap”. In the first step the state of the art and initial proposals for technology developments have been proposed in Deliverable D2.2 [3]. This document has been made available to the European stakeholders e.g. ESA, CNES, ONERA, DLR-agency and industrial primes. After an on-line workshop held in February 2021 dedicated splinter meetings were organized and recommendations of the various experts were collected. The second and final Technology Development Roadmap workshop in FALCon has been organized April, 28th 2022, one day after the VKI-Lecture on “In-Air-Capturing” and together with a dedicated session at the 9th EUCASS-conference in Lille on June, 30th, 2022 allowed for an in-person critical assessment and coordination of the technology development needs. This second issue of Deliverable D2.4 concludes the development roadmap definition in FALCon. An overview of these meetings and comments from the review [4] of D2.2 had been included in the first issue of the update of the Technology Development Roadmap [5]. Review remarks [6] and latest updates from the second dedicated workshop as well as final demonstration status of FALCon are included.

Based on the intended achievements in FALCon the necessary next demonstration steps for in-flight verification are defined. Suitable test ranges accessible to Europe are identified and evaluated. Synergies to RLV-demonstrator flight tests of complementary programs are critically assessed. A rough cost assessment of development effort is provided.

This deliverable serves as a document to be made publicly available to the European space transportation community. The special purpose of this Issue 2 is to provide guidance tor future technology maturation activities in the field of reusable space transportation.

1.2 Results

This deliverable includes a short summary of the results of the task 2.1. The In-Air-Capturing (IAC) method using a capturing and towing aircraft is compared to the alternative return option vertical landing with downrange landing (DRL) on a sea-going platform and if equipped with wings for aerodynamic lifted reentry and horizontal landing either by LFBB method (Liquid Flyback Booster) using turbo-engines for an autonomous propelled flyback or using the IAC.

From a performance perspective, the IAC mode is highly attractive. Figure 1 presents a comparison of the inert mass ratio for generic TSTO-launchers and different return modes of the reusable first stage. All launchers have been sized for 7.5 tons GTO payload with a variation in separation Mach-number of the RLV. As mission and stage number are identical, the inert mass ratio can be presented as function of the total ascent propellant loading.

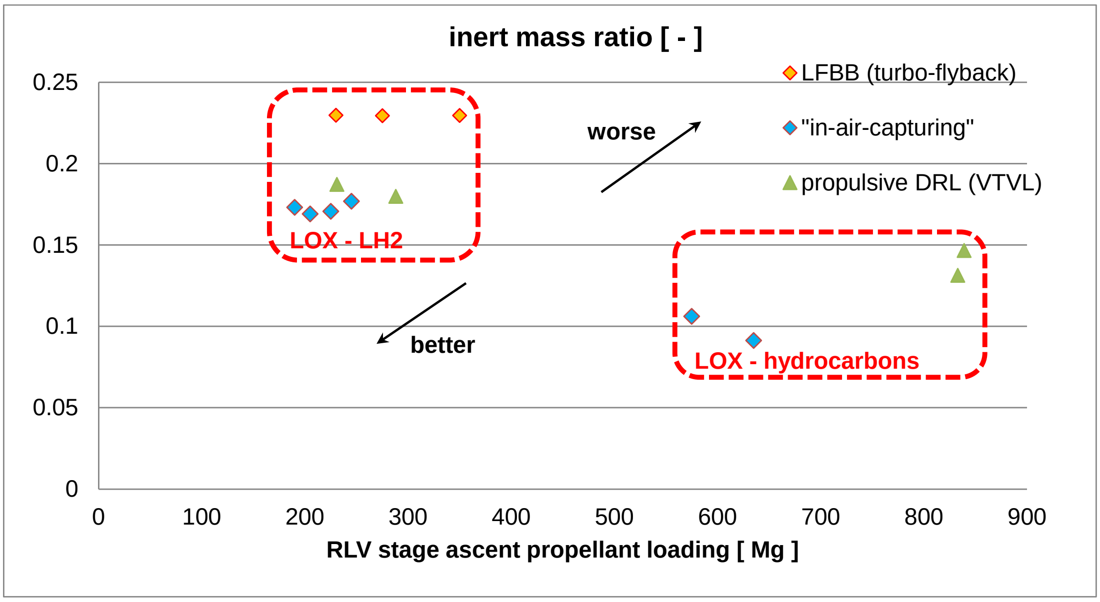

Figure 1: Performance interest of “In-Air-Capturing” demonstrated by inert mass ratios of different RLV-return modes (all same GTO mission)

Bottom-up cost analyses of the recovery operations for the IAC- and the DRL-mode investigated for large reusable first stages show both methods close in the estimated expenditure. Direct and indirect operational costs are considered and total recovery costs are estimated around 500000 € per flight. As the efforts for recovery and refurbishment operations are coming close for all investigated RLV-return-methods, then the size and weight of the launcher stages are the dominant cost factors. The benefit of IAC shown in Figure 1 on performance can serve as input for costs estimations. Depending on the architecture and the operational scenario this improvement can allow cost reductions between 10% and 25% for “in-air-capturing” compared to the vertical landing method downrange on a ship as operated by SpaceX.

Based on latest simulations, a feasible technical procedure for the approach and capturing has been elaborated which is described including necessary hardware for connecting and coupling the two vehicles. Depending on the size of the RLV, existing used airliners are suitable for the towing role.

The current technology status including final status of technology development in FALCon is presented and maturation plans for the different relevant technical areas are explained. The TRL-goal of IAC is set to 6 with target date 2029 for a technology development roadmap oriented on a large-scale launcher and its RLV lower stage. Figure 2 shows which system demonstration milestones need to be achieved in the coming 5 to 8 years. After successful lab-scale demonstration another subscale demonstrator will be needed for increased scale, increased speed capturing and towing in all relevant weather conditions and in day- and night-time. Operational, certification and legal issues as well as an environmental compatibility assessment are to be addressed in the second half of the decade when a consolidated scenario has been established.

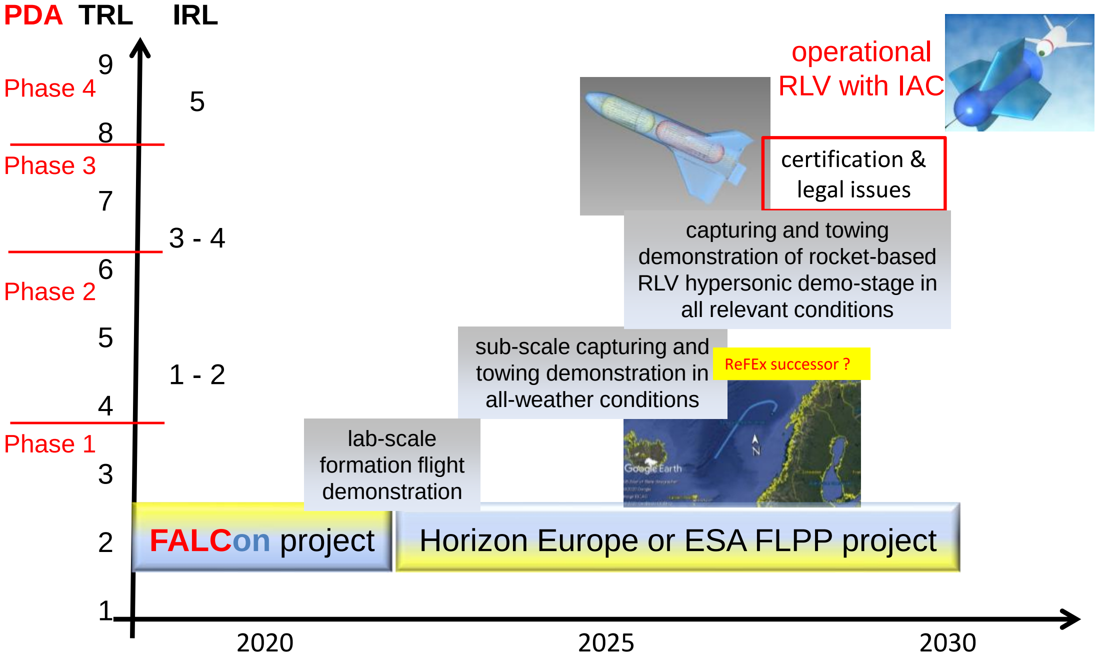

Figure 2: Proposed Development Roadmap for “In-Air-Capturing” major system demonstrations

The definition of high-level requirements for the “In-Air-Capturing” and early simulation results allow deriving technology development needs. These are specified for all major areas and focus on technology integration and operational demands. These roadmaps have been presented in an online workshop and discussed in dedicated splinter meetings and in a second and final workshop with European stake-holders. A summary of topics addressed and expert’s recommendations received during the meetings is included.

Based on the latest development roadmaps the next steps after FALCon in the time frame up to 2026 are identified. A rough cost estimation shows that these activities with extensive subscale flight testing could be completed for around 10 M€. Further, all necessary steps up to industrial development start when reaching TRL of 6 are very affordable compared to alternative VTVL maturation.

1.3 Specific highlights

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1.4 Forms of integration within the work package and with other WPs

The proposed development roadmap is linked to all other FALCon work packages.

1.5 Problems

The organization of stakeholder workshops has been severely impacted by the “Corona-crisis” causing some delays. Nevertheless, at the end of the project all objectives for the establishment of the technology development roadmap have been achieved.

2 Introduction

Any RLV degrades the launcher's performance compared to an ELV due to additional stage inert mass. This mass increase is on the one hand due to increased life-time requirements of the major components. The major impact on additional RLV mass stems from the need to bring the used stages fully intact back to the launch site. This task is a fundamental challenge of all RLV compared to ELV for which expended stages are simply crashing into oceans or desert areas. The controlled deceleration of high-speed vehicles in the atmosphere and the subsequent landing on ground are having a significant impact on the RLV-stage inert mass.

Several different technical approaches have been proposed in the past for the return of RLV. The technical approaches of SpaceX and Blue Origin are similar with vertical take-off and vertical landing (VTL) of the reusable stages. Despite the fact that this is obviously a feasible and potentially promising option, several other methodologies of the first stage's reentry and return exist. Four different return modes are most relevant:

- RTLS: autonomous rocket-powered return flight (similar to some Falcon 9 missions that return to Cape Canaveral),
- DRL: down-range landing; in case of Kourou-missions only possible on a sea-going platform ("barge") which subsequently brings the stage back to the launch site,
- LFBB: autonomous airbreathing-powered return flight at subsonic speed,
- IAC: capturing in flight of the winged unpowered stage with an aircraft and subsequent towing back for an autonomous landing in gliding flight.

The approach currently chosen by some players in the USA is not necessarily the optimum for each application or different operational scenario. A comparison of the different performances is of strong interest because these are related to stage size and hence cost. Since a reliable and sufficiently precise estimation of RLV costs is almost impossible today, the performance impact comparison gives a first sound indication of how promising the modes are.

2.1 Purpose of this document

The innovative "In-Air-Capturing" (IAC) RLV-return mode is in focus of the H2020-project FALCon [1]. One of the key-tasks of the project is defined as "proposing a European development roadmap, first up to TRL of 6 and then estimating the effort for reaching the full-scale operational system with TRL of 9." This task is to be iterated jointly with the European stakeholders in agencies and industry in dedicated workshops.

In the first step the state of the art and initial proposals for technology developments have been proposed in Deliverable D2.2 [3]. This document has been made available to the European stakeholders e.g. ESA, CNES, ONERA, DLR-agency and industrial primes. After an on-line workshop held in February 2021 dedicated splinter meetings for certain technology areas were organized and recommendations of the various experts were collected. A complete overview of these meetings is included in this update of the Technology Development Roadmap. Some adjustments on preliminary versions of the roadmaps as described in Deliverable D2.2 [3] are comprised and latest results of the FALCon-project are considered in the Issue 2 of D2.4.

The first part of Deliverable D2.4 describes the performance advantage of IAC compared to other RLV-return modes and a first assessment of related operational costs. The principal interest and attractiveness of the approach are to be demonstrated in order to justify any future investment. "In-Air-Capturing" has always been proposed in the past as a return mode for large-scale RLV-booster stages. However, the required technologies for the automatic capturing and towing process may find additional applications in the field of spaceflight or even beyond in aeronautical applications. Such technical options have been collected and are to be evaluated in how far they could support, de-risk or speed-up the development process.

This section is followed by a brief description on how "In-Air-Capturing" might actually work supported by a new set of refined numerical simulations of full-scale vehicles generated in the FALCon-project. The current status of lab-scale flight experiments performed in previous work at DLR and what has been achieved within the FALCon project since March 2019 is described afterwards.

This description is followed by a list of technology development needs identified. A latest updated version of technology development roadmaps in comparison with [3][5] for all relevant technological areas with inputs from the second Technology Development workshop is included in this final issue 2 of this document.

The next development steps after FALCon in the coming years are to be identified. A first, rough cost estimation should support sound decisions in the area of future European space transportation.

2.2 Tools used

N/A

3 Interest of “In-Air-Capturing“ for RLV first stages and further applications

Four different return modes of RLV first or booster stages are most relevant:

- RTLS: autonomous rocket-powered return flight (similar to some Falcon 9 missions that return to Cape Canaveral),
- DRL: down-range landing; in case of Kourou-missions only possible on a sea-going platform (“barge”) which subsequently brings the stage back to the launch site,
- LFBB: autonomous airbreathing-powered return flight at subsonic speed,
- IAC: capturing in flight of the winged unpowered stage with an aircraft and subsequent towing back for an autonomous landing in gliding flight.

The FALCon deliverable D2.1 [7] is focused on the systematic comparison of the above considered RLV return options. This includes a description of the major characteristics, all launcher performance assessments and preliminary cost estimations of recovery costs. This section summarizes the superior performance of “In-Air-Capturing” for all investigated modes and missions and compares estimated operational, mainly recovery costs.

3.1 Return Option “In-Air-Capturing” (IAC)

Introducing any kind of reusability method to a launch vehicle degrades the launcher’s performance compared to an ELV due to additional stage inert mass. A comparison of the different performances is of strong interest because these are related to stage size and hence cost. Since a reliable and sufficiently precise estimation of RLV development and refurbishment costs is almost impossible today, the performance impact comparison gives a first sound indication of how promising the modes are.

The vertical landing RLV-return modes RTLS and DRL as used with the SpaceX Falcon9 do not have wings for the generation of aerodynamic lift while at the same time strongly raising the aerodynamic drag. Both lift and drag allow significantly reducing the peak aerothermal loads on the reusable stage during atmospheric reentry. Instead propellant is to be used for active deceleration with the rocket engines. Therefore, vertical landing stages save structural mass for the wing and related systems but pay for this advantage by additional propellant mass.

Techniques of powered return flight of winged RLV like LFBB have been proposed in several past studies. However, LFBB-type vehicles obligate an additional propulsion system and its fuel, which raises the stage's inert mass. The patented “In-Air-Capturing” [15] offers a different approach with better performance: The winged reusable stages are to be caught in the air, and towed back to their launch site without any necessity of an own propulsion system [16]. The idea has similarities with the DRL-mode, however, initially not landing on ground but “landing” in the air. Thus, additional infrastructure is required, a relatively large-size capturing aircraft. For this task used, refurbished and modified airliners should be sufficient.

A schematic of the reusable stage's full operational circle is shown in Figure 3. At the launcher's lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable winged stage is separated from the rest of the launch vehicle and afterwards performs a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. At this point a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system.

Differently, within the “In-Air-Capturing” method, the reusable stage is awaited by an adequately equipped large capturing aircraft (most likely fully automatic and unmanned), offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio. Both vehicles have the same heading still on different flight levels. The reusable unpowered stage is approaching the airliner from above with a higher initial velocity and a steeper flight path, actively controlled by aerodynamic braking. The time window to successfully perform the capturing process is dependent on the performed flight strategy of both vehicles, but can be extended up to about two minutes. The entire maneuver is fully subsonic in an altitude range from around 8000 m to 2000 m [11]. After successfully connecting both vehicles, the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released, and autonomously glides like a sailplane to Earth.

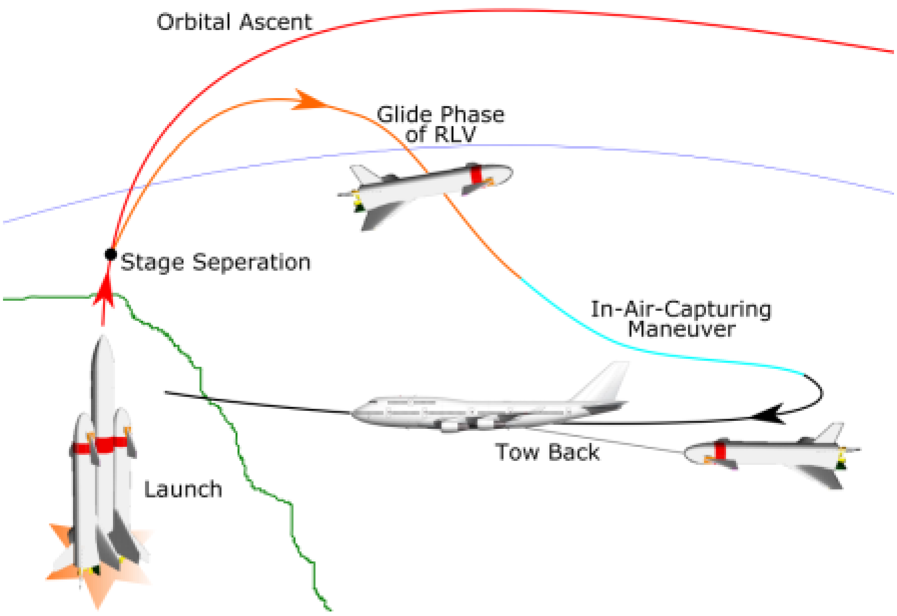


Figure 3: Schematic of the proposed In-Air-Capturing

The selected flight strategy and the applied control algorithms show in simulations a robust behavior of the reusable stage to reach the capturing aircraft. See section 4.1 and [8] for more details!

3.2 “In-Air-Capturing” (IAC) in performance comparison

The performance impact of an RLV is directly related to its (ascent) inert mass ratio or net-mass fraction, reasonably assuming that the engine Isp is not considerably affected. Inert masses of the stage during ascent flight are its dry mass and its total residual propellants including all those needed for controlled reentry, landing, and potentially fly-back. A specific inert mass ratio is then defined as:

$$\text{inert mass ratio}_{\mathrm{i}} = \frac{\mathrm{m}_{\mathrm{i,inert}}}{\mathrm{GLOW}_{\mathrm{stage}}}$$

The higher the inert mass ratio of a stage, the lower is its acceleration performance if propellant type and engine performance are unchanged. Figure 4 shows a comparison of the inert mass ratio for generic TSTO-launchers (design assumptions described in [7], [10], [12]) and different return modes of the reusable first stage. The smaller the inert mass ratio and the smaller the propellant loading for the same mission, the better the system performance and hence potential cost reduction.

All launchers have been sized for 7.5 tons GTO payload with a variation in separation Mach-number of the RLV [7], [10], [12]. As mission and stage number are identical, the inert mass ratio can be presented as function of the total ascent propellant loading. For better visibility, the propellant combinations are separated in Figure 4: LOX-LH2 (top) and LOX-hydrocarbons methane and RP (bottom). In all presented cases the IAC-stages have a performance advantage not only when compared to the LFBB with turbojet flyback (as already claimed in the past, see [16], [17]) but also in comparison to the DRL-mode used by SpaceX for GTO-missions.

NB: The RTLS-mode using rocket-powered toss-back of the RLV-stage toward its launch site requires a non-negligible amount of fuel in GTO-missions. Targeting 7.5 tons of payload for TSTO results in excessively large and heavy launchers. Consequently, any RTLS-mode configuration is removed from Figure 4. SpaceX has also never used the RTLS-mode of the Falcon9 first stage in any of its high energy GTO-missions but instead the DRL-mode. RTLS is used by SpaceX only in case of small payloads and lower energy LEO-missions when the Falcon9 offers generous payload performance margins.

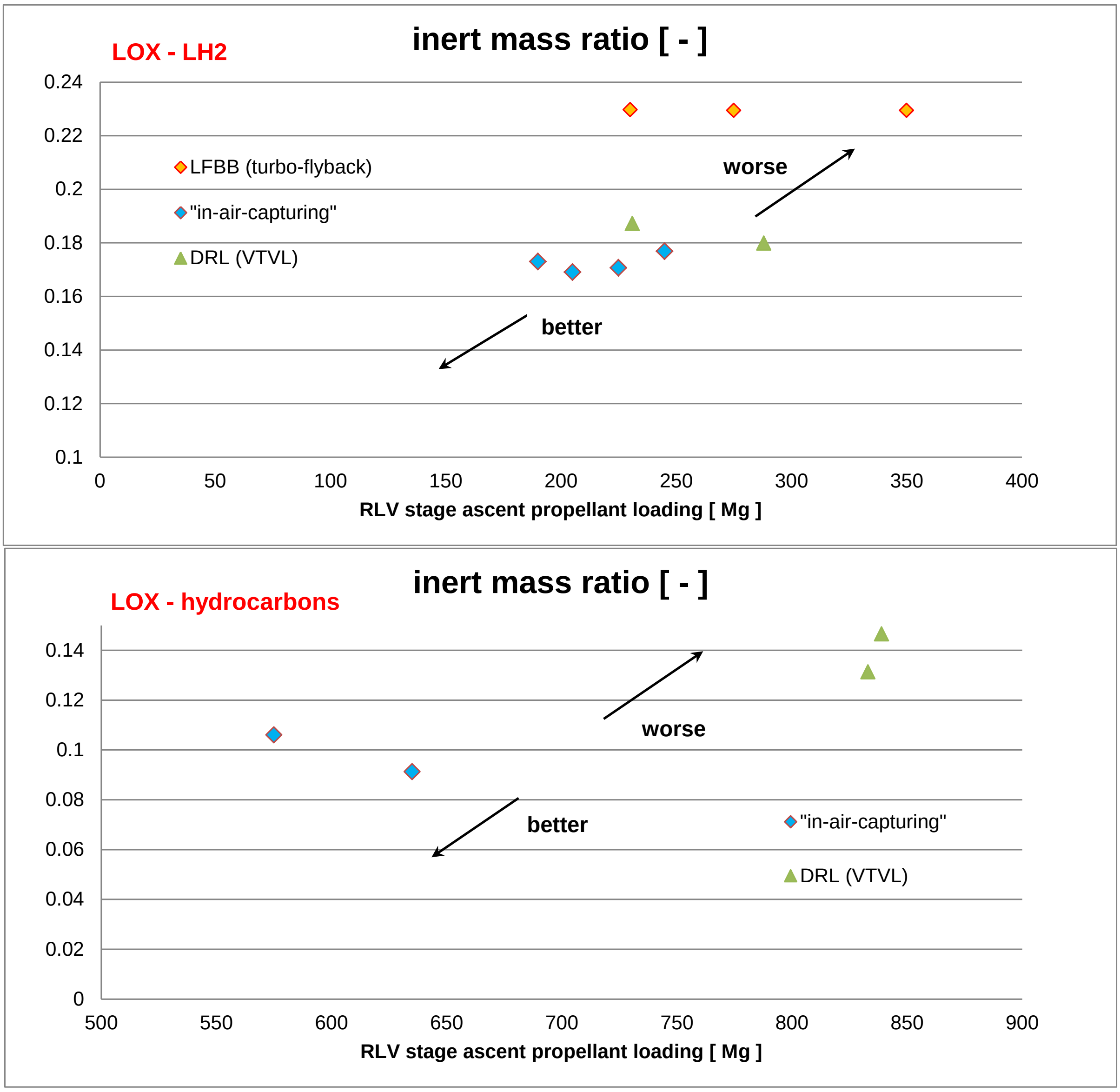


Figure 4: Inert mass ratio depending on RLV-return modes and ascent propellant loading, GTO-mission TSTO (LOX-LH2 top, LOX-hydrocarbons bottom) [11]

A direct comparison between two winged RLV first stages with the same GTO-mission requirement and similar separation Mach-number around 12 but different return-modes is depicted in Figure 5. Data for both launch vehicles have been generated in preliminary sizing loops taking into account ascent trajectory optimization and atmospheric re-entry and return flight. The turbofan-powered LFBB mode requires a significantly heavier and larger stage compared to an IAC-mode RLV.

The potential for improvement when using the “In-Air-Capturing”-mode is found between 22% and almost 46% in this example using realistic sizing conditions. The stage dry mass, usually correlated with development and production costs, is reduced by 37% compared to the reference LFBB-configuration. Even when considering the additional infrastructure costs of operating the capturing aircraft, the huge cost reduction potential of “In-Air-Capturing”-RLV compared to more conventional approaches becomes obvious with these numbers.

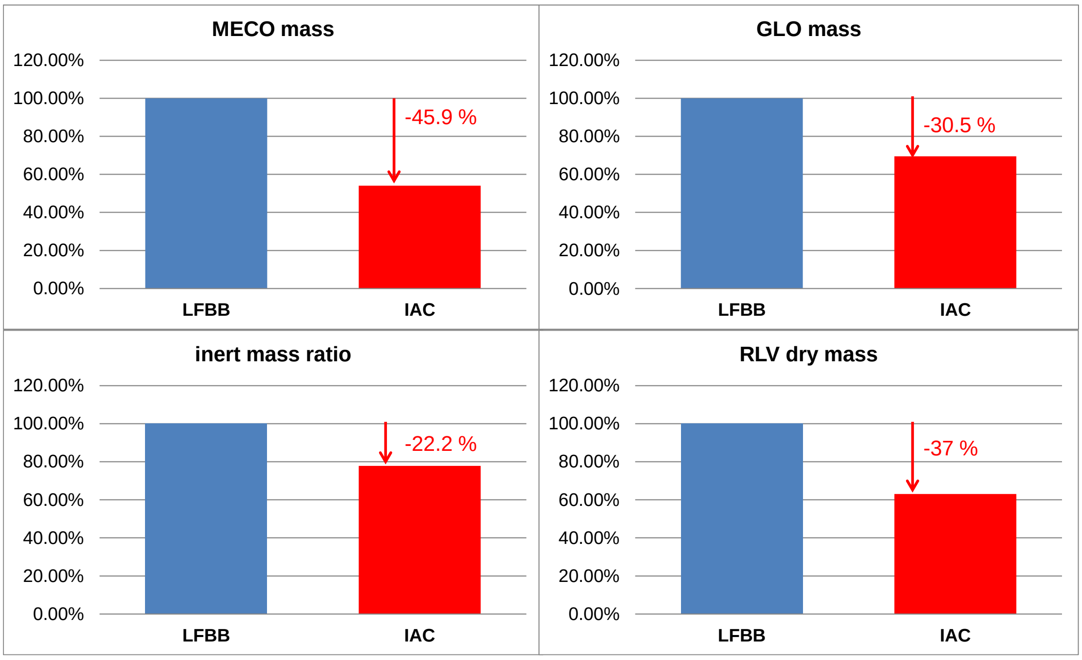


Figure 5: Relative comparison LFBB-mode with "In-Air-Capturing"-RLV mode, GTO-mission

3.2.1 Summary

In FALCon deliverable D2.1 [7] the technical differences of the four return methods In-Air-Capturing (HL), Flyback Booster (HL), Downrange Landing (VL) and Return-to-Launch-Site (VL) are presented and discussed. The major key points of this comparison with highlight on the IAC with respect to the other return methods will be summed up in the following:

- **System Design and Size:**
  - The size of RLVs using In-Air-Capturing is lower than the size of RLVs using the vertical landing method when comparing launchers with the same propellant combination and payload capability
  - Winged RLVs require more added hardware compared to the VL method, respectively wings, aerodynamic control surfaces, landing gear and capturing hardware
  - LOX/LH2 as propellant in combination with IAC leads to the lowest-sized vehicles
- **Mass and Performance:**
  - Lowest Masses for LOX/LH2 launchers with IAC followed by VL launchers with downrange landing
  - Higher structural indices and dry mass weight of HL IAC compared to conventional ELV or VL stages due to more hardware for re-entry and controlled flight
  - Lowest performance losses of all return strategies observed when using IAC and LOX/LH2
- **Re-entry and Loads:**
  - Re-entry Loads are low for IAC and LOX/LH2 but get high when using hydrocarbons
  - Loads are highly dependent on separation conditions (velocity, flight path angle) and determine the size of the TPS

Considering these results, the In-Air-Capturing strategy seems to be a viable and efficient option compared to conventional ELVs and even the VL SpaceX method. This can be deduced due to the low masses and performance losses, the comparably compact size, and the manageable re-entry loads during its flight back to the earth. Since a winged reusable stage was already operational in the past and expertise and know-how was already gained in returning such stages, the focus clearly has to be set on investigating the In-Air-Capturing method and developing the technology that will enable its use for a future possible European launch vehicle.

3.3 Economic Analysis RLV

3.3.1 Overview

Economic viability and the possibility to decrease the launch costs is the main rational behind reusability. Hence, the consideration of these costs is of great importance to determine feasible and economically viable RLV designs. However, determining these costs is difficult due to a lot of uncertainties and the unavailability of reliable cost data.

The costs of a launch vehicle can be expressed in two different cost types: *recurring* and *non-recurring costs.* In launcher development, the *non-recurring costs* (NRC) include the **development costs** of the launch vehicle. This includes the costs for the system development and all tests and experiments including prototypes and the first flight unit (theoretical first unit = TFU). *Recurring costs* (RC) include **production and manufacturing costs** and **operational costs** including ground operations, mission control, preflight operations and post-flight operations. For a reusable launch vehicle **recovery** and **refurbishment costs** are added.

Figure 6 shows the cost breakdown for a typical launch vehicle according to the TransCost model [22] which was used to determine costs within the FALCon-project [7]. The costs added by reusability are considered as well. The operations costs can be further divided into direct operational costs (DOCs), indirect operations cost (IOC) and refurbishment and spares cost (RSC). The direct costs include all costs linked directly to the operation of the vehicle such as materials, propellant, labor and fees. Indirect costs which include so-called overhead costs refer to the costs that are not directly related to the operation of the vehicle such as facility and management costs, administration and all support activities.

