High Altitude Long Endurance UAV Configurations:

Civil UAV APplications & Economic Effectivity of Potential CONfiguration Solutions

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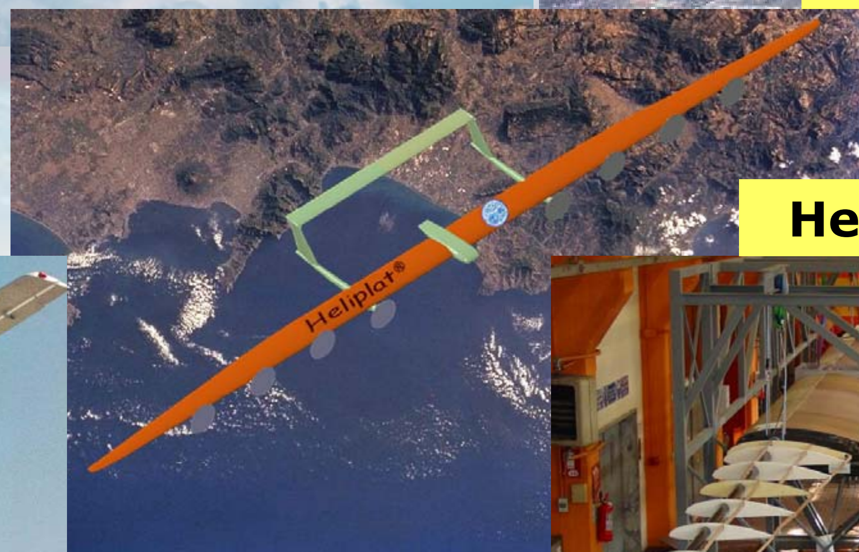
- Zvi SHAVIT, Israel Aircraft Industries, Israel
- Zdobyslaw GORAJ, Warsaw Univ. of Technology, Dept. of Airplane & Helicopter Design, Poland
- Jean HERMETZ, Onera, France
- CIRA, DLR, UNINA

Global Hawk

Helios



Lockheed Martin



HeliPlat – EC 5FP


Heron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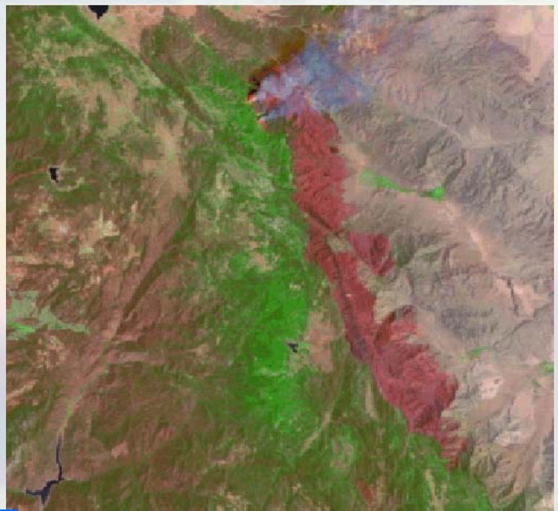
BIRD - Orbit: 570 Km
Spatial Resolution: 370 m
Repeat Cycle: 24 HOURS
Design Life: 5 years

LANDSAT - Orbit: 705Km
Spatial Resolution: 15-60m
Repeat Cycle: 14 days
Design Life: 5 years


4.6.1 – Landsat Image of Fire from Helicopter Crash

Integration

SATELLITE + UAV

=

Higher Resolution +

Continuous Data

HALE UAV Configuration

MAIN GOAL: to define and consolidate, within a 2 iteration design cycle, 3 HALE Configurations:

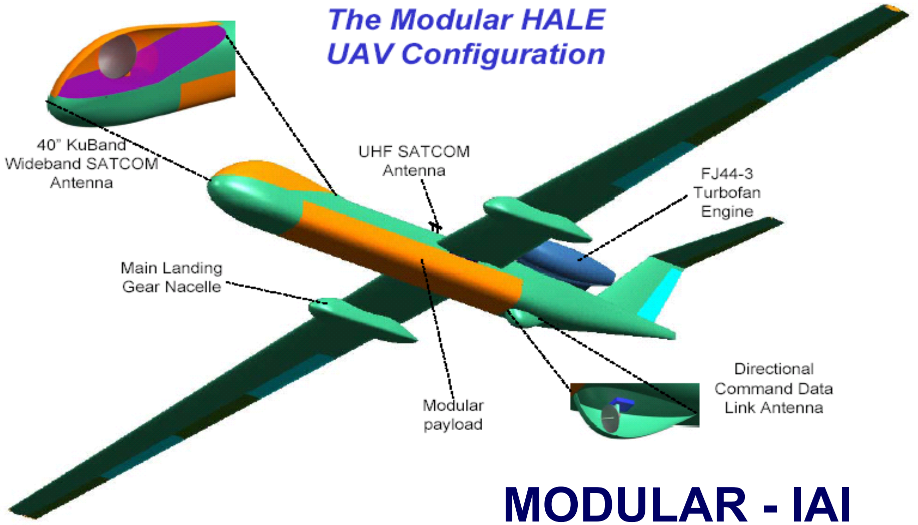
- MODULAR
- SOLAR
- BLENDED

MULTI-DISCIPLINARY OPTIMISATION SOFTWARE developed to - obtain the Optimised configuration

FINAL CONFIGURATIONS: as result of best compromise among production cost, aerodynamic performance efficiency, structural efficiency and aeroelastic behaviour, propulsion efficiency, and safety.

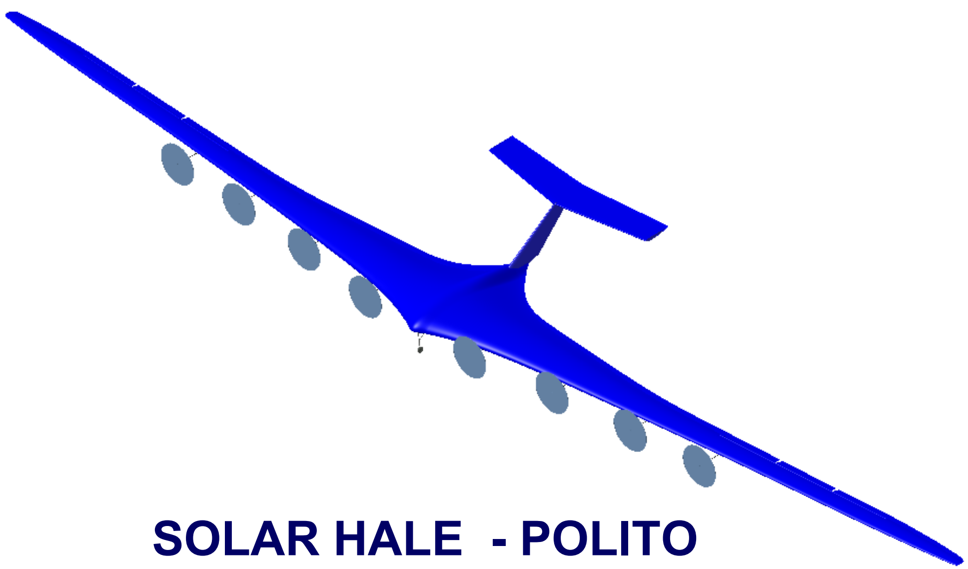
PERFORMANCE shall be improved by at least 20% with respect to current technologies.

Design of 3 HALE UAVs



MODULAR - IAI

BLENDED WING - ONERA



SOLAR HALE - POLITO

BLENDED WING - WUT

SHAMPO Main Characteristics

Description	Symbol	Value
Flight Altitude	Z	17.000 m
Max. Power available for the Payload	P_{PL}	1300 W
Avionic Mass	W_{AV}	32.0 kg
Max. Payload Mass	W_{PL}	100 kg
Structural Mass	Wstr	430 kg
Solar cells Mass	Wsc	127 kg
Take off Weight	W_to	924 kg
Power available for the Avionic	P_{AV}	325 W
Cruise Flight Power supplied to the electric motors	P_fly	6700 W
Sun Power (38°N April)	P_sun	11560 W
Efficiency Energy storage system (Fuel cell + al.)	η_{FC}	0.6
Density Energy storage system (Fuel cell + al.)	W_{FC}	550 Wh/kg
Efficiency Solar cells	η_{SC}	0.21
Density Solar cells	W_{SC}	0.6 Kg/m²
Efficiency Electric Motor	η_{M}	0.95
Efficiency Propeller	η_{PROP}	0.85
Number of Motors	N	8
Cruise Airspeed (TAS)	TAS	25 m/s

SOLAR HALE UAV

Solar
Hale
Aircraft
Multi
Payload &
Operation

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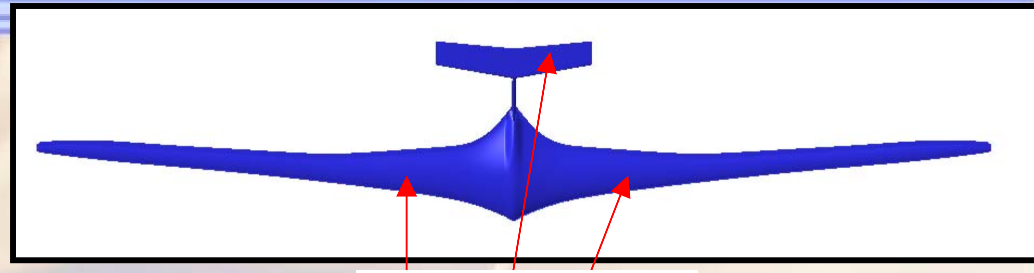
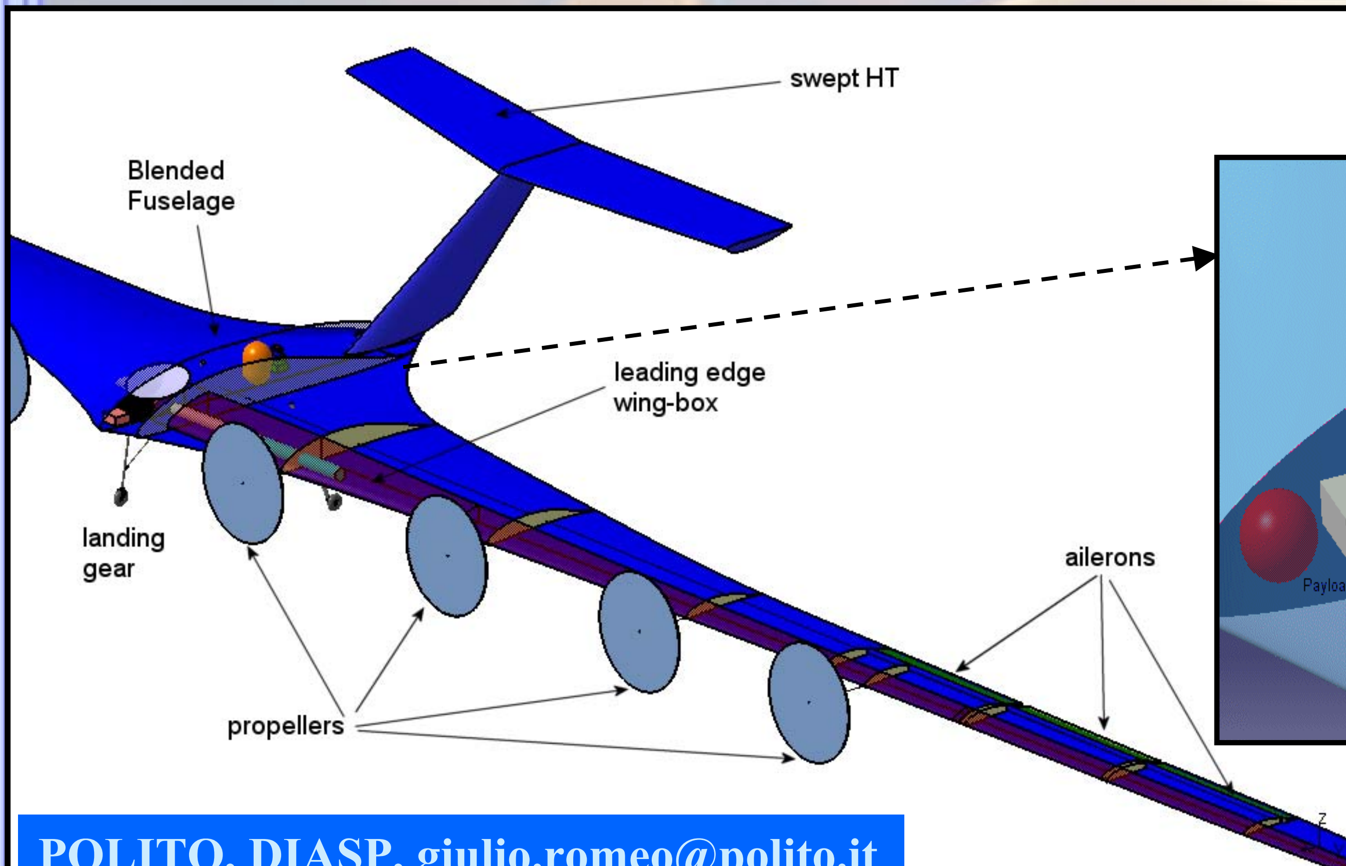
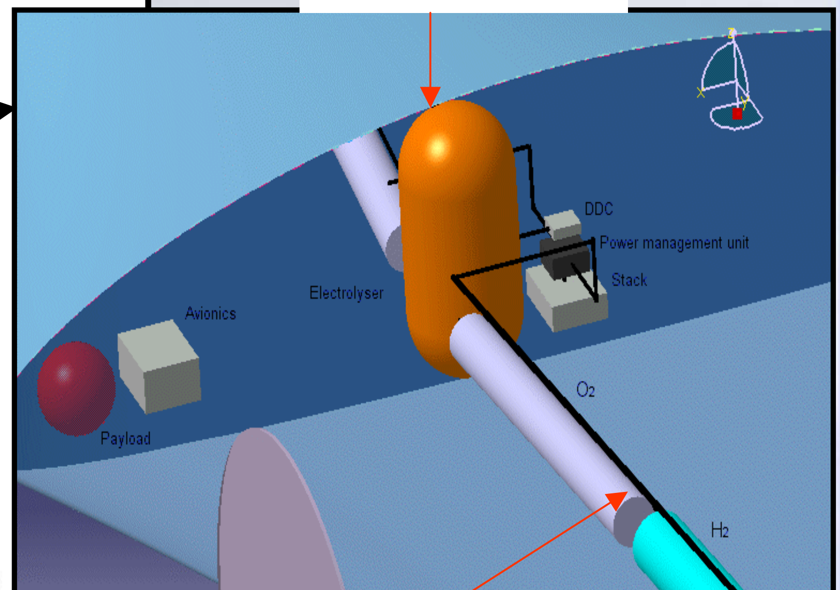
Main Systems

SOLAR HALE UAV







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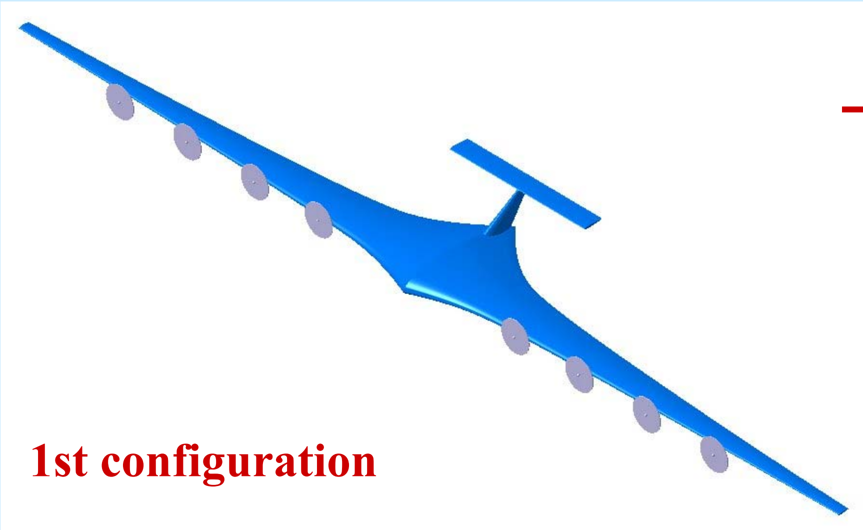
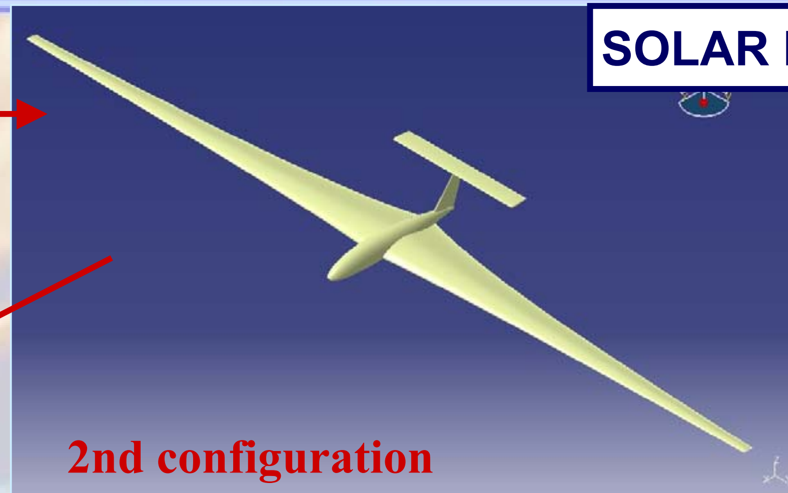
Development of Solar HALE-UAV

SOLAR HALE UAV

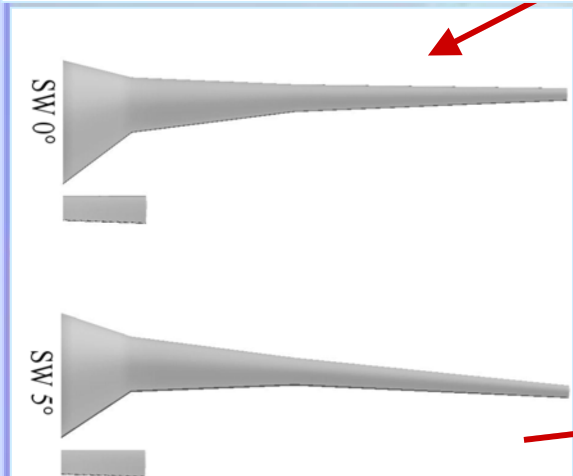


1st configuration

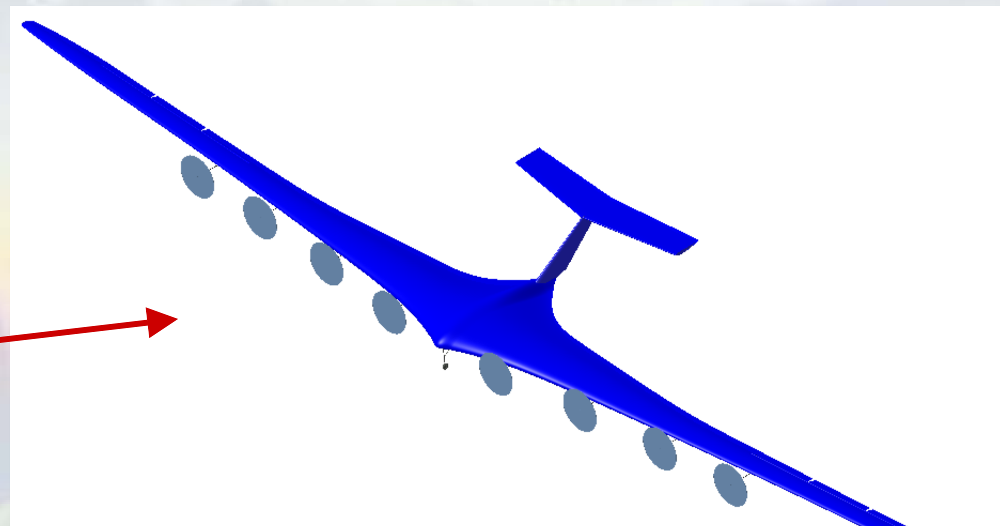


2nd configuration

Classical configuration
to improve longitudinal stability



Introduction of sweep angle to improve
longitudinal stability



3rd configuration

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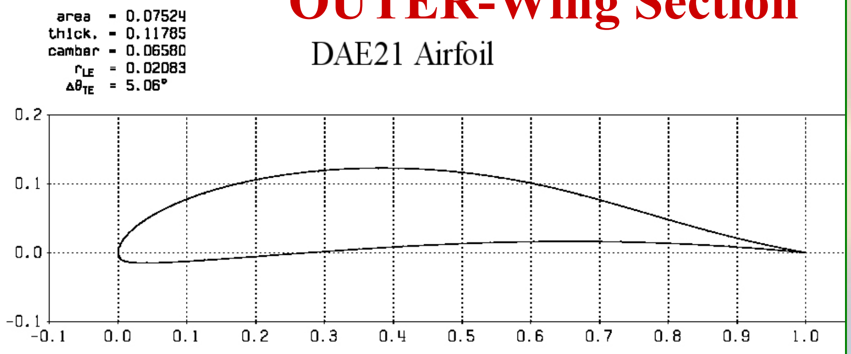
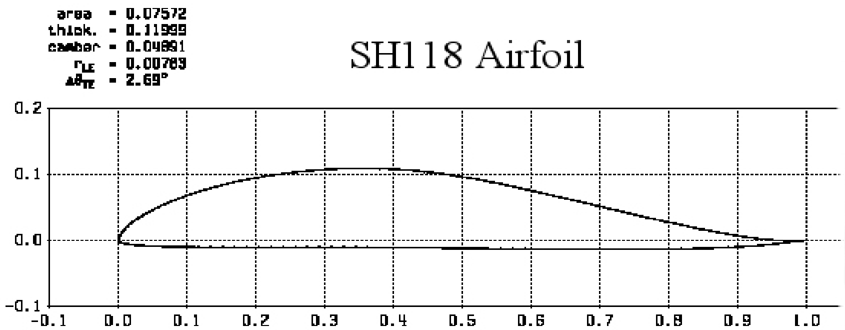
Solar HALE Wing Section

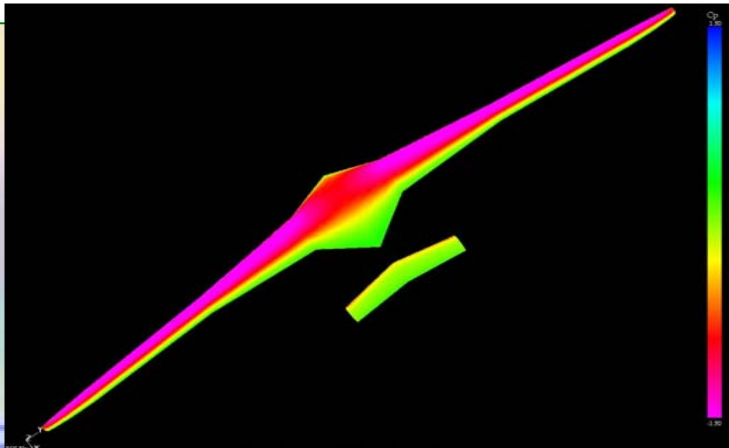
OUTER-Wing Section

DAE21 Airfoil



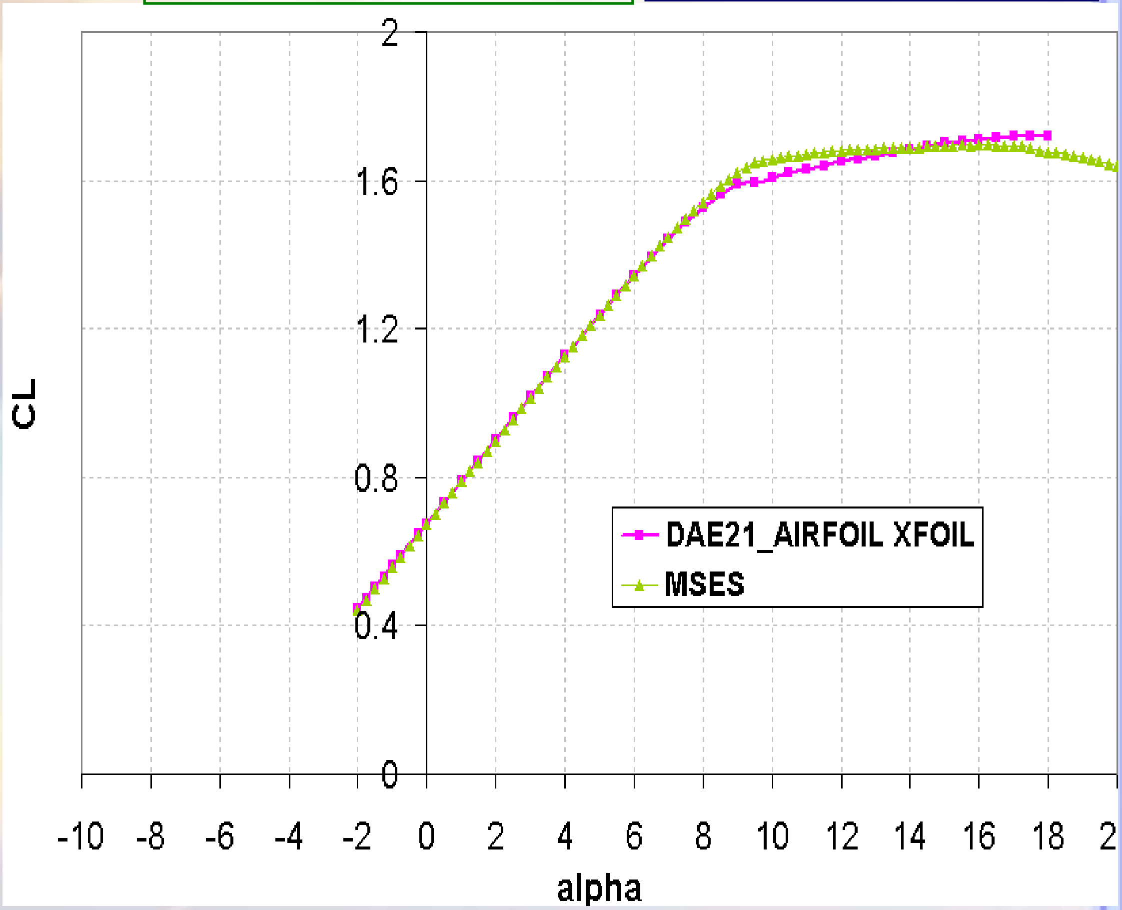
SH118 Airfoil





Aerodynamics

SOLAR HALE UAV



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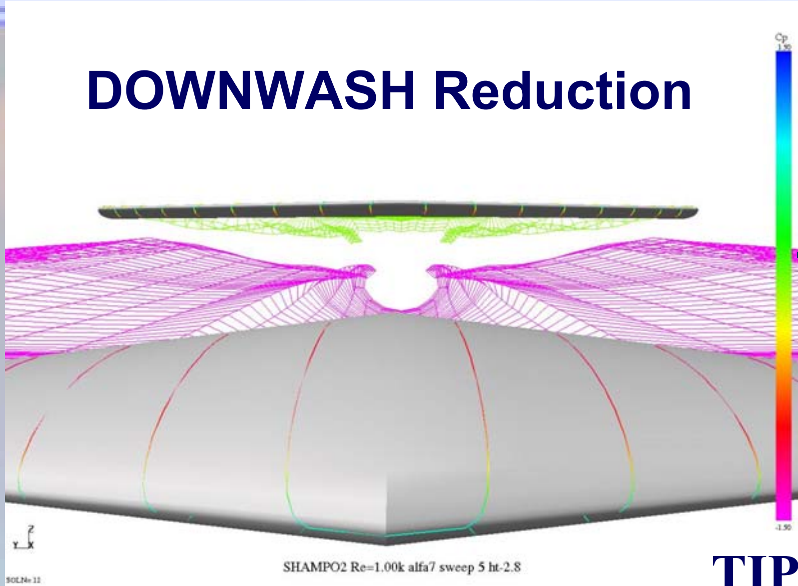
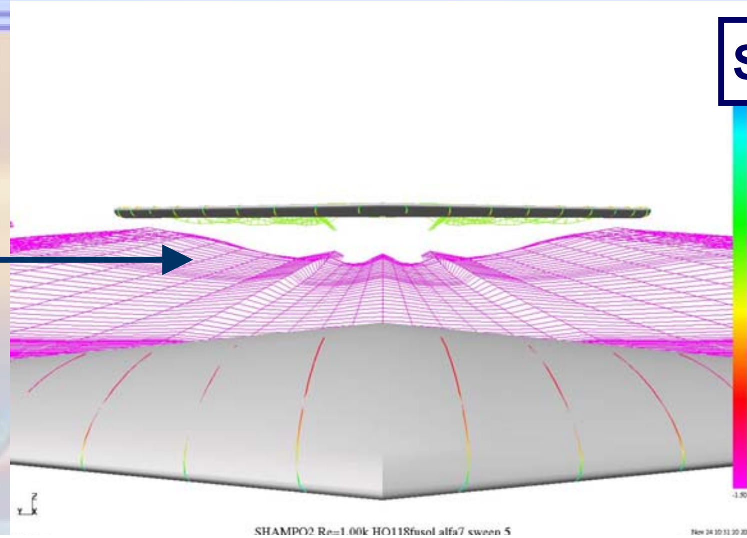
Aerodynamic development

