FALCon

Formation flight for in-Air Launcher 1st stage

Capturing demonstration

Scaled Experiment Scenario Description

Deliverable D2.3

EC project number 821953
Research and Innovation action
Space Research Topic: SPACE-16-TEC-2018 – Access to space

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Deliverable Reference Number: D2.3

Due date of deliverable: T0+6

Actual submission date: T0+9

Start date of FALCon project: 1st of March 2019

Duration: 36 months

Organization name of lead contractor for this deliverable: DLR

Revision #:

Dissemination Level		
PU	Public	**X**
PP	Restricted to other program participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

APPROVAL

Title	issue	revision
Scaled Experiment Scenario Description	2.0	1

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Abbreviations

ACCD	Automatic Controlled Coupling Device
CoG	Center of Gravity
CoM	Center of Mass
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IAC	In Air Capturing
LiDAR	Light Detection and Ranging
MECO	Main Engine Cut-Off
RADAR	Radio Detection and Ranging
RLV	Reusable Launch Vehicle
RLVD	Reusable Launch Vehicle Demonstrator
RTD	Research, Technology & Development
TAD	Towing Aircraft Demonstrator
TN	Technical Note
TRL	Technology Readiness Level
TSTO	Two Stage to Orbit
WP	Work package

1 Description of full-scale RLV Scenario using In Air Capturing

The following section presents an overview about the real, full-scale RLV cycle. The focus lies on the In-Air-Capturing phase that is also in the focus of the scaled demonstration of the FALCon project. The concept of the scaled demonstration is presented in section 2.

1.1 Overview complete RLV cycle

A schematic of the reusable stage's full operational RLV-cycle is shown in Figure 1. The whole cycle can be divided in seven phases:

1. Lift-off launcher
2. MECO of launcher and stage separation
3. ballistic trajectory and glide phase of winged booster stage
4. In-Air-Capturing (only this phase is part of the scaled demonstration
5. Towing
6. Separation of towing connection
7. Glide landing of winged stage

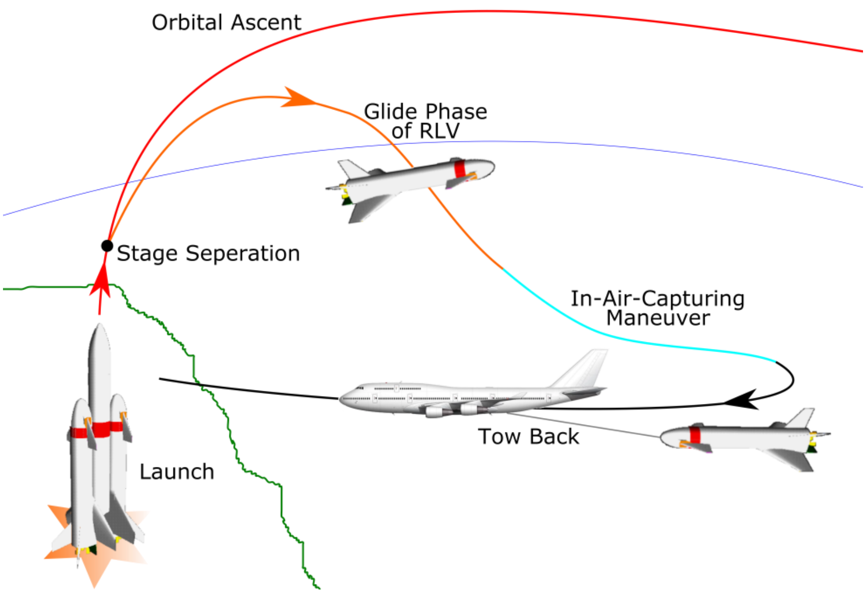


Figure 1: Overview over whole RLV/IAC cycle

At the launcher's lift-off the capturing aircraft is waiting at a predefined rendezvous area. After main engine cut off (MECO) the reusable winged booster stage is separated from the rest of the launch vehicle and follows a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and enters a steady gliding flight path. At this point a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system. Differently, within the in-air-capturing method, the reusable stage is awaited by an adequately equipped large capturing aircraft, offering sufficient thrust capability to tow a winged launcher stage with low lift to drag ratio. The entire maneuver is conducted subsonic in an altitude range from around 8000 m to 2000 m. The velocity of the RLV during the maneuver is approximately Mach 0.4 - 0.5. After successfully connecting both vehicles, the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released from its towing aircraft and autonomously lands on the landing runway similar to a conventional sailplane.

1.2 In Air Capturing Phase

The In-Air-Capturing phase starts approx. 500 seconds (see below at Figure 3) after the lift off of the booster and ends with separation of the booster stage and the towing aircraft. The fourth phase (In-Air-Capturing) can be divided in three sub phases:

4. In-Air-Capturing
   4.1. Rough formation based on a global/absolute positioning system
   4.2. Fine formation based on relative sensor information (Radar, radio beacons, visual data, …)
   4.3. Contact between coupling unit and winged booster stage.

To initialize phase 4.1 an adequate towing aircraft loiters in approx. 8000 m near to the assumed glide trajectory of the booster stage. If both vehicles are in radio distance the booster stage transfers its state (trajectory, position, velocity, etc.) continuously to the towing aircraft. The towing aircraft controller uses this information to determine an interception trajectory, with the aim to acquire a state vector (trajectory, velocity, gliding path, etc.) in front of the booster stage to build up a stable formation. The approach of the towing aircraft and the positioning ahead of the booster stage bases in general on GNSS information and the respective inertial measurements data of each vehicle. At the end of this phase the two vehicles have a stable formation with fixed position deviations within the limits of the GNSS accuracy. The velocity of the whole formation is between 150 m/s to 110 m/s, mainly depending on the L/D ratio and mass of the RLV stage. The relative velocity between the vehicles should be less than 2 m/s. Both vehicles follow a straight trajectory with a glide path of approx. -8 to -12 degrees.

The booster stage has only limited controllability and no propulsion after reentry from orbit and will thus have the flight performance of a passive glider with poor flight characteristics and high inertia, as described in section 1.3. The towing aircraft could be a modified civil or military transport aircraft, which has the necessary power for towing the client. However, their high mass and limited maneuverability pose a challenge in the context of the In-Air-Capturing maneuver. To compensate the limited maneuverability and agility of both aircraft a further active/agile device was included in the maneuver, an aerodynamically controlled capturing device (ACCD, compare Figure 2) [1]. The ACCD is a trailed system just like trailed measurement probes, but equipped with aerodynamic control surfaces and an independent control system to compensate/decrease actively deviations between the RLV and the towing rope.

If all the requirements, written above, are fulfilled, which can be achieved in the frame of GNSS accuracy and aircraft agility, the ACCD will be extracted from the tow aircraft. When the ACCD arrives in its initial position, it means the towing rope is pulled off, phase 4.2 starts. This phase bases on the final formation requirements from phase 4.1 and has the aim to minimize the deviation between ACCD and RLV and to enable a subsequent coupling. The formation in phase 4.1 is set up only GNSS data and inertial data and can only been implemented in accuracy limits[1] of this data.

To acquire more precise position information, image based environment perception is used to estimate the ACCD positon relatively to the RLV. Possible sensors are camera, LiDAR or RADAR. In the current state of investigation, these sensors are located in the nose of the RLV to detect and track the relative position of the ACCD with respect to the RLV coupling probe. The deviation among the ACCD and probe will be transmitted to the ACCD.

