FALCon

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

# In-Air-Capturing Development Roadmap (State of the Art)

Deliverable D2.2

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

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# (State of the Art)

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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 |
| $\alpha$ | Angle of attack | ° |
| $\gamma$ | 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 |
| DRL | Downrange Landing |
| 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 |
| RANS | Reynolds-Averaged Navier-Stokes |
| RLV | Reusable Launch Vehicle |
| 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] the WP 2.2 is about the "Definition of Technology Development Roadmap". This task is defining a potential development roadmap in cooperation with the European stakeholders e.g. ESA, CNES, CIRA, and industrial primes.

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

Several dedicated meetings and workshops with the stakeholders are planned. This deliverable serves as a document to be made publicly available to the European space transportation community. Its special purpose is to provide input for discussions in the first dedicated workshop.

## 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.

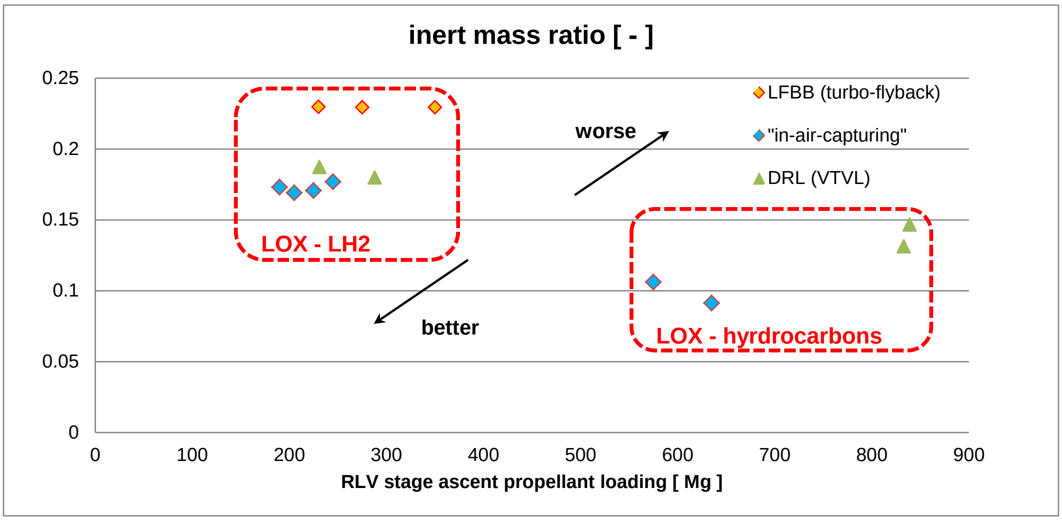


**Figure 1: Performance interest of "In-Air-Capturing" demonstrated by inert mass ratios of different RLV-return modes (all same GTO mission)**

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.

Based on simulations, a feasible technical procedure for the approach and capturing 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. DLR in its internal project AKIRA has performed lab-scale flight experiments supporting IAC aiming for a TRL between 3 and 4. The reached status of the investigations is summarized.

The current technology status including on-going 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 in FALCon 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 are to be addressed in the second half of the decade when a consolidated scenario has been established.

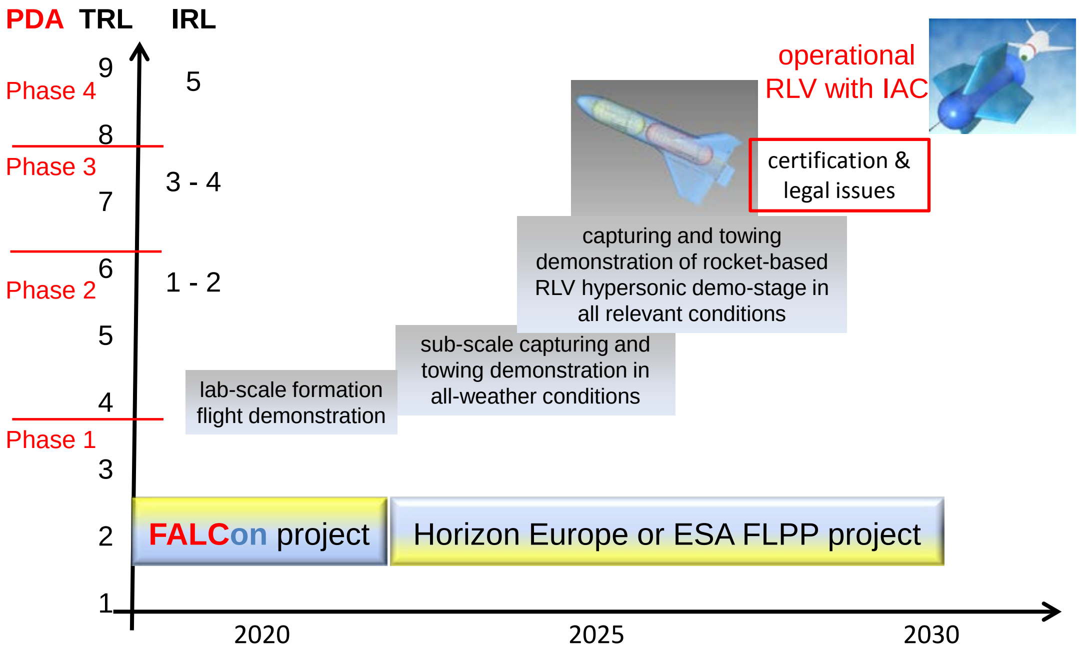


**Figure 2: Proposed Development Roadmap for "In-Air-Capturing" major system demonstrations**

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.

This roadmap is intended to be critically assessed in workshops with European stakeholders.

## 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

-

# 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.

The document should provide necessary baseline information for the participants of the first workshop which are not directly involved in the study and demonstration of "In-Air-Capturing" RLV-return mode technologies.

The first part 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 is to be demonstrated in order to justify any future investment. This section is followed by a brief description on how "In-Air-Capturing" might actually work based on numerical simulations of full scale vehicles. 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 state of the art description is followed by a list of technology development needs already identified. An early version of a technology development roadmap is proposed and explained.

"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. Such technical options will be collected and are to be evaluated in how far they could support, de-risk or speed-up the development process.

## 2.2 Tools used

N/A

# 3 Interest of “In-Air-Capturing“ for RLV first stages

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 [3] 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” [9] 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 [10]. 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 [7]. 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.

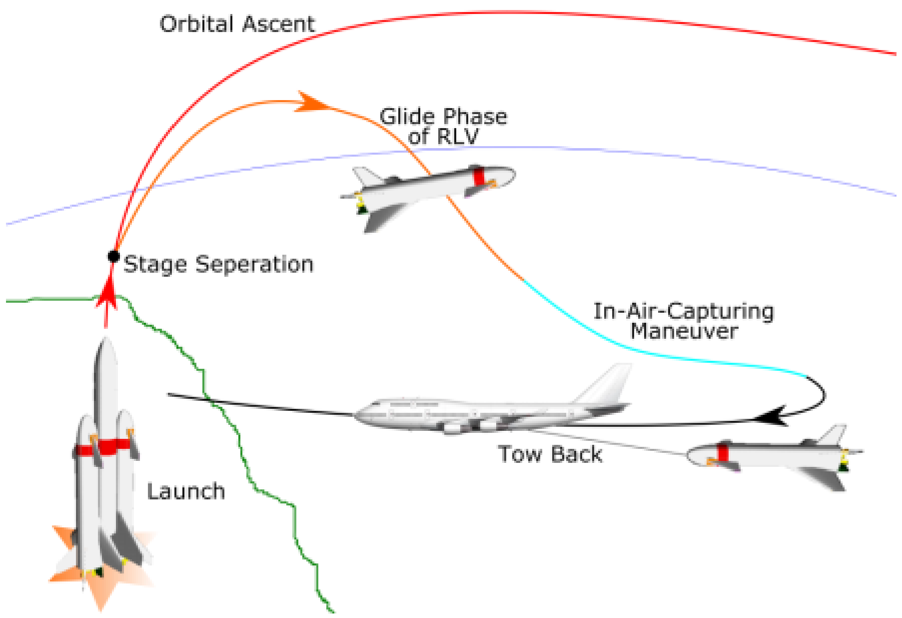



**Figure 3: Schematic of the proposed In-Air-Capturing**

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 [4] for more details!

## 3.2 "In-Air-Capturing" (IAC) in performance comparison

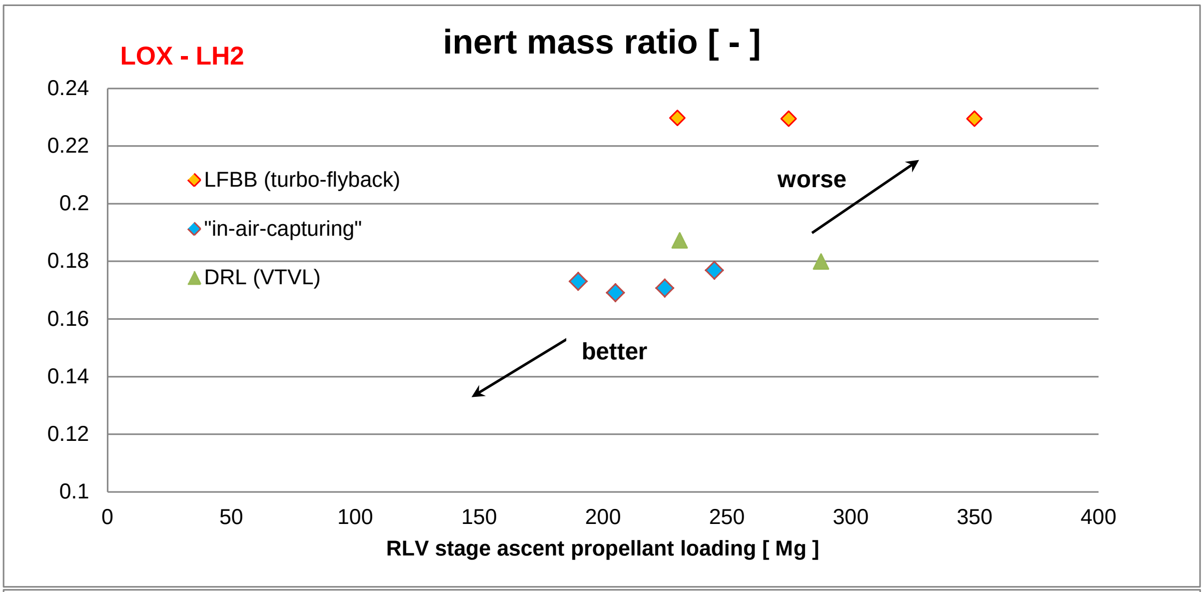
The performance impact of an RLV is directly related to its (ascent) inert mass ratio or net-mass fraction, reasonably assuming that the engine Isp is not considerably effected. Inert masses of the stage during ascent flight are its dry mass and its total residual propellants including all those needed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

$$\text{inert mass ratio}_i = \frac{m_{i,\text{inert}}}{\text{GLOW}_{\text{stage}}}$$

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 [3], [6], [8]) 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 [3], [6], [8]. 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 [10], [11]) 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.



