Status of DLR investigations: „in-air-capturing“ history, interest for RLV, simulation & analyses

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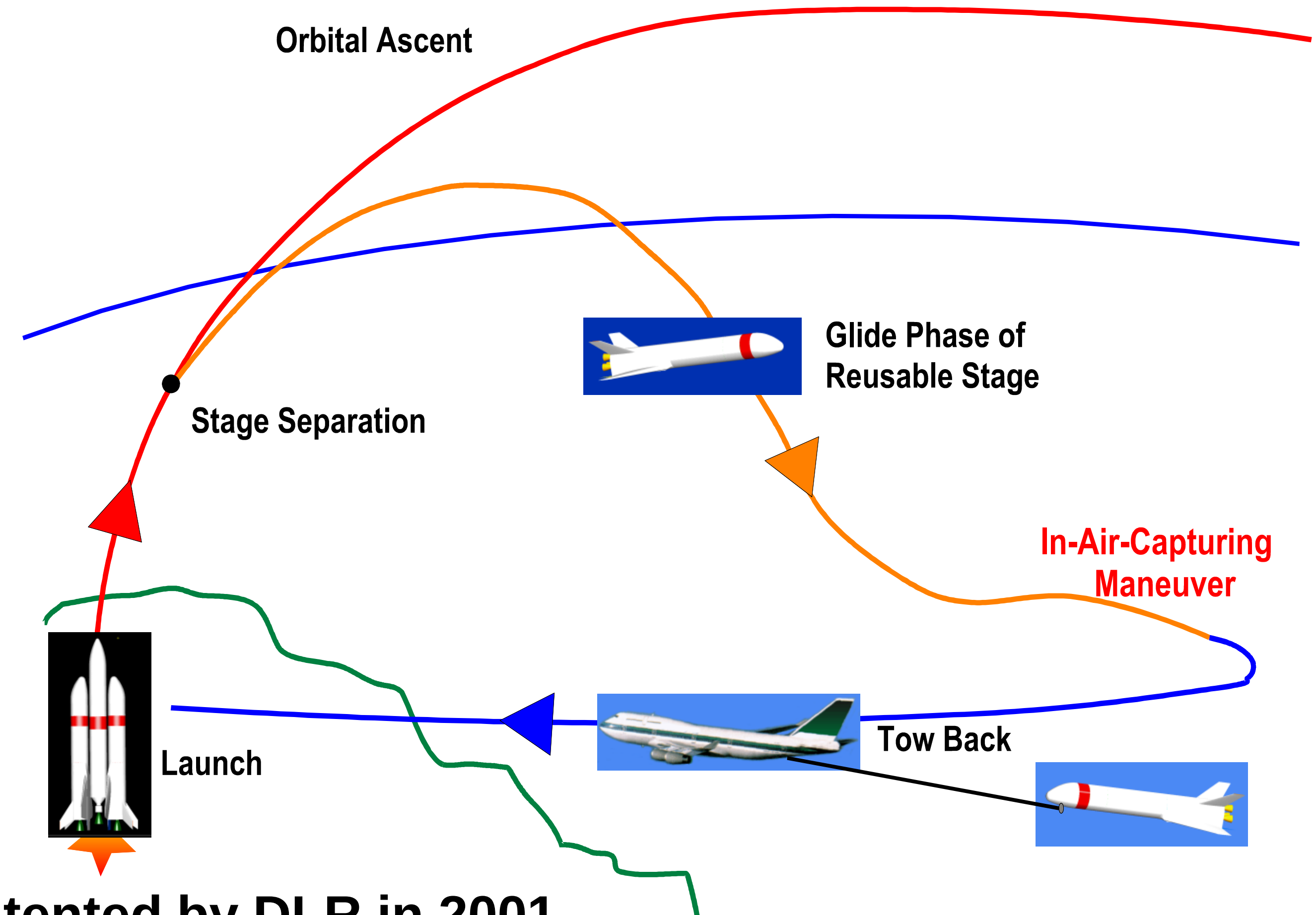
- What is “in-air-capturing“?
- History of “in-air-capturing“ and mid-air-retrieval
- Interest of “in-air-capturing“ for RLV 1st stages
- How “in-air-capturing works
- Preliminary design of capturing device ACCD
- Towing airplane requirements
- Off-design behavior

What is “in-air-capturing“?

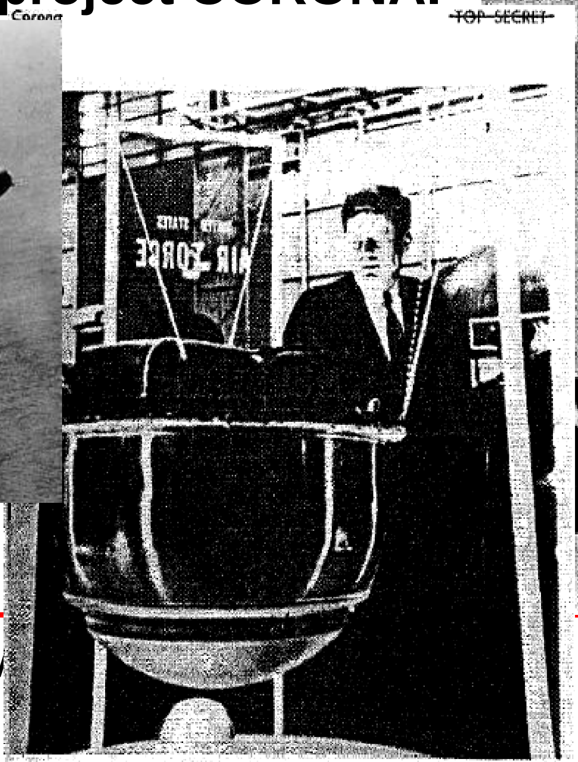
- Schematic of the innovative “in-air-capturing”



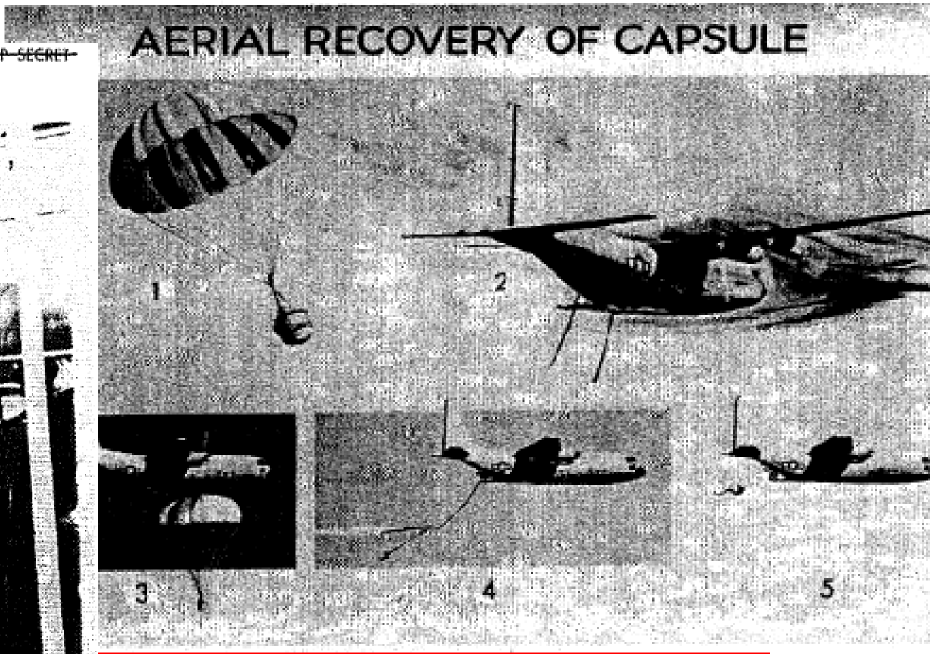
- Patented by DLR in 2001
- Kind of downrange “landing” – but landing in the air!

History of “in-air-capturing“ (IAC) and mid-air-retrieval (MAR)

- Mid-air-retrieval (MAR) of flying craft and objects is not at all new and revolutionary technology.
- MAR by airplanes or helicopters is commonly used since decades
- August 18th 1960 first successful recovery of film from space in top-secret CIA-project CORONA.



First Aerial Recovery



History of “in-air-capturing“ (IAC) and mid-air-retrieval / 2

- **Estimated about 2 million Mid-air-retrieval operations by 2007** according to S. V. Antonenko and S. A. Belavskiy, 2ND EUCASS**.**
- **MAR Technology used to capture or retrieve: Containers of Earth satellites (CIA-project CORONA or “Discovery” and NASA “Genesis”, geophysical rockets and spacecrafts**

more information at
https://en.wikipedia.org/wiki/Corona_(satellite)

History of “in-air-capturing“ and mid-air-retrieval / 3

- Idea of “in-air-capturing” first proposed in SART-workshop on RLV-return technologies, May 2000
- First step: feasibility analyses and estimation of potential performance gain
- Promising results followed 2001 by patenting process in DLR
- First published as IAF-01-V.3.08 at 52nd International Astronautical Congress, 1-5 October 2001, Toulouse

IAF-01-V.3.08

Innovative Method for Return to the Launch of Reusable Winged Stages

Martin Sippel, Josef Klevanski, Jens Kauffmann

Space Launcher Systems Analysis (SART), DLR, Cologne, Germany

- Motivation and Background
- Baseline Engine Description
- Principal Function
- In-Air-Capturing
  - Numerical Simulation
  - Methods for Capturing
- Advantages
- Off-Design Performance
- Conclusions

52nd International Astronautical Congress , 1-5 October 2001, ESTEC, Toulouse

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SART Systemanalyse Raumtransport

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IAF-01-V.3.08

Innovative Method for Return to the Launch Site of Reusable Winged Stages

Martin Sippel, Josef Klevanski, Jens Kauffmann
Space Launcher Systems Analysis (SART), DLR, Cologne, Germany

This paper proposes a new, and different approach for return to the launch site of non-SSTO reusable space transportation vehicles. 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. This so called in-air-capturing method (patent pending) is initiated by large cargo transports, offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio. Technical requirements of the tow-aircraft indicate, that (depending on the stage's size) an Airbus A-340 or B-747-class jet offers good thrust margins. The performance gain by the advanced capturing method shows a possible increase in delivered payload between 15 % and 25%, assuming the same structural technology level of the stages. Alternatively, the size of a reusable system can be significantly reduced compared to the standard approach, without any loss in payload mass.

The paper presents a detailed description of the proposed method, giving data of numerical simulations regarding the nominal mission. A comparative analysis, looking also at conventional systems quantifies the advantages. The second part of the paper proofs the viability of the proposed in-air-capturing method by regarding its off-design performance. Assuming different perturbations of the normal flight, including a change in atmospheric wind or slightly different stage-separation conditions. Analysis shows the flight dynamic potential of the descending vehicle to dissipate energy to be quite comfortable.

History of “in-air-capturing“ and mid-air-retrieval / 4

- “in-air-capturing” submitted as patent application by DLR in September 2001
- Patent granted and published in February 2003

(19) BUNDESREPUBLIK DEUTSCHLAND

DEUTSCHES PATENT- UND MARKENAMT

(12) **Patentschrift**

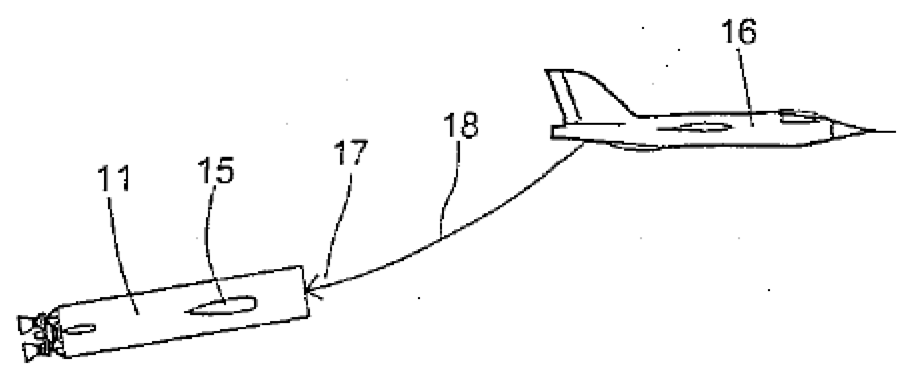
(10) **DE 101 47 144 C 1**

(51) Int. Cl.[7]:
B 64 G 9/00
B 64 G 1/62

(21) Aktenzeichen: 101 47 144.0-22
(22) Anmeldetag: 25. 9. 2001
(43) Offenlegungstag: –
(45) Veröffentlichungstag der Patenterteilung: 13. 2. 2003

