Multidisciplinary Design and Flight Test of the HEXAFLY-INT Experimental Flight Vehicle

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INTRODUCTION (1/3)

- The HEXAFLY-INT project (High-Speed Experimental Fly Vehicles – International), funded by the European Commission (EC) in the 7th Framework Program and by the European Space Agency (ESA), stems from the interest of Europe in hypersonic civil transportation vehicles. It involves partners from Europe, Russian Federation and Australia operating under ESA/ESTEC coordination.

- The project aims to demonstrate the feasibility of different critical aspects for high-speed flight in a dedicated experimental flight campaign and collect valuable flight data to validate methods and technologies suitable for high-speed flying systems.

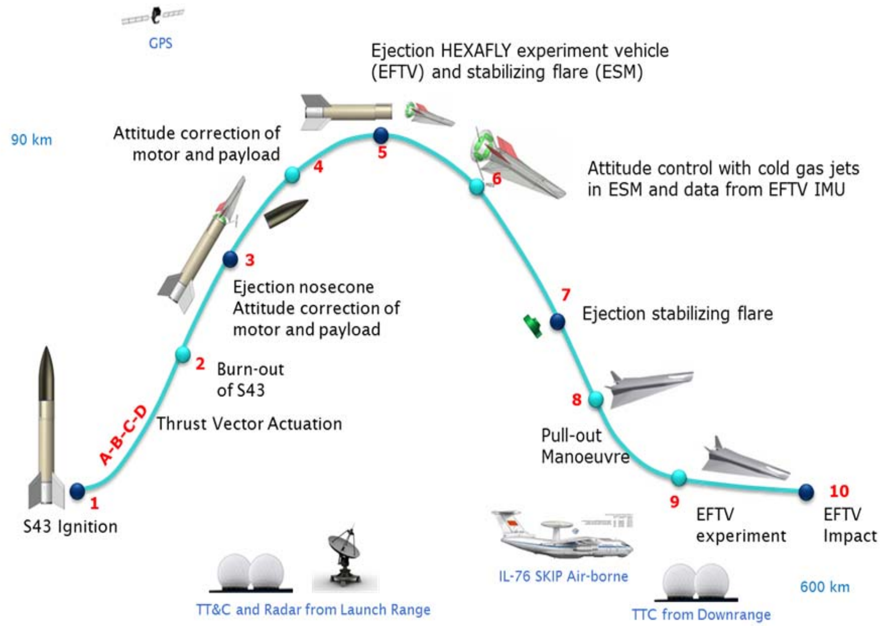
- High speed cruise capability is tested by the Experimental Flight Test Vehicle (EFTV), a non-propelled glider.

INTRODUCTION (2/3)

This presentation focuses on the activities performed within the project by the Italian partners CIRA and TET, coordinated by ESA/ESTEC:

- Configuration design, aerodynamic and aerothermodynamic design, thermal analysis and TPS design, structural loads definition, flight trajectory analysis and GNC (**CIRA**);
- Structural Design, stress analysis, configuration management and equipment accommodation (**TET**).

FLIGHT SCENARIO



- Vertical launch from the Centro de Lançamento de Alcântara (CLA) in Brazil by a sounding rocket, the VS43 launcher;
- EFTV early descent flight docked to the ESM; control vehicle’s attitude controlled by a cold gas system (CGS);
- EFTV-ESM separation at about 55km; EFTV pull out. Experimental window;
- Controlled hypersonic banking maneuver;
- Fly within the telemetry covered area (a 600 km radius circle with the town of Fortaleza as center);
- End of mission at about Mach=2.

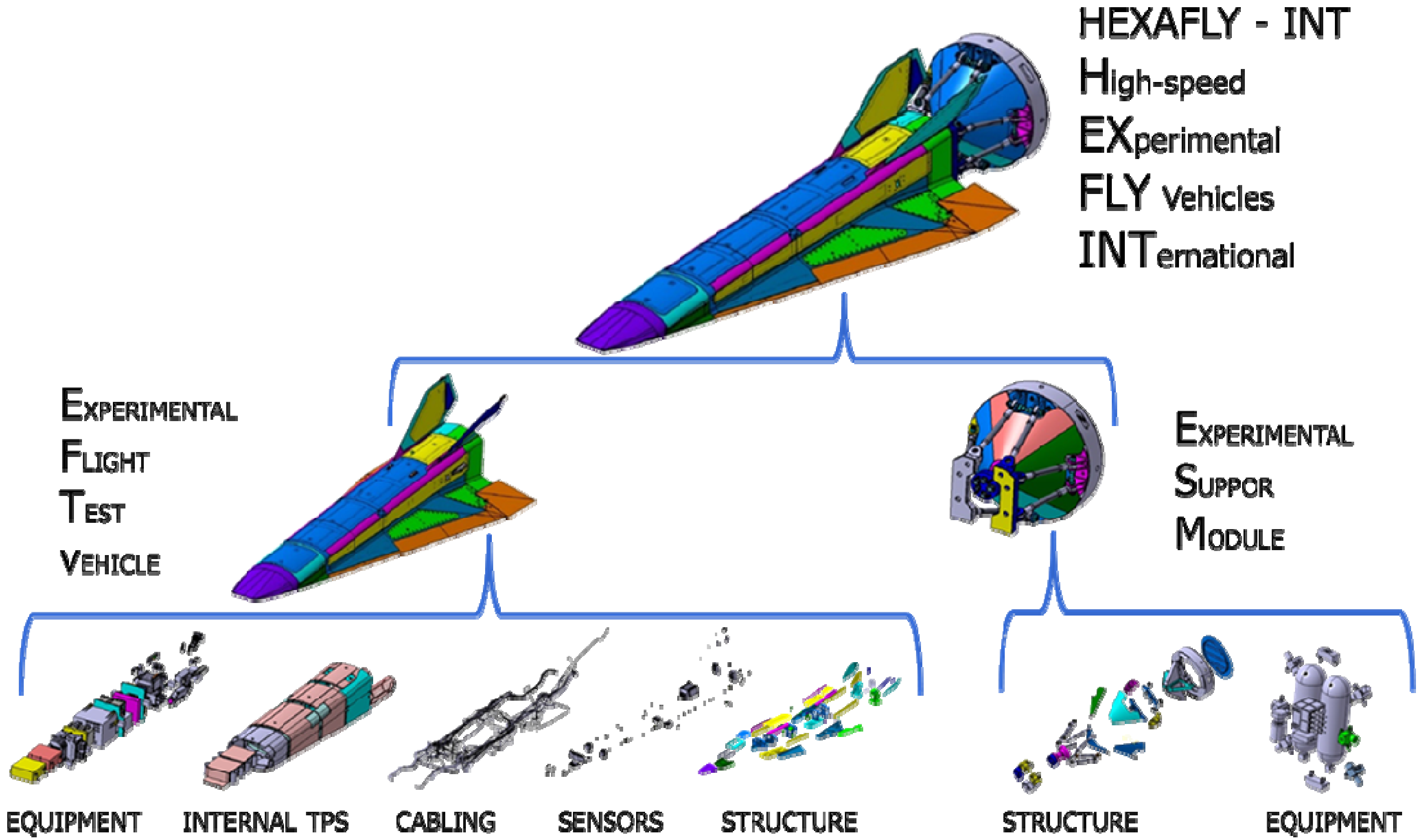
MAIN MISSION OBJECTIVES

The flight experiment shall demonstrate:

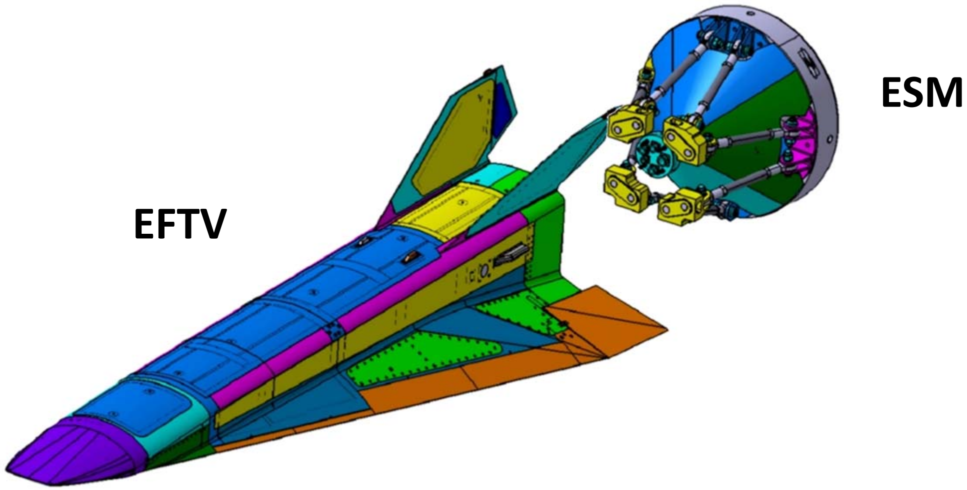
- high aerodynamic efficiency (L/D ≥ 4)
- positive aerodynamic balance at a cruise Mach number of 7 to 8 in a stable and controlled way at altitude 28-32 km
- gliding performance from Mach 8 down to Mach 2
- the potential for performing maneuvers
- optimal use of advanced high-temperature materials and/or structures

