System Impact of additive manufacturing technologies Final Presentation

February, 18th, 2016, ESTEC

16/02/2016

[illegible]AM-TASE-SY-MN-004

83230918-DOC-TAS-EN-001

ThalesAlenia Space

A Thales / Finmeccanica Company

Agenda (1/2)

- Morning:
- 9h00 –9h10 : Introduction (ESA)
- 9h10 – 9h20 : Study current status & milestones (TAS-F)
- 9h20 – 9h40: AM technics and material overview – WP 1100 (TAS-F/SIRRIS)
- 9h40 – 10h00: High level screening of AM design features – WP 1200 (TAS-I)
- 10h00 – 10h20: Impact evaluation methodology and application ranking– WP 2100/3600 (TAS-F)
- 10h20 – 10h40: Application screening on Sentinel 3 satellite – WP 3100 (TAS-F)
- 10h40 – 11 h00: Application screening on Euclid satellite – WP 3200 (TAS-I)
- 11h00 – 12h00 : Structural optimization – Quantitative evaluation on applications and redesign activities -– WP 3400/4200 (RUAG-Switzerland)
- 12h00 – 12h40 : Electronic units & thermal application - Quantitative evaluation on applications and redesign activities – WP 3300/4100 (TAS-B)

Agenda (2/2)

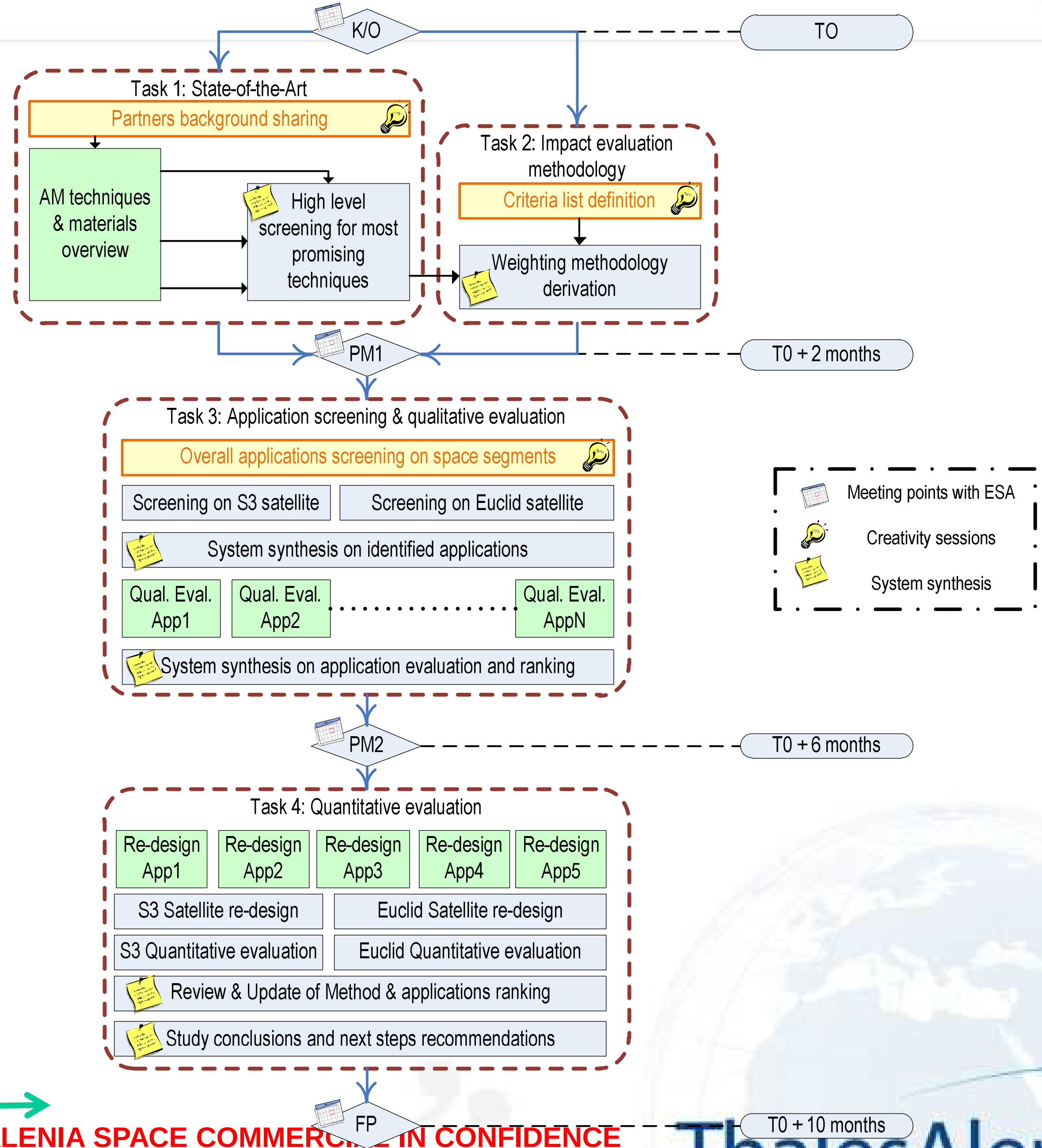
- Afternoon:
- 14h00 – 14h30 : Quantitative evaluation on Sentinel 3 satellite design - WP 4400 (TAS-F)
- 14h30 – 15h00 : Quantitative evaluation on Euclid satellite design - WP 4500 (TAS-I)
- 15h00 – 15h30 : Wrap-up
- 15h00 – 15h40 : Optical payloads application – Quantitative evaluation on applications and Redesign activities -– WP 3500/4300 (TAS-F) –restricted attendance (patent in progress)