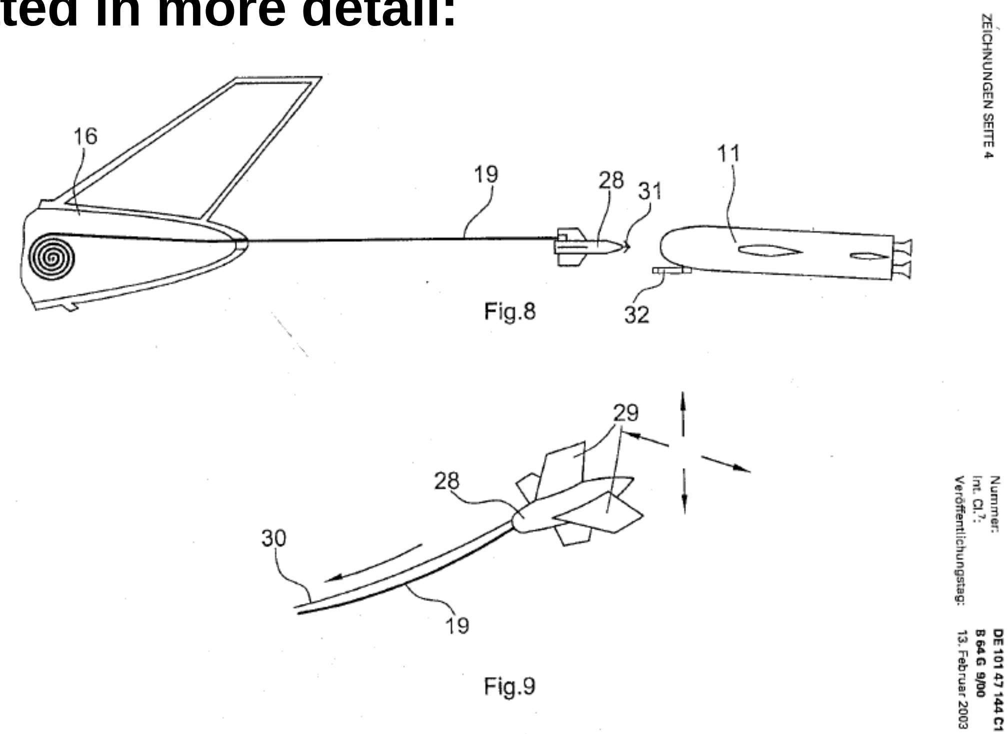
Verfahren zum Bergen einer Stufe eines mehrstufigen Raumtransportsystems

Eine wiederverwendbare aufwerfbare Stufe (11) eines Raumtransportsystems wird zum Zwecke des Bergens in einen Gleitflug versetzt und von einem Schlepper-Flugzeug (16) im Flug eingefangen, um anschließend im Schleppflug an den vorgesehenen Landeplatz verbracht zu werden. Die wiederverwendbare Stufe (11) benötigt keinen zusätzlichen Treibstoff für den Rückflug und sie kann von dem Flugzeug über beliebige Entfernungen transportiert werden.



History of “in-air-capturing“ and mid-air-retrieval / 5

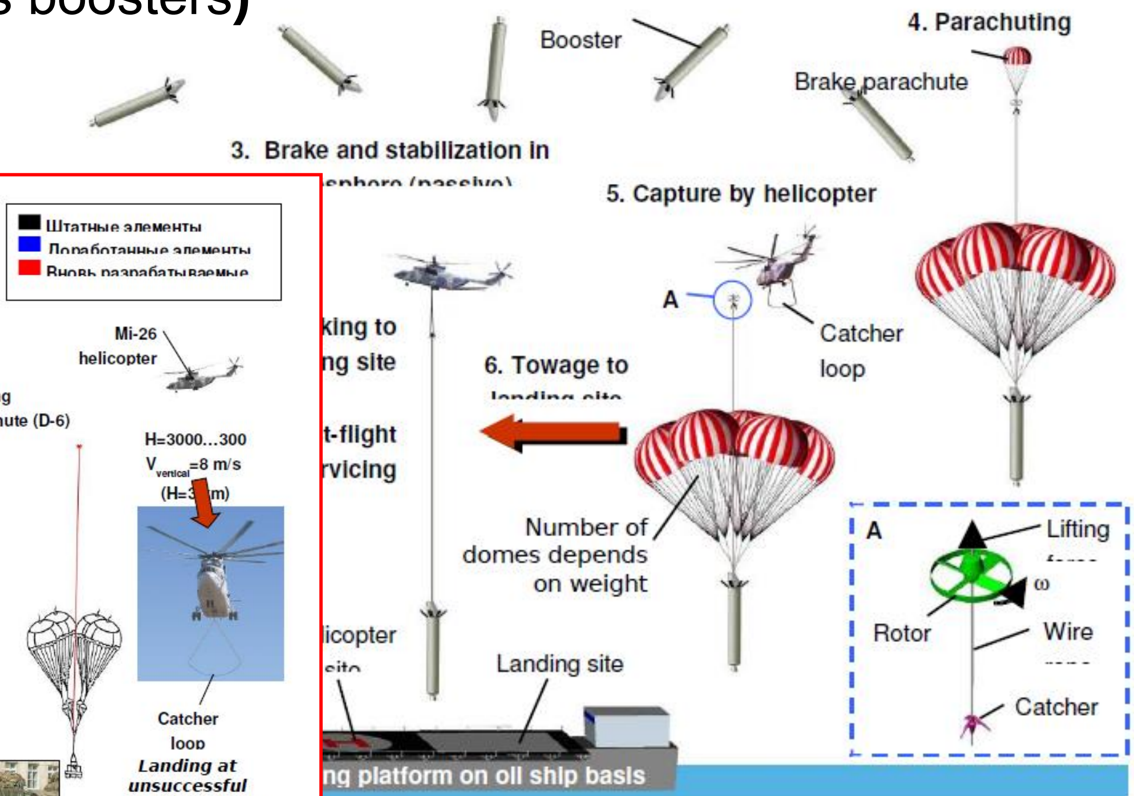
- **DLR patent DE 101 47 144 C1 contains already all key-elements, later investigated in more detail:**

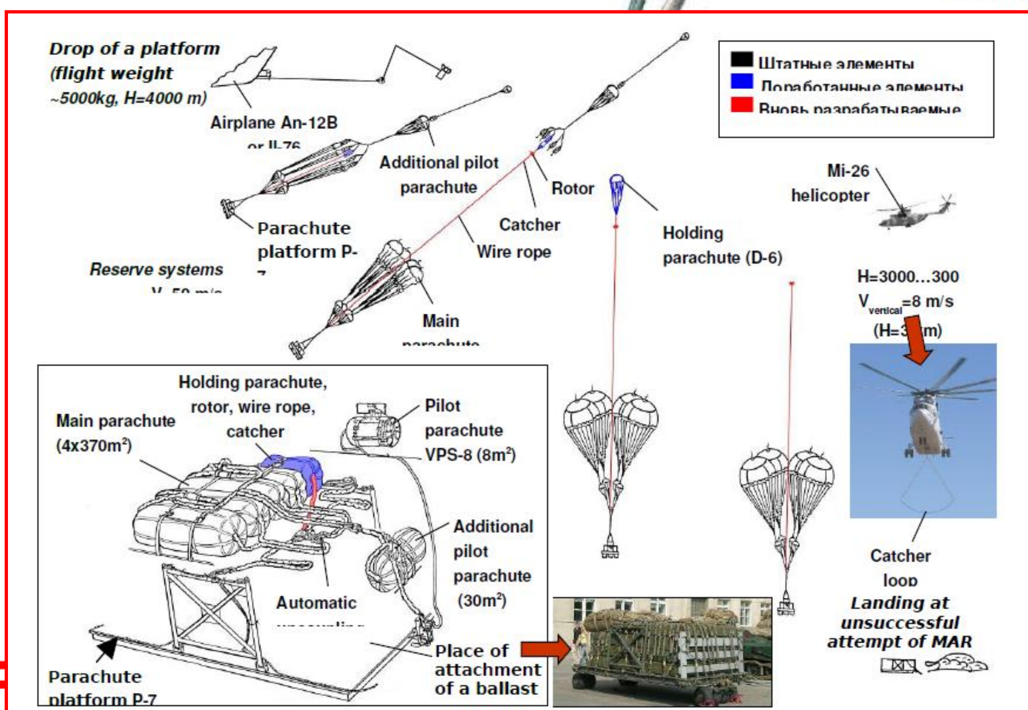


- As only towing airplane and winged RLV-stage explicitly mentioned – other MAR-options as combination of parachute and helicopter not covered and hence used by Khrunitchev & ULA.

History of “in-air-capturing“ and mid-air-retrieval / 6

- **Recovery of launcher first stages proposed by Khrunichev, Moscow** (S. V. Antonenko, S. A. Belavskiy: The midair retrieval technology for returning of the reusable LV’s boosters**)**
- **Using large helicopters**
- **Flight testing:**





History of "in-air-capturing" and mid-air-retrieval / 7

- **ULA SMART Re-Use: Recovery of engines and engine bay only:**

Interest of "in-air-capturing" for RLV 1st stages

Basics of RLV-design:

- **Any RLV-mode degrades launcher performance compared to ELV due to additional stage inert mass.**
- **Performance impact of RLV is directly related to its (ascent) inert mass ratio or net-mass fraction.**
- **Inert stage masses (ascent flight) are stage dry mass and total residual propellants (including reentry, landing, and potentially fly-back).**
- **A specific inert mass ratio is defined as:**

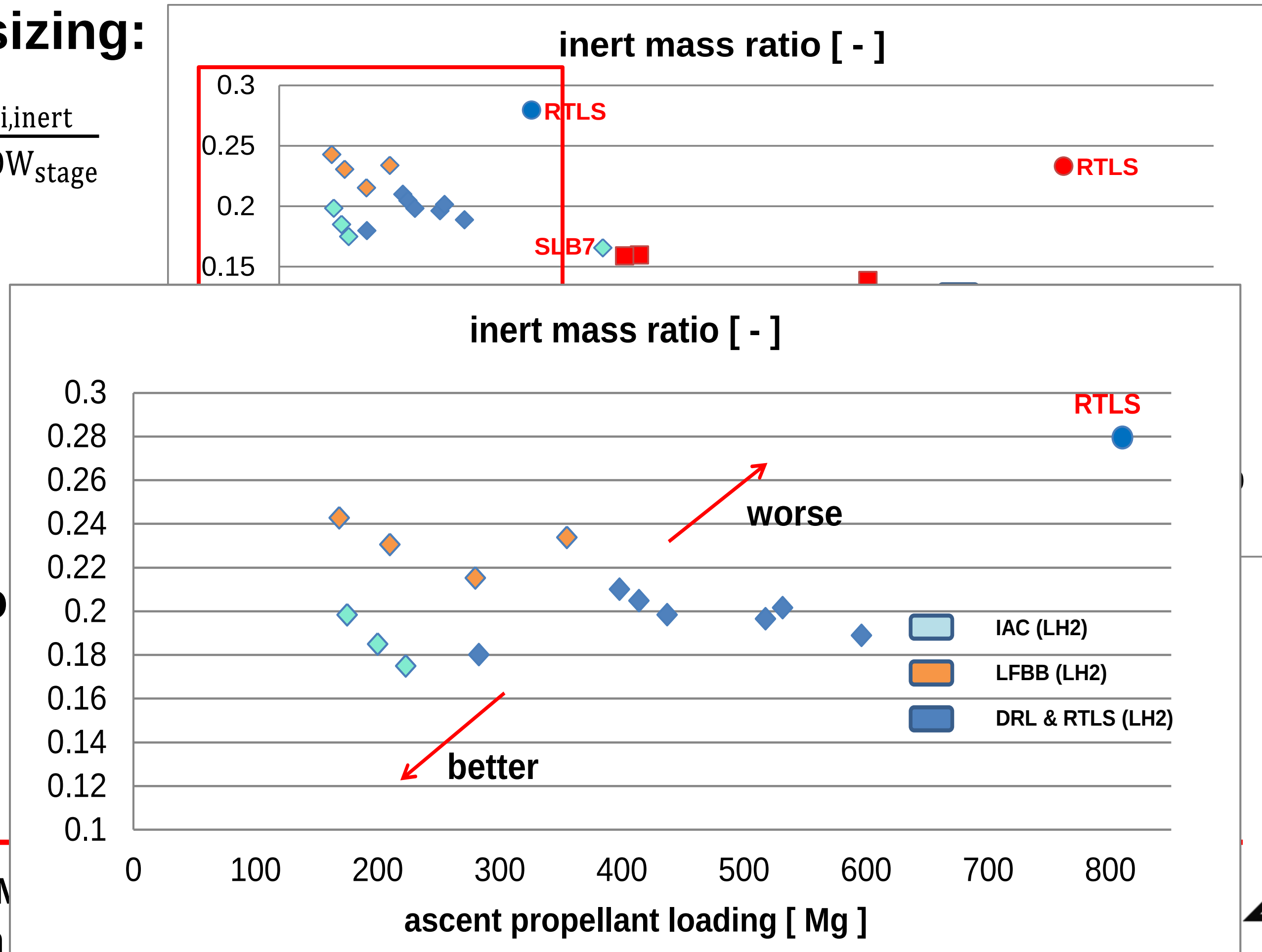
$$\text{inert mass ratio}_i = \frac{m_{i,\text{inert}}}{\text{GLOW}_{\text{stage}}}$$

- **Since reliable and sufficiently precise estimation of RLV costs is almost impossible today, performance impact comparison gives first sound indication of promising modes.**

Interest of “in-air-capturing“ for RLV 1st stages / 2

- The higher the inert mass ratio of a stage, the lower is its acceleration performance.
- Comparison of different RLV return mode based on systematic DLR launcher sizing:

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

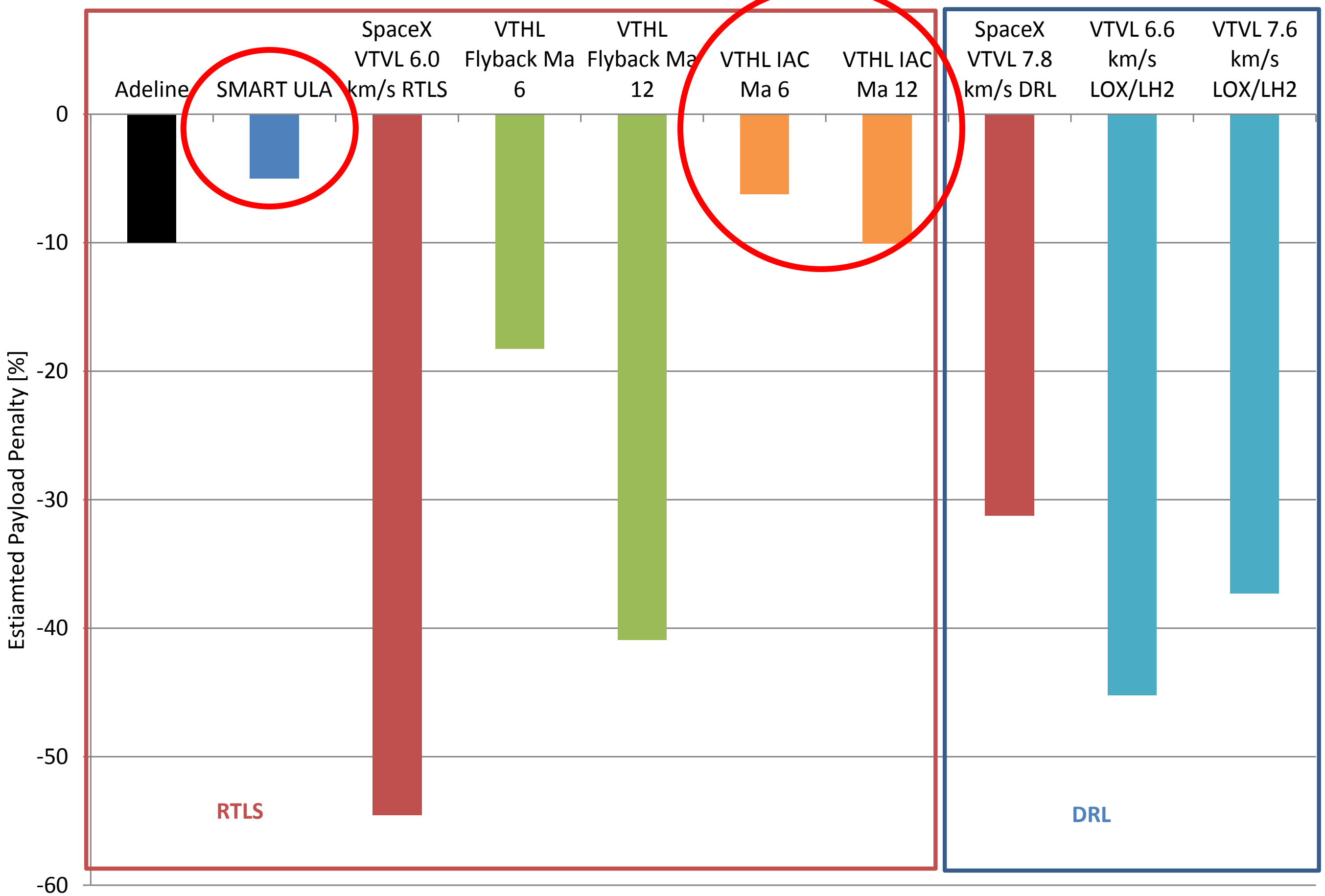


- Zooming into

Interest of “in-air-capturing“ for RLV 1st stages / 3

- **Estimated or calculated penalty loss of RLVs with different return options compared to ELV**

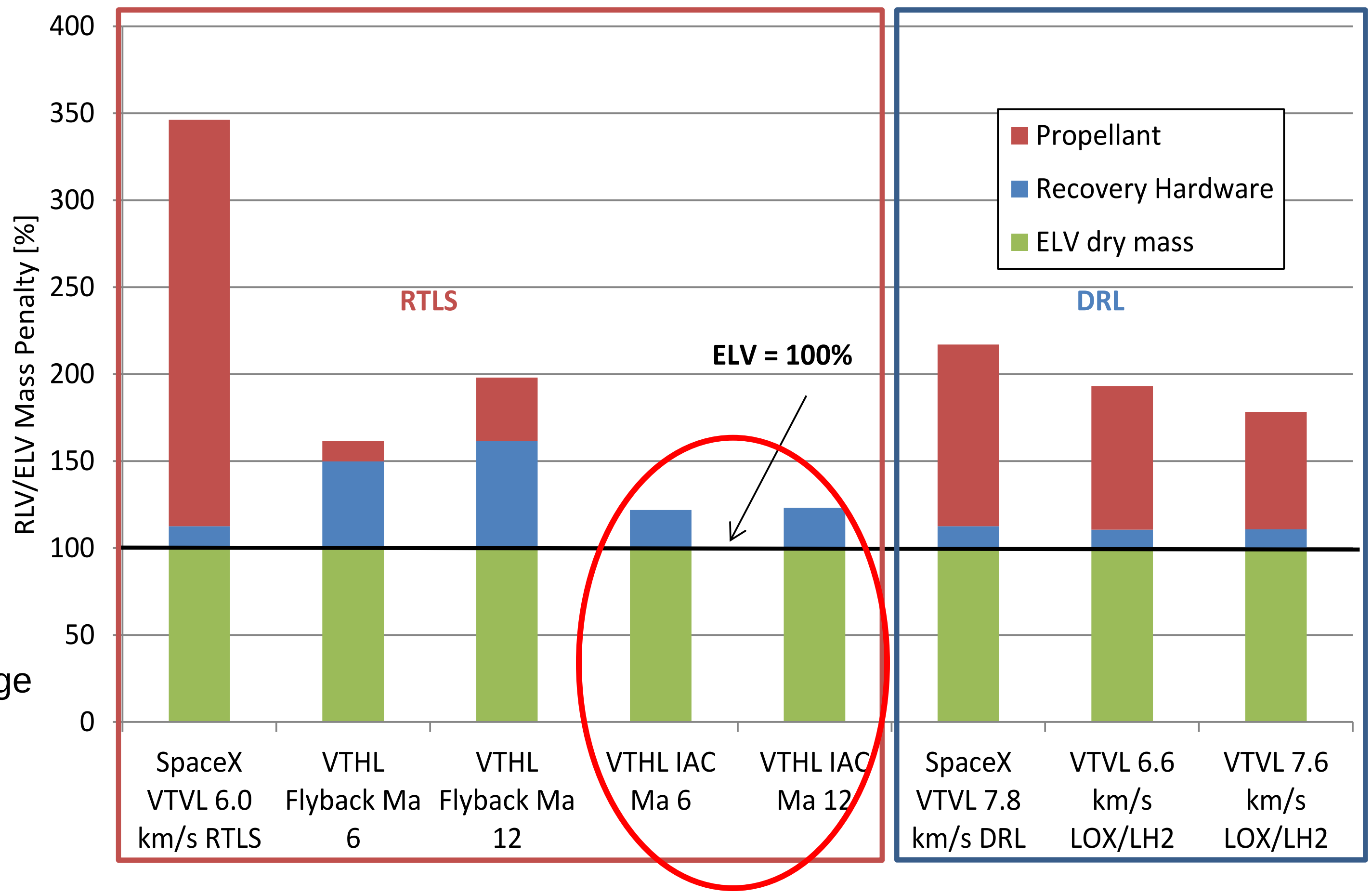
- RTLS – Return to Launch Site (by rocket engine)
- VTVL – Vertical Take-off Vertical Landing
- VTHL – Vertical Take-off Horizontal Landing
- IAC - “in-air-capturing”
- DRL - Down Range Landing (by rocket engine)



Interest of "in-air-capturing" for RLV 1st stages / 4

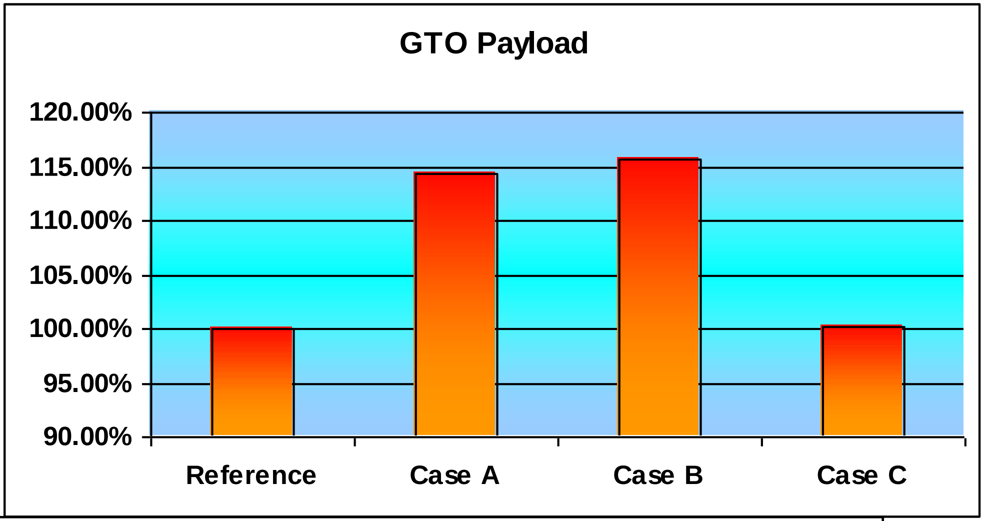
- Mass increase of VTHL and VTVL RLVs with respect to ELV

- RTLS – Return to Launch Site (by rocket engine)
- VTVL – Vertical Take-off Vertical Landing
- VTHL – Vertical Take-off Horizontal Landing
- IAC - "in-air-capturing"
- DRL - Down Range Landing (by rocket engine)



Interest of “in-air-capturing“ for RLV 1st stages / 5

- **Already in presentation of October 2001:**
  - LFBB vs. IAC: Medium Separation Velocity (about 2 km/s or Mach 6), GTO

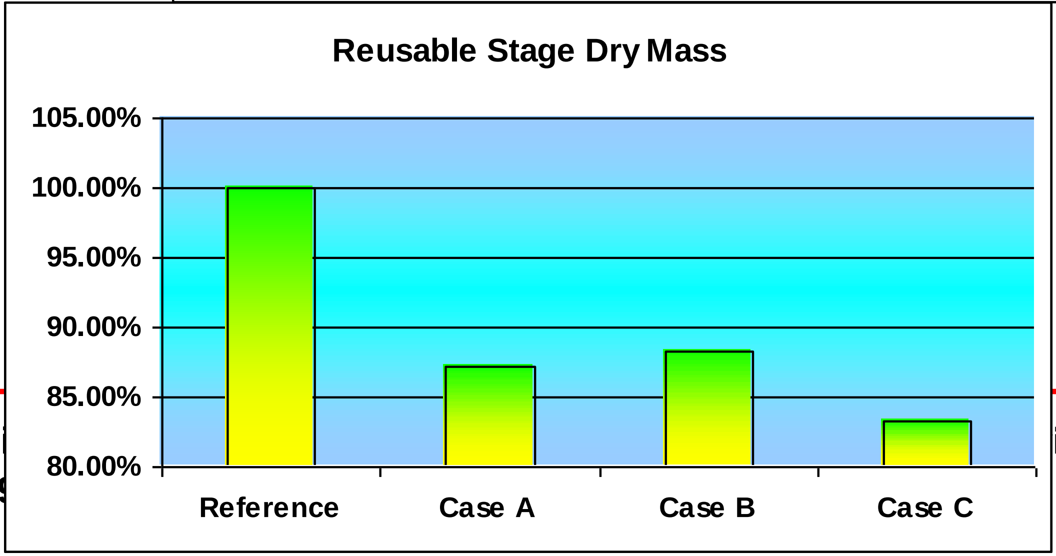


3 separate In-Air-Capturing cases investigated and compared to conventional fly-back booster approach:

A: No fly-back equip.