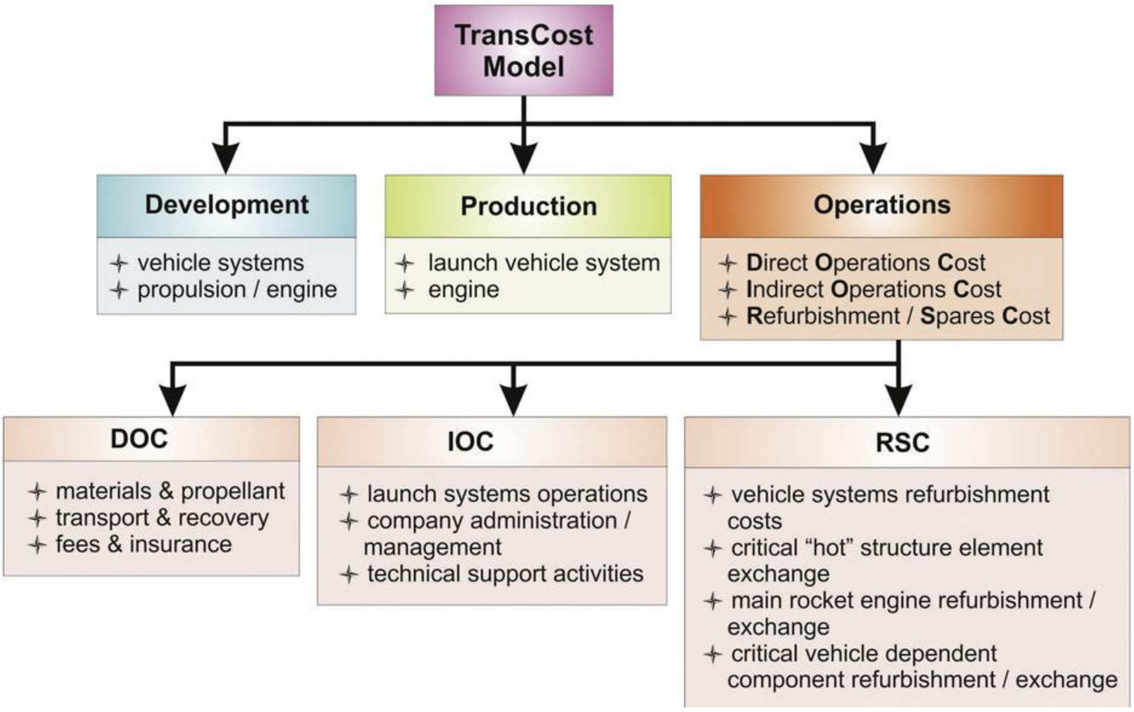


Figure 6: Launch Vehicle Cost Breakdown according to the TransCost model [22]

The TransCost model uses a so-called "top-down" approach to estimate the respective costs as depicted in Figure 6. This means that the costs are evaluated on a very high system level based on cost estimation relationships (CERs) which are statistically derived values based on actual cost data of historical or operational launchers. Estimating the cost of European expendable launchers has been sufficiently validated by DLR with this cost model. However, using this model to determine reusable vehicles' launch costs is difficult and unreliable since the model requires a sufficiently large database of RLV's cost data. Up to date there are only two reusable launch vehicles that are or were used to deliver payload to orbit: the Space Shuttle or STS and the Falcon 9 of SpaceX. In TransCost RLV development costs are mostly based on system studies of the 1980s and 1990s [22].

Some cost data for development of the Space Shuttle and of Energia Buran orbiters are available and have been validated as far as possible [23]. Operational cost and especially maintenance and refurbishment cost of RLV are hardly available and consequently are not included in TransCost. Another concern or restriction is the fact that both Space Shuttle and Buran are manned orbital systems obviously subject to increased aerothermal loads and to much more demanding safety and reliability requirements than unmanned winged RLV booster stages. On the other hand, the Falcon 9 reusable first stage mission is similar to the RLV configurations of interest here but cost data is unavailable to the public and most likely operational cost is dynamically changing. Recent operations, however, show that short turn-around times are realized by SpaceX with their Falcon9 first stages indicating that refurbishment effort is likely limited [14].

Any reusable launch vehicle requires hardware and additional personnel to recover or land the stage. It is important to note that RLV-recovery costs represent only a minor portion of overall launch costs. Nevertheless, as this part is directly related to the “in-air-capturing”-procedure, it is worth to have a closer look and compare with other recovery options. Despite all uncertainty, an alternative model to determine all cost related to recovery operations has been established and is presented in the section 3.3.2. Instead of a “top-down” approach, a “bottom-up” approach was chosen to determine these costs [7]. In FALCon deliverable D2.1 [7] the main operational differences between the four recovery methods, RTLS, DRL, LFBB and IAC are explained and the cost model to calculate the IAC costs is described. This model used for the calculation of the respective costs has been established DLR-internally and the documentation of all and assumptions can be found in [24].

3.3.2 “In-Air-Capturing” Recovery Costs

The objective of the flight performance model is to provide values of the IAC operation factors affecting the cost model by a preliminary approximation of the total aircraft mission and towing performance. Large passenger aircrafts are considered due to their availability, flexibility and large propulsion capabilities, suitable for towing a first stage (see section 4.3 below). The aircrafts analyzed are the B747-400, the B747-8F, A330-800NEO, the A380-800 and the A 330. The aircraft and engine characteristics are obtained from the manufacturer websites and are provided in [7].

Figure 7: Commercial Aircraft that could be used for In-Air-Capturing: B747-400 (top) and A340-600 (bottom)

The flight mission for the aircraft for the stage retrieval operation can be considered similar to a classical military “drop and go” mission but in reverse. Figure 8 shows the typical mission profile considered for an IAC mission with all phases that were taken into account. The fuel consumed during the mission is assessed considering all the major flight phases and assumptions are described in [7]. Note, the 700 km range is typical for an RLV first stage recovery operation and exact values depend on launcher mission, separation Mach number, ballistic coefficient and aerodynamic performance of the RLV.

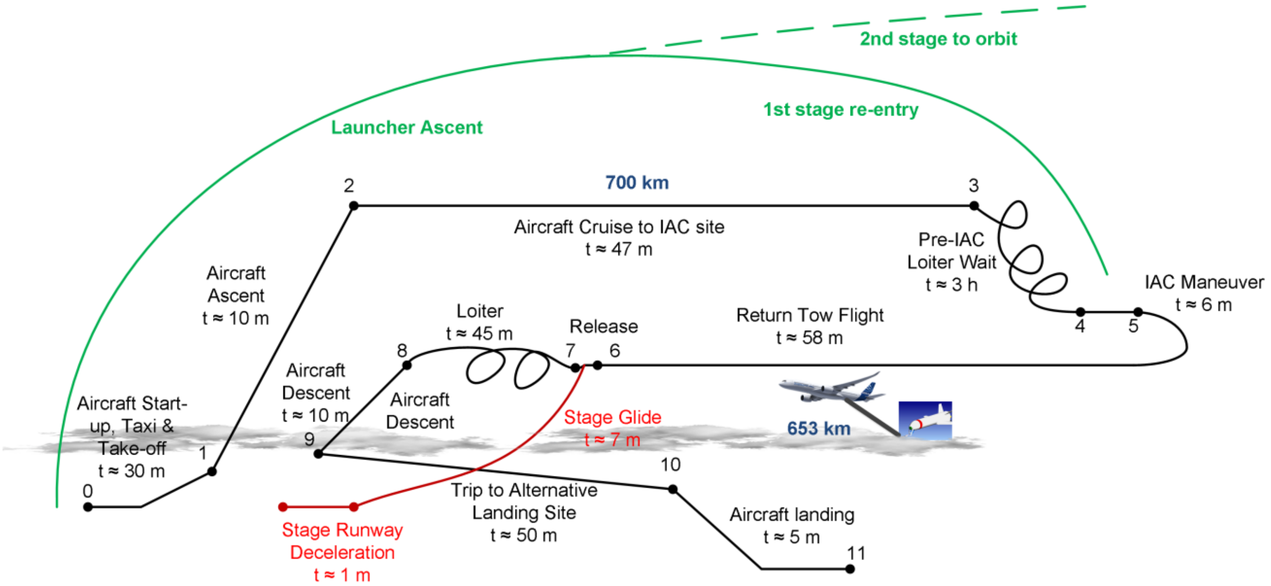


Figure 8: Typical IAC Towing Aircraft Mission Profile [7]

For the capturing and towing flight, the large, long-range aircrafts considered have more than enough fuel capacity to complete the mission. Therefore, it is assumed that the aircraft is not fully loaded to realistically increase its towing performance capabilities.

Aircraft Direct Operating Costs (DOC) are directly related the flying costs of a particular aircraft mission and type. The model includes depreciation, insurance, crew, fuel and maintenance costs, interest rates, as well as navigation and landing fees. The method used is based on the Liebeck method, adapted with some specific corrections. [7]

3.3.2.1 Aircraft Acquisition Costs Estimation

The IAC method requires a commercial aircraft to be bought and modified so it is able to perform the tasks according to the requirements. Hence, a second-hand or used commercial aircraft should be selected for this task since only a few flights per year are necessary and acquiring a new-constructed aircraft would lead to high costs.

For the Boeing B747 there is a huge second-hand market due to the fact that the first B747 was produced in 1969 and over 1500 aircraft were produced since then. This leads to quite low prices on the second-hand market starting from 16 M$ US (2018). The A340 acquisition prices range from 9 M$ to 110 M$ thus making it also a viable option for the towing aircraft.

3.3.2.2 Aircraft Upgrades and Modifications Costs Estimation

In addition to the acquisition costs, a major cost driver would be the aircraft modifications to allow for the towing flight. To do so, the aircraft would require an aerodynamically controlled capturing device (ACCD) system which would catch the stage during its final gliding flight and approach to the towing aircraft. This system could be analogous to Multi-Port Refueling Systems (MPRS) used for aerial refueling operations, although it would require a stronger rope device to be able to tow the stage. In this report it is estimated that the cost to adapt a KC-135 aircraft to accept an MPRS could be of roughly 5.1 M$ in FY2004, or 6.8 M$ in FY2018 according to [24].

In addition to the ACCD system, the aircraft might require specific structural reinforcements to be able to cope with the additional forces at the ACCD attachment point. A closer analogy could be the costs associated to converting a passenger B747 aircraft to a cargo aircraft. In [24], it was estimated that this could cost 14.3 M$ in FY1982, or 37.1 M$ in FY2018. In WP7 the Airbus A340-600 has been selected as the reference airplane for capturing and towing. A first contact with the airframe manufacturer has been established and potential modification needs were discussed (see section 6.4.6 on p. 55). Some indications give hope that necessary modifications are limited and could be realized at an affordable prize.

3.3.2.3 Aircraft Ownership Costs/Indirect Costs

Such costs are not directly linked to the aircraft flight, but to an overhead on the flight. They are estimated as the sum of the depreciation costs, the interest costs and the insurance costs.

Interest rates are strongly dependent on the world economic climate, local exchange rates, credit standing, off-set agreements and other difficult to quantify factors. Therefore, these factors are ignored by many models although it's a big contributor to costs. Therefore, the model explained in [24] is used, assuming no relative residual value of outside capital remaining in the company. The European Central Bank highest historical interest rate of 4.75% was used in this analysis as a conservative estimate. [24]

Insurance rates are directly proportional to the involved risks and potential claims given an aircraft loss. For the case of an IAC aircraft, although the failure probability could be considerably high as compared to commercial aircraft operations, the loss potential is much lower, as there are no passengers on-board and the operations is mainly performed in open seas. An insurance rate of 0.35% from [24] is used.

3.3.2.4 Direct Cash Costs

Direct costs are those that depend directly on the operating mode of the aircraft. These operations are defined by the towing phase and the launching interface, by accounting for holding patterns due to launch window delays, and other possible issues.

Fuel costs account for the majority of the DOCs in commercial aviation. However, in case of the IAC, for the relatively low launch rates considered and the limited range to be covered in each mission, fuel accounts for a small part (around 5%) of the total DOCs. The whole operation should be semi-autonomous/remote to increase the safety and reduce crew requirements and costs. Therefore, remote operators in the mission control center would oversee the operation, directly controlling the combined flight of both vehicles. Although a single operator could control a fleet of Unmanned Autonomous Vehicles (UAV) it is considered that a team of 6 aerospace engineers (in mission control and for support) would be responsible for the operations. When the towing phase is taking place, it is assumed that 14 additional engineers in mission control are also working in the operation. This is based on the FESTIP studies [29].

Maintenance costs typically account for 10-20% of the DOCs of an aircraft under business as usual airline operations. These costs are divided traditionally in scheduled and unscheduled maintenance costs, with the later one being the highest as a consequence of the unexpected appearance, resulting aircraft downtime, facility and spare costs, etc. Scheduled maintenance costs, on the other hand, are divided into different work packages which are the A-Checks, B-Checks, C-Checks and D-Checks. The first one involves daily visual inspections of different aircraft subsystems such as fluid levels and tires, whereas the later one is performed every 6 to 12 years, with duration of approximately a month, and involves a major aircraft overhaul with detailed structural and hydraulic inspections. Considering the low number of flights per year and the cost of a D-Check it should be discussed if an IAC aircraft should not just be dispensed and replaced by a new (second-hand) aircraft once a D-Check is about to take place.

In this preliminary model, the total maintenance costs per launch are estimated based on [24]. Based on NASA methodology, the overhead costs are assumed to be two times the direct labor costs.

In Liebeck/NASA methodology, the navigation fee only applies for international flights, although it is unknown if this also applies currently to national flights. Nevertheless, as the flight could enter international waters, it is assumed that it also applies in this case. Landing fees are also modeled with the following CER from [24] for international flights. It is assumed that the landing and ground handling costs apply also if the airport is operated by the same launch provider, as an effort for aircraft ground handling operations and landing site maintenance per launch.

3.3.2.5 Limitations of Cost Model

There are some factors that are not accounted by the cost model, such as aircraft availability, maintenance hour's dependency on aircraft age or cumulated flight hours, and maintenance dependency on operation conditions.

The first factor is not considered to be limiting for this analysis as a consequence of the low launch rates compared with airline operations, providing the possibility to schedule maintenance accordingly with launch planning. Combining this with the risks of unscheduled maintenance operations could put an additional requirement on 1 or 2 extra aircrafts for redundancy, increasing ownership costs.

The second factor would penalize older aircraft. Nevertheless, maintenance costs predicted are around 15% of the cash costs which in turn are a lower fraction of the direct operation costs, which are highly driven by the ownership costs as a consequence of low aircraft utilization. Therefore, this factor is not considered significant for the analysis. Nonetheless, when acquiring the aircraft, age should be considered in a trade off with the acquisition costs considering also major maintenance checks and expected overhauling.

The last factor could be important as a consequence of the higher thrust required and the possible structural wear caused during towing. The higher thrust requirement, as a consequence of a heavier reinforced airliner requiring more thrust and leading to higher engine wear, was accounted for by adding a 2% increase in maintenance labor hours per year.

3.3.2.6 Indirect and Other Further Ownership Costs

This section describes the IOC and other ownership costs related to the IAC recovery operations, including vehicles and facilities.

In addition to the acquired aircraft, a new large runway would be necessary in Kourou CSG. Irrespectively of the price, it is assumed that this cost would be provided by ESA-member states through CNES as all other launcher system ground infrastructure. Such an investment could be a major improvement to CSG since the airport would also be suitable for payload processing, which currently arrives to Cayenne via airplane and then travels by road. Therefore, the airport landing fee estimation used in Section 3.3.2.1 is assumed enough, although it is probable that the launch site user fee (currently around 1 M$ per launch + 4 M$ of fixed costs per year) would increase as a consequence of the use of these installations. Nevertheless, a key issue for cost saving strategies here would be to regulate spaceport fees in a similar way as commercial airports.

Regarding vehicles for operations, once the stage has landed and arrived to a waiting position, a recovery convoy is deployed to service and examine the recovered vehicle and prepare it for towing operations to the Stage Processing Facility. For the Space Shuttle, more than 25 vehicles were required to conduct all the safety operations. Operations took approximately 2 hours after the stage landed with 2 hours of team preparation and purge system chill down before the actual landing. It has to be noted that for the Space Shuttle, these were hazards associated to hypergolic and toxic propellant used for the Attitude and Orbit Control System, which are not considered for this analysis, as well as astronauts on-board which required medical evaluation and had to de-board safely. This also explains the required team of approximately 150 trained personnel. A reduced team is assumed, based also on observed SpaceX employees working on the stage securing operations after landing. For the 2 hour preparation before the mission, it was assumed that each worker would perform one task to be conservative, and the minimum between the assumed maximum of 46 employees and the total number of workers is used.

Firstly, an initial atmosphere check looking for possible fuel/oxidizers in the surroundings takes place, taking approximately 15 minutes. Once done, the recovery convoy and personal can approach the vehicle and conduct the propellant and pressurant purging and draining operations, taking approximately 50 minutes as for the Space Shuttle. The vehicle is then prepared for towing by positioning the taxi vehicle in the front wheel while control surfaces and the landing gear are locked. This operation can take approximately 30 minutes. All these activities are listed in [7].

It is assumed that an off-the-shelf towing vehicle is to be used. It is estimated that this vehicle costs around 1.5 M$. The taxibot can operate at 20 knots or more when towing. Therefore, it would only take around 5 minutes to tow the stage to the processing facility for a 3 kilometer distance, and 1.5 minutes to detach from it. This labor time, although negligible was accounted for in the model.

For mission control operations it was assumed that a group of aerospace engineers are overlooking the operations and data acquisition at the mission control center, as was done for the Space Shuttle. This is taken from a FESTIP concept study, mentioning that 15 engineers would be required to overlook the operations plus a fraction of support engineers, totaling around 20 engineers if a high degree of autonomy is used [29].

3.3.2.7 Cost Breakdown of Recovery Costs

The cost breakdown for an exemplary recovery mission with IAC using the B-747-400F is shown in Figure 9 to Figure 11. Concerning direct costs, the major contributor are fuel costs with almost 2/3 of the total direct recovery costs. All remaining direct costs are small compared to the fuel costs with the 2nd and 3rd highest costs by landing fees and crew. The crew in this case is a team of aerospace engineers and UAV pilots that are able to remotely control and monitor the capturing aircraft.

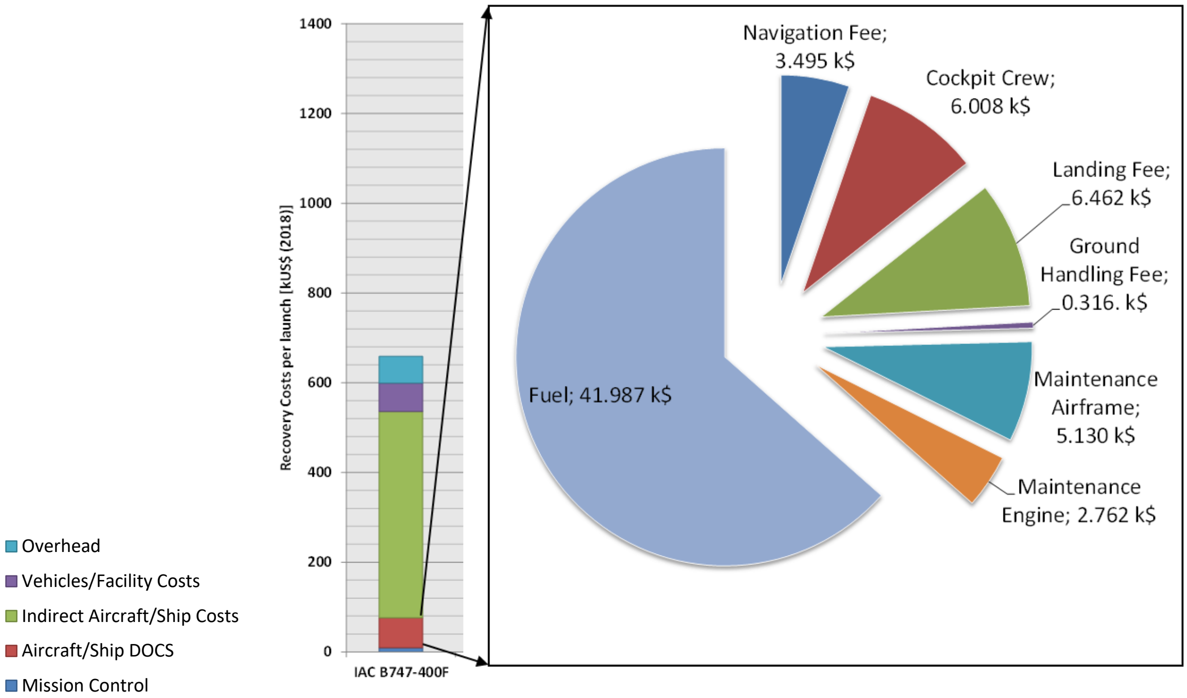


Figure 9: Direct Cost Breakdown for exemplary IAC recovery mission

Indirect costs are, compared to the direct costs, much higher due to the low number of missions per year. Whereas a commercial airline has to make sure that an aircraft flies as often as possible to be economically viable, this requirement is not valid for the In-Air-Capturing operations plan. Hence, the share of depreciation and interest get much higher per mission compared to commercial airliners (compare ~100 hours per year flight time with IAC vs. roughly 3000 hours flight time with commercial aircraft). Since indirect and ownership costs are the highest contributor to total recovery costs per mission it is of great importance to acquire an aircraft to a low acquisition price at good conditions. A very high acquisition price renders the recovery strategy too expensive.

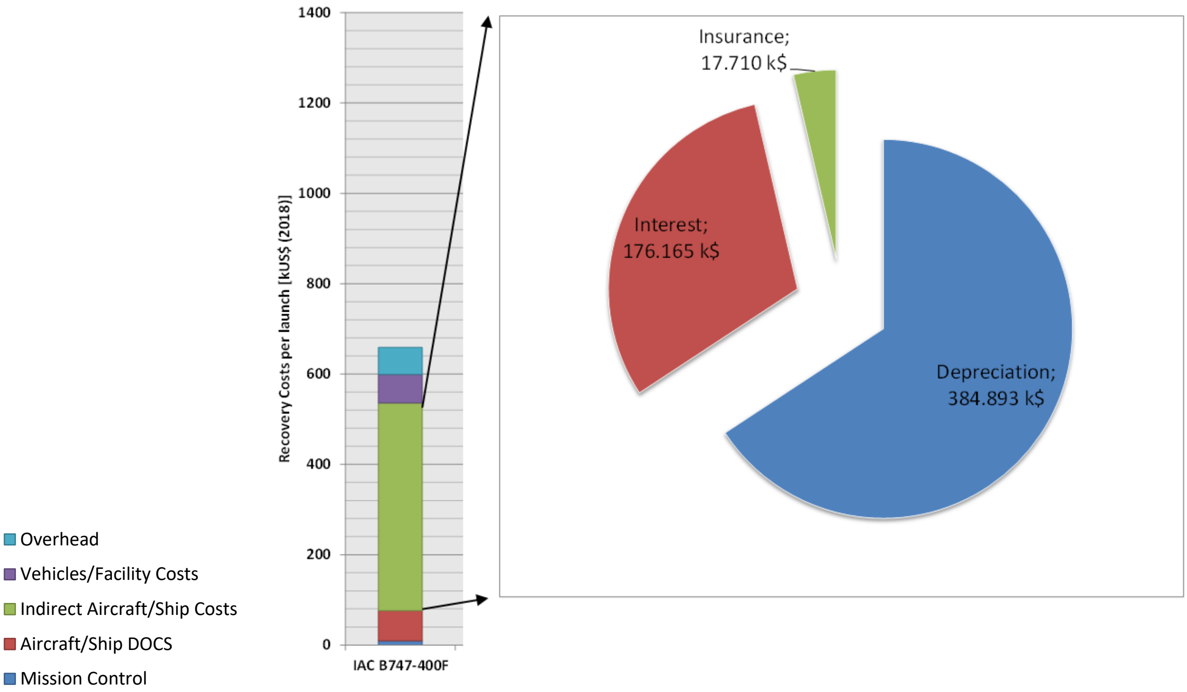


Figure 10: Indirect Cost Breakdown for exemplary IAC recovery mission

Figure 11 shows the cost breakdown for all additional vehicles and facilities costs. These are about the same magnitude as the direct operating costs of the aircraft. The vehicles/facilities cost are mainly driven by additional material costs which represent the cost of spare parts for the required vehicles and maintenance hours that have to be spend on said vehicles. The 2nd highest contributor to vehicles/-

facilities costs are the taxi vehicle which tows the stage on the airport (including acquisition) and additional post-flight operations, here referred to as airstrip operations.

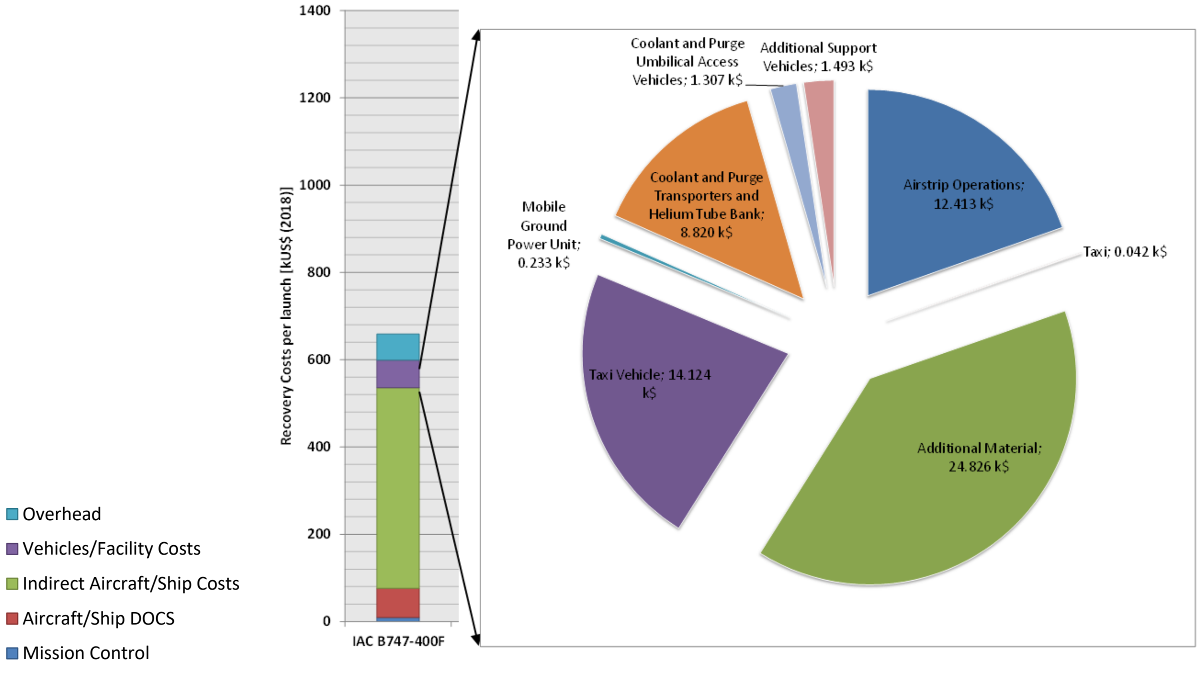


Figure 11: Vehicles and Facilities Cost Breakdown for exemplary IAC recovery mission

3.3.3 Comparison of Recovery Costs

Vertical Down-Range Landing (DRL) is a different recovery mode of RLV which is used for high energy missions and is potentially in competition to IAC. Opposed to the IAC method, it involves the use of more systems (ships, harbor and activities) and longer time to transport the launch vehicle back to the landing site. The FALCon deliverable D2.1 [7] describes the different approaches used to estimate the costs associated to the DRL recovery mode.

The costs of recovery per launch for different return methods for VL and HL stages are shown in Figure 12. The costs are given in US$ with respect to the economic conditions of 2018. For In-Air-Capturing, the costs of the B-747 and the A330 are presented. For VL recovery the SpaceX and Blue Origin barge/ship recovery methods and RTLS costs are added. The RTLS costs are also more or less valid for the HL flyback when assuming similar efforts in landing strip construction. The reference HL stage for the mission calculation is a ~50-ton landing mass stage and for VL a ~45-ton landing mass stage. However, the impact of landing mass on the mission is negligible due to the comparatively low direct launch costs in all cases.

The recovery costs end up between 250 k$ (RTLS) to 670 k$ (SpaceX barge landing) to almost a million US$ for the Blue Origin method for VL related methods. Recovering the stage via IAC costs around 650 k$ US depending on the selected aircraft [7]. The greatest share, regardless of VL or HL, is made up of indirect costs and overhead costs. This great share is due to the depreciation of the acquisition and modification costs over all launches assuming a remaining lifetime of 15 years. Hence, the recovery costs are highly dependent on the aircraft price.