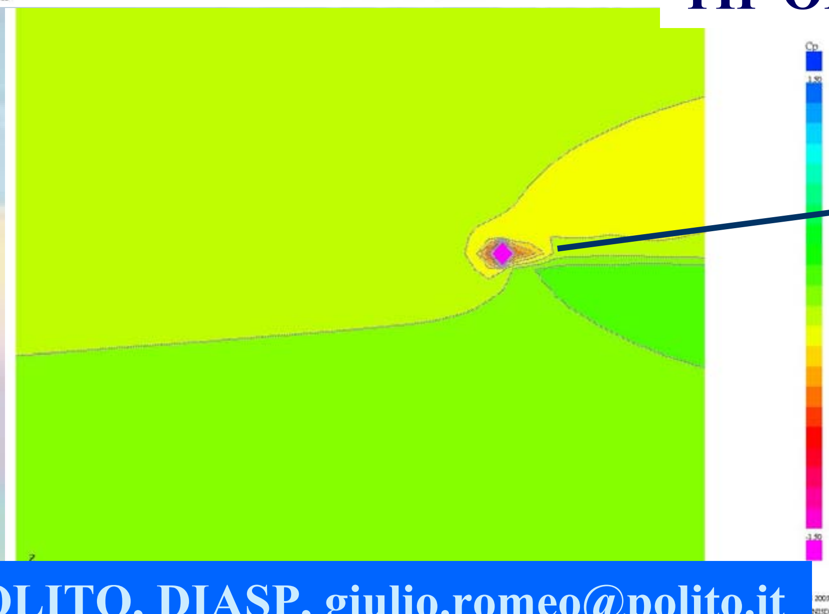
SOLAR HALE UAV

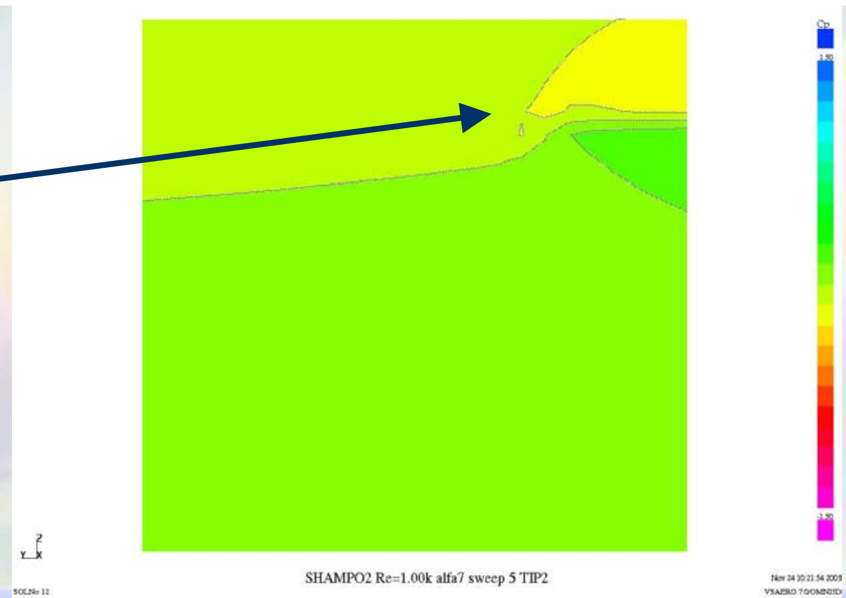
DOWNWASH Reduction





TIP OPTIMIZATION (Tip Vortex Energy Reduction)





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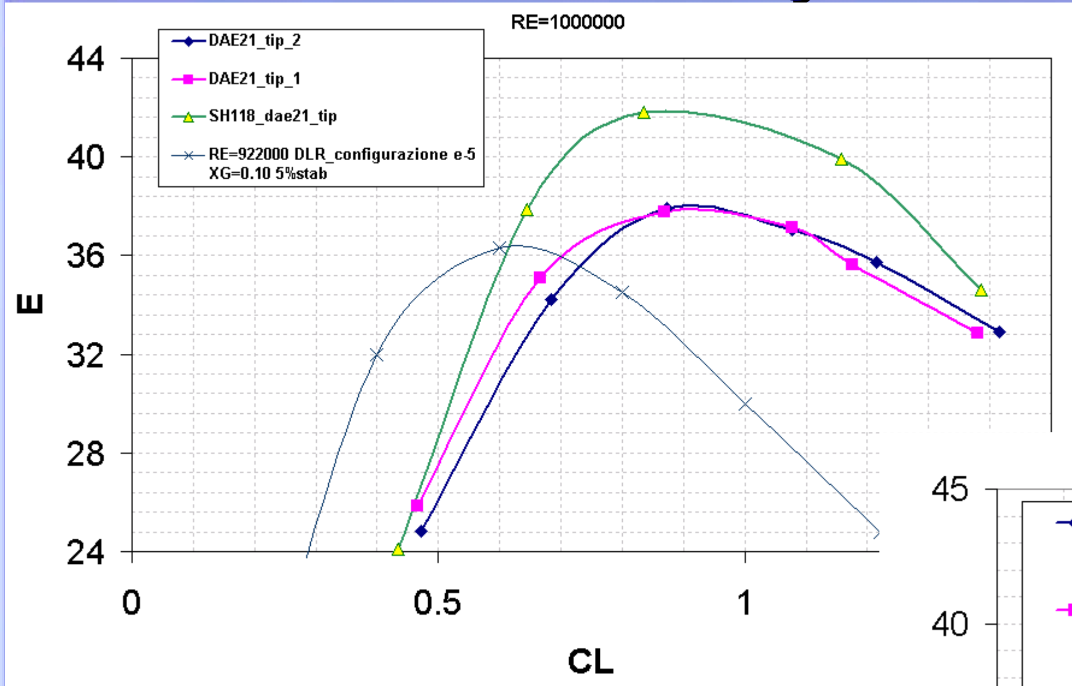
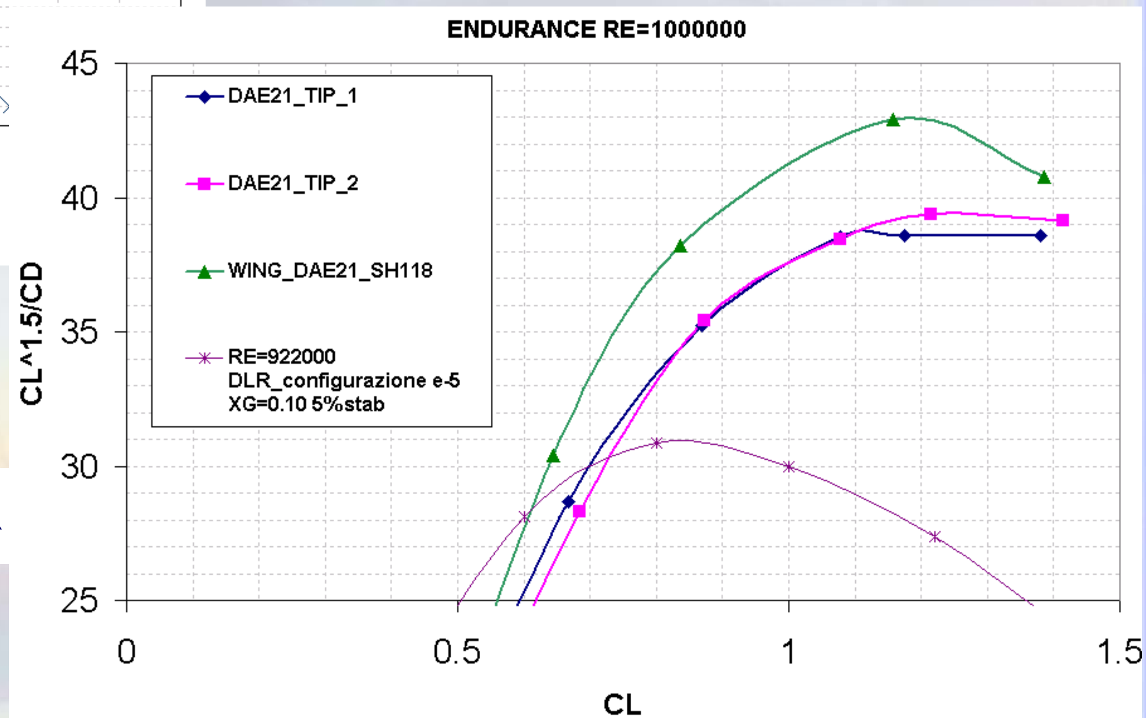
Aerodynamic Results

SOLAR HALE UAV

EFFICIENCY



ENDURANCE PARAMETER



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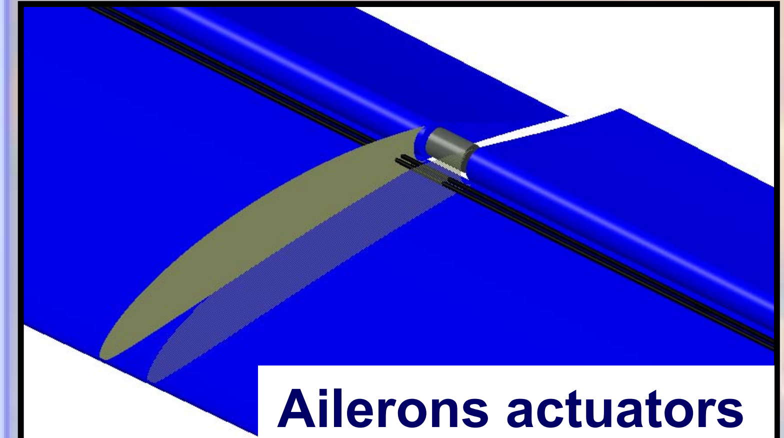
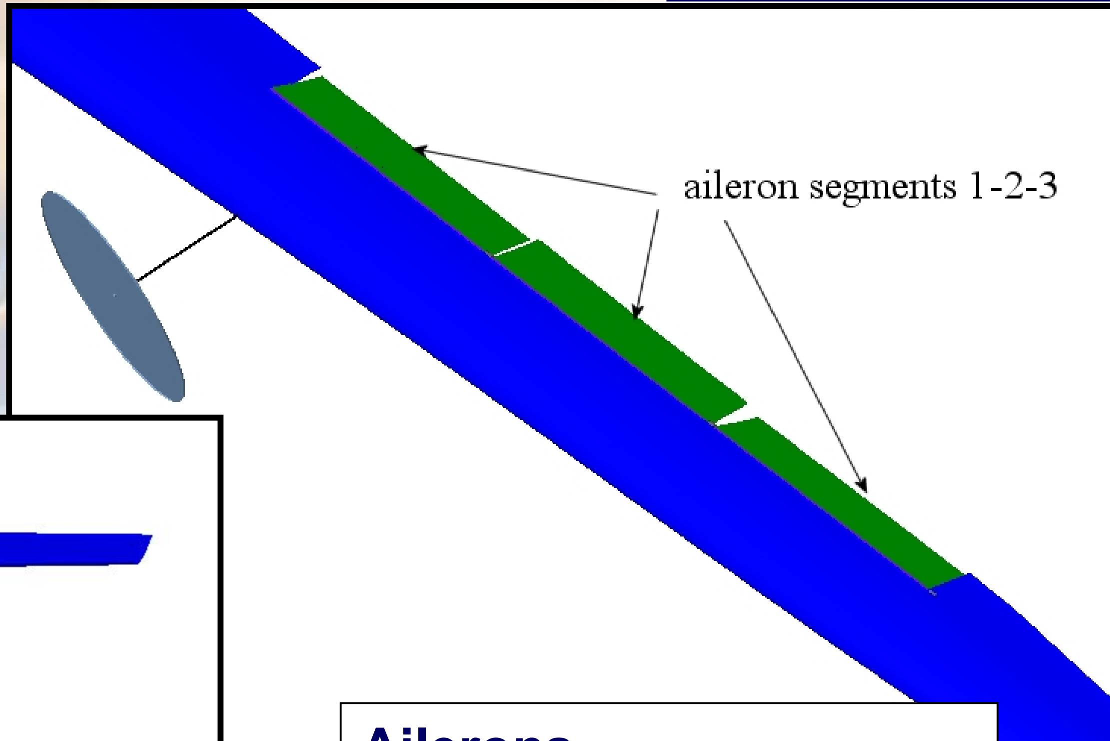
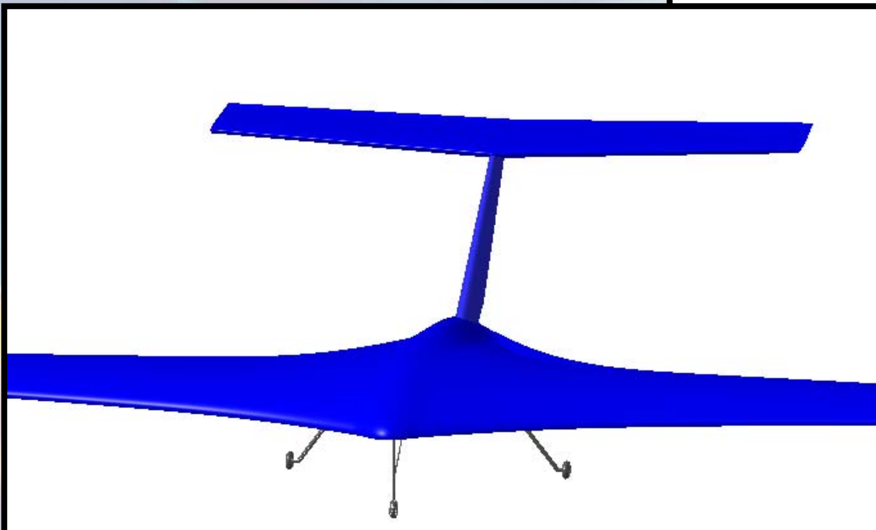
Ailerons & Landing Gear

SOLAR HALE UAV



Ailerons actuators





Tricycle Landing Gear

Ailerons
Inboard section:18.8m
Outboard section:30.8m

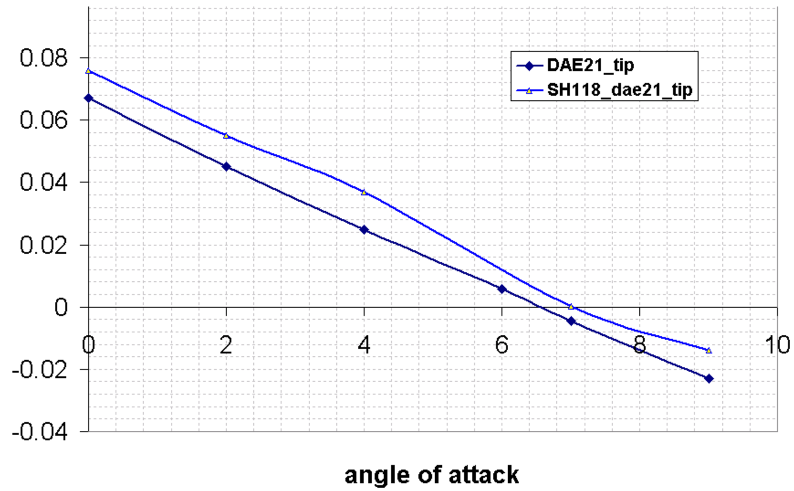
Flight Performance

SOLAR HALE UAV

TAKEOFF		
Ground roll		
V final	8.31	m/s
Vinitial	0	m/s
S Ground roll	138.77	m
Rotation		
time to rotate	3	S
S Rotation	24.92	m
Transition		
load factor	1.2	
Radius	38.43	m
Vtr	8.68	m/s
Vclimb	9.06	m/s
Drag	272.2	N
Angle of climb	1.3	deg
Htr	0.010	m
S transition	0.9	m
Climb		
h obstacle	15	m
S climb	639.9	m
Total length	804.5	m

LANDING		
Approach		
V approach	9.8	m/s
h obstacle	15	m
Drag	455	N
gamma approach	2.8	deg
S approach	305	m
Flare		
load factor	1.2	
V td	8.7	m/s
Vflare	9.3	m/s
Radius	44	m
Hfl	0.053	m
S flare	2.1	m
Ground roll		
V final	0	m/s
V initial	8.68	m/s
S Ground roll	113.	m
Total length	421	m

Longitudinal Static Stability



Lateral Static Stability

$$C_{n\beta}=0.012$$

$$C_{l\beta}=-0.083$$

Take off & Landing distances:

Take-off: 804m - Landing: 420m

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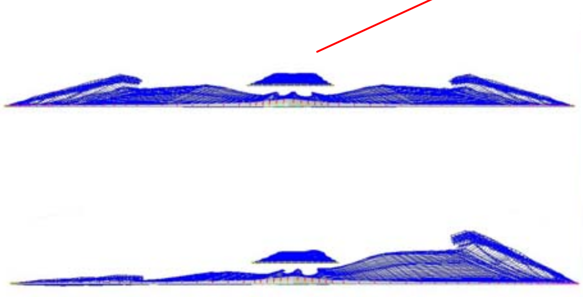
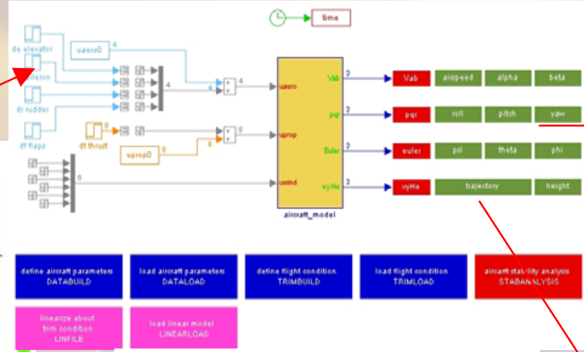
Flight Dynamic Analysis

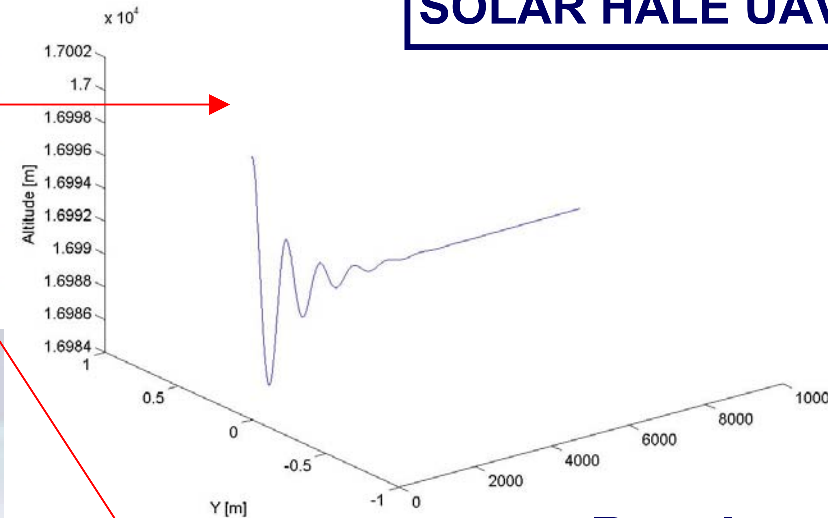
SOLAR HALE UAV

DERIVATIVES database



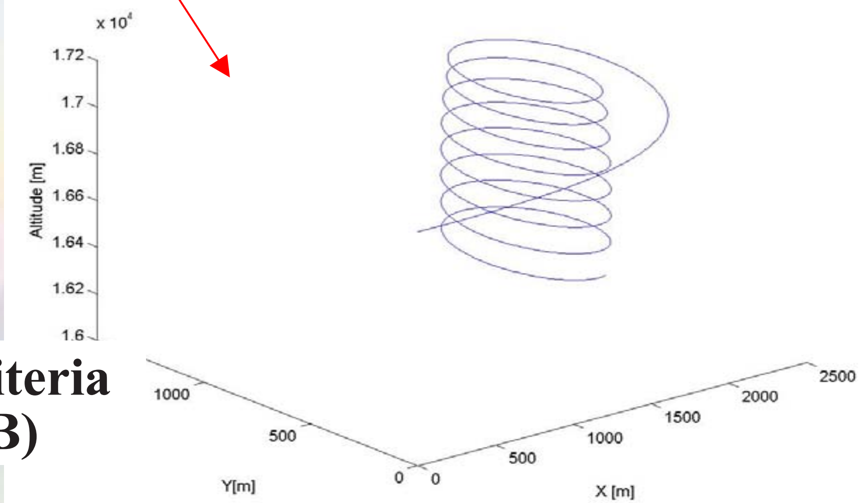


MATLAB-Simulink



Results

Response to a Rudder step i



Longitudinal Dynamic Stability

MODES	
2 aperiodic	*stable*
1 periodic	*stable*

Lateral Dynamic Stability

MODES	
2 aperiodic	*1 stable 1 instable*
1 periodic	*stable*

Within the MIL-F-8785C flying qualities levels criteria for a small light Aircraft in cruise condition (Cat B)

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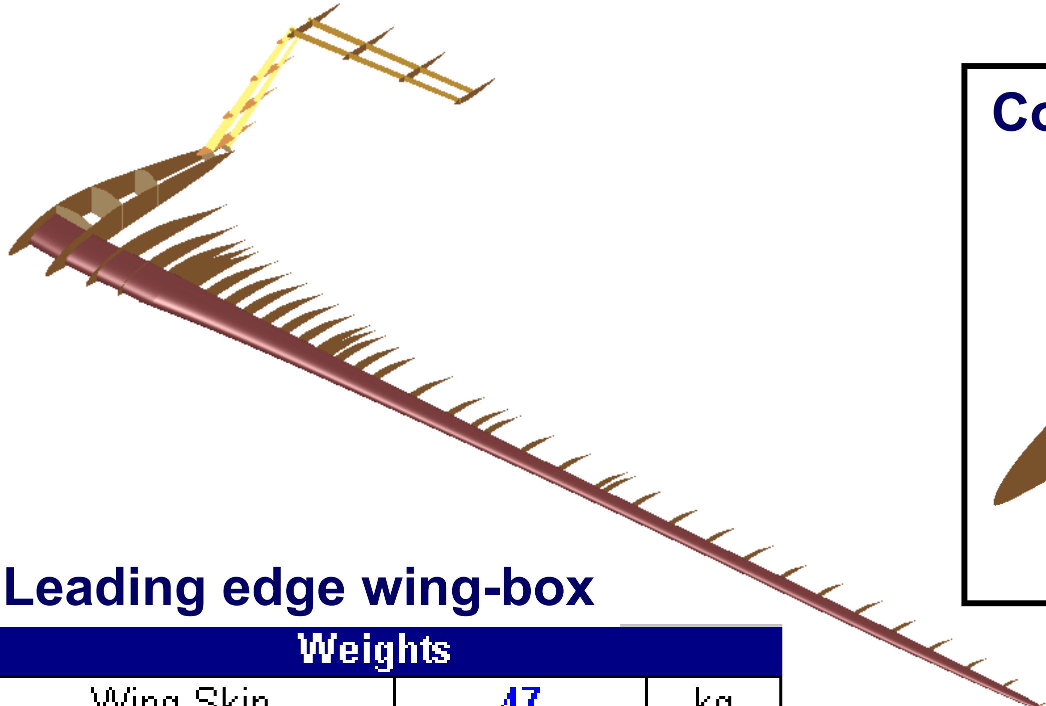
Structural design & analysis