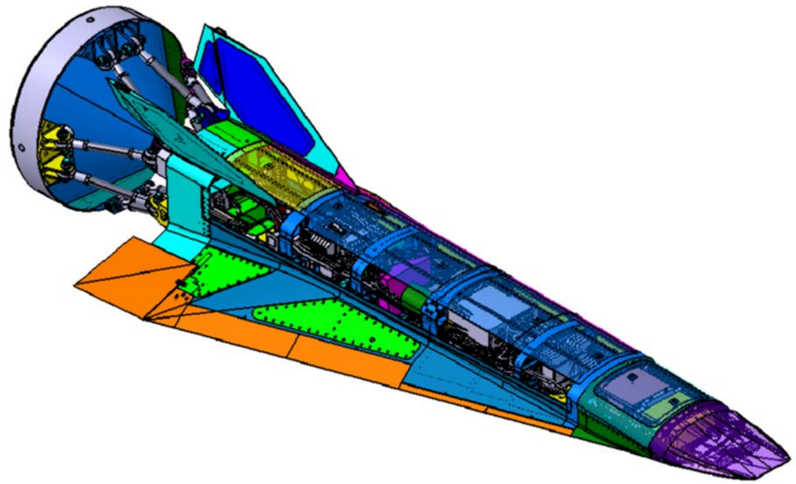
Requirement	Target Value	Min. Value	Max. Value	Comment
Phase I: insertion into level flight: Mach number [-]	7.4	7	8	Phase I: addressing aerodynamic balance after pull out manoeuvre
Phase II: Gliding Phase: ➔ Flight Mach number [-]	5 to 7.4	2	8	Phase II: Mach number gradually dropping during gliding phase potentially including manoeuvres.
Flight altitude [km]	30	27	33	Optimal: level flight
Flight path angle [°] Phase I	0 (level)	0	10 to 15 (TBD)	Accuracy: 0.1 (measured) Accuracy: +/-5 (TBD) for insertion
Test time (Phase II) [s]	Max. possible	150	Till Impact	Gliding Phase duration defined by aero-stability range

Vehicle Design Configuration



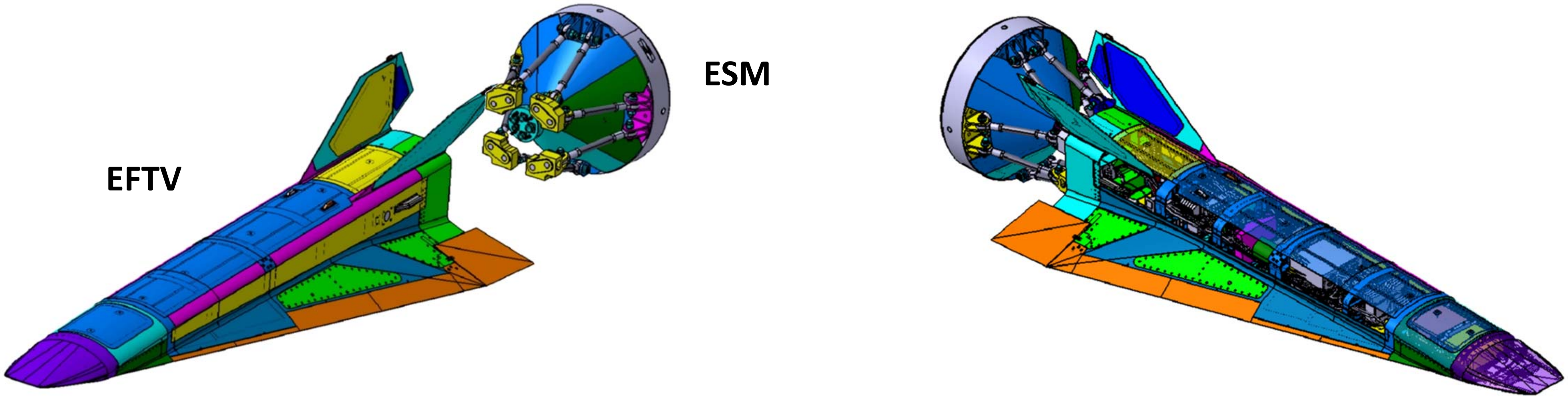
Experimental Flight Test Vehicle





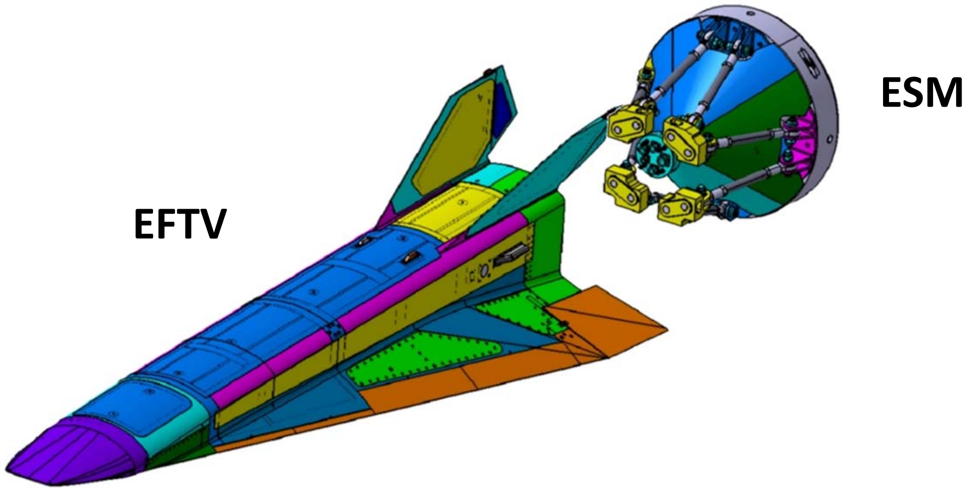
EFTV	Geometry
Dimensions	Length 3.29m, Wing span 1.23m
Wing	80-deg sweep angle, 14-deg negative dihedral angle, 1mm rounded leading edge
Ailerons	Lenght 0.4m, width 0.32m
Fixed vertical fins	68.5-deg sweep angle, 54-deg angle between the two fins in the transversal plane

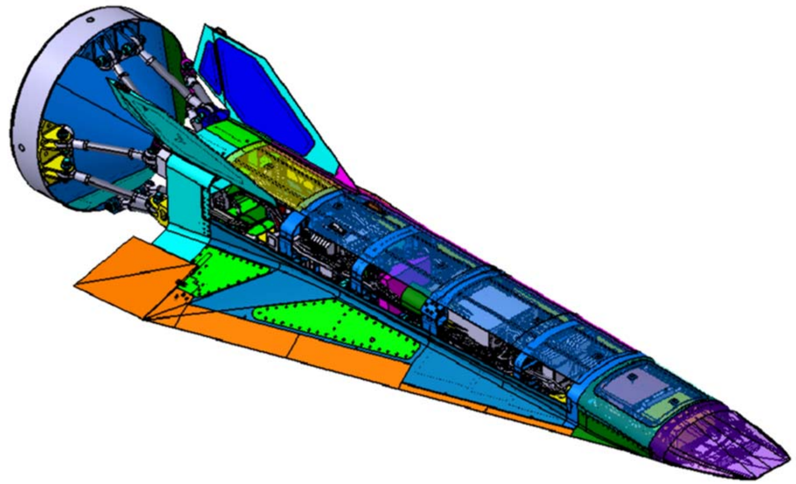
Experimental Flight Test Vehicle



EFTV	Materials
Cold structure, fusalege and wing panels, fin	Titanium alloy
Nose	Copper
Hot structures (ailerons, wing leading edges)	C/C-SiC
Thermal Protection	ZrO2 coating, high emissivity paint
Thermal Insulation	Aeroguard® (PROMAT) light flexible microporous insulator