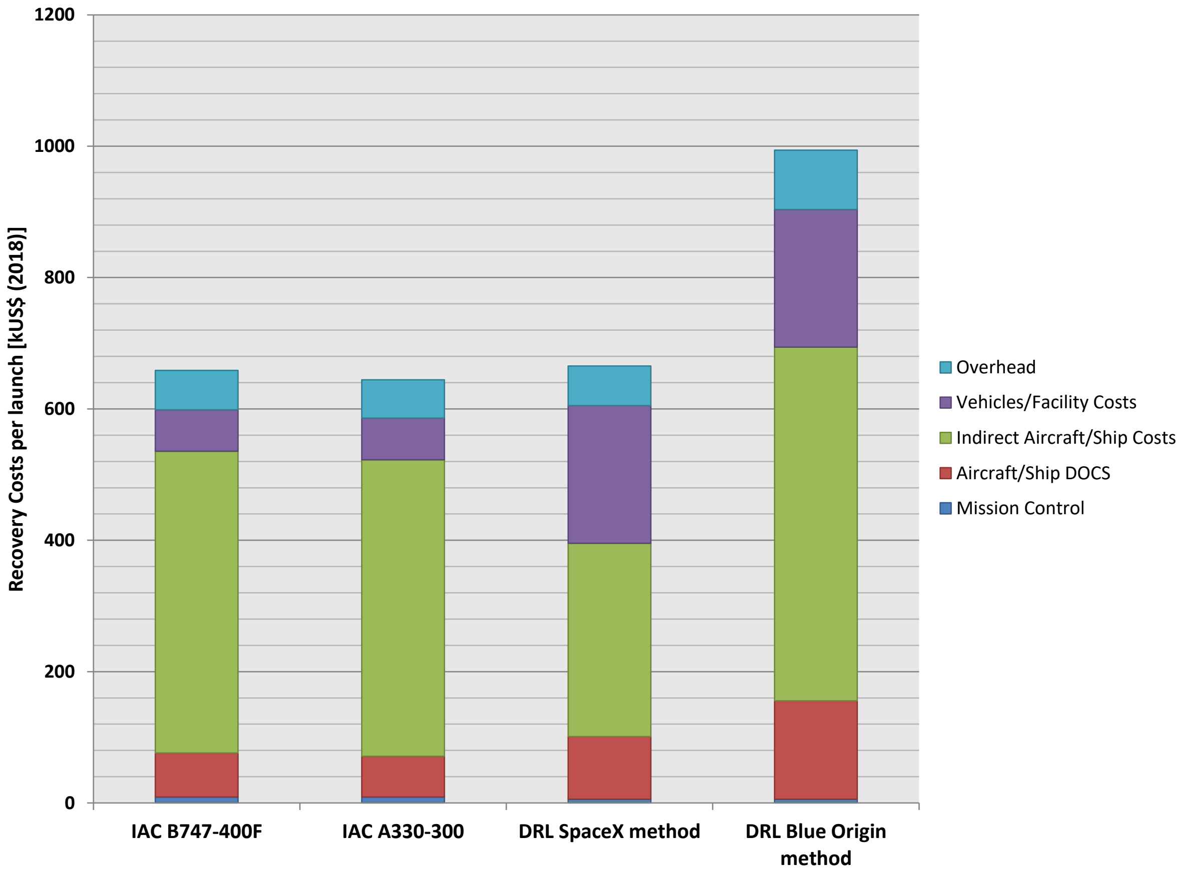


Figure 12: Recovery Cost breakdown for different return strategies

Direct costs, including fuel and crew costs, landing fees, navigational fees or harbor fees and costs for extra services account for only roughly 100 k$ per mission or 1.5 million – 2.5 million US$ per year depending on the recovery method. Of these direct costs 2/3 of costs are related to fuel for IAC. For VL methods, the greatest share of direct costs is due to crew costs. The facility and vehicles costs are higher for the VL recovery methods which can be explained by the fact that crane acquisition costs are increasing total costs. Contrary, the IAC costs don't include depreciation costs of the airstrip or hangar building. Including those costs would add additional 250 k$-400 k$ per launch.

As expected, the recovery costs are certainly dependent on the launch rate. Figure 13 shows that dependency over launch rates from 5 to 45 launches per year. The same assumptions as described previously were used for this calculation. The recovery costs calculated with the top-down model TRANSCOST were added for comparison. In this model, the recovery costs are calculated according to equation (3-1) where L is the launch rate m_{rec} is the mass of the recovered stage/hardware and f_i are country- and business dependent factors.

$$WYr_{REC}^{TRANSCOST} = \frac{1.5}{L}(7 * L^{0.7} + m_{rec}^{0.83}) * f_i \tag{3-1}$$

The recovery costs depend exponentially on the launch costs with a negative exponent. Hence, the decrease of costs per launch in the comparably low launch rate regime is greater whereas the costs approach a boundary value when reaching very high launch rates. Nevertheless, doubling the launch rate from 15 to 30 launches per year would result in a decrease of -30% for the SpaceX method, -40% for the Blue Origin method and -35% for IAC. Using IAC as recovery method seems to be favorable for a launch rate greater than 15 launches per year. The recovery costs of using RTLS are negligible since they fall below 200 k$ per launch with a launch rate greater than 20 launches per year. The recovery costs calculated with TRANSCOST while in the same order of magnitude are considerably higher. This can be explained by the fact that its recovery CER is based on the retrieval operations of the Space Shuttle solid boosters (SRM), which required a relatively high effort for retracting the two SRM floating in the Atlantic. The simple fact of two stages to be recovered out of the sea not necessarily in close proximity to each other is driving these costs.

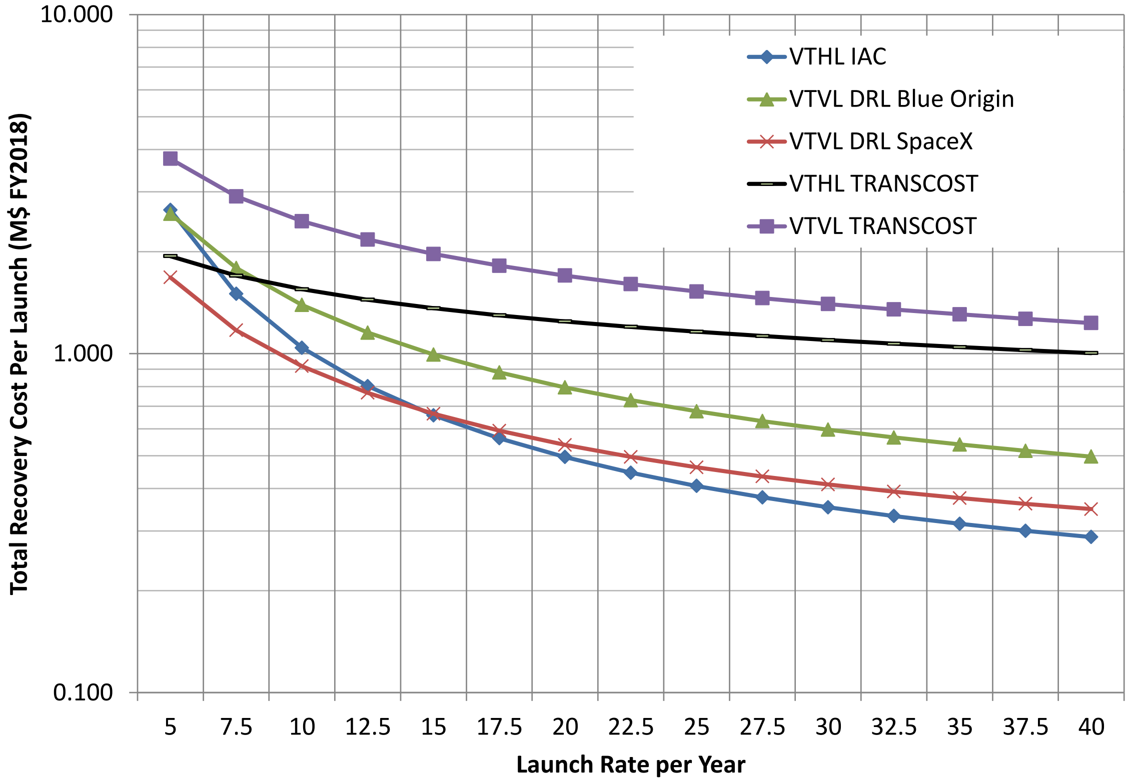


Figure 13: Recovery Costs per launch in M$ (economic conditions: 2018) for VTVL and VTHL recovery methods

3.3.3.1 Small launcher recovery costs

Using IAC for small-sat launchers should make use of smaller and cheaper turboprop aircraft as investigated by DLR [13]. The recovery costs could be reasonably low at 150000 US$ per flight. The share of recovery costs using a smaller turboprop aircraft to total launch costs (5 million US$ for Electron) would be 3% and thus comparable to the heavy-lift scenario [13].

The tendency of IAC having significant better performance than the propulsive vertical landing is again confirmed for the small launchers. In case of extremely light-weight stages of micro-launchers the option of inflatable devices could be feasible and would then show even better performance than IAC. Even then the recovery would probably best be achieved by kind of MAR which is closely related to the IAC-method.

3.3.4 Remarks on RLV Launch-Costs

It is important to note that RLV-recovery costs represent only a minor portion of overall launch costs. The reason why it has been described in such detail in the previous section 3.3.2 is because recovery is directly related to the “in-air-capturing”-method.

Another factor is hardware refurbishment after each flight for which limited experience is available today because of the low number of operational RLV to date. The short turn-around times realized by SpaceX with their Falcon9 first stages indicate that the refurbishment effort is limited [14]. In case of winged RLVs using the IAC-method similar operational experience is not yet available. However, comparing the mechanical and thermal loads of horizontal landing vehicles with those using propulsive deceleration and vertical landing, it is to be expected that refurbishment costs for VTHL are probably less than for VTVL. This statement is supported by the facts that the rocket engines of VTHL do not require multiple ignition during a mission and the winged stage for “in-air-capturing” is not flying into its own exhaust plume during reentry. Both phenomena are creating additional loads on the VTVL-hardware which usually impact the number of safe reuses or the effort for refurbishment after each flight.

If the efforts for recovery and refurbishment operations are coming close for all investigated RLV-return-methods, then the size and weight of the launcher stages are the dominant cost factors. The comparison of different return modes of the first stage RLV all sized for the same mission as described in section 3.2 and shown in Figure 4 can serve as input for RC and NRC-costs estimations. The ascent propellant loading is between 15% and 32% less for the IAC-mode compared to VTVL in DRL-mode resulting in significantly smaller and lighter stages. Depending on the architecture and the operational scenario this improvement can allow cost reductions between 10% and 25% for “in-air-capturing” compared to the vertical landing method downrange on a ship as operated by SpaceX.

Accurate numbers on the cost-saving would require the selection of a specific launcher system and its mission and application scenario. However, it is safe to state that for an Ariane 6 class partially reusable launcher the reduction in cost per flight could be several million € and over the total life-cycle the saving potential could be well beyond a billion €. A dedicated study on relevant European launch scenarios should provide in the future more precise assessments on cost saving potential for IAC.

3.4 Alternative technical applications of “In-Air-Capturing”

The “In-Air-Capturing” procedure has been invented for the task of highly efficient recovery of winged reusable stages. All investigations up to now and the previously described technology development-needs focus on this application.

Beyond this primary use case, alternative technical applications might exist for the technology. Such applications could have an influence on a technology development roadmap of which the current version is described in section 7.

3.4.1 Space applications

Somehow similar technologies have been used in the past with the mid-air-retrieval of film-capsules de-orbited from spy-satellites. The CIA’s Corona project in the US is the most famous example and a brief overview on the technology developed in the early 1960s is provided in [8]. This application of photographic film retrieval from space has become obsolete since a long time and has been replaced by electronic transmission of images.

After DLR had patented the “In-Air-Capturing”-method (IAC) for future RLVs, two similar approaches have been proposed and another one has initiated some flight testing. However, those named *mid-air retrieval* or *mid-air capturing* are all relying on parachute or parafoil as lifting devices for the reusable parts and on helicopters as capturing aircraft. The first proposal was made by the Russian launcher company Khrunichev [8], [35] and later by the American company ULA for its newly proposed Vulcan launcher. The ULA proposal intends recovering not more than the first stage’s engine bay instead of a full stage [8]. In April 2020, the NZ-based company Rocket Lab has successfully performed a drop test and helicopter recovery of its Electron micro-launcher first stage in subsonic flight and an altitude of approximately 1500 m (Figure 14).

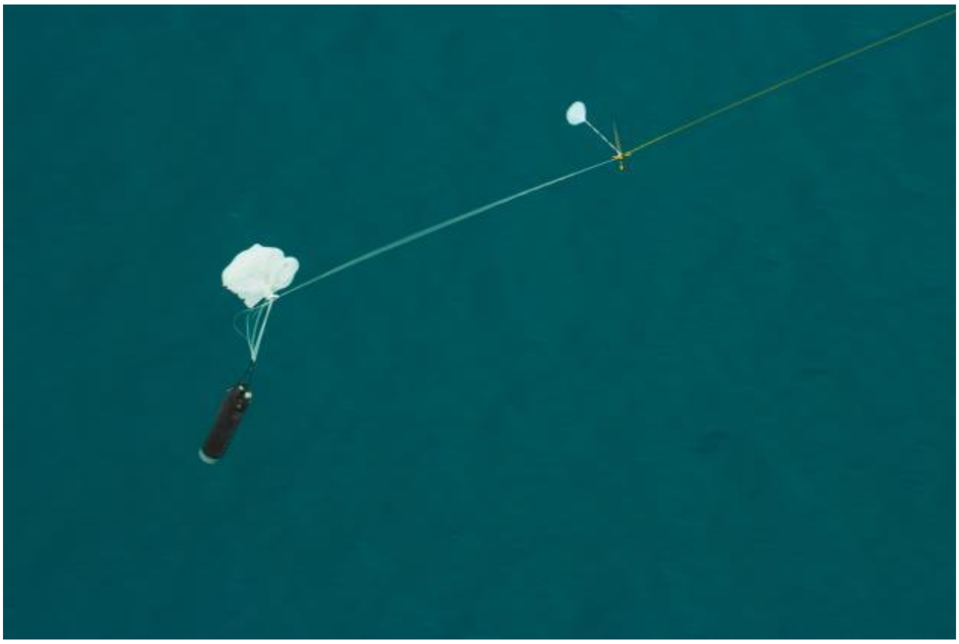


Figure 14: Flight demonstration MAR of Electron first stage test article [36]

The company has announced their intention to recover the first stages using mid-air retrieval [36]. Such capture of a first stage involved in a launcher mission to space has been achieved for the first time with Electron flight #26 on May, 2nd 2022 (Figure 15). As this stage was released by the helicopter shortly after and splashed down to the ocean, the full recovery for subsequent operational use is still to be demonstrated.

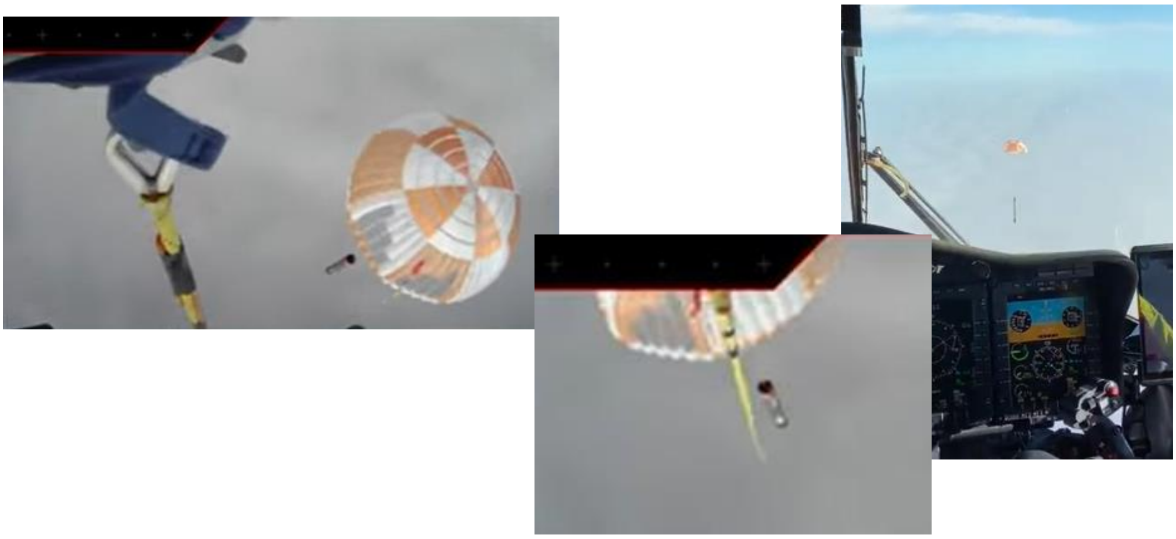


Figure 15: Pictures from video sequence of air-capturing (MAR) of Electron first stage after flight #26

Obviously, the size and mass of the stages to be captured by MAR are much more restricted than for IAC due to mass limitations of parachutes and helicopters. For this reason, probably, ULA switched to partial recovery of the engine bay only of the relatively large Vulcan first stage.

A similar approach for the aerial recovery of the first stage engine of a LOX/Methane launcher in China is designed including reentry deployable aerodynamic deceleration technology and helicopter aerial retrieval technology [37].

The following spaceflight related applications are directly relevant to “In-Air-Capturing” and have been proposed within project duration:

- consider “In-Air-Capturing” as retrieval technology for reusable fairings. Note, SpaceX is currently operating medium-size ships equipped with large booms and huge nets in-between for successful retrieval of payload fairings (Figure 16). Capturing the fairings already in the air at higher altitudes is probably a much more elegant and cost-efficient and at the same time more reliable procedure.

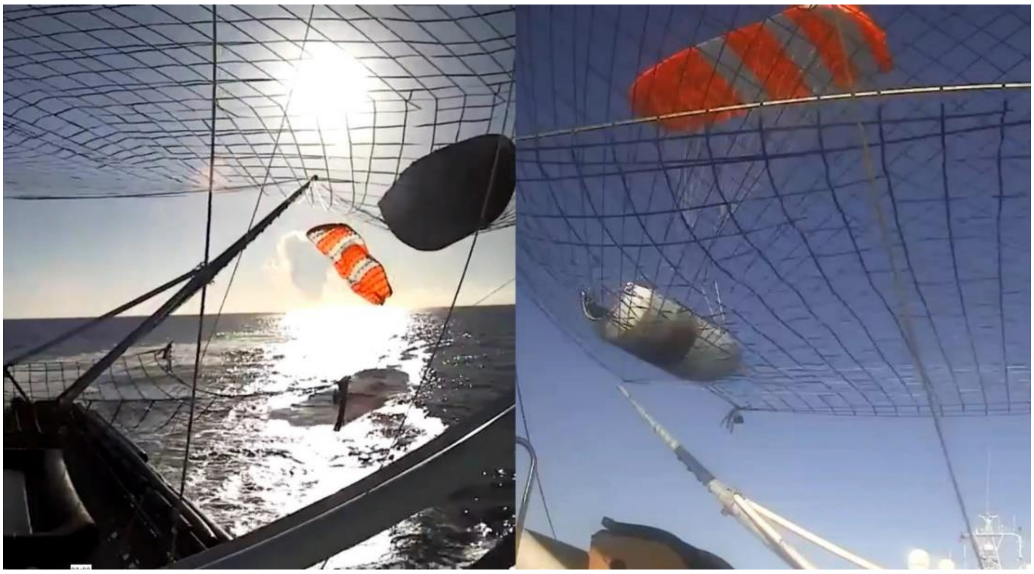


Figure 16: SpaceX recovering Falcon9 fairings with nets on dedicated ship

- using IAC not only for large booster stages of launchers but for small reentry vehicles returning from orbit. The ACCD should not only capture but should also provide landing gear which would allow for significant simplification and mass saving on the reentry vehicle. A typical example of such reentry configurations is the X-37B (Figure 17).

Figure 17: Reusable X-37B with own landing gear assembly and open gear bay doors after landing

- Virgin Orbit (VO) is using a B747-400 carry aircraft for future launches of the micro rocket Launcher One. This aircraft might serve in its 2nd role as capturing aircraft for the IAC-maneuver of different, larger launchers.
- VO has expressed interest in future cooperation with DLR on fully automated large aircraft for the launching and recovery role.

3.4.2 Aeronautical applications

Beyond the above listed spaceflight related synergies also aeronautical applications have been identified with many technological similarities to the automatic approach and formation flight maneuver:

- One application is the automatic air-to-air-refueling of long-range UAV which could see both military and civil use.
- Another related application is the DARPA funded program X-61A Gremlin. For October 2021 the successful in-air recovery of four X-61 UAV by C-130 cargo aircraft (Figure 18) has been reported [45]. The interest lies with deployment and later recovery of a large number of small swarming drones. Although several characteristics in size and available propulsion on the UAV are different to the RLV-recovery, flight control challenges and establishing the right choreography [45] between the vehicles with different agility shows also many technological similarities.

Figure 18: X-61A successful in-flight capturing maneuver (October 2021)

4 Technical status of “In-Air-Capturing”

4.1 How “In-Air-Capturing works

The winged reusable stages are to be caught in the air, and towed back to their launch site without any necessity of an own propulsion system [16]. The idea has similarities with the DRL-mode, however, initially not landing on ground but “landing” in the air. Thus, additional infrastructure is required: a relatively large-size capturing aircraft. Used, refurbished and modified airliners are suitable for such a task. Also, a robust and autonomous capturing device would be required to connect the two vehicles.

A schematic of the reusable stage's full operational cycle has been shown already in Figure 3. At the launcher's lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable winged stage is separated from the rest of the launch vehicle and afterwards performs a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. At this point, a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system.

Differently, within the In-Air-Capturing method, the reusable stage is awaited by an adequately equipped large capturing aircraft offering sufficient thrust capability to tow a winged launcher stage with a limited lift to drag ratio. The reusable unpowered stage approaches the airliner from above with a higher initial velocity and a steeper flight path, actively controlled by aerodynamic braking. For a short period of time, they remain in a parallel formation, such that both vehicles have the same heading but are at different flight levels. During this, an agile and autonomous Aerodynamically Controlled Capturing Device (ACCD) makes its way to the returning stage and establishes connection (via a rope). The entire maneuver is fully subsonic in an altitude range from around 8000 m to 2000 m [17]. After successfully connecting both vehicles, the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released from its towing aircraft and autonomously lands onto the runway horizontally.

For the selected test cases, the flight strategy and applied control algorithms show in simulation that it is possible to maintain the formation required for In-Air Capturing. This would require both actively controlled vehicles to be in a gliding (unpowered) flight. Full-scale simulations (3DOF) with reasonable assumptions of mass and aerodynamic properties for the selected test cases, prove that a minimum distance below 350 m between RLV and towing aircraft (TA) can be maintained for up to 70 s [38][17].

The simulation results presented in the following sections on the “in-air-capturing” of a full-scale launch vehicle are significantly more refined and closer to existing aircraft hardware than the original work presented in [3] [8].

4.1.1 Simulated approach maneuver (Formation Flight)

The parallel formation for IAC requires both the participating vehicles to be in a gliding flight with similar altitudes, velocities and flight path angles (FPAs) separated by a safe distance. One critical aspect to ensure such a formation is that the aerodynamic performance of both the RLV and TA should be closely matched. Typical winged re-entry vehicles have a maximum Lift to Drag (L/D) ratio between 2 - 4.5 in subsonic regime. On the other hand, long range commercial aircraft can reach an L/D ratio of up to 20. Therefore, to reduce this gap in aerodynamic performance and prepare the vehicles for a successful approach maneuver, careful design selection and alterations may be required.

For the current research, the RLV is selected to be the first stage of a 3 Stage-To-Orbit (3STO) launch vehicle proposed in [26]. This returning winged stage called RLVC4-IIIB has a special swept wing configuration. The outer wings of the spacecraft are folded in during the hypersonic re-entry to avoid shock-shock interaction. Then, once the vehicle has slowed down to subsonic velocity, the outer wings are deployed (or unfolded) as shown in Figure 19. The larger wings facilitate a higher trimmed L/D ratio of up to 5.5 in the subsonic regime, making the configuration advantageous for IAC. Its assumed that this relatively large stage weighs 80 tons during its unpowered descent.

Based on this, an Airbus A340-600 is chosen as the capturing aircraft. The long-range jetliner with large loading capacity and four powerful Rolls Royce Trent 556 engines can support the towing loads from the large stage. The relatively advanced flight control system is also advantageous for the complex maneuvers required in IAC. Further, repurposing the retired fleet would not only prove to be economically advantageous but also add a component of reusability to the now withdrawn aircraft. The cruise L/D ratio for a typical aircraft from the A340 family can reach up to 19.3. However, for the capture of RLVC4-IIIB using IAC, the desired L/D ratio is close to 5.5. Therefore, some additional drag sources must be included to lower the L/D ratio of the TA. Drag can be generated using the existing control surfaces like the spoilers and also, other components such as landing gear.

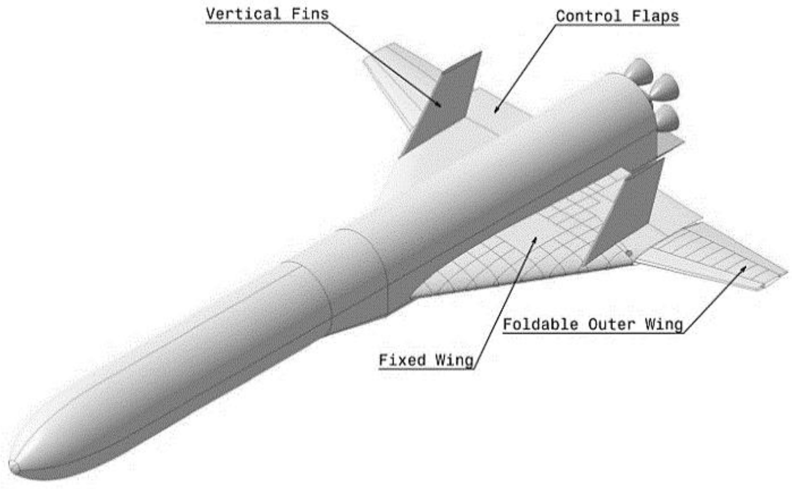


Figure 19: Subsonic Configuration of RLVC4-IIIB [26]

A comparative study of different aerodynamic configurations of the TA yielded that a configuration with front and main landing gear deployed and spoilers at -20° would provide the most suitable fit with a Lift-to-Drag ratio of up to 8 [38]. Further, the centerline landing gear can be removed to house the capturing device in the bay and provides close access to the structural elements near the aircraft Center of Gravity (CoG) for the distribution of towing loads.

An elaborate model of the two vehicles, linked with environment models like atmosphere, gravity and wind as shown in [38] is used for the final trajectory simulations. A simple PID controller is included to influence the velocity, altitude and FPA of both TA and RLV to match a reference trajectory for the RLV. The RLV is controlled and trimmed using flaps that can be deflected up to ±20°. The TA is trimmed using Trimmable Horizontal Stabilizers (THS), which can be deflected between -14° and +2°, and the elevons or elevators that can be deflected between -30° to +15° are used for rapid maneuvering.

To get a better understanding of the formation flight phase, sensitivity of the trajectory to several factors like idle thrust, initial conditions and external disturbances like wake and wind gusts are analyzed. The goal is to maintain a minimum of 60 s of formation to allow the capturing device to attempt the capture of RLV. The criteria or constraints for formation are defined as follows:

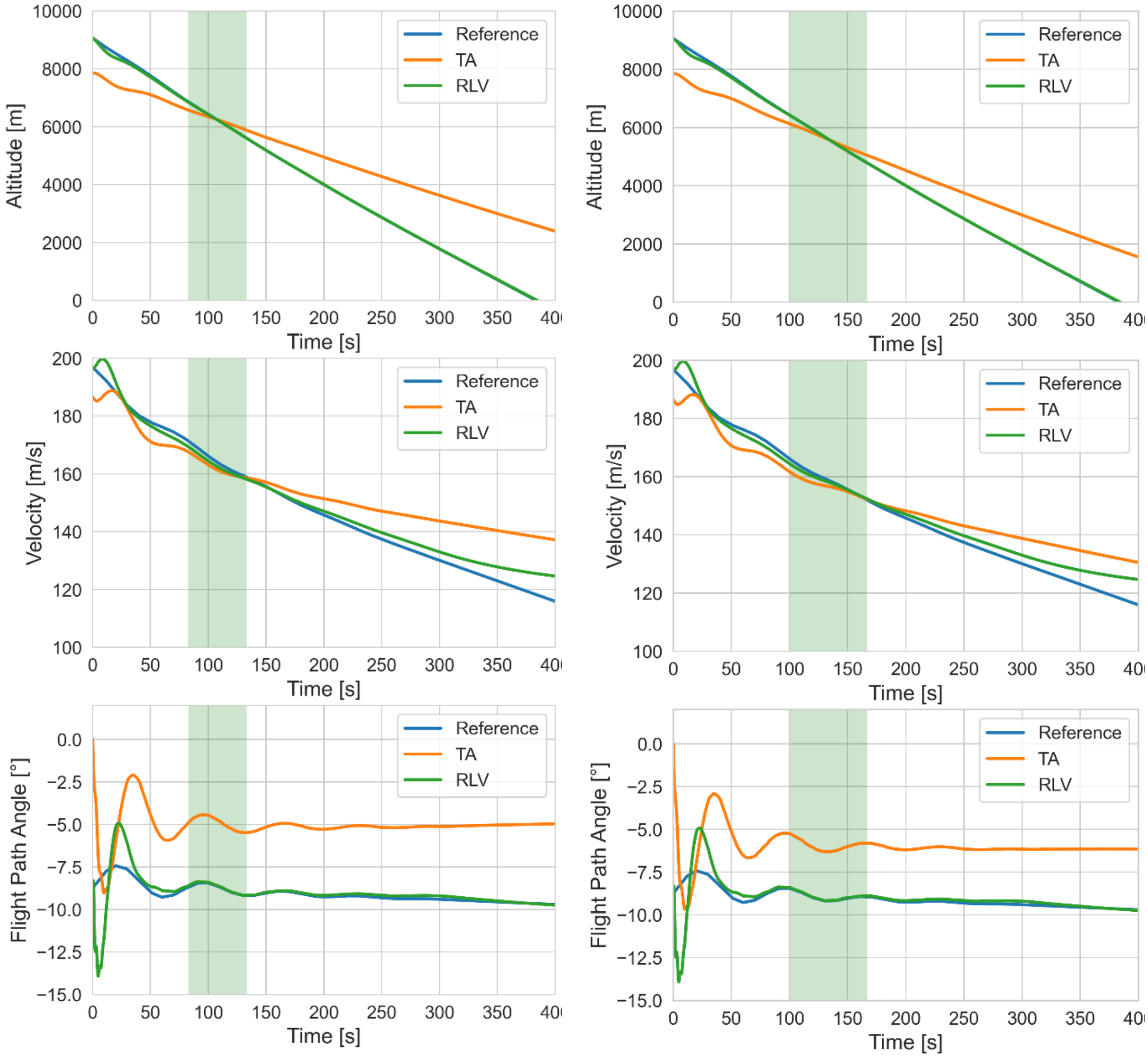
- The formation flight must be achieved between an altitude of 3000 m and 8000 m.
- The RLV should remain behind the TA throughout the formation.
- The relative distance between the TA and RLV should be maintained between 70 m to 350 m.
- The relative velocity between the TA and RLV should not exceed ±3.5 m/s.
- The FPA should be in close agreement.
- The control surfaces should be unsaturated to allow room for maneuverability.