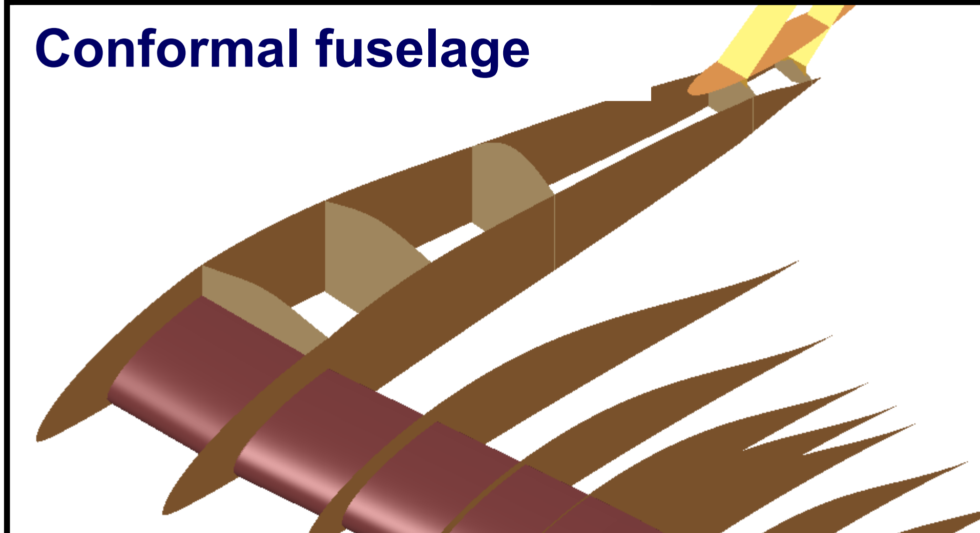
SOLAR HALE UAV



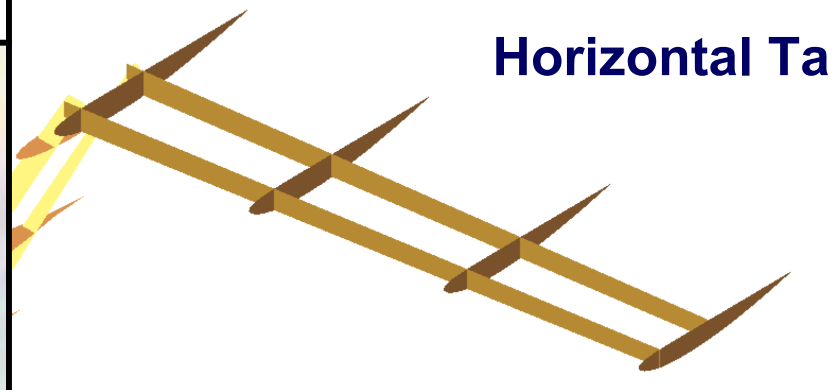
Leading edge wing-box

Weights		
Wing Skin	47	kg
Wing Ribs	36	kg
Wing Box	258	kg
Pay-load	100	kg
Avionic	33	kg
Pins	0.93	kg
Total	890	kg
Structural Weight	382	kg

Conformal fuselage

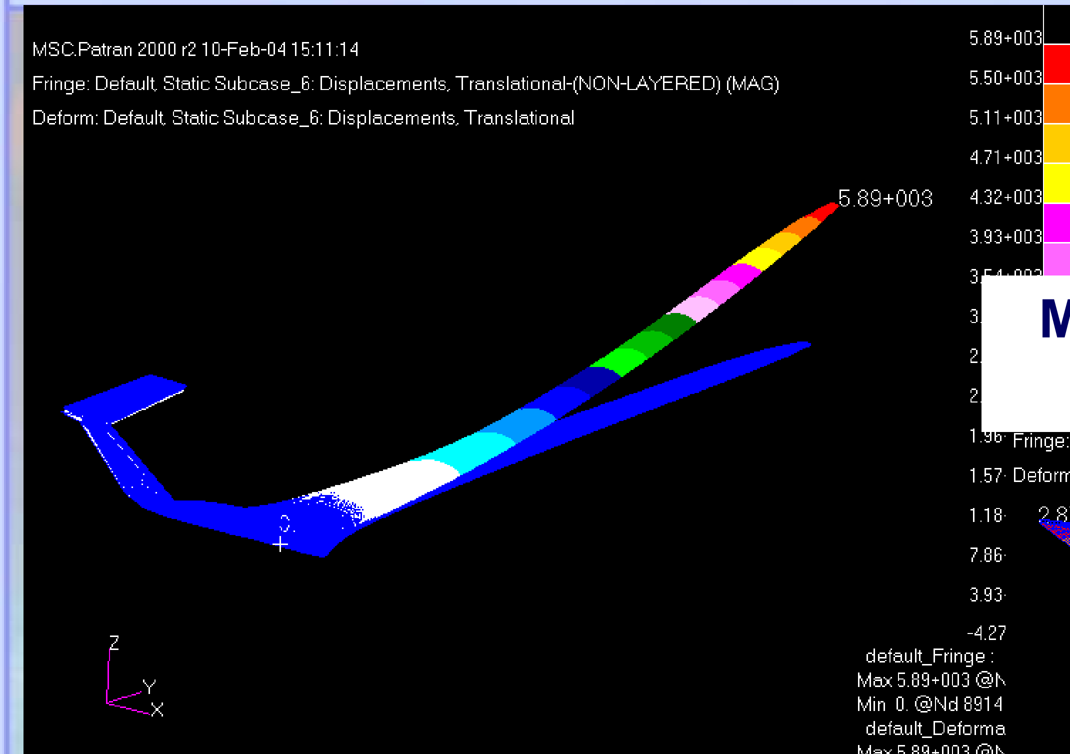


Horizontal Tail

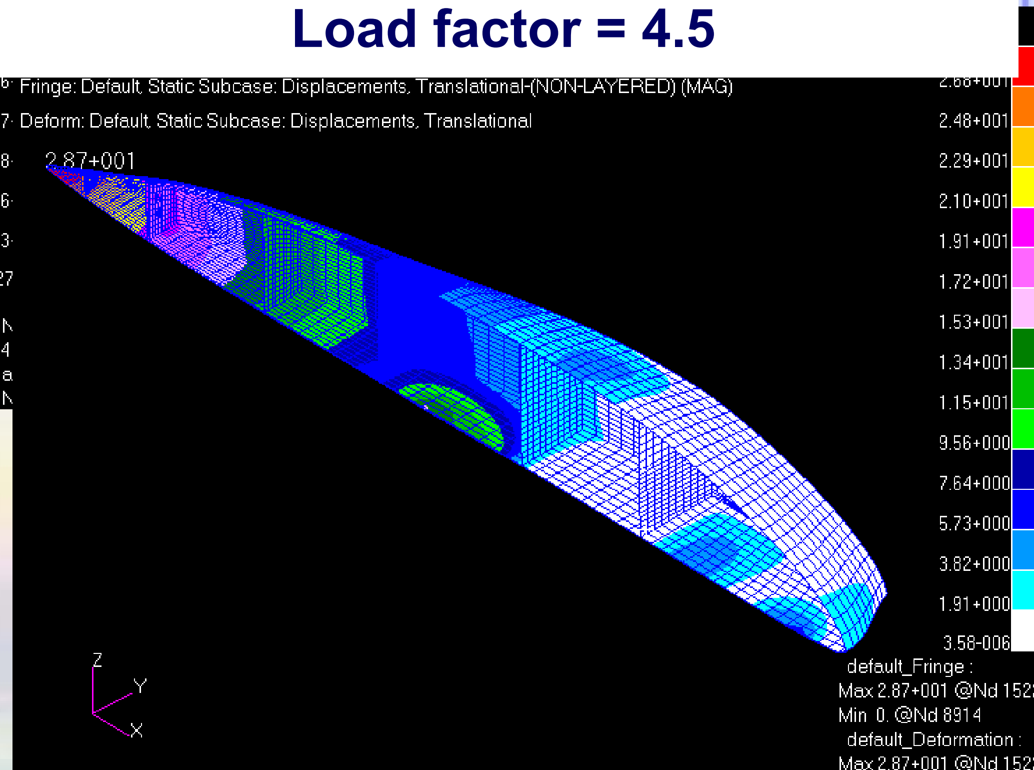


Structural design & analysis

SOLAR HALE UAV



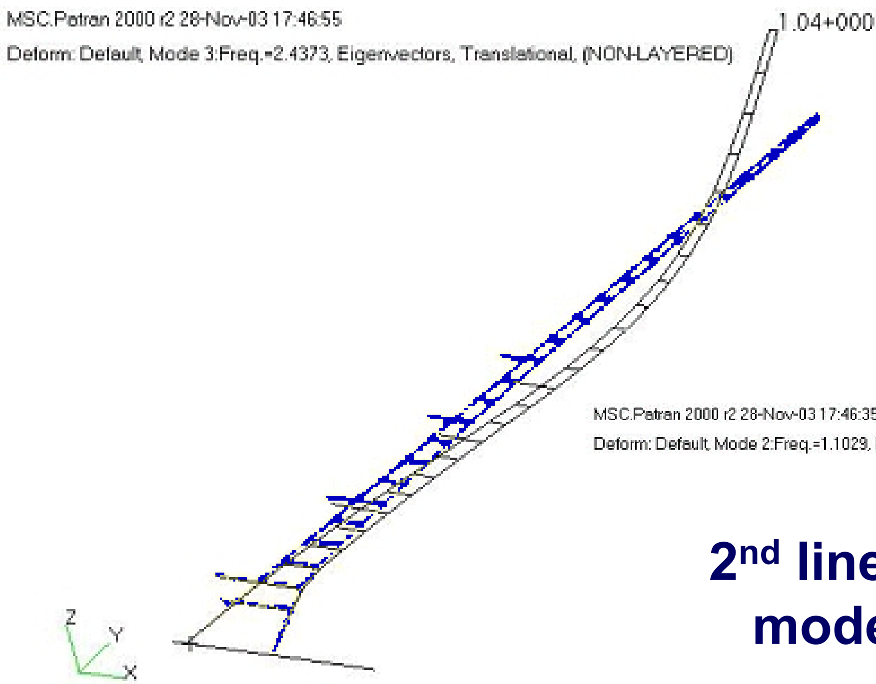
Maximum wing deflection: 5.89m
Load factor = 4.5



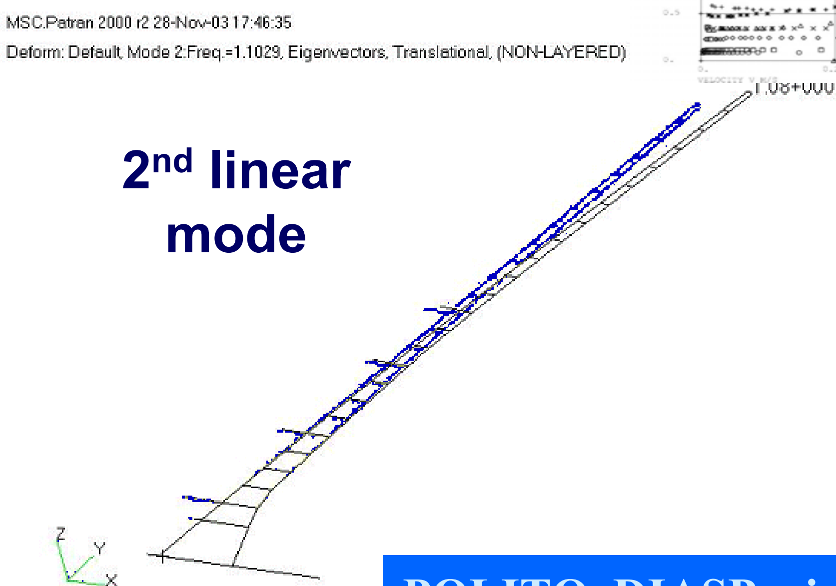
Maximum fuselage deflection:29mm
Load factor = 4.5

Linear Flutter Analysis

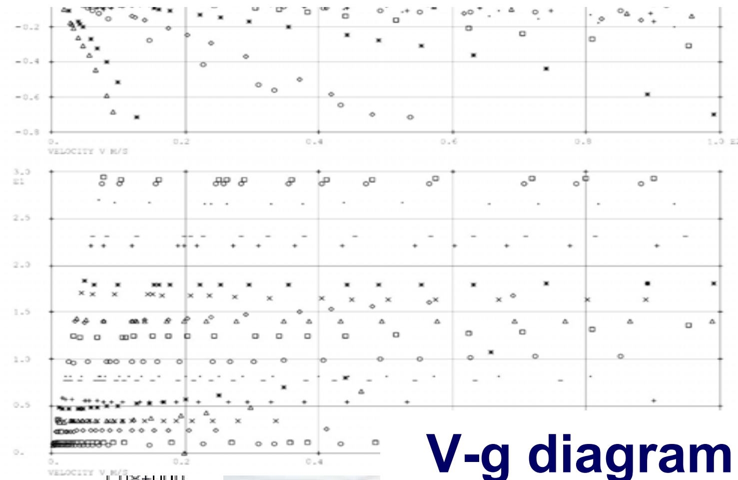
Non-linear effect due to high-aspect ratio structure is not included in a 1st attempt. No critical speed detected up to 100m/s (at 17000m). Normative requirement fulfilled.



1st linear mode



2nd linear mode

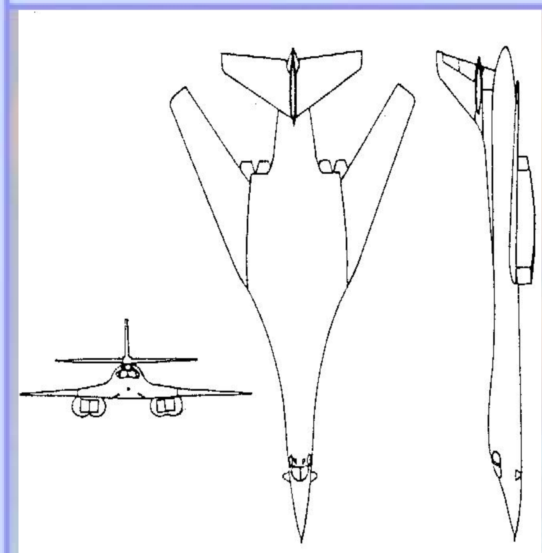


V-g diagram

SOLAR HALE UAV

Flight Dynamic of Flexible Aircraft

SOLAR HALE UAV



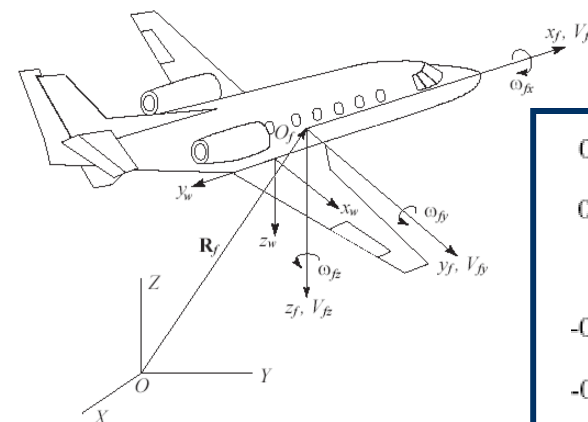
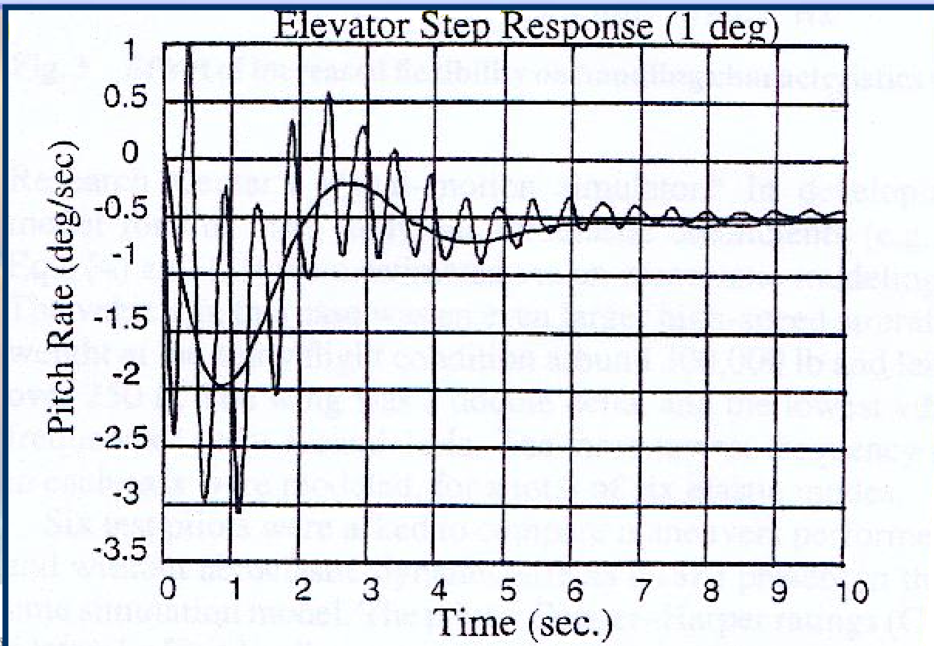


Figure 1. Flexibile Aircraft Model



Waszak and Schmidt (1988) performed in the Visual and Motion Simulator facility at NASA Langley Research Center

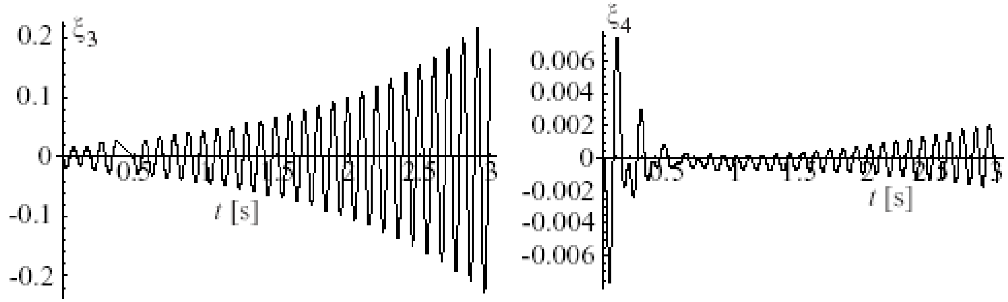


Figure 9. Generalized Elastic Displacements

Tuzcu & Meirovitch Virginia Polytechnic institute 2003

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PRELIMINARY RELIABILITY

SOLAR HALE UAV

The platform has to have a very long endurance of flight (4-5.000h)

is supposed to fly continuously without failure

the loss of a platform must not cause damage to the service.

Catastrophic failure conditions must be extremely improbable, i.e.:

The probability that a failure condition would occur maybe assessed on the order of 10^{-9} or less.

“The safety standard that should be maintained is one in which UAVs are operated as safely as manned aircraft, insofar as they should not present or create a hazard to persons or properties in the air or on the ground greater than that created by manned aircraft conducting similar operations” (FAA Advisory Circular 8/5/96).

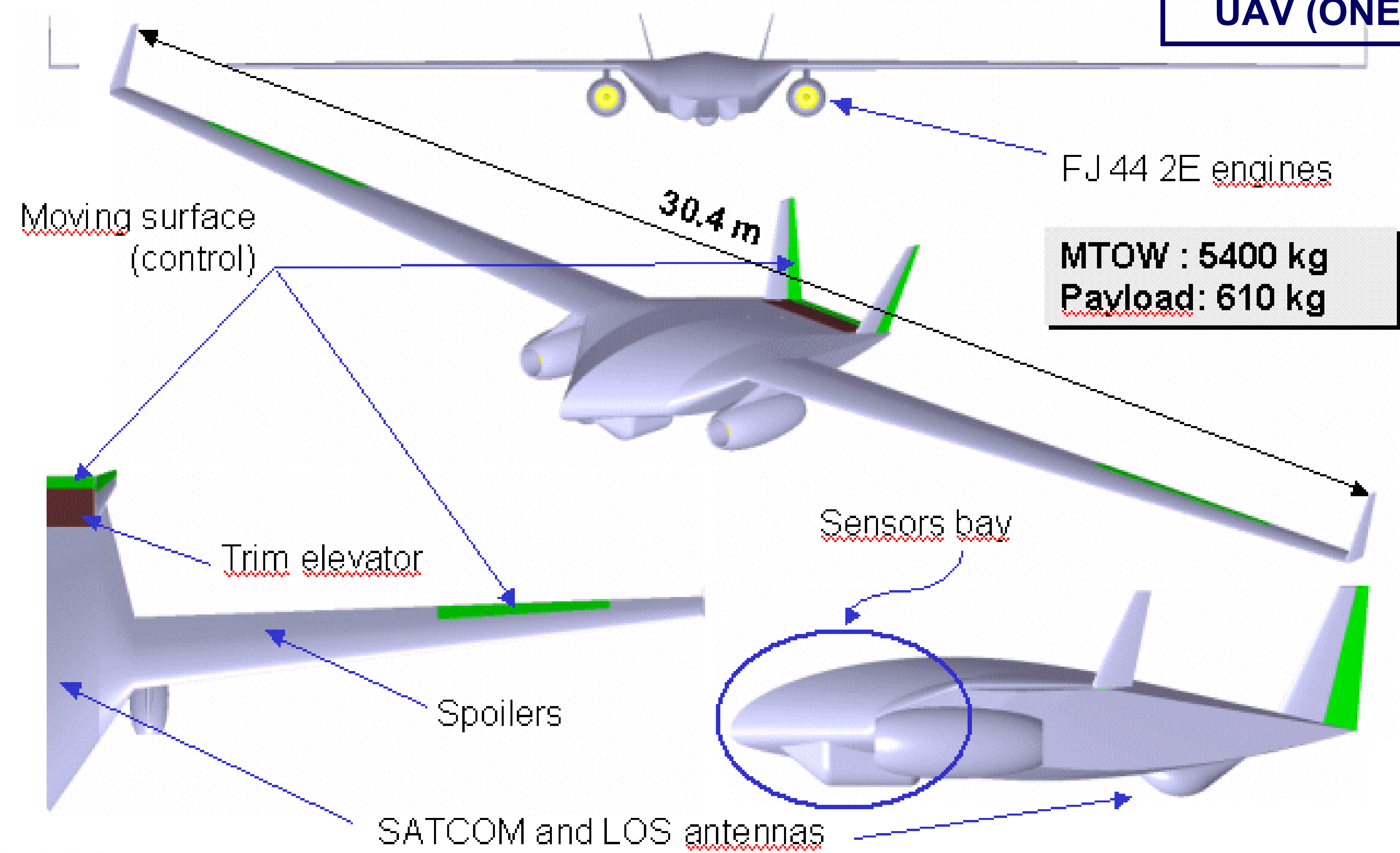
A MTBF=40000h for each motor and a MTBF=100000h for each propeller is assumed for the reliability analysis obtaining a 0.991.