[1] For Example, the US government commits to broadcasting the GPS signal in space with a global average user range error (URE) of ≤7.8 m (25.6 ft.), with 95% probability for Standard Positioning Service (SPS) [4].

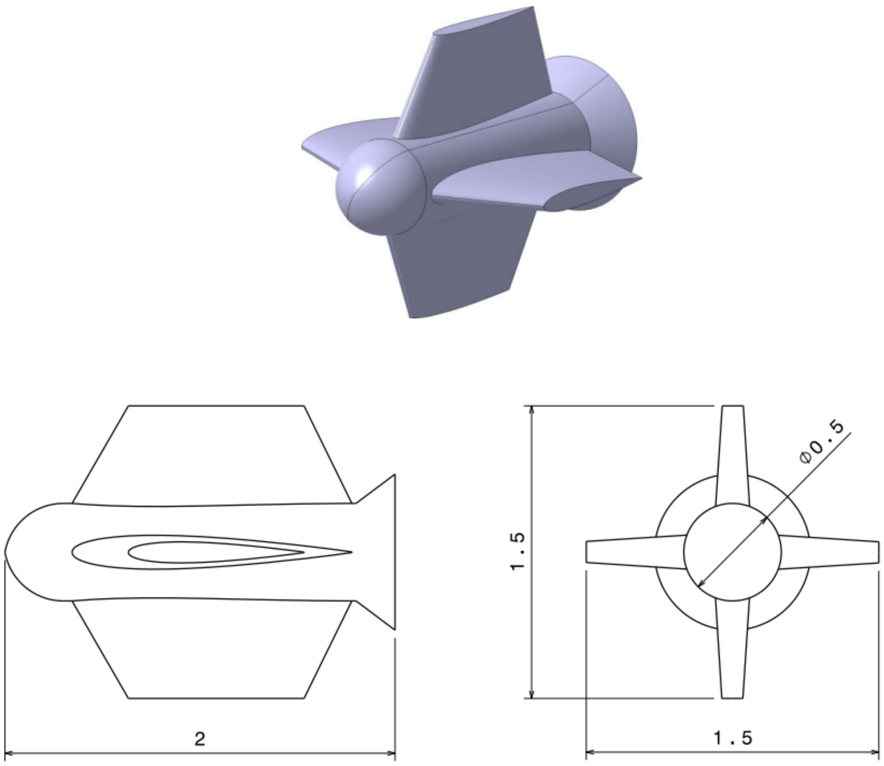
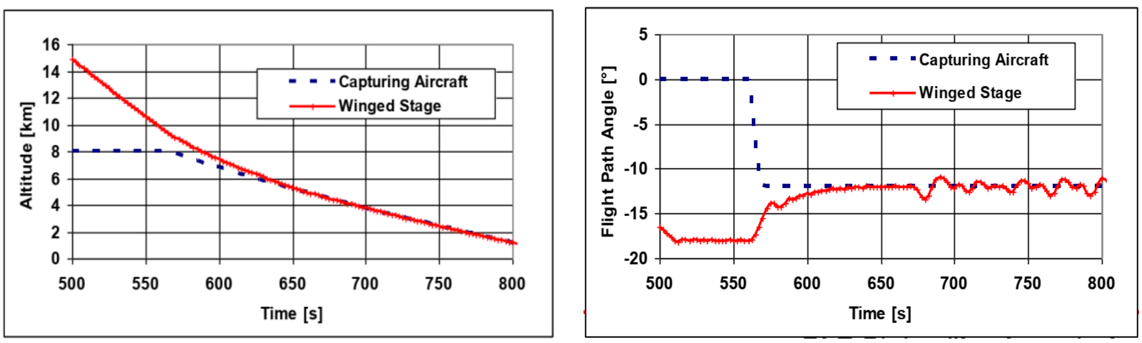


Figure 2: Overview of a preliminary ACCD design (Units: m)

As described above phase 4.1 is the basis of the implementation of phase 4.2. The GNSS-based formation between the towing aircraft and the RLV generates a relative stable frame. The manipulation of the ACCD position inside this frame is realized by using the active control surfaces of the ACCD and the possibility to extract and retract the towing rope. These motions enable a three dimensional positioning of the ACCD inside the “fix” formation between towing aircraft and RLV stage.

Based on movements of the ACCD it should be possible to locate the ACCD in front of the coupling probe of the RLV-Stage. With a final extraction of the towing rope the drogue will move over the probe and an automatic lock will connect the probe with the drogue to transit to the towing phase (5.) of the whole RLV-Cycle (see section 1.1).

The requirements of the IAC-phase (phase 4 of the whole RLV-cycle, see section 1.1) are an altitude range between 8000 m and 2000 m above sea level, a velocity between 150m/s to 110m/s and a glide path of -12° to -8° [2]. Figure 3 shows simulation results of the RLV and the towing aircraft behaviors during the fourth phase following these requirements. Based on these assumptions, a horizontal flight path with the length of 28227 m in a period of 188 s is overflown. This time slot should enable three repetitions of phase 4.2. Meaning, the RLV following its initial path and the GNSS formation being stable, the ACCD has the chance to repeat a coupling attempt three times.



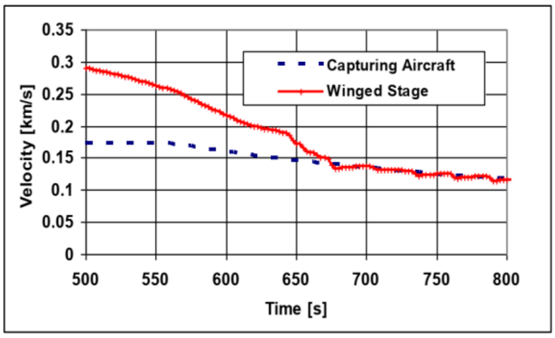


Figure 3: Overview Altitude, gliding angle and Velocity of the real IAC maneuver [2]

1.3 RLV Design

The typical range of subsonic, trimmed lift-to-drag ratio (glide ratio) and center of mass position for typical RLV stages will be discussed based on a selection of conceptual and operational vehicles. The presented numbers are part of the DLR-SART RLV database and have been obtained as a result of concept preanalysis and recalculation.

The importance of subsonic aerodynamic performance is evident for a reusable launch vehicle first stage which is to be in-air captured and towed back to launch site by an aircraft. The success of the In-Air-Capturing maneuver, the feasibility of the tow back flight and requirements towards the towing aircraft, such as fuel consumption of the towing aircraft as well as reusable stage landing performance is highly dependent on its subsonic aerodynamics performance, see [3].

Below some examples of reusable first stages as well as orbital stages is presented. A selection of this type of stages analyzed in DLR-SART is then used to show typical numbers for RLV aerodynamic performance and CoM (Center of Mass) position.

One concept of a fully reusable RLV system is SpaceLiner, a TSTO vehicle capable of ultrafast, intercontinental transport, see Figure 4.

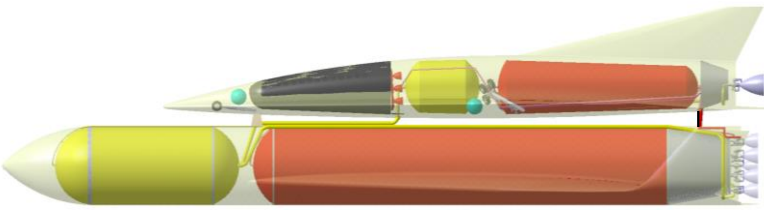


Figure 4: SpaceLiner – Two stage to orbit concept

A variant of the SpaceLiner booster stage, the SLB8V3, is shown in Figure 5. The wing can be adapted depending on the different requirements of hypersonic and subsonic flight. Below the configuration with unfolded wing for improved subsonic aerodynamic performance is shown.