4.1.1.1 Sensitivity to Idle Thrust

Jet engines for commercial airliners are typically kept in idle mode for gliding. The idle thrust acting against the drag contributes to the aerodynamic performance of TA, thereby virtually increasing the originally observed L/D ratio. For the formation flight, this could increase the challenges because the gap in the aerodynamic performance of both vehicles is increased. To analyse the impact of this factor, the formation trajectories are analysed both with and without the idle thrust (10% engine throttle).

Figure 20 shows the formation flight trajectories with and without the idle thrust respectively. It can be observed in Figure 20a that the TA is able to meet the formation criteria for barely 50 s (shaded in green). The main challenge comes from the TA not being able to descend steep enough to match the RLV trajectory. Also, in the lower altitudes, the increased air density leads to increased thrust in TA, which makes the velocities difficult to match. On the other hand, Figure 20b shows that without any thrust, the TA can match the RLV trajectory for a longer duration of approximately 72 s. The TA can now glide at a steeper FPA, allowing it to match the altitude more closely. Moreover, the additional drag helps the TA achieve a closer velocity to the RLV.

To conclude, when the idle thrust is considered the TA could not achieve at least 60 s of formation flight required for the capture phase. However, when no idle thrust was included, longer formations of more than 60 s could be maintained. Thus, the latter can be considered the more favorable option. It must also be established that 60 s may be not be sufficient to allow for multiple capture attempts in case of failure. Hence, in future studies, more approaches to introduce drag to the TA would be examined. Some approaches include, introduction of drag through landing bay doors and inclusion of sideslip in the aircraft trajectory.



a. With Idle Thrust

b. Without Idle Thrust

Figure 20: Formation Flight Trajectory with Idle Thrust (Left) and without Idle Thrust (Right) [26]

4.1.1.2 Sensitivity to Initial Conditions

Before the formation flight, the TA is cruising and waiting at about 10 km altitude. Once the RLV is in close proximity, the TA is expected to glide and get into the formation. The initial altitude and velocity at which this maneuver begins can influence the formation time strongly, especially when the aerodynamic performances of both the vehicles are not the same. For instance, if the TA starts the dive at the same altitude, the formation cannot take place because a steep descent beyond the capacity of TA would be required. Therefore, a Monte Carlo study is performed to identify which initial conditions would provide the longest formation times. This study is performed with an initial altitude range between 7500 m to 9000 m and an initial velocity range between 170 m/s and 200 m/s. The RLV is assumed to be non-cooperative at an altitude of 9170 m with a velocity of 197 m/s at the start of the dive.

Figure 21 shows the effect on formation time for 500 combinations of initial altitude and initial velocity of TA. It can be observed that the longest formations are obtained when the TA dives from a slightly lower altitude between 7500 m and 8500 m. Here a strong correlation with velocity can also be noticed. Diving from higher altitudes work better with lower initial velocities because a lower FPA would be required to match the trajectory. This in turn increases the velocity, which is compensated by starting with a lower initial velocity. However, it is not favorable to start at lower velocities at high altitudes because the flight envelope for commercial aircraft tend to be limited to higher velocities at high altitudes. Therefore, a more affirmative choice would be to select lower altitudes (7500 m – 8000 m) with higher velocities (185 m/s – 200 m/s).

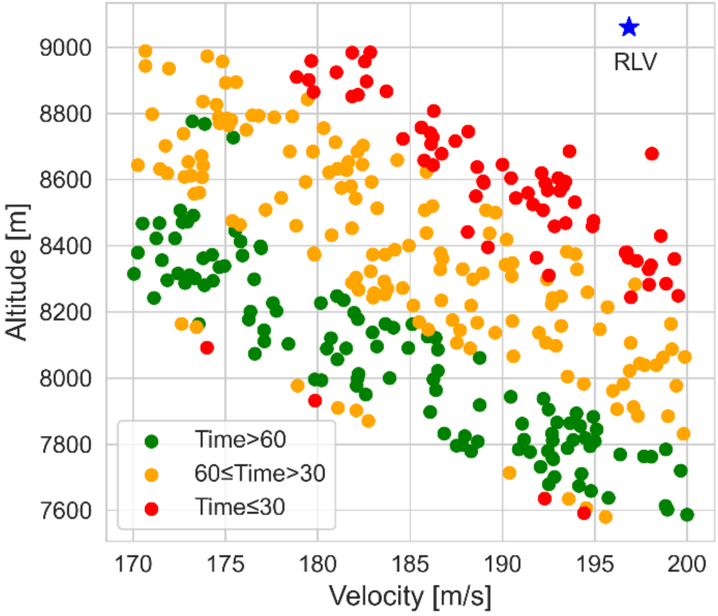


Figure 21: Sensitivity of the Formation Flight Trajectory to the Initial Conditions [26]

4.1.1.3 Wake Disturbances

Based on a detailed study of aircraft wake documented in 67[43], it can be concluded that the aircraft wake has a significant downwash (vertical) component at higher angles of attacks (AoAs). For an AoA of 8°, this component was found to reach up to 11% of free stream velocity. During the formation, exposure of the RLV to the wake is very likely and can drastically disturb the formation. Thus, it should be analyzed.

Figure 22 shows the effect of wake on the AoA of RLV. The time period in which the RLV was exposed to the wake is marked by the orange area, while the green area shows the duration of formation flight. It can be observed from the plot that substantial disturbance has been caused to the RLV AoA at the peak of wake exposure. However, since the duration of exposure to the most perturbing part of the wake is short, the formation was not broken.

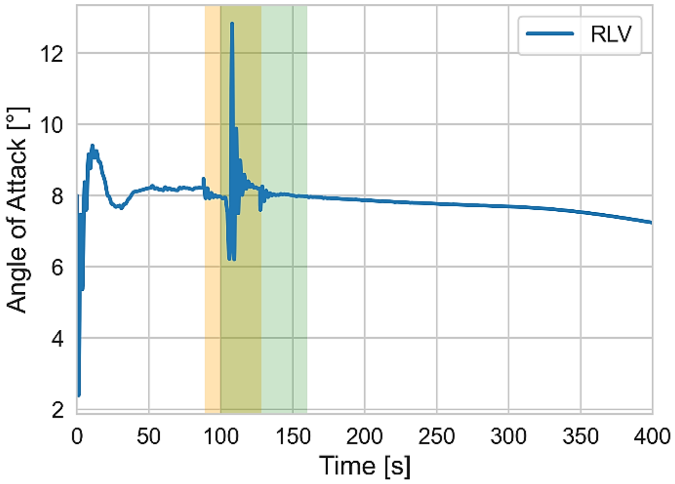


Figure 22: Sensitivity of RLV to the TA Wake during Formation Flight

4.1.1.4 Wind Gusts

Wind gusts during formation flight could be challenging since both the vehicles are exposed to it and are affected differently. Large wind gusts can therefore strongly disturb the formation. Since the current simulation is in 3DOF, only the effect of headwind is included. Hence, to analyze the effect of wind as well as wind gusts, a constant wind of 15 m/s is assumed throughout the trajectory with wind gusts of up to 50 m/s applied during the formation flight (indicated by orange area in Figure 23). More detailed wind models will be included in future work.

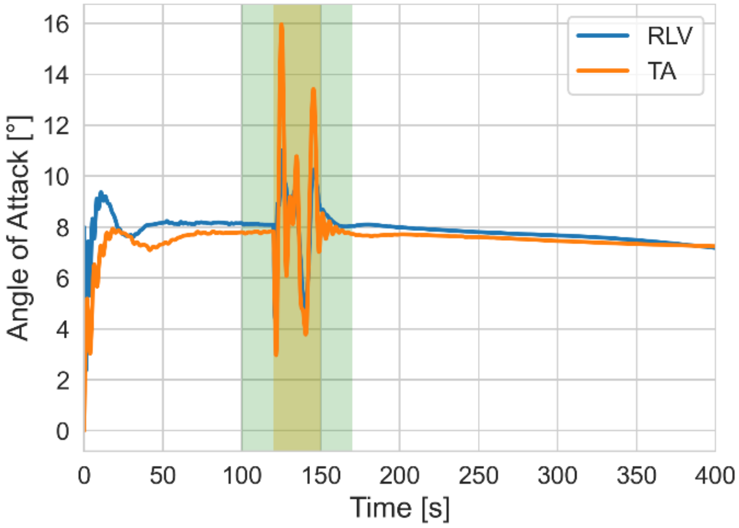


Figure 23: Sensitivity of TA and RLV to Wind Gusts during Formation Flight [17]

It is clear from Figure 23 that major disturbances are caused in the AoA of both vehicles due to the wind gusts during the formation. However, both vehicles regain stability quickly and are able to maintain the formation. The minimum requirement of a 60 s formation was also met, despite the perturbations (shown in green in Figure 23).

Simulations (3DOF) regarding reasonable assumptions in mass and aerodynamic quality prove that a minimum distance below 350 m between RLV and TA can be maintained for up to 72 minutes [17]. Next the ACCD is used to connect the two vehicles via rope during the formation. Once the connection is confirmed, both vehicles pull-up from a gliding to a cruise flight at a suitable altitude. This phase will be examined in the coming section 4.1.2.

4.1.1.5 Alternative Approach

It is worth to be noted that meanwhile an alternative approach to the “in-air-capturing” of launcher stages has been investigated in trajectory optimizations which are avoiding the formation flight of two vehicles (see [40][41]!). Velocity and flight path of the vehicles involved remain at significantly different values enabling only a very short capturing window. Obviously, this approach is reducing the demand on the capturing aircraft but would be riskier to be realized and hence would likely achieve a lower capturing reliability.

Although this work is performed at DLR in Oberpfaffenhofen, it is not part of the FALCon-project.

4.1.2 Pull-Up Maneuver

The mated diving configuration is now required to pull-up to a suitable altitude and achieve cruise flight. Shortly after the capture, the towing aircraft retreats its landing gear and spoilers, regaining its ideal aerodynamic performance. Further, the engines are throttled up to support the additional drag coming from the RLV. At this point, the aircraft serves as an external propulsive system for the RLV, allowing the mated system to gain altitude.

For preliminary simulations of pull-up maneuver, a primary dataset was generated using Inviscid Euler CFD calculations. Since, Euler Inviscid simulations do not provide a good estimation of drag coefficient (C_D) due to the lack of viscosity, the drag coefficient was further estimated using empirical methods. Here, the TA is considered in clean configuration and RLV in subsonic configuration with its outer wings deployed. The first dataset dubbed AEDB01, shows that the trimmed L/D ratio of the aircraft in clean configuration reaches a maximum value of 17.5 at an AoA of 6° and RLV reaches a maximum trimmed L/D of 6.2 also at 10° AoA. This is shown in Figure 24.

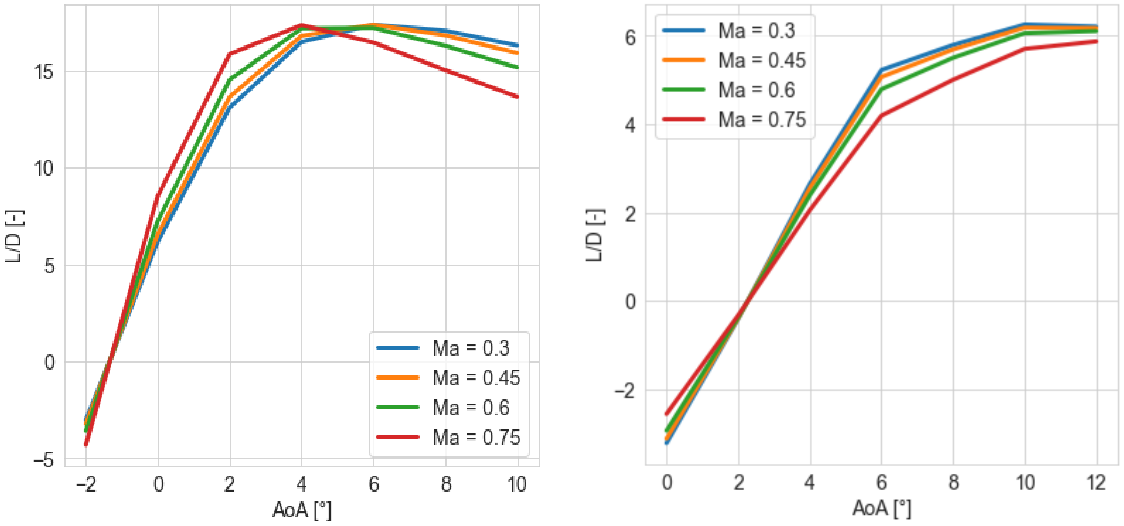


Figure 24: AEDB01 - Trimmed Aerodynamic Performance for TA (Left) and RLV (Right)

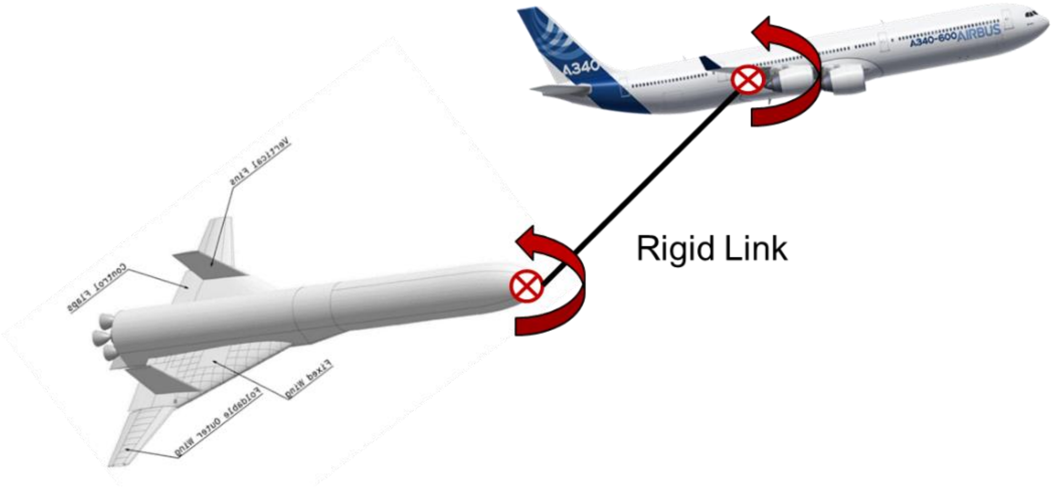


Figure 25: Simple Representation of Pull-Up Maneuver Simulation Model

Figure 25 shows a basic representation of assumptions made in the dynamic simulations. The two vehicles are assumed to be connecting via a massless rigid link. The attachment point of the TA is considered to be its CoG, while the RLV is assumed to be connected at its nose via a spherical joint that constrains translational motion but not rotational motion.

An intricate propulsion dataset for TA was generated using GasTurb tool, which is a professional software for gas turbine performance calculations. Figure 26 shows the variation of net thrust per engine (Trent 500) as well as specific fuel consumption with altitude [m] and Mach number assuming at full-throttle as required for the pull-up maneuver.

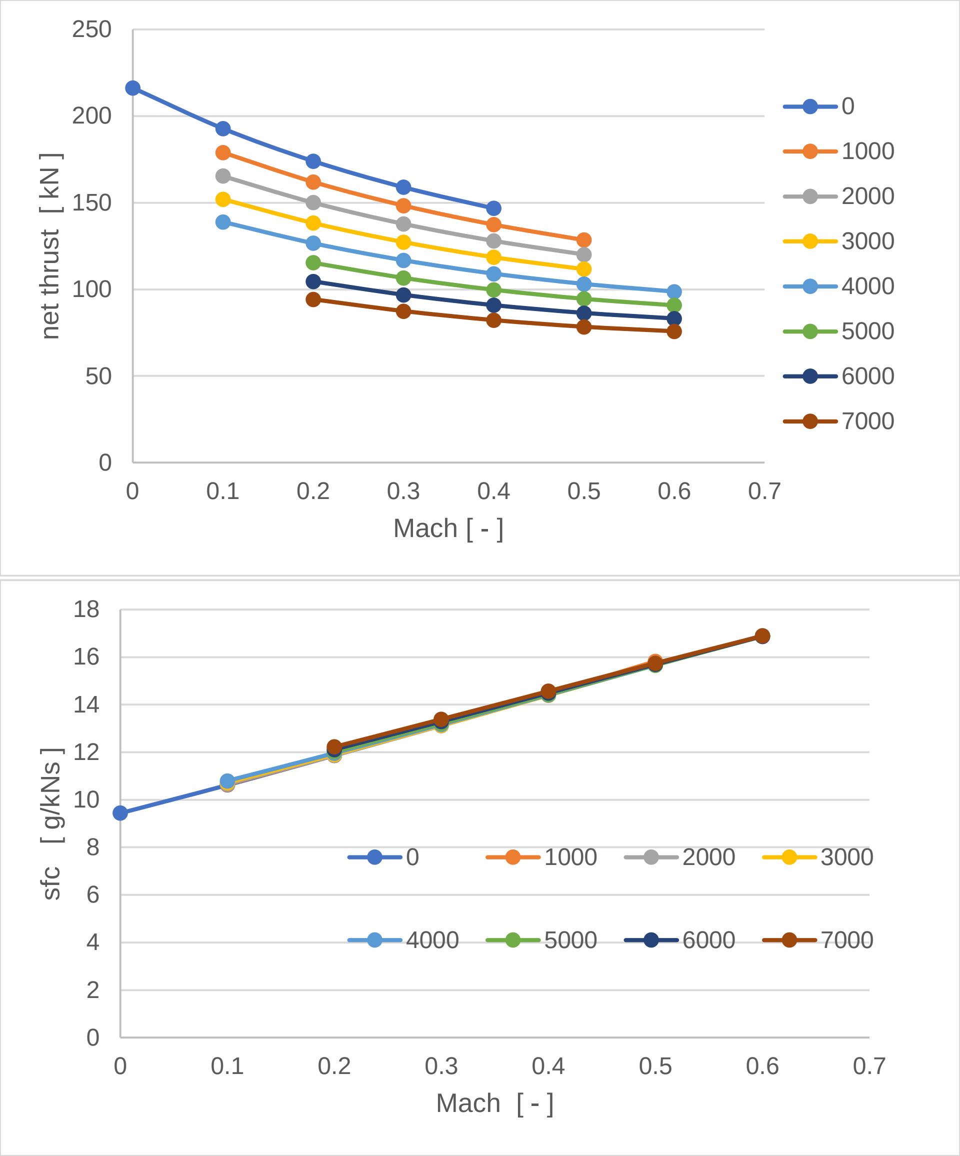


Figure 26: Net Thrust per Engine and Specific Fuel consumption of Rolls-Royce Trent 500 engines varied with Mach no. and Altitude (Generated using GasTurb)

Formation flight to pull-up maneuver requires a change of aircraft configuration, which is expected to change the dynamics of the system drastically. Therefore, to get a more realistic picture, the trajectory simulation was divided into different phases:

- **Phase 0** [10 s]: Here, the aircraft retracts its landing gear and spoilers, reducing drag considerably and enabling the aircraft to reach high L/D ratios. This is represented through a linear transition of aerodynamic datasets from Formation Flight Configuration to Pull-Up Configuration.
- **Phase 1** [10 s]: Next the aircraft must throttle up from 0% to defined throttle value up to 100%. The turbojet propulsion model is turned on, and can vary between idle thrust (10% throttle) until full-thrust (100% throttle).

- **Phase 2**: This phase constitutes the controlled flight wherein the mated configuration pulls up or climbs from a descending flight to a positive FPA based on the target altitude.
- **Phase 3**: Lastly, the altitude hold control or cruise control is performed. This phase continues to the tow-back phase until the landing site is reached.

Figure 27 shows the preliminary trajectory simulations of the pull-up maneuver with indication of different phases. It can be seen that the configuration is able to pull-up at a safe altitude of about 4500 m. This was already possible with a constant 60% throttle setting (by linear scaling from data in Figure 26) during the climb phase. Larger throttle can be considered during the climb to achieve higher cruise altitudes. Next iterations would involve inclusion of adaptive throttle control for efficient fuel consumption while reaching the optimal cruise altitude. An updated and more accurate aerodynamic dataset will also be included in the future simulations.

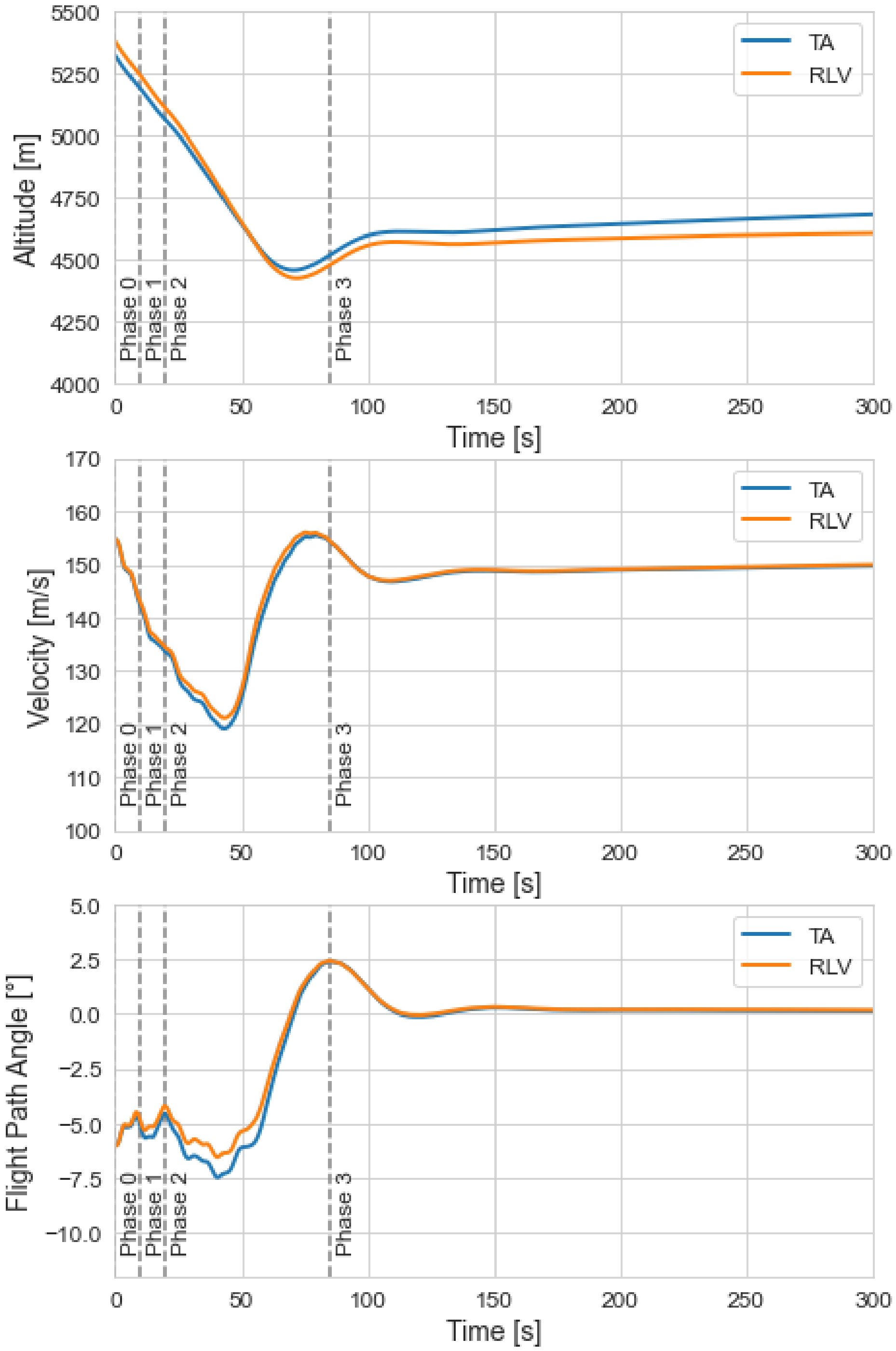


Figure 27: Pull-Up Maneuver with Constant Thrust (indicating different phases)

4.2 Potential capturing hardware

4.2.1 Conceptual lay-out

The most promising capturing technique is using an aerodynamically controlled capturing device (ACCD), showing the best performance and lowest risk [8] [17]. The ACCD is to be released and then towed by the airplane. This device (shown in Figure 28 and Figure 29) contains the connecting mechanism and simply advances the stage by its own drag and lift. It is 2 m long with a cross-sectional diameter of 1.5 m including the fins. The four flaps, which can deflect up to a maximum of ±15° provide 6DOF agility and control. The nose of the ACCD is attached to the TA via rope and the capturing mechanism at the back of the ACCD secures the connection with the RLV.

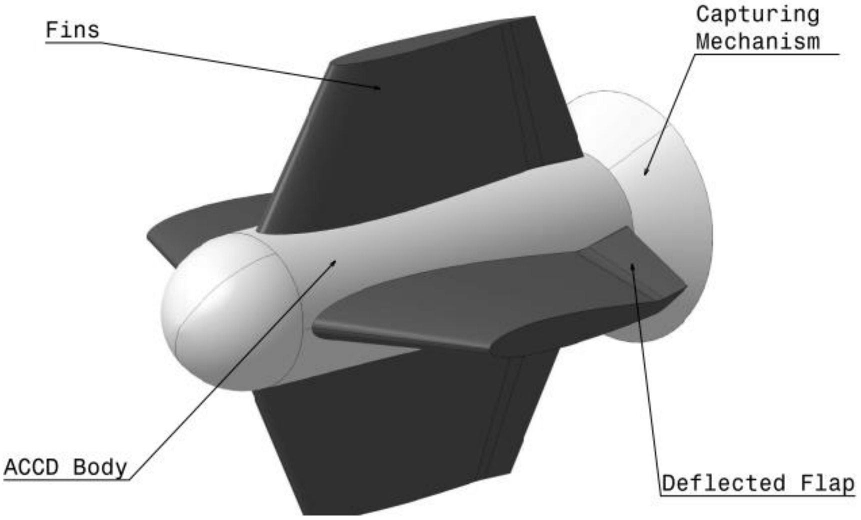


Figure 28: ACCD Geometry with Four Symmetric Fins

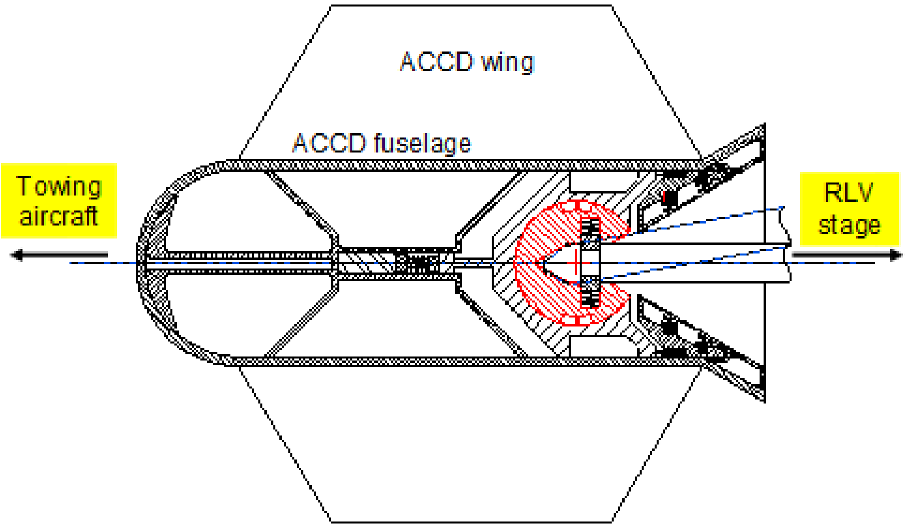


Figure 29:Sketch of the capturing mechanism inside the ACCD geometry highlighting the ball-shaped head in red and the RLV stage anchor shown in parallel and deflected position [6]

The capturing mechanism inside the ACCD is a critical part which has been preliminarily designed for the static load conditions encountered when capturing and towing a large fictive RLV stage. The mechanism lay-out has to be defined for correct kinematic functioning in capturing-, towing-, and release-mode, as well as for good shock attenuation.

A preliminary design of such a capturing mechanism has been developed (see first design iteration in Figure 29) and has been subsequently mechanically sized supported by Finite-Element stress and deformation analyses [6]. All elements of the mechanism fit into the ACCD fuselage and consist of:

- a ball-shaped head with ball jacket,

- industrial shock-absorber,
- different spring and damping elements, and
- additional support structure.

The principal idea of the mechanism is to direct a long passive anchoring device from the RLV to the capturing- and hold mechanism inside the ACCD. A funnel like opening at the ACCD's back with a 30° cone opening allows for the mechanically steered guidance in case of small flight position imperfections prior to connection and for the required axial deflection between both flying items in the capturing procedure and thereafter, in towing flight. Inside the ACCD, all axial loads as well as the relative pitch and yaw movements between the different flight vehicles are transferred through a ball joint to its jacket capable of axially gliding inside the ACCD fuselage. Relatively high local pressures between the ball and the jacket will require also a good lubrication between those two metallic parts.

The connecting shock between both vehicles is transferred in the ACCD's forward direction to an industrial shock absorber (in the center of Figure 30). Such a device allows for a constant deceleration with a moderate axial force and rapid oscillation damping.