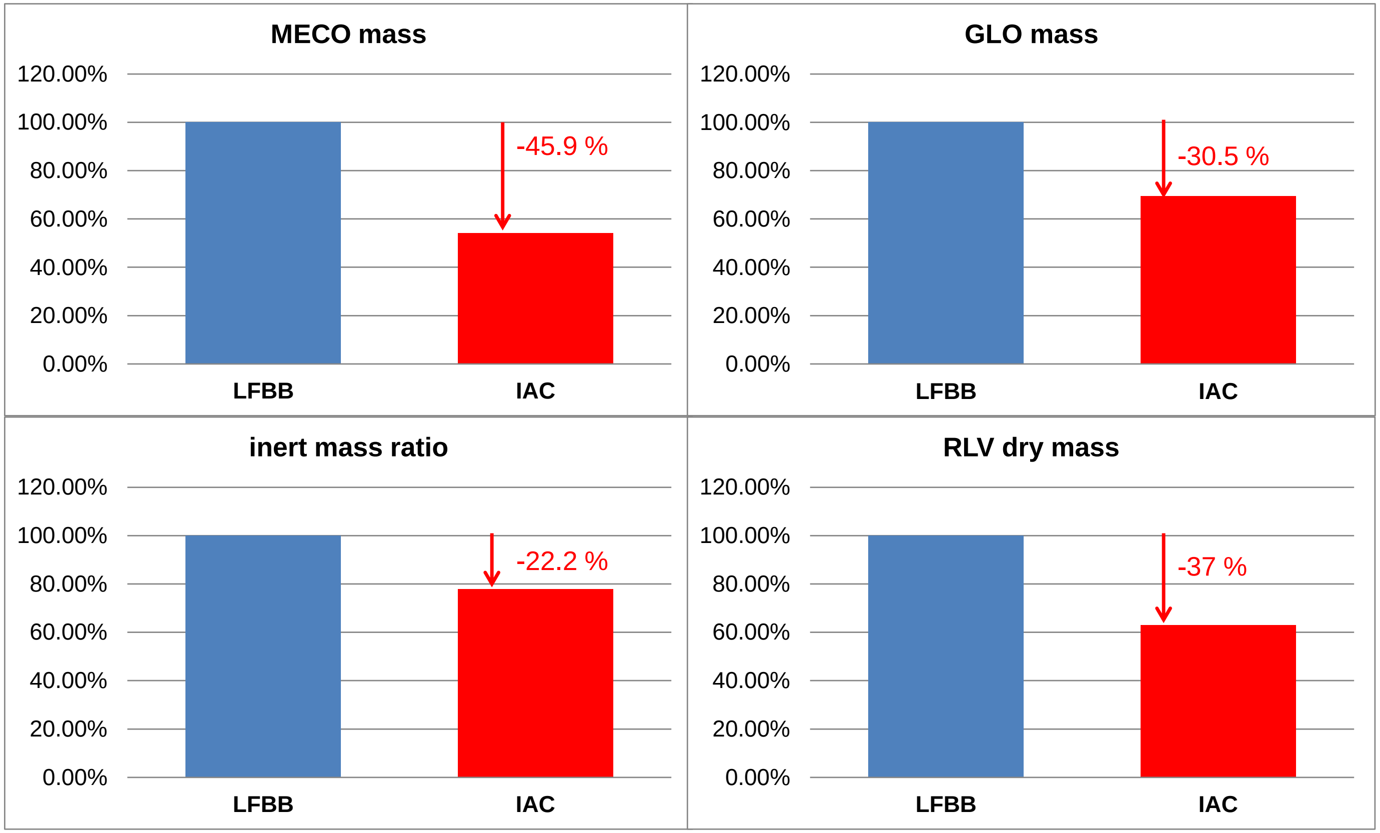
B: Same Launcher GLOW + A

C: Same Payload



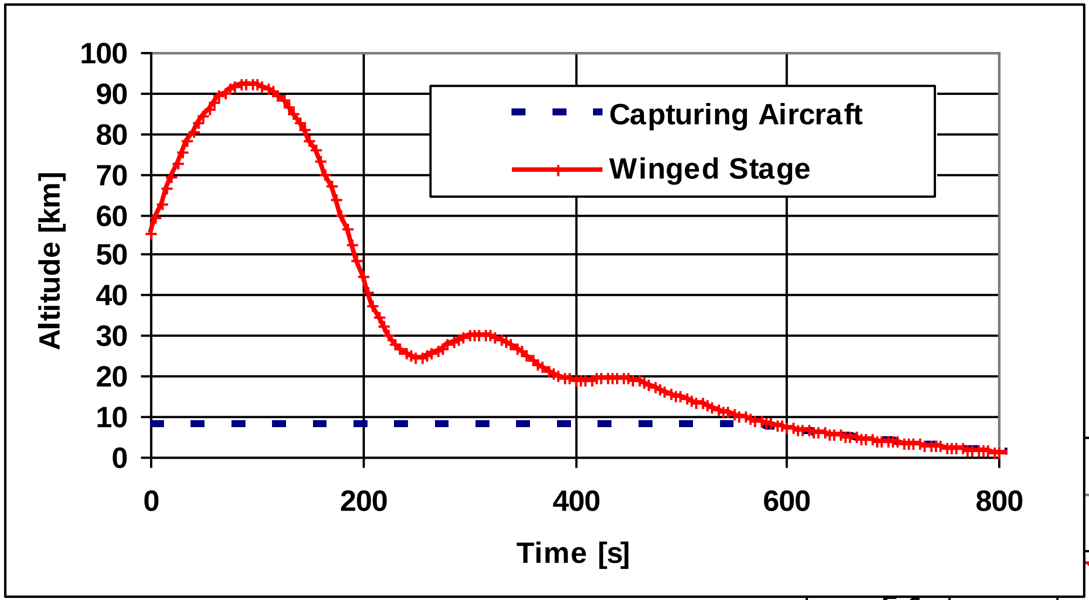
Interest of “in-air-capturing“ for RLV 1st stages / 5

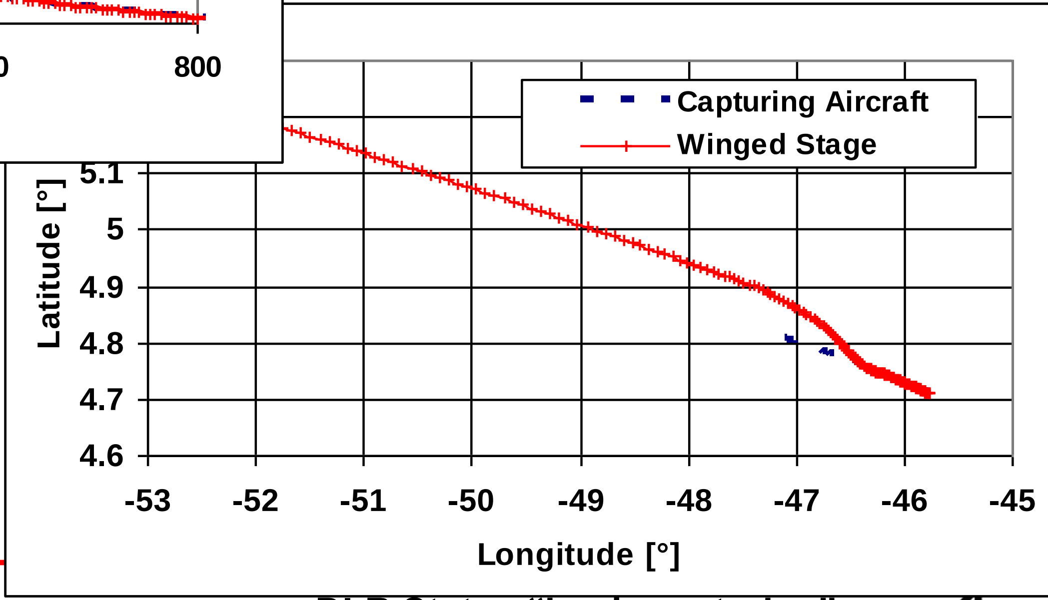
- Mass comparison again for LFBB vs. IAC same GTO-payload:
  - Higher separation Mach number 12 shows increased benefit of “in-air-capturing” compared to Mach 6)



How “in-air-capturing works

- **3/4DOF-simulation for LFBB with separation at approx. 2 km/s**

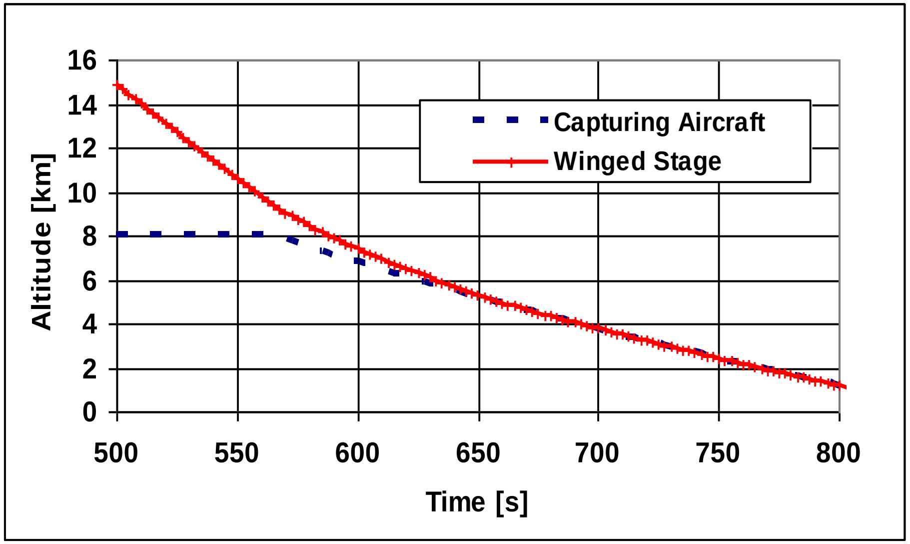


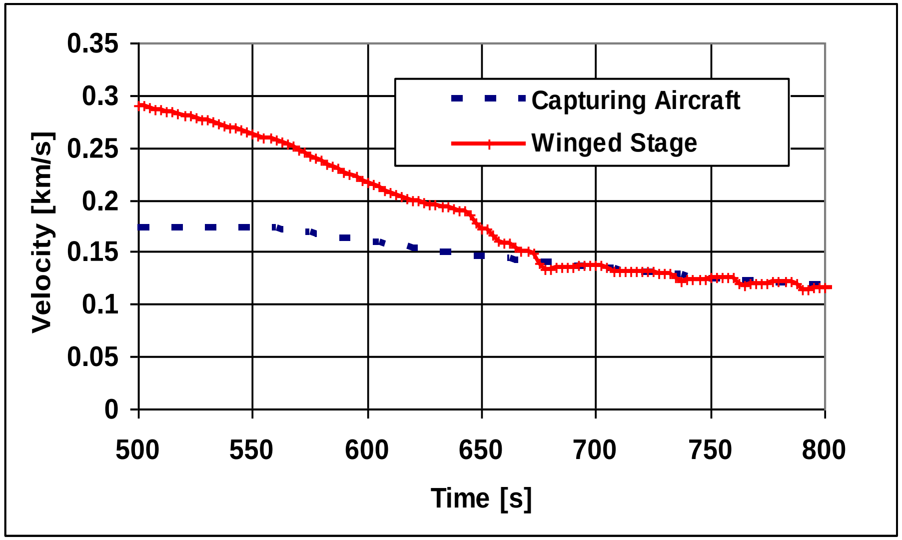


From stage separation up to the In-Air-Capturing by the airplane

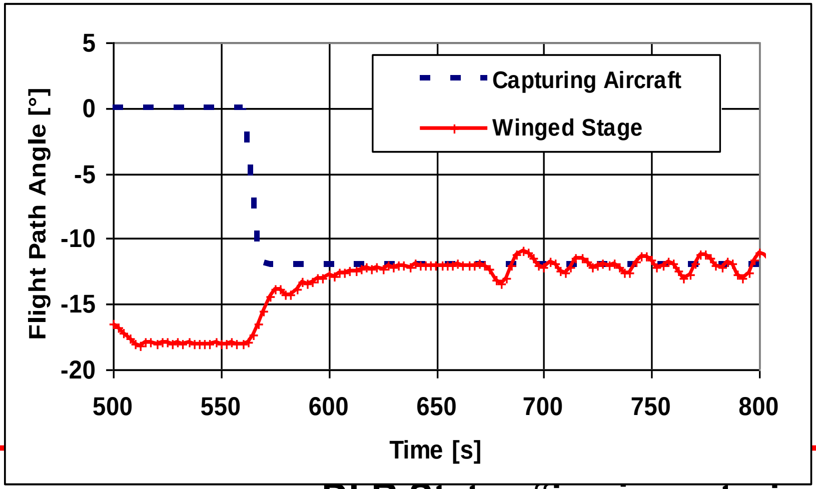
How “in-air-capturing works / 2

- **Numerical simulation of the approach maneuver (final phase):**



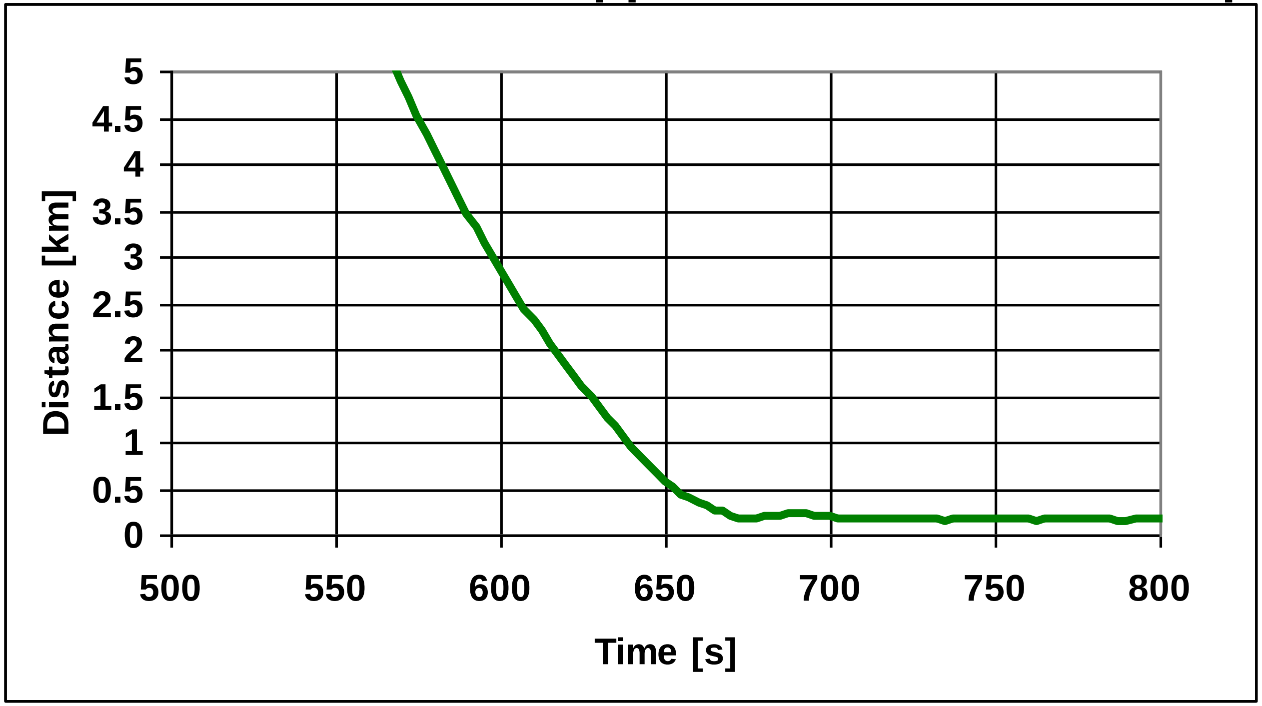


Nominal approach is only controlled by the winged stage



How “in-air-capturing works / 3

- Numerical simulation of the approach maneuver (final phase):



- A close (< 200 m distance) and nearly parallel descent of both flight vehicles can be extended up to more than 2 minutes.