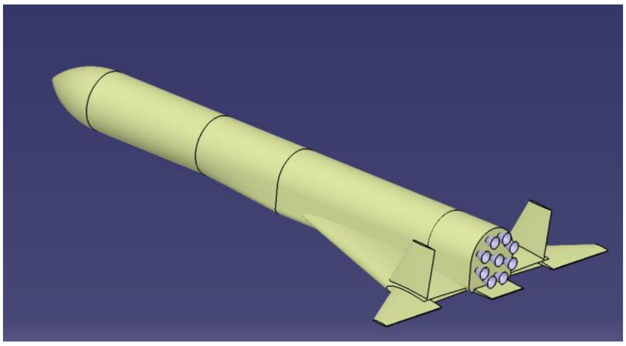


Figure 5: SLB8V3 stage with unfolded outer wing

A reusable first stage (H205) of a concept for delivery of payload to GTO combining an RLV first stage and an expendable upper stage is shown in Figure 6 with its characteristic dimensions (dimensions in mm).

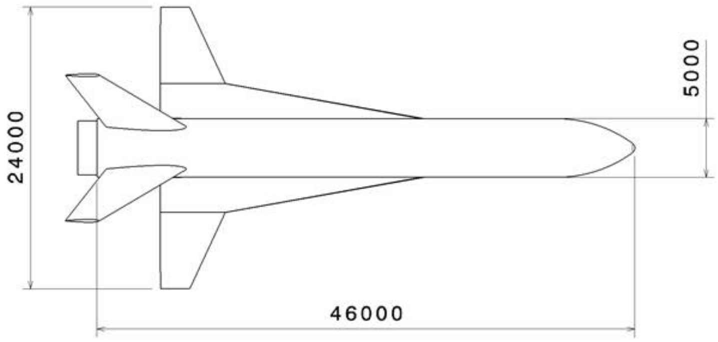


Figure 6: H205 reusable first stage

1.3.1 Typical range of lift-to-drag ratio and longitudinal center of mass position for reusable, first and orbital stage concepts and operational vehicles

Following the introduction of several RLV stage examples, the subsonic, trimmed aerodynamic performance of a selection of this type of stages will be shown. In addition to the lift-to-drag ratio, also the CoM position in longitudinal direction will be shown. This is of importance for the balancing of the aerodynamic pitch moment by aerodynamic control surface deflection (trimming) and hence also for the presented glide ratio values. The typical range of lift-to-drag ratio (glide ratio) for first as well as orbital stage concepts is shown in Figure 7. Focusing on reusable first stages, first stage glide ratios are shown in Figure 8. Maximum values of glide ratio are shown in Figure 9. CoM positions are shown in Figure 10. Aerodynamic performance for all stages was analyzed at an altitude of 6 km, a Mach number of 0.5 and a Reynolds number of 6.5e+6. Center of mass values are obtained from a “dry” mass model.

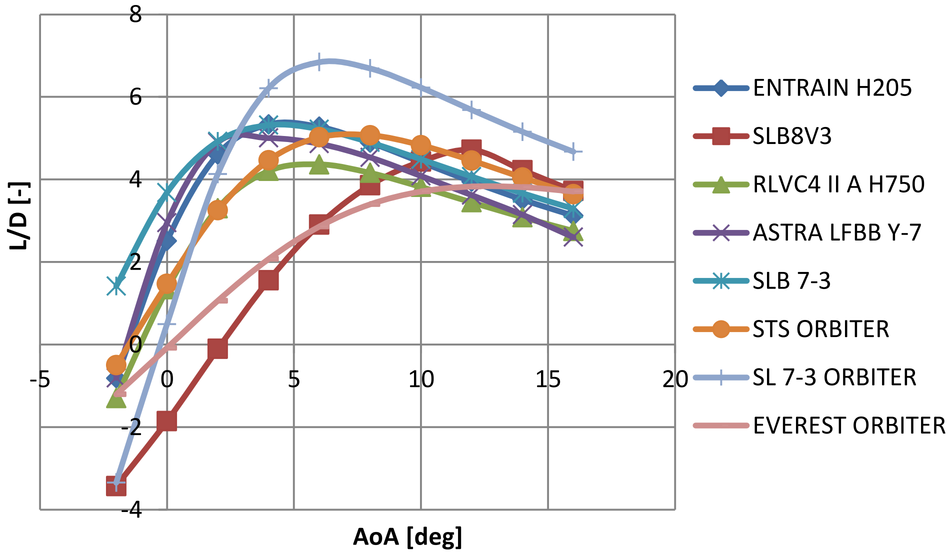


Figure 7: Trimmed glide ratio over angle of attack for booster and orbital stages