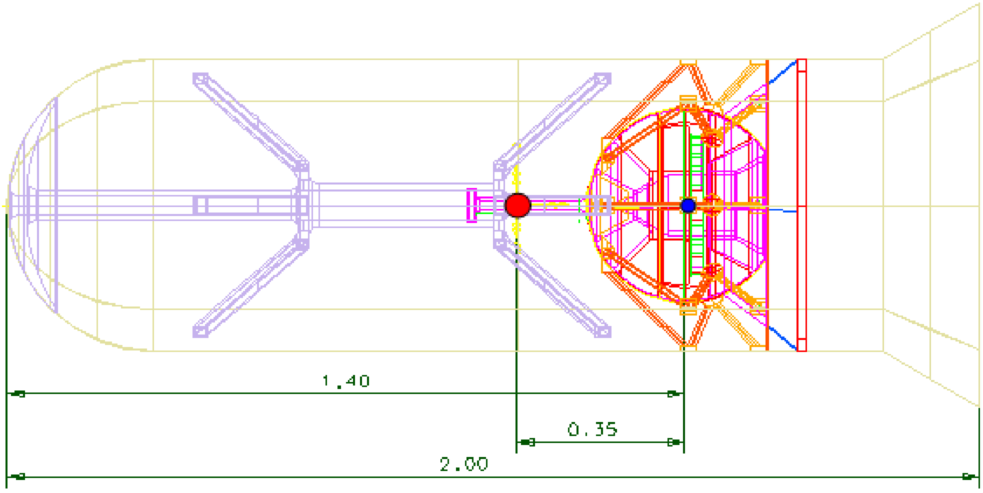


Figure 30: Design drawing of optimized capturing mechanism inside the ACCD geometry with major dimensions in [m] [6]

Figure 31 shows how roll, pitch and yaw deflections are realized using the four flaps. For pitch, both horizontal flaps deflect in the same direction. For yaw, both the vertical flaps are deflected in the same direction. And for roll, all flaps are deflected. These symmetric configurations of flap deflections up to 10° for pitch, yaw and roll motion were simulated using CFD for the range of ±15° AoA to get a better understanding of its aerodynamic performance and stability characteristics. The simulation specifications and detailed analysis of the aerodynamic characteristics can be found in [39],[43].

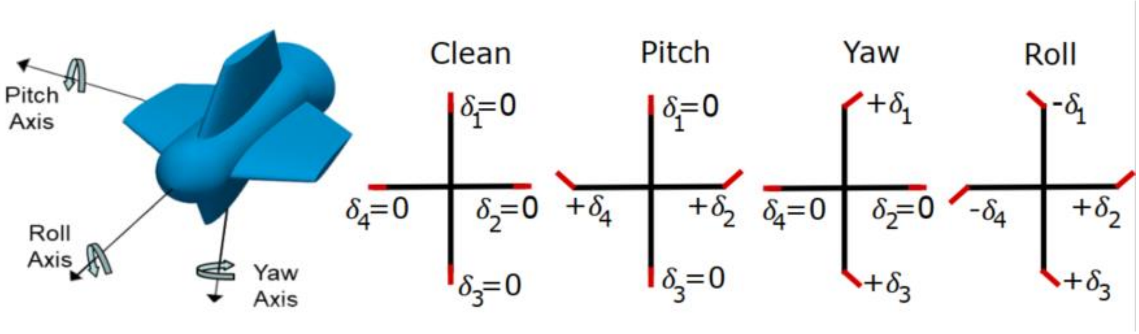


Figure 31: Conventions for ACCD Flap Deflections and Resulting Moments

4.2.2 Aerodynamic Performance and Stability

A critical review of the preliminary ACCD design has been performed to identify potential design improvement, and satisfy the requirements for aerodynamic performance and stability. The ACCD aerodynamic performance during pitch maneuvers is presented in Figure 32. The efficiency curves shown in Figure 32 (Left), defined by the ratio of lift and drag coefficients, reach an absolute maximum of approximately 2 at an AoA of 15°, independent of the flap deflection. Above this AoA, a drop in the efficiency, due to the big increase in the CD (while the CL grows linearly), is observed for the base condition (no flap deflection). As it can be seen in Figure 32 (Right), the slopes of the pitch moment coefficients are negative. This indicates that the selected Center of Gravity (CoG) located 0.6 m from the nose gives a stable ACCD configuration. The negative slope of the pitch moment coefficient indicates static stability such that, if AoA increases, the pitch moment brings back the device to equilibrium.

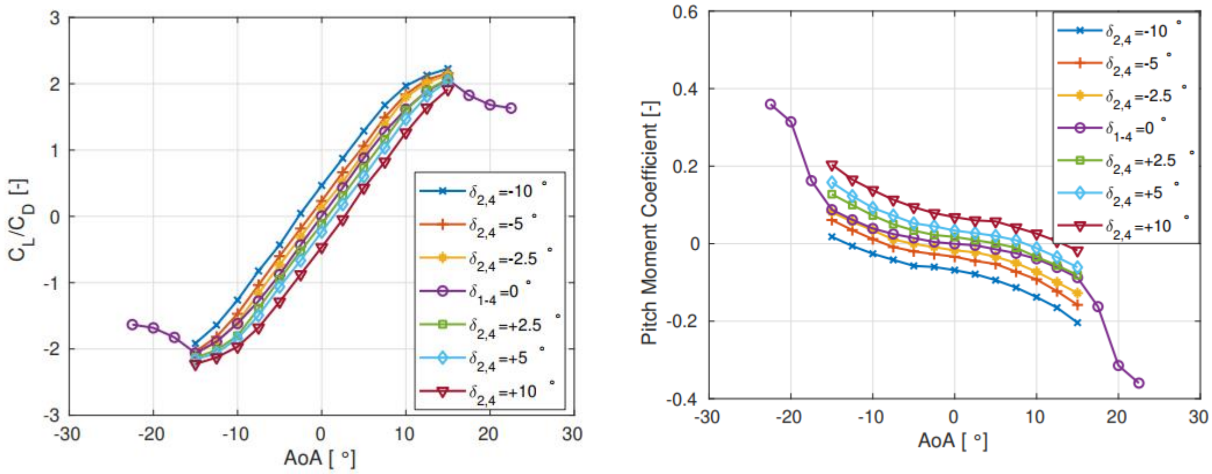


Figure 32: Lift-to-Drag Ratio (Left) and Pitch Moment Coefficient for CoG = 0.6 m

4.3 Towing airplane requirements

Technical requirements of the tow-aircraft are given in [17]. The rope and its mechanism have to be designed to withstand the pulling stress with regard to dynamic loads. The maximum values are most likely being reached during pull-up of the assembly after capturing. A towing rope diameter of 1.6 cm is estimated to be sufficient for up to 200 kN load [17].

The thrust requirements of the capturing aircraft are dependent on the reusable stage's mass and its L/D-ratio. The thrust reserve of the capturing aircraft has to exceed 50 to 200 kN (equivalent to approximately 25 to 80 tons of to be towed stage mass) in an adequate flight altitude [17]. A four-engine jetliner without normal cargo loading offers sufficient thrust margins. This is corresponding to an Airbus A-340 or Boeing-747-class jet, which have been produced in large numbers. Moreover, a considerable quantity of these airplanes is available at an affordable price, since significant numbers have been retired from commercial airline service (see section 3.3.2.1).

A catastrophic mid-air collision has to be avoided by fully automatic and redundant control avionics of both vehicles operating in a synchronized mode. Any pilot interference in this maneuver from the capturing aircraft would be far too slow, to have a positive impact. Since no real demanding pilot work is foreseeable, it has been seriously considered previously redesigning the capturing and towing aircraft as an unmanned aerial vehicle. By giving up on board pilot control for all capturing missions, it might be also possible to broaden the flight envelope, which will not be acceptable with men on board. This further enables high risk maneuvers – if ever required - which are otherwise excluded and would result in the loss of the returning stage. Hence it has been believed, an unmanned towing aircraft would augment overall reliability and safety of the In-Air-Capturing method. The certification process of the large unmanned vehicles is to be addressed early in the design phase. As the full capturing mission is to be performed exclusively over uninhabited areas off-shore of a launch site, the required certification is currently not assessed as a blocking point.

However, the latest refined simulations (sections 4.1.1 and 4.1.2) and consultation with a senior expert at Airbus flight testing in Toulouse (see following section 6.4.6!) indicate that a complete unmanned operation is neither necessary nor attractive. From a technical perspective a purely unmanned operation could be realized on the A340 but would raise severe cyber-security requirements. In any case, the actual approach and capturing maneuver should be run fully automatic. Nevertheless, on-board human intervention would still be possible in case of abort and in other less time-critical flight phases.

DLR performed a preliminary technical feasibility assessment of the airliner's towing performance [24] under static conditions. To ensure that the aircraft and stage could operate in the towing configuration, the flight envelope was computed as an example for a A340-600 with four Rolls-Royce Trent 556 turbofans connected to a generic winged RLV stage of approximately 50 tons return mass. As can be seen in Figure 33, the towing operating point (TOW_{ref}) is well within the limiting speeds. Performance speeds of an RLV-stage and the Boeing 747-400 as an alternative tow plane are quite similar as described in references [3][7]. The relatively high towing altitude and cruise speeds are due to the generous margins of this calculated aircraft-RLV-combination. A check on the towing aircraft robustness concerning a heavier RLV with lower maximum trimmed L/D confirmed suitability of the A340-600 resulting in a slightly reduced flying envelope with lower maximum ceiling [24].

Results from a first set of dynamic simulations of the pull-up maneuver (section 4.1.2) confirm the towing aircraft's envelope assessment.

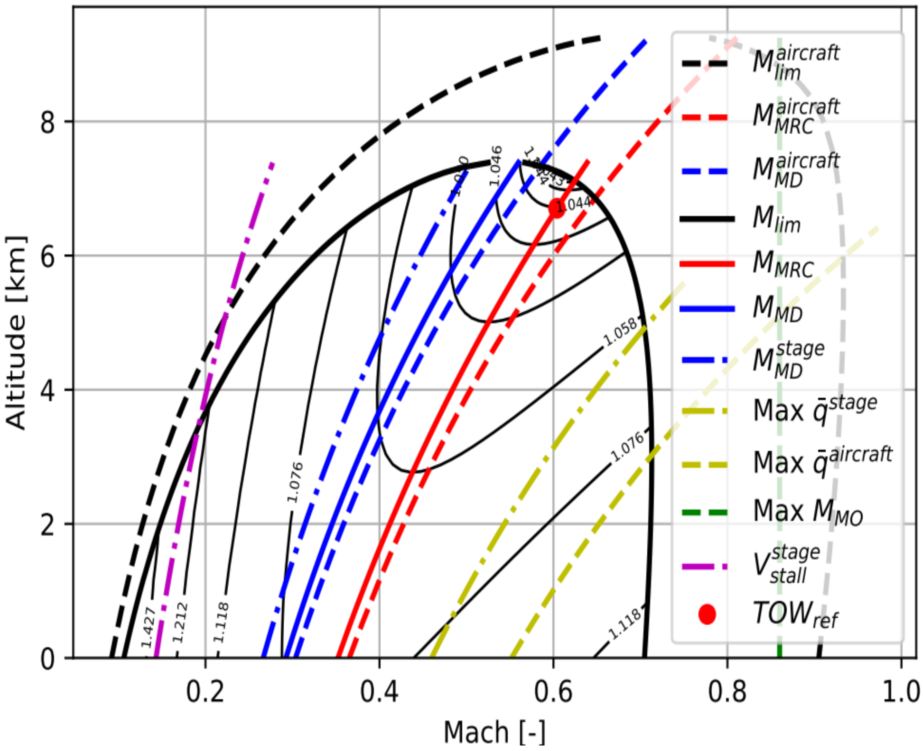


Figure 33: Calculated flight envelope for A340-600 and typical RLV-first stage towing configuration

4.4 "In-Air-Capturing" procedure high-level requirements

Based on the previous descriptions of already performed analyses (see sections 3.1, 3.3, 4.1, 4.2, 4.3) on the "In-Air-Capturing" (IAC)-procedure, the following high level requirements can be derived which should guide the technology development:

- **R1:** capturing of winged RLV-stages in subsonic flight in altitudes below 10000 m in areas down-range of the launch site
- **R2:** subsequently towing of winged RLV-stages in subsonic flight back to a release area close to the launch site
- **R3:** cost efficient operations making use of modified, existing, subsonic aircraft capable of towing the winged RLV-stage
- **R4:** safe operations of IAC with capturing success-rate > 99.9% (tbc) with minimum environmental impact and risk of third-party damage less than nominal space launcher operation

4.5 Status lab-scale flight demonstrations

4.5.1 Work prior to FALCon project

DLR in its internal project AKIRA has started lab-scale flight experiments aiming for a TRL between 3 and 4. One of the key-tasks was the development of a functional coupling device for the lab-scale flight experiments. Besides the already previously defined ACCD (see section 4.2), the original idea is derived of an air-to-air-refueling drogue or aerodynamic trailing cone [8]. A cone instead of a strut construction allows even lower weight for the small-scale ACD. The simple cone has been equipped with control surfaces to enable active control of the ACD along two axes.

For its basic functionality, the subscale coupling device (Figure 34) consists of a cone, ensuring the stable flight behavior by its own drag and four control surfaces, which deflect for roll, vertical and horizontal movements. The main components are:

- center body with avionics, servo motor support and coupling to the towing rope
- adapter from center body to the cone
- cone
- control surfaces including adapter plates to servo motors

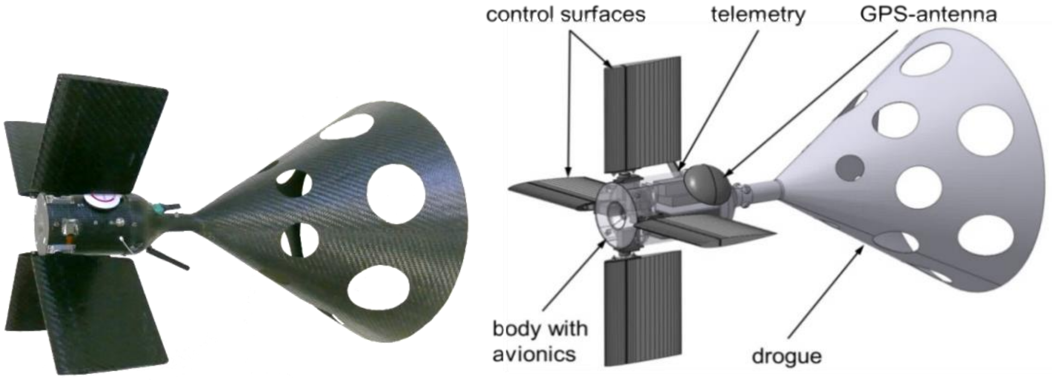


Figure 34: ACD prototype device and drawing showing major subcomponents [8]

Early tow-tests of the ACD attached to a moving ground vehicle have been used for first verification of ACD flight behavior and roll stabilization. During the flight tests, the in-flight behavior at higher speeds over a longer period of time was evaluated. The flights were performed at speeds of about 120 km/h and with a rope length of 30 m. The MAL UAV of DLR was used as the towing aircraft and the autopilot automatically flew waypoint missions in addition to its remote-control connection [8].

The determination of the achievable vertical movement of the ACD was performed during the flight tests. An example of the data from these tests is shown in Figure 35.The upper graph of Figure 35 compares the towing aircraft altitude (h_{MAL}) and the altitude of the ACD (h_{ACD}). It can be observed that the ACD follows the MAL with a deviation in altitude of around ±3 m until the time t = 510 s, when the controller is activated. This is also observed in the middle graph, which shows the altitude deviation between MAL and ACD ($h_{MAL}-h_{ACD}$). From t = 510 s the horizontally oriented control surfaces are manually deflected upwards and downwards, shown as remote-control vertical input (RVIN) in the middle graph of Figure 35.

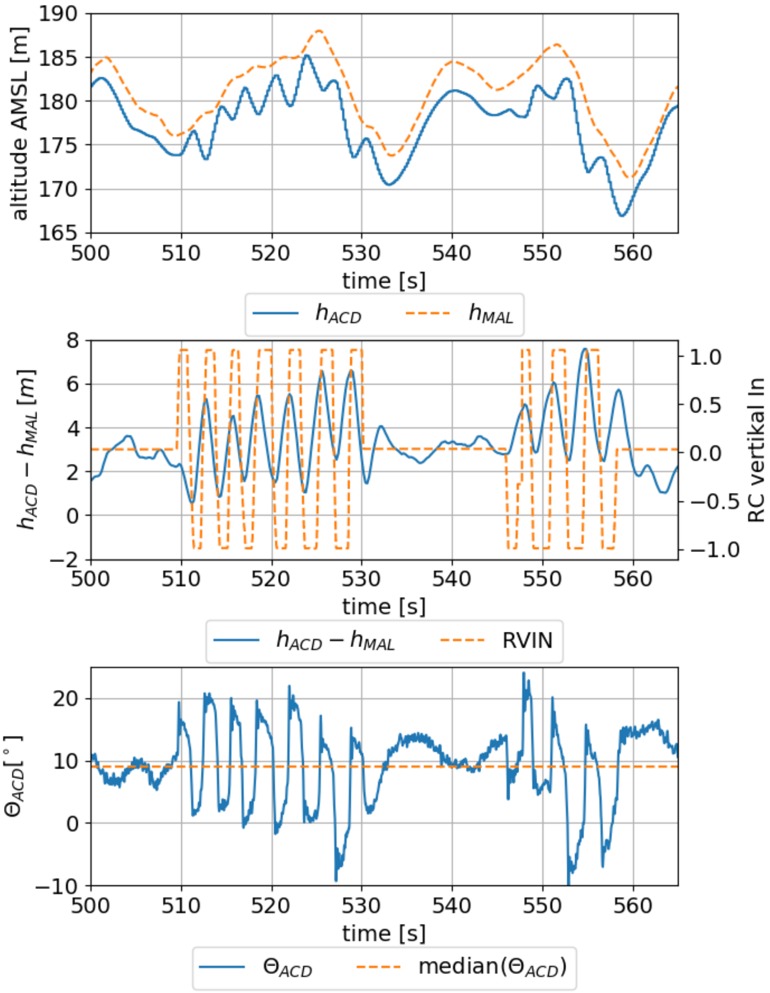


Figure 35: Altitude, altitude offset, and pitch angle during vertical motion [8]

The main result of the flight tests for the vertical movement is the fact that the vertical displacement with respect to the towing aircraft position can be kept within +/-3 m in the expected range and allows compensation of position offsets to the client. The attitude of the coupling unit is not constant during the movements. As the cone of the configuration compensates the changes in pitch, problems for the capturing maneuver are not expected. By changing the position of the control surfaces relative to the rope attachment point, a reduction of these pitch attitude changes might be achieved [8].

Flight testing in AKIRA has proven the ACD provides the necessary capacity to carry all avionic equipment and perform automatically controlled maneuvers. The toolchain for the integration of auto-generated code for the controller from a model-based design into the basic framework provides an effective method for the implementation of different controllers to carry out the coupling maneuver. [8]

During the flight test, a first approximation of the possible displacements from the equilibrium state was determined. The implemented roll stabilization acts as a crucial basis for well-directed movements. The control capability around the longitudinal axis meets the requirement, since the simple controller is able to achieve the target roll angle with sufficient precision even in the presence of large disturbances. The displacements were found at 2.5 – 3 m in each orthogonal direction, which allows for an active placement in an approximately 6 m x 6 m field. [8]

Establishing connection between the RLV-stage and the large carrier aircraft requires formation flight of both vehicles during the approach maneuver. In AKIRA the definition of formation flight for two unmanned aerial vehicles is established, which represents sufficiently accurate the in-air capturing (IAC) scenario. Formation flights in AKIRA have actually been performed using two very lightweight test vehicles, the Ranger EX with takeoff masses at <3 kg to keep the risk and effort at a minimum (Figure 36). These planes are nevertheless fully equipped to perform automatic missions and capture video data. Experiments with such a communication established have been completed and the evaluation showed good reproducibility and stable formation flight up to 60 s with controlled distances between 10 m and 40 m. [8]

Figure 36: Ranger EX vehicles for automated formation flight testing

In summary, a command concept has been established, modification of COTS auto pilots was performed, and both communication and safety concept were implemented. Available results demonstrate the reliability of the concepts and their implementations in the flight tests. [8]

A vision-based detection of the coupling unit with respect to the RLV-stage demonstrator has been investigated. Such a concept has the task of detecting and tracking the relative position deviation between RLV-demonstrator and coupling unit. Different sensors have to adapt to several environment situations like “over-/ underexposure”, relative and absolute measurements with detection required at visual and near infrared spectrum. After processing the video data, it can be stated that the 2D tracking works well while size estimation for 3D estimation of the exact object’s position is not yet sufficient. [8]

4.5.2 Work within FALCon project

Within FALCon, the goal for flight testing is the successful demonstration of formation flight with UAVs at conditions derived from the full-scale scenario. These conditions are summarized in the FALCon project deliverable D2.3 [19]. The goals are extended with respect to the flight-testing goals from the AKIRA project:

- Altitude: Up to 2000 m
- Velocity: ~ 150 km/h
- Glide Angle (Flight Path Angle): -10°
- Connection between nose boom and ACCD for more than 1 second
- Autonomous, BVLOS (Beyond Visual Line-Of-Sight) operating UAVs

In order to meet those requirements, the UAVs representing the towing aircraft and the RLVD were modified and even specifically designed for this task.

The towing aircraft demonstrator is the APUS aircraft shown in Figure 37, which was built and is operated by the DLR UAV apartment ULF in Braunschweig. The APUS aircraft was specifically modified for the FALCon project. It is propelled by a combustion engine which allows the vehicle to achieve velocities of up to 180 km/h. The control and avionics systems are capable of allowing autonomous flight and control of the different mission sections within the IAC subscale flight testing, but can also be remote-controlled by a safety pilot for take-off and landing. The MTOW is around 30 kg [44].

Figure 37: APUS tow aircraft demonstrator (TAD)

As coupling unit, which is towed by the APUS aircraft, an updated version of the AKIRA coupling unit is used. Some upgrades include newer and smaller avionics and an updated controller toolchain.

A major progress in the FALCon project was the development and construction of the RLV-demonstrator or RLVD. This task was done by EMBENTION in Spain. The airframe was based on the Rapier flight model and was custom-built for the FALCon project. The vehicle is equipped with as modified nose as shown in Figure 38 that contains a sensorhead necessary to allow the environment detection and formation flight holding during the final flight tests. As propulsion system, a turbine engine is used which is active during take-off, climbing, loitering and return. During the actual formation flight dive and holding procedure, the engine will be turned off in order for the RLVD to act as a glider. The Lift-to-Drag Ratio can be modified to better represent the aerodynamic qualities of a full-scale RLV. For the formation flight, a L/D of 6 can be achieved by extending additional spoilers to increase the drag of the system. The MTOW of the RLVD is around 75 kg.

Figure 38: RLV demonstrator (RLVD)

5 Technical demonstration needs and current status

5.1 Technology Readiness Level (TRL) and Integration Readiness Level (IRL)

Talking about technology and its development needs requires a reliable metric to establish a common understanding. The Technology Readiness Level (TRL) is a well-known and well-established indicator of the readiness of certain technology elements to reach operational status. The definition of the different TRLs according to NASA is presented in Figure 39. The definition of the European Commission is very similar [30]. Note that the section relevant to research projects like FALCon is TRL 1 to 5 reaching from Basic Technology Research up to Technology Development. This section is highlighted by the red box in Figure 39.

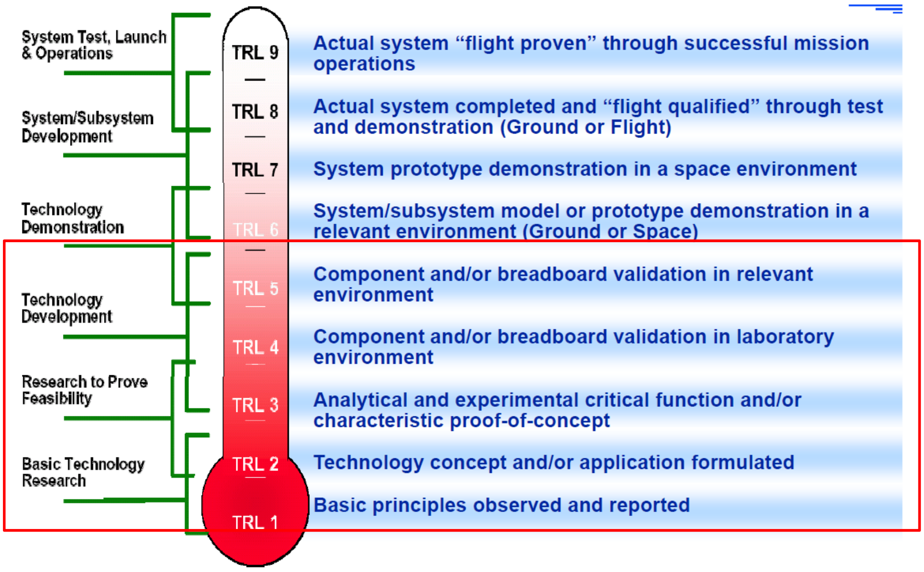


Figure 39: Technology Readiness Level (TRL) according to NASA

The TRL indicator is applied in the following two sections describing first the technology development and demonstration needs (section 5.3) addressing all relevant technological and operational fields and afterwards the "In-Air-Capturing"-technology demonstration status before and within the FALCon-project (section 5.4).

TRL is used for the evaluation of all sub-technologies and for the "In-Air-Capturing"-technology itself. Obviously, "In-Air-Capturing" as a technology is combining several sub-technologies in a complex system which makes the Integration Readiness Level (IRL) another indicator suitable for the assessment. The relationship between IRL and TRL as defined by NASA is shown in Figure 40.

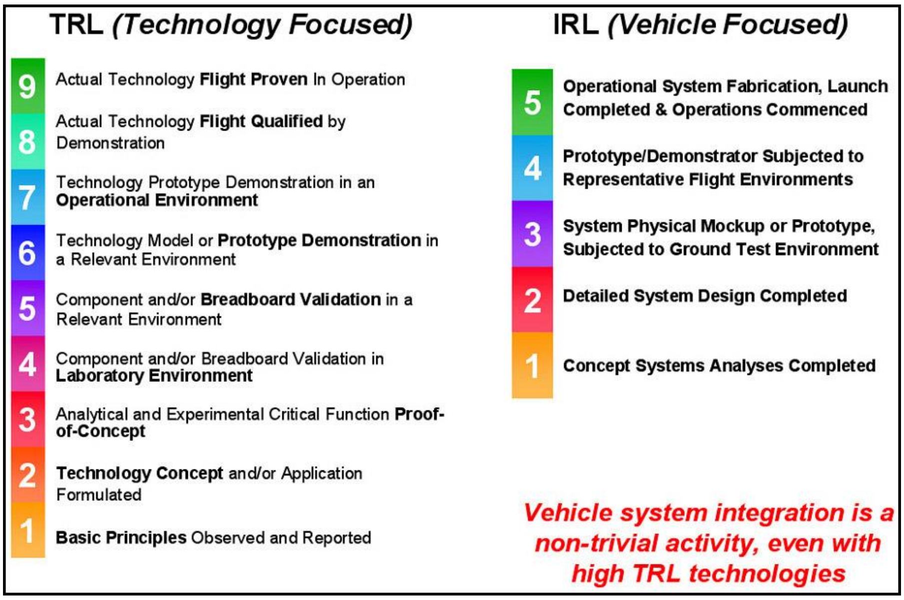


Figure 40: Technical and Integration Readiness Level Definitions according to NASA [31]

5.2 Phased Development Approach (PDA) of NASA

Although, the TRL-/IRL-approach is helpful, it has been found not necessarily sufficient for successful development of RLV. Therefore, a NASA-led working group has proposed a “Phased Development Approach (PDA) using Integration Readiness Levels (IRLs) to facilitate selection, sequencing and staging of flight test demonstrations to reduce the risks inherent in technology development.” [31] Exactly this methodology is implemented in FALCon for the establishment of the “In-Air-Capturing” roadmap.

The NASA PDA model [31] has four key steps, or phases. Phase 1 is the basic laboratory research and testing of concepts and component technologies. Phase 2 involves selected flight or ground demonstrations focusing on the tested technologies. Phase 3 combines the component technologies into a system demonstration vehicle to test the integration of the components. Phase 4 is the final development of a new operational vehicle based on the proven technologies and system demonstrations (Figure 41).

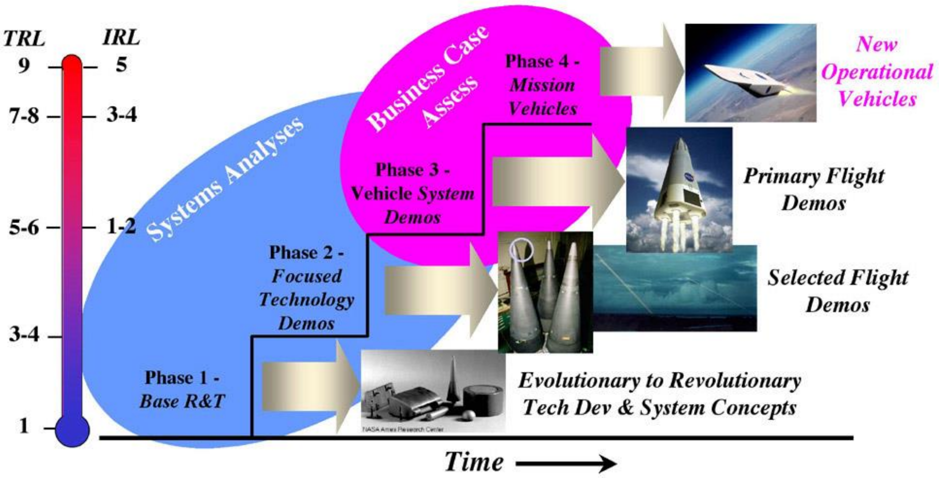


Figure 41: Phased Development Approach (PDA) for technology maturation according to NASA [31]

The PDA model uses both the standard Technical Readiness Level (TRL) and the Integration Readiness Level (IRL), defined in Figure 40, to gauge the maturity of technology components and the vehicle system integration. Figure 42 shows the relationship between TRL and IRL. These measures are used by the NASA-led working group to help establish the appropriate phase and activities for each development step.