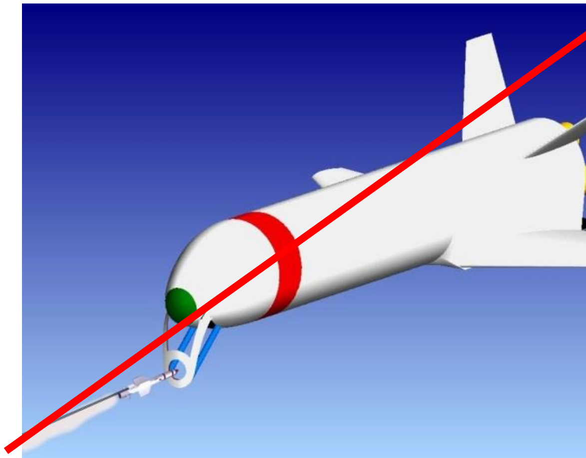
- But, how to actually perform the capturing itself?

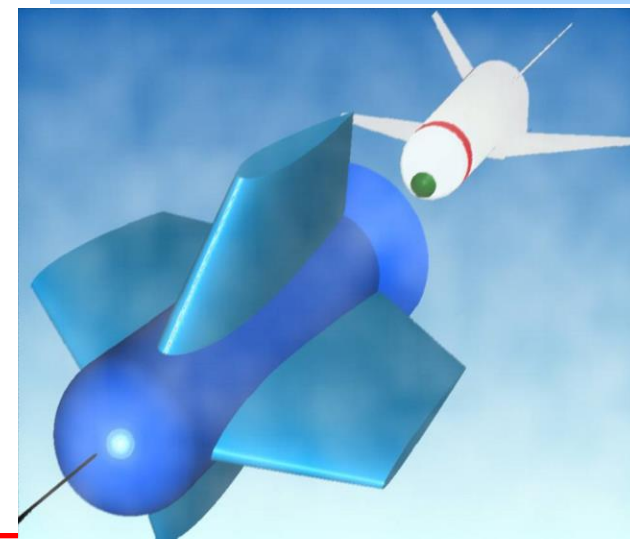
How “in-air-capturing works / 4

Four different types of capturing methods have been studied in the past:

- ~~The harpoon principle with a missile launched from the capturing aircraft and directly shot versa the returning stage,~~
- ~~A variant requiring the missile to perform a loop maneuver and then approaching the RLV from behind.~~
- ~~The third option fires the missile from the reusable stage versa the capturing aircraft, also decreasing relative velocity and hence loads.~~

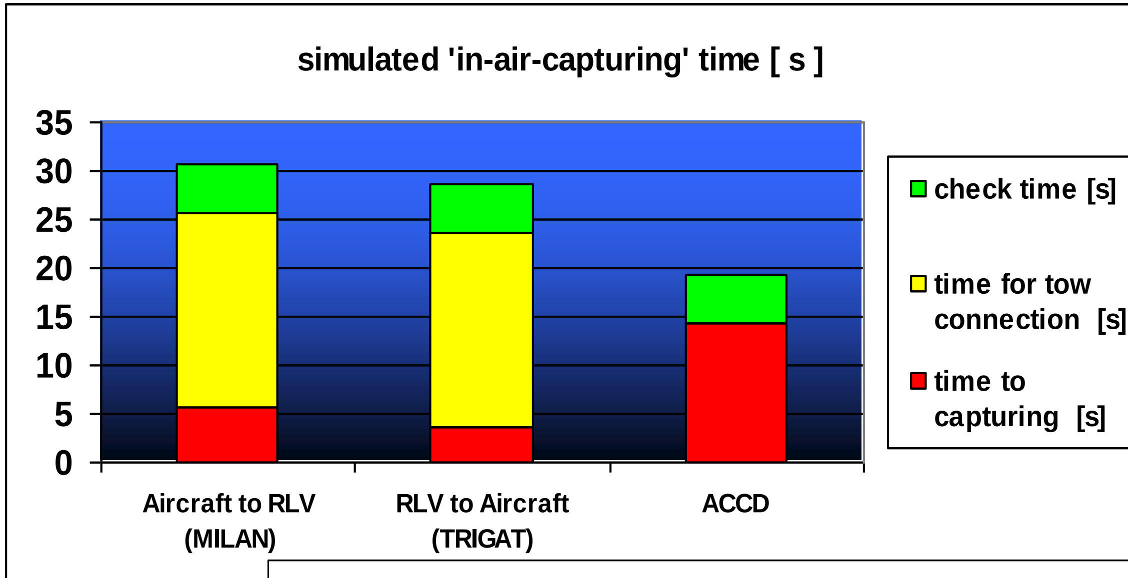
- An aerodynamically controlled capturing device (ACCD), which is to be released by the airplane and then towed, cautiously approaching the launcher

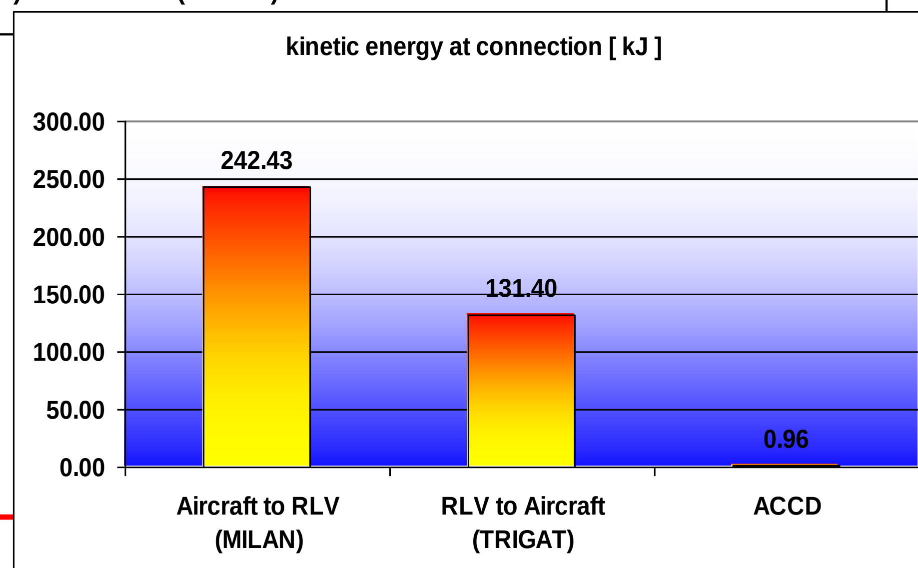




How “in-air-capturing works / 5

3 DOF simulations of self-homing missiles and ACCD deliver:



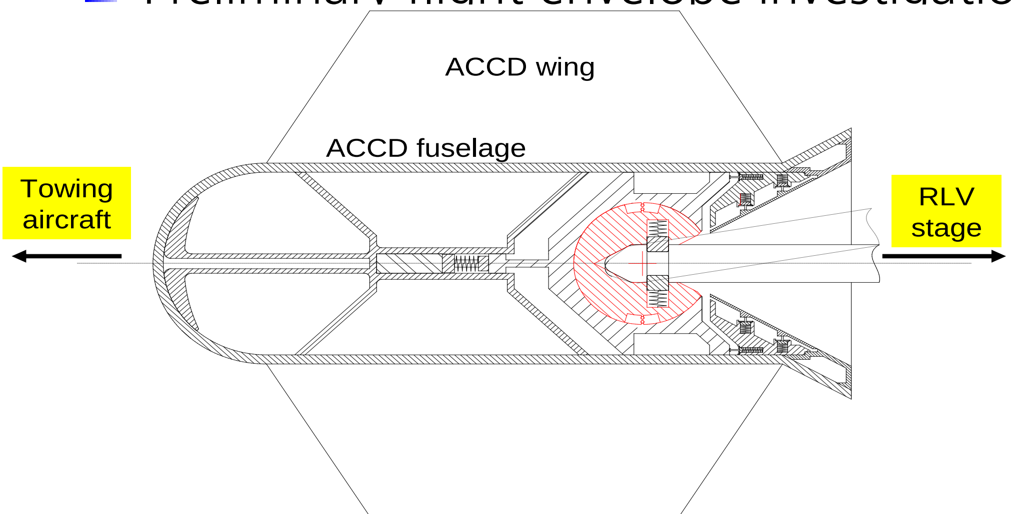


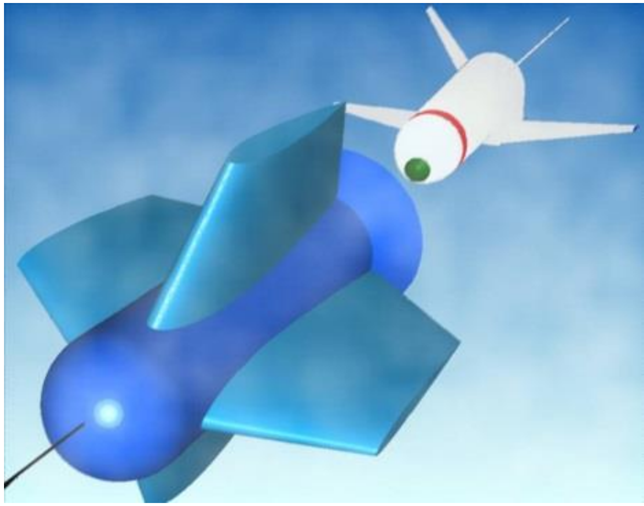
ACCD has the largest time margin (> 500%) and the lowest impact energy

ACCD is reference ‘In-Air-Capturing’ device

Capturing hardware ACCD

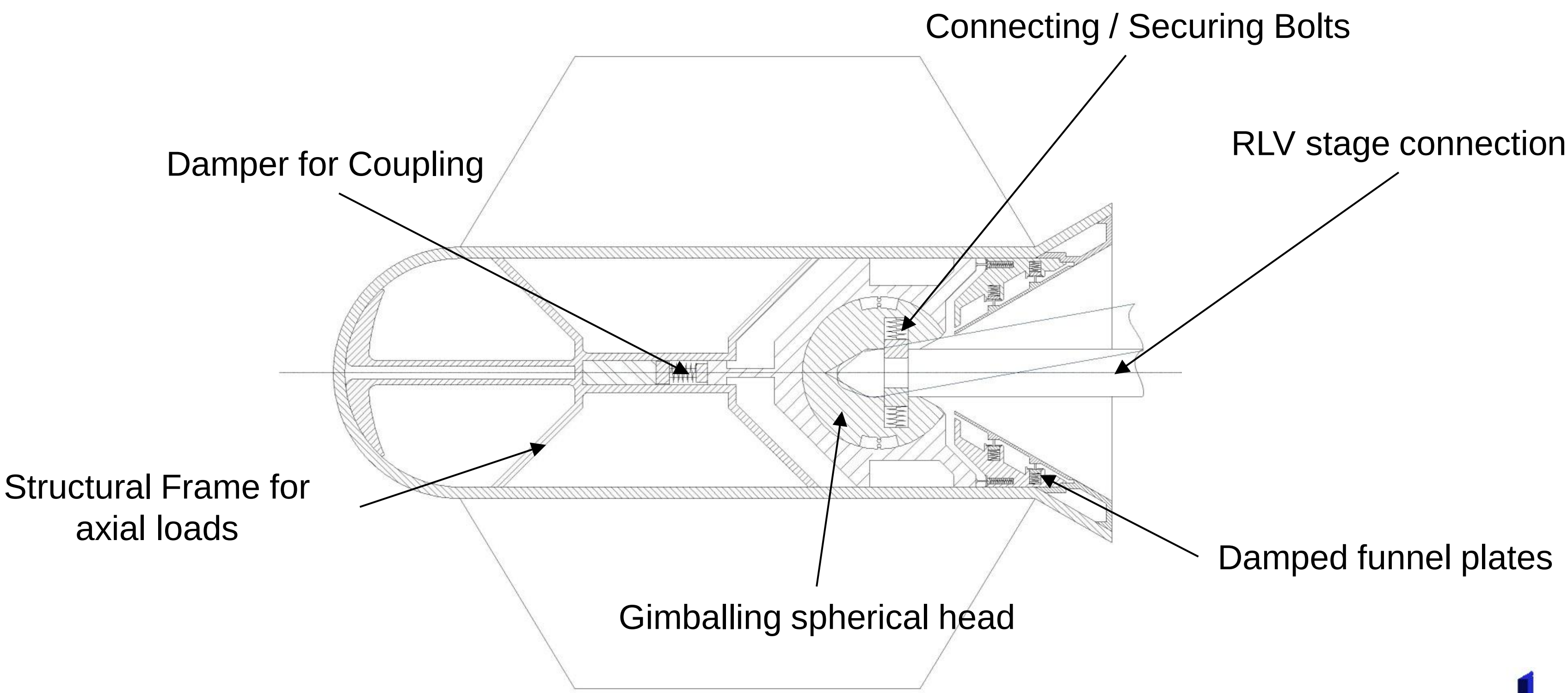
- **Numerical simulation of approach maneuver shows feasibility of establishing contact within 14 s**
- **Relative velocity moderate at around 5 m/s, but potential for further reduction**
- **Previous analyses at DLR:**
  - Preliminary sizing of internal mechanisms
  - Preliminary Structural Design
  - Preliminary Aerodynamic Design
  - Preliminary flight envelope investigation