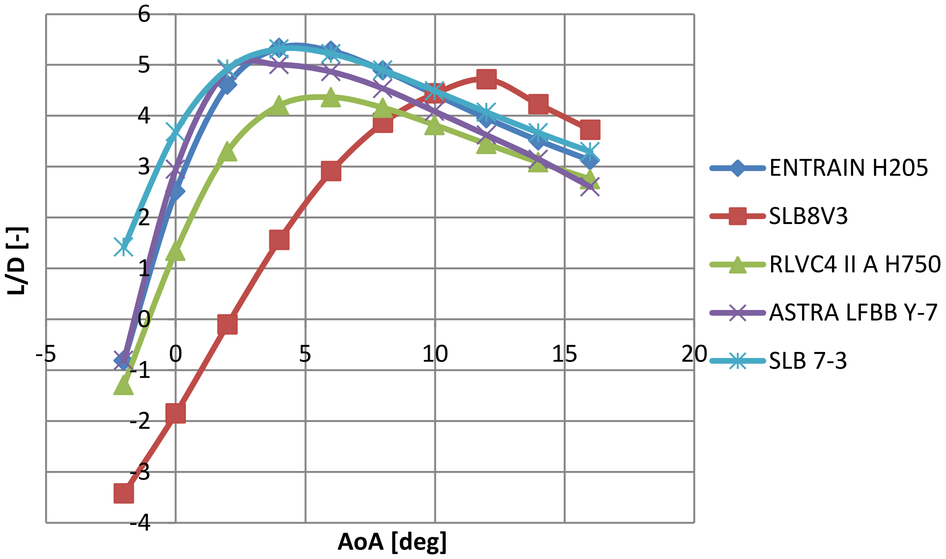


Figure 8: Trimmed glide ratio over angle of attack for booster stages

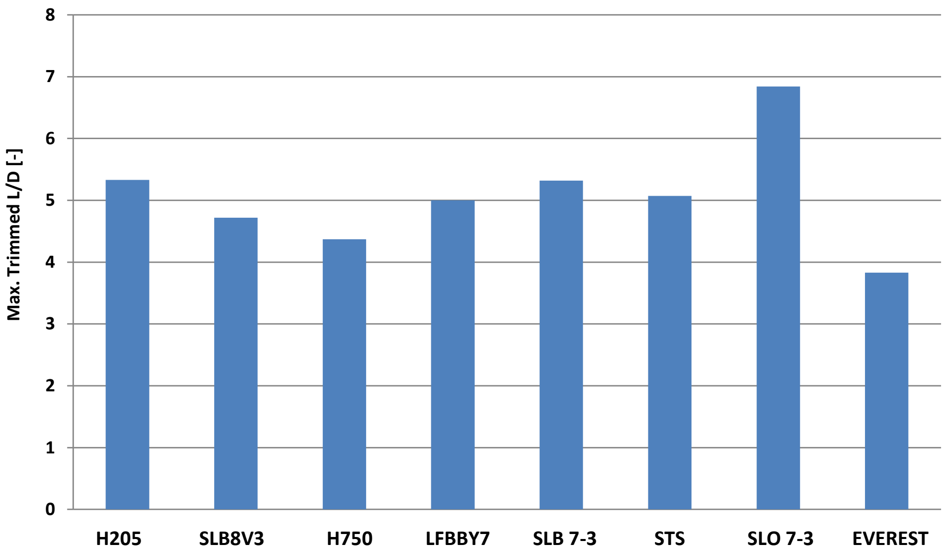


Figure 9: Maximum, trimmed glide ratio for booster and orbital stages

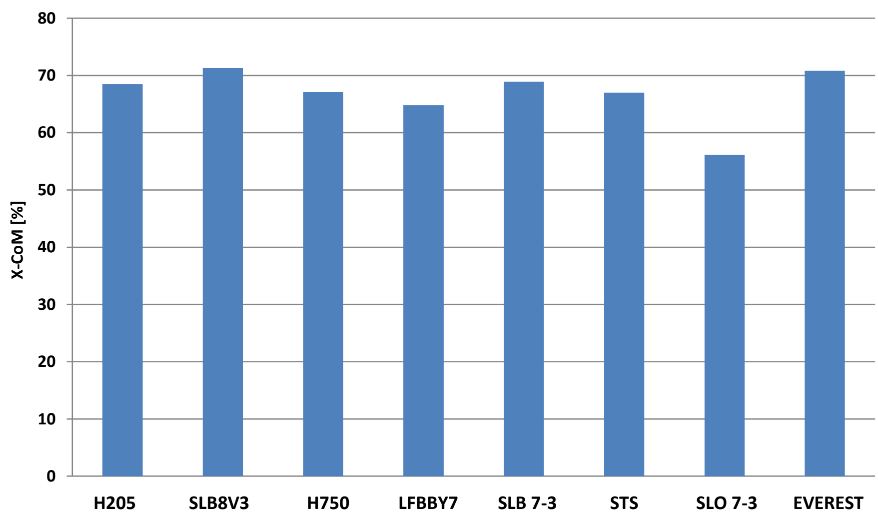


Figure 10: Longitudinal CoM position for booster and orbital stages in percentage of body length

1.3.2 RLV Results Summary

The above results are summarized with respect to the trimmed, subsonic glide ratios as well as the longitudinal CoM positions:

- Range for maximum, trimmed subsonic glide ratio for **booster stages**:
  - 4.4 – 5.7
- Range for **booster stage** x-CoM (% of stage length):
  - 65 – 72 %
- Range for maximum, trimmed subsonic glide ratio for booster and orbital stages:
  - 3.8 – 6.8
- Range for booster and orbital stage x-CoM (% of stage length):
  - 56 – 72 %

2 Scaled Experiment Scenario

2.1 Goal of Scaled Experiment Scenario

The aim of the scaled demonstration is to demonstrate the formation and coupling procedure including sensor concepts between two aircraft demonstrators, towing-aircraft demonstrator (TAD) and winged reusable launcher stage demonstrator (RLVD), by using an aerodynamically controlled capturing device (ACCD). The scope is on the formation flight between the both aircraft systems during the required glide path based on absolute and relative sensor information.

A subsequent tow of the RLVD by the tow-aircraft isn't part of the scenario. The demonstration will be implemented with small up to medium sized UAVs. Engine power of the available TAD is not sufficient to enable a towing procedure.

While the subscale demonstration scenario which will be executed in FALCon differs from the full-scale scenario in certain aspects, the successful demonstration of the subscale scenario is widely applicable to the full-scale IAC scenario. In the following, the major objectives of the subscale scenario and their applicability to the full-scale scenario are described:

- *Autonomous formation flight of the RLVD and the TAD:* A successful formation flight of the subscale scenario is a necessary step towards implementing such automated formation in a full-scale scenario. The subscale scenario encounters similar problems, respectively formation and approximation flight under disturbances (wind, sensor uncertainties, wake field…). For the subscale demonstration, the vehicles are much more agile than their full-scale counterparts, meaning that disturbances have a greater influence on the flight dynamics. Hence, the subscale flight test might even require tighter flight control laws than the full-scale scenario. Nevertheless, both the subscale scenario such as the full-scale scenario will be simulated in the framework of FALCon, thus the applicability of said algorithms can be quantified by the end of the project.

- *Communication between RLVD and TAD:* In the subscale and full-scale scenario, a communication chain between RLV and towing aircraft has to be established. Here, the full-scale scenario also has similar requirements (relative position within certain accuracy, GNSS based positioning plus sensor recognition), but some of the requirements of the full-scale scenario differ (communication and recognition have to be possible in clouds, without sunlight, in rain…). Nevertheless, the recognition and communication algorithms and logic can be used in the full-scale scenario. The upscaling will require some different sensors (e.g. possibly RADAR instead of LidDAR) but the sensor data processing and logic can be used from the subscale experiment. Moreover, the subscale scenario has tighter margins considering accommodation of the required sensors, which are not a problem in the full-scale IAC, since RLV and ACCD have much more volume to accommodate said systems.

- *Subscale scenario flight path angle:* In the full-scale IAC the gliding path of the returning RLV is dependent of its aerodynamic performance, especially of the gliding capability expressed as the lift-to-drag ratio. Usually, RLV stages have worse gliding capacities than commercial aircraft: their glide path angle in stable flight is comparably steeper. Hence, it is very important for the full-scale scenario to reproduce the gliding properties of the RLV stages, since it creates the same problems we will encounter in the full-scale scenario: bad aerodynamic performance and steep gliding path of the RLV stage, good aerodynamic performance of the towing aircraft and thus some kind of breaking device required. Studies at DLR conducted in the past have shown, that RLV stages have L/D ratios between 4 and 6.5, thus a glide path angle of -10° reproduces the average of RLV stage gliding path angles.

- *Subscale demonstration scenario speed and altitude requirements:* The subscale scenario occurs at a different velocity and altitude than the full-scale IAC will. This is partly due to the limited performance of the demonstrator aircraft that does not allow the same speed or altitude than the full-scale scenario will encounter. Considering speed the relevant factor for IAC is the relative velocity of towing aircraft to RLV, which shall be as low as possible in the final phase of capturing. Hence, the successful demonstration of IAC at low velocity allows deducting that at higher velocities, which are in the design space of full-scale vehicle, the coupling can also be successfully executed. Concerning altitude, the more relevant factor is the time that is available for the In-Air-Capturing. This is equal for both full-scale scenario and subscale scenario in our case.

- *Successful capture between RLVD and ACCD/capturing device:* Demonstrating the capability of successfully capturing the RLVD with the capture device for a certain time shows that the most critical part of IAC, matching speed and glide path angle of the towing aircraft to that of the RLV while the ACCD counteracts any disturbances, can be successfully and safely performed. This allows us to assume that it is possible for full-scale vehicles as well.

2.2 Scaled Scenario

The final scaled mission differs in several points from the real mission. In addition, the scaled demonstration is separated in three parts. The central part, the measurement section, contains the implementation of the scaled IAC mission. This section is framed by a preliminary phase and a subsequent phase. The preliminary phase contains the take-off and the necessary preparation of aircraft to enable the entry into the measurement section in the required states. The subsequent phase contains the separation after the IAC formation and the landing of aircraft.