OBW-02 concept

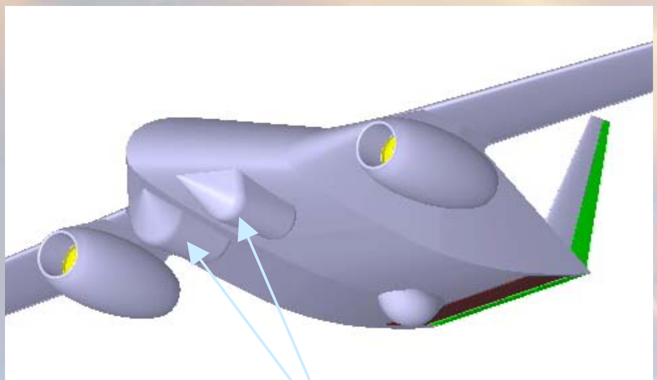
EXTERNAL VIEW

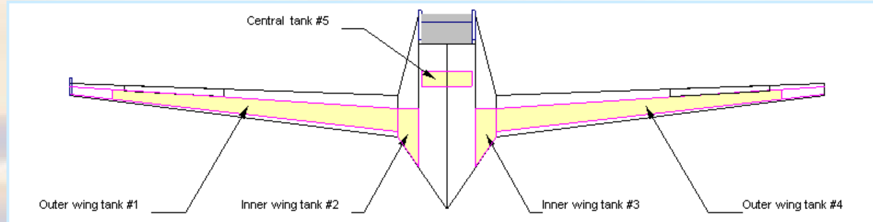
BLENDED HALE UAV (ONERA)

MTOW : 5400 kg
Payload: 610 kg



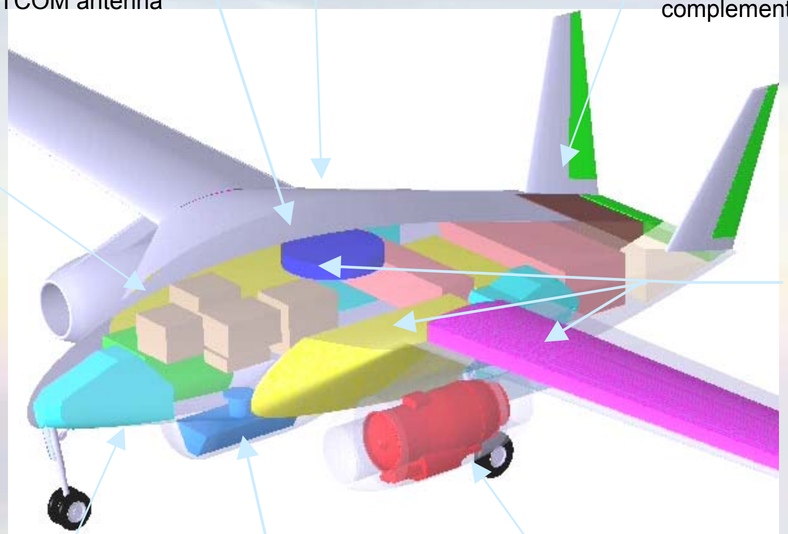
External & internal views





Max. fuel capacity : 2800 kg

BLENDED HALE UAV (ONERA)



Reference area:	**51.3 m²**
Aspect ratio:	**18**
Wing loading :	**105.3 kg/m²**
Max LD ratio (M=0.6):	**32**
MMO:	**0.636**

OBW-02 concept

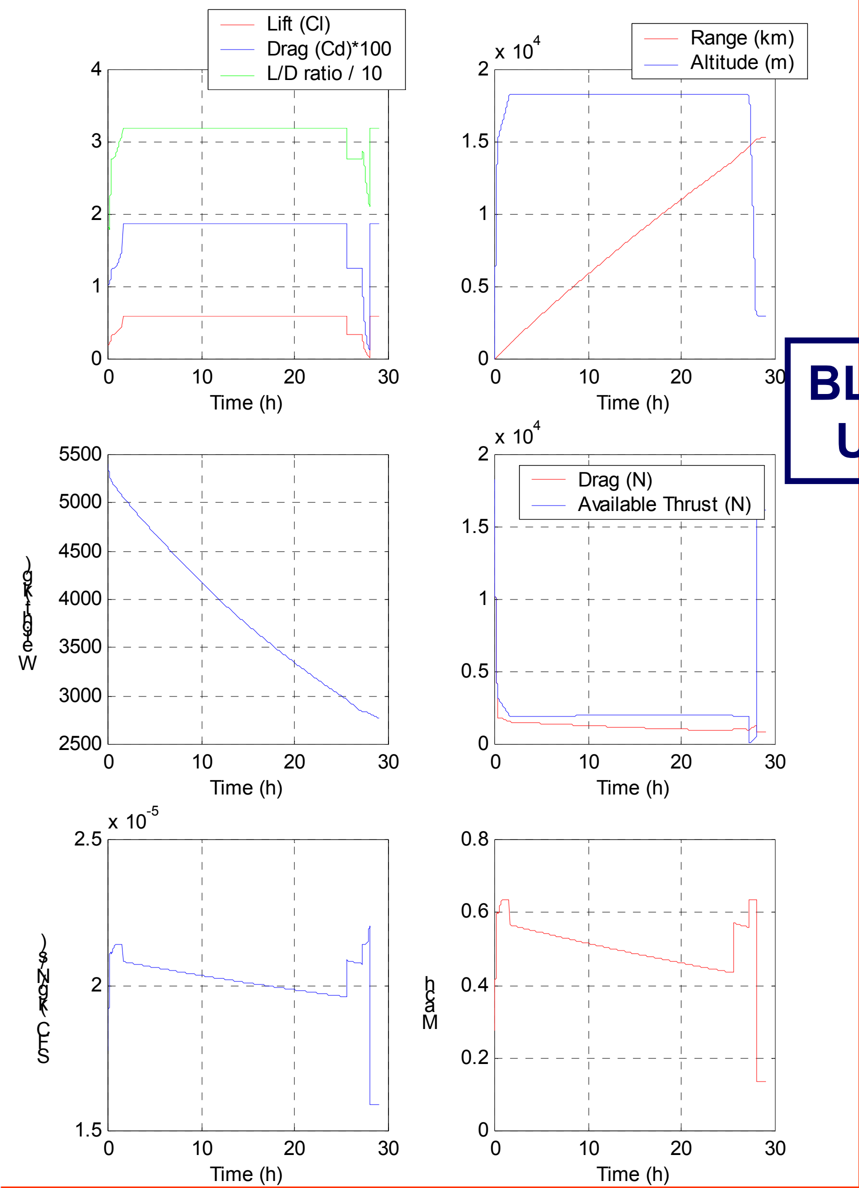
ONERA

CAPECON

Performance & Flying qualities

Main performance (ONERA & IAI)

- Initial climb altitude: 50 000 ft, achieved in 20 min
- hold: 1 h at 10 000 ft
- loiter: 24 h at 60 000 ft
- loiter alt. reached during cruise segment (climbing cruise)
- Overall fuel consumption: 2628 kg
- Service ceiling reached in 1h33
- Overall mission duration: 29 h
- Take off distance: 542 m (obs. 35 ft)
- BFL: 655 m
- Landing distance: 610 m
- Best RoC at SL: 28 m/s (at 138 m/s TAS)



BLENDED HALE UAV (ONERA)

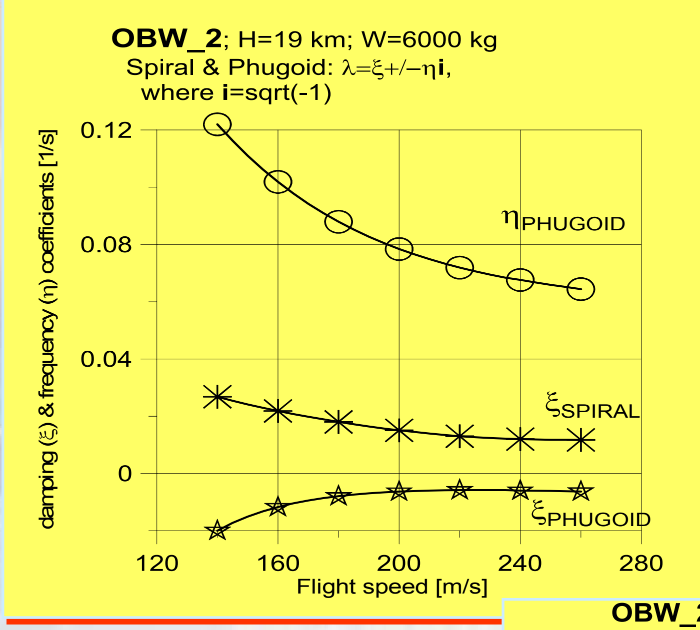
Performance & Flying qualities

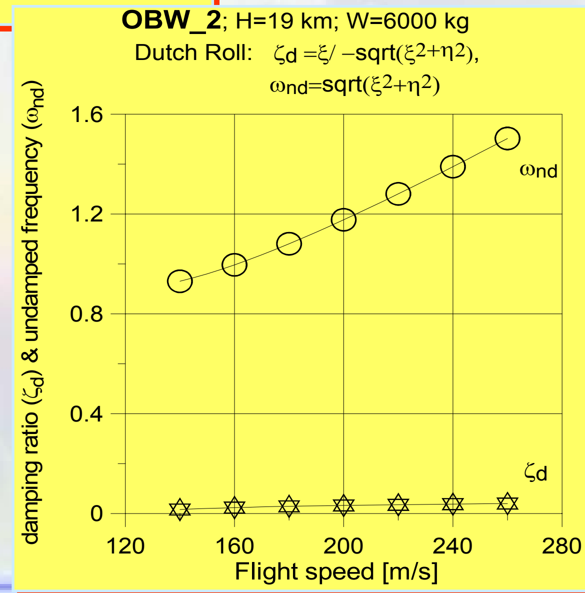
ONERA

BLENDED HALE UAV (ONERA)

Flying qualities (ONERA & WUT)

- **Computation of short period, dutch roll, phygoïd and spiral motions**
- **Vehicle doesn't satisfy requirements for Dutch roll mode**
  - OBW_2 fulfils FAR 25 and MIL-F-8785C at (level 3)
  - Does not fulfill FAR 23 and MIL-F-8785C at (level 2).
  - Cannot be human manned in a backup -> use of a robust automatic flight control



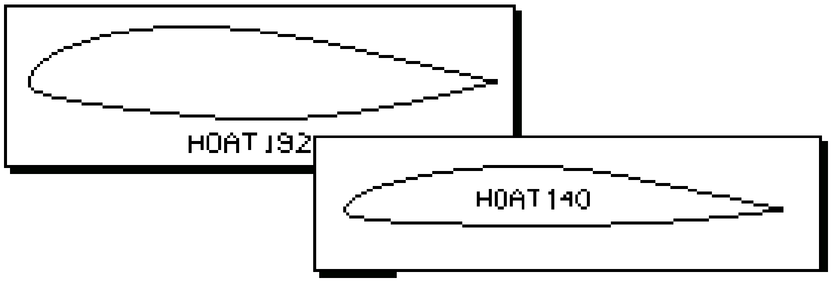


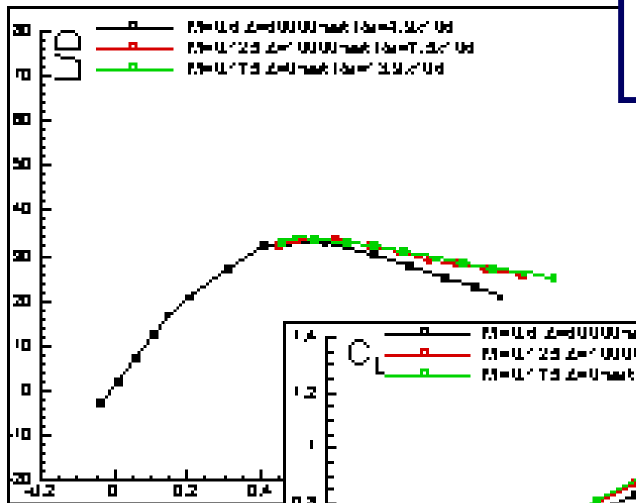
Aerodynamic analysis

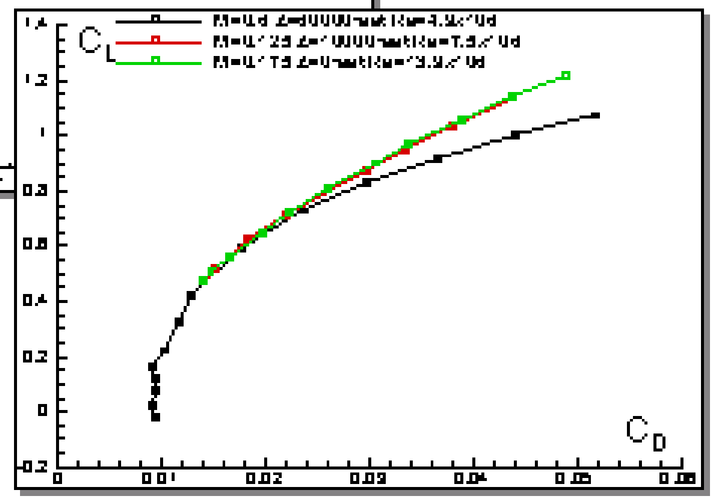
- Objective : maximizing of the global aerodynamic efficiency in loiter conditions
- Airfoils design drivers : low nosed-up or zero moment coefficient
- Geometric constraints for central part

BLENDED HALE UAV (ONERA)

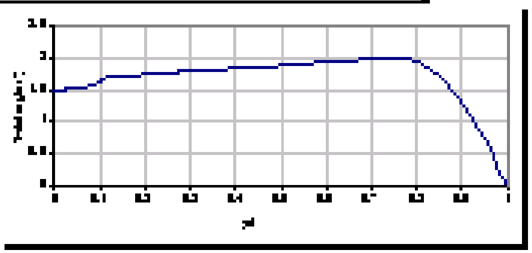
- Two ONERA specific airfoils: HOAT 192 (central part) and HOAT 140 (outer wing)





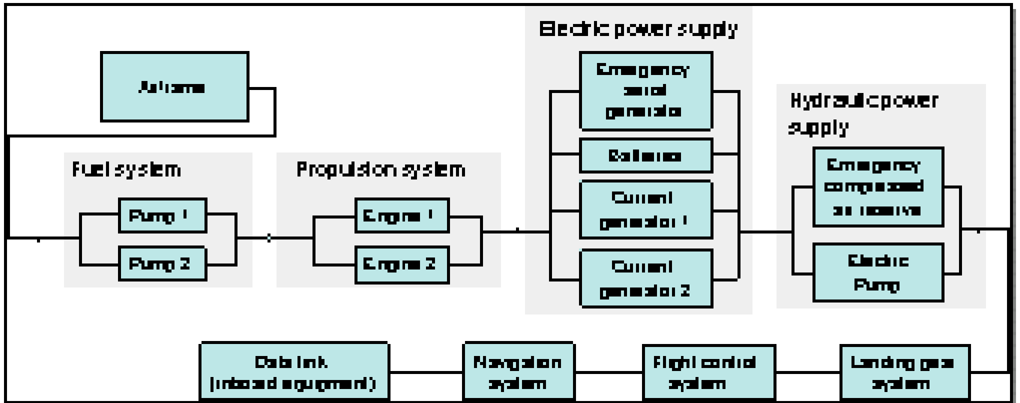


- An optimized twist distribution



Safety & Reliability

- Based on systems block diagrams and unit reliability of equipment/components
- Systems block diagrams using parallel and serie architectures



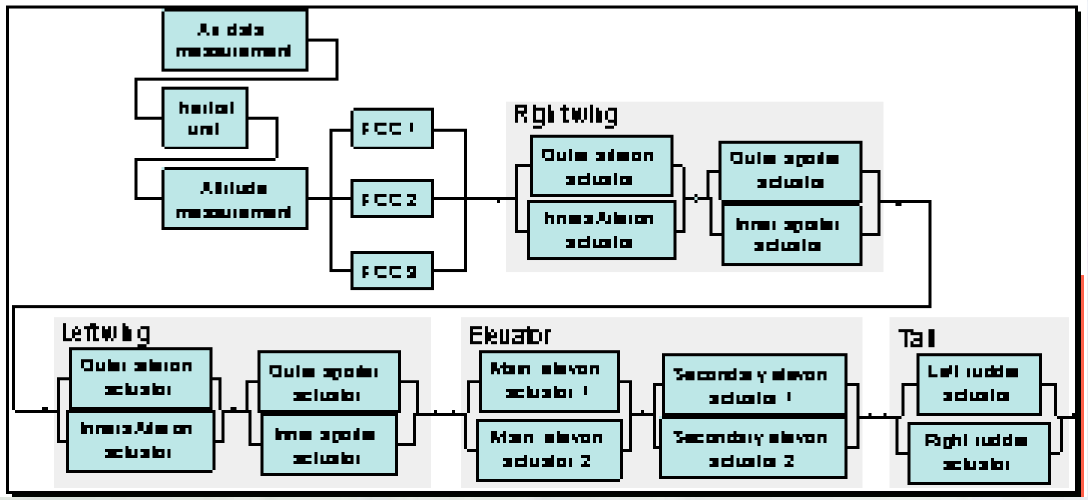
BLENDED HALE UAV (ONERA)

Shared ONERA and UNINA work

MTBCF ~ 741 hr

MTBL ~ 51 500 hr

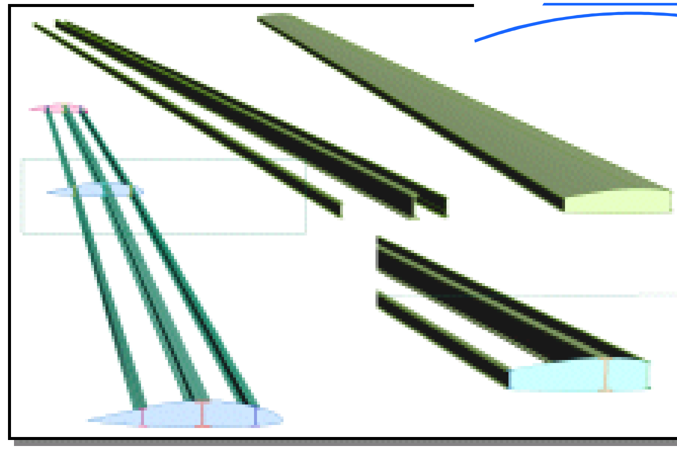
MTBUCL 515 000 hr



Structural design & analysis

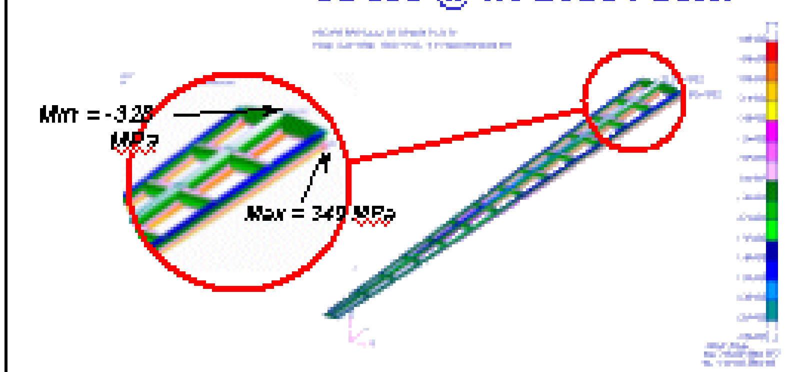
ONERA

- Loads compliant with CS-23 (gust and manoeuvers)
- Wing torque box with 3 I-beam spars
- Carbon-epoxy composite materials
- First sizing :
  - Usual safety factor (1.5) applied
  - Sizing with bending limits about 16% of the semi wing span (at the tip chord) for 3.2g
  - Verification of stress limits at 4.8 g

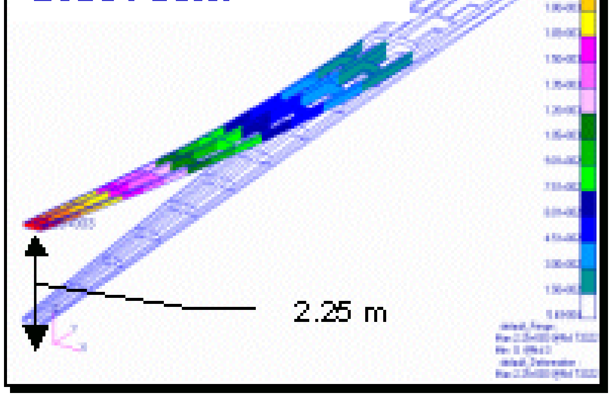


BLENDED HALE UAV (ONERA)

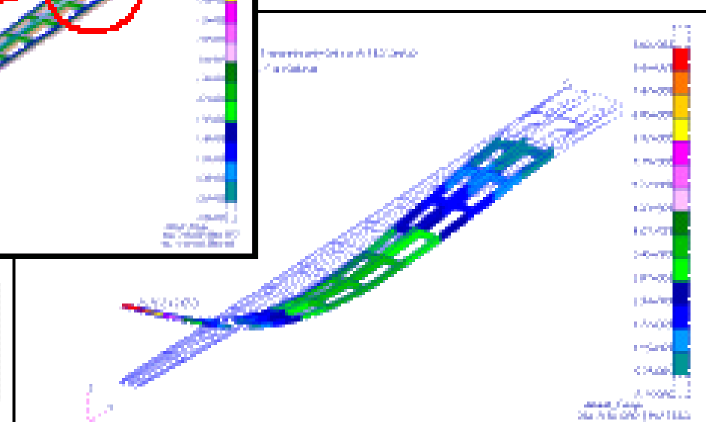
Stress @ 4.8 Load Factor



Deformation at 3.2 Load Factor



Design from ONERA
Analysis done by UNINA



2° flexural in yz plane @ 10.934 Hz

OBW-02 concept

ONERA

CAPECON

- A concept for which the two cycles analysis done gives confidence in its ability to fulfil requirements and missions specifications (500 kg during 24 h at 60 kft and 1000 km egress bound)

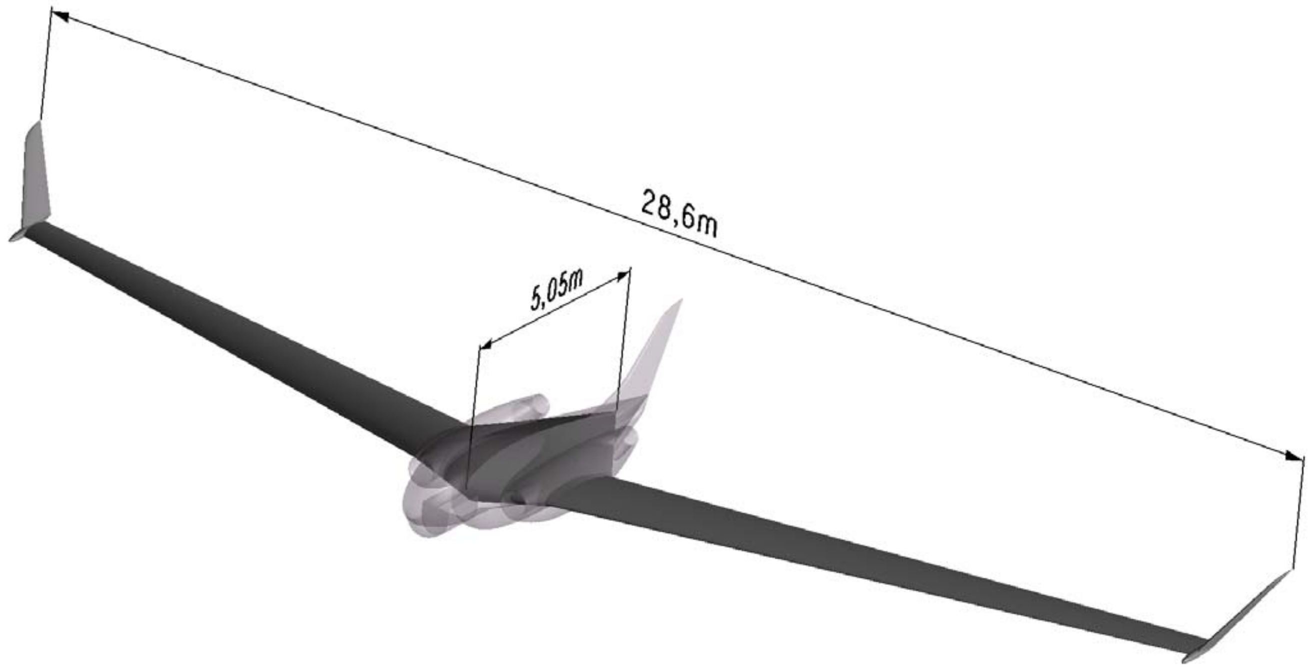
- This concept demonstrates the potential of blended wing configuration
- Analysis also points out the high sensibility of Blended Wing UAVs to several aspects, mainly :
  - flutter risks which require a deeper analysis
  - the rather poor stability of such a vehicle that could lead to the use of robust automatic flight control system

BLENDED HALE UAV (ONERA)

PW114 Concept

AN OVERALL DESCRIPTION

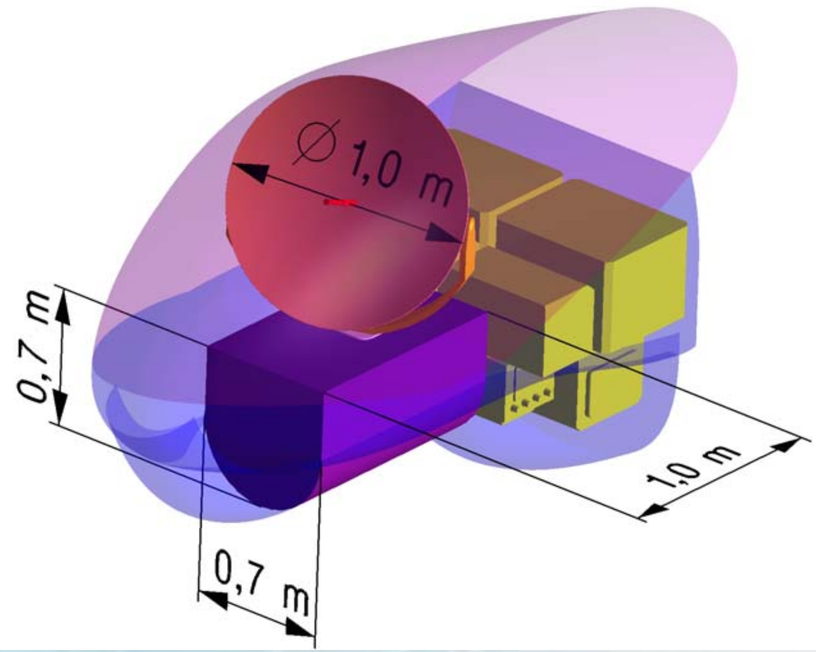
BLENDED HALE UAV (WUT)



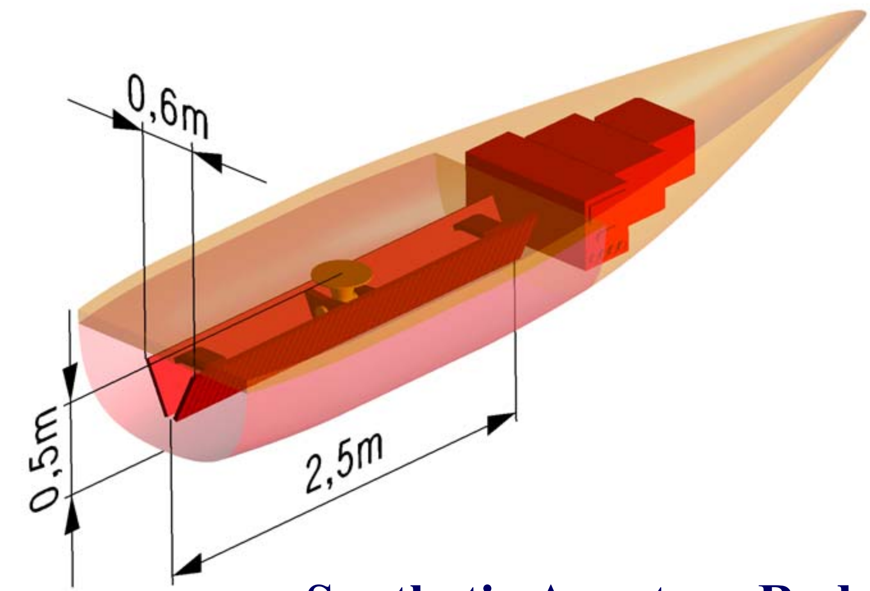
Flying wing
Overall AR: 17.7
MTOW: 6350 kg
Wing area: 44.4 m^2
Wetted area: 119.7 m^2
Wing loading: 143 kg/m^2
Engines: 2xWilliams FJ44-3, FJ44-4 in the future

Main Sensors

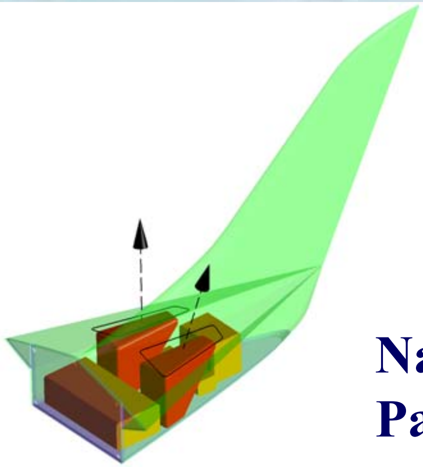
BLENDED HALE UAV (WUT)



EO/IR sensor
SATCOM antenna
Electronic racks



Synthetic Aparture Radar

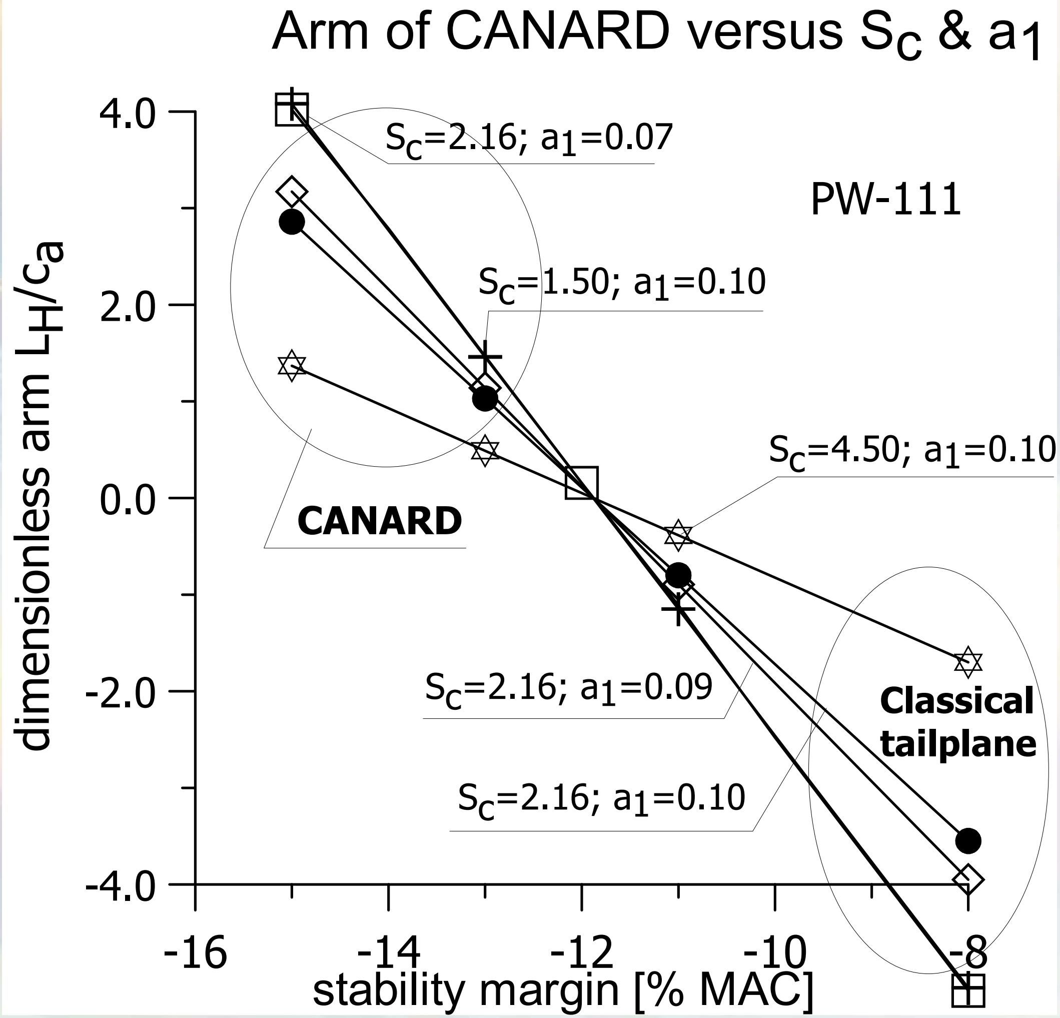


Navigation system
Parachute recovery system

BLENDED HALE UAV (WUT)

Fly- by-wire or classical configuration?