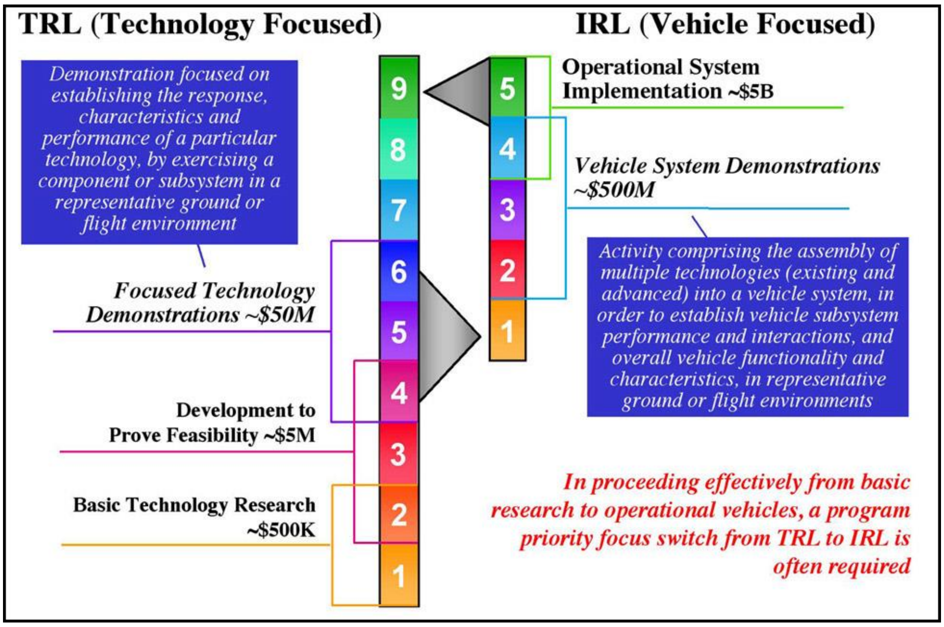


Figure 42: Relationship between Technical and Integration Readiness Levels according to NASA [31]

Activities in FALCon to maturase the “In-Air-Capturing”-method are in the TRL range 3 to 4 called in Figure 42 “*Development to Prove Feasibility*” and exactly at the point where the IRL activities are to be initiated.

The NASA report [31] states, IRL assessment was introduced to measure a technology’s system-integration readiness for a given application in much the same way TRL assessment measures the readiness of individual technology components. IRL assessment has been used in commercial industry for modular software development to ensure that programs and systems operate as intended when new versions are compiled. Although the concept of integration readiness has been applied in past development programs, this PDA model is the first formal application of IRL assessment in hardware development [31].

Further, it is interesting to see in Figure 42 an order of magnitude cost assessment in $US for the sub-sequent development steps or phases. Technology demonstrations are evaluated by [31] to be much less expensive than system demonstrations because the flight tests can often be flown on proven vehicles, greatly reducing the risk of flight failure. This is explained by the situation that the risks associated with the low TRL of the demonstration technologies are mitigated by the high IRL of the host system. Note, the 5 M$US associated to the Technology Demonstrations in Figure 42 exceed the funding of the FALCon-project. However, parts of the “In-Air-Capturing” technology have already previously been investigated and matured by internal DLR-funding as the AKIRA-project and others (see [8] for a more detailed list of these activities). Therefore, the cost assessment given in Figure 42 roughly fits with the actual spending for IAC in Europe up to TRL 4 - 5.

5.3 Technology development and demonstration needs

As an aerospace system, the following technology areas are of potential relevance in the development and demonstration of the “In-Air-Capturing”-technology for the recovery of winged RLV-stages:

- Aerodynamics
- Structure & Mechanical Systems
- Propulsion
- GNC
- Software, IT, communication
- Electrical system

An operational system would have a potential impact on the following areas:

- Operations in flight & on ground
- Certification & Qualification
- Manufacturing
- Safety and legal issues
- Environmental issues
- Economics

5.3.1 Technology domain

As described in sections 4.1 to 4.3, three aerospace vehicles are planned to be used in the IAC procedure:

- winged RLV stage,
- towing aircraft and
- a capturing device or ACCD (see section 4.2)

Each of these vehicles might require new and innovative technologies but, in many cases, existing, off-the-shelf components and technology are probably fully sufficient. This will be outlined in more detail for each technology field and vehicle. However, even if many components and hardware already exist, the successful interaction and interconnection of all these components in a new application with time-and safety-critical operations raises some developmental challenges. Therefore, this aspect is explicitly included in the following list for each technology area:

- Aerodynamics
  - RLV stage: winged vehicle, fully controllable by aerodynamic means with subsonic maximum L/D > 5 – state-of-the-art technology but challenge comes from integration

  into launch vehicle with flight envelope spanning huge Mach number range and contradictory requirements in the different flight regimes. Speed brakes for controlling drag which are almost neutral to lift and moment coefficients are useful for fast approach and connecting maneuver.
  - Towing aircraft: fully controllable in mode of degraded aerodynamic performance in diving flight – state-of-the-art technology but such operation mode should be realized by minimum modification of existing airliners.
  - Capturing device ACCD: highly agile system, fully controllable by aerodynamic means – state-of-the-art technology to be implemented in newly designed vehicle. Aeroelastic issues, if any, are to be investigated.
  - Interaction & Interconnection: significant flow-field interaction to be expected with some vehicles closely following others while flying in their aerodynamic wake
- Structure & Mechanical Systems
  - RLV stage: connecting port – state-of-the-art technology to be implemented in newly designed vehicle.
  - Towing aircraft: load introduction in towing operations – state-of-the-art technology but such operation mode should be realized by minimum modification of existing airliners.
  - Capturing device ACCD: light-weight structural mechanism which allows shock attenuation during coupling, damped 3DOF movement of coupling device in towing mode and adequate load transmission with structural dynamic damping in towing mode. In principal state-of-the-art technology to be integrated in a suitable design; preliminary concept shown in Figure 28 and Figure 29 from [8].
  - Interaction & Interconnection: controlled structural dynamics of towing rope in all relevant flight conditions.
- Propulsion
  - RLV stage: nothing related to the IAC-process
  - Towing aircraft: existing, off-the-shelf turbofan engines might see extended operations at full-thrust level. However, such technology is only required in those cases when the towing aircraft has insufficient thrust margins, which in many cases can easily be addressed by selecting larger aircraft. New, improved turbine technology with extended lifetime at elevated TET might only be required for very large booster stages with poor subsonic trimmed L/D.
  - Capturing device ACCD: no propulsion system foreseen in current design proposal and due to its already high aerodynamic agility it seems unlikely that any propulsion will be needed for the device.
  - Interaction & Interconnection: -
- GNC
  - RLV stage: specifics related to the IAC-process are controlled and sufficiently precise approach maneuver in perturbed, turbulent flow conditions (relative deviations < 1 m, < 5 m/s TBC), requiring adequate sensor package, interlink communication and adequate on-board computing capabilities.
  - Towing aircraft: existing on-board GNC to be modified and adapted to IAC capturing and towing operations. Autonomous unmanned operations of towing aircraft in restricted airspaces over uninhabited areas was intended baseline, however, is now under reconsideration if actually needed and beneficial. Flight guidance is to be based on 4D-prediction and 4D-precision including time synchronization with other vehicles.
  - Capturing device ACCD: fully controlled and sufficiently precise approach maneuver in perturbed, turbulent flow conditions (relative deviations < 1 m, < 5 m/s TBC), requiring adequate sensor package in all-weather day- and night conditions, interlink communication and adequate on-board computing capabilities.
  - Interaction & Interconnection: the IAC-process is highly interconnected between the three vehicles. In towing mode operation interconnected control processes might be needed for adequate damping of dynamic loads.
- Software, IT, communication
  - RLV stage: nothing specific related to the IAC-process which is not part of GNC-section. Maximum autonomy on ground for taxiing with remaining kinetic energy aspired.
  - Towing aircraft: redundant satellite data link with sufficiently high bandwidth aspired – state-of-the-art technology.
  - Capturing device ACCD: multiple sensor data (e.g. visual, radar, IR, DGPS, IMU) to be adequately fused for accurate positioning in the IAC-process; connected to GNC-section.

  - Interaction & Interconnection: fully autonomous, artificial neural network (ai) software might be of interest
- Electrical system
  - RLV stage: nothing related to the IAC-process.
  - Towing aircraft: probably no modifications on the aircraft needed for the capturing and towing mode.
  - Capturing device ACCD: likely battery-powered during IAC-process – state-of-the-art technology.
  - Interaction & Interconnection: -

In summary the maturation and development efforts are evaluated and current TRL is preliminarily quantified for the following technology areas:

- Aerodynamics: some development effort required but overall state-of-the-art technology and no technology maturing necessary. (current TRL: 6)
- Structure & Mechanical Systems: some development effort (mostly for ACCD mechanisms) required but overall state-of-the-art technology and no technology maturing necessary. (current TRL: 6)
- Propulsion: almost no development required for IAC procedure. (current TRL: 8 or 9 for aircraft propulsion, else N/A)
- GNC: major development effort required and some technologies beyond state-of-the-art with maturation process necessary, especially in automation of formation flight in turbulent flow conditions and all kinds of vehicles interaction. (current TRL: 3, see section 5.4)
- Software, IT, communication: some development effort required but overall state-of-the-art technology and no technology maturing necessary. (current TRL: 4)
- Electrical system: little development effort required but nothing beyond state-of-the-art technology necessary. (current TRL: 6)

5.3.2 Integration Readiness Level (IRL)

Many aspects to be addressed in the IAC development are more system integration related than technology development related. Thus, the Integration Readiness Level (IRL) of “In-Air-Capturing” is to be addressed and its status to be evaluated.

Fully in-line with the relationship between TRL and IRL as shown in Figure 42, the IRL of IAC currently hardly has reached level 1. Concept system analyses including functional simulations were run in the past (see sections 4.1 through 4.3) all based on strongly simplified and mostly generic models. In the FALCon-project the system analyses will be significantly refined with elaborate models used for the simulations of the full-scale capturing- and towing-process. These simulations will allow for a better definition of the operational domain and define the technology and subsystem requirements. At the end of FALCon an IRL of 1 might be approached.

5.3.3 Operational domain

5.3.3.1 Operations in flight & on ground

An operational concept of the “In-Air-Capturing” procedure has been established and was presented in Figure 8 showing the typical flight mission profile. A detailed breakdown is provided in reference [7]. Note that the nominal mission should be operated only in restricted airspaces also used by the launcher during its orbital ascent mission. Nevertheless, the capturing, towing, and subsequent release and landing approach of the RLV-stage and its airliner are all happening below 65000 feet altitude and thus are subject to Air Traffic Management (ATM).

Both flying vehicles could operate as Unmanned Aerial Vehicles (UAV) with controller crews in continuous supervision of the process from the ground control center (IAC-GCC). This center might be collocated with the launch control center as similar communication and safety infrastructure will be required. Other locations are possible and might be attractive from a cost perspective if operational synergies could be realized. Similar control centers already exist for long-range military UAV and are operational since decades in the US and other countries. Adequate operations procedures will have to be defined without the need for inventing fundamentally new processes.

A single runway of sufficient length and width will be required being capable of safely operating wide-body airliners. The winged RLV stage is to be designed for landing on such a runway which is a state-of-the-art development process. As the towing airplane has sufficient cruise and loitering margin, the

RLV is released first for a gliding approach and landing. The rocket stage will be required to automatically roll in a parking bay on the taxi-way without additional propulsion (tbc) and remain there in safe mode. The capturing airliner subsequently performs its automatic landing on the runway and taxis itself to its maintenance and parking area (tbc). The RLV is to be towed on ground to its refurbishment facility where the preparation for the next launch mission is to be performed. The latter operational step is already out of the IAC-procedures.

The unmanned operation of two large aircraft in flight and in relative proximity to each other is the major innovation and potentially operational challenge. The question if such completely unmanned operation of the towing aircraft is really desirable has been raised within FALCon-project activities. Such potential on-board human intervention would simplify the flight operations procedures and is under consideration. The landing approach and all ground operations after landing are standard businesses well known from aviation.

5.3.3.2 Certification & Qualification

All rocket type launchers are to be qualified before first flight according to the reliability requirements of the operator and the range safety rules of the launch site. A launcher qualification review is part of the qualification process and has been successfully used since the dawn of spaceflight. The few RLVs already developed and being operational were all following this philosophy.

This approach of today's launcher qualification is very much different to aircraft certification process. The latter is much more demanding and in case applied to the launch of large-size orbital space transportation would become excessively expensive. Therefore, it is unlikely that certification will be applied to launching rockets. The return and recovery are different issues. The return of Falcon9 booster stages is nevertheless not requiring any certification. However, the FAA issues now a policy approval to an RLV mission license applicant upon completion of a favorable policy review according to CFR14, PART 431 [33] and the addition of part 450 as a result of the Streamlined Launch and Reentry Licensing Requirements final rule [34]. The ”In-Air-Capturing” and mainly the to be modified airliner for towing will either see the need for a similar European policy approval or certification. This could follow the rules for experimental aircraft according to EASA23.

5.3.3.3 Safety and legal issues

All safety and legal issues are strongly related to many aspects of process certification or qualification. If IAC is to be used for recovery of RLV-stages launched from CSG, Kourou, all safety has to be compliant with the CSG regulations. All legal issues have to be compliant with the laws of the French Republic.

Third-party damage by IAC operations has to be acceptably low. The risk of third-party fatalities has to be $< 10^{-7}$. This requirement is probably not overly ambitious to be satisfied as the complete capturing and towing maneuver is happening in the medium subsonic regime (< 600 km/h airspeed) with limited kinetic energy. Remaining fuel in the RLV-stage is low or the stage might be even chemically fully inert. The airliner will also operate with a comparably low fuel loading and as an unmanned system is intended to be operated only in restricted airspaces. Acceptable reusable launch vehicle mission risk of RLV as required by [33] is set not to exceed 10^{-6} and excludes persons in water-borne vessels and aircraft. A policy approval according to CFR14, PART 431 is likely in reach for the IAC process.

5.3.3.4 Manufacturing

Currently, no specific needs have been identified for the “In-Air-Capturing”-process in the field of industrial manufacturing. State-of-the-art procedures should be fully sufficient for realizing the required hardware.

5.3.3.5 Environmental issues

The environmental footprint of the “In-Air-Capturing”-process is expected to be small. No toxic materials or fuels are planned to be used in any of the vehicles. During the IAC maneuver and subsequent towing, the only exhaust emitting vehicle is the towing aircraft using JP-fuel in the troposphere, mostly likely full operation below the stratosphere. The low fuel consumption of air-breathing engines is generating a modest amount of emissions compared to rocket decelerated systems.

Thus, a major advantage in environmental compatibility assessment is to be expected for the IAC-mode compared to the DRL-mode used by SpaceX.

5.3.3.6 Economics

An investigation on the economic interest of the "In-Air-Capturing" has been performed considering launcher performance (see section 3.2) and a bottom-up model of the recovery operations has been established (see section 3.3.2). The launch vehicle performance is correlated with launch mass which is correlated in a non-linear dependency with launcher recurring and non-recurring costs.

For obvious reasons all cost models of reusable booster stages have a significant range of uncertainty because no actual cost data of operational stages are available. Nevertheless, numerically investigated RLV using the "In-Air-Capturing"-method for recovery consistently show the best performance (best payload ratio) compared with all other options and thus gives realistic hope that IAC-recovered stages are among the most cost-efficient. The cost of recovery is found very close to down-range landing on a sea-going platform and well below 1 Million € per flight (section 3.3.3 and [7]) which would be a minor contribution to total recurring launch cost.

Although preliminary cost analyses are looking promising for IAC, more advanced cost estimations with detailed cost breakdowns are to be performed and subsequently to be applied to European mission scenarios. Beyond that work, the development cost for "In-Air-Capturing" applied to reusable launchers will have to be estimated in a bottom-up approach based on a development roadmap.

5.4 Technology development and demonstration status

Based on the development and demonstration needs described in the previous section 5.3, the current status is described taking into account analyses, preliminary design and hardware testing performed in DLR (see also [8]) and in the FALCon project. Those development and demonstration activities planned in FALCon until the end of the project in 2022 are furthermore mentioned.

5.4.1 Technology domain

Similar to the needs, the status is described for each technology area and TRL is estimated for a European perspective:

- Aerodynamics
    - RLV stage: winged vehicles, fully controllable by aerodynamic means with subsonic maximum L/D > 5 and with flight envelope spanning huge Mach number range have been preliminarily designed by DLR (and other institutions) in the past. See for example references [9], [12], [21], [26], [28]. TRL is 5 to 6
    - Towing aircraft: aerodynamics in mode of degraded aerodynamic performance in diving flight is under CFD-analyses by VKI in FALCon for existing reference airliner Airbus A340-600. TRL is 5 to 6
    - Capturing device ACCD: preliminary data sets of aerodynamic coefficients generated in DLR project AKIRA and CFD-analyses performed by VKI in FALCon. TRL is 4 to 5
    - Interaction & Interconnection: flow-field interaction is numerically investigated using CFD-analyses by VKI in FALCon. TRL is 2 to 3.
- Structure & Mechanical Systems
    - RLV stage: limited investigations on connecting port to date. TRL is 4 to 5.
    - Towing aircraft: limited investigations to date on modifications, preliminary activities planned in FALCon. TRL is 2 and should reach 4 in FALCon.
    - Capturing device ACCD: some investigations to date [8]. TRL is 3.
    - Interaction & Interconnection: no investigations to date, preliminary activities planned in FALCon, TRL is 1 to 2 and should reach 3 to 4.
- Propulsion
    - RLV stage: N/A
    - Towing aircraft: N/A
    - Capturing device ACCD: N/A
    - Interaction & Interconnection: N/A
- GNC
    - RLV stage: controlled and sufficiently precise approach maneuver in perturbed, turbulent flow conditions TRL is 3 and should reach 4 to 5 in FALCon.
    - Towing aircraft: preliminary evaluation on feasibility of modification of existing on-board GNC, TRL is expected to be at 5 (TBC).

    - Capturing device ACCD: fully controlled and sufficiently precise approach maneuver in perturbed, turbulent flow conditions to be demonstrated in daylight and lab-scale experiment should reach TRL of at least 4 at the end of FALCon.
    - Interaction & Interconnection: TRL should reach 4 to 5 in FALCon performing lab-scale flight experiments and 6DOF-simulations of representative full-scale variant in undisturbed and wake-flow conditions, should approach IRL of 1.
- Software, IT, communication
    - RLV stage: no activities planned, TRL is 5 to 6.
    - Towing aircraft: TRL is 8 to 9.
    - Capturing device ACCD: visual object recognition and perception is at TRL 3 from DLR flight tests and should reach TRL 4 in FALCon, other, non-visual recognition tbd.
    - Interaction & Interconnection: generic flight controller will be developed for 6DOF-simulations in the GNC-section (full-scale TRL:3; lab-scale TRL: 5 to 6)
- Electrical system
    - RLV stage: N/A
    - Towing aircraft: probably no modifications needed, TRL is 6 or higher.
    - Capturing device ACCD: TRL is 6.
    - Interaction & Interconnection: N/A

Most of the current activities in the FALCon-project have been focused on the technical fields of aerodynamics, structure & mechanical systems, GNC and a bit on software, IT. These are exactly those areas identified as most critical for the realization of “In-Air-Capturing” of RLV-stages.

In the Annex in section 10 on page 68 the TRL status prior to the FALCon-project and the target TRL to be achieved within the FALCon-project are listed for all technical disciplines. Major steps forward are expected in GNC with a focus on the capturing device ACCD including its aerodynamics.

5.4.2 Operational domain

The operational aspects have only been partially addressed yet:

- Operations in flight & on ground: preliminary scenario established (see sections 3.3.2 and 5.3.3.1)
- Certification & Qualification: no activities yet
- Manufacturing: no activities yet, probably no specific need
- Safety and legal issues: no activities yet
- Environmental issues: no activities yet
- Economics: several investigations on performance advantages for different types of RLV booster or first stages, model for recovery operations costs (see section 5.3.3.6)

6 Workshops on “In-Air-Capturing” with European Stakeholders

One of the key-tasks of the project is defined as “proposing a European development roadmap” for the innovative “In-Air-Capturing” (IAC) RLV-return mode “, first up to TRL of 6 and then estimating the effort for reaching the full-scale operational system with TRL of 9.” [1] This task is to be iterated jointly with the European stakeholders in agencies and industry in dedicated workshops [1].

This task should define a potential development roadmap in cooperation with the European stakeholders ESA, CNES, CIRA, and industrial primes. Relevant ESA technology development programs like FLPP are to be considered as a suitable framework without excluding other options.

Based on the intended achievements in FALCon the necessary next demonstration steps for in-flight verification are to be defined, suitable test ranges accessible to Europe are to be identified and evaluated. Synergies to RLV-demonstrator flight tests of complementary programs are to be critically assessed.

Several dedicated meetings and workshops with the stakeholders are projected. The intended lecture at VKI has been identified as one option of bringing the community together for review and coordination of the proposed Roadmap.

Unfortunately, the 1st roadmap development workshop "in-air-capturing" was scheduled in Paris exactly at the time when the spread of Corona-Virus (Sars-CoV-2) and CoViD-19 cases and related regulations by authorities made all professional events of this type impossible. Organization of the workshops during the “Corona-crisis” with ban on personal meetings and travel turned out to be much more complicated and longer lasting than anticipated.

6.1 Initial Workshop planning in 2019 and 2020

The stakeholders’ workshop has been discussed at PM1 in Sofia in September 2019 and preliminarily scheduled for end of March 2020, potentially in Paris. The Paris location allows many potential participants an easy and fast access as several launcher industry and research organizations are close by. The 2nd roadmap workshop in the FALCon project was to be held in mid-2021 at VKI near Brussels.

The invitation for the 1st roadmap workshop on "in-air-capturing" development was distributed Europe-wide to space industry, aerospace research organizations and space agencies. The email was sent December, 20th, 2019 announcing the intended dates March, 26th afternoon until March, 27th 2020 in the afternoon and the intended location, a meeting room at ESA-Launcher Directorate, 52 rue Jacques Hillairet, 75012 Paris. It has been clearly indicated that the participation to the workshop is limited to organizations from ESA or EU member states and participants need to have ESA or EU member state nationality.

A preliminary detailed agenda was announced by email on 4.3.2020:

- **Thursday, 26th March 2020:**
    - 14h Welcome and introduction of participants
    - 14h30 Key-note speech *Access To Space chapter of the Strategic Research and Innovation Agenda for Horizon Europe* by Jean-Michel Monthiller, EC, DG DEFIS (not finally confirmed)
    - 15h15 Overview basic idea "in-air-capturing" for launchers, how it works, what is the performance interest of "in-air-capturing" as RLV-recovery method compared to alternatives, necessary hardware (modifications), early cost assessment
    - 16h15 Overview technological status of ongoing lab-scale flight demonstration, windtunnel testing etc. in FALCon and in previous DLR-project AKIRA and planned next steps in H2020
    - 17h15 Preliminary proposal for technology development roadmap "in-air-capturing" and first list of technology maturation steps after H2020
    - approx. 17h30 Open discussion and refinement of 2nd day agenda
- **Friday, 27th March 2020:**
    - 9h30 Presentations by participants (outside of FALCon-project) on new applications for "in-air-capturing"/mid-air-retrieval or interesting related technologies

  - approx. 11h Necessary technology maturation steps after H2020: scale and flight conditions of the capturing and towing demonstration, aircraft modification, ATM-integration, certification and legal issues etc.
  - approx. afternoon: technological synergies of other/new applications
  - approx. afternoon: future EC, ESA, national projects, private funding, industry investment for development "in-air-capturing"/mid-air-retrieval
  - approx. afternoon: cooperation and workshare issues of future technology development "in-air-capturing"/mid-air-retrieval
  - approx. 16:30 end of 1st roadmap workshop on "in-air-capturing" development - we might continue with plenum or splinter discussions if needed.

Overall duration of the 1st workshop planned as an on-site event was approximately 10 hours, excluding breaks and the option of organizing splinter meetings in parallel during the second day.

Despite Europe at that time already subject to the spread of Corona-Virus (Sars-CoV-2) it was still intended to run the workshop as planned. The email already cautioned about “some dynamic developments which are difficult to predict or decisions by authorities which are beyond our control.”

6.2 Cancellation of workshop initially planned for March 2020 at ESA

Shortly after, on March, 6th 2020, ESA was no longer in a position to host the meeting with several external participants on its premises due to health safety considerations. The option of using a very large meeting room at ONERA was evaluated but due to the highly dynamic critical situation developing in Europe with most of the international travel options being annulled, the workshop scheduled March 26th/27th 2020 as an in-person event had to be cancelled by email on 13.3.2020 to those who already registered before.

It was promised that “the event is postponed but not cancelled forever” as the topic of the workshop still remains highly relevant to be discussed. The intention was to organize the development roadmap workshop as originally planned in summer 2020, likely not before June or July. Spring gave some hope of the pandemic coming soon to an end with news about then developments in China.

6.3 Organization of on-line workshop February 2021

In summer and autumn 2020 the pandemic situation did not improve sufficiently that any planning for an in-person workshop could be started. In contrary, the overall situation with Sars-CoV-2 infections deteriorated such that in November 2020 almost all public activities in all relevant countries were stopped. Any significant improvement which would have allowed travelling and having an in-person workshop within the next half year became illusionary.

Therefore, an alternative approach discussed since the FALCon PM2 video-meeting in September 2020 had to be followed. Although less efficient in arranging a technical dialogue with the stakeholders, a pure virtual on-line meeting was intended now for the 1st Roadmap Workshop.

An email-announcement on 14.1.2021 invited to the 1st roadmap workshop on "in-air-capturing" development to be organized as a “virtual” online conference on February, 10th 2021 in the afternoon from 15h to 18h.

This event had been planned for reduced duration of 3 hours, understood as more adequate for an online meeting. This is not the same format and duration as originally planned for the physical presence meeting, actually less than half of what was scheduled for March 2020 in Paris.

In the first part of this workshop the "in-air-capturing" method was to be explained to the European stakeholders and its superior calculated performance as an RLV-recovery method to be demonstrated. Afterwards the current status of ongoing simulations, experiments and lab-scale flight demonstration in the FALCon project should be presented and complemented by an outlook on the next steps in the H2020-project. Further, the workshop should describe a first proposal for the following technology maturation steps after H2020 in the form of dedicated technology development roadmaps as published in D2.2 [3]. A relatively short session for Q&A was intended on February, 10th at the end of the event. The discussions and feedback scheduled for the 2nd day of the cancelled Paris workshop has now been proposed as separate, dedicated meetings in a bilateral or multilateral form with all interested partners. These splinter workshops should address selected critical topics of the development roadmap.

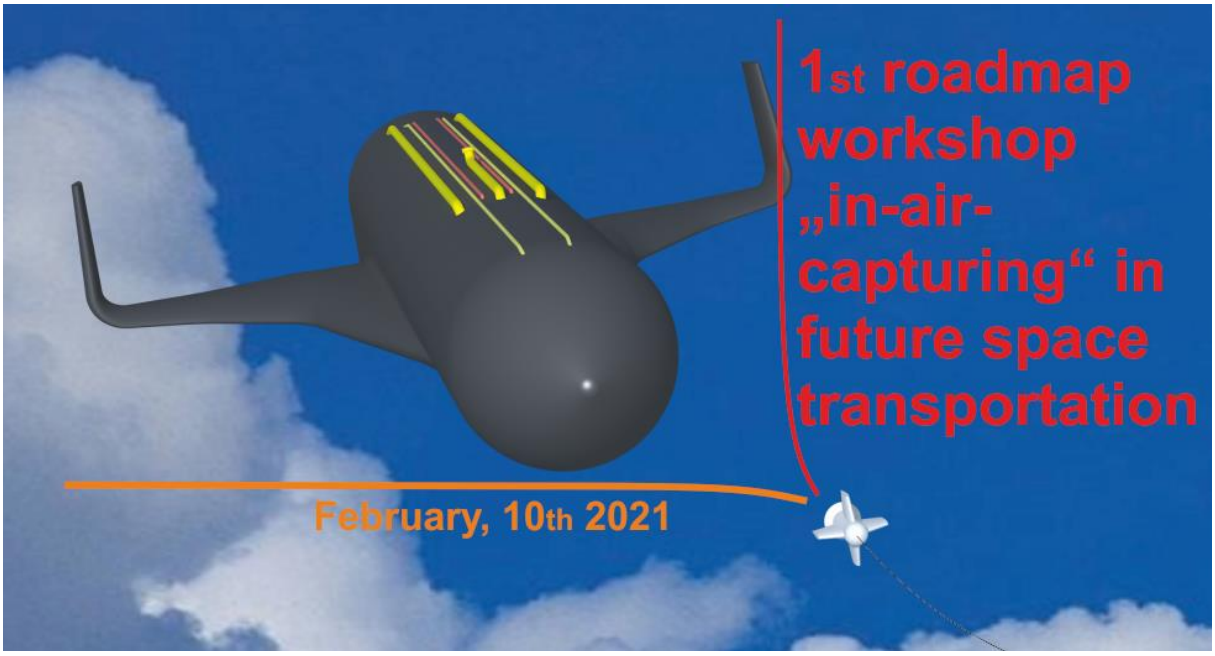


Figure 43: Website picture for 1st roadmap workshop

The agenda of the online workshop on Wednesday, **February, 10th 2021** on the roadmap development "in-air-capturing" was distributed by email 5.2.2021 to all interested and registered participants:

- 15h Welcome, H2020 project FALCon and explanation of Workshop procedure
- 15h15 Outlook Space in *Horizon Europe* work program (Jean-Michel Monthiller, EC)
- 15h25 „in-air-capturing" in space transportation: idea, interest, history
- 15h45 Quantified performance gain for RLV
- 16h Research progress achieved in DLR and in H2020 project FALCon
    - Flight experiments
        - Formation
        - Environment perception and data
    - Ground experiments, modeling and simulations
        - Windtunnel testing
        - Subscale experiments modeling
        - Full scale simulation reference concept
- 16h50 Outlook planned flight demonstrations in H2020 project FALCon
    - Demonstration experiment (logic, range, size, limitations)
    - Selected test site
    - Vehicles and hardware
- 17h10 Technology Development Roadmap
    - “in-air-capturing” procedure high-level requirements
    - Technology Readiness Level (TRL) and Integration Readiness Level (IRL)
    - Technology development and demonstration needs
    - Intended TRL status, timeline
    - Proposed technical maturation plan, Roadmaps
- 17h35 Alternative technology applications and exploitations
- 17h45 Time for European stakeholders' feedback and future involvement

  - Open round for comments, recommendations, questions, critical assessment
  - Agreement on dedicated splinter meetings, workshops and dates with all interested parties
- ca. 18h+ Intended closure of online event

6.3.1 Participating organizations

Participants from the following organizations were registered and actually participating at least partially in the three and a half hours online-event:

ASTOS (DE, RO), CIRA (IT), CNES (FR), Dassault (FR), Deimos (ES), DLR (research and space agency) (DE), European Commission (REA), Embention (ES), ESA HQ Paris, ESA-ESTEC, GTD (ES), Lockheed Martin (UK), ONERA (FR), Pangea (ES), REL (UK), RFA (DE), S2T (DE), VKI (BE)

A total of up to 46 participants was observed.