2.2.1 Scaled IAC Experiment Section

The scaled IAC maneuver will be implemented in an altitude between approx. 2000 m and 200 m, with a velocity of roundabout 42 m/s (150 km/h). The non-propulsive RLVD will follow a straight path by -10° glide angle (L/D ratio is approx. 5.6).

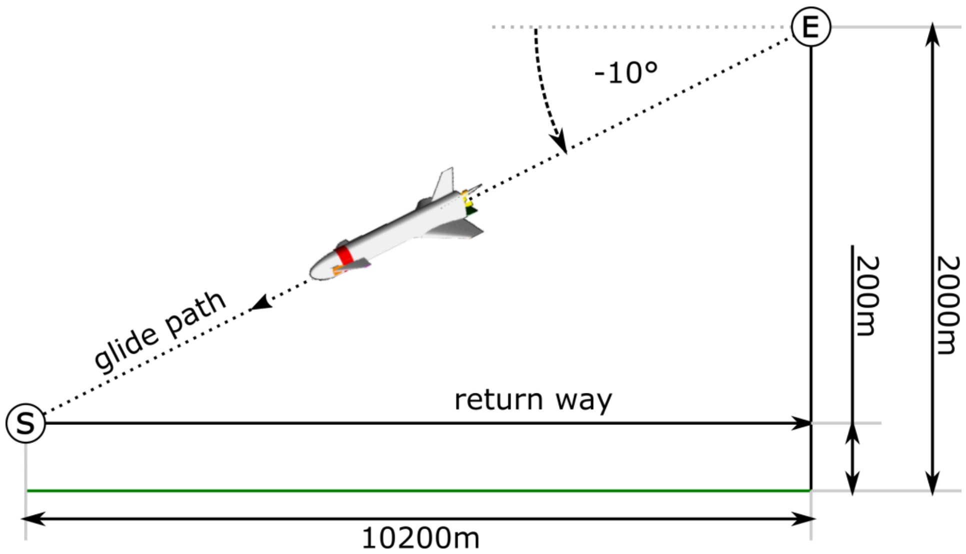


Figure 11: Overview over scaled scenario measuring section

Glide angle and initial altitude lead to a flight path that covers a distance on earth surface of approx. 10.2 km. The respective flight time to this distance is approx. 245 sec. Figure 11 gives an overview about this setup. The point “E” (entry) marks the entry in the central part of the mission at which the IAC will be investigated. Point “S” (separation) marks the point at the end of this central part, at which the formation will be separated and the single aircrafts will be landed independently.

2.2.2 Ascent Phase

The preliminary phase of the coupling demonstration contains the takeoff of the TAD and RLVD and the necessary procedures to achieve predefined states of each aircraft, which is the requirement to go beyond point “E”. The required parameters to achieve this state for the RLVD are shown at Table 2-1.

Table 2-1: Origin state the RLVD at the entry of the IAC Maneuver

Parameter	Value
Glide angle	*Average -10° (+/-1°)*
Altitude	*Min. 2000 m*
Velocity	*42 m/s (+/- 2 m/s)*
Propulsion	*Off or Idle, no additional throttle influences the flight*

For the TAD the required parameter are presented at Table 2-2.

Table 2-2: Origin state the TAD a the entry of the IAC Maneuver

Parameter	Value
Glide angle	*Average -10° (+/-2°)*
Altitude	*2000 m (+/-20 m)*
Velocity	*Adjusted on RLVD*
Towing rope	*Towing rope is extracted. ACCD flies 30 m behind the TAD.*

The preliminary phase starts with the take-off of the TAD. For the take-off the TAD is located on the runway followed by the ACCD which is placed on a start trolley. The TAD and the ACCD are connected by a towing rope which has an approx. length of 15 m. The ACCD doesn’t have a landing gear. The start wagon substitutes the landing gear. When the TAD takes off and the rope transfers the force to the ACCD it will release from the trolley. The trolley stays back at the runway after take-off and will be manually removed. The landing of the ACCD is managed with a parachute that is located in a capsule at the towing rope.

The take-off can occur manually by a remote pilot or automatically by the usage of an automatic take-off controller. If the take-off is performed manually, a switching into an automatic flight mode follows. The mode change will be conducted in a safe altitude, e.g. 100 m above ground. After achieving the automatic flight mode an automatic mission is started that contains a climb up to 2000 m and a subsequent loiter circle in 2000 m, in which the TAD waits for arrival of the RLVD. The radius of the loitering pattern isn’t defined yet. This will be done when the TAD is flying and flight behavior can be evaluated. The procedure is shown in Figure 12 with the green path. The holding pattern is located outside the central planed demonstration section, but close to it.

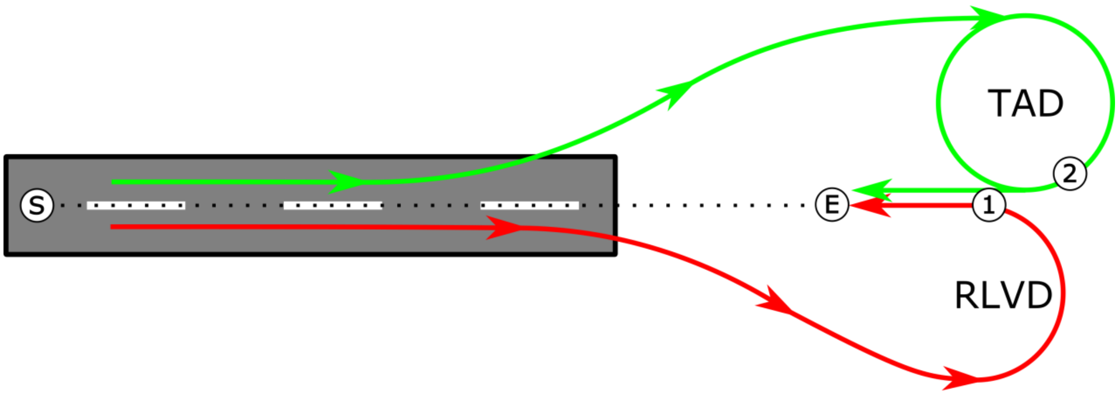


Figure 12: Preliminary mission phases of subscale IAC demonstration

If the TAD successfully follows the pattern, the take-off of the RLVD follows. The take-off of the RLVD may be as well manually or automatically. Depending on the chosen procedure, the mode is changed to an automatic flight mode at a safe altitude (e.g. 100 m). The subsequent automatic mission contains a climb of the RLVD up to an altitude slightly higher than the holding altitude of the TAD followed by a turn, which brings the RLVD on a straight path through points “E” and “S”. The RLVD trajectory is shown in Figure 12 by the red path.

During the turn of the RLVD from the summit (e.g. 2000 m above “E”) to the coordinates of the entry point “E” a communication between RLVD and TAD is built up to prepare the entry into the demonstration phase. The communication is only one-directional, from the RLVD to the TAD and contains the state of the RLVD, with its position and attitude, the velocities along and around all axes and its system time. This information is based on GNSS and inertial measurements. The common time base during the maneuver is CET (UTC+1). The synchronization should base on the GNSS time stamps.