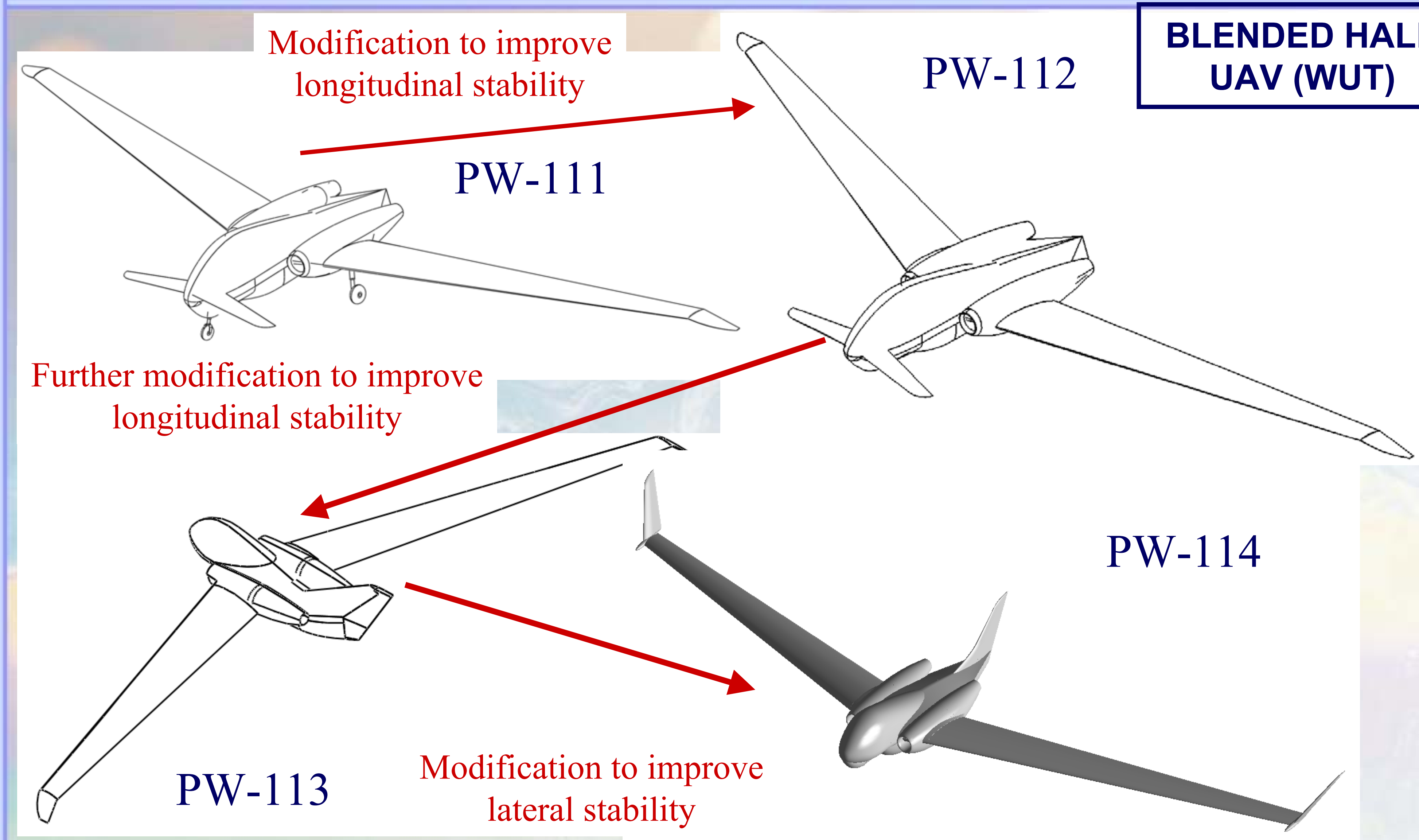
To reduce instability at the CG fixed one had to move the foreplane back



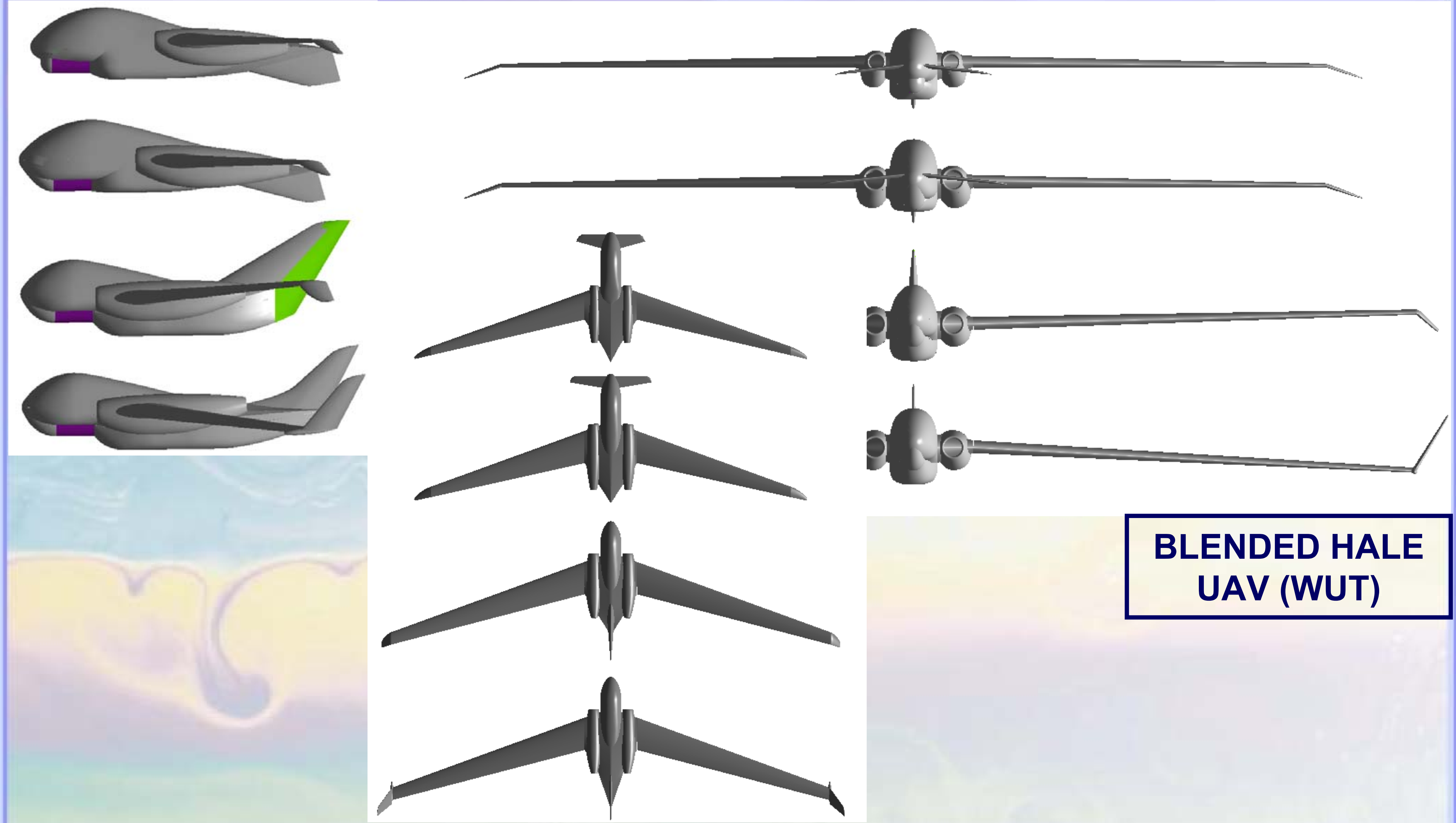
EILAT, May 18-19th 2005

Development HALE PW-11x

BLENDED HALE UAV (WUT)



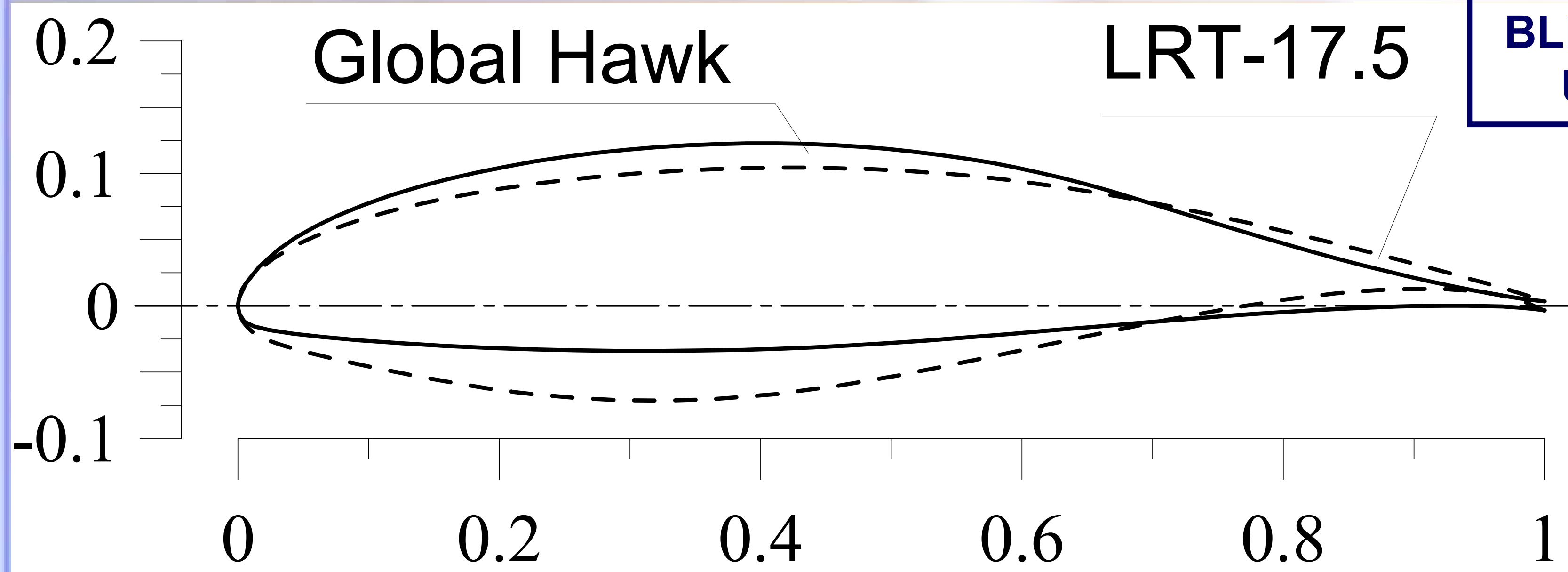
Development HALE PW-11x



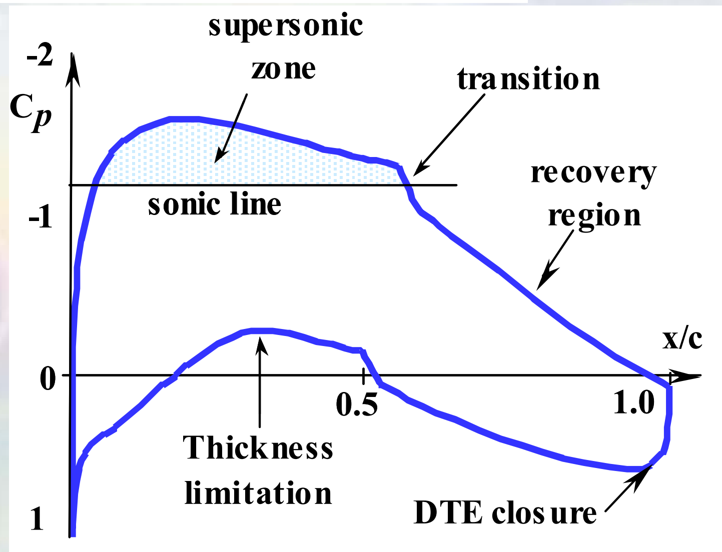
BLENDED HALE UAV (WUT)

HALE - Wing section

BLENDED HALE UAV (WUT)

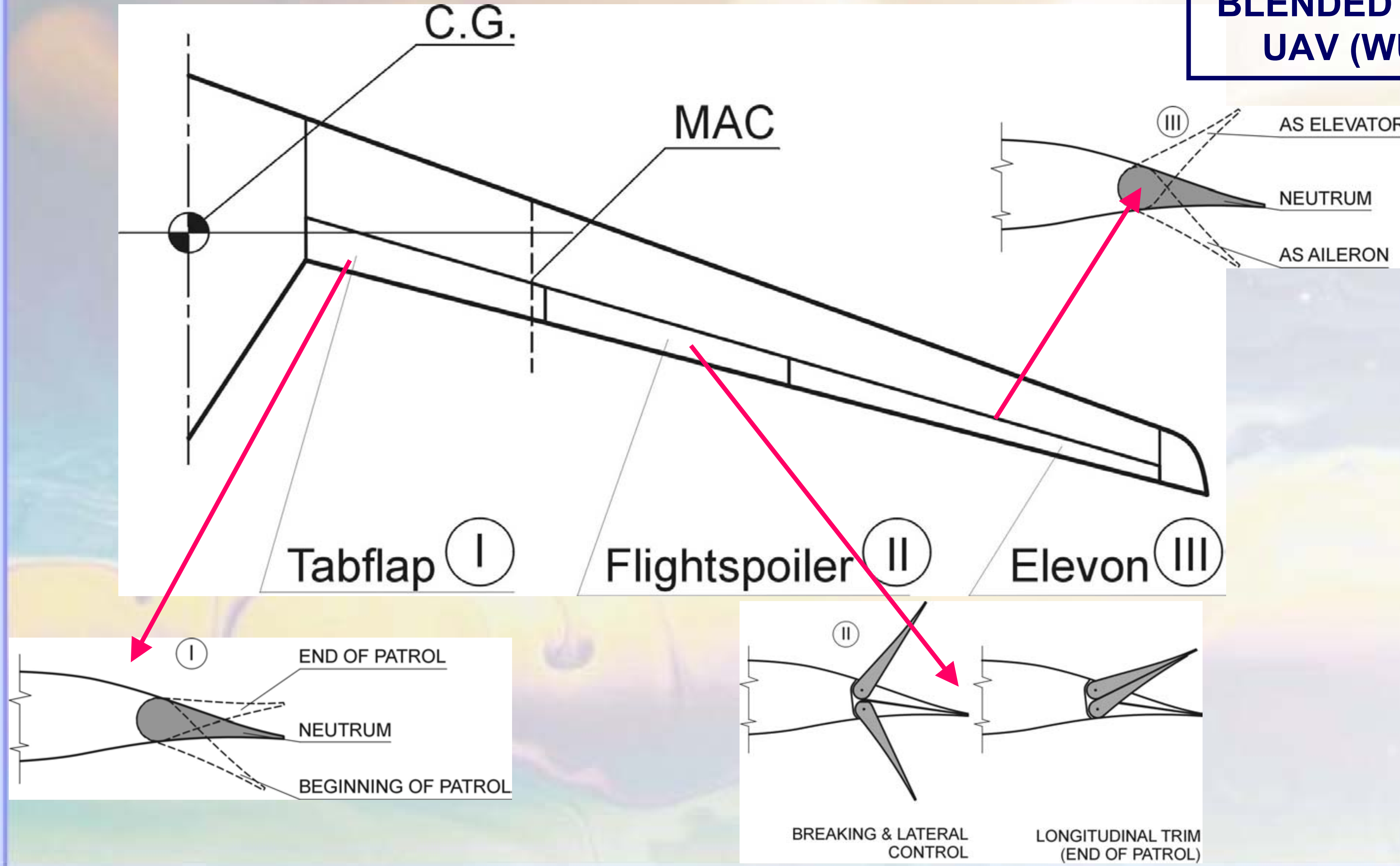


LRT-17.5: $(t/c)_{max}$=17.5%, M_{des}=0.62
Re_{des}=1.5*10⁶, $C_{l\ des}$=1.18



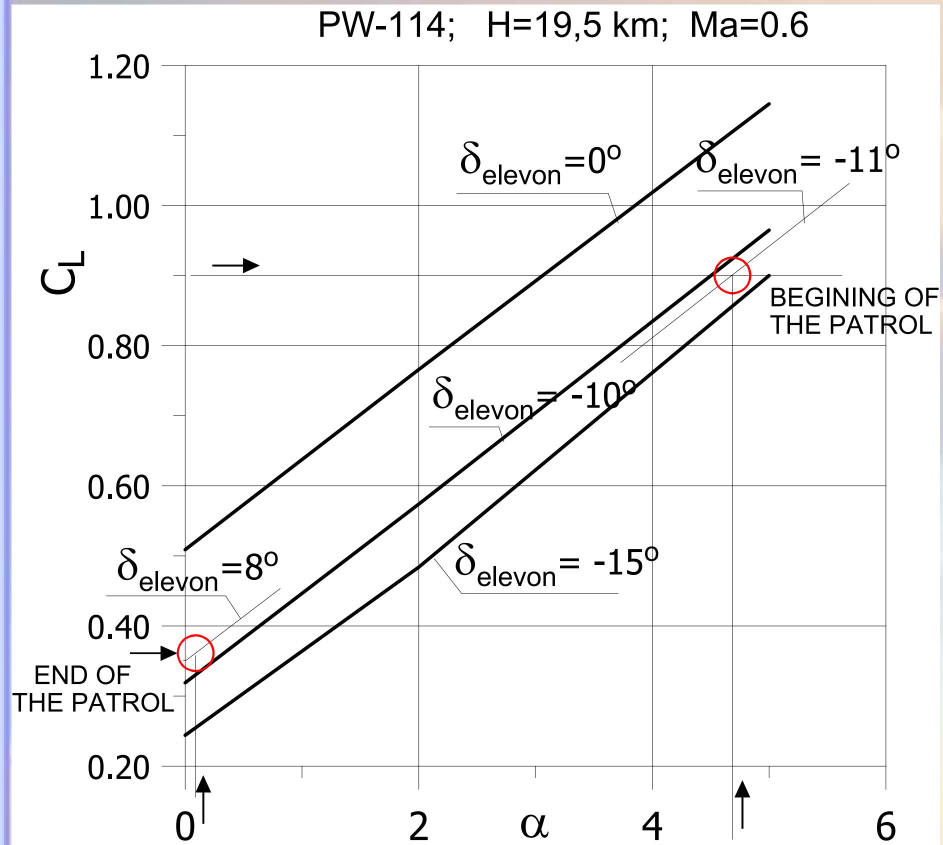
Flaps, spoilers, elevons

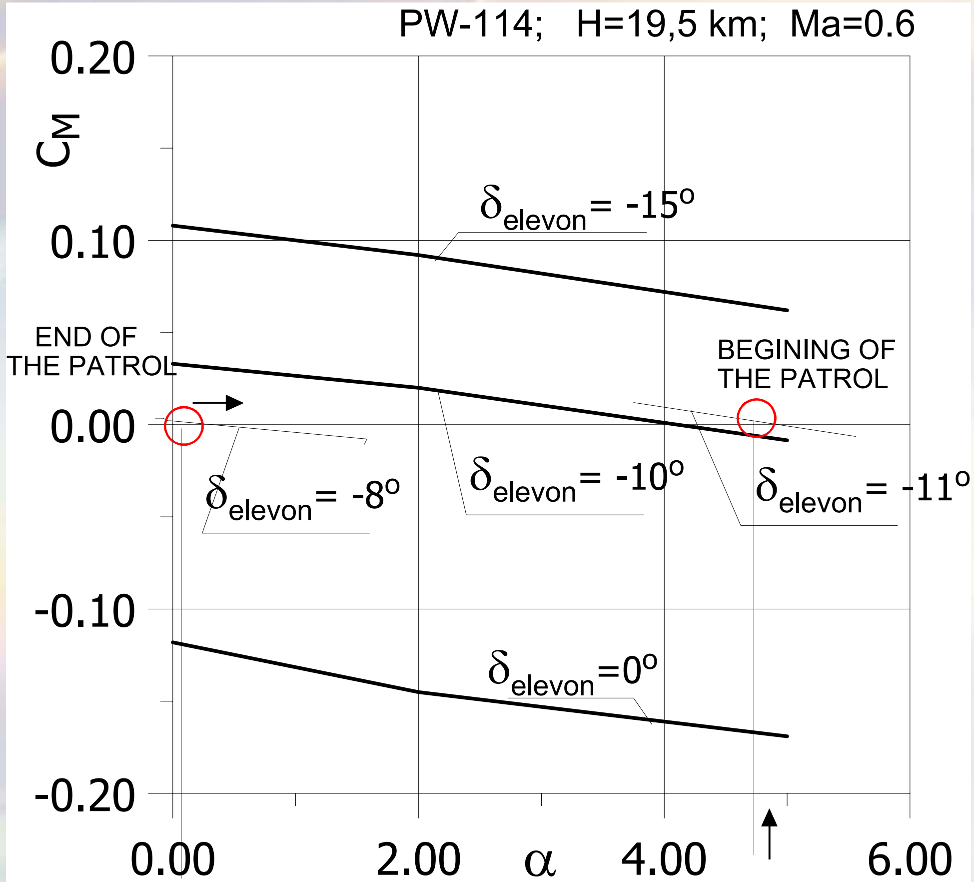
BLENDED HALE UAV (WUT)



Longitudinal trimming

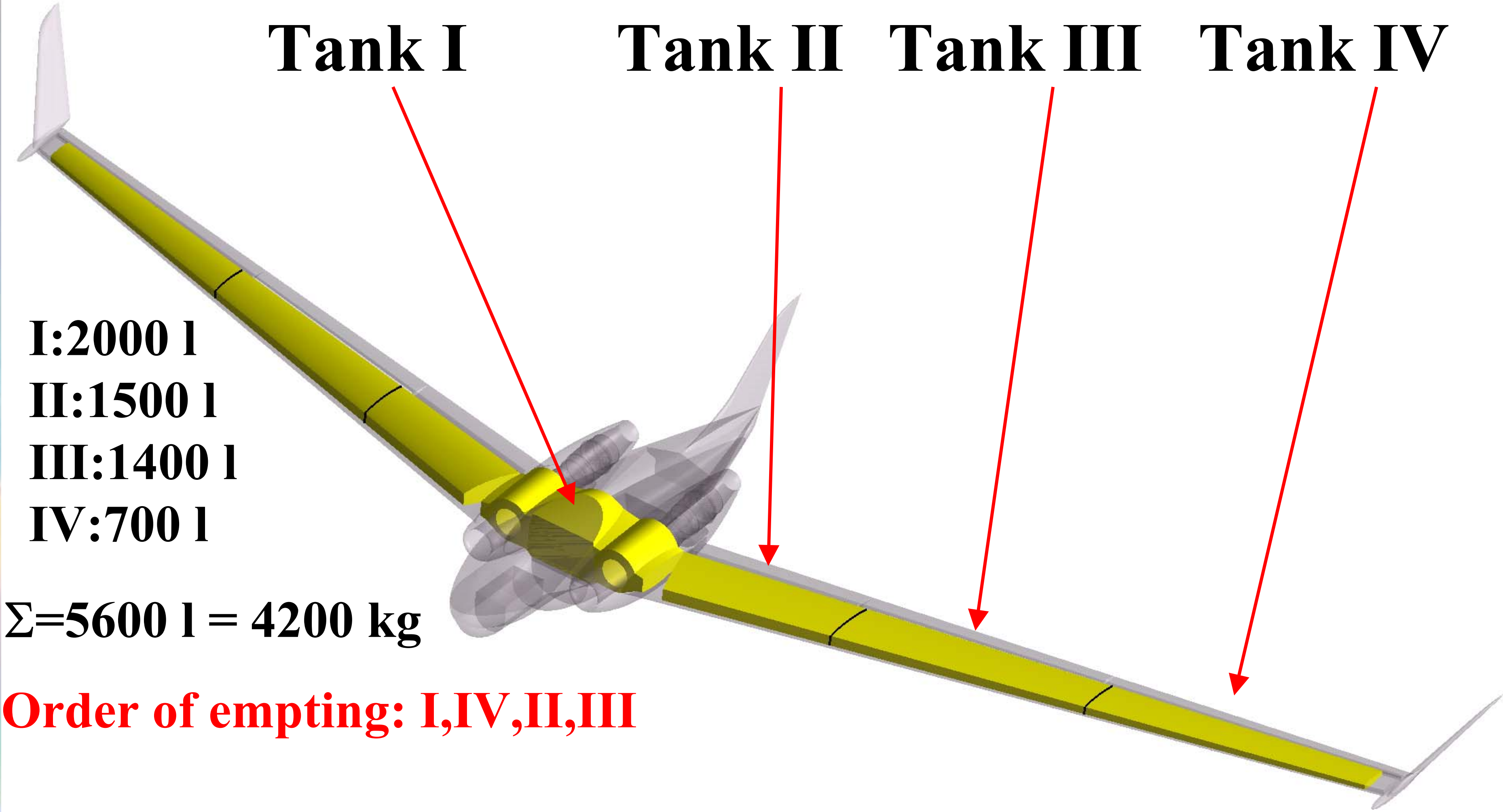
BLENDED HALE UAV (WUT)