- 1. Introduction

- 2. Study current status & milestones

2. Study current status & milestones

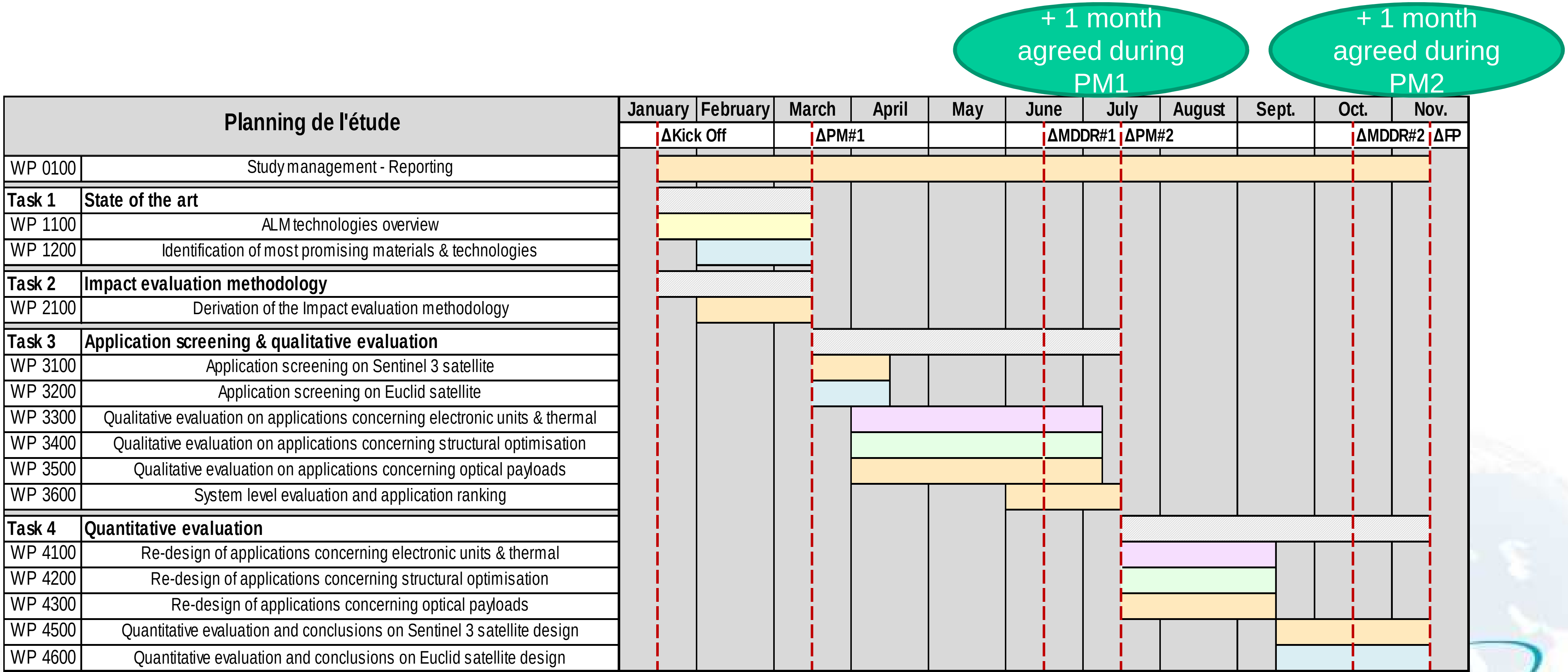
- Task 1 completed
- Task 2 completed
- Task 3 completed
- Task 4 completed
  - Satellite re-design