Experimental Flight Test Vehicle



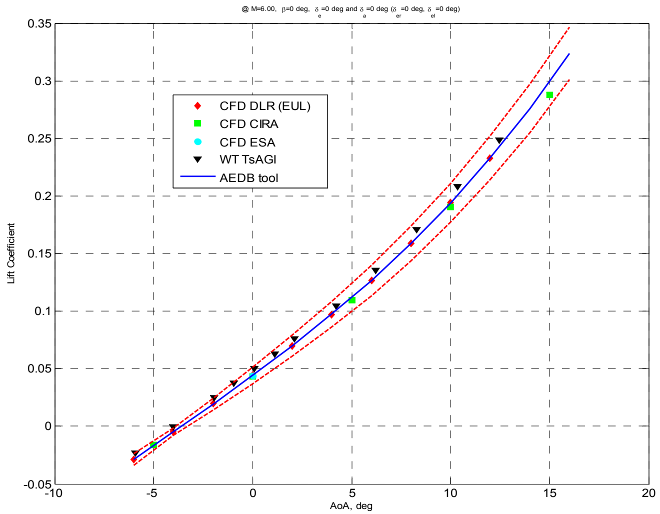


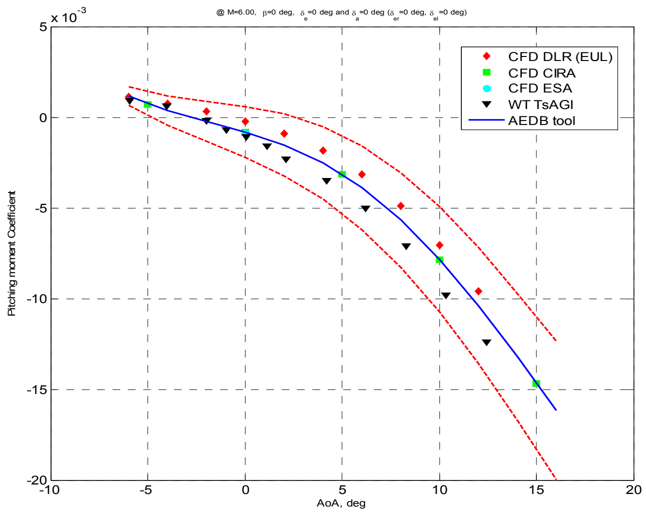
EFTV	Equipment
Avionic system	Inertial measurement unit (IMU), GPS, two servo-actuators for the ailerons, flight control computer (FCC) for on-board mission management. Downlink telemetry (some antennas) will transmit all mission data to the Ground Control Station
In–flight measurement	▪ heat flux (HF), thermocouples (TC), pressure sensors, strain gauges and accelerometers; ▪ Flush Air Data System (FADS); ▪ External and internal cameras to get visual feedback from the vehicle flight status and wall temperature measurements.

Design Numerical Activities

EFTV AEDB is a tool that provides aerodynamic force and moment coefficients with uncertainties. It is composed by the aerodynamic model + uncertainty model, fed by:

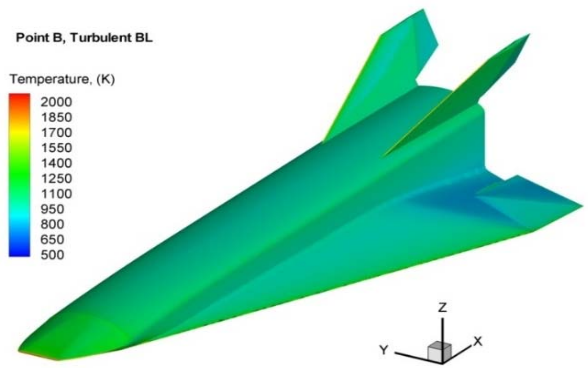
- Euler CFD computations (more than 1000), Navier-Stokes CFD computations (more than 200) performed by DLR, ESA, TsAGI and CIRA;
- Experimental data from the test campaign in the supersonic/hypersonic wind tunnel T-116 at TsAGI.

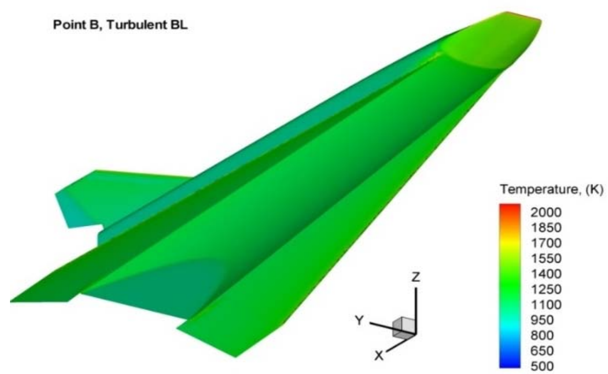




Lift and pitching moment coefficients in clean configuration at M_{∞}=6.0

- Temperature/heat flux distributions computed by CFD in radiative equilibrium conditions; points along the reference trajectory constitute the input data for the thermal analysis;
- Laminar/turbulent transition analysis (engineering correlations, CFD, experimental test campaign at TsAGI T-116);
- Micro-aerothermodynamics effects computations (ESA).

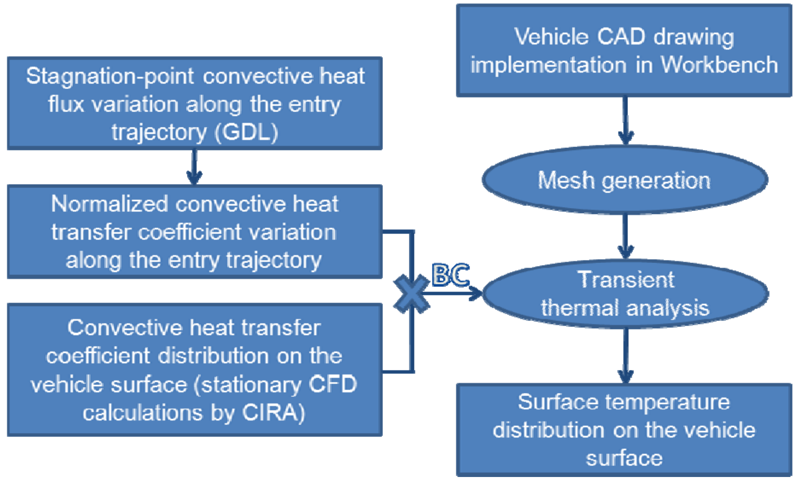




Thermal Design

- Definition of the vehicle TPS (materials, thicknesses, coatings)

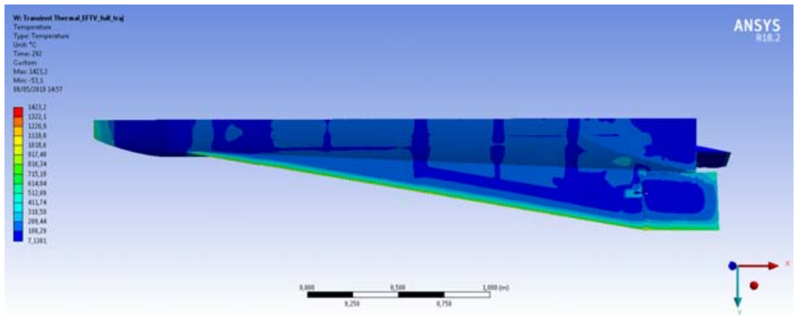
- Inputs for transient thermal analysis (FE method in ANSYS®): 12 CFD computations along the reference trajectory