Fuel system

BLENDED HALE UAV (WUT)



I:2000 l
II:1500 l
III:1400 l
IV:700 l

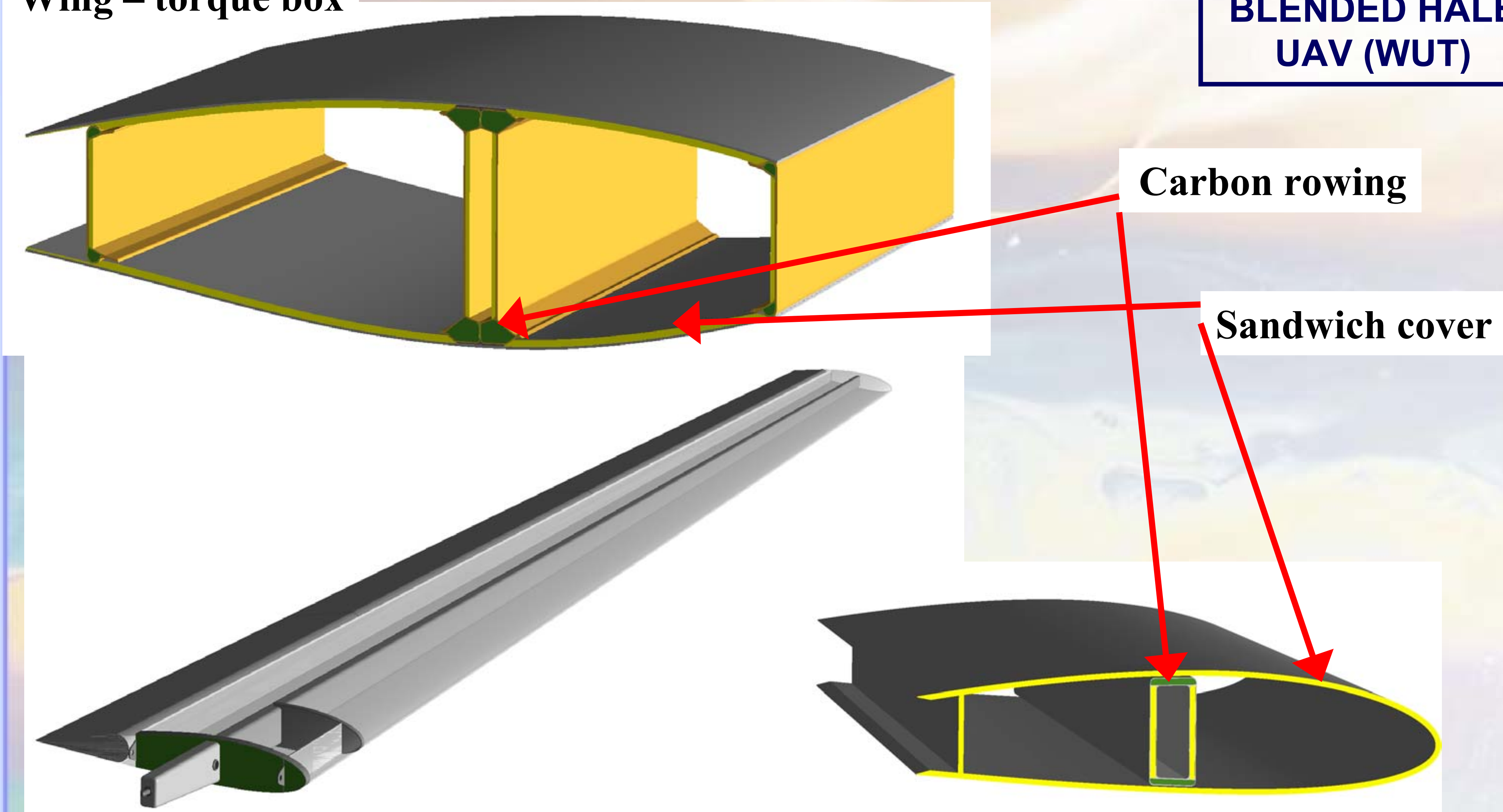
Σ=5600 l = 4200 kg

Order of empting: I,IV,II,III

Wing structure

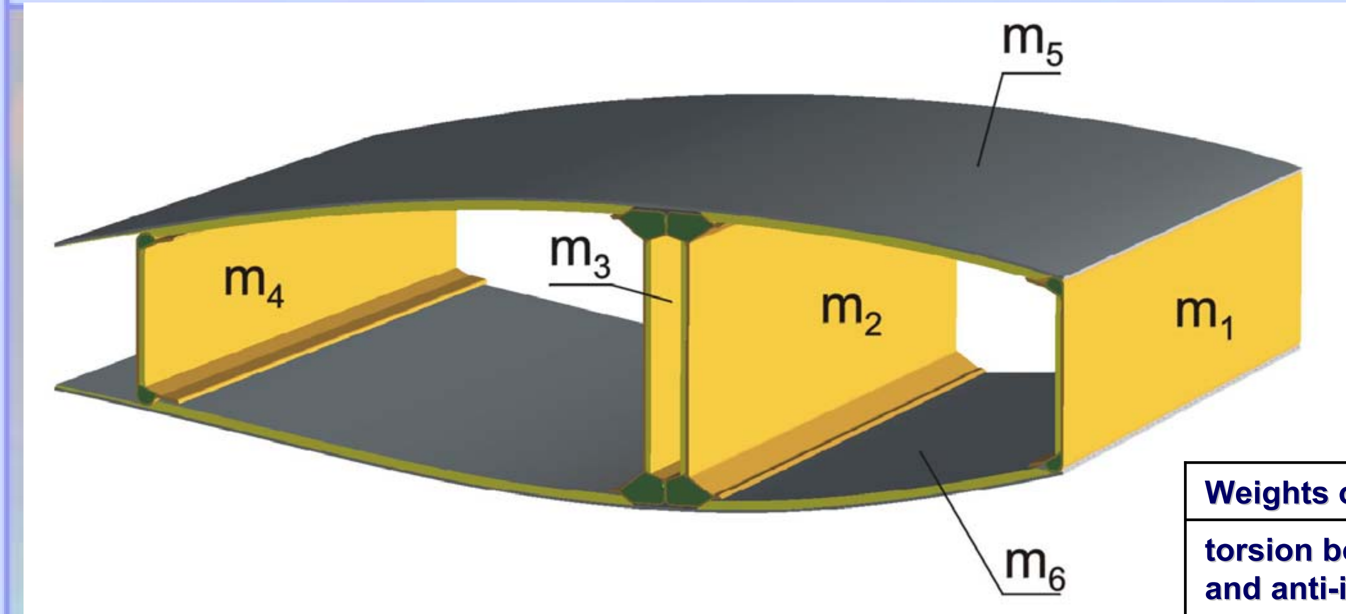
BLENDED HALE UAV (WUT)

Wing – torque box



Torsion box section

BLENDED HALE UAV (WUT)

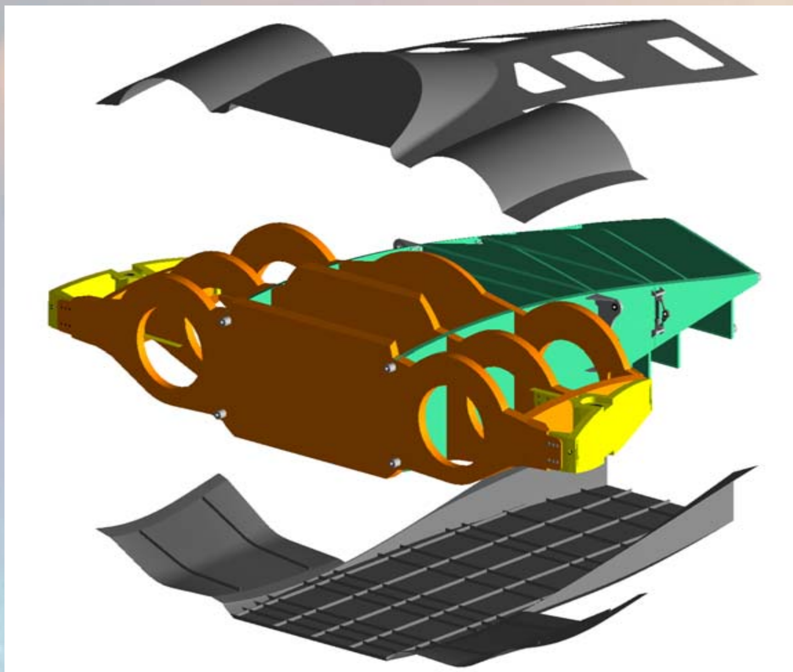


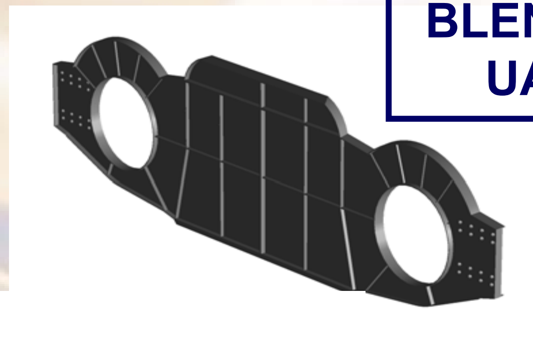
	Mass [kg]	%
m_1	0,60	6,5
m_2	3,17	34
m_3	3,17	34
m_4	0,59	6,5
m_5	0,87	9,5
m_6	0,88	9.5
Torsion box total	9,28	100

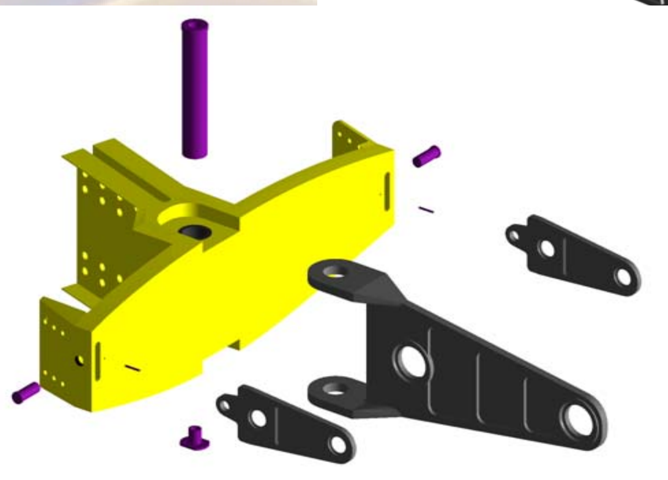
Weights of wing components	[kg]
torsion box with fuel ribs, nose and anti-icing installation	96
control surfaces	11.5
wingtip with brackets	7.8
control surfaces' consoles	3
actuators	16.5
fuel installation	6
Whole wing	2x 140,8 = 281.6 kg ≈ 4,5 % of max TOW

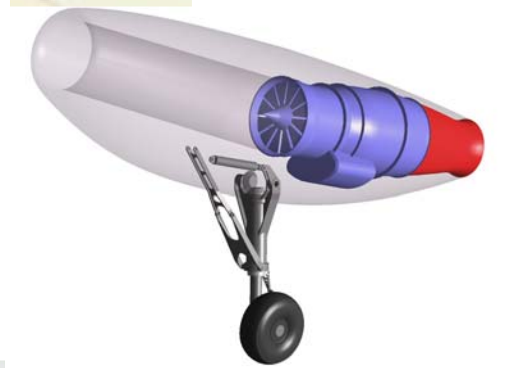
Structure of fuselage

BLENDED HALE UAV (WUT)





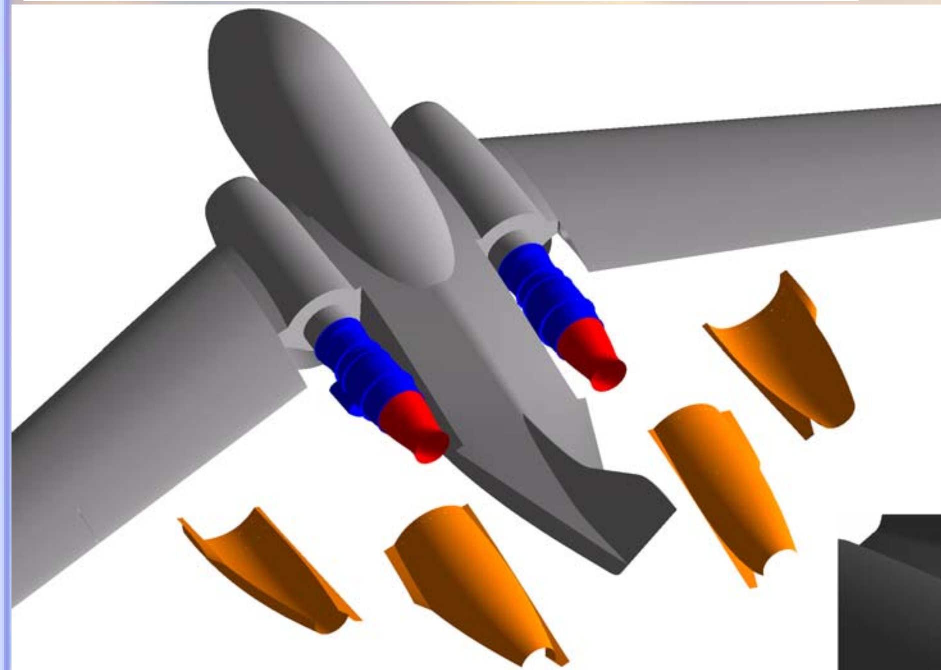




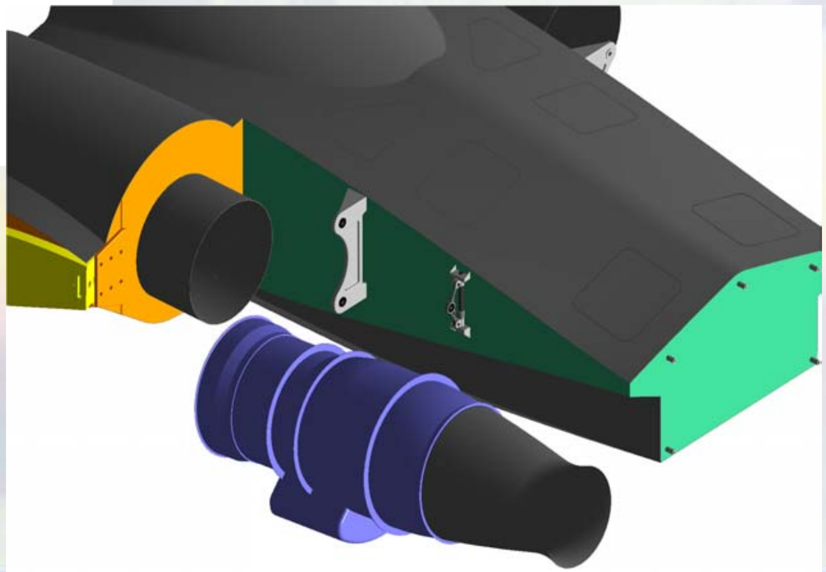
Power unit

Location and attachment

BLENDED HALE UAV (WUT)

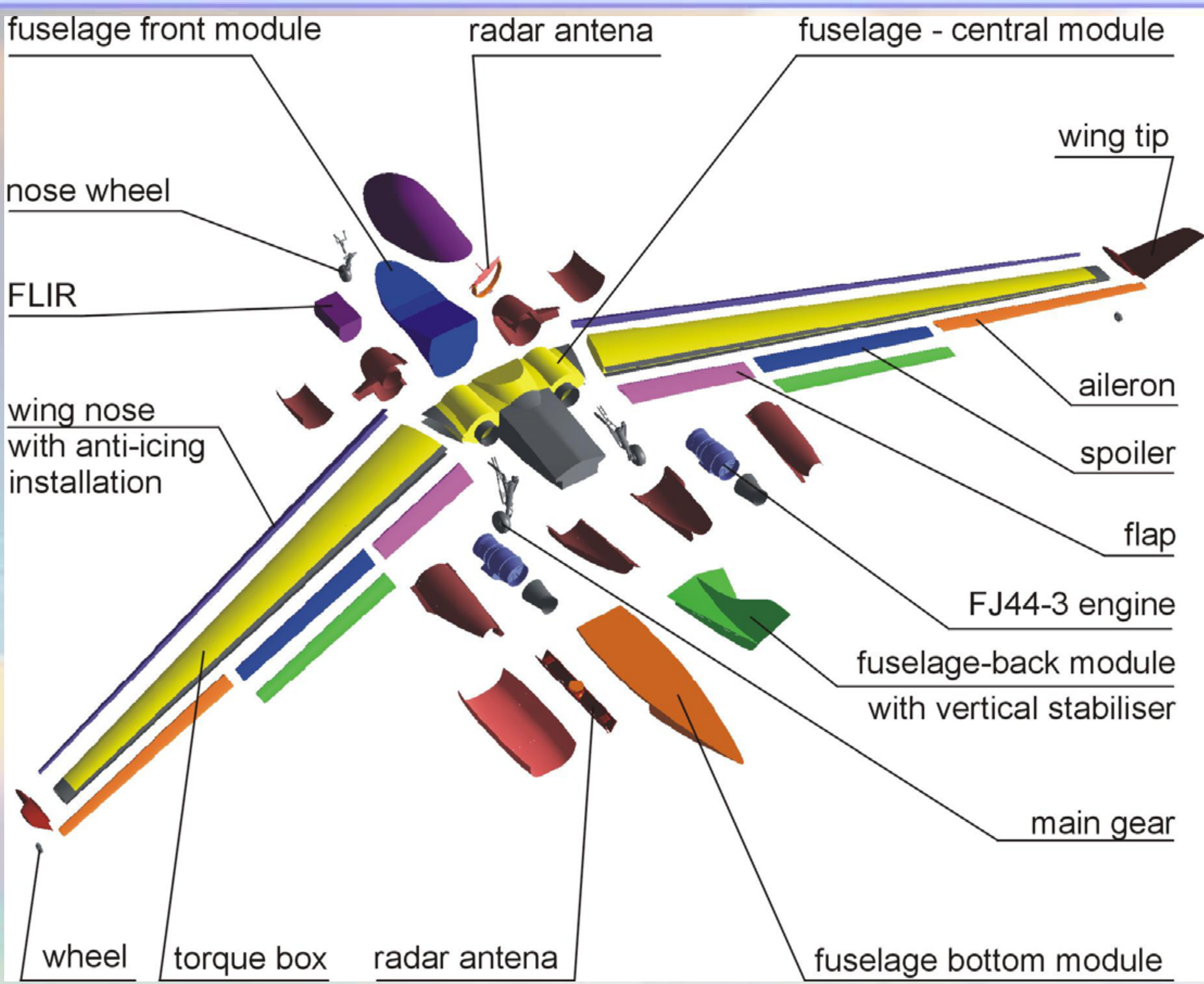


- *Compact design*
- *Small interference drag*
- *Small assembly weight*
- *High efficiency of straight intakes*
- *Easy access & simply maintenance*



PW114 main systems

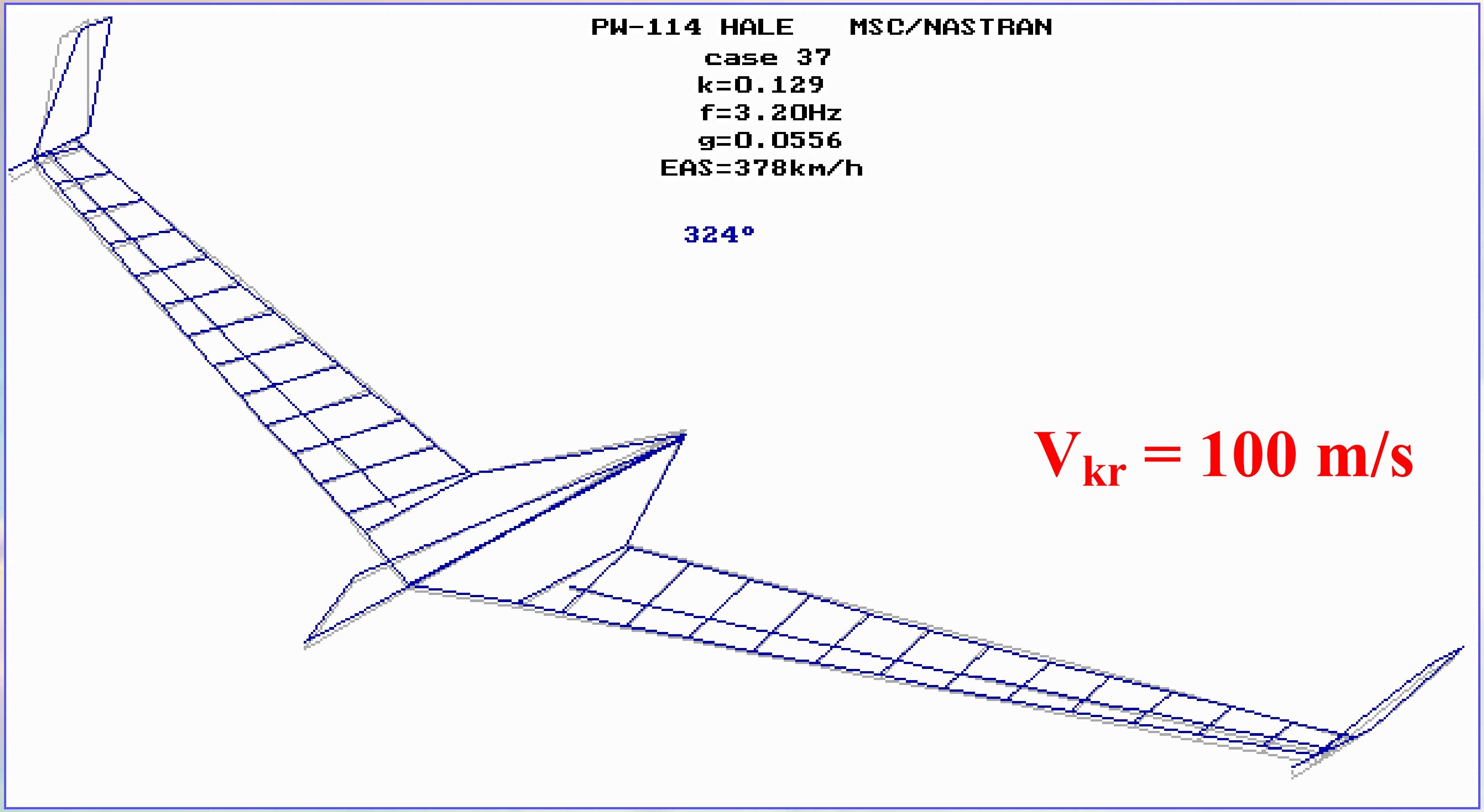
BLENDED HALE UAV (WUT)



Flutter

Symmetric mode, fuel in wing only

BLENDED HALE UAV (WUT)



$V_{kr} = 100$ m/s

PW114 & Global Hawk

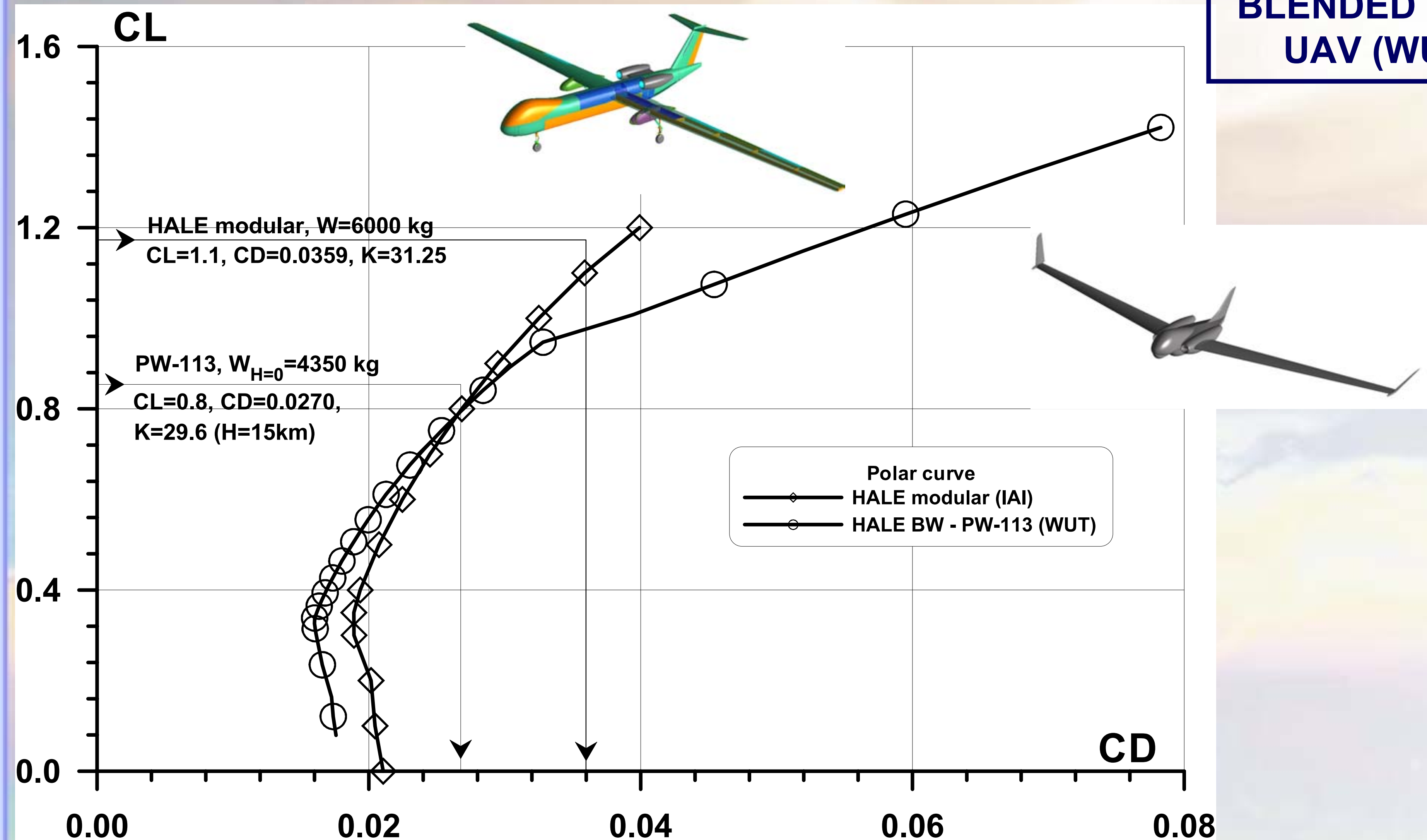
BLENDED HALE UAV (WUT)