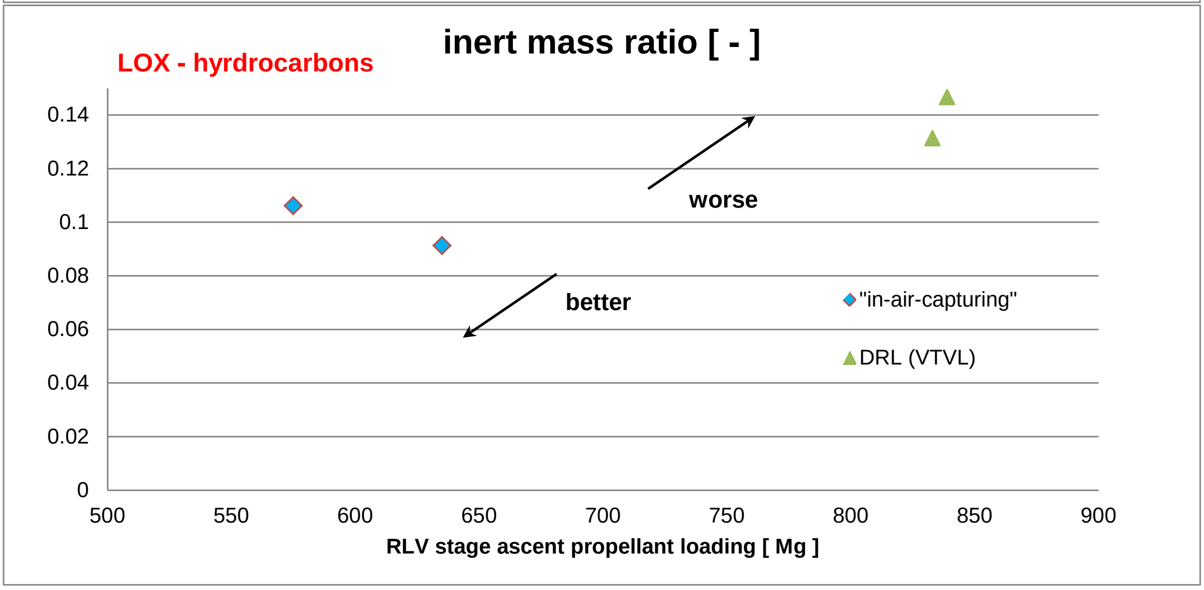




**Figure 4: Inert mass ratio depending on RLV-return modes and ascent propellant loading, GTO-mission TSTO (LOX-LH2 top, LOX-hydrocarbons bottom) [7]**

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 taking into account 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.

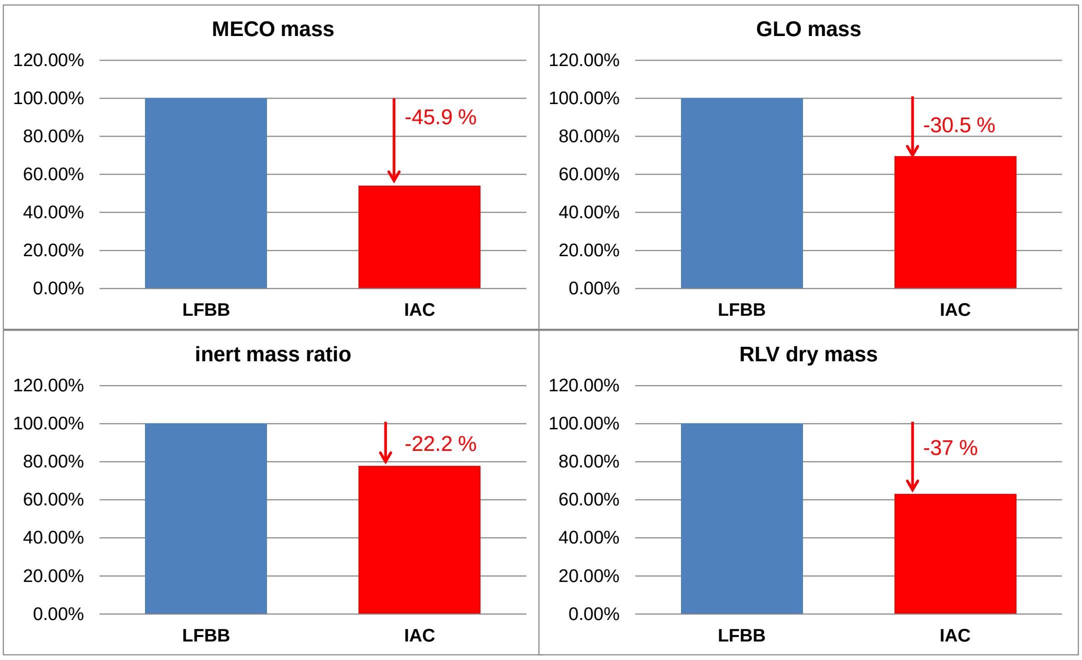



**Figure 5: Relative comparison LFBB-mode with "In-Air-Capturing"-RLV mode, GTO-mission**

### 3.2.1 Summary

In FALCon deliverable D2.1 [3] 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 Recovery Operations

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* 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* 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 [16] which was used to determine costs within this project [3]. 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.

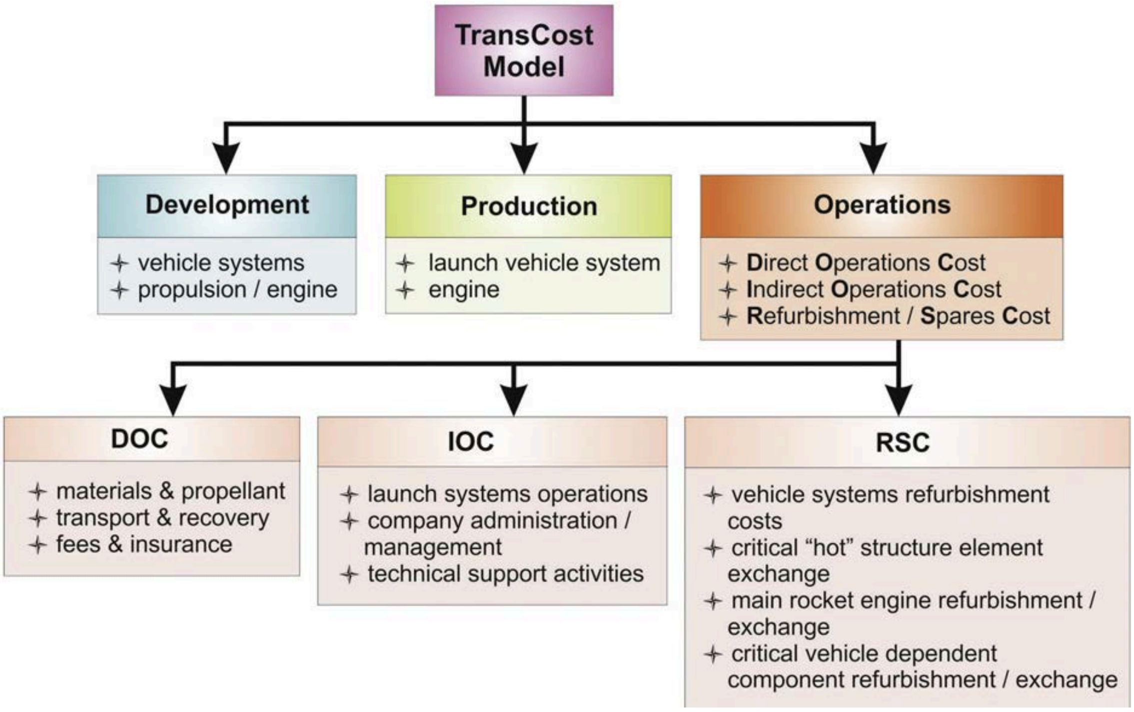



**Figure 6: Launch Vehicle Cost Breakdown according to the TransCost model [16]**

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 [16].

Some cost data for development of the Space Shuttle and of Energia Buran orbiters are available and have been validated as far as possible [17]. 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.

Any reusable launch vehicle requires hardware and additional personnel to recover or land the stage. Despite all uncertainty, an alternative model to determine all cost related to recovery operations has been established and is presented in the section 3.3.1. Instead of a “top-down” approach, a “bottom-up” approach was chosen to determine these costs [3]. In FALCon deliverable D2.1 [3] 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 [18].

### 3.3.1 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 [3].


**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 [3]. 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.

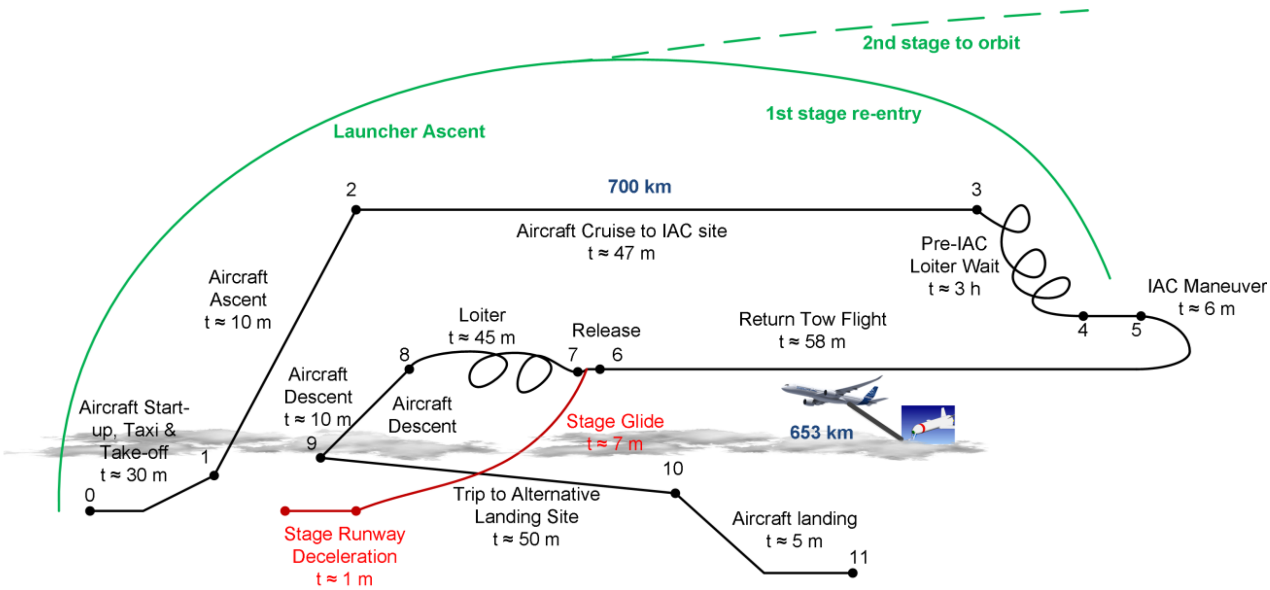



**Figure 8: Typical IAC Towing Aircraft Mission Profile [3]**

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. [3]

### 3.3.1.1 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.

### 3.3.1.2 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 [18].

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 [18], 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. Some indications give hope that necessary modifications are limited and could be realized at an affordable prize.

### 3.3.1.3 Aircraft Ownership Costs/Indirect Costs

These 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 [18] is used, assuming no relative residual value of outside capital remaining in the company.

Checking the European Central Bank interest rate, a value of zero is observed (recent effort to revive the economy). Nevertheless, the highest interest rate was of 4.75%, which was used in this analysis as a conservative estimate. [18]

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 [18] is used in the following equation

#### 3.3.1.4 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 [23].

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 [18]. 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 [18] 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.

#### 3.3.1.5 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.

#### 3.3.1.6 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 landing strip would be necessary in Kourou. Irrespectively of the price, it is assumed that this cost would be provided by Arianespace, ESA, or other governmental agencies, 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 3.3.1.1 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. These activities are listed in [3].

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 [23].