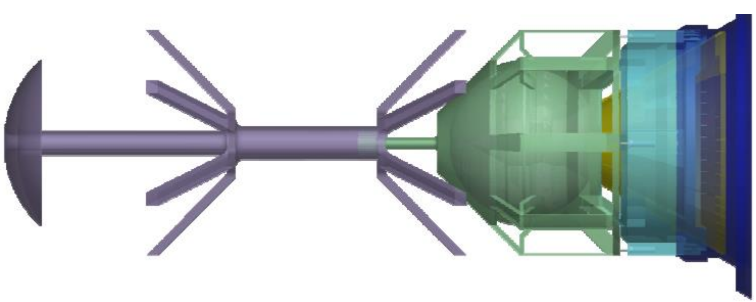


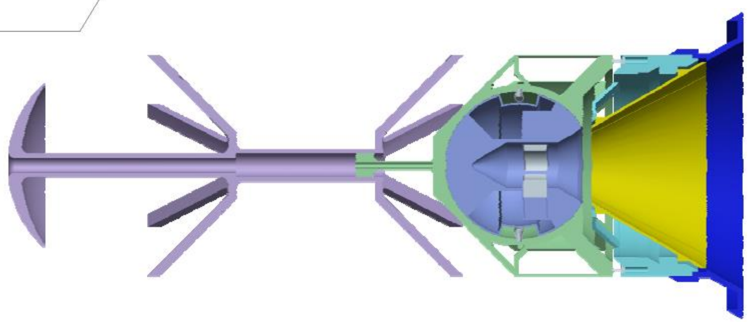


- Reference ACCD-sizing suitable for towing of large RLV-stage with 80 t return mass

ACCD Internal Mechanisms



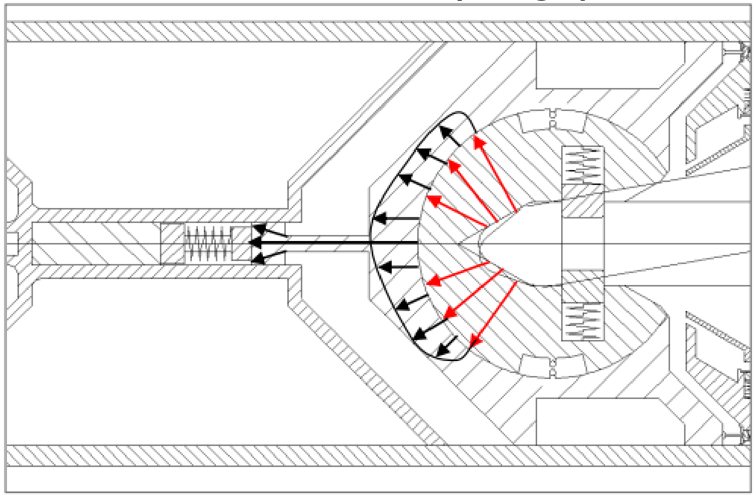


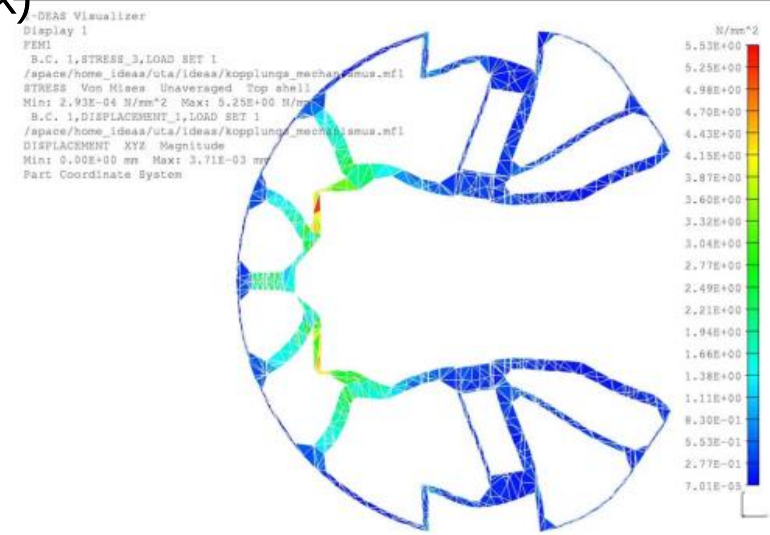


Video Animation !

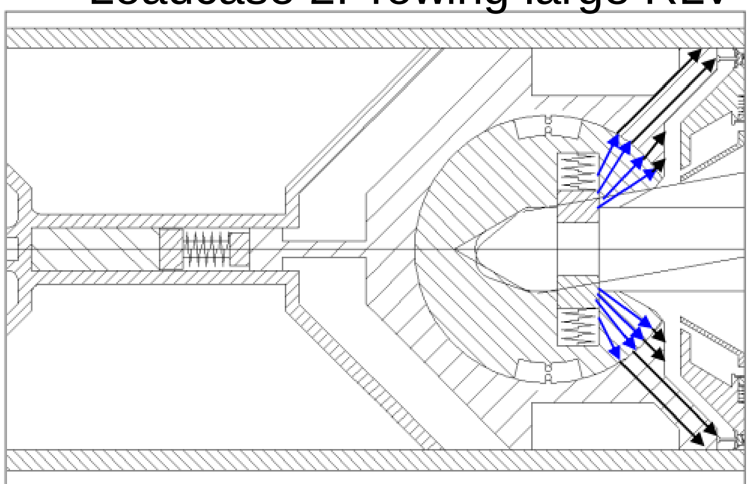
ACCD FEM Calculations

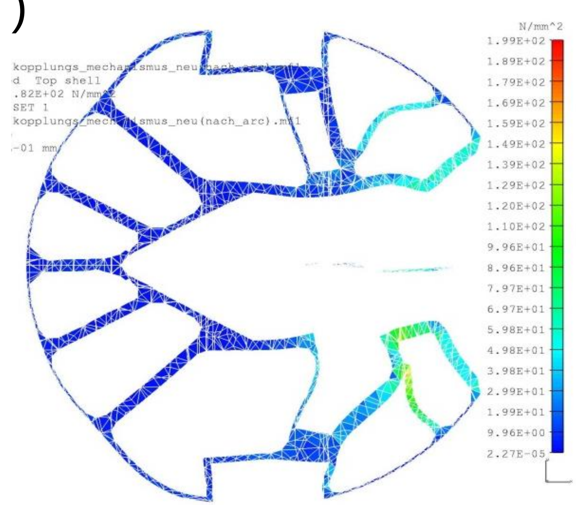
- Loadcase 1: Coupling (27 kN shock)





- Loadcase 2: Towing large RLV (174 kN)

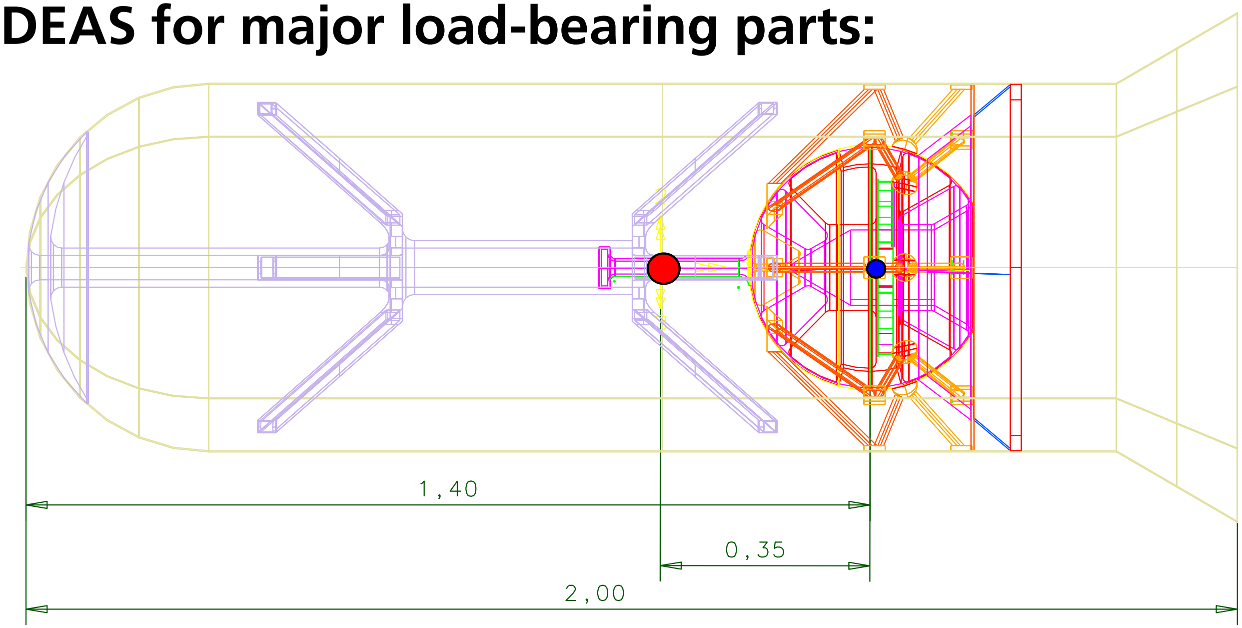




von Mises stresses (< 200 MPa) and strongly magnified deformations in spherical head

Status ACCD Internal Layout

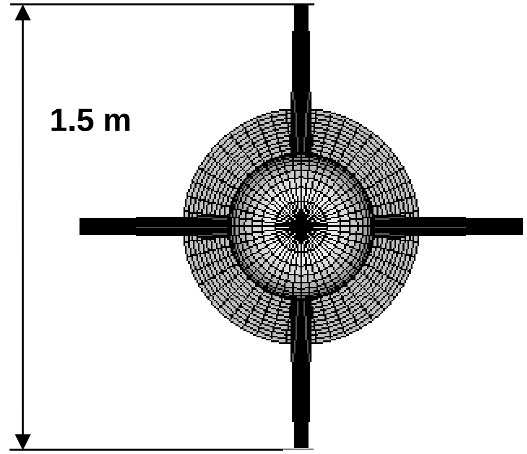
- Structural Analyses performed with ANSYS and later optimized with I-DEAS for major load-bearing parts:

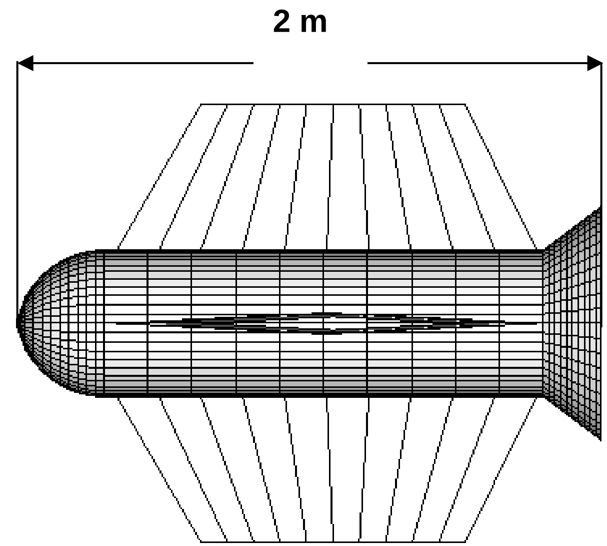


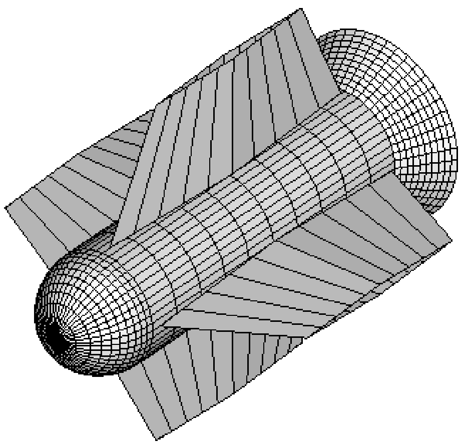
- Structural parts of fuselage designed at 79.7 kg
- Additional masses for wings, fins, actuators and equipment
- CoG at 1.05 m (as above) leads to longitudinal/lateral instability
- Trim mass (e.g. equipment) achieves desired CoG at 0.88 m
- Estimated total mass of ACCD 165.4 kg