Final Presentation

2. Study current status & milestones (2)

- Task 4 to FP : Quantitative evaluation and conclusions in Sentinel 3 and Euclid re-design



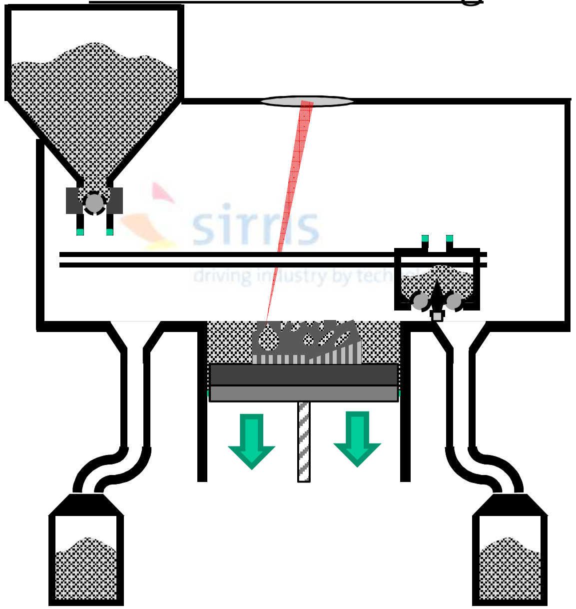
- 3. AM technics and material overview - WP 1100 (TAS-F/SIRRIS)

3.1 TN1 synthesis – AM technologies design features

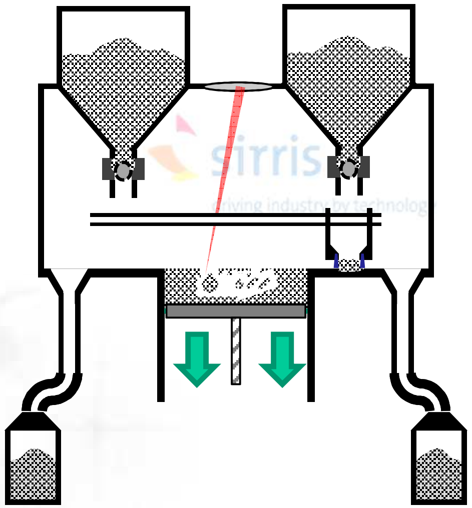
- Materials to investigate :
  - Aluminium, Titanium, Stainless steel, Inconel, composites, PEEK, Al_2O_3
- Technologies : LBM, DED
- Design features and current capabilities
- Advantages and disadvantages
- In-process inspection, post processing, defect reduction
- Modelling and assessing functional properties techniques