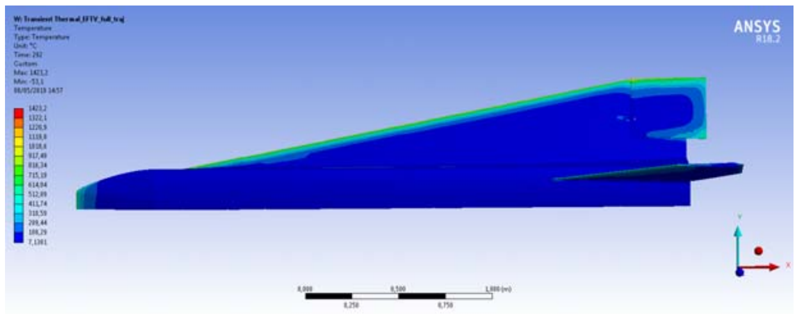


Flight trajectory splitted in a certain number of legs defined by the specific flight conditions analyzed, where:

$$h(x,t) = h(x)\Big|_{CFD_i} \cdot \frac{h_0(t)}{h_0(t_{CFD_i})}$$

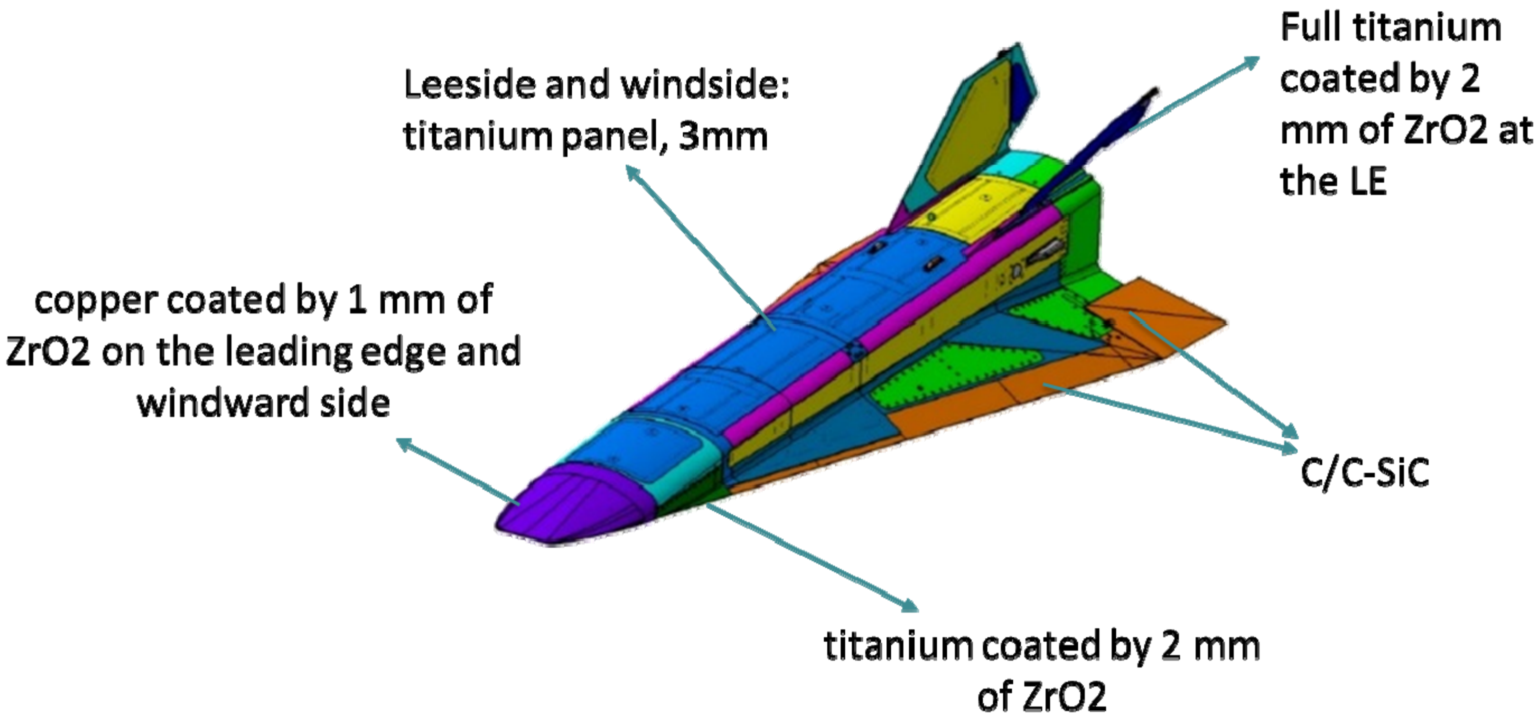
- Several FEM analyses have been performed to evaluate the aerothermal sustainability of the different materials as well as the coating and heat flux margin effect.
- Zirconia coatings, C/C-SiC and copper components on EFTV would widely survive the aerothermal environment (service temperatures, respectively: 2400°C, 1600°C and 800°C).
- Temperatures on the titanium structures slightly exceed their upper working temperature limits (700 °C) in some critical regions. This has been solved with the use of a high emissivity painting.