ACCD Aerodynamic Layout

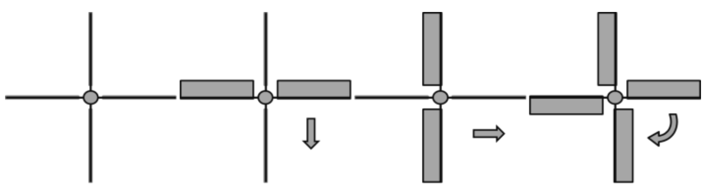
- 4 fins with symmetrical hexagonal profile (13% thickness)
- AoA Range of fins ± 15°
- **Horizontal fin deflection for pitch control**
- **Vertical flap deflection for yaw control**



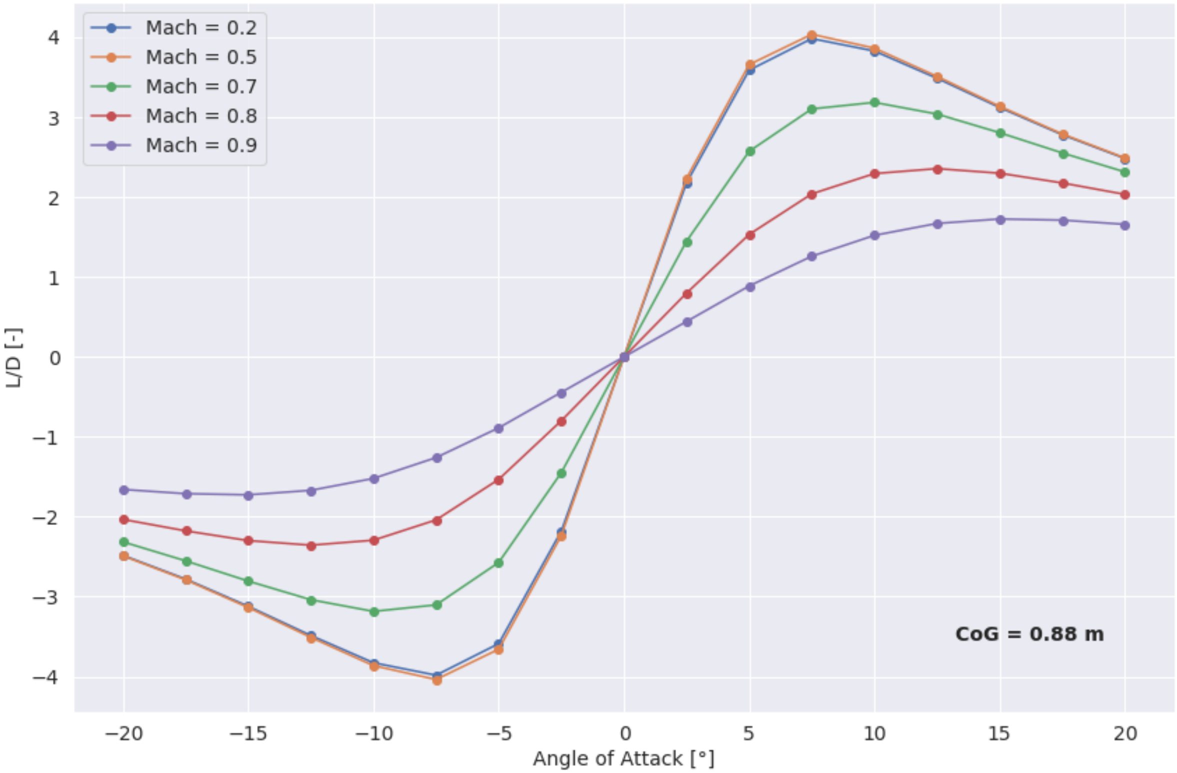


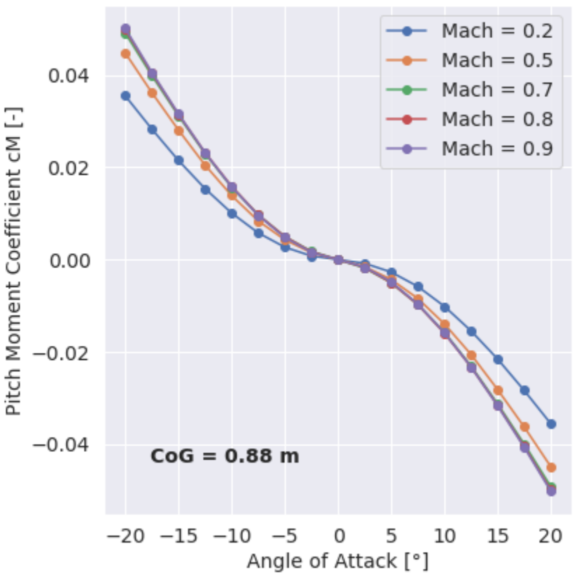


Value		Fins
Root chord length	[m]	1.434
Tip chord length	[m]	0.9
Span	[m]	0.5
Leading edge sweep angle	[°]	30.0
Flap Chord to Fin Chord Ratio	[%]	15



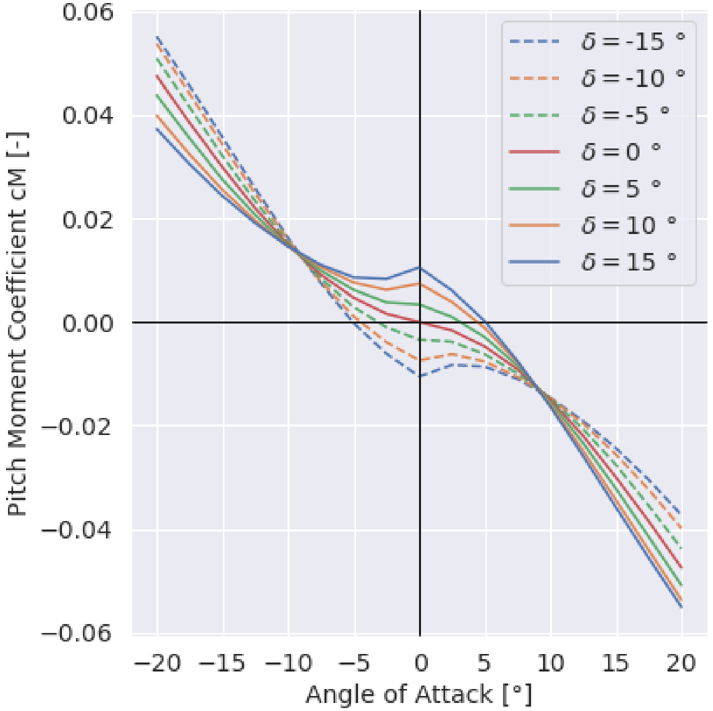
Preliminary ACCD Aerodynamics

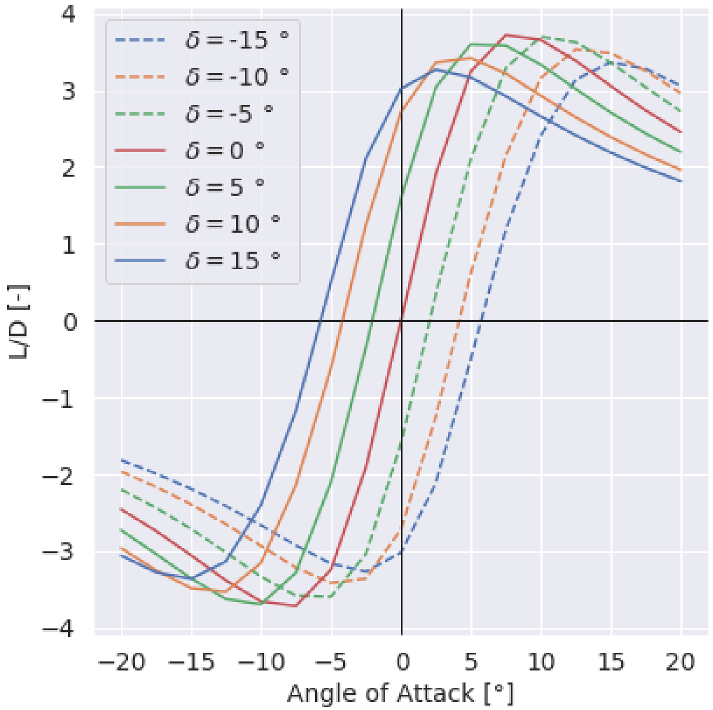




Preliminary ACCD Aerodynamics

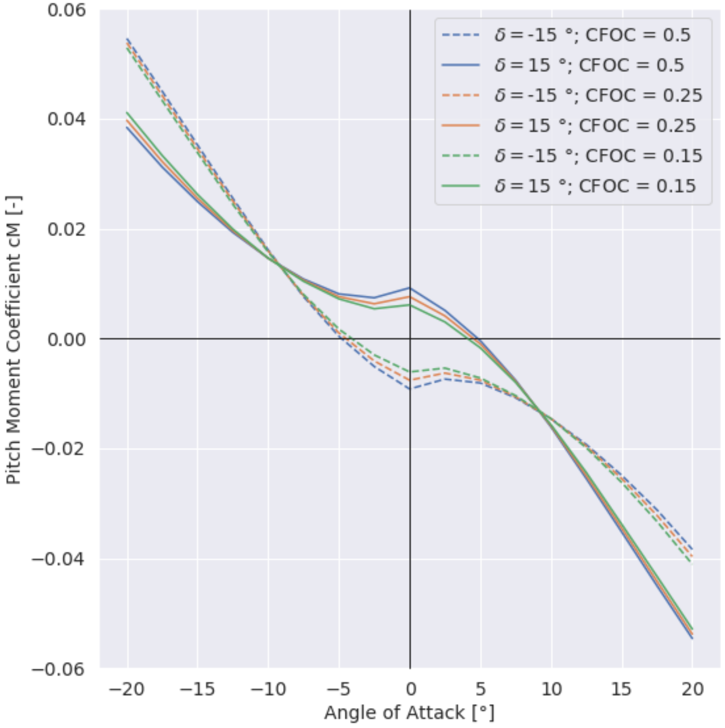
- Aerodynamic Coefficients for horizontal flap deflection (pitch control)
- **Mach = 0.6**

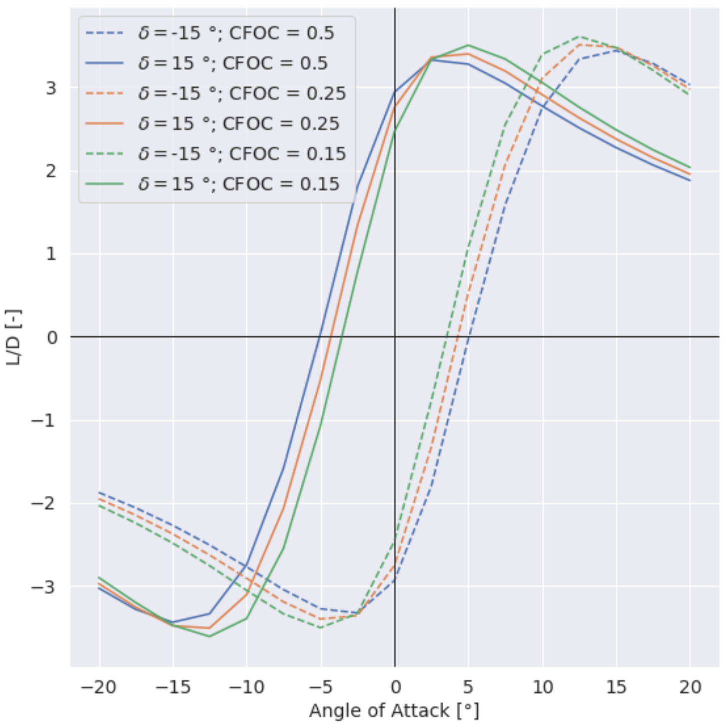




Preliminary ACCD Aerodynamics

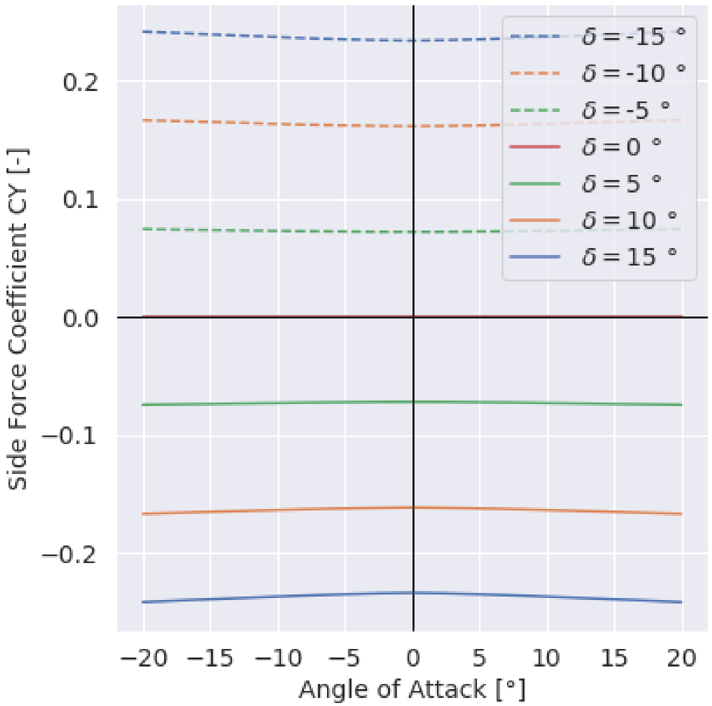
- Aerodynamic Coefficients for horizontal flap deflection (pitch control): influence of flap-to-chord ratio
- **Mach = 0.6**