Comparison

parameter	GH	PW-114
Wing span [m]	35,4	28
Wing area [m^2]	50,2	44,4
Aspect ratio	25,1	17,7
Empty weight [kg]	4177	2200
Payload [kg]	1000	700
Fuel weight [kg]	6583	4150
Take-off weight [kg]	11622	6350
Take-off thrust [kN]	37	20,9
Wing loading [kg/m^2]	231,5	143
Thrust loading [kg/kN]	314,1	304,1
Payload/wing area [kg/m^2]	19,9	15,8
Payload/take-off thrust [kg/kN]	27	33,5
Payload/empty weight [kg/kg]	0.24	0.32

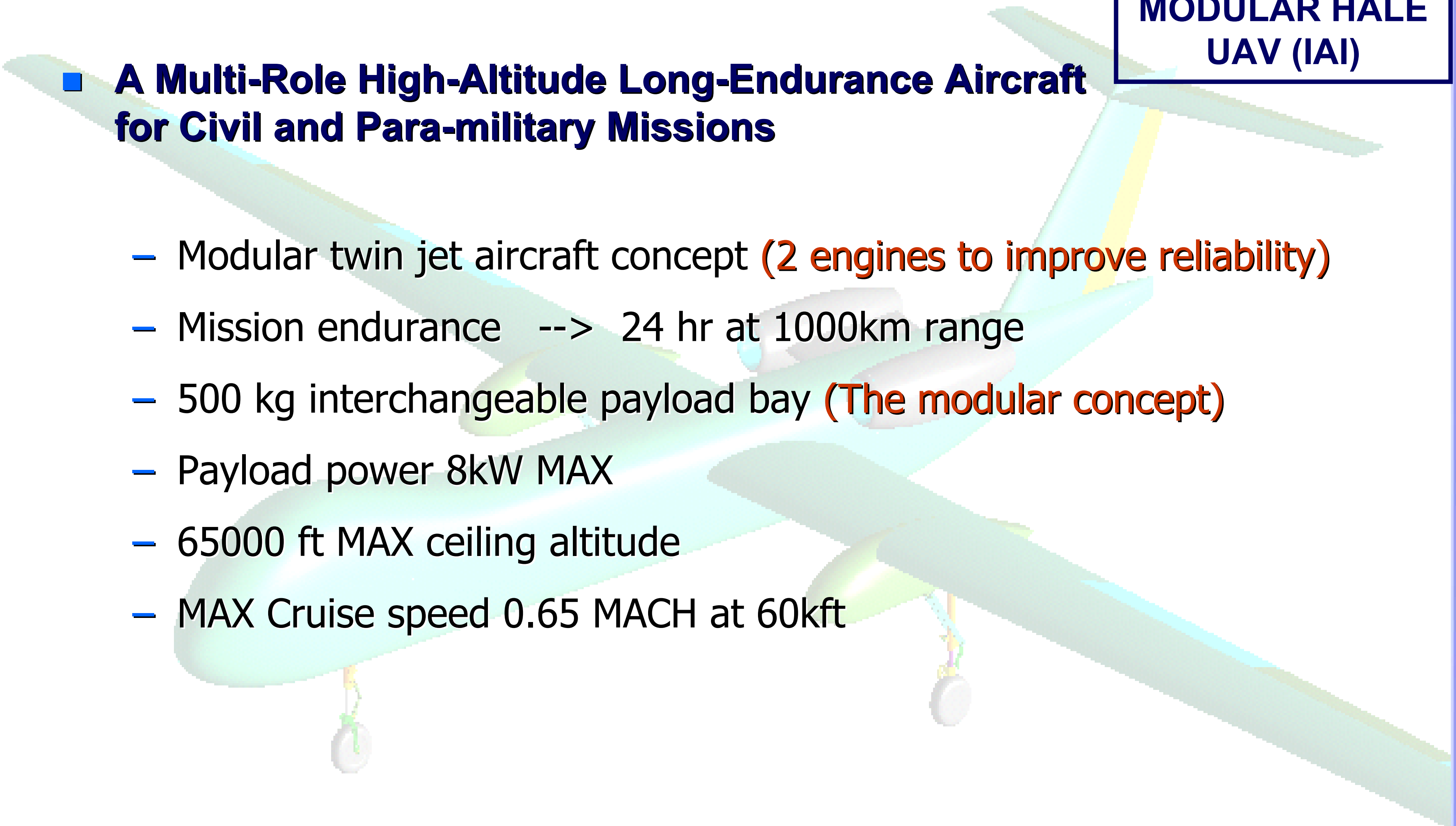
Aerodynamic comparison

BLENDED HALE UAV (WUT)



Modular HALE - UAV

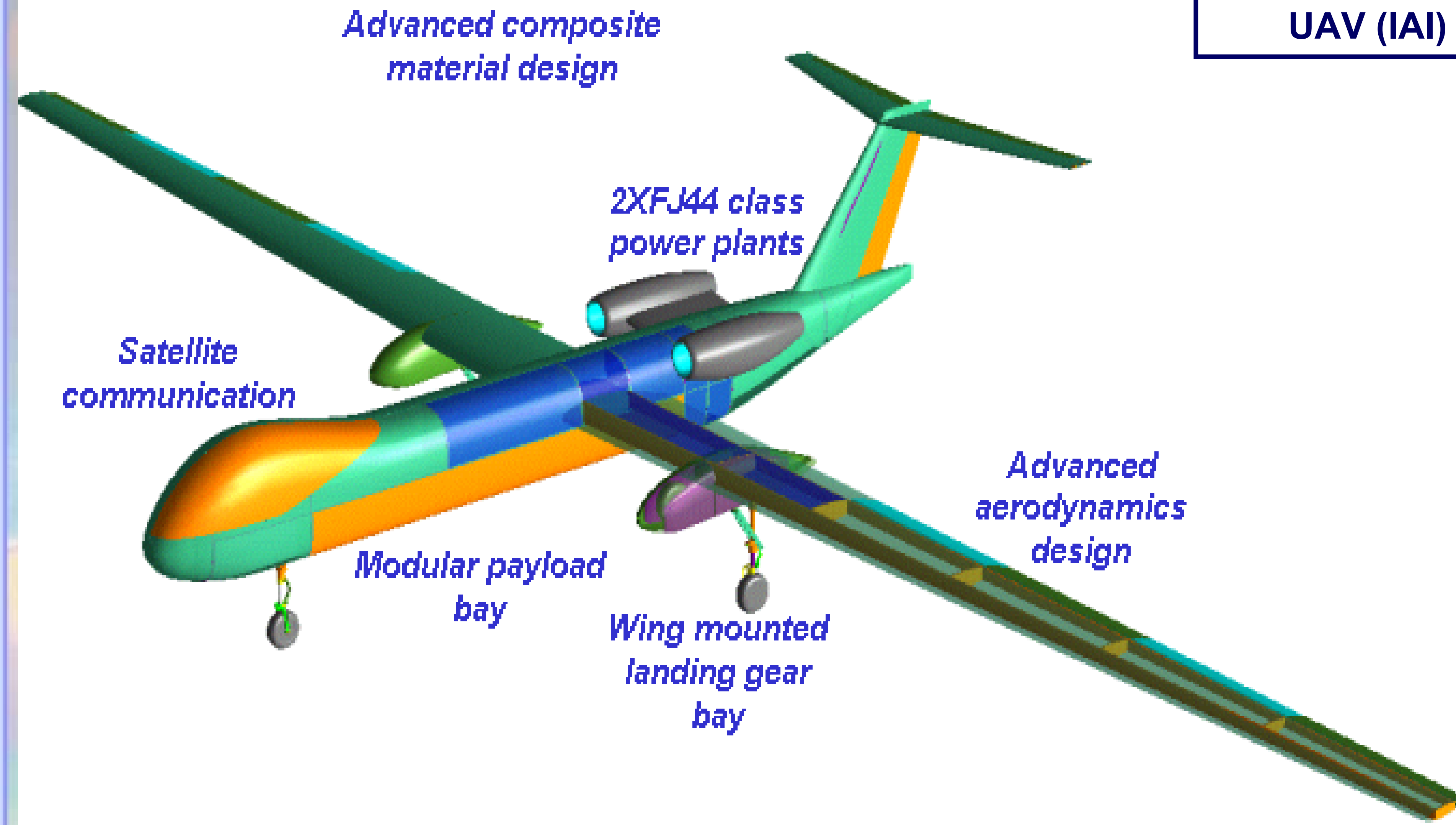
MODULAR HALE UAV (IAI)



- **A Multi-Role High-Altitude Long-Endurance Aircraft for Civil and Para-military Missions**
  - Modular twin jet aircraft concept (2 engines to improve reliability)
  - Mission endurance --> 24 hr at 1000km range
  - 500 kg interchangeable payload bay (The modular concept)
  - Payload power 8kW MAX
  - 65000 ft MAX ceiling altitude
  - MAX Cruise speed 0.65 MACH at 60kft

Configuration Features

MODULAR HALE UAV (IAI)



Requirements

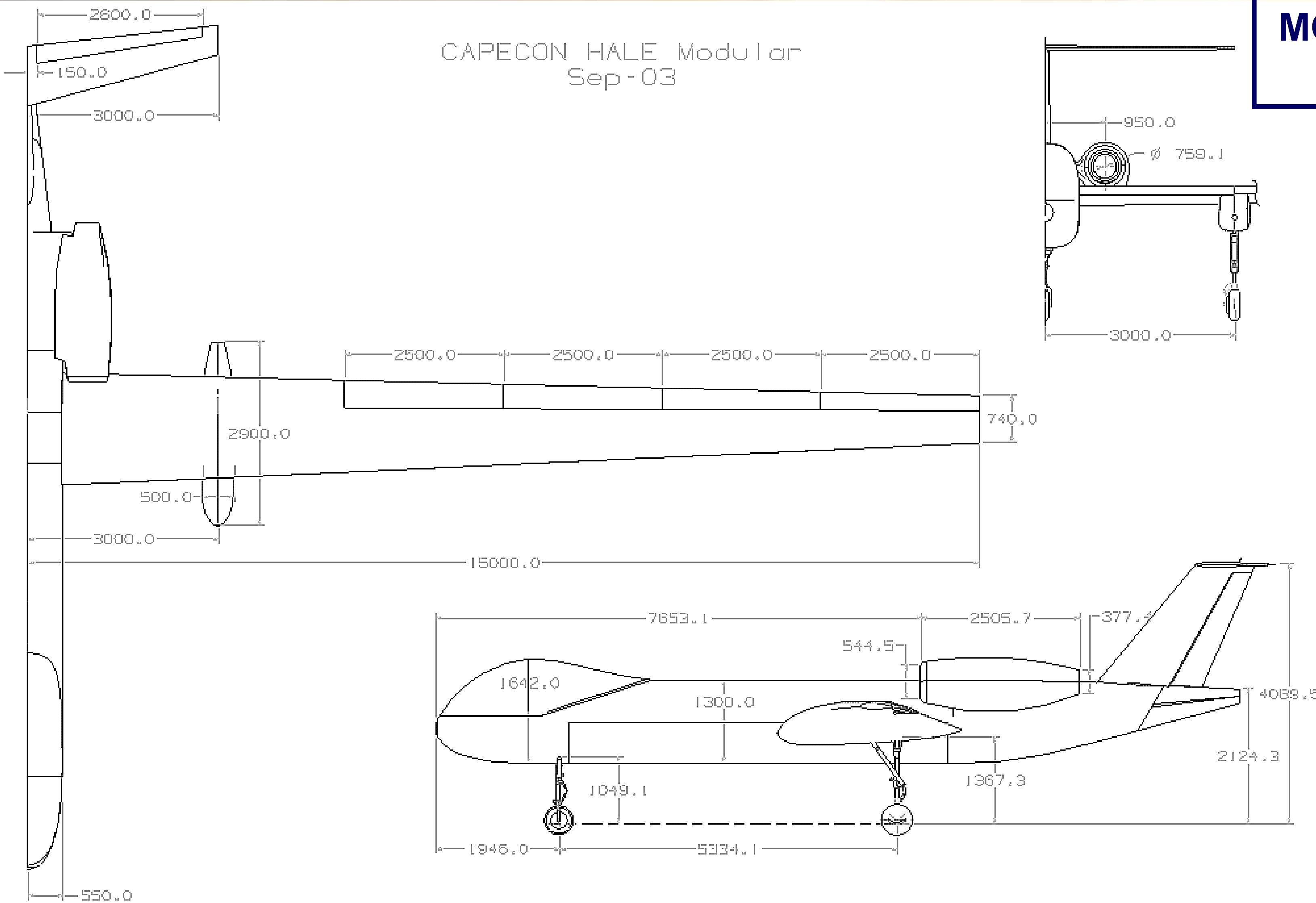
Performance requirements (Starting point)

MODULAR HALE UAV (IAI)

No.	Parameter	Starting Value	Current Value	
1	Empty Weight	~3400kg	~2010	kg
2	Payloads Weight	500kg	500	kg
3	Fuel Weight	3400kg	3490	kg
4	Take-off Weight	7700kg	6000	kg
5	Ceiling	66kft	66	kft
6	Endurance	24hr	24	hr
7	Mission Altitude	55-66kft	55-66	kft
8	R.O.C @ S.L >	2000ft/min	3200	ft/min
9	Max Airspeed	340ktas	340	ktas
10	Take-off Ground Roll	2000m	1100	m

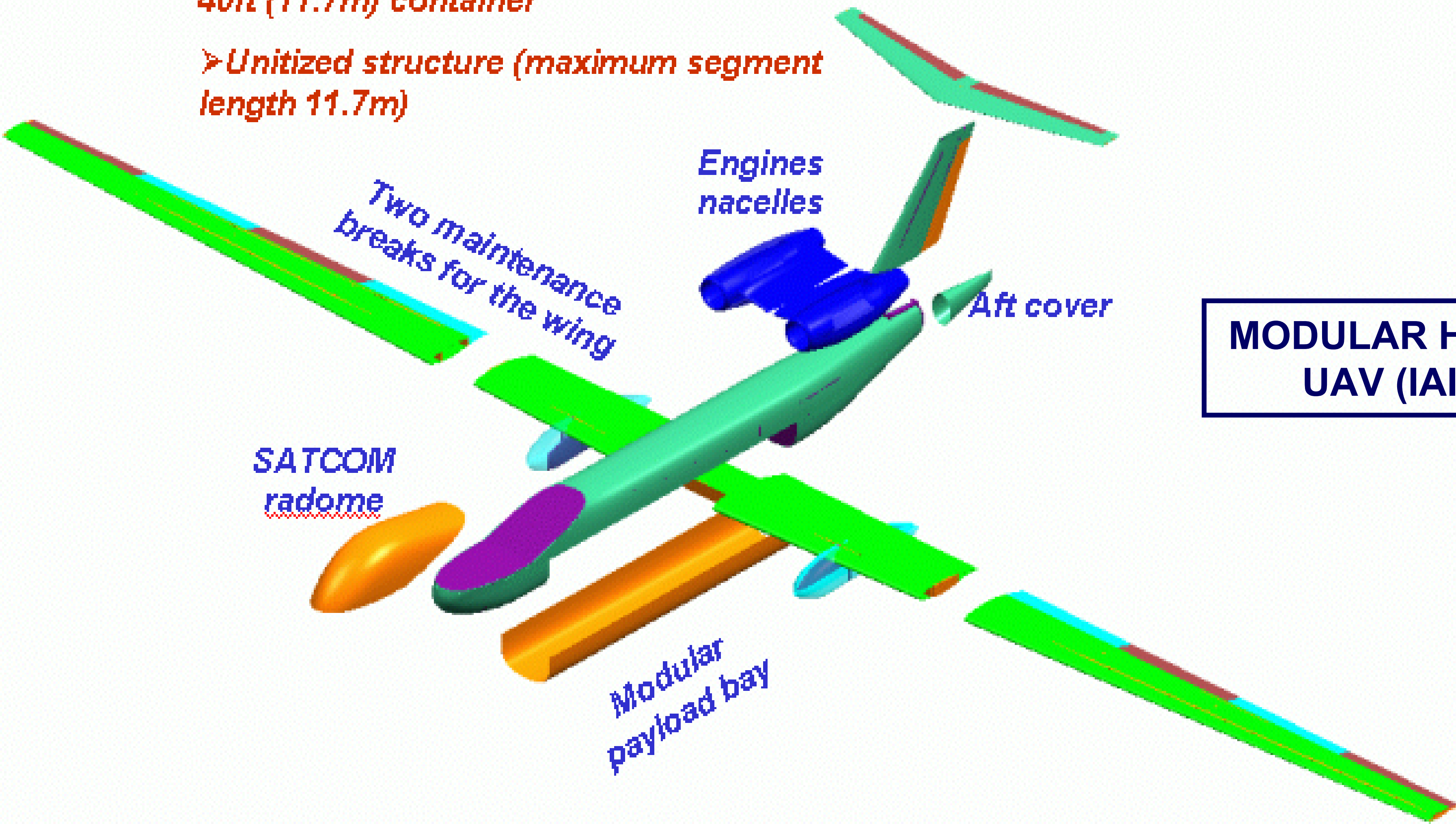
3 views Drawing

MODULAR HALE UAV (IAI)



Structural design

- *Reducing the transportability Footprint to one standard 40ft (11.7m) container*
- *Unitized structure (maximum segment length 11.7m)*

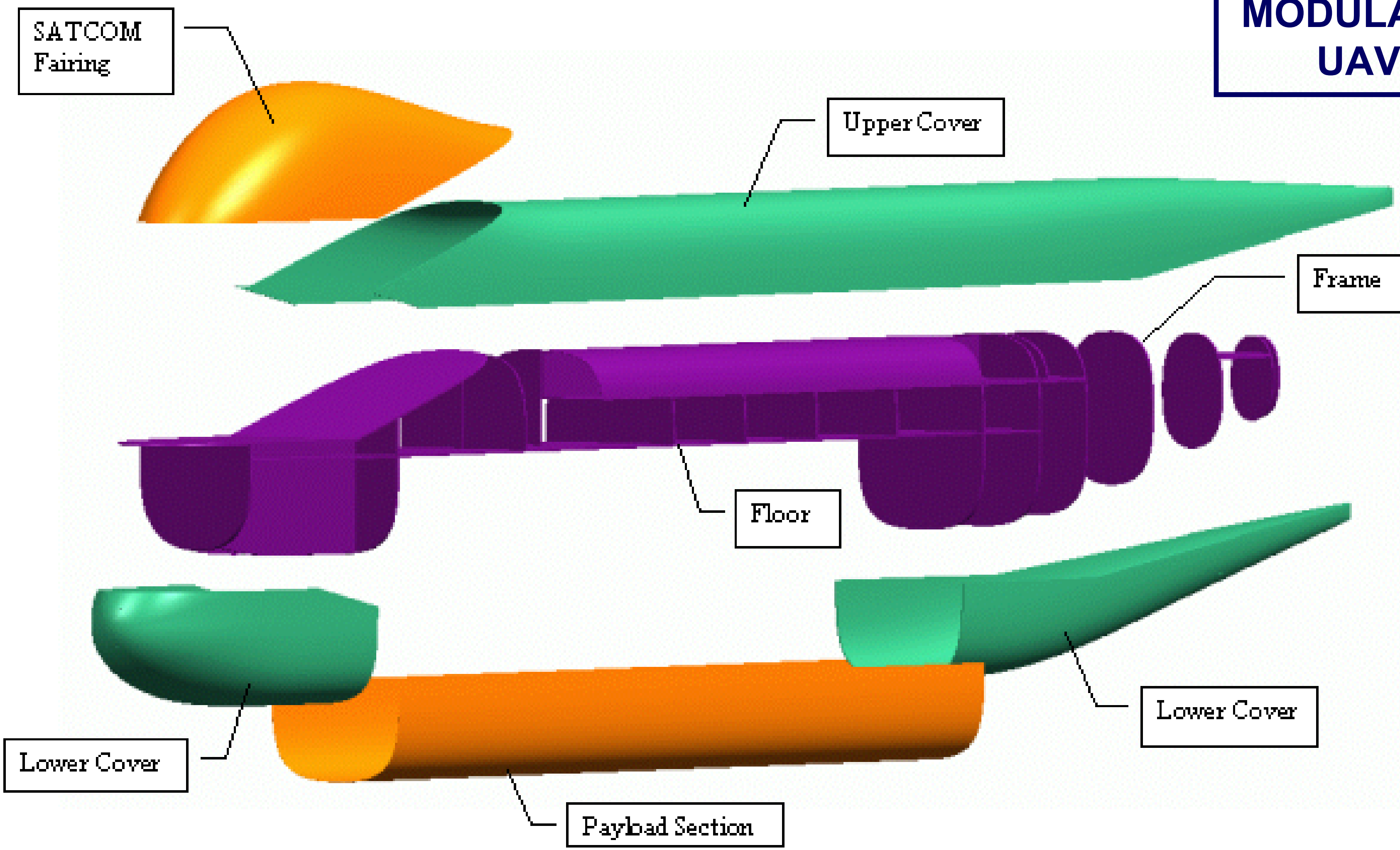


MODULAR HALE UAV (IAI)

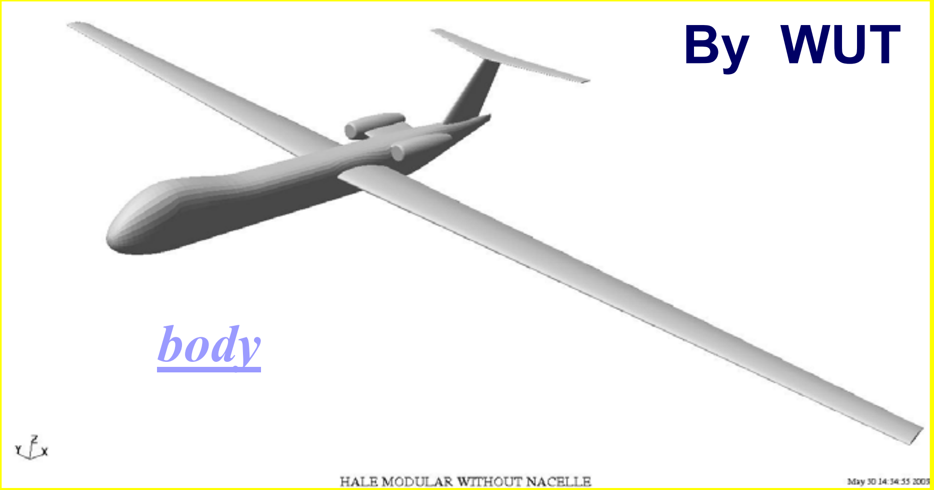
Fuselage

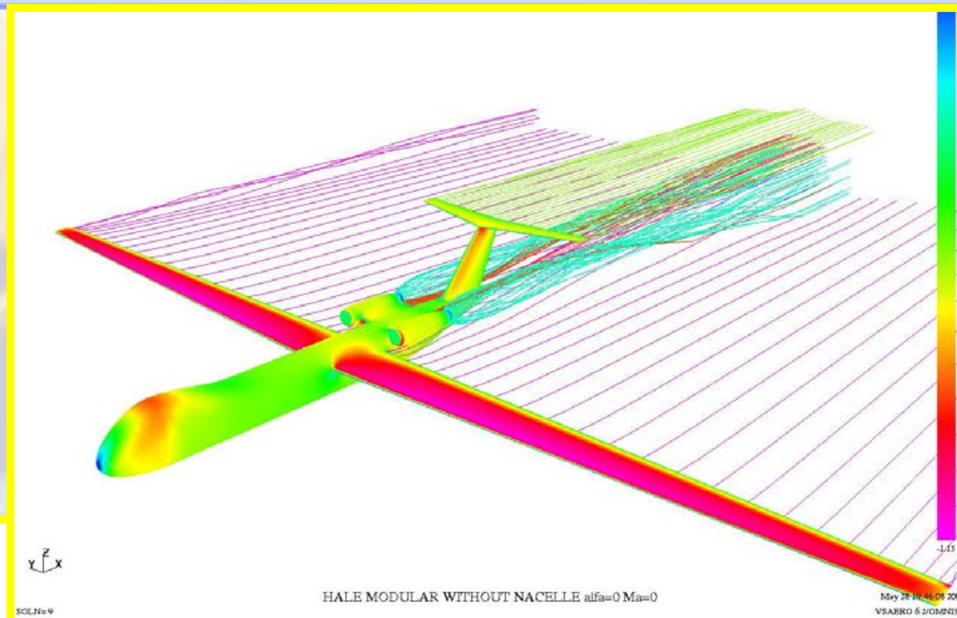
Fuselage production breakdown concept

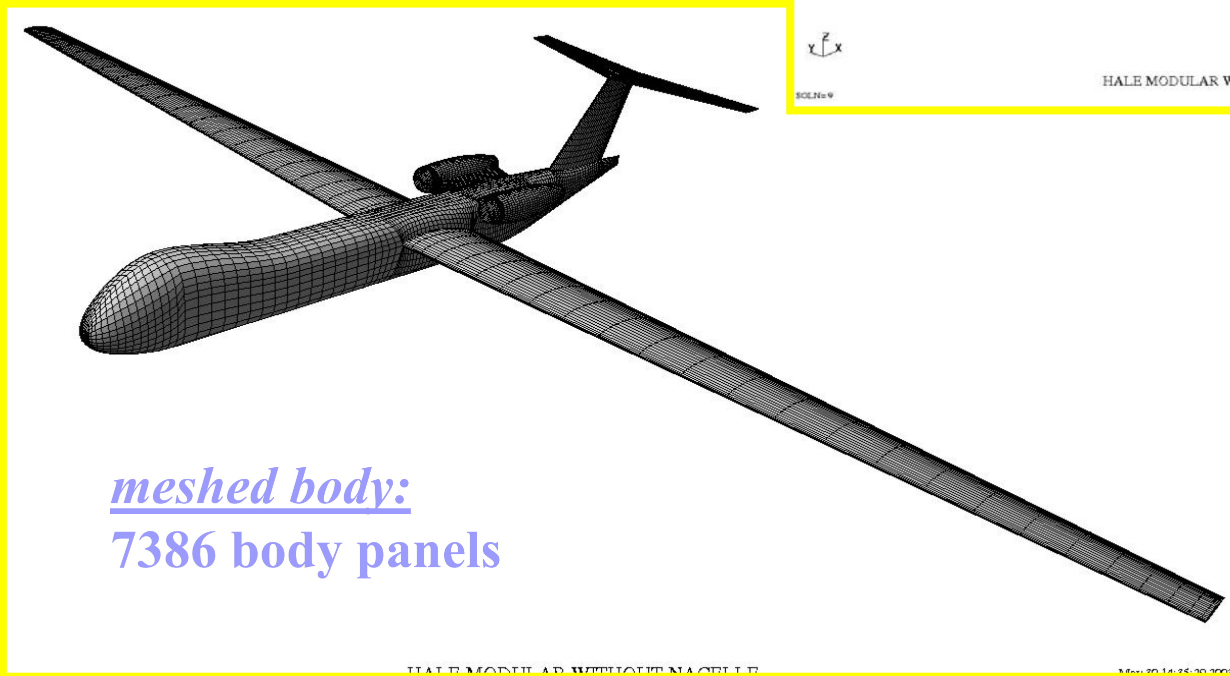
MODULAR HALE UAV (IAI)