Based on this communication a synchronization of both vehicles with focus on position and time with the goal to achieve a 4D (position and time) positioning of the TAD and RLVD at the entry point “E” of the central demonstration section is performed. The entry point ”E” is separated in two parts “E_1” and “E_2”. Both parts represent the starting positions of the both vehicles for the central experiment section. “E_1” is the entry point of the RLVD. The entry point of the TAD is “E_2” and has an orthogonal, horizontal deviation of n_1=50 m to the planned trajectory of the RLVD. Figure 13 shows this setup. If the RLVD and the TAD arrive at their respective entry points they have also reached the states, described at the Table 2-1 and Table 2-2 .

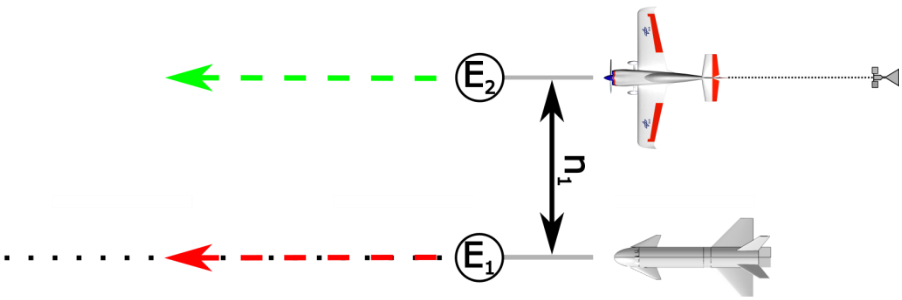


Figure 13: Origin state at the Entry Point of the IAC demonstration

An intermediate step to reach the situation in Figure 13 is a swing by phase, which is introduced by the crossing of point “1” by the RLVD and the point “2” by the TAD, seen in Figure 12. The crossing of point “1” leads to a mode change from the propelled to the gliding flight and the transition from the horizontal to a descent flight with a glide angle of -10°. Point “2” marks for the TAD the leaving of the holding pattern and a transition into the flight path of the actual demonstration section. The points “1” and “2” are located in a way that required time and distance are sufficient for each aircraft to reach the “E”- line at approximately the same moment.

2.2.3 Concluding Phase

The latest point of separation of the IAC formation is the point “S” 200 m above ground at the end of the central part of the IAC demonstration. The starting situation in the formation at this point is that the RLVD follows the descripted scaled IAC trajectory. The TAD flies ahead in front of the RLVD. The ACCD follows the TAD at the towing rope with a length of 15 m. In the case the rope is longer, a reduction of the rope length to 15 m is the first step.

During the rope retraction to the TAD, the TAD also increases its velocity and transitions from the decent flight in to a horizontal flight trajectory. When the horizontal distance between ACCD and RLVD exceeds a safety threshold from 30 m the RLVD restarts its engine and changes to a horizontal flight path.

If both vehicles are on a straight horizontal flight path, the TAD leaves the straight path of the central IAC maneuver with a right turn. This turn introduces a loiter circle trajectory at which the TAD waits until the RLVD is successfully landed.

The RLVD leaves the horizontal extension of the central IAC maneuver trajectory by a left turn, which guides it back to the runway where it lands. If the landing of the RLVD is successful, the TAD leaves the waiting pattern and lands immediately. The described paths of the TAD and RLVD are visualized by Figure 14.

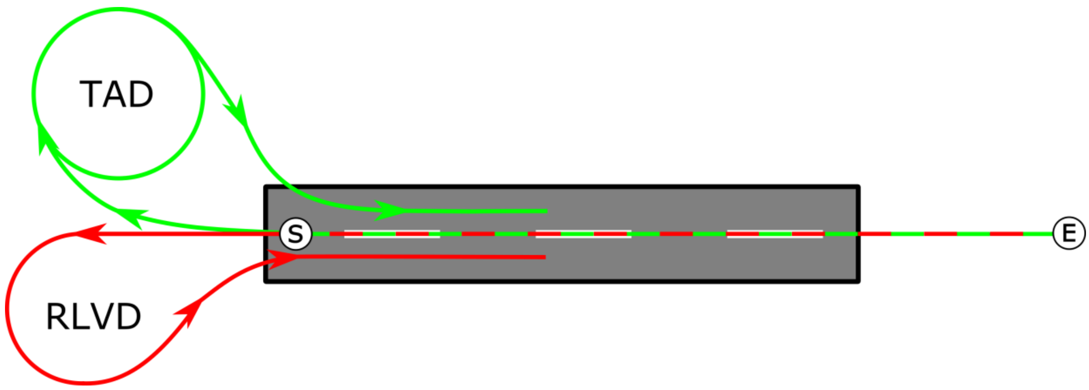


Figure 14: Behavior of the vehicles in the subsequently phase

2.2.4 Coupling Behavior

The following section describes the behavior of the RVLD, TAD and ACCD in the central part of the IAC demonstration, the measurement section, presented in section 2.2.1. The initial state for the following description is the situation in Figure 13. The IAC behavior can be divided in three steps: First is the rough positioning of the RLVD and the TAD with GNSS data, which represent the outer frame of the formation. Inside this frame an optical environment perception which is installed in the RLVD detects the ACCD and estimate the deviation between both vehicles as a second step. The estimated deviations will be provided to the ACCD, which tries to reduce these up to a coupling. The coupling is the final step within the IAC maneuver.

2.2.4.1 GNSS based formation

The starting point of the GNSS based formation is the entry in the central part of the IAC demonstration and by reaching the points “E_1” and “E_2” by the RLVD and the TAD. This situation is described in Figure 15.

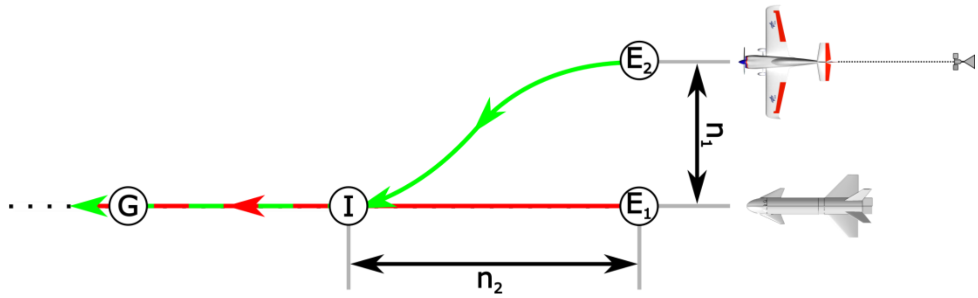


Figure 15: Initial Situation for the GNSS formation

With approaching these points the communication, which was used to achieve these points, is also used to build up the outer frame of the formation. The communication is only in one direction, from the RLVD to the TAD. The content of the communication is the state of RLVD, especially its position, velocities along and around all axes and the system time stamp. All these information are based on GNSS and inertial measurements. In the TAD, where the information will be received, an interception trajectory is computed, which brings the TAD ahead of the RLVD. In this situation, the TAD already tows the ACCD with a rope of approx. 30 m length. The interception trajectory is scheduled in a way that at the moment the TAD crosses the flight path of the RLVD the distance between ACCD and RLVD is approx. 15 m. Hence, the TAD flies ahead the RLVD with a distance of $n_2 >$ 45 m. The resulting situation in the formation shows Figure 16.