Technologies principle overview

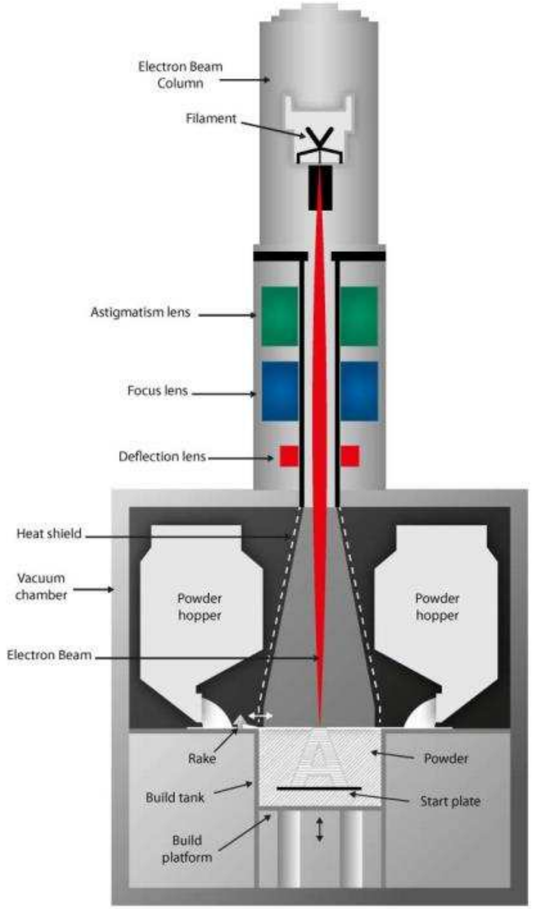
Laser Beam Melting



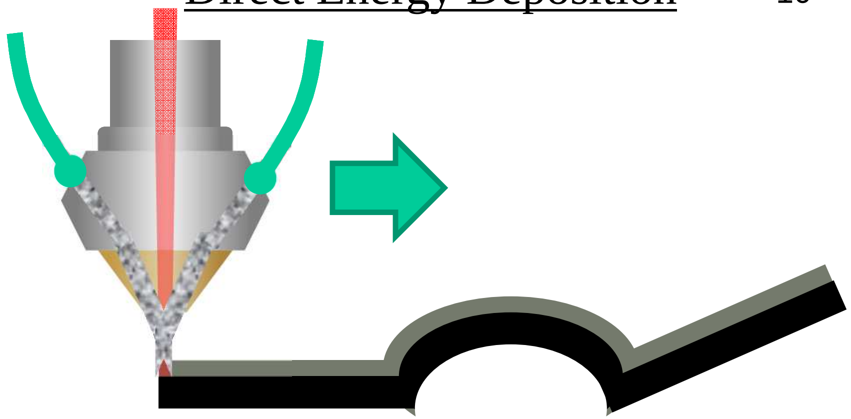
Selective Laser Sintering



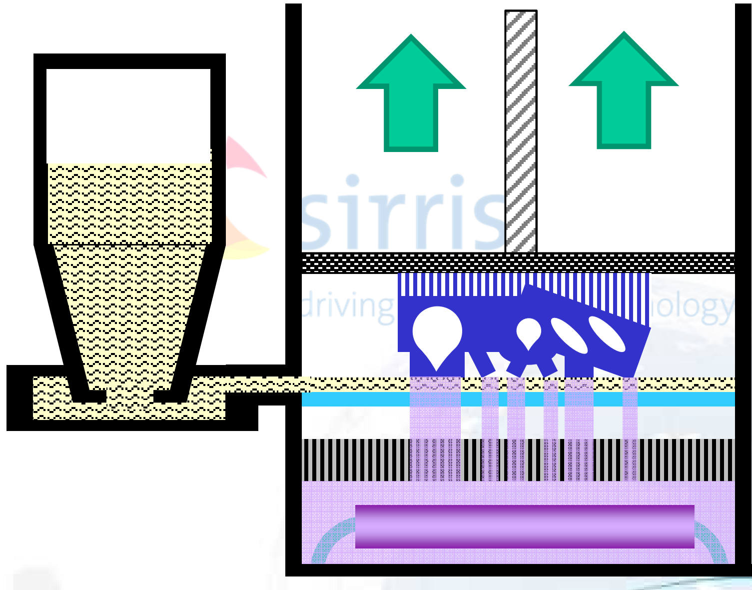
Electron Beam Melting



Direct Energy Deposition



Vat Polymerization



Technologies overview (! indicative values !)

Features	LBM	EBM	DED	SLS	Vat Polym.
Means	IR Laser	EB	IR Laser	IR Laser	UV Laser
Configuration	Powder bed	Powder bed	Powder nozzle	Powder bed	Resin bed
Environment	Ar, 200°C	Vacuum, 700°C	Air/Ar	Air/N_2	Air
Build envelop	640x400x500	Ø350x380	n.a.	550x550x750	(2100x700x800)
Layer thick.	30 – 60 µm	50 – 70 µm	0,X – X mm	80 – 150 µm	20 – 150 µm
Wall thick.	0,3 mm	0,8 mm	0,X – X mm	1 mm	0,2 mm
Accuracy	0,1% -> 0,1 mm	0,3% -> 0,3 mm	0,X% -> 0,X mm	0,3% -> 0,3 mm	0,2% -> 0,1 mm
Supply	Single compo	Single comp	Multi comp	Single comp	Single comp
Supports	plenty	few	no	no	plenty
Ra	5 – 15 µm	10 – 20 µm	n.a.	10 – 15 µm	5 – 15 µm
Speed	+	++	-	++	+
Materials	Metals, (ceramics)	Metals	Metals + ceramics	Polymers (+ “fibers”)	Resins (+ powder)