Aerodynamic analysis



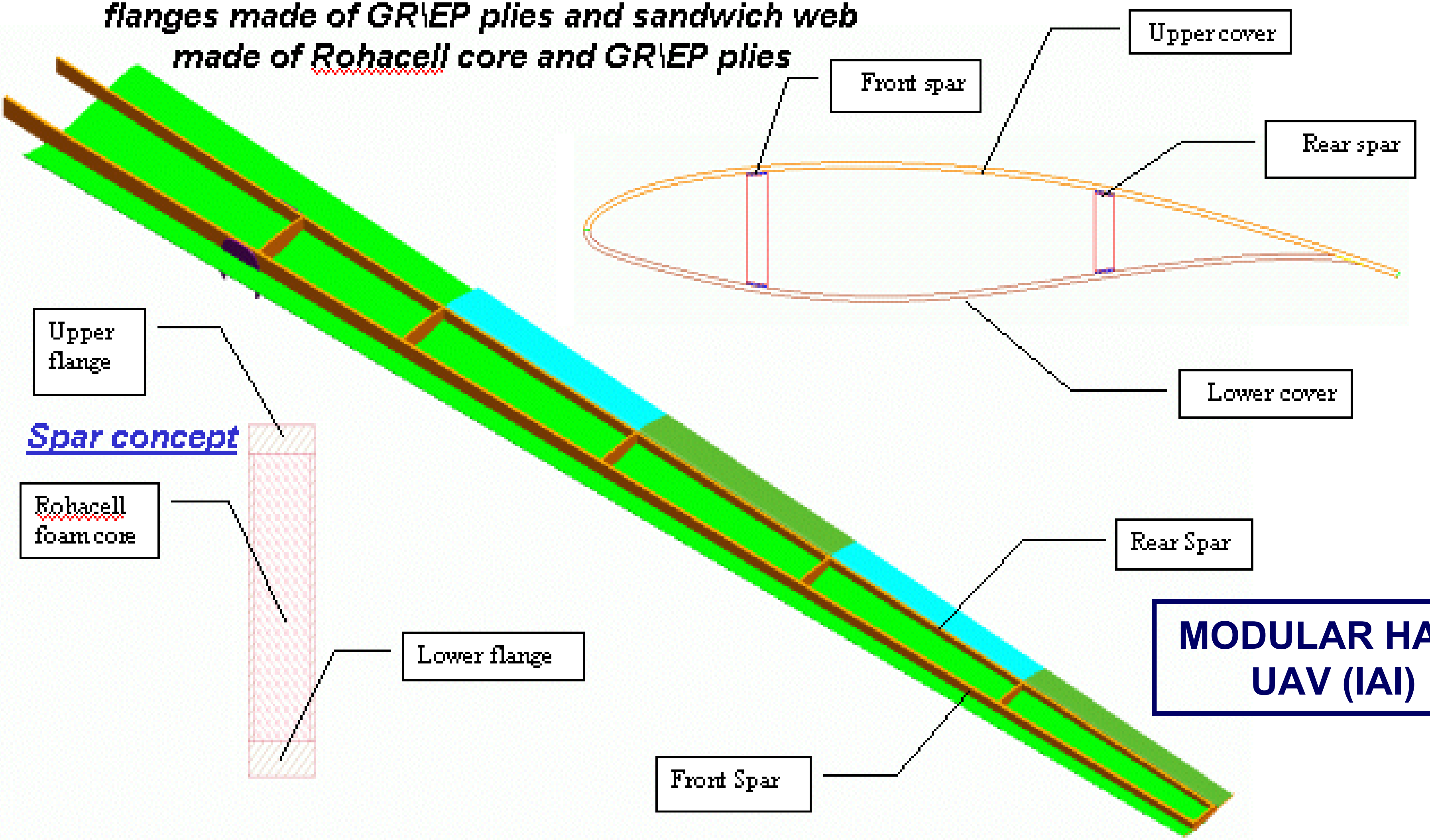




MODULAR HALE UAV (IAI)

Wing structure concept

The spars are comprised of upper and lower flanges made of GR\EP plies and sandwich web made of Rohacell core and GR\EP plies

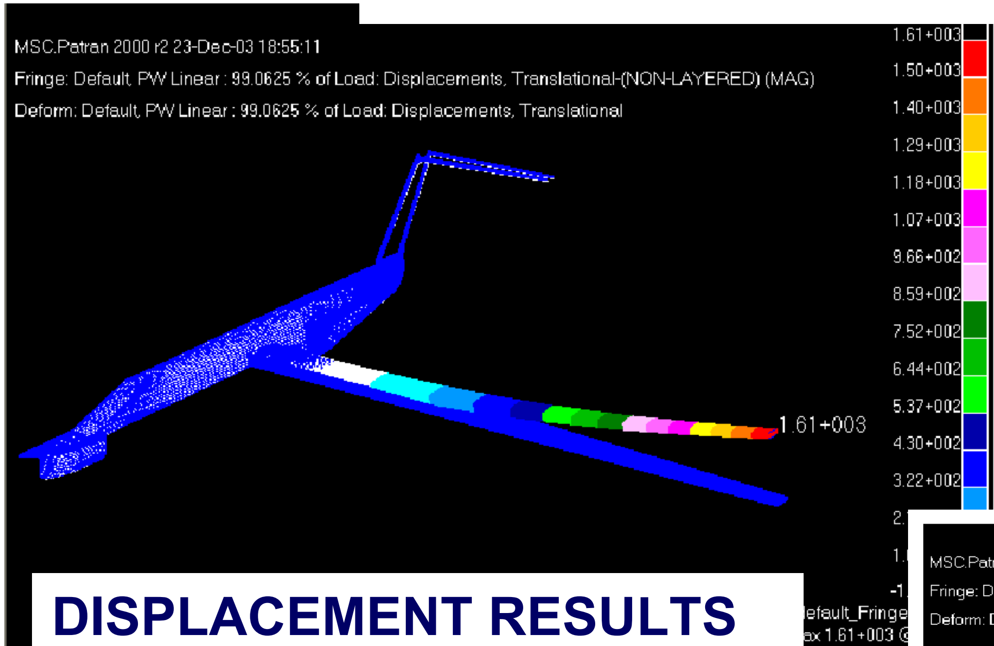


MODULAR HALE UAV (IAI)

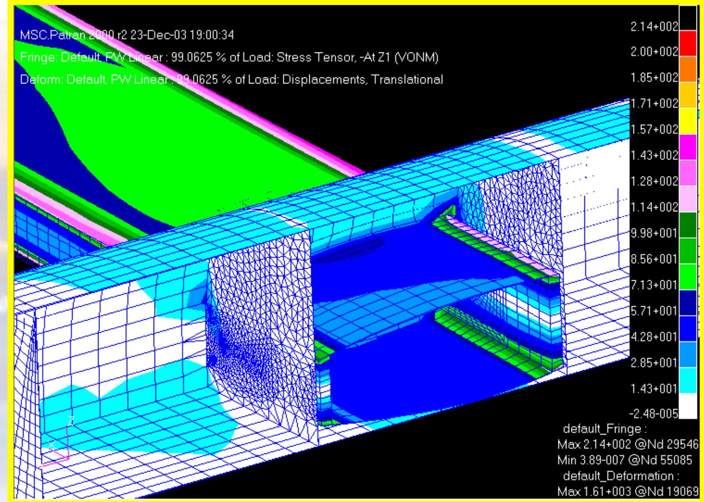
Wing structure analysis

MODULAR HALE UAV (IAI)

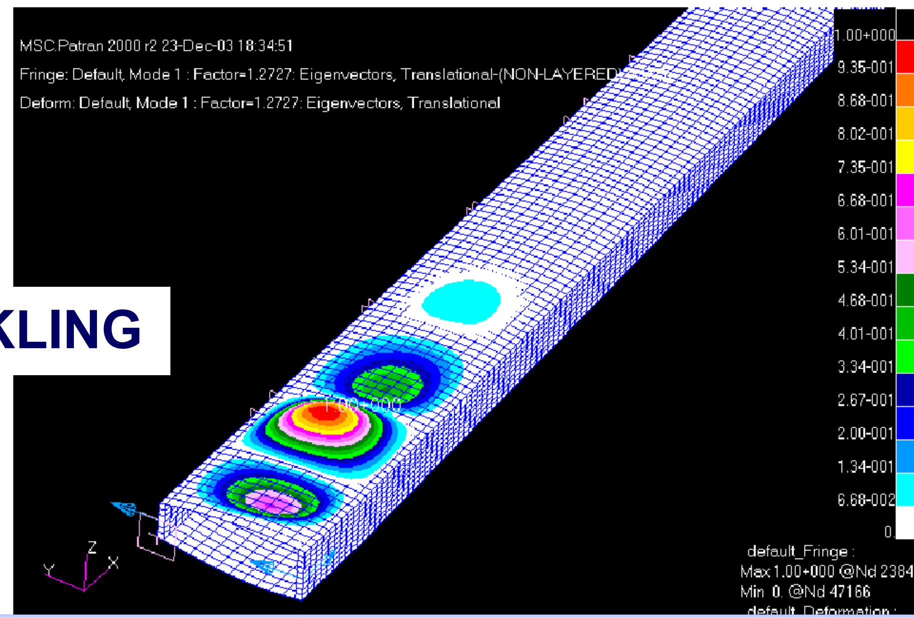
FEM ANALYSIS BY POLITO



DISPLACEMENT RESULTS



WING BOX BUCKLING



Avionics system

MODULAR HALE UAV (IAI)

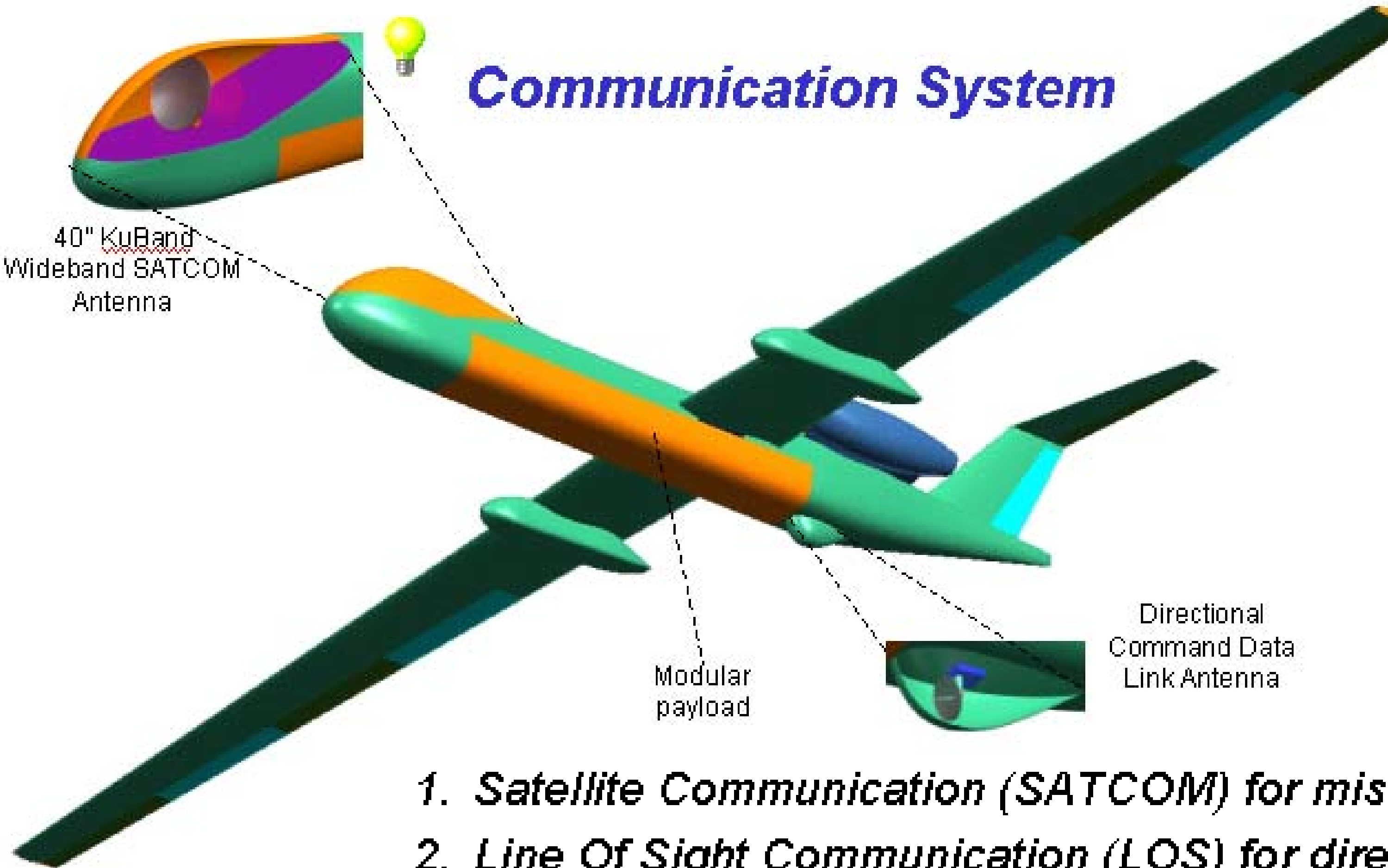
Autonomous Flight

The System Architecture shall enable:

- *Automatic Take Off*
- *Automatic Landing*
- *Autonomous Navigation and Flight Path Execution.*

  (Human Operators became mission level managers and not pilots)
- *Continuous BIT for Failure Detection*
- *Automatic In-Flight Reconfiguration Capability*

Communication system



MODULAR HALE UAV (IAI)

1. *Satellite Communication (SATCOM) for mission and control*
2. *Line Of Sight Communication (LOS) for directional command and control*

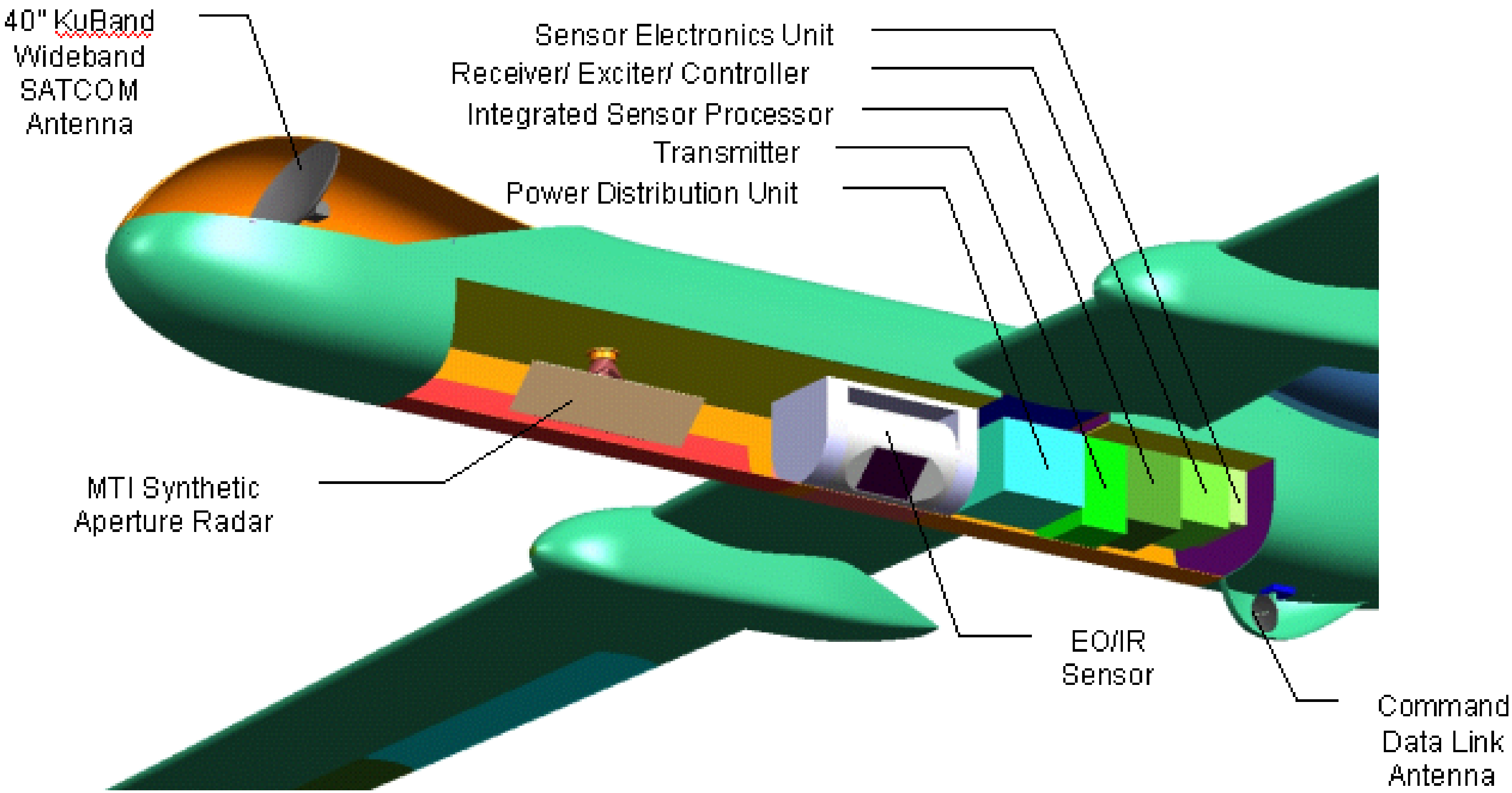
The Antenna's pedestal will be stabilized, in order to continuously track the satellite, while the UAV is moving and maneuvering.

Payload

Typical SAR/MTI with EO/IR

for sensor cross-cueing and multi sensor fusion

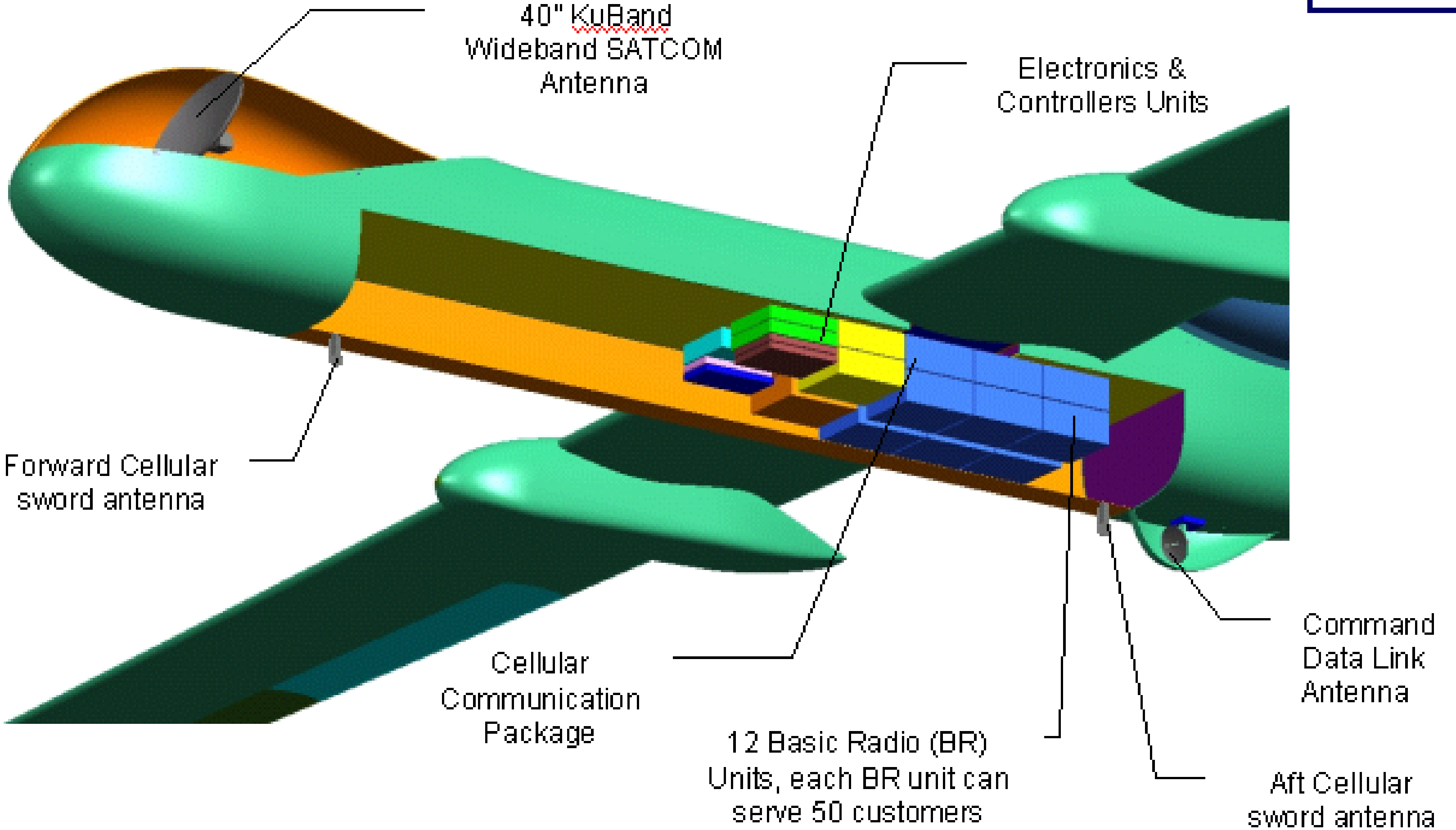
MODULAR HALE UAV (IAI)



of aerial surveying, mapping, border patrol, law enforcement and other missions.

Typical Cellular Communication Payload

MODULAR HALE UAV (IAI)



Conclusion & Recommendations

HALE UAV

- *Light and low cost airframe structure*
    - *Composite materials*
    - *Unitized segments structure*
    - *Low cost/weight processes*
    - *LRI (Liquid Resin Infusion)*

- *The production technologies should be aimed towards cost reduction in one hand and increased performance (reduced weight) on other hand, leading to improved effectiveness.*

Conclusion&recommendations

HALE UAV

- *The aeroelastic issue is important , especially for our configuration*
  - *High aspect ratio*
  - *Target to reduce structure weight in order to increase performance*
- *An iterative design loop is needed, this loop includes;*
  - *Aircraft structure*
  - *Aerodynamic*
  - *Flight control*
  - *Aeroelasticy.*
- *The flight control solution to rigid body is not adequate here, and also if the flutter analyses show that the aircraft is free from dynamic aeroelastic instability within the flight envelope, we still have to design the flight control with interaction to aircraft structure, aerodynamic and aeroelasticy.*

Conclusion & Recommendations

HALE UAV

- ***Aerodynamics***
  - *Clean design*
  - *Advanced laminar wing design*
- ***High altitude turbofan propulsion (modification of the FJ44-3 to high altitude)***
  - *Lower SFC*
  - *Noise reduction*
  - *High reliability*
- ***Using the new/future 3500-pound thrust Williams FJ44-4 engine (modified to high altitude) with a continued infusion of improved technology, will give advantages in flight performance, especially in case of grows in takeoff weight.***

Conclusion&recommendations

HALE UAV

- *Concept of operation that will allow multi mission/multiple payloads operation to reduce operation cost per hour >> more sales.*
- *High reliable and durable systems – fail safe reliability concept, assuming that in case of failure the mission will be aborted (return home) if the next similar (like) failure may caused UAV Loss.*
- *Reducing maintenance requirements through system design*
  - *Selection of reliable and durable components*
  - *Selection of durable and corrosion resistant materials*
- **Maintenance concepts to reduce Mean Time To Repair (MTTR), Man Hours per Operating Hours (MMH/OH), crew, training, support equipment and spares.*

**This reduction in maintenance requirements improves the UAV system Life Cycle Cost (LCC)*