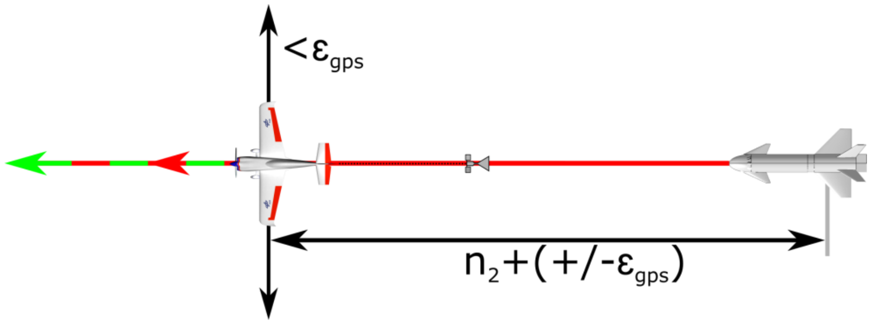


Figure 16: Final setup of the GNSS formation

Based on the accuracy of a standard GPS resolution it's not to be expected that an ideal formation setup can be build up immediately. Rather, deviations are expected which are in a range up to ϵ_{gps}<7.8 m @ 2σ [4] for standard GPS solution depending on atmospheric disturbances, the satellite distribution or the behavior of different GNSS devices.

The communication between both vehicles continues during IAC demonstration to keep the formation stable and constant in relation the RLVD.

2.2.4.2 Vision based formation

After a successful formation build up with GNSS and inertial data the second phase of the formation is started. As described above the GNSS formation is the outer frame of the IAC formation and implements a relative positioning between the TAD and the RLVD. Within this frame, a second relative positioning between the ACCD and RLVD is activated in order to decrease the remaining deviation between the ACCD and the RLVD. This positioning is done by movements of the ACCD relative to the RLVD.

As described, the accuracy of the GNSS position estimation can only be expected to be accurate in above written limits. Therefore, an additional relative position estimation of the ACCD is implemented via optical sensors that observe the ACCD from the RLVD. This procedure runs parallel to a GNSS position estimation of the ACCD.

These sensors are a camera and a laser scanner. Both sensors are located in the front of the RLVD to have the biggest possible field of view. The processing unit of the optical data is also installed in the

RLVD. The result of the processing is an estimation of the relative position of the ACCD with respect to the RLVD. This position is transmitted via data link to the TAD. The links between the different aircraft and GCS will be described in D5.1 “Concept description of formation scenario”.

The estimation data is received and distributed by TAD. The distribution is necessary because the motion of the ACCD is realized through control surfaces at the ACCD itself and a winch in the TAD. Therefore it is necessary that the TAD works as a relay and sends the needed information to ACCD.

The winch at the TAD controls the rope length between the TAD and the ACCD. Because the relative positioning between the TAD and RLVD is fixed by the GNSS based formation, the winch in the TAD also modifies the relative distance between the ACCD and the RLVD. Simplified, the winch manipulates the ACCD position along its x-axis. The control surfaces of the ACCD enable movements of the ACCD along its y and z axes.

In the case that the vision-based formation must be aborted, e.g. the ACCD cannot be moved in front of the RLVD-Boom, the winch retracts the rope and the TAD and RLVD move back to the initial positions of the vision based formation. The time period and flight path length in the IAC-demonstration path, was chosen in a way, that the vision based formation and the attempt to connect the ACCD with the RLVD can be repeated three times.

2.2.4.3 Coupling

A fixed mechanical coupling between ACCD and RLVD and a subsequent towing of the RLVD will not be implemented in the FALCon project. Rather the established connection between the both should be visualized. The nose boom of the RLVD is equipped with a contact switch which detects the presence of the ACCD. In the case the ACCD is inside the predefined detection area/range over an also defined time period (e.g. 1s), the contact will be displayed. After the contact is detected over a defined time period the formation will be dissolved. This procedure is initialized by the retraction of the ACCD towing rope by the winch up to a point TAD plus ACCD and RLVD can regarded as separated aircrafts. The separation phase is described in section 2.2.3.

2.3 Environment Conditions

The scaled experiment scenario is an experiment at laboratory conditions. A demonstration of the IAC, at its current state of development and with planned, scaled demonstrators is only possible under best environment conditions. Best environment conditions mean in this case, less or no wind, low air humidity (no snow or rain) and best sight conditions (no fog or low hanging clouds). If one of these requirement is not fulfilled no flight demonstration is implemented. Table 2-3 show the minimal environment limitations.

Table 2-3: Minimal Environment Condition Requirements

Condition	**Value**
Maximal wind speed (all directions, including cross wind or gust)	25 km/h (7 m/s, 14 kn)
Minimal Cloud Level	13000 ft (4000 m)
Minimal Air temperature (ground)	5°C
Maximal precipitation	0 mm
Minimal visibility range	10000 m

The flight demonstration will be implemented in airspace G and E. The airspace is unlikely to be fully closed to public air traffic. In order for third parties to be able to perceive the demonstrators, CAVOK (Clouds And Visibility OK) weather conditions must be fulfilled.

2.4 Beyond Vision Line of Sight Condition

Figure 11 shows that the maximal distance between formation initialization and final separation is approximately 10 km. Further, Figure 11 additionally shows that the maximal altitude above ground is 2000 m. The experience of the DLR safety pilots shows that a visual observation of plane with a 3 m wingspan, without extended support equipment like binoculars, and with the aim to estimate the plane state to control it with RC, is possible up to a Cartesian distance of 750 m.

Based on this experience an observation of the demonstrators by ground observatory, without extensions, is only possible for a small part of the planned demonstration.

The whole demonstration can be divided in seven sections;

- Take-Off,
- Ascent,
- GNSS based formation
- Perception based formation
- Coupling
- Separation and
- Landing

Only the sections takeoff and landing of each demonstrator are in the direct view of the pilots and will be performed manually. All other sections are beyond the visual line of sight.

For the RLVD these seven sections are combined to the four sections takeoff, ascent, descent and landing. The descent phase contains the sections GNSS-based formation, perception-based formation, coupling and separation because the RLVD is a passive participant at all covered sections which exercises the same behavior in each phase.

The flight paths for ascent and descent are pre-defined and the RLVD follows the paths fully automatically. The RLVD does not get further inputs nor does it have the task to react to behavior of other demonstrators or conditions. In the nominal case the following of the pre-defined path is observed by ground crew members. The ground crew uses a virtual cockpit, which shows them necessary information to estimate the vehicle state. A back channel also allows modifying key parameter to adapt possible deviations from the planned scenario.

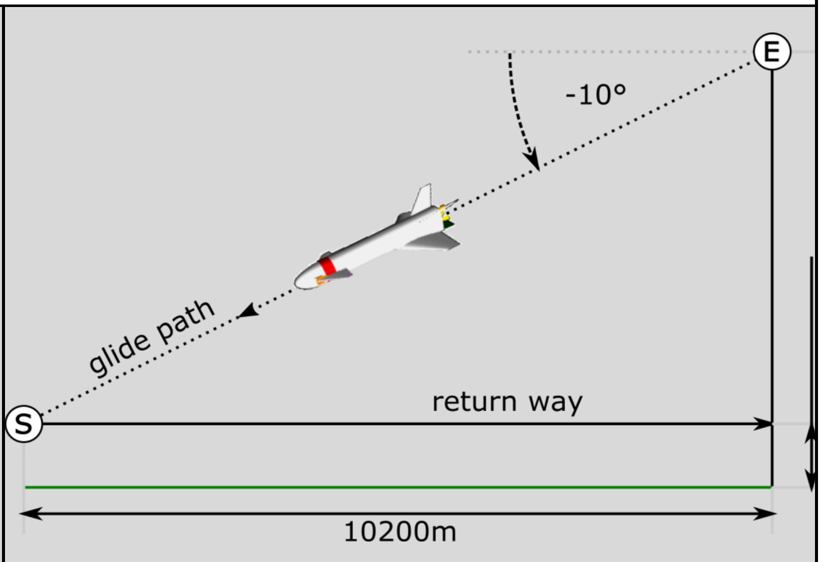
As written above the TAD operations are divided in seven subsections. In the nominal operation case the takeoff and landing are done within the visual line-of-sight, manually by the demonstrator operator. The other subsections base on predefined way point missions or adaptive behaviors which are based on received inputs from the RLVD. The ascent is a way point mission, which is predefined and runs fully automatically. Based on the information at the delivered telemetry information from TAD and RLVD the ground crew decides the change from the pre-defined ascent section to the adaptive sections; GNSS based formation, perception based formation and coupling. In all those mission parts the TAD reacts to behavior of the RLVD. In the nominal case no input of the ground crews is necessary in these phases. After the coupling is successful the ground crew initializes the separation phase.