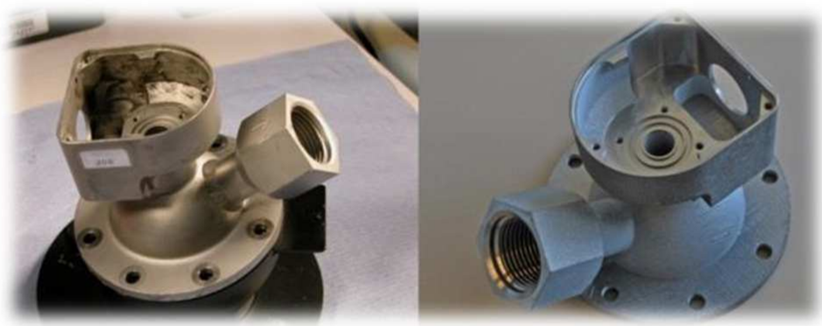
Materials and illustration by applications

Titanium

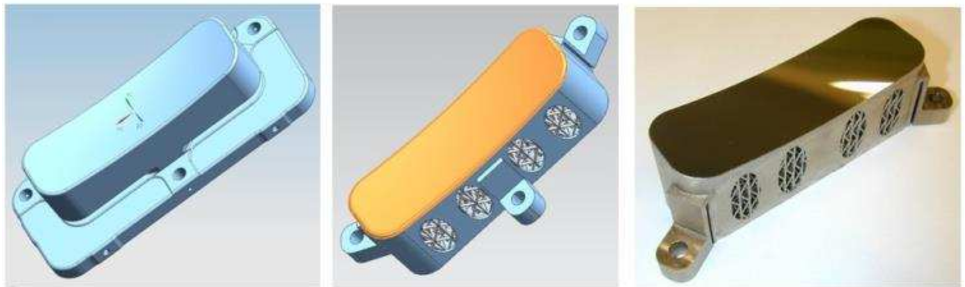
Commercial launcher Electron (2016)
Main components made by EBM
(Combustion chamber, pumps, valves,…)

http://www.rocketlabusa.com/

Water on-off valve (Woov) flown aboard ESA's Columbus module attached to ISS – 40% weight reduction



http://phys.org/news/2014-06-3d.html



Original design	New design	Selective laser melting
Mass: 284.6 g	Mass: 129.7 g	Mass: 127.7 g
Material: Al 6061		Material: Ti6Al4V
1st eigen freq ~2100 Hz		1st eigen freq ~2100 Hz
NiP coating		NiP coating

http://www.esa.int/Our_Activities/Space_Engineering_Technology/Mirror_mirror_testing_3D_printing_for_space

A320 hinge bracket

http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study

ThalesAlenia Space
A Thales / Finmeccanica Company

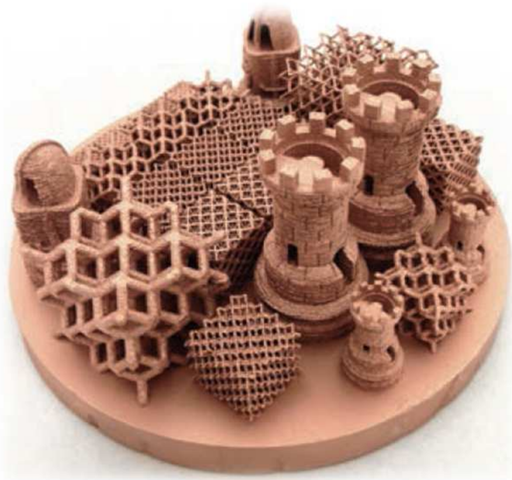
Copper

Copper made by FDM
15% Polymer + 85% Copper
Post sintering

Rocket engine part @ Nasa.
11 hours manufacturing

http://www.nasa.gov/marshall/news/nasa-3-D-prints-first-full-scale-copper-rocket-engine-part.html

http://www.thevirtualfoundry.com/3d-printing



http://www.3trpd.co.uk/3t-success-with-pure-copper-am-production/

http://www.asminternational.org/documents/10192/19735983/amp17207p20.pdf/2a87d5ae-86ec-4f27-bdd1-f74af1a2f523

Ni based

Rocket injectors of NiCr by LBM

http://www.nasa.gov/exploration/systems/sls/3d-printed-rocket-injector.html

http://www.nasa.gov/centers/marshall/images/content/757405main_Machined_DMLS_injector_1296x968.jpg