6.4 On-line follow-on splinter meetings

Following the IAC development workshop from February 2021, several smaller splinter group meetings were held in order to appropriately address some of the open questions with regards to In-Air-Capturing and the development roadmap. These meetings were focused on several subtopics and challenges related to IAC:

- System
- Avionics/GNC
- System dedicated to Microlauncher
- Operations
- Flight Testing
- Towing Aircraft Modifications

For those meetings, a group of experts on the respective field, not only limited to FALCon internal personnel but specifically including external experts, were invited to discuss the respective topics. The outcome and results of those splinter meetings will be summarized in the following sections.

6.4.1 System aspects

The splinter meeting on system aspects took place on the 24/03/2021 as an online meeting.

6.4.1.1 Topics addressed

The following topics were part of the discussion:

- RLV stage design for In-Air-Capturing application → how would a launcher using IAC look like? What are implications to the launcher on a system level (engines/structure/aerodynamics/-shape/mass)?
- Towing Aircraft: which aircraft can be used? What modifications/changes to the aircraft would be necessary?
- Economic Viability of In-Air-Capturing? Is it possible to lower the launch costs by using this technology?
- In-Air-Capturing for microlaunchers → Is it possible to use this technology for smaller launchers?
- In-Air-Capturing from a European launcher perspective → how can the “In-Air-Capturing” technology be implemented in a European context?
- In-Air-Capturing Roadmap → how to get from FALCon to a fully operational system?

6.4.1.2 Participating organizations

The following participants joined the splinter meeting:

- ONERA: Nicolas Bérend
- DLR: Martin Sippel, Guillermo Calabuig, Sven Stappert

6.4.1.3 Key remarks and recommendations

Some of the following remarks and recommendations were proposed.

RLV Design

- Target Payload to GTO of 12 t – 15 t might be too high since current GTO satellites have lower mass and GTO is not the market with the highest commercial share of 2021. Also, this high payload leads to a high dry mass of the RLV stage and makes IAC and towing more difficult. **It was recommended to consider lowering the target payload.**
- A development approach which centers on flight testing instead of extensive analysis might work for RLV development in Europe. This would be comparable to the approach SpaceX is taking, with a step-by-step adaption of already flying hardware to meet their reusability requirements. **Such a test focused approach has the potential to lower the development costs, reduce the risk and gain experience by actual flight-testing data.**
- **Any RLV design should offer the ability of growth potential and/or high versatility in order to meet the flexible demands of today's launch market.**

Towing Aircraft

- **The towing aircraft could be used for secondary missions if not in use for IAC recovery.** This could lower the operational costs and increase the flexibility and versatility of the whole IAC procedure. Also, it could allow for a fleet of aircraft to be used in order to reduce the risk of losing an aircraft. Potential secondary uses for the towing aircraft could be as telemetry station, as airlaunch system for air-launched small stages or as transport aircraft.
- **It is recommended to not rely solely on a single aircraft in case of malfunctions, maintenance or other reasons that can potentially ground aircraft.**
- **One of the main concerns and challenges are not imposed by technical limitations but rather by regulations** of authorities with regards to flying either a remote-controlled, unmanned aircraft or a manned, but partially autonomous aircraft close to populated areas
- A question which remains to be answered is if the aircraft should be manned or un-manned.

Microlaunchers

- **Launch rate should be very important for microlaunchers.** If sufficiently high launch rates could be achieved, then a "mass production" effect as for Falcon 9 might come into play. But very few launches per year in combination with a big capturing aircraft might be economically inviable. **Consider also smaller aircrafts and economic analysis of launcher costs.**

6.4.2 Avionics, GNC

The Avionics/GNC splinter meeting took place on 21/04/2021 as an online meeting.

6.4.2.1 Topics addressed

The following topics were part of the discussion:

- **Modifications to Existing Flight Control System of the Towing Aircraft:** For the current full-scale concept, the towing aircraft is selected to be Airbus A340-600. What could be the required modifications to the flight control system and the associated challenges, for both piloted and remotely piloted towing aircraft to be fit for In-Air-Capturing. Are necessary modifications more or less similar for large-size airliner or do remarkable differences between types exist (Airbus vs. Boeing-philosophy)?
- **Navigation for Capturing Device:** The In-Air-Capturing concept requires autonomous control of a capturing device to ensure a secure mating with the RLV. Multiple attempts may be made in case of failure during the capturing phase. This entails highly accurate close-range navigation. What sensors would be suitable for such a maneuver?
- **Navigation for Towing Aircraft:** Further, the Towing Aircraft must maintain a close range for a target between one and three minutes, to allow the capturing process. In such a case, is it

sufficient to rely on GPS? What other possible sensors would be applicable? What can be done to achieve a fast, reliable and redundant datalink between the two aircraft?

- **Guidance System for In-Air Capturing:** Since this technology involves two aircraft, which need to be actively controlled to ensure formation, multiple risk factors must be considered. Some possible challenges and contingency plans based on your expertise would be beneficial for the project.
- **Technology Development needs:** Will it be necessary to develop completely new avionic components (sensors, on-board computers etc.) or new GNC-software or will be adaptation or modernization of existing components sufficient?

6.4.2.2 Participating organizations

- Elecnor Deimos: Alvaro Conde
- Embention: Javier Espuch
- ESA: Orr Cohen
- DLR: Alexander Funke, Sunayna Singh, Martin Sippel, Guillermo Calabuig

6.4.2.3 Key remarks and recommendations

- Main Challenge about IAC formation flight will be the navigation and guidance aspect of the procedure, not the controller itself. The controller tuning is comparably straight-forward with respect to the challenges in relative navigation and redundant environmental perception.
- COTS components probably are sufficient the next-step demonstrations.
- Several research projects focusing on relative navigation ongoing (DMS satellite research project). Contacts could be established to help develop the guidance/navigation technology necessary for IAC.
- It is recommended to define the concept of operations (CONOPS) and then selecting sensors and sensor systems according to that concept.
- For environmental perception, visual and IR cameras, such as stereoscopic cameras, could be sufficient.
- For redundancy, as many sensors as possible should be used.
- It is recommended to check whether the ACCD should be externally powered via an electrical connection to the aircraft or internally powered by a battery. The latter could be the simpler solution, but would also depend on power consumption.

6.4.3 System aspects dedicated to Micro-launcher

In the first system aspects splinter meeting it was originally planned to include participants from the commercial microlauncher businesses. However, none of the invitees could attend at this first meeting. Following this meeting a contact to the German microlauncher company “Isar Aerospace” could established and a second meeting was organized which was specifically focused on microlauncher aspects and possible application of IAC on that scale.

6.4.3.1 Topics addressed

- Is it possible to use this technology for smaller launchers?
- Are there potential means of collaborating or testing IAC on microlaunchers?

6.4.3.2 Participating organizations

- Isar Aerospace: Johanna Pardo
- DLR SRT: Martin Sippel, Sven Stappert

6.4.3.3 Key remarks and recommendations

- It was decided that IAC could be a potentially interesting application, also for microlauncher, but the implications on the system design and performance would have to be checked by a study.
- Hence, DLR initialized a system study focusing on comparing recovery methods (Vertical Landing, Parachute, Ballute, Horizontal Landing with In-Air-Capturing and further more…) for microlaunchers on a system level. Results are going to be available within FALCon-project.

6.4.4 Operations

The Operations splinter meeting took place on 03/11/2021 as an online meeting.

6.4.4.1 Topics addressed

- **Operations & Airspace for RLV**: A 60-80 tons heavy empty RLV stage returning to earth by actively and autonomously controlling its trajectory to be finally captured by an aircraft is by no means “business-as-usual”. Therefore, operations, airspace clearance and flight regulations & permits are quite unknown terrain as of now.
- **Operations & Flight Regulations for the towing aircraft**: Capturing the reusable stage with an aircraft, either manned or unmanned, is a great challenge considering operations. How will a nominal pre-mission turnover of the aircraft look like, what are the challenges related to autonomous and automatic, maybe even remote, control of that aircraft? What additional infrastructure would be needed? What are the implications for flight permits and how can the topic of obtaining permits be addressed?
- **Flight Safety:** Are there contingency plans needed and what would they look like? How could a flight corridor of a returning RLV stage look like? What are procedures in the case of a malfunction or failure? Are there any flight safety issues we didn’t consider yet and how can they be solved?
- **Experience with In-Air-Capturing/Mid-Air-Retrieval in general?** Any feedback on past experience with helicopter or mid-air-retrieval and problems/difficulties related to this technology are helpful.
- Post-landing operations – what actions might be required once the booster has landed? What infrastructure might be required?
- Booster transportation – What is the feasibility of re-using this system during other phases of the system’s life (e.g. initial delivery to launch site)?

6.4.4.2 Participating organizations

- Reaction Engines: Matthew Clay
- DLR-ASM (Air Space Management): Sven Kaltenhäuser, Thorsten Mühlhausen, Lorenz Losensky
- DLR-SRT: Martin Sippel, Sunayna Singh, Sven Stappert

6.4.4.3 Key remarks and recommendations

- The capturing process for a launch from Kourou would take place in the Atlantic Ocean, most probably over International Waters. Air traffic here is very scarce and danger areas are usually issued as NOTAMS (Notice to Airmen) and NOTMARs for sea traffic (Notice to Mariners). Since the risk related to the capturing procedure is comparable to usual rocket launches, the required applications and application procedures should be quite familiar.
- It is recommended to have a landing airfield specifically dedicated for landing the RLV. Landing the RLV on a commercial airport would probably have serious implications on risk.
- For the approach airspace for Kourou, there are several airspaces with specific regulations each that have to be applied for each to enable crossing the airspace with the towing aircraft/ towed RLV combination. Also, some airspace will probably have to be restricted to allow for the TA/RLV only.
- For NOTAM/NOTMAR application an analysis of the required danger area would be necessary, meaning the downrange and crossrange spread of the potential recovery area.
- Contingency landing sites for RLV and towing aircraft are a must and should be considered in the future.
- It was recommended to man the towing aircraft, as it would simplify obtaining the required permits and facilitating the certification process. A remote-controlled aircraft would be a completely new and unknown class of airspace vehicles which would require an extensive certification process.
- It should be considered to vent residual propellants in the RLV prior to landing In-Air. It limits the risks related to hazardous propellants and the on-ground post-landing operations.
- The transportation of the RLV back to the launch site should be considered in the future. There could be potential limitations to road transportation that were not considered yet.

- Similar to a point that was raised in the systems splinter meeting, it was recommended to consider secondary uses of the aircraft. Potential applications could be point-to-point transportation of RLV stages from production to launch site, cargo transport or satellite transport. Nevertheless, secondary uses might impede the certification process.

6.4.5 Flight testing

The flight-testing splinter meeting took place on 19/01/2022.

6.4.5.1 Topics addressed

- **Flight Testing UAVs**: What kind of UAVs can be used for the next steps of In-Air-Capturing flight testing, representing the towing aircraft, the coupling device and the reusable stage. Which sizes and what capabilities (autonomous, BVLOS…) would those UAVs have to have and who manufactures such systems? How to incorporate the lessons learned of FALCon and previous work into the next steps? Is there any other heritage or know-how that we can rely on? Any collaborations or possible joint usage of UAVs or testing ranges & facilities?
- **Flight Testing Range**: Selecting an appropriate range for UAV flight testing turned out to be one of the most critical tasks in the FALCon project. Receiving the required flight permits by the authorities is crucial, but due to the experimental nature of IAC the process is not yet clear to anyone involved. What could be suitable ranges for upscaled UAV flight testing? What are the required permits, what are the regulations and how to approach authorities? What are suitable testing ranges in Europe?
- **Flight Safety:** Are there contingency plans needed and what would they look like?

6.4.5.2 Participating organizations

- Embention: Joaquin Gonzales, Olmo Lucena
- Polaris Raumflugzeuge GmbH: Alexander Kopp, Kasra Mohebian, Yannick Claussnitzer, Wolfgang Fischer
- ONERA: Gerard Ordonneau
- DLR-ULF (Unmanned Aerial Vehicles): Stefan Krause, Sebastian Cain, Alexander Funke
- DLR-SART: Martin Sippel, Sven Stappert

6.4.5.3 Key remarks and recommendations

- Next generation flight testing for IAC should occur at higher velocity of up to 300 km/h and higher altitude of up to 8000m.
- A suitable vehicle could be the upcoming Polaris “Aurora” flight demonstrator which would be capable of achieving velocities up to 500 km/h and 20 – 30 km of range. The vehicle could be equipped with rocket or turbine engines, depending on the requirements. However, the vehicle is yet to be developed and the flight-testing permit has not been applied for yet.
- There are several already existing test ranges which offer the potential to be used for the next-gen IAC testing. Those areas are Namfi test range in Greece (https://www.namfi.gr/), Andoya Space Center (https://www.andoyaspace.no/what-we-do/testing) or the Kiruna/Vidsel range (https://sscspace.com/services/science-and-launch-services/).
- Alternatively, potential testing sites could be testing over the German part of the North Sea or Baltic Sea. The Peenemünde airport could offer all the capabilities needed, since it has an old landing strip, which points directly towards the Baltic Sea. The airport is today privately owned and the owner already expressed interest in allowing flight testing from the airport. However, testing rocket propelled vehicles from Peenemünde is, considering the history as former weaponry and rocket production site during WW2, politically difficult.
- For UAV flight testing, the SORA application process has to be done which is a time-consuming and complex process. That should be kept in mind for any UAV flight testing consideration.
- As towing aircraft demonstrator, the “Aurora” demonstrator by Polaris could also be a possibility. Polaris is planning on building two of these demonstrators of which one could serve as RLV, with adapted lift-to-drag ratio to better represent the RLV stage, and the other one the towing aircraft.

6.4.6 Towing Aircraft Modifications

The meeting took place as a teleconference already on 20/07/2020. As this was still before the 1st online workshop it is not part of the regular splinter meetings. Nevertheless, some valuable recommendations were obtained on necessary A340-600 tow-aircraft modifications which are summarized in the following.

6.4.6.1 Topics addressed

- **Selection of Aircraft**: The Airbus A340-600 was chosen as the towing aircraft for the 'In-Air Capturing' of a large 80-ton RLV. Would such an aircraft with four engines be sufficient for such an application? Are there any challenges in terms of manoeuvrability?
- **Structural Modifications**: Can the airframe sustain the estimated loads associated with the drag of the RLV? Would any structural reinforcements be required? Could there be any challenges associated with deploying the landing gear during the flight at higher altitudes? What possible modifications could be made to house the ACCD.
- **Flight Control System:** Is it possible to modify the flight control system to enable remote piloting? Are there any challenges associated with regulations and certification of such large UAV?
- **Cost Affordability:** Would the retired fleet provide cost benefits as a repurposed aircraft? How can the cost of structural modifications be minimized? What could be the associated cost of modifying the flight control system for remote piloting?

6.4.6.2 Participating organizations

- Airbus Toulouse: Thierry Fol
- DLR-SART: Sunayna Singh, Martin Sippel

6.4.6.3 Key remarks and recommendations

- A340-600 is an overpowered aircraft and fits the loading requirements of IAC. However, there could be potential challenges in terms of maneuverability and aerodynamic control required for the formation flight. This should be examined in detail in the full-scale simulations.
- Structural concerns may arise if the landing gear is deployed beyond the specified limits (Mach 0.55 and altitude of 6400m). Turbulent wakes and structural vibrations may arise due to the deployment of landing gear mid-air, this should be checked with the CFD calculations. A safer approach to creating drag would be to use the landing bay doors as additional control surfaces.
- Moments can be a problem to the aircraft stability and the towing forces should be distributed as close to the CoG as possible. The part of airframe closest to CoG can be accessed through the central landing bay.
- It is possible to remove the central landing gear since the aircraft is not so heavy during landing anymore. In the central landing gearbox, the ACCD can be stored and the towing attachments can be installed close to the central airframe.
- While it is theoretically possible to modify the control system for remote piloting, however, the degree of difficulty is almost an order higher than the structural challenges. Typical drone ships are mostly operated by the Air Force and the IT security of such unmanned aircraft is a major defence concern. Manned operation may be much easier, if it is possible to prove that the FAA standards are met through simulation and sub-scale demonstrations.
- As long as there are no changes to primary structure (the load bearing structure), the costs of making the modifications would be affordable. Advice is to minimize any interaction between the existing systems on the aircraft and the new systems added for In-Air Capturing.
- Failure modes and risk assessment should also be included in the project planning, technical and cost assessment.

6.5 Organization of second hybrid workshop April 2022

The 2nd roadmap workshop on "in-air-capturing" development was organized as initially planned right after the VKI-Lecture Series at VKI in Rhode St. Genèse close to Brussels, Belgium. Due to a relaxation in the CoViD-restrictions it became possible to have this workshop as a hybrid event with personal presence at VKI premises or alternative online connection option. The workshop took place on April, 28th 2022 from morning until early in the afternoon. An email-announcement/invitation was sent on 24.3.2022 to the participants of the first workshop and the splinter meetings as well as to a broad range of the European aerospace community. A pre-registration of all interested participants to the free event was required.

The agenda of the workshop has been kept flexible to allow for adaptations to the interests of the participants. An extensive explanation of the idea and method of “in-air-capturing” was expected unnecessary because being part of the 1st workshop and the documentation available for download on the falcon-iac.eu-website. A summary of latest results and recommendations from splinter meetings should initiate the discussions by the participants. The following agenda has been distributed as a guideline on April, 21st:

- **10h Introduction** into the workshop
    - status "in-air-capturing" in the FALCon-project and related challenges
    - interest as an attractive RLV return method (including new studies on micro- and mini-launchers)
    - similar related technologies and developments
    - summary of recommendations from splinter meetings in 2021 and 2022
    - technology development roadmap proposals by technology
    - open discussion on potentially missing points, critical issues, best practice [ALL]
    - approx. 13h lunch break
    - 14h wrap-up and next (joint) steps [ALL]
- **15h end of the workshop**

6.5.1 Participating organizations

Participants from the following organizations were registered in the roughly four hours event:

CIRA (IT), CNES (FR), DLR (DE), ESA-ESTEC (NL), ISAE Supaero (FR), ONERA (FR), REL (UK), VKI (BE)

All were actually participating, with the exception of ONERA due to last minute unavailabilities.

6.5.2 Key remarks and recommendations

Some of the following remarks and recommendations were proposed:

- Future end-to-end full-scale simulations of IAC should also consider off-nominal reentry conditions
- The connecting elements including an emergency-case fast release mechanism at ACCD and towing aircraft should be pre-designed as full-scale variant
- Communication requirements are to be formulated for the selection of suitable communication links
- Suitable hypersonic test-beds or micro-launchers to be evaluated for next development steps
- Environmental aspects including full life cycle assessment to be investigated and should be compared with other space launch systems to demonstrate potential benefit of “in-air-capturing”

7 Technical maturation plan and preliminary development roadmap

The development roadmap for "In-Air-Capturing" has been defined in cooperation with the European stakeholders e.g. ESA, CNES, ONERA, CIRA, VKI, DLR and industrial primes and "New Space" companies. This process considers the classical Technology Readiness Level (TRL) definition (e.g. [31]). Although, the TRL-approach is helpful, it has been found not necessarily sufficient for successful development of RLV. Therefore, a NASA working group had proposed a "Phased Development Approach (PDA) using Integration Readiness Levels (IRLs) to facilitate selection, sequencing and staging of flight test demonstrations to reduce the risks inherent in technology development." (see previous section 5.2 and [31]) The combination of TRL, IRL and PDA is considered in FALCon for the establishment of the "In-Air-Capturing" roadmap.

7.1 Roadmap proposed prior to FALCon

Starting point of all activities concerning "In-Air-Capturing" is the technology development status from the DLR AKIRA-project. Results on IAC from this project are summarized and compared to the then planned FALCon-project activities in [8]. Completion of AKIRA approximately finished PDA Phase 1 and reached a TRL of 3 to 4. The Horizon2020 FALCon-project was intended to initiate PDA Phase 2, consolidate the TRL of 4 and should bring all relevant technologies close to a TRL of 5.

An early version of a potential development roadmap shown in Figure 44 has been proposed in 2018 [2] [11]. Based on the achievements in FALCon (e.g. better, more accurate simulations, windtunnel measurements, sensor data integration procedures, etc.), the next demonstration steps are in-flight verification of the RLV-demonstrator, of the capturing aircraft and of the coupling unit to confirm the aerodynamic qualities, ballistic coefficients and control margins of the system. At this stage the TRL of 6 and system integration IRL between 1 and 2 will be achieved. Funding could be provided by relevant ESA technology development programs like FLPP which were considered as a suitable framework.

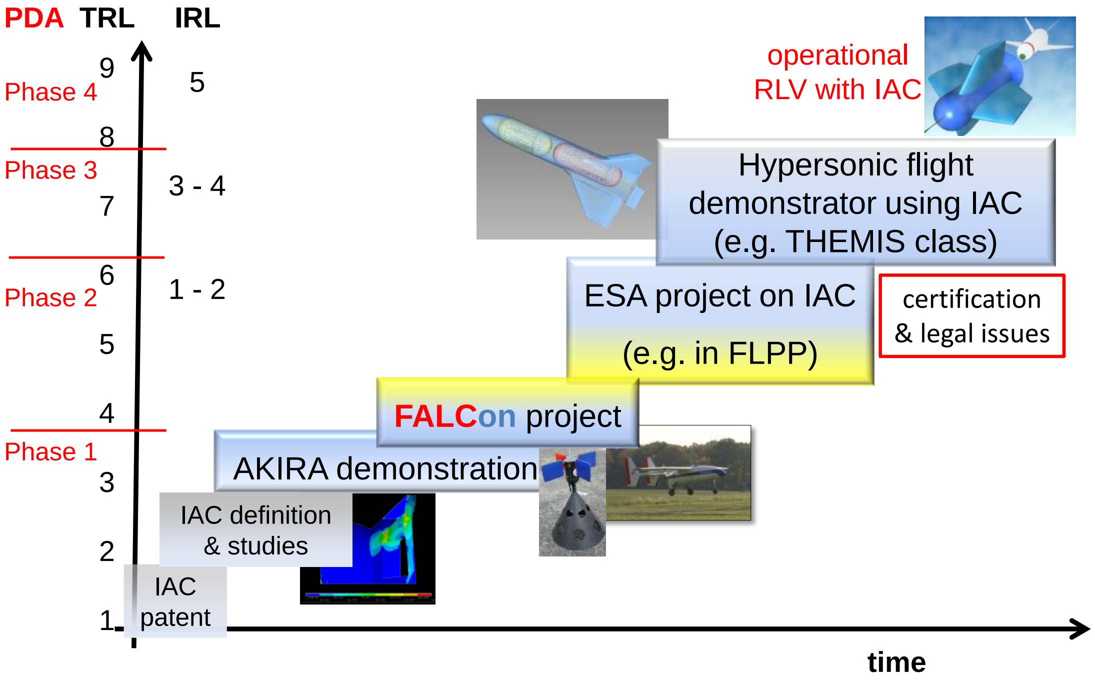


Figure 44: Early "In-Air-Capturing"-Development Roadmap proposed before start of the FALCon project [2] [11]

The following PDA Phase 3 flight demonstration will include the full vehicle system integration and thus require capturing a winged hypersonic reentry stage which should be at the same time a large-scale RLV-flight demonstrator. A significantly larger capturing aircraft, similar to those required for the full-scale application would be required. The necessary ground support equipment is also to be tested in this phase and certification and legal issues are to be addressed.

7.2 Technical maturation plan defined in FALCon

The subsequently presented technical maturation plans have been established in the FALCon-project, have been discussed in the workshops and splinter meetings summarized in section 6 and were again updated at the end of the project considering the actually achieved results and technology status. Therefore, some modifications to roadmaps in certain areas have been included compared to those previously published in [3] and [5].

The following technical maturation plans are structured along the main technical areas requiring major development work as outlined in section 5.3.1. Propulsion and electrical systems are not considered because almost no development effort seems to be necessary.

Note, the placement of the box "FALCon project" in all figures of this section shows the time but not necessarily the TRL position reached in FALCon.

7.2.1 Aerodynamics

The most important technology development activities in the field of aerodynamics are presented in Figure 45. The center of each box is located close to the intended TRL and its width represents approximately the time extension of the activity.

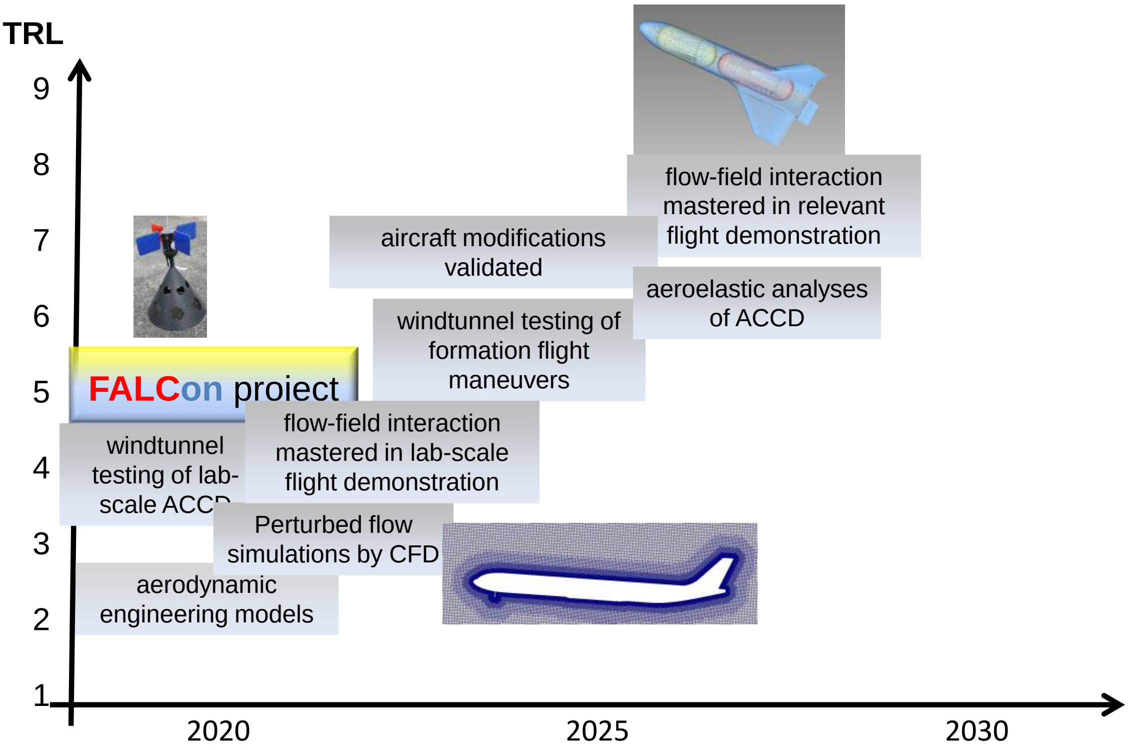


Figure 45: Development Roadmap proposed for aerodynamic technologies

Major activities of the future will have to focus on the formation flight of different vehicles in close proximity and perturbed wake flow conditions. Both, CFD-simulations and windtunnel tests will contribute. Aeroelastic analysis of the consolidated ACCD-design for real application will have to be carried-out which could become already part of the final development process.

7.2.2 Structures and Mechanics

The most important technology development activities in the field of structures and mechanics are presented in Figure 46. The center of each box is located close to the intended TRL and its width represents approximately the time extension of the activity. Modifications on the existing towing aircraft are probably minor changes (see section 6.4.6.3) that this box' span has been reduced compared to the previous release [5].

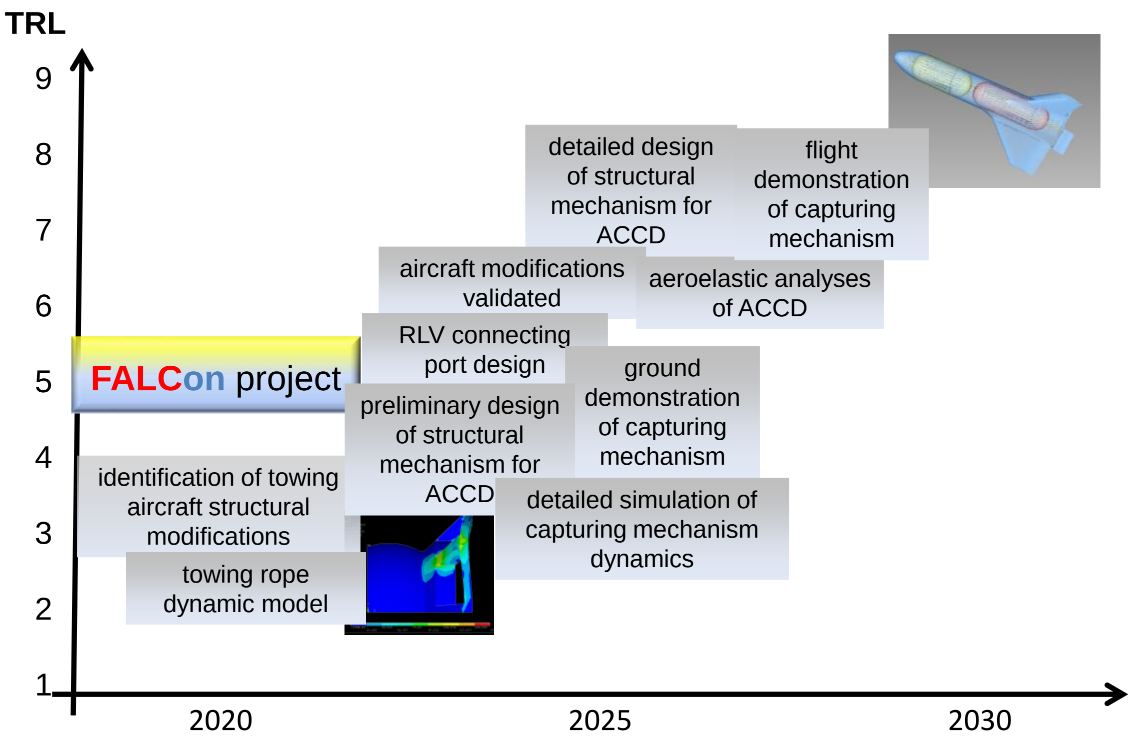


Figure 46: Development Roadmap proposed for structures and mechanics

Major activities of the future will have to focus on component and mechanisms development and ground testing considering structural dynamic behavior.