#### 3.3.1.7 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.

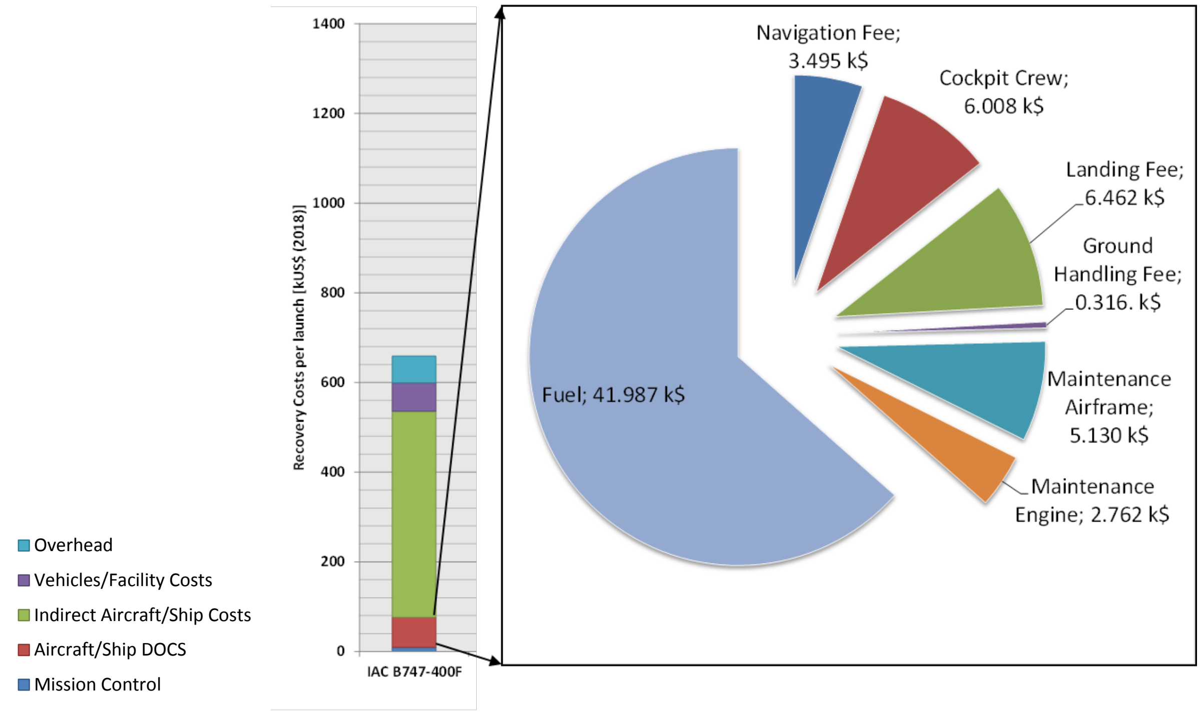



**Figure 9: Direct Cost Breakdown for exemplary IAC recovery mission**

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.

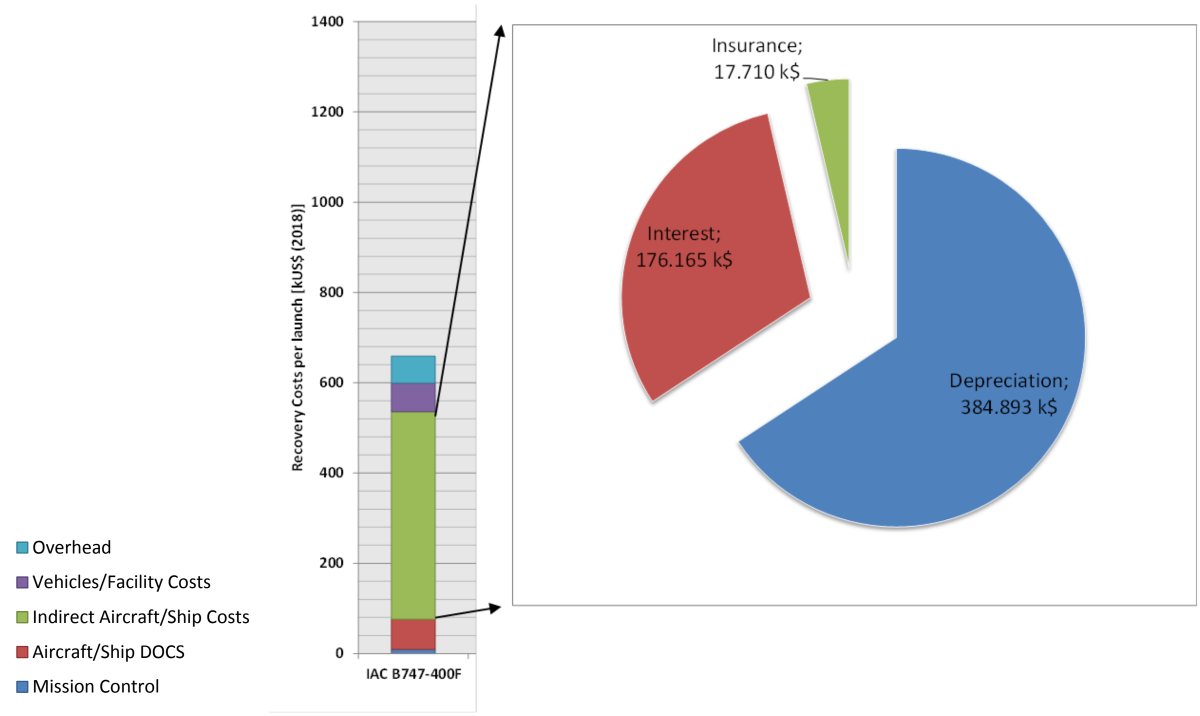



**Figure 10: Indirect Cost Breakdown for exemplary IAC recovery mission**

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.

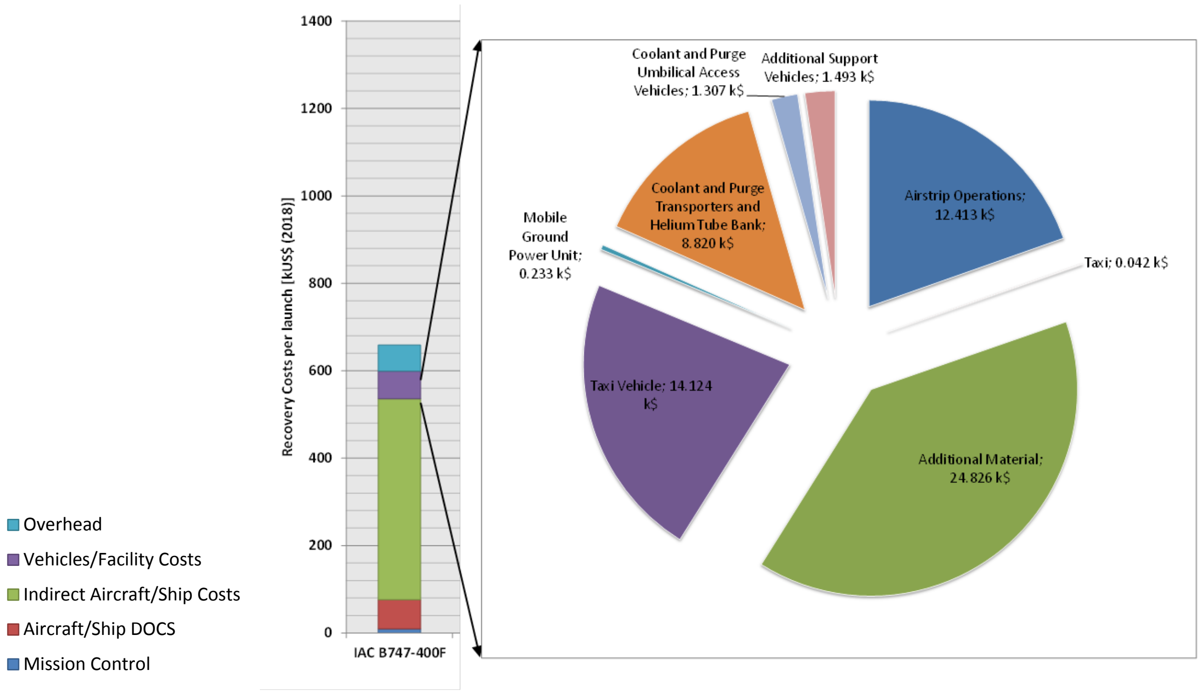



**Figure 11: Vehicles and Facilities Cost Breakdown for exemplary IAC recovery mission**

### 3.3.2 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 [3] 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 [3]. 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.

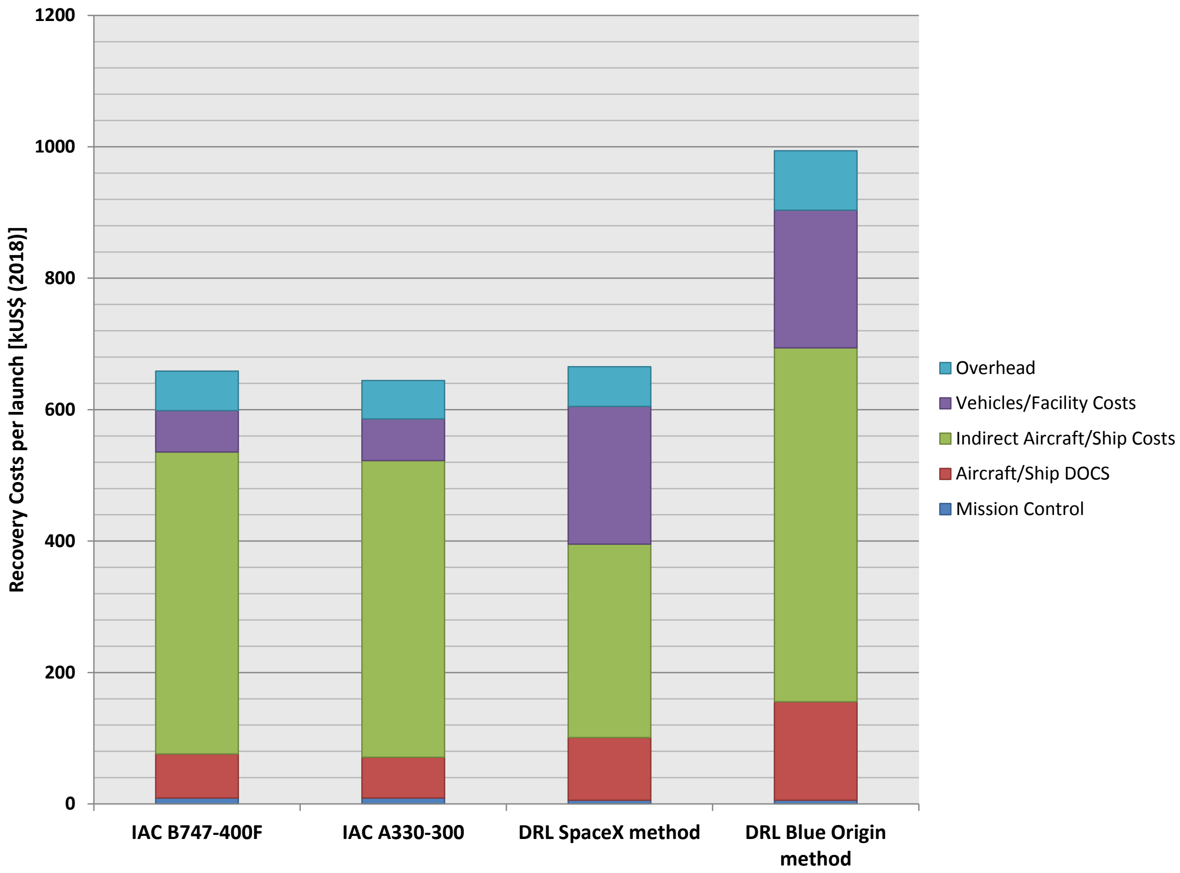



**Figure 12: Recovery Cost breakdown for different return strategies**

Direct costs, including fuel and crew costs, landing fees, navigational fees or harbor fees and costs for extra services account for only roughly 100k$ 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 fi are country- and business dependent factors.

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

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.