Demo part in IN 625 @ Efesto-RPM
2108x500x500 – 330 h

http://www.efesto.us

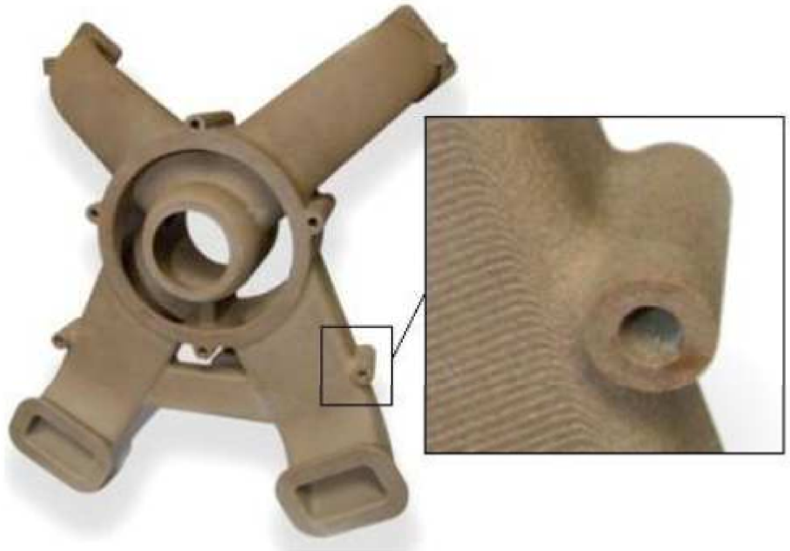
Rocket engine @ GPI Prototype
Made of IN 718, 750 lbs of trust

http://gpiprototype.com/blog/gpi-prototype-builds-3d-printed-inconel-718-rocket-engine-for-seds-ucsd

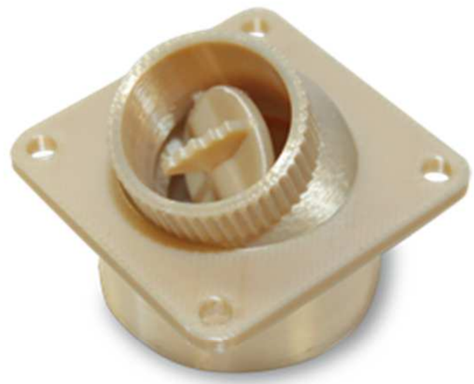
Materials and illustration by applications

PEEK

Made by FDM
Nozzle @ 420°C



The P 800 system is shown above. An air duct manufactured out of PEEK HP 3.
Photos courtesy, EOS GmbH.

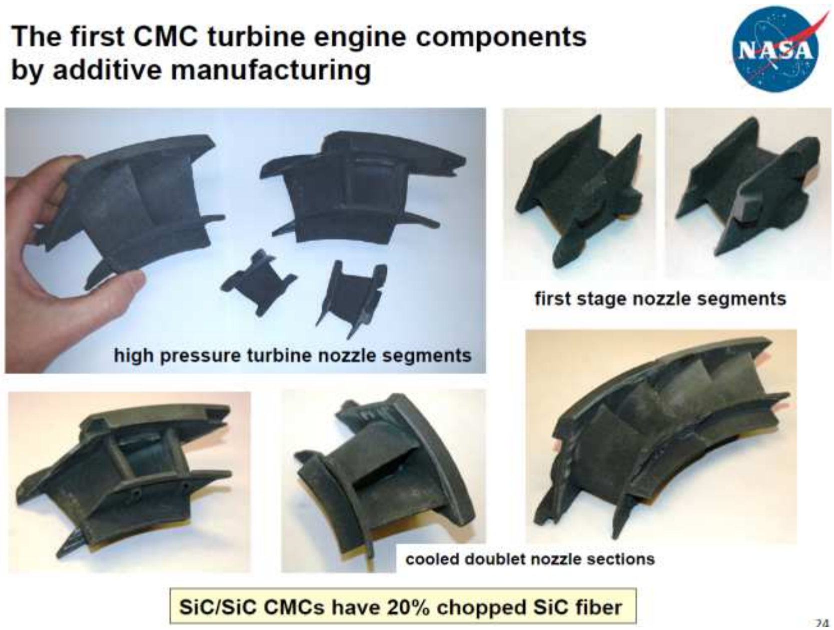


http://www.stratasys.com/materials/fdm/ultem-9085

http://www.indmatec.com/en/home-2

http://www.designfax.net/cms/dfx/opens/article-view-dfx.php?nid=4&bid=161&et=featurearticle&pn=02