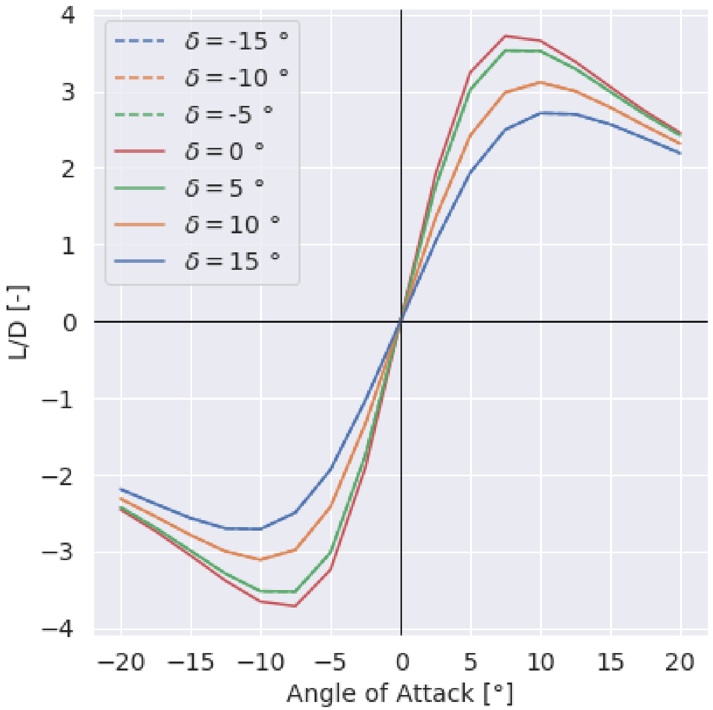




Preliminary ACCD Aerodynamics

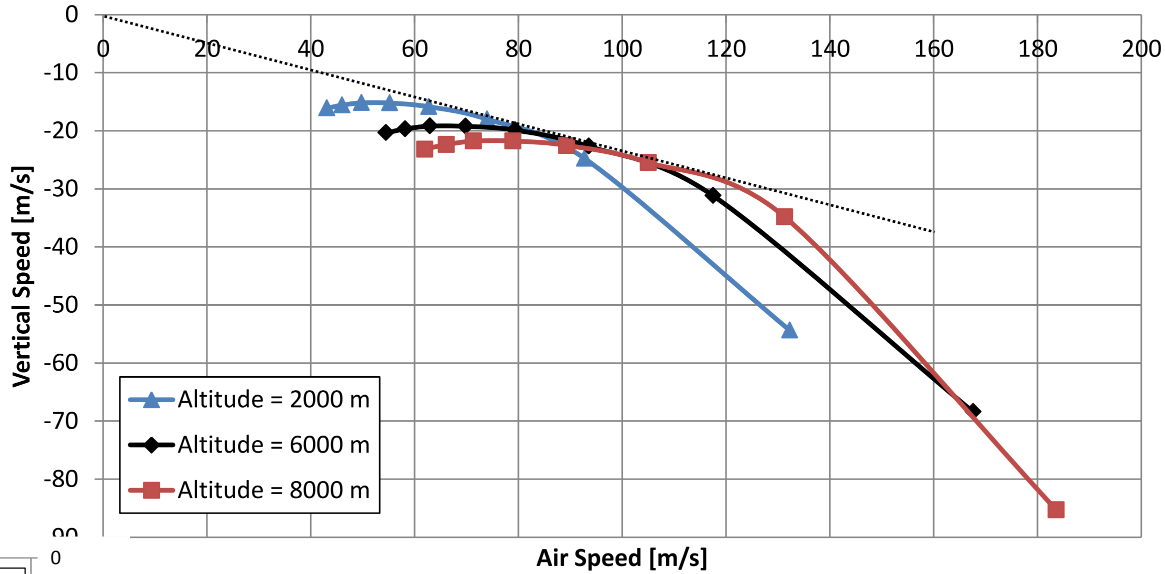
- Aerodynamic Coefficients for vertical flap deflection (yaw control)



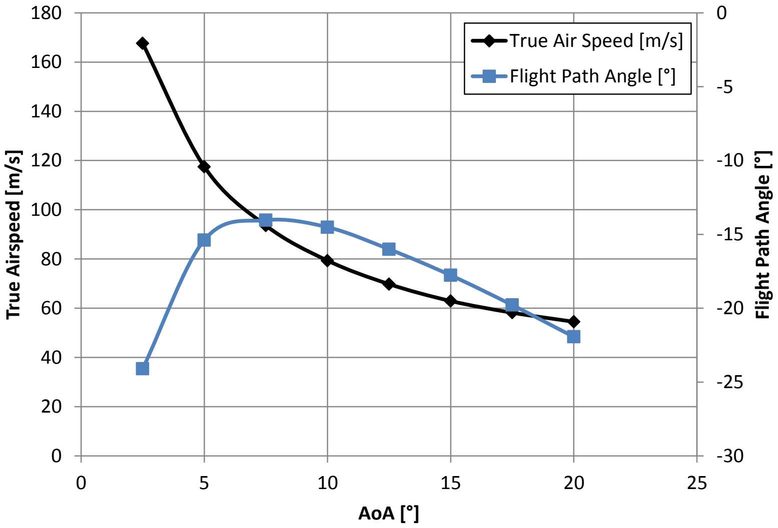


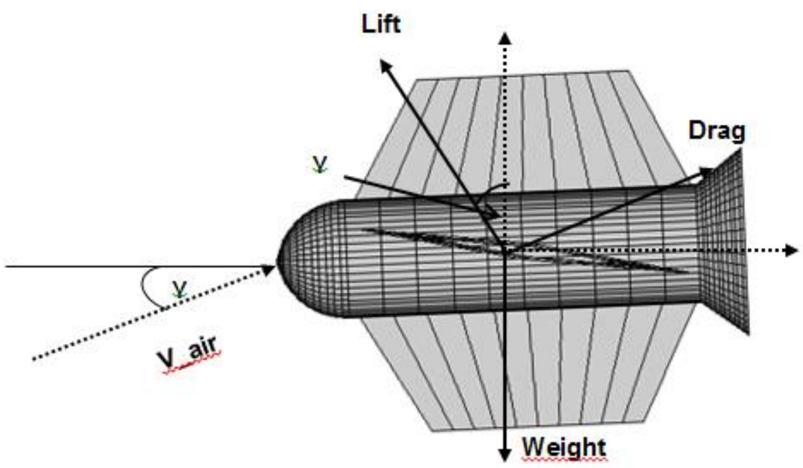
ACCD Flight Envelope

- Gliding flight with constant flight path angle



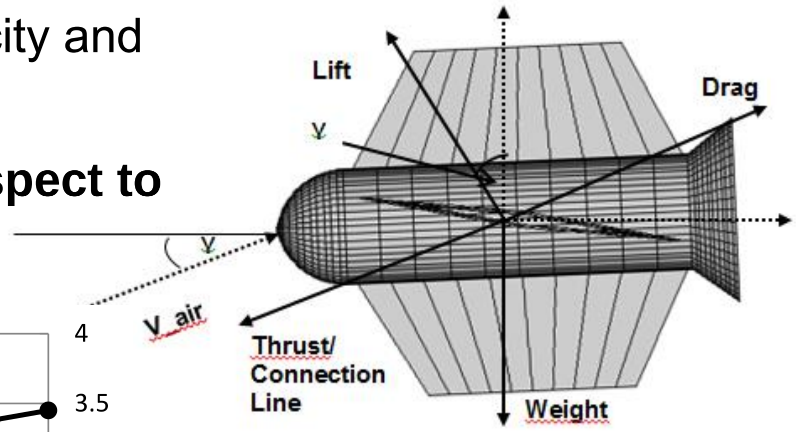
altitude 6000 m:

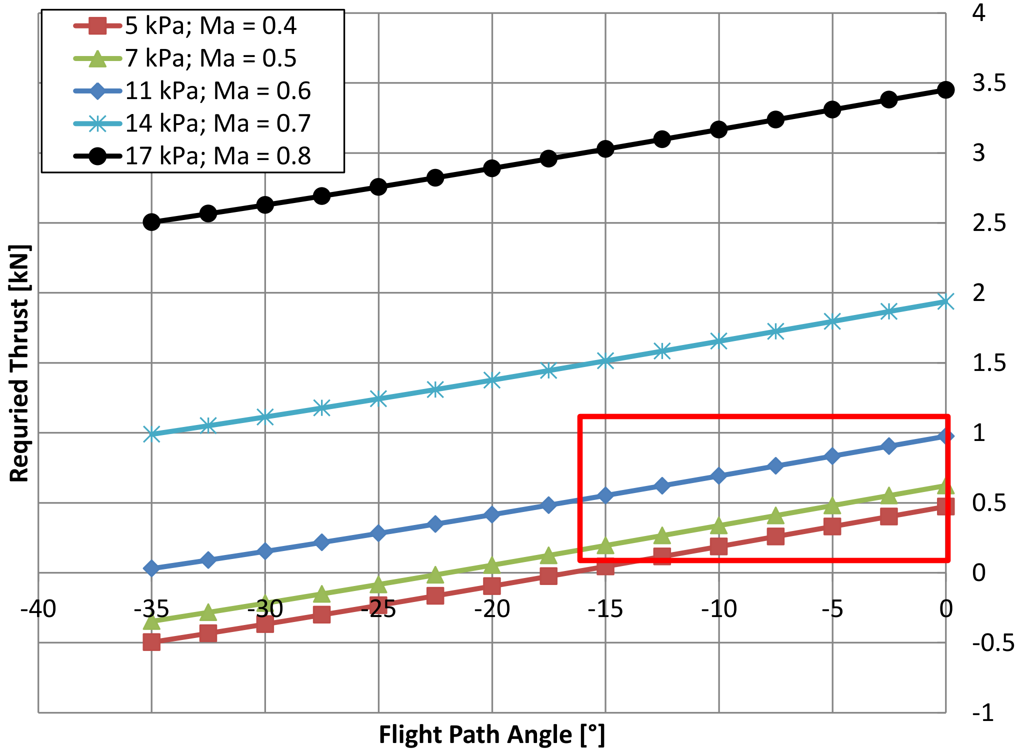




ACCD Flight Envelope

- “Capturing” Flight with constant velocity and flight path angle
- **Required additional thrust with respect to velocity and flight path angle**





relevant operational box

Requirements towing airplane

- Thrust requirements of capturing aircraft dependent on reusable stage's mass and L/D-ratio.
- Thrust reserve of aircraft has to exceed 50 to 200 kN in adequate flight altitude – depending on size of RLV-stage.
- Used Airbus A-340 or Boeing-747 suitable for large RLV-towing and considerable quantity available at affordable price.

- These aircraft should be operated unmanned under remote control. Only over the sea operation intended.
- Minor modifications to structure and speed control expected.

Off-Design Performance

- Nominal:
  - When starting aerodynamically controlled descent, the reusable stage should have a distance of about 20 km to the capturing aircraft.
  - Longitudinal and lateral deviations of about 2 km can be compensated by the returning RLV-stage alone.

- Perturbations of nominal flight:
  - Unforeseen conditions at separation (e.g. early MECO) or high wind speeds unknown at launcher's lift-off have to be corrected by energy dissipation early in the reentry trajectory.
  - In the worst case, the capturing aircraft has an additional capability to correct its geographical position by up to 100 km during the stage's ballistic phase.

Conclusion 1st part DLR

- Innovative method for return to the launch site of reusable winged stages by “in-air-capturing” shows significant performance advantage compared with all other return modes.
- Flight strategy and applied control algorithms show robust behavior (3DOF-simulations) of reusable stage to reach capturing aircraft.
- Most promising capturing technique uses separate aerodynamically controlled vehicle (ACCD), showing best performance and lowest risk.
- ACCD in full scale suitable for large RLV-stage has been preliminarily sized. Still major open points remaining which are to be addressed in FALCon.

- DLR is progressing with the “in-air-capturing”-technology by performing lab-scale flight experiments aiming for TRL between 3 and 4. See following presentation!