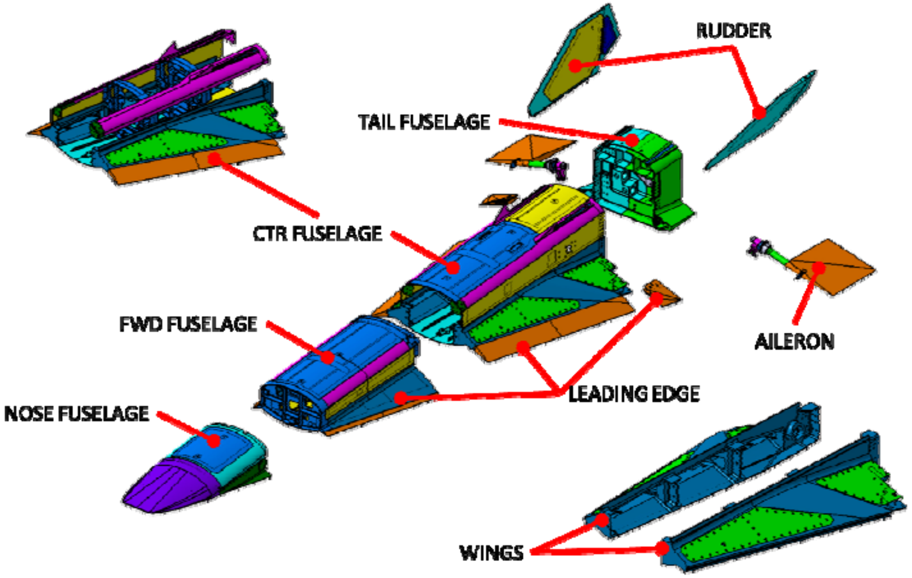


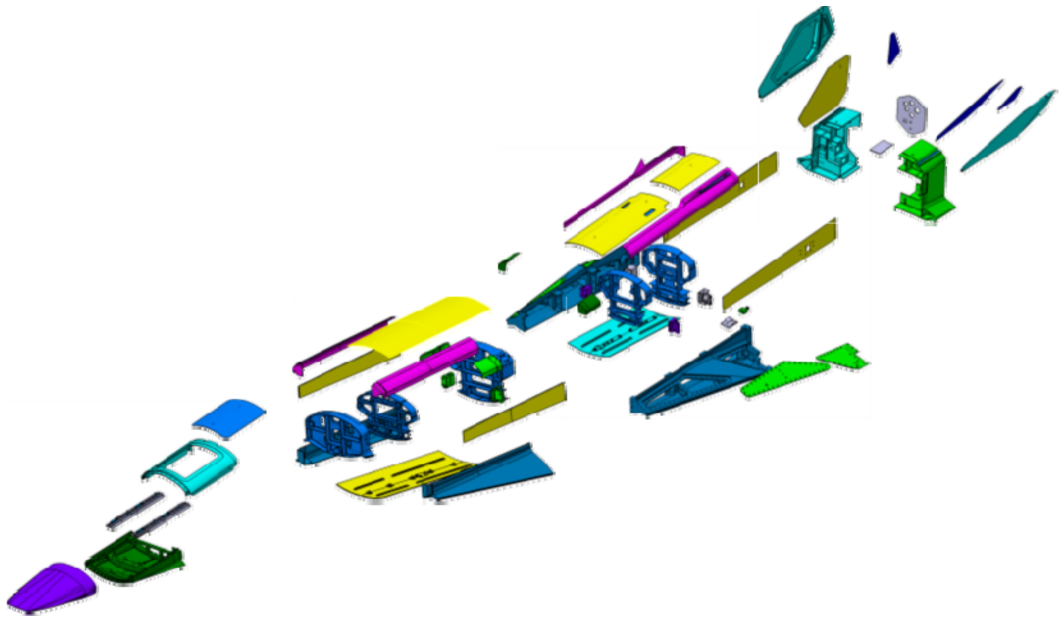
❑ TPS final configuration

High emissivity painting on the EFTV metallic surfaces, even on coating



❑ Structural main components

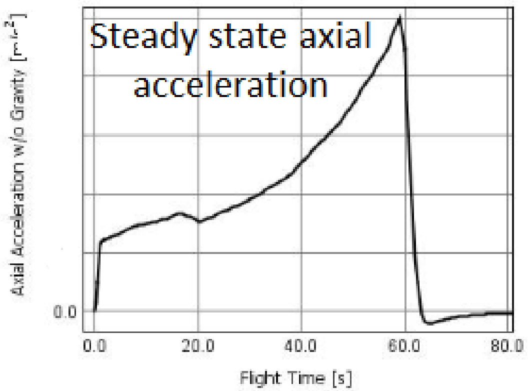


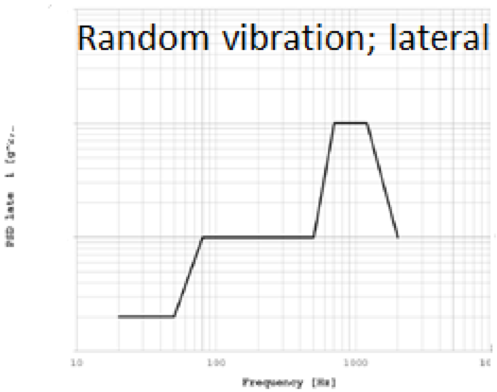


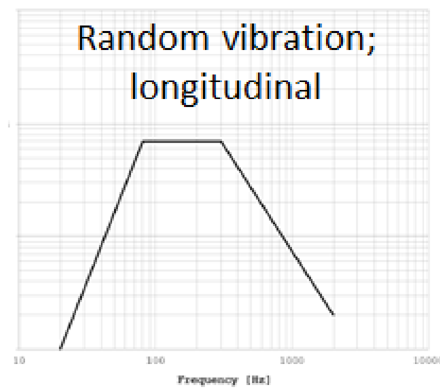
- The loads analysis carried out by CIRA takes into account two different approaches for the two trajectory phases (ascent-descent):
  - Ascent phase: Launcher Loads;
  - Descent phase: Aerodynamic+Thermal+Inertial Load.

- Launcher Loads

Loads at launch are provided within the VS-43 launcher Mechanical Environment manual:







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Ignition shock at payload interface

➢Ascent Phase: Launcher Loads Analysis

- Static and dynamic behavior assessed by means of the 3D Finite Element Dynamic Model implemented in the software MSC Nastran;
- Modal parameters of the vehicle evaluated with respect to launcher requirements, to avoid any coupling effects;
- Static and dynamic loads combined to give equivalent quasi-static loads at the vehicle CoG;
- Frequency Response Analysis for each on board equipment.

Design Limit Loads [g]					
X Direction		Y Direction		Z Direction	
±	31.30	±	6.07	±	6.88
±	31.30	±	6.07	±	3.88
±	31.30	±	3.07	±	6.88
±	31.30	±	3.07	±	3.88
±	1.30	±	6.07	±	3.88
±	1.30	±	6.07	±	6.88
±	1.30	±	3.07	±	6.88
±	1.30	±	3.07	±	3.88

Amplification Factor Q=50

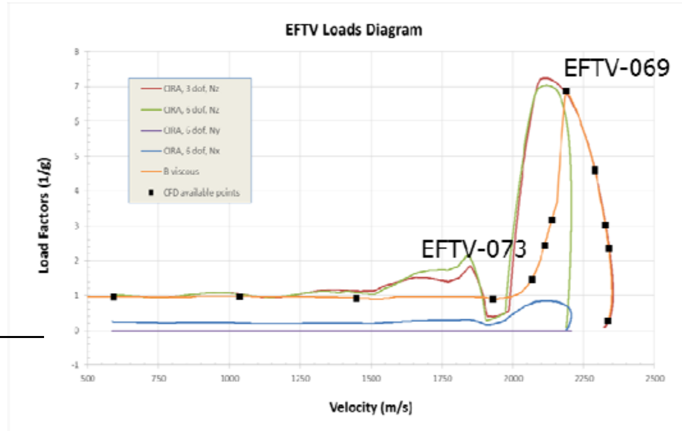
Design Factor=1.5

➢Descent Phase: Maneuvers Loads

- Vehicle structure submitted to: pressure loads due to flight maneuvres, stresses due to temperature and inertial loads.
- Sizing cases for inertial loads: pull-out manoeuvre (Nz=7.3 g) and bank (Ny=2.17g);
- Pressure loads from CFD along the trajectory;
- Sizing cases for temperature: Max Qst, Max Tframe

Descent Phase Loads (DPL) combination

t=0s EFTV-ESM separation	Pressure field (CFD)	Temperature field (thermal analysis)	Inertial Load
DPL-1	TV-069 (t=27s)	Max Qst (t=24s)	Nz=7.3g
DPL-2	TV-073 (t=77s)	Max Tframes (t=142s)	Ny=2.17g



EFTV-069 max inertial load
EFTV-073 Pdyn max

Structural Loads and Stress Analysis

- For each load case, a static linear analysis has been performed (MSC Nastran) to calculate the distribution of displacements, internal forces and stresses in FE model.
- The maximum stress has been compared with the allowable in order to obtain the safety margins (FoS according to ECSS-E-HB-32-23A):
  - For each part number the max stress of Von Mises has been calculated;
  - For the bolts, the forces have been extracted from the FEM and a hand calculation analysis has been performed.

Part number analysis

Margin of safety $= \frac{\sigma_{allowable}}{FoS \times \sigma_{von\ mise\ FEM}} - 1$

Bolt analysis

Margin of safety $= \frac{Shear_{allowable}}{FoS \times Shear_{FEM}} - 1$

Margin of safety $= \frac{Bearing\_allowable}{FoS \times Bearing_{FEM}} - 1$

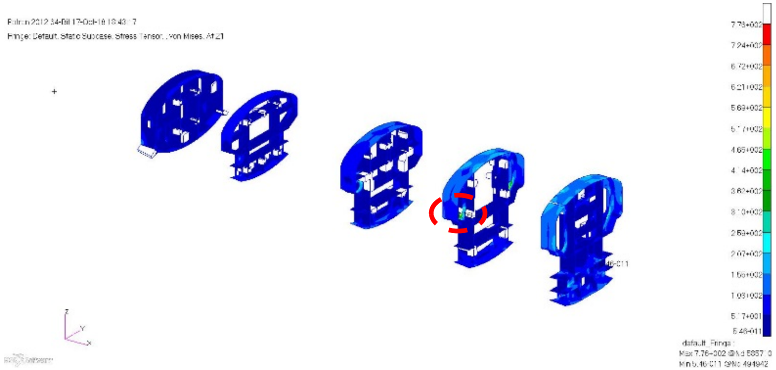
Young modulus in temperature E Yield strength $\sigma_{0,2}$ Ultimate strength σ_B		
^{0}C	0	
E	kgf/mm^2	12000
$\sigma_{0,2}$	kgf/mm^2	8
σ_B	kgf/mm^2	24
Density ρ	kg/m^3	8950
Specific heat c	kJ/(kg·^{0}C)	0,377
Thermal conductivity λ	W/(m·^{0}C)	385
Passon ratio μ		0,34
Thermal expansion coefficient α	α10^{6}1/^{0}C	16,8

M1 copper alloy characteristics

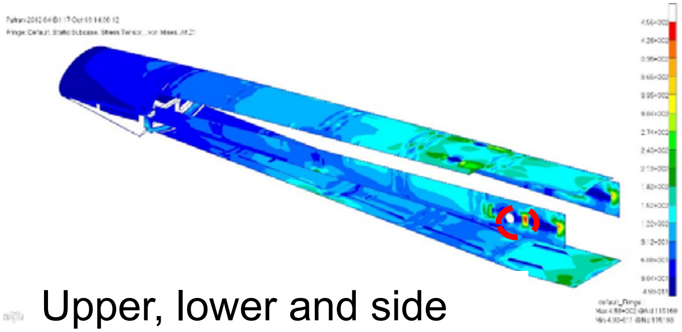
Fty (Tensile Yield Strength)	861	Mpa	
Ftu (Ultimate Tensile Strength)	988	Mpa	
Fsu (Ultimate Shear Strength)	622	Mpa	
Fbru (e/D=1.5) (Ultimate Bearing Strength)	1186	Mpa	
E (Young's Modulus)	121399	Mpa	
G (Shear's modulus)	44130	Mpa	
e (elongation value)*	6-8%		* - for BT-20 bar that length equals five diameters