Ceramics

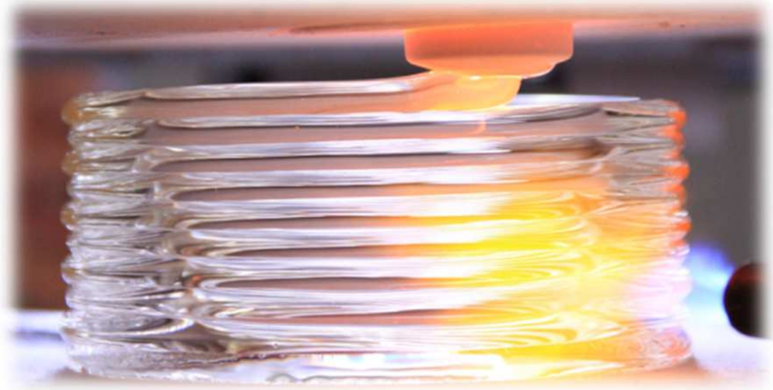


http://nari.arc.nasa.gov/sites/default/files/GradySeedling.pdf

HA/TCP by Stereolithography (Kasios)

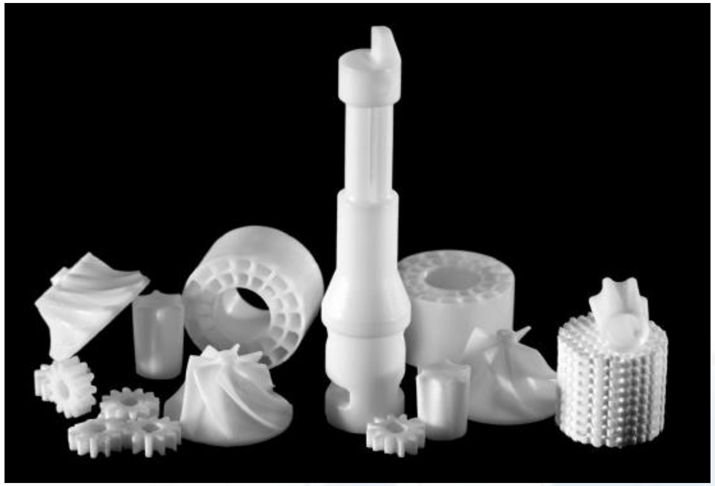
http://www.kasios.com/doc-pdf/CervicalRSF-FrGb.pdf

Glass at MIT



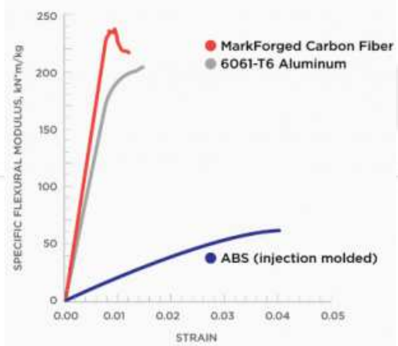
Alumina by LBM at CRIBC

Alumina by Stereolithography (Lithoz)



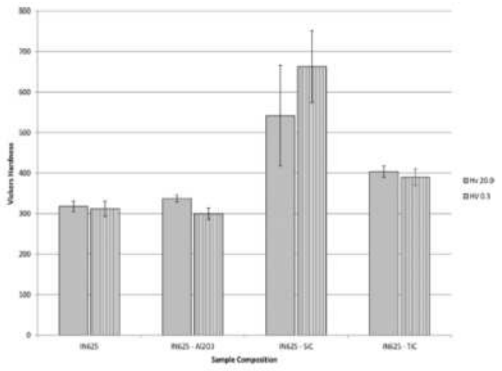
Materials and illustration by applications

Composites :