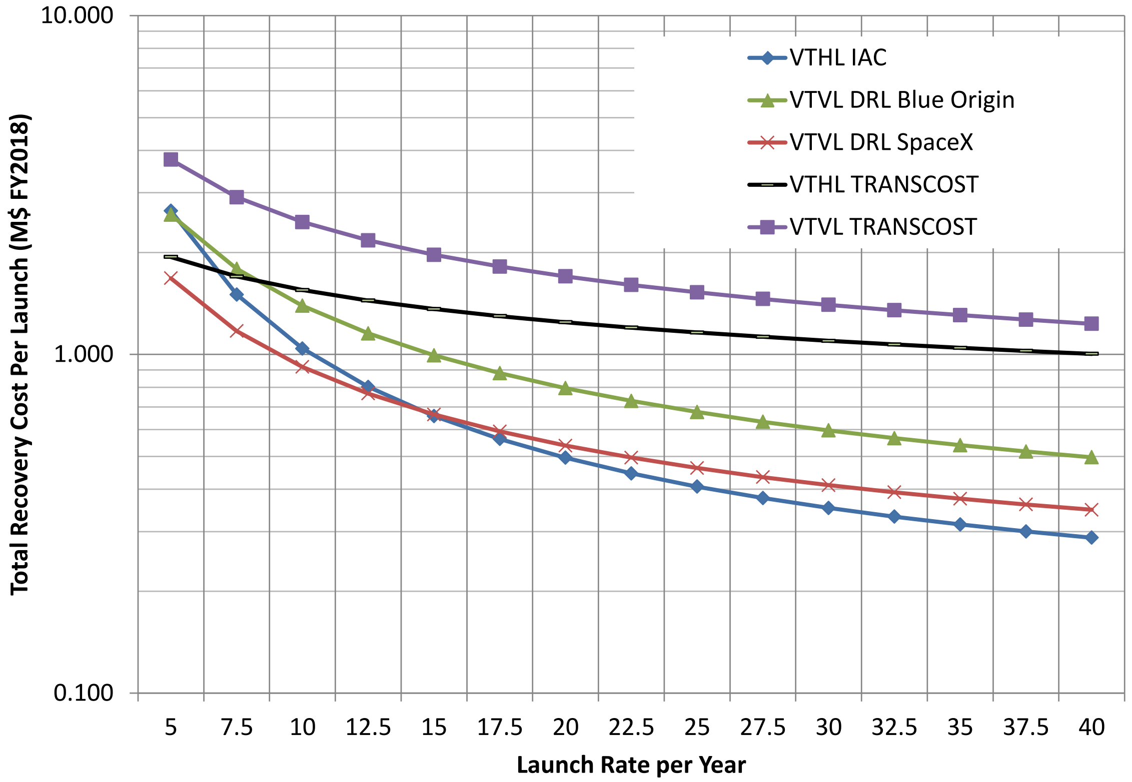



**Figure 13: Recovery Costs per launch in M$ (economic conditions: 2018) for VTVL and VTHL recovery methods**

# 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 [10]. 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 should be sufficient for the task.

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 (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 but 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 from its towing aircraft and autonomously glides back to Earth like a sailplane.

The selected flight strategy and the applied control algorithms show in simulations a robust behavior of the reusable stage to reach the capturing aircraft. In the nominal case the approach maneuver of both vehicles requires active control only by the gliding stage. Simulations (3DOF) regarding reasonable assumptions in mass and aerodynamic quality proof that a minimum distance below 200 m between RLV and aircraft can be maintained for up to two minutes [11].

### 4.1.1 Simulated approach maneuver

After deceleration to subsonic speed at an altitude around 20 km, the winged stage is actively heading towards the capturing aircraft. Under nominal circumstances the latter is assumed to be in a 'passive' mode, just cruising at constant altitude (e.g. 8000 m) and relatively low flight Mach-number of about 0.55 which corresponds to the equivalent earth speed 400 km/h. It has to be assumed that both vehicles are now permanently in communication with each other. During descent the reusable stage is able to perform some position-correction maneuvers and to dissipate kinetic energy, if required. It plays the 'active' part in the approaching maneuver.

The absolute value of the angle between both vehicles $\eta$ decreases gradually during descent. At the instant when this angle becomes smaller than the winged stage's glide path ($| \eta | < | \gamma_{gl} |$), the capturing aircraft receives a signal from the reusable stage to also start its descent flight at a pre-chosen capturing angle $\gamma_{as} = \gamma_{capt}$. The launcher stage itself adapts the path angle such, to follow the capturing aircraft. As a result, after a short time both vehicles fly in line with an inclination angle corresponding to the chosen capturing glide path angle.

The winged stage follows the capturing aircraft reducing its distance $\Delta S$ and its velocity V. The approach maneuver has been simulated for different reusable stages (see [11] for type description) according to the above explained method, and the control constraints are applied. A reusable stage with separation velocity around 2 km/s is used as an example case.

The aerodynamically controlled approach as shown in Figure 14 is initiated when the reusable stage reaches the denser atmospheric layers and decelerates to the subsonic regime. The steep glide angle of around –18 degrees is performed with a slowly decreasing air speed of around 265 m/s. After the capturing aircraft has received the appropriate signal, both vehicles are descending on nearly the same glide slope (600 s). As can be clearly seen, the returning stage is still the active vehicle, since it is subject to some control deviations in flight path angle $\gamma_{capt}$. The winged stage actively reduces velocity up to the point where its minimum safety distance is achieved (675 s).

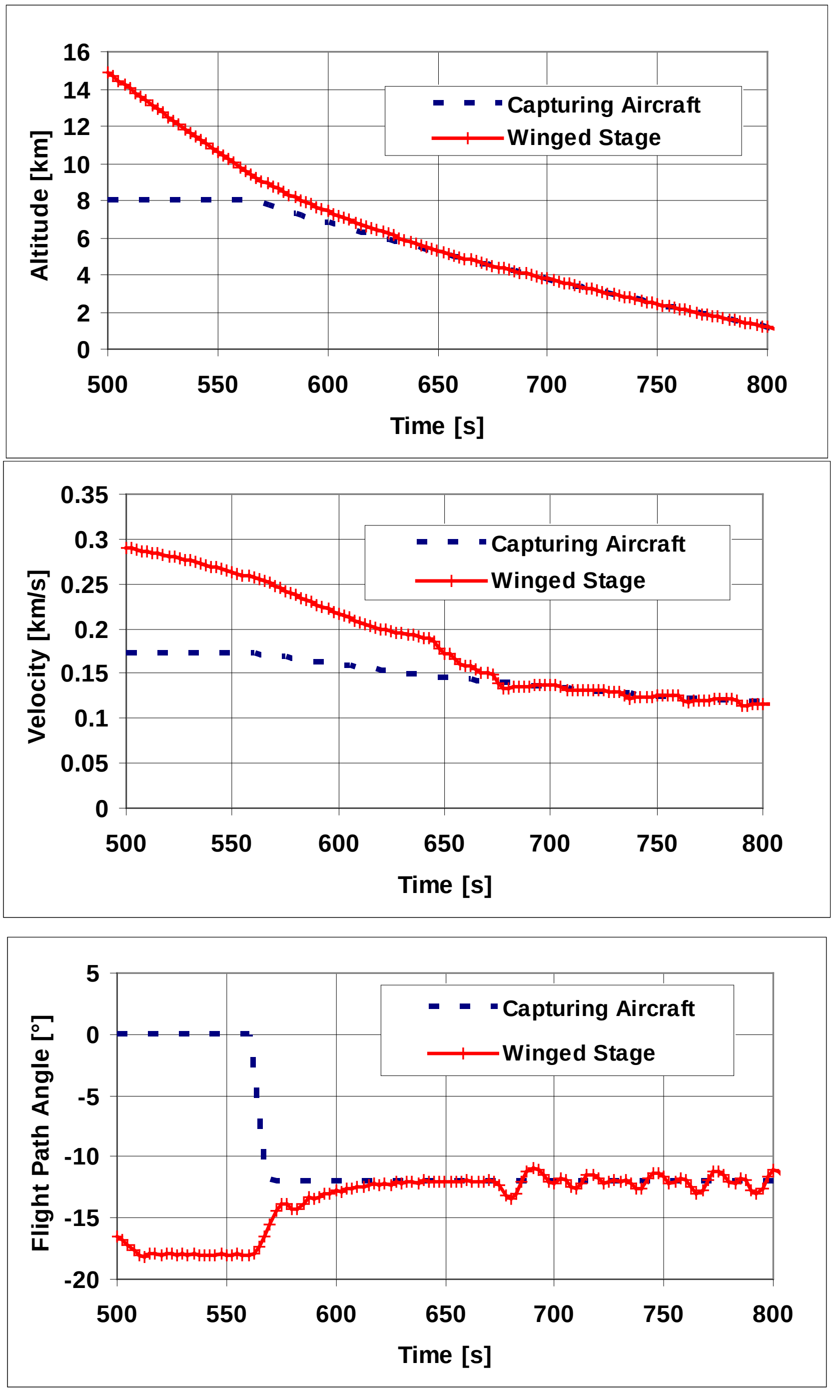



**Figure 14: Simulation of the reusable stage's final approach procedure to the capturing aircraft starting 500 s after separation from launcher [4] [11]**

As can be seen from Figure 15, the total distance between the two flying craft falls short 0.5 km around 655 s after separation. Subsequently, the distance could be controlled in this simulation at a minimum range between 155 and 200 m for duration of 130 s. The upper boundary is not set by vehicle control, but by a minimum acceptable level above ground. The final altitude in this simulation is as low as 1.2 km. A time for capturing up to at least one minute is nevertheless well within reach, since the altitude after this period still accounts for more than 2.8 km.

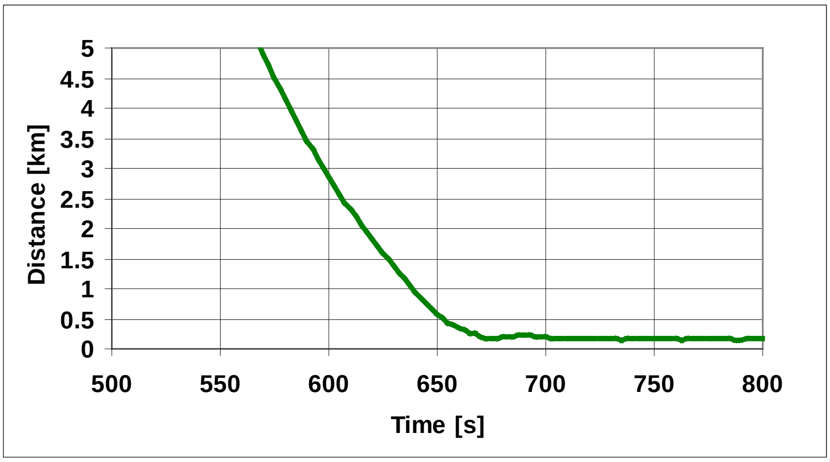



**Figure 15: Total distance between the two stages in final approach procedure starting 500 s after separation from launcher [4] [11]**

In the nominal case the approach maneuver of both vehicles requires active control only by the gliding stage. Simulations (3DOF) regarding reasonable assumptions in mass and aerodynamic quality proof that a minimum distance below 200 m between RLV and aircraft can be maintained for up to two minutes [11]. The most promising capturing technique is using an aerodynamically controlled capturing device (ACCD), showing the best performance and lowest risk.

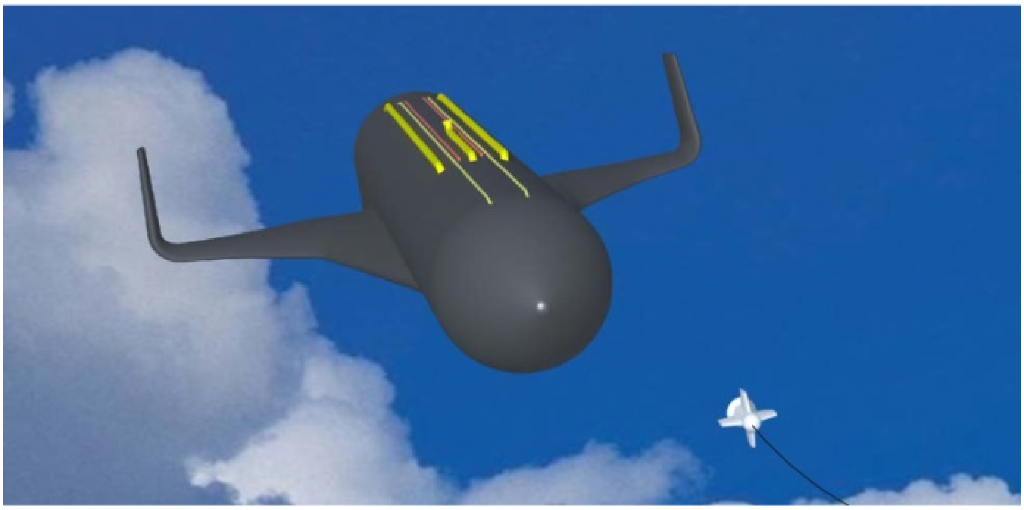


**Figure 16: Artist's Impression of the SpaceLiner7 Booster during In-Air-Capturing**

## 4.2 Potential capturing hardware

The most promising capturing technique is using an aerodynamically controlled capturing device (ACCD), showing the best performance and lowest risk [4] [11]. The ACCD is to be released and then towed by the airplane. This device (a preliminary artist impression is shown in Figure 17) contains the connecting mechanism and simply advances the stage by its own drag and lift, provided by small wings (typical span 1.5 m). Geometry data are summarized in [4].