BT-20 titanium Yield and Ultimate Strengths at room temperature

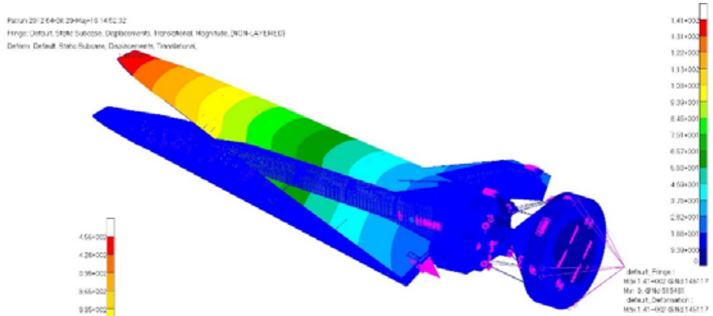
➢Maximum Stress for equivalent static loads



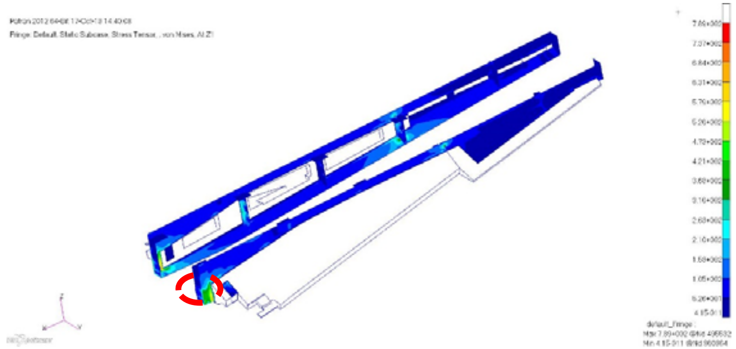
Frames – Max stress von mises= 776 Mpa



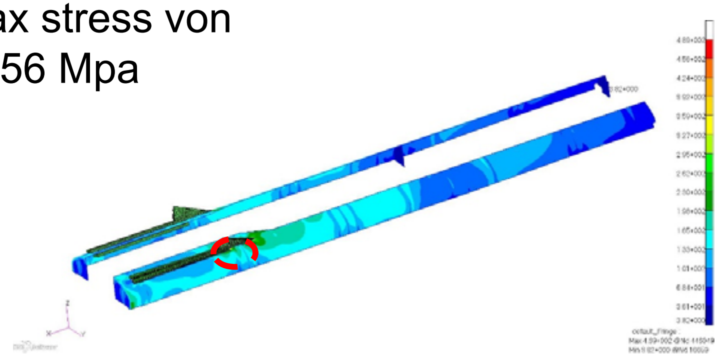
Upper, lower and side Panel Max stress von mises= 456 Mpa



Max displacement – [141 mm]



Wing -Max stress von mises= 789 Mpa

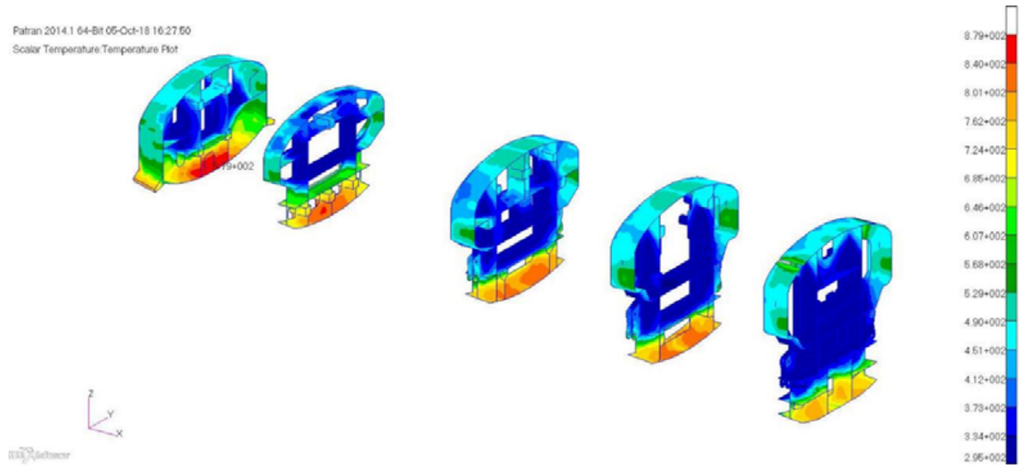


Stringer
Max stress von mises= 489 Mpa

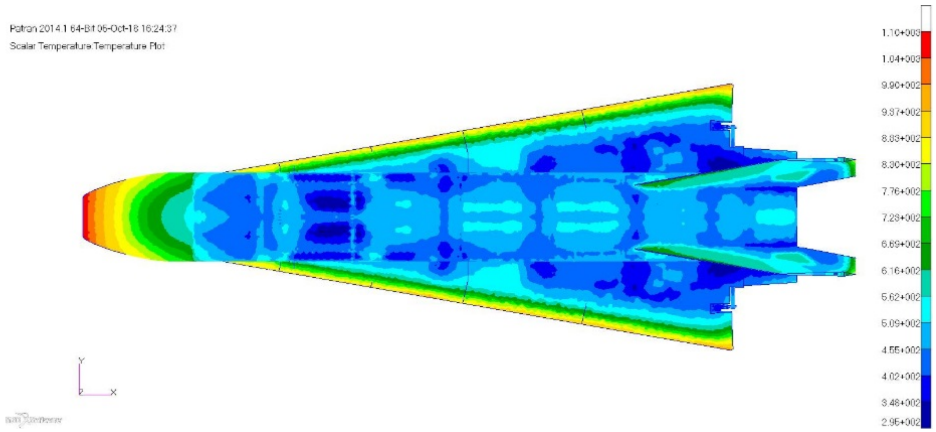
➢Maximum Stress for equivalent static loads

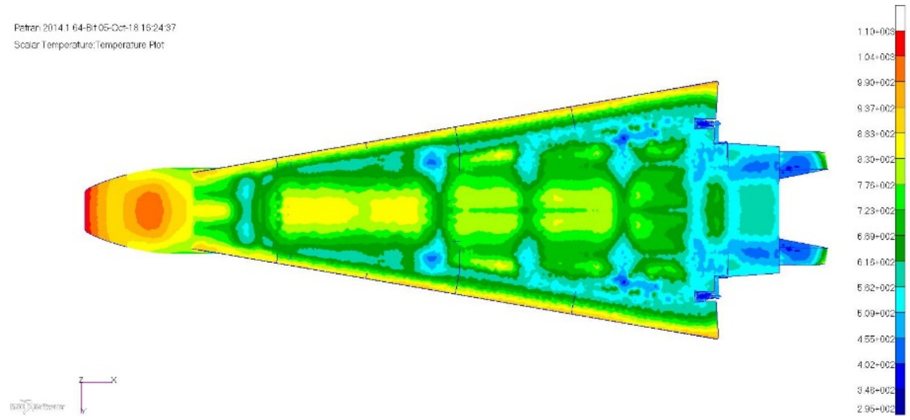
- All safety margins result positive;
- In some areas, some critical issue has been investigated in order to guarantee the safety of the vehicle;
- In case of junctions a greater margin of safety has been guaranteed by properly defining diameters and mechanical characteristics of the bolts;
- For other parts it has been sufficient to locally increase the panel thickness in some regions.