The observation of the TAD is done by a control and command telemetry data link and a live video data link.

In abnormal behavior cases, if one of the demonstrator shows an unexpected behavior or third party flight objects enter the test area or airspace, the ground crew can interact with the RLVD to deescalate the situation. These actions are special and are not part of the here shown base experiment description. The description of the abnormal case behavior of the vehicles and crews will be shown in deliverable report 8.2 “Flight Test and Risk Management Description”.

3 Requirement Summery

3.1 Overall scaled demonstration

#	Requirement	Value
R1	Descent angle of mission	-10°
	- Corresponding to the descent angle of the full scaled IAC mission	
R2	Mission velocity	150 km/h
	- Aim of the previous project AKIRA was between 40-80 km/h - Increase the value in direction of the real scaled target Speed of < 500 km/h	
R3	Overall Target	Connection between ACCD and RLVD nose boom for more than 1 sec
	- Size of the ACCD doesn't enable an integration of a lock mechanism - Limited size and surplus power of the TAD doesn't enable towing the RLVD - Development of ACCD or TAD is only a minor part of FALCon, only modification → usage of existing devices - 1 sec is chosen to demonstrate a stable connection	
R4	Mission shape	

	- Requirements R1 and R2
	- It is assumed that a coupling attempt will not be successful at first
	  - possibility of trying 2 attempts per demonstration flight
	  - several attempts are also a necessary prerequisite for the real scaled mission
	  - 120 seconds per attempt	

R5	Environment condition	- No rain or other precipitations - Minimal visibility range: 1000 m - Minimal air temperature: 5°C - Minimal cloud level: 13000 ft (4000 m) - Maximal wind speed (all directions, including cross wind or gust) 25 km/h (7 m/s, 14 kn)
	Demonstration is a scaled experiment with a maximal TRL of 4 under simplified laboratory conditions	

3.2 Formation

#	Requirement	Value
R6	Sensor position	Nose of RLVD
	- TAD and ACCD are too small that ACCD can carry an additional sensor payload - A new development of TAD or ACCD is not part of FALCon - Position of sensors in the nose of the RLVD or ACCD isn't relevant; algorithms and hardware are the same	
R7	Towing rope length between TAD and ACCD	*n* meter
R8	Initial horizontal distance between ACCD and RLVD for optical based formation	*15* meters
	- approx. +/- 7.8 m accuracy of standard GPS solution	
R9	Final distance between TAD and RLVD	*n* + 15 meters
	- Sum of requirement R7 and requirement R8	
R10	ACCD vertical and horizontal deviation	+/- 3 m
	- ACCD could be commanded a controlled deviation of +/-3 m at AKIRA project - The FALCon project uses the same ACCD as the AKIRA project, a further development is not planned	
R11	Horizontal and vertical deviation between TAD and RLVD	< +/- 3 m
	- Considering the requirement R10 the vertical and horizontal deviation of the final	

	GNSS formation must be less the motion ability of the ACCD

3.2.1 Environment Perception

#	Requirement	Value
R12	Accuracy of estimation	+/- 2.5 cm at coupling
	- Diameter of boom target area is 5cm.	
R13	Range	0 … 15 m
	- Range achieved with GNSS in AKRIA - Distance between sensor package and ACCD will be 1.5 m at coupling - Requirement R8	
R14	Flight conditions	Visual, clear sky
	- Lab scale demonstration purposes only	
R15	Update rate	10 Hz
	- Comparable to update rate of flight controller	
R16	Power and weight	- Max. weight: approx. 3 kg - Camera VC nano Z 0252 (sensor head) 0.3 kg - Lidar Velodyne “Puck” (sensor head) 1 kg - Mounting and camera glass 0.3 kg - Companion computer 2 kg - Three Communication Devices 0.8 kg - Power consumption: - LiDAR: 8 W - IR-Camera: 2.4 W
	- Details, including exact dimensions listed in documents “Lidar_CD_Falcon_1.0”, “Camera ICD_Falcon_1.0” on teamsite - The size and payload ability of the used demonstrators are limited	
R17	Sensors	Camera and LiDAR
	- Previous project AKIRA → Focus on Camera & Lidar (fixed in Grant Agreement)	

3.3 RLVD Demonstrator

#	Requirement	Value
R18	Lift to Drag ratio	Adjustable 4-8.5
	- Full scaled scenario requirement	

R19	Position of COG	20% Mean Aerodynamic Chord
	- Full scaled scenario requirement	
R20	Duration	- Fuel Tank: 20 l - Climb: 6,7 min (8,5 l) - Coordination phase: 5 min (3,0 l) - Gliding phase: 6,7 min (0,0 l) - Landing phase: 5 min (3,0 l) - Reserve fuel: 8 min (5,5 l)
	- Passive gliding phase (main engine is off) is a full scaled scenario requirement	
R21	Payload	- Sensors and communications link (see R16) - Veronte AP, wires, batteries 5 - Coupling Switch 0.3 - Safety parachute System (TBC) 4 - TOTAL 13.3
	- Requirement R16	

3.4 TAD Demonstrator

#	Requirement	Value
R22	Duration	45 min
	- Formation procedures:	
R23	Safety equipment	- Parachute rescue system - Independent termination link - Redundancies to prevent a control lost at mal functions - Increase electronic visibility (FLARM) - Increase knowledge about other air space participants ADS-B receiver
	- SORA analysis of Demonstration → reduction of initial air & ground risk validation for BVLOS operations, prevention of fly away	
R24	Mission velocity	150km/h (towing the ACCD)
	- Requirement R2	

4 References

[1] M. Sippel, S. Stappert, S. Krause and S. Cain, "FALCon Deliverable D2.5, Issue 2 - Status of DLR investigations „in-air-capturing“," DLR, Bremen, 2020.

[2] M. Sippel and J. Klevanski, "Progresses in Simulating the Advanced In-Air-Capturing Method," in *5th International Conference on Launcher Technology*, Madrid, 2003.

[3] M. Sippel, S. Stappert, L. Bussler, S. Krause, S. Cain, J. Espuch, S. Buckingham and V. Penev, "Highly Efficient RLV-Return Mode “In-Air-Capturing” Progressing by Preparation of Subscale Flight Tests," in *8TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS) 2019*, Madrid, Spain, 2019.

[4] N. a. T. National Coordination Office for Space-Based Positioning, "GPS Accuracy," 05 12 2017. [Online]. Available: https://www.gps.gov/systems/gps/performance/accuracy/. [Accessed 12 11 2019].