Actuators control the ACCD's orientation and the approaching velocity might be further controlled by braking of the towing rope from inside the aircraft. With a release initiated at 230 m distance between the two crafts, the whole maneuver takes about 14 s in the nominal case. All loads remain below 3 g and the final relative velocity is at 5 m/s [11].

The configuration shall be aerodynamically stable and at the same time allow maneuverability to enable corrections of the ACCD's position and attitude. The ACCD preliminary aerodynamic lay-out defined by DLR consists of 4 fins with symmetrical hexagonal profile with 13% relative thickness. The AoA range of the fins is set at ± 15°. Horizontal fin deflection is used for pitch control and vertical flap deflection for yaw control. The aerodynamic coefficients and derivatives have been determined and an overview is provided in [4].

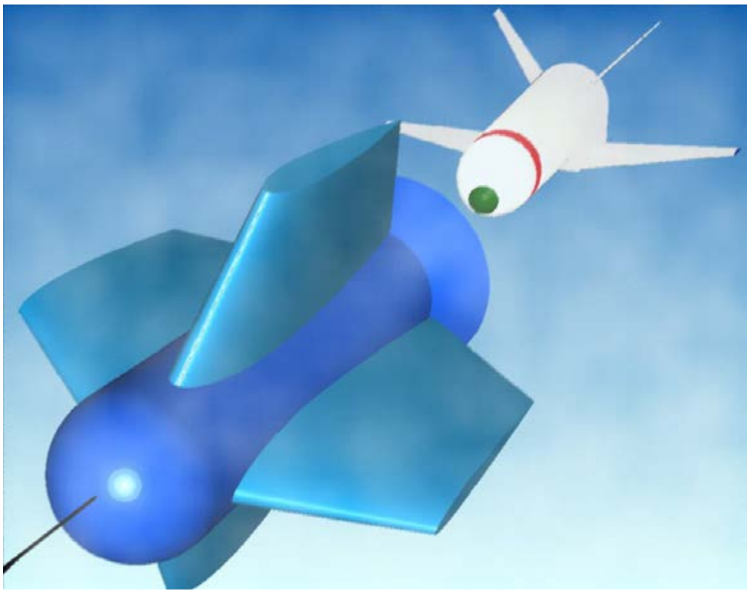


**Figure 17: Rendering of the ACCD and a returning RLV-stage cautiously approaching each other [4] [11]**

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 18) and has been subsequently mechanically sized supported by Finite-Element stress and deformation analyses [4]. 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.

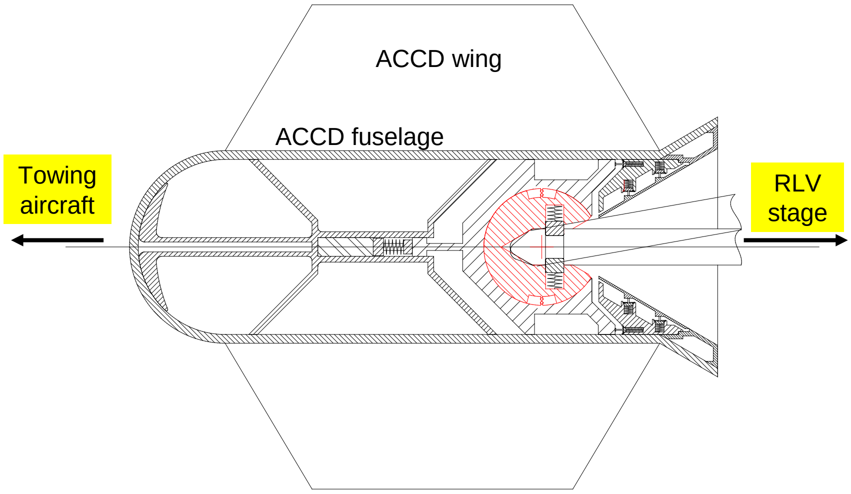



**Figure 18: Sketch of the capturing mechanism inside the ACCD geometry highlighting the ball-shaped head in red and the RLV stage anchor shown in parallel and deflected position [4]**

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 deg. 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 also 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 18). Such a device allows for a constant deceleration with a moderate axial force and rapid oscillation damping.

Figure 19 depicts a suitable design of the ACCD capturing mechanism with major dimensions for a full scale variant capable of connecting to and towing of an 80 tons winged stage. Such an RLV with approximately more than 400 tons GLOW is a good check on the principal feasibility of the capturing devices. Obviously, smaller versions of the ACCD could be sized for reduced scale reusable stages.

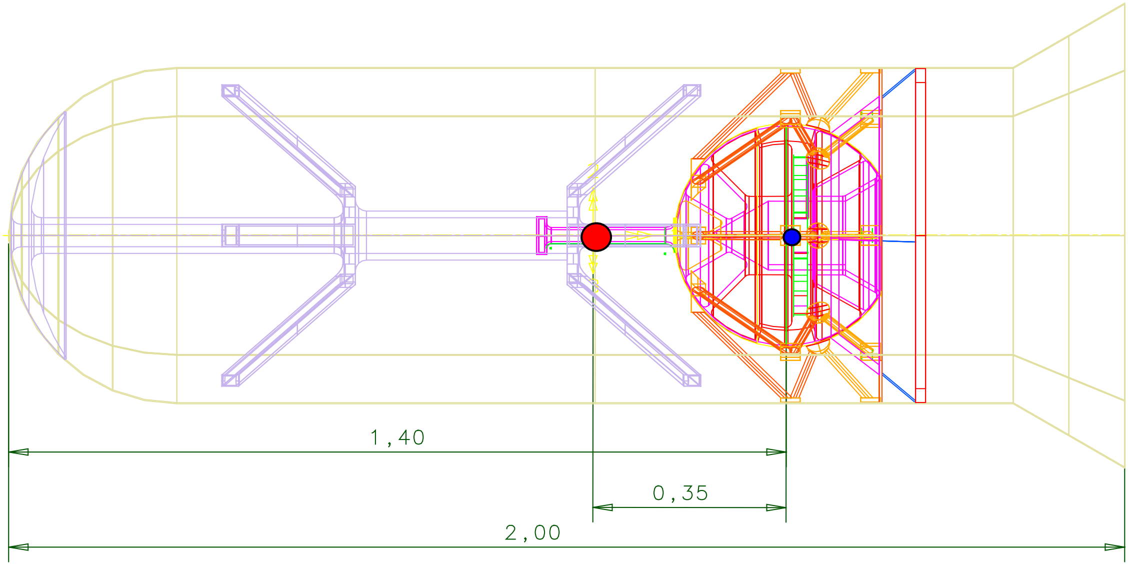



**Figure 19: Latest design drawing of optimized capturing mechanism inside the ACCD geometry with major dimensions in [m] [4]**

## 4.3 Towing airplane requirements

Technical requirements of the tow-aircraft are given in [11]. 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 [11].

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 [11]. 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 3.3.1.1).

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, one should seriously consider 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 an unmanned towing aircraft will 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.

DLR performed a preliminary technical feasibility assessment of the airliner’s towing performance [18]. To ensure that the aircraft and stage could operate in the towing configuration, the flight envelope was computed as an example for a B747-400 with four CF6-80C2A5 turbofans connected to a generic winged RLV stage of approximately 50 tons return mass. As can be seen in Figure 20, the towing operating point ($TOW_{ref}$) is well within the limiting speeds. Performance speeds of the RLV-stage and the 747-400 are quite similar (Figure 20), highlighting the suitability of this aircraft for the mission. 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 B747 resulting in a slightly reduced flying envelope with lower maximum ceiling [18].

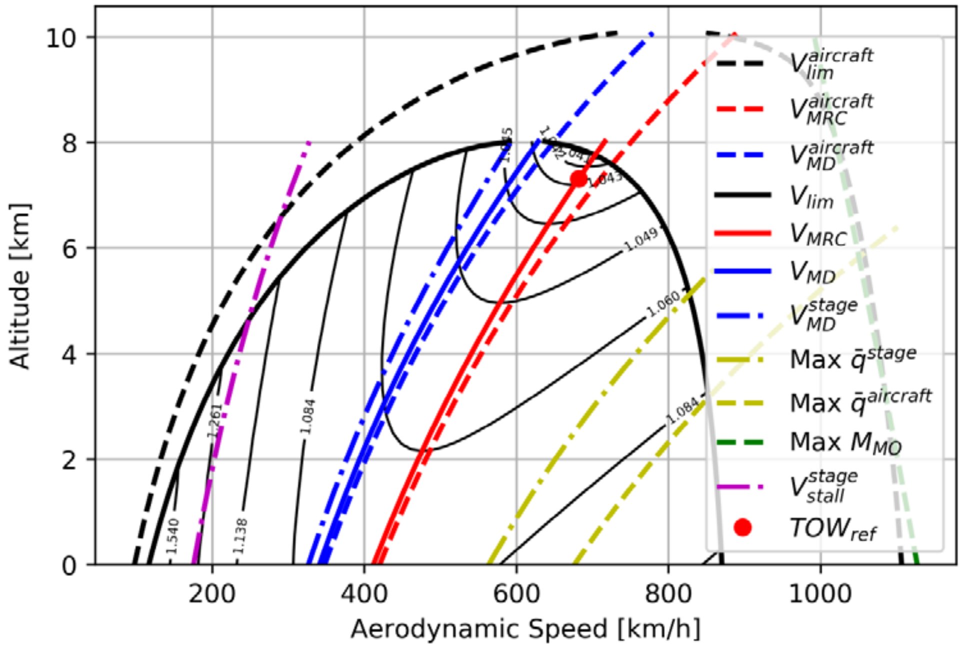



**Figure 20: Calculated flight envelope for B747-400 and typical RLV-first stage towing configuration [18]**

## 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 downrange 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

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 [4]. 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 21) 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

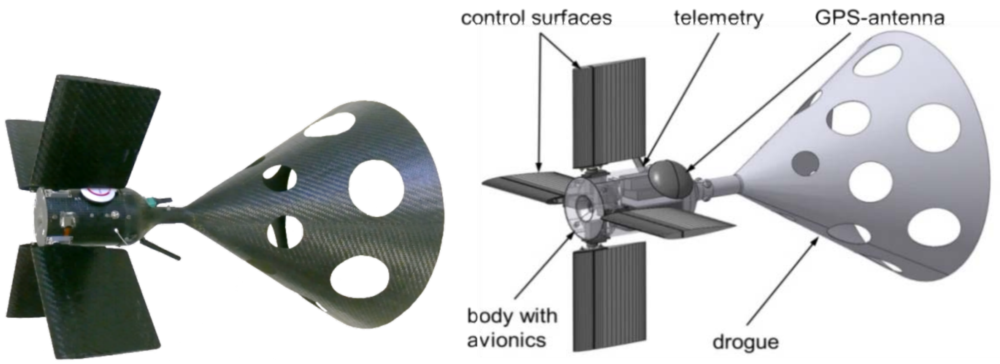



**Figure 21: ACD prototype device and drawing showing major subcomponents [4]**

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 [4].

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 22.

The upper graph of Figure 22 compares the towing air-craft 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 22.