➢ Maneuvers loads analysis, DPL-2



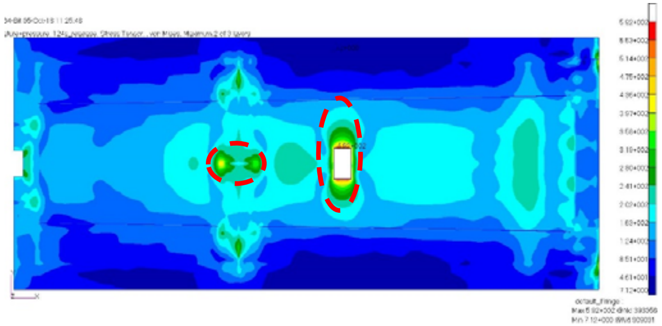
Temperature distribution 142s after release from ESM



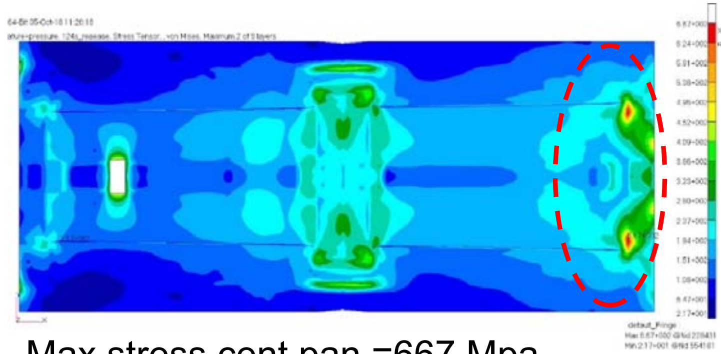


➢ Maneuvers loads analysis, DPL-2

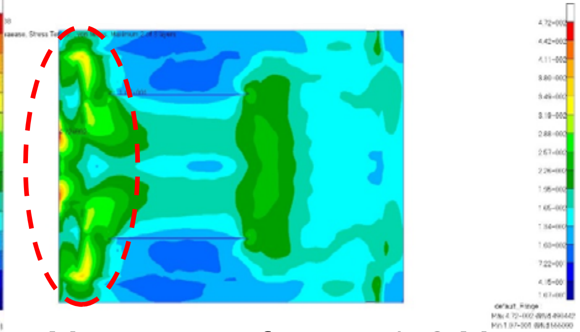
Stress distribution – windward panels



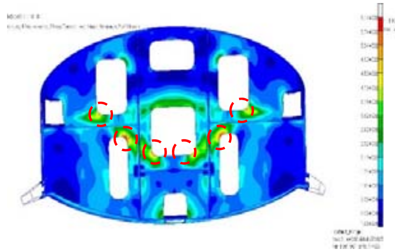
Max stress fwd pan =592 Mpa



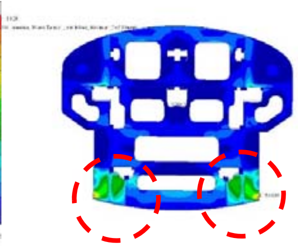
Max stress cent pan =667 Mpa



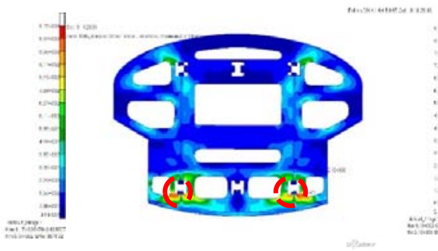
Max stress aft pan =472 Mpa



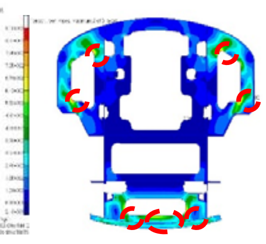
614 Mpa



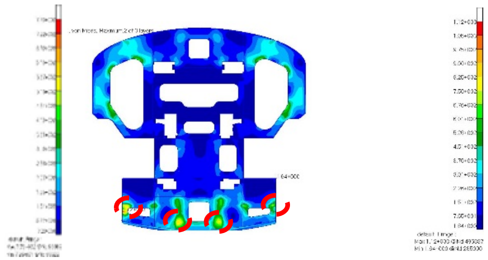
1150 Mpa



918 Mpa



773. Mpa



1120 Mpa

➢ Maneuvers loads analysis

- Safety margins are all positive for DPL-1;
- Some critical regions for the most loaded condition (DPL-2);
- The results of the final thermal analysis on the complete vehicle seem to recover some criticalities (that if confirmed would involve a locally increase of the panels thickness); final stress analysis is on-going.

EFTV Trajectory

- The EFTV shall perform a flight above Mach 7, maximizing the aerodynamic efficiency, in a specified altitude range and in a quasi-levelled flight.
- Additional constraints are defined for the lateral manoeuvre, led by safety and/or telemetry reasons.

3dof and 6dof flight simulator from an initial state (ESM release) + Monte Carlo (1000 runs)

Sources of uncertainty :

- EFTV mass and AEDB uncertainties (Δmass ±10%, ΔCL ±10%, ΔCD ±20%);
- Position and velocity measurement errors (ΔPGPS ±10m, ΔVGPS ±0.1m/s);
- Tracking errors of AoA and bank angle, due to non-ideal control laws (±2deg).

EFTV Trajectory

Mission Requirements and Constraints for:

Phase 0: pull-out manoeuvre; starting from the release from the ESM at 55km, and ending at 33km

Phase I: level flight; starting from end of Phase 0 and ending when either M is under 6.5 or altitude is below 27km

Phase II: gliding flight; starting from end of Phase I till splash-down

Phase 0

	Constraint Value	Hard/Soft
Convective heat flux parameter ρ*v [kg/m²/s]	< 75	H
Hinge Moment [Nm]	< 332 along the whole trajectory	H
Distance from Alcantara, Fortaleza or Natal [km]	< 600	H
Distance from the coast [km]	> 100 along the whole trajectory	H
Trim deflection range [deg]	> -20 and <10 along the whole trajectory	H

Phase 1

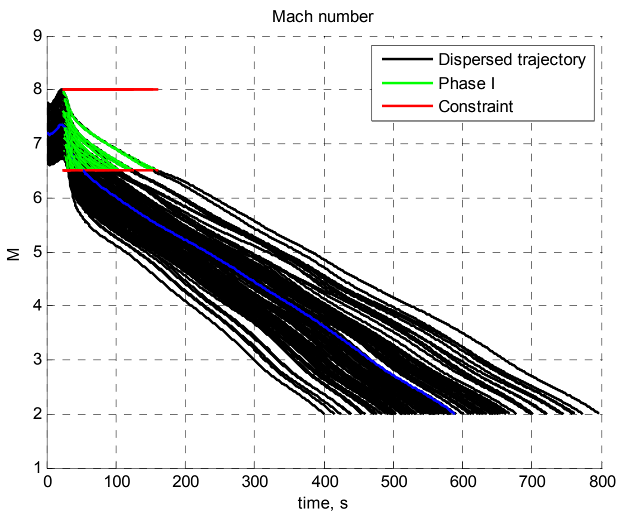
	Constraint Value	Hard/Soft
Convective heat flux parameter ρ*v [kg/m²/s]	< 75	H
Hinge Moment [Nm]	< 332 along the whole trajectory	H
Aerodynamic efficiency	> 4 for at least 3s	H
Flight Mach number [-]	6.5 < M <8	H
Flight path angle [deg]	< 5	H
Altitude [km]	> 27 and <33	H
Distance from Alcantara, Fortaleza or Natal [km]	< 600	H
Distance from the coast [km]	> 100 along the whole trajectory	H
Trim deflection range [deg]	> -20 and <10 along the whole trajectory	H

Phase 2

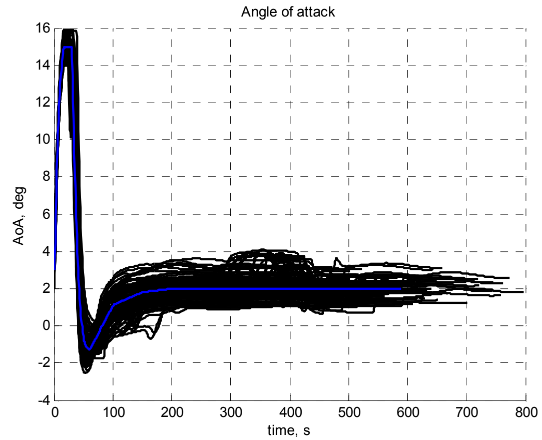
	Constraint Value	Hard/Soft
Hinge Moment [Nm]	< 332 along the whole trajectory	H
Flight Mach number [-]	2 < Ma <6.5	H
Downrange [km]	> 500km (To be maximized)	H
Cross range [km]	> 50km	H
Distance from Alcantara, Fortaleza or Natal [km]	< 600 along whole trajectory	H
Distance from the coast [km]	> 100 along the whole trajectory	H
Final Heading [deg]	-40	H
Final Heading error [deg]	< 2 (CIRA assumption)	H
Trim deflection range [deg]	> -20 and < 10 along the whole trajectory	H