7.2.3 GNC

The most important technology development activities in the field of GNC are quite extensive, both in numerical simulation of future full-scale operational types and flight testing of subscale size. Therefore, these are presented separately in Figure 47 and Figure 48. The center of each box is again located close to the intended TRL and its width represents approximately the time extension of the activity.

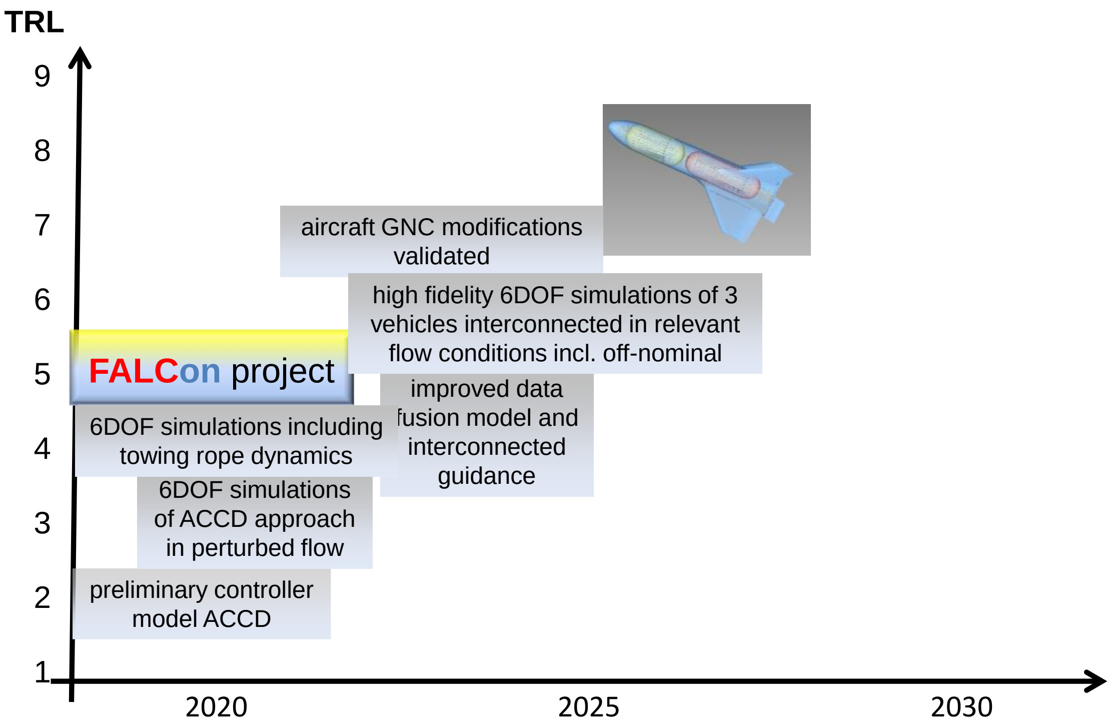


Figure 47: Development Roadmap proposed for GNC simulation (full-scale)

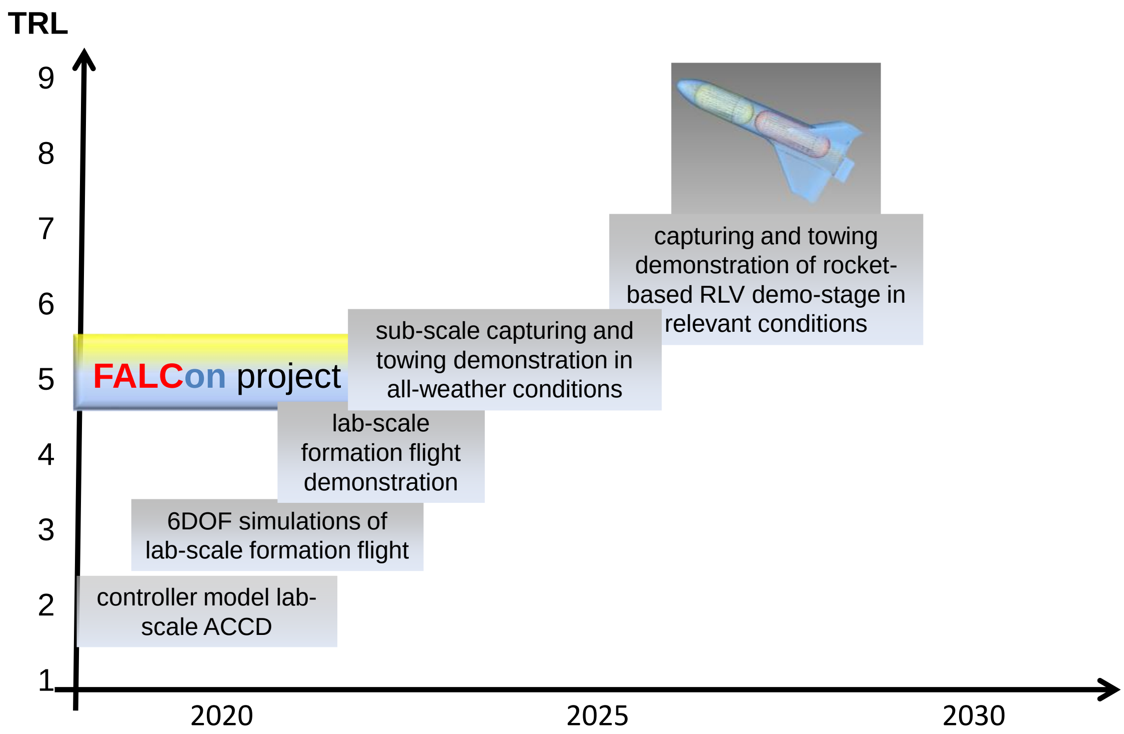


Figure 48: Development Roadmap proposed for (subscale) flight testing

Major activities of the future will have to focus on suitable data fusion and connected guidance and high-fidelity simulations of the In-Air-Capturing process of an RLV stage, including simulations of relevant off-nominal behavior. The next step in flight demonstration will introduce larger scale vehicles performing the full procedure of approach, capturing, towing in all-relevant-weather, day & night conditions. The final flight demonstration step at the end of the 2020s is the multiple successful capturing and towing of a returning hypersonic RLV demonstrator.

Figure 48 has been adapted compared to [5] because the lab-scale formation flight demonstration has been prepared but, unfortunately, could not be completed within the FALCon-project due to a flight anomaly causing significant damage to the TAD. From a system perspective it is strongly recommended to validate the lacking lab-scale demo before going the next step to the more ambitious and complex subscale demonstration. Both activities could be realized in a new joint project at moderate cost and risk if existing lab-scale hardware is reused.

For all future UAV flight testing, the SORA application process has to be followed which is according to experience in FALCon time-consuming and complex. Future flight testing should be performed over the sea for ground risk mitigation. Existing test ranges which offer the potential to be used for the next-gen IAC testing are **Namfi** test range in Greece or the **Kiruna/Vidsel** range in Sweden. An alternative potential testing could be over the German part of the North Sea or Baltic Sea. The **Peenemünde** airport could offer all the capabilities needed, since it has a landing strip, which points directly towards the Baltic Sea.

A critical point for the subscale flight testing becoming more apparent in the discussions in 2021 was the fact that the right size of UAV required for the next demonstration steps are not readily available in Europe. Either UAVs are too small and hence limited in towing- or sensor-integration-capability and having insufficient range or are few classified military systems, expensive to operate and probably not available for the intended civil application. An alternative could be using small manned aircraft modified for remotely piloted operations or taking opportunity of using two similar launcher-related drones (remark in section 6.4.5.3) when these become realized.

7.2.4 Software, IT

The most important technology development activities in the field of software and IT are mostly related to object recognition, perception and data fusion. An overview is presented in Figure 49. The center of each box is located close to the intended TRL and its width represents approximately the time extension of the activity.

Major activities of the future will have to focus on suitable data fusion and perception techniques which are connected guidance and potentially to an autonomous artificial neural network for vehicle GNC.

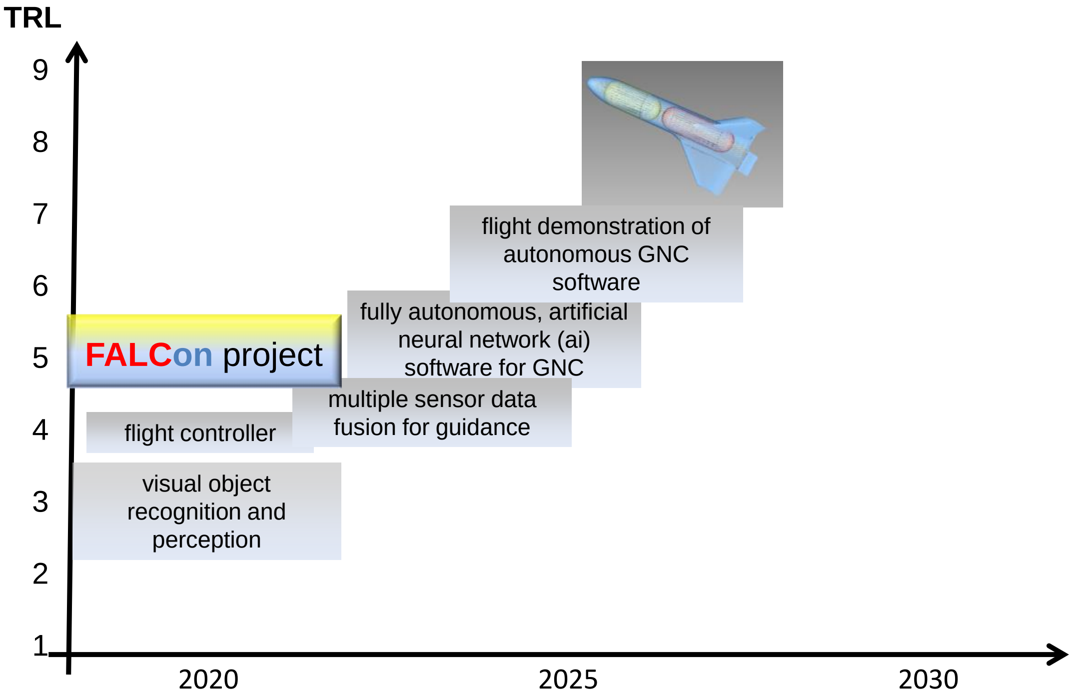


Figure 49: Development Roadmap proposed for software and IT

7.2.5 Integration readiness

An IRL-centric view on "In-Air-Capturing" development is presented in Figure 50. The FALCon-project should run system simulations of the maneuver at full-scale, reaching the lowest IRL of 1 at the end of the project. The next step will see a detailed system design of all mechanical and electrical systems needed for IAC. The question if any mechanical or sensor prototypes are required for ground testing is to be evaluated.

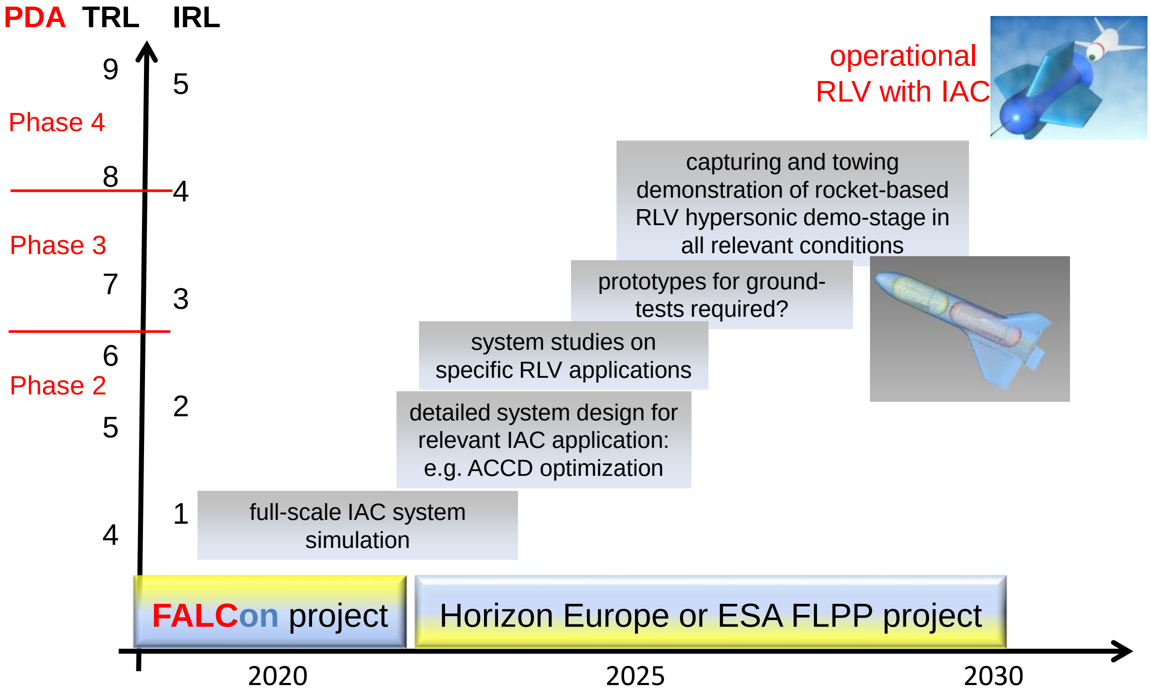


Figure 50: Development Roadmap proposed for "In-Air-Capturing" Integration Readiness

As part of necessary next steps, the full-scale simulations will extend beyond the FALCon-project with subsequently refined models of the subsystems. As the application size of the launcher and to be captured RLV-stage mass and dimensions are not yet frozen, systematic system studies on different launcher applications should be performed. The models developed in FALCon could be adapted in relatively short time for simulation of operational systems of different size and flight conditions. A generated database of various preliminarily designed RLV-concepts will help in the definition of realistic and attractive system requirements.

7.3 Development Roadmap proposed in FALCon

A realistic Initial Operational Capability (IOC) target date for a completely new, partially reusable European launch vehicle is probably around 2035. Further assuming at least 5 years for development and qualification of the RLV, a TRL of 6 should have been achieved in 2029 by capturing and towing a representative hypersonic flight demonstrator. A TRL between 5 and 6 is usually accepted at the start of industrial development. As the IAC has a major impact on the overall launch system architecture, the TRL-requirement is set to 6.

This TRL with target date 2029 is used as the baseline of the updated technology development roadmap. Recent delays in the development of Ariane 6 could push the IOC of a next generation launcher with reusable first stage further to the right. The baseline target date is kept unchanged to the previous roadmap [5] but it should be kept in mind that some additional time margins might become available. Figure 51 shows which system demonstration milestones need to be achieved in the coming 5 to 8 years. After successful lab-scale demonstration another subscale demonstrator will be needed for increased scale, increased speed capturing and towing in all relevant weather conditions and during day- and night-time. The related demonstration challenges are mentioned in section 7.2.3. Assuming funding is available without major delays, the lab-scale demonstration can be completed in 2023 and the subscale flight testing in 2026.

The option of linking “in-air-capturing” technology with recovery of the potential successor of DLR’s hypersonic demonstrator ReFEx should be investigated. Operational, certification and legal issues as well as an environmental compatibility assessment are to be addressed in the second half of the decade when a consolidated scenario has been established.

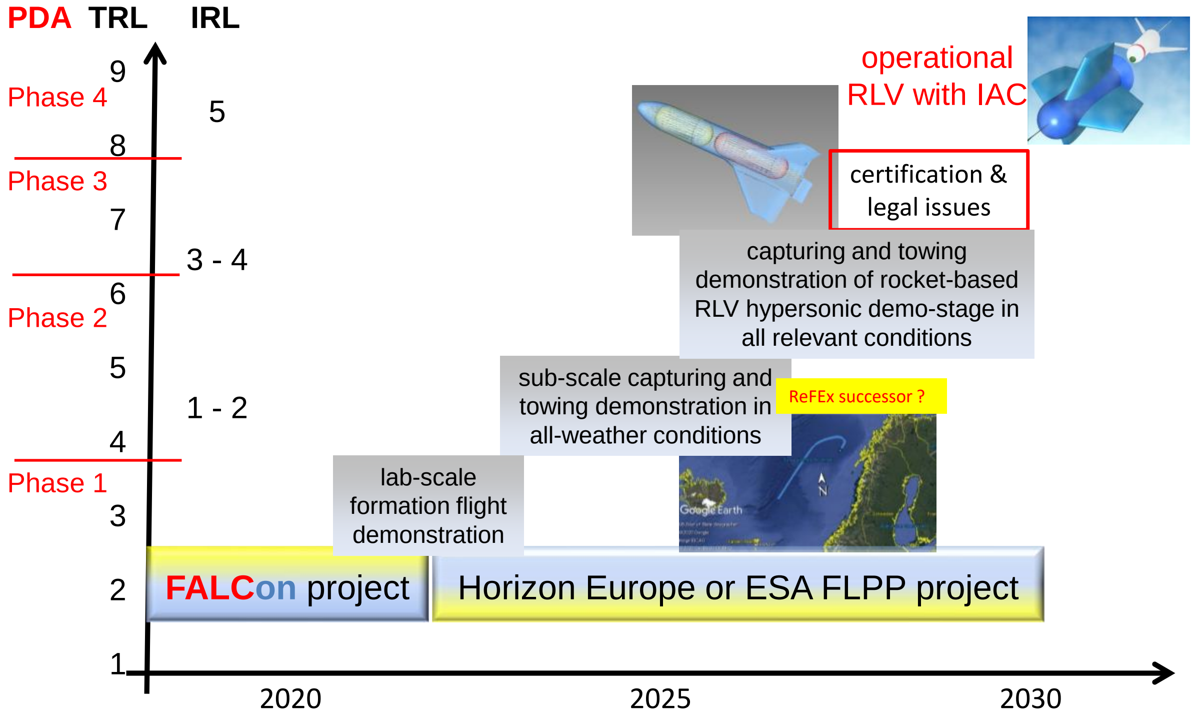


Figure 51: Development Roadmap major system demonstrations for “In-Air-Capturing”

The development roadmap shown in Figure 51 is oriented on a large-scale launcher and its RLV lower stage. Alternate operational scenarios of the “In-Air-Capturing” technology on potential micro-launchers or capturing reentry configurations or payload fairings have been proposed (see section 3.4 starting on page 19). Those applications were thought needing an adapted development of the major system demonstrations [3]. Such roadmaps were planned to be worked-out during the first European stakeholder's workshop on "In-Air-Capturing". The restrictions due to the "Corona-crisis" did not allow to organize the event with in-person participation which would have been essential for joint definition. Instead several online splinter meetings were organized (see section 6.4) providing valuable remarks on the key technology topics. In general, these splinters did not show any significant changes or additions to the presented technology roadmaps depending on the size or application.

Talking to Isar Aerospace in an online conference (section 6.4.3) and again at IAC2021 in Dubai separately with Pangea and Isar Aerospace at their respective booths showed a major interest on their side in understanding the potential of reusability. Nevertheless, their primary attention at the moment is getting their systems flying and reaching orbit even as an ELV. Lockheed Martin UK initially showing a strong interest in the "in-air-capturing" technology, probably linked to reentry systems, was participating in the online workshop in February 2021. Unfortunately, it was not possible to get them involved in the follow-on splinter meetings because of personnel fluctuations and probably shift in company focus.

The overall potential funding perspective in Europe has not significantly changed since proposing the first [2] [11] and the second [3] technology development roadmap. Reuse and hence recovery of rocket stages is receiving more and more attention worldwide. The main driver in this field is probably SpaceX by regularly returning the Falcon9 booster stages [14] and with their ambitious and spectacular StarShip flight demonstrations. Institutional funding from programs like Horizon Europe or FLPP (neo) are suitable to support the IAC-technology maturation. These sources are targeted by traditional launcher companies and launcher institutions and by new players from the mini- or micro-launcher business.

7.3.1 Proposed next step actions

Based on the technology maturation plans defined in paragraph 7.2 the immediate next steps after FALCon can be identified. Considering a time frame up to roughly 2026, mainly the following actions should be addressed:

- extensive perturbed flow analyses in different scales
- preliminary design of structural mechanism in ACCD and RLV-connecting port
- avionic component pre-selection for different full-scale applications
- improved data fusion model and interconnected guidance
- finalizing lab-scale flight demonstration
- sub-scale capturing and towing demonstrations (up to 250 km/h, up to 6000 m) flying in all relevant weather conditions during day and night
- full-scale simulations with refined models of the subsystems in nominal and off-nominal conditions
- systematic system studies on different launcher applications
- environmental compatibility assessment, refined cost-benefit analysis, operational, certification and legal issues to be addressed

The estimated effort for these activities is presented in the following section 7.3.2.

7.3.2 Development cost assessment "In-Air-Capturing"

Using the technology development roadmaps for "in-air-capturing" a *rough* estimation of the investment needed to bring this advanced technology up to the industrial phase of launcher system development could be performed. The efforts are estimated for three phases subsequently following the FALCon-project:

- up to TRL5 / IRL1: **10 M€** (for actions as listed in section 7.3.1)
- up to TRL6 / IRL2: **40 M€** (+ hypersonic rocket demonstrator 30 M€ to 150 M€)
- up to TRL8, qualification: **100 M€** (+ launcher development)

These costs are to be accumulated and are all based on e.c. 2022.

Figure 52 shows the technology development effort of the phases split by major elements with the assumption of a hypersonic demonstrator flight costing 30 M€ alone. Actually, the latter is strongly dependent on the size and demonstration purposes and its reusability. The 30 M€ is at the lower end and might be the ReFEx-successor as mentioned above and shown in Figure 51. Using an operational mini-launcher's first stage for recovery at the end of a commercial mission might reduce this cost item and a larger, autonomous, rocket-powered demonstrator might go up to 150 M€ or beyond. The right column shows the development costs from TRL 6 to TRL8 with qualification before first launch only for "in-air-capturing"-related activities. The launch vehicle and ground infrastructure costs of the system are specific to the chosen design architecture and, thus, are not included.

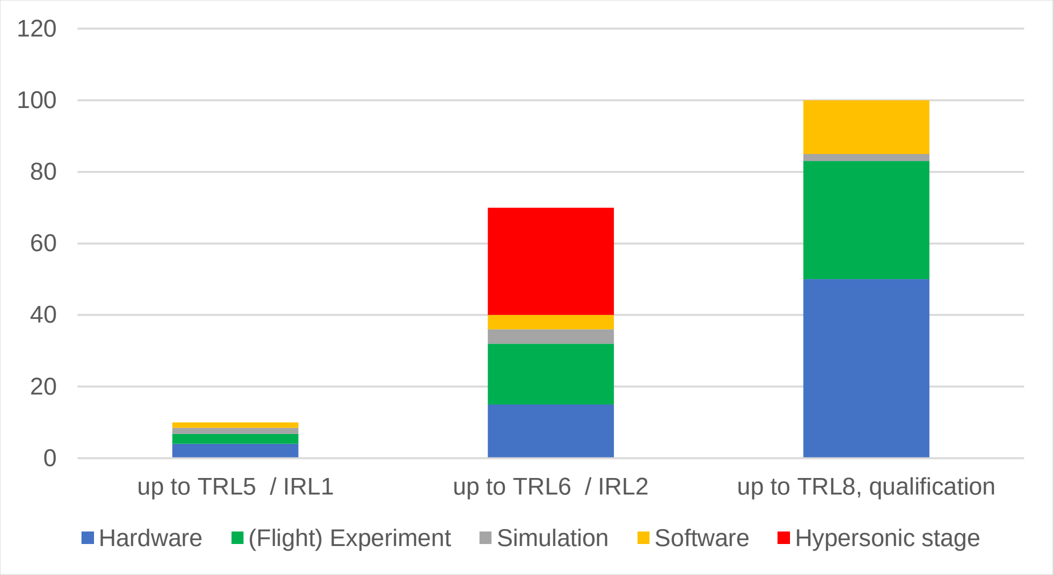


Figure 52: Technology development effort ROM [M€] (e.c. 2022) for "In-Air-Capturing"

For the next step activities after FALCon a relative distribution shows in Figure 53 that 2/3 would be dedicated to hardware and flight testing. The target should be several ten experimental flight demonstrations in order to generate a reliable database for the following development steps and launcher system optimization.

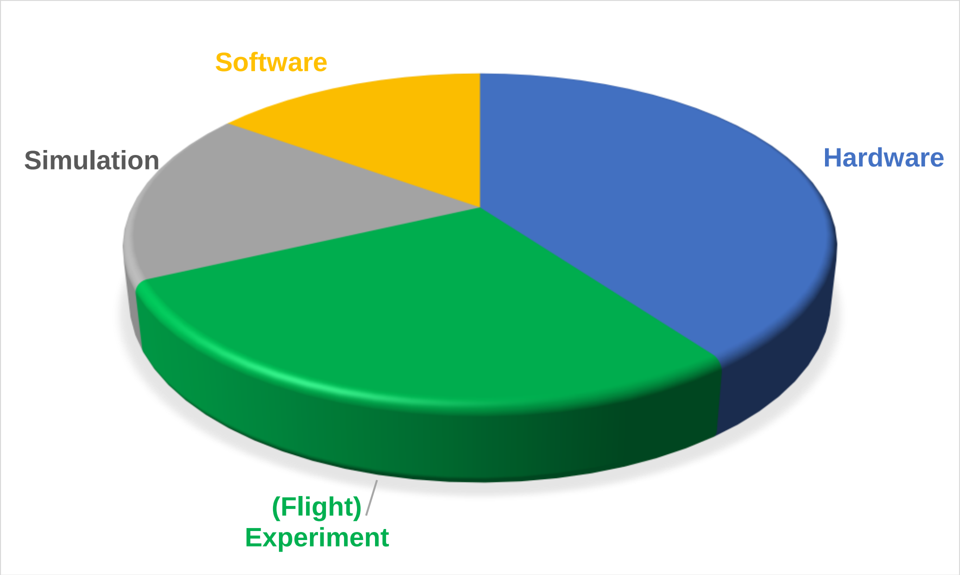


Figure 53: Relative distribution of activities up to TRL5 / IRL1

Although the estimation on the development effort is not more than a first rough assessment, it already demonstrates that maturation and qualification of IAC are quite affordable. The alternative RLV-recovery method VTVL with powered deceleration and landing is significantly more costly if based on dedicated rocket-powered stages. This is exactly the way Europe has to go because Ariane 6 and Vega stages are not suitable for such demonstrations in a secondary role as once done by SpaceX with Falcon 9 first stages. Comparing the ROM effort of combined "up to TRL5 and 6" for IAC and VTVL alternative shows that "in-air-capturing" might reach less than 25% of the costs for vertical landing demonstration. The reason for this major difference is mostly due to the fact that IAC-demonstrations do not require relatively large and costly rocket engines.

8 Conclusion

This is the second report on the “In-Air-Capturing” development roadmap in its final issue and describes the iterated (updated) version refined within the FALCon project. Comments and recommendations from European stakeholders’ workshops are considered.

An overview on the functional characteristics of “In-Air-Capturing” is provided summarizing latest flight dynamic simulations of the maneuver. The performance and economic interest are summarized and the major cost saving potential for future RLV is explained.

The preliminary development roadmap is built by the identification of critical relevant technologies and the TRL-IRL-approach. The following technology areas are regarded:

- Aerodynamics
- Structure & Mechanical Systems
- Propulsion
- GNC
- Software, IT, communication
- Electrical system

An operational system would have a potential impact on the following areas:

- Operations in flight & on ground
- Certification & Qualification
- Manufacturing
- Safety and legal issues
- Environmental issues
- Economics

These aspects have been evaluated and technology development needs are identified.

Based on this assessment a system development roadmap is proposed which allows reaching a TRL of 6 by the end of the decade if continuous stepwise technology maturation is followed. Thus, “In-Air-Capturing” for the recovery of reusable first stages is not an exotic idea but can be seriously considered for the next generation of a completely new launch vehicle.

The roadmap proposals have been updated with actually achieved results of the FALCon-project. Based on these plans the next steps after FALCon in the time frame up to 2026 are identified. A rough cost estimation shows that these activities with extensive subscale flight testing could be completed for around 10 M€. Further, all necessary steps up to industrial development-start when reaching TRL of 6 are very affordable compared to alternative VTVL maturation.

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10 Annex

10.1 TRL status prior to FALCon-project

	winged RLV stage	towing aircraft	capturing device / ACCD
Aerodynamics	5…6	5	3
Structure & Mechanical Systems	4…5	2	3
Propulsion	N/A	N/A	N/A
GNC	3	5	3
Software, IT, communication	5…6	8…9	3
Electrical system	N/A	> 6	6

10.2 TRL target after FALCon-project

	winged RLV stage	towing aircraft	capturing device / ACCD
Aerodynamics	5…6	6	4…5
Structure & Mechanical Systems	4…5	4	3
Propulsion	N/A	N/A	N/A
GNC	4…5	5	4
Software, IT, communication	5…6	8…9	4
Electrical system	N/A	> 6	6

10.3 Actual TRL after FALCon-project

	winged RLV stage	towing aircraft	capturing device / ACCD
Aerodynamics	5…6	6	4
Structure & Mechanical Systems	4…5	4	3
Propulsion	N/A	N/A	N/A
GNC	3	5	3
Software, IT, communication	5…6	8…9	3
Electrical system	N/A	> 6	6