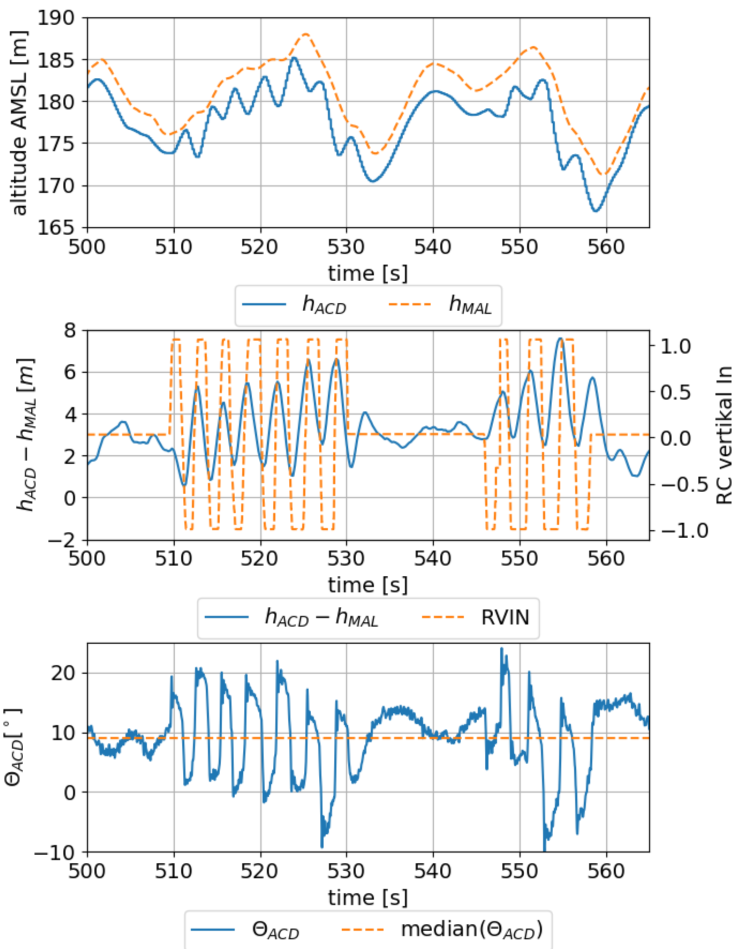



**Figure 22: Altitude, altitude offset, and pitch angle during vertical motion [4]**

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 [4].

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. [4]

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. [4]

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 23). 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. [4]

**Figure 23: 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. [4]

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. [4]

# 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 24. The definition of the European Commission is very similar [24]. 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 24.

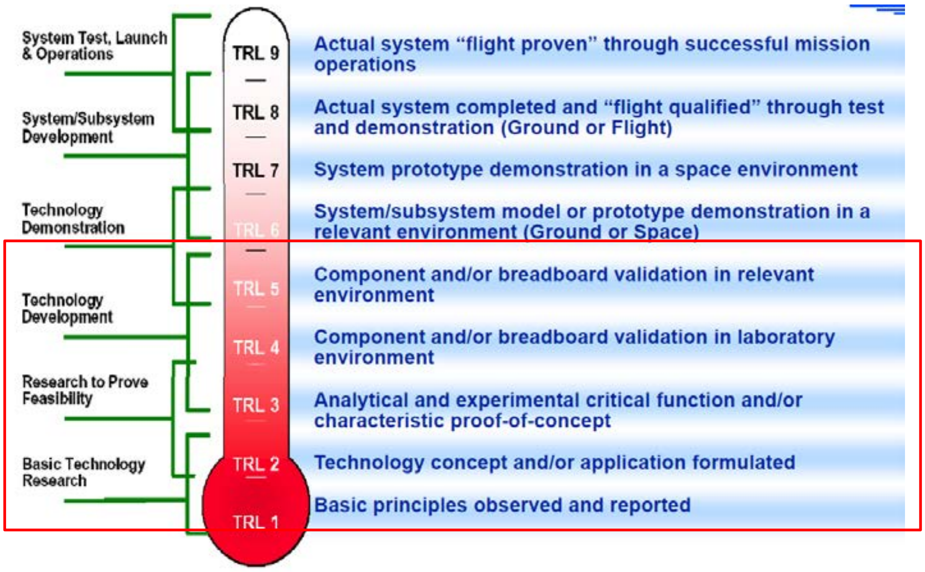



**Figure 24: Technology Readiness Level (TRL) according to NASA**

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 25.

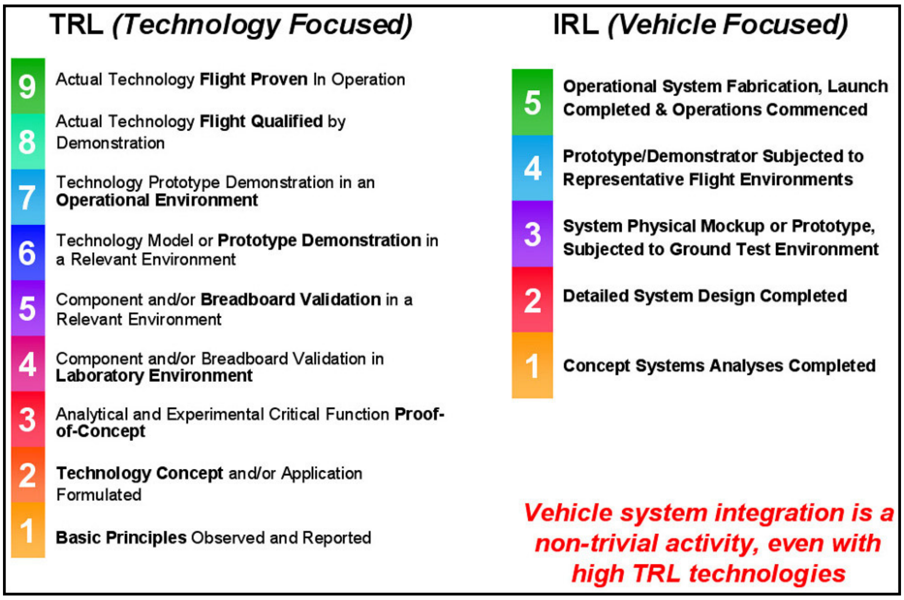



**Figure 25: Technical and Integration Readiness Level Definitions according to NASA [25]**

## 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." [25] Exactly this methodology will be implemented in FALCon for the establishment of the "In-Air-Capturing" roadmap.

The NASA PDA model [25] 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 26).

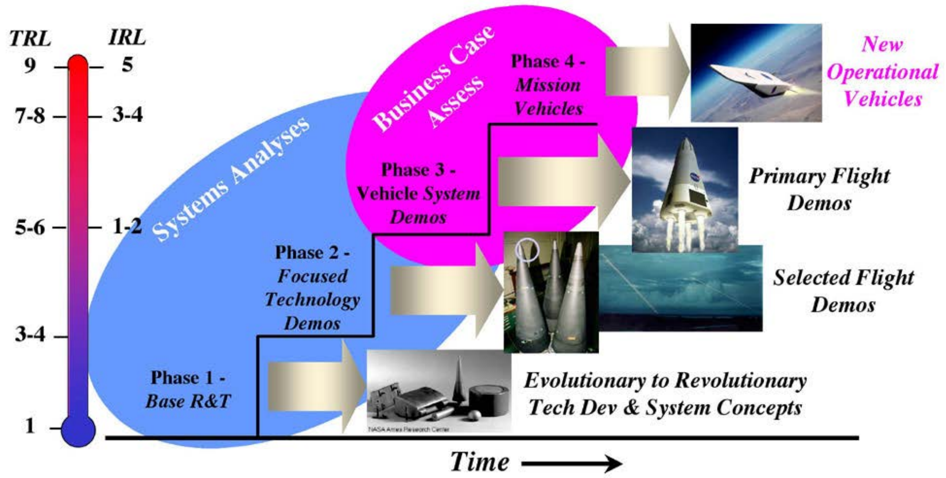



**Figure 26: Phased Development Approach (PDA) for technology maturation according to NASA [25]**

The PDA model uses both the standard Technical Readiness Level (TRL) and the Integration Readiness Level (IRL), defined in Figure 25, to gauge the maturity of technology components and the vehicle system integration. Figure 27 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.

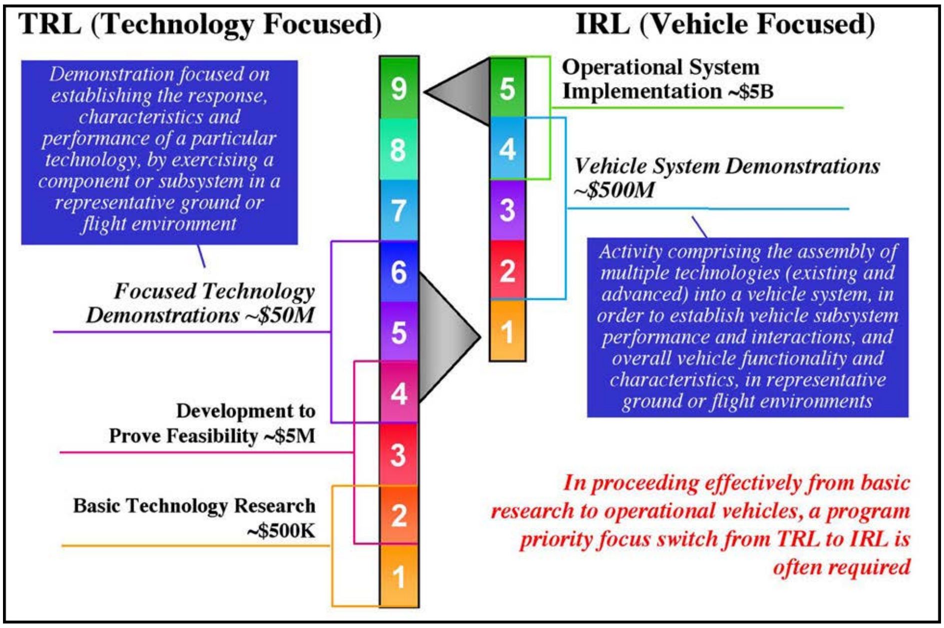



**Figure 27: Relationship between Technical and Integration Readiness Levels according to NASA [25]**

Activities in FALCon to maturase the "In-Air-Capturing"-method are in the TRL range 3 to 4 called in Figure 27 "*Development to Prove Feasibility*" and exactly at the point where the IRL activities are to be initiated.

The NASA report [25] 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 [25].

Further, it is interesting to see in Figure 27 an order of magnitude cost assessment in $US for the subsequent development steps or phases. Technology demonstrations are evaluated by [25] to be much less expensive than system demonstrations because the flight tests can often be flown on proven vehicles, greatly reducing the risk of flight failure. This is explained by the situation that the risks associated with the low TRL of the demonstration technologies are mitigated by the high IRL of the host system. Note, the 5 M$US associated to the Technology Demonstrations in Figure 27 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 [4] for a more detailed list of these activities). Therefore, the cost assessment given in Figure 27 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
    - o 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 18 and Figure 19 from [4].
  - 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 are intended.
  - 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 effort is 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 27, 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 [3]. 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 should 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 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 [27]. 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 [27] 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 3.3.1). 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 3.3.2 and [3]) 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 [4]) 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 [5], [8], [15], [20], [22]. 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 [4]. 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 44 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 3.3.1 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 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 a preliminary version is described in the following section 7.

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 [4]. 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 [4], [28] 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 [4]. 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. The company has announced they intend to recover the first stages in the near future using mid-air retrieval (MAR) [29].

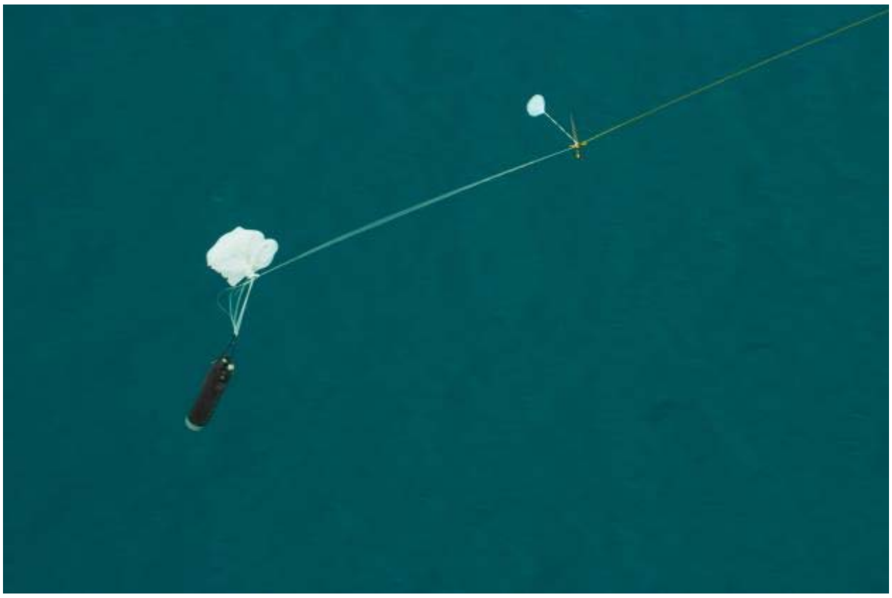


**Figure 28: Flight demonstration MAR of Electron first stage test article [29]**

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.