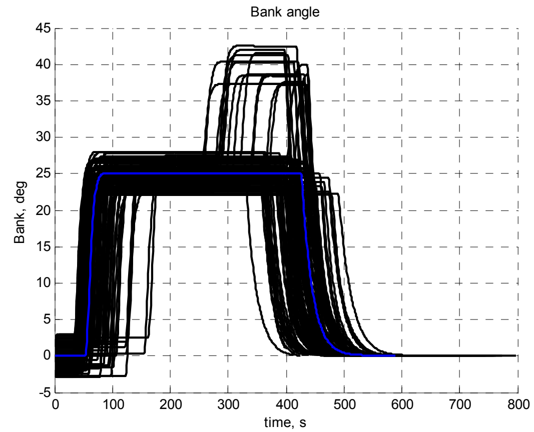
EFTV Trajectory

Main mission objectives well reached in the experimental window (Phase 1)

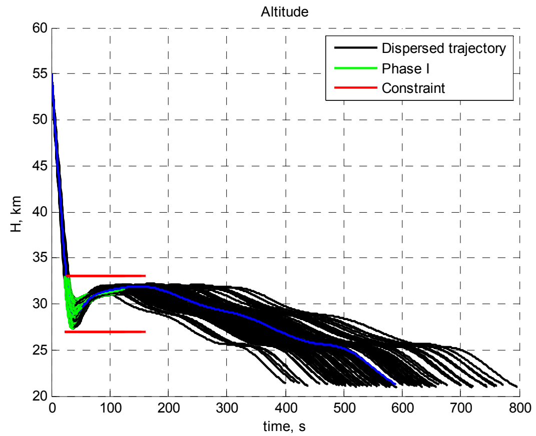


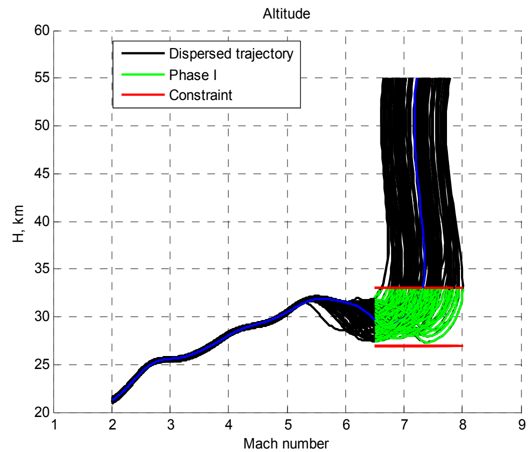
Dispersed Mach number





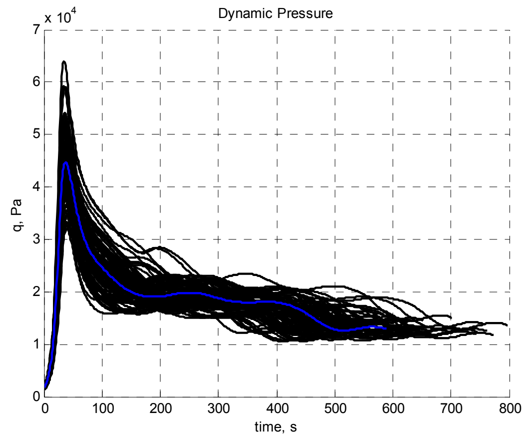
Dispersed AoA commands (left) and bank commands (right)



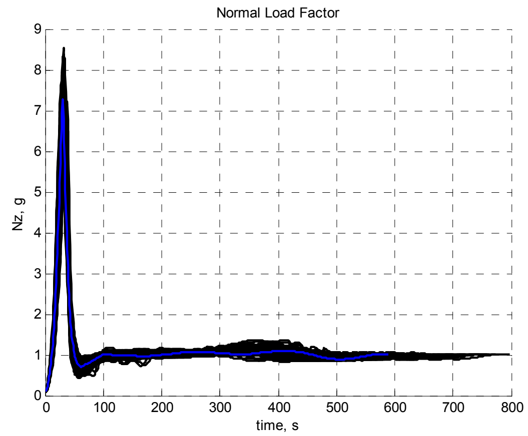


Dispersed altitude vs time (left) and altitude vs Mach (right)

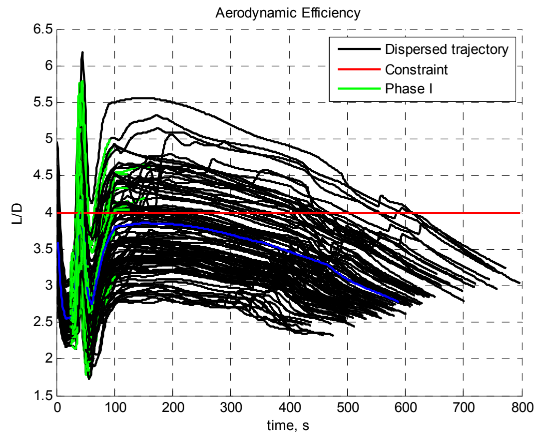
EFTV Trajectory



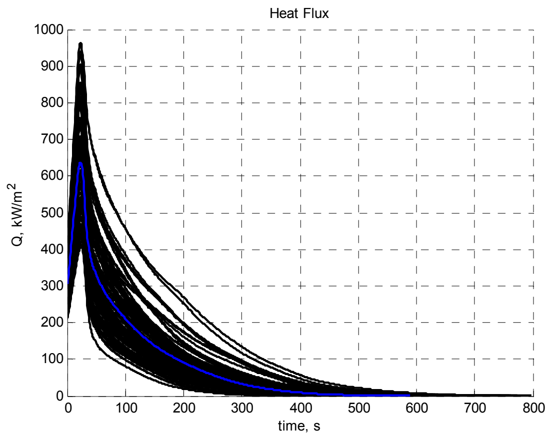
Dispersed Dynamic Pressure



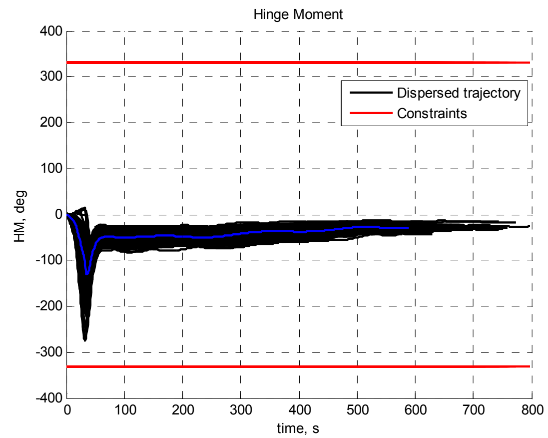
Dispersed Load Factor



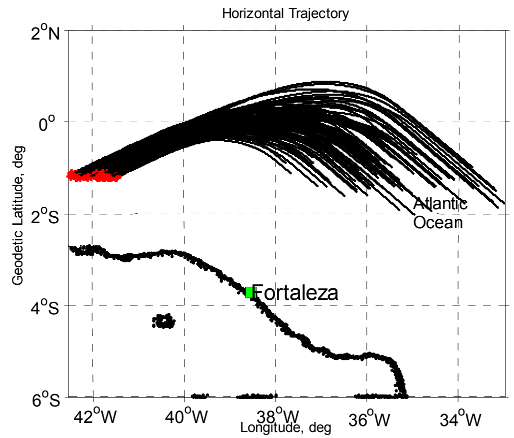
Dispersed L/D



Dispersed Heat Flux



Dispersed Hinge Moment



Dispersed Horizontal Trajectory

CONCLUSIONS

- The project HEXAFLY-INT has the final aim to demonstrate the technical feasibility of concepts and technologies for the hypersonic flight and to increase the Technology Readiness Level (TRL) of the breakthrough technologies on board;
- Some of the key features and activities performed for designing the payload have been described;
- The project is now concluding its Critical Design Review (CDR);
- The flight test is actually planned by the end of 2020.

This work was performed within the 'High Speed Experimental Fly Vehicles - International' project fostering International Cooperation on Civil High-Speed Air Transport Research. HEXAFLY-INT, coordinated by ESA-ESTEC, is supported by the EU within the 7th Framework Programme Theme 7 Transport, Contract no.: ACP3-GA-2014-620327. Further info on HEXAFLY-INT can be found on http://www.esa.int/techresources/hexafly_int.