The following spaceflight related applications are directly relevant to "In-Air-Capturing" and have been proposed recently:

- 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. 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.
- 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.

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

Beyond the above listed spaceflight related synergies also an aeronautical application has been identified with many technological similarities to the automatic approach and formation flight maneuver. This application is the automatic air-to-air-refueling of long-range UAV which could see both military and civil use.

# 7 Technical maturation plan and preliminary development roadmap

The development roadmap for “In-Air-Capturing” is to be defined in cooperation with the European stakeholders e.g. ESA, CNES, ONERA, CIRA, VKI, DLR and industrial primes and “New Space” companies. This process will consider the classical Technology Readiness Level (TRL) definition (e.g. [25]). Although, the TRL-approach is helpful, it has been found not necessarily sufficient for successful development of RLV. Therefore, a NASA 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.” (see previous section 5.2 and [25]) The combination of TRL, IRL and PDA will be 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 most recent technology development status from the DLR AKIRA-project. Results on IAC from this project are summarized and compared to the planned FALCon-project activities in [4]. 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 29 has been proposed in 2018 [2] [7]. 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 are considered as a suitable framework.

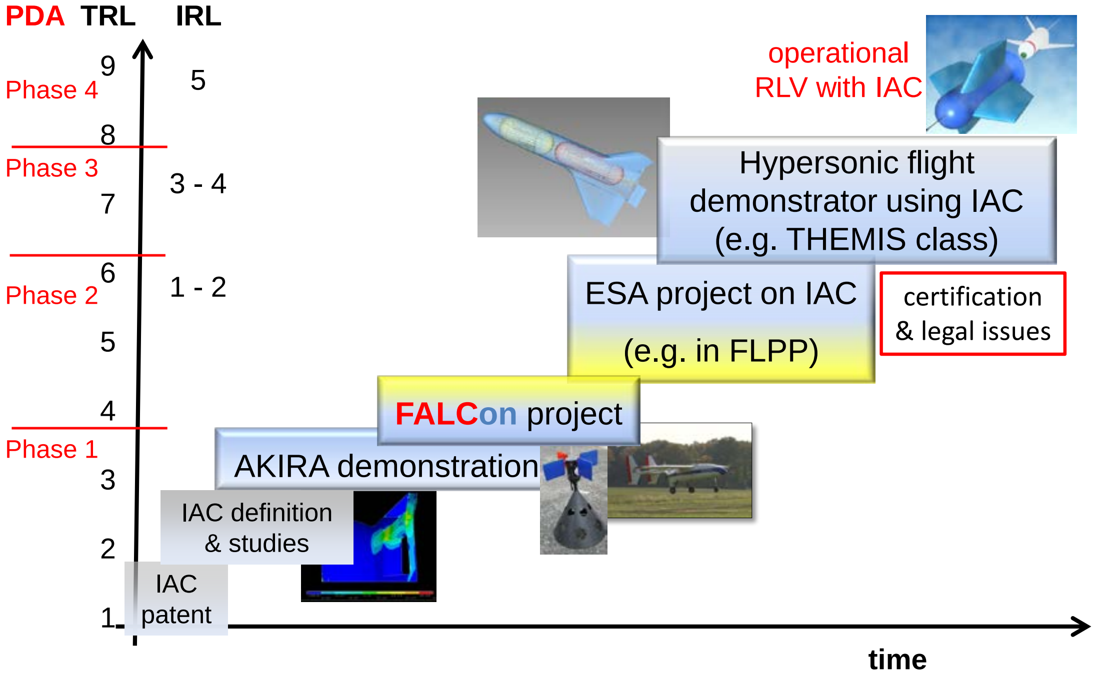



**Figure 29: Early “In-Air-Capturing”-Development Roadmap proposed before start of the FALCon project [2] [7]**

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

The subsequently presented 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 30. The center of each box is located close to the intended TRL and its width represents approximately the time extension of the activity.

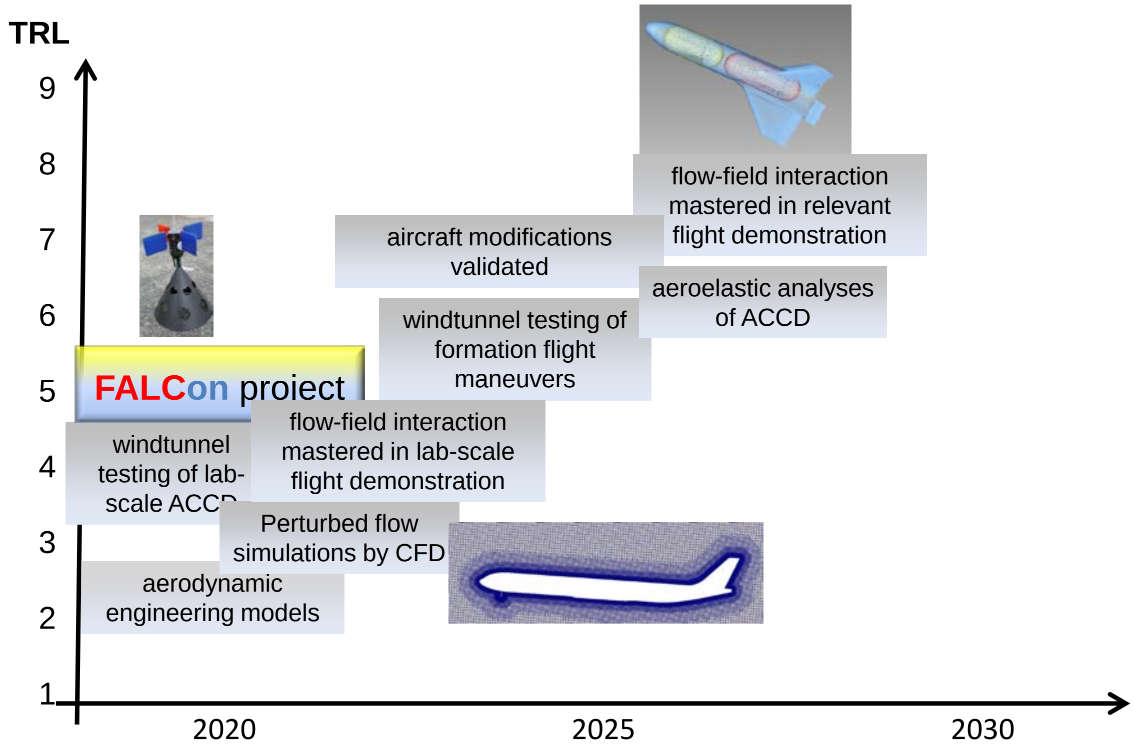



**Figure 30: Development Roadmap proposed for aerodynamic technologies**

Major activities of the future will have to focus on the formation flight of different vehicles in close proximity and perturbed wake flow conditions.

### 7.2.2 Structures and Mechanics

The most important technology development activities in the field of structures and mechanics are presented in Figure 31. The center of each box is located close to the intended TRL and its width represents approximately the time extension of the activity.

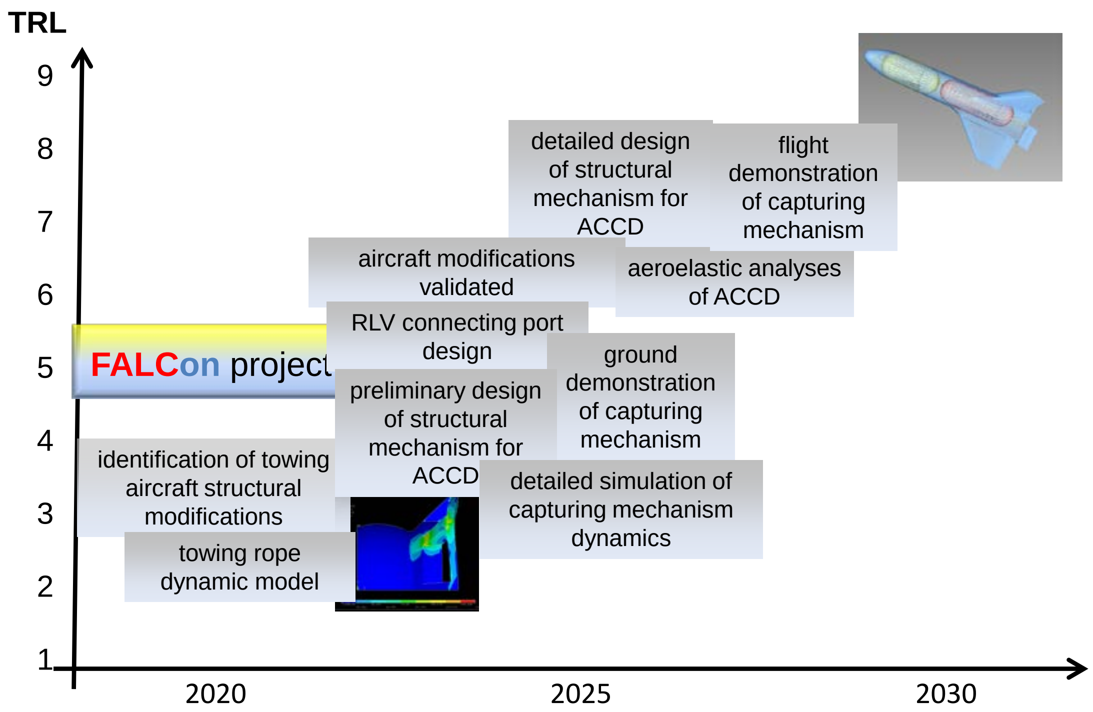



**Figure 31: Development Roadmap proposed for structures and mechanics**

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 in Figure 32 and Figure 33. The center of each box is again located close to the intended TRL and its width represents approximately the time extension of the activity.

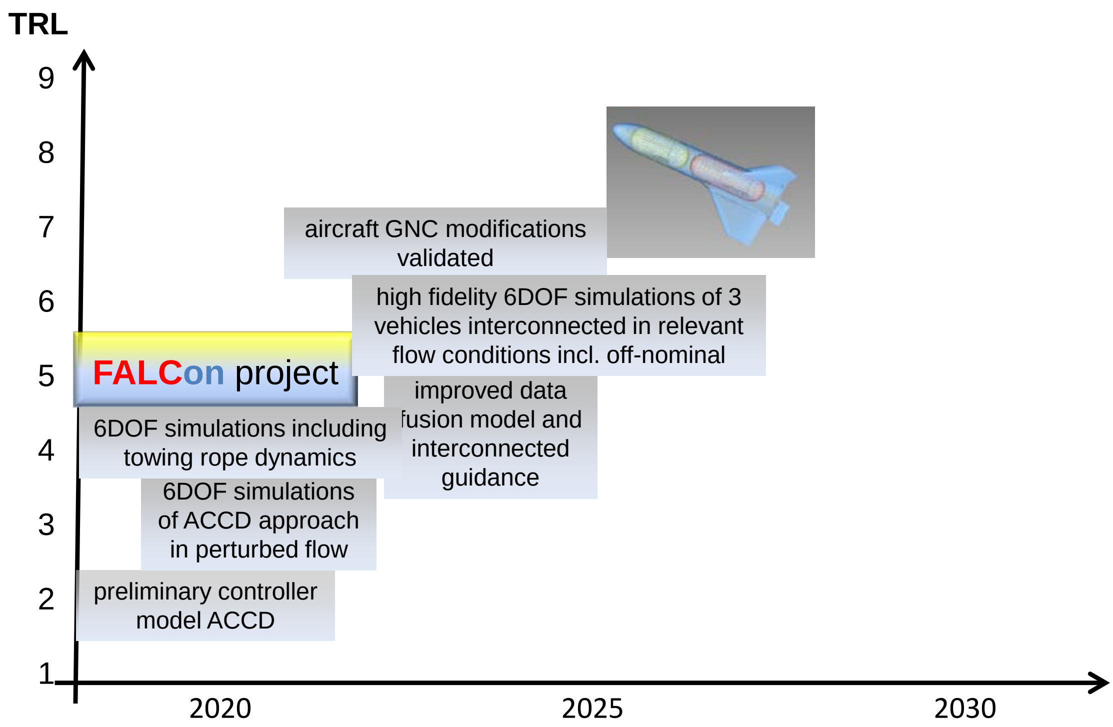



**Figure 32: Development Roadmap proposed for GNC simulation (full-scale)**

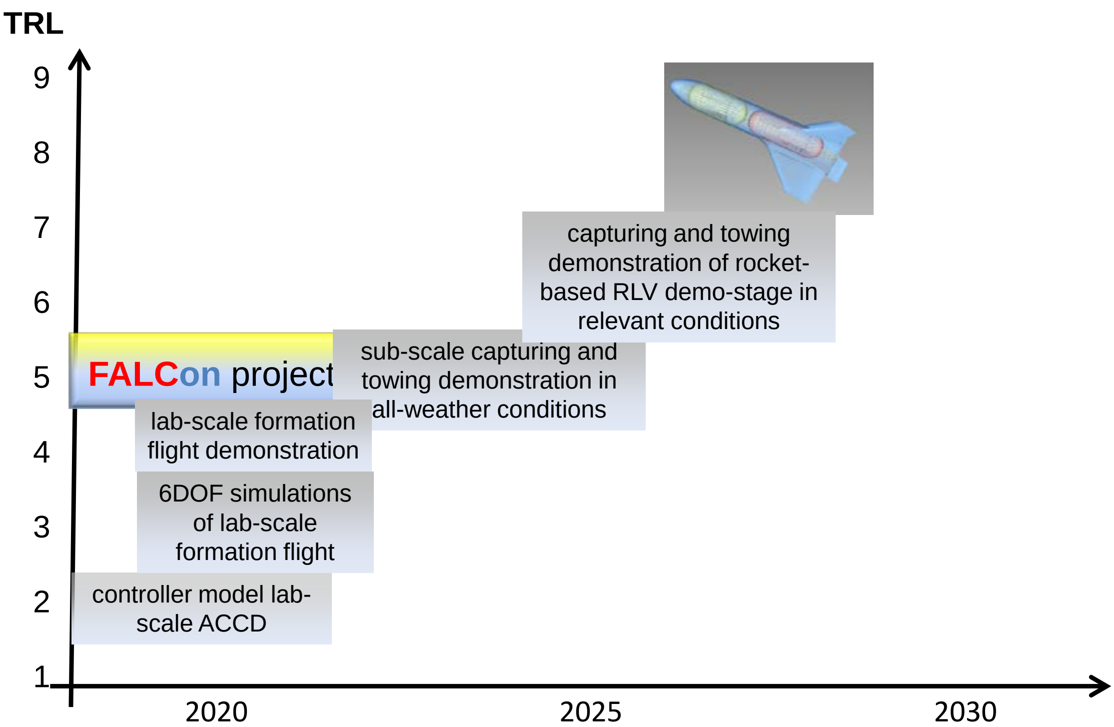



**Figure 33: Development Roadmap proposed for (subscale) flight testing**

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-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.

### 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 34. 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.

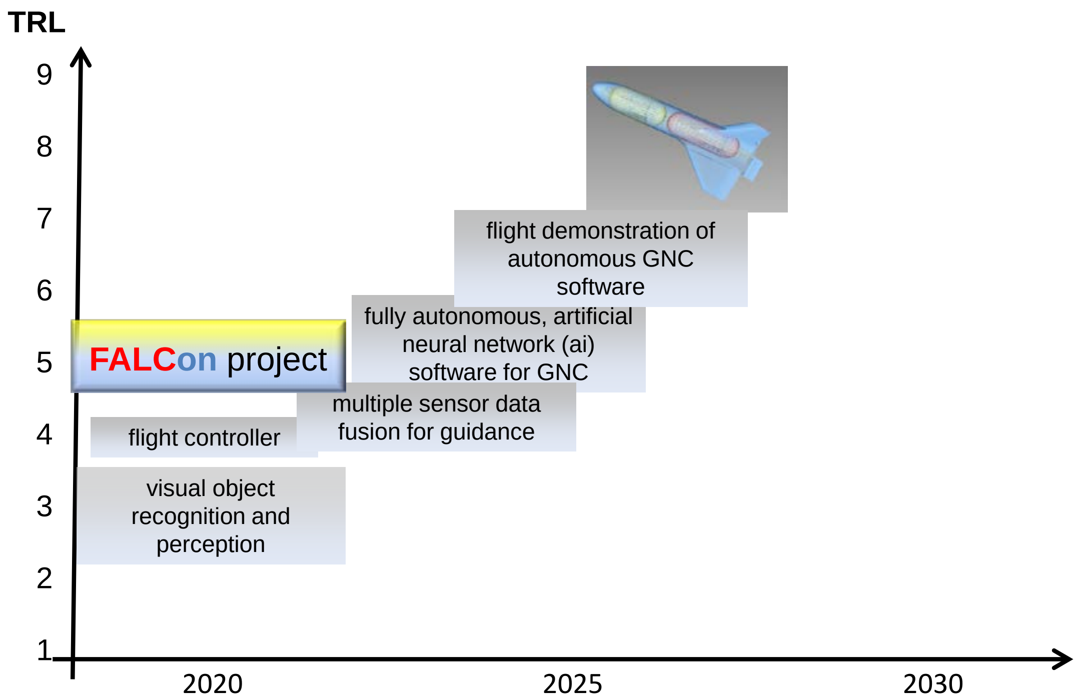



**Figure 34: Development Roadmap proposed for software and IT**

### 7.2.5 Integration readiness

An IRL-centric view on "In-Air-Capturing" development is presented in Figure 35. 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.

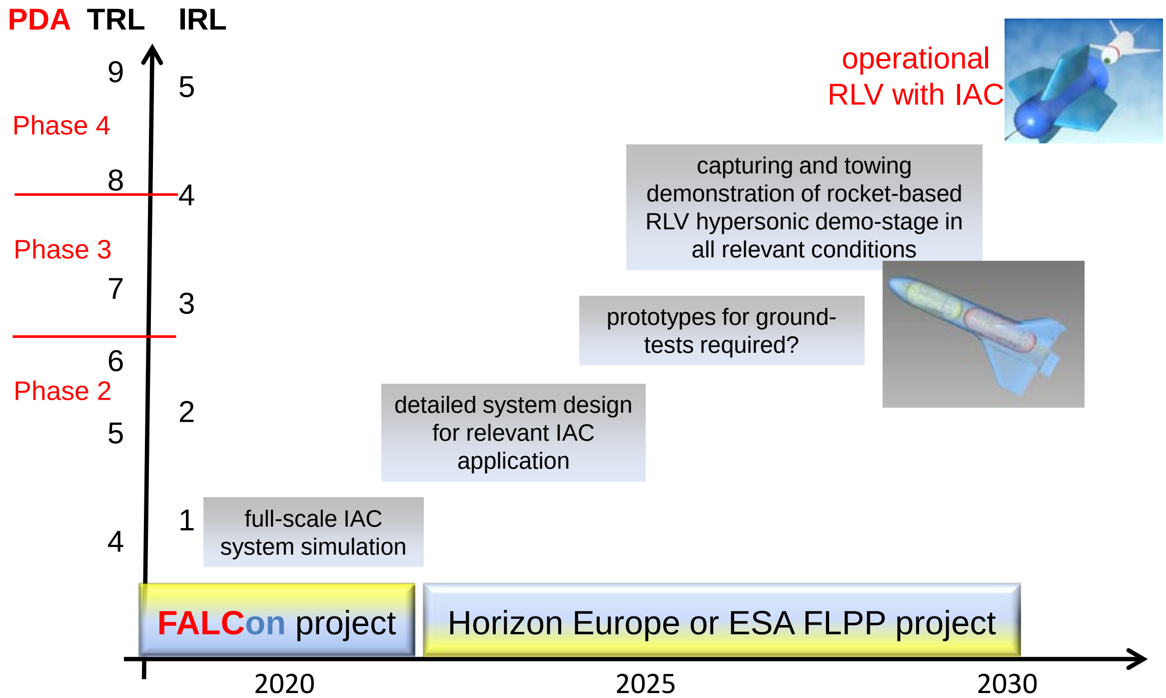



**Figure 35: Development Roadmap proposed for "In-Air-Capturing" Integration Readiness**

## 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. Figure 36 shows which system demonstration milestones need to be achieved in the coming 5 to 8 years. After successful lab-scale demonstration in FALCon 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 are to be addressed in the second half of the decade when a consolidated scenario has been established.

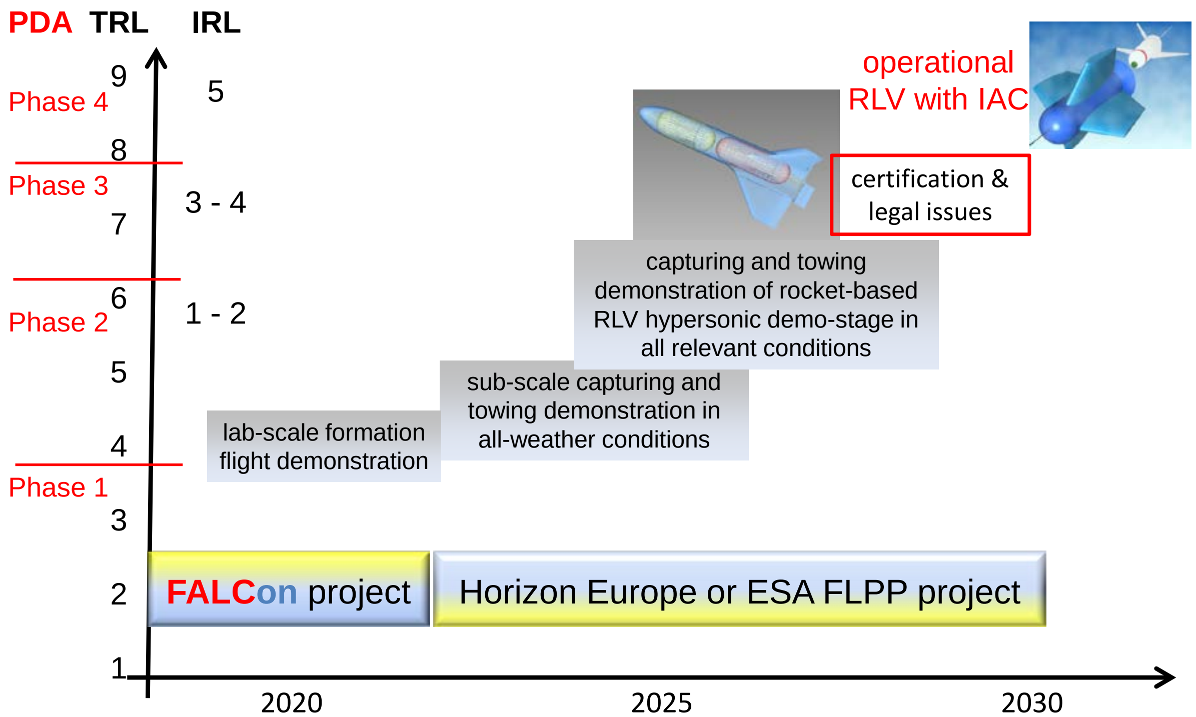



**Figure 36: Development Roadmap major system demonstrations**

The development roadmap shown in Figure 36 is oriented on a large-scale launcher and its RLV lower stage. Alternate operational scenarii of the "In-Air-Capturing" technology on potential micro-launchers or capturing reentry configurations or payload fairings have been proposed (see section 6 on page 33). Those applications would probably need an adapted development of the major system demonstrations. Such roadmaps are planned to be worked-out during the first European stakeholder's workshop on "In-Air-Capturing".

# 8 Conclusion

This is the first report on the “In-Air-Capturing” development roadmap and describes the initial version defined within the FALCon project. This description serves as an input for a European stakeholders’ workshop.

An overview on the functional characteristics of “In-Air-Capturing” is provided and the performance and economic interest are summarized.

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 can be seriously considered for the next generation of a completely new launch vehicle.

The presented results and roadmap proposal are open for a European debate. Ideas for additional, alternative applications are welcome and should be evaluated how they could be merged in the development and verification process.

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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 |