FDM with Carbon, glass or Kevlar fibers @ Markforged

https://markforged.com/applications/



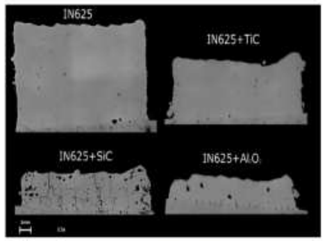
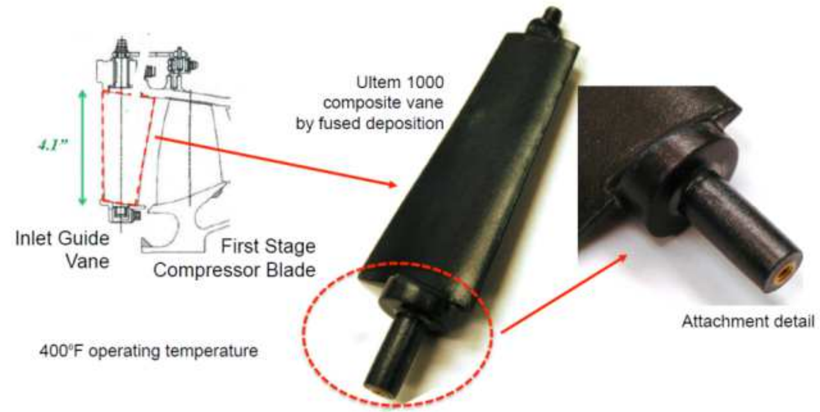


Fig. 5. Optical microscope montages of sample sections, at 2.5× magnification.

Cooper, D., Blundell, N., Maggs, S., & Gibbons, G. (2013). Additive layer manufacture of Inconel 625 metal matrix composites, reinforcement material evaluation. *Journal of Materials Processing Technology 213*, 2191-2200.

Fabricated Compressor Inlet Guide Vanes with High Temperature Polymer Matrix Composites



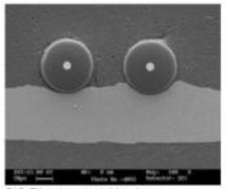
- Ultem 1000 (T_g = 423°F) with chopped carbon fiber
- First Polyetherimide composite fabricated

http://nari.arc.nasa.gov/sites/default/files/GradySeedling.pdf

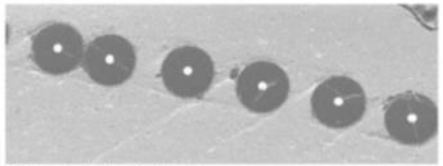
Alloys couples tested @ Fabrisonic

	Al	Be	Cu	Ge	Au	Fe	Mg	Mo	Ni	Pd	Pt	Si	Ag	Ta	Sn	Ti	W	Zr
Al Alloys	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Be Alloys		●	●			●										●		
Cu Alloys			●		●	●	●	●	●	●	●		●	●		●	●	●
Ge					●						●							
Au					●	●			●	●	●	●	●			●	●	●
Fe Alloys						●			●	●	●		●	●		●	●	●
Mg Alloys							●						●			●		
Mo Alloys								●	●		●			●		●	●	●
Ni Alloys									●	●	●			●		●	●	
Pd										●			●	●				
Pt Alloys											●	●		●		●	●	
Si													●	●				
Ag Alloys													●	●				●
Ta Alloys														●		●	●	
Sn															●			
Ti Alloys																●	●	
W Alloys																	●	
Zr Alloys																		●

● Material pair proven for ultrasonic welding



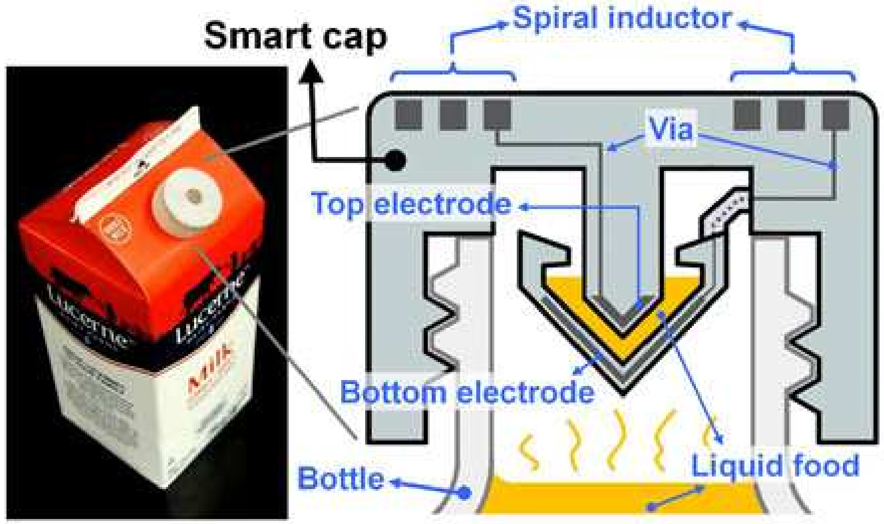
SiC Fibers in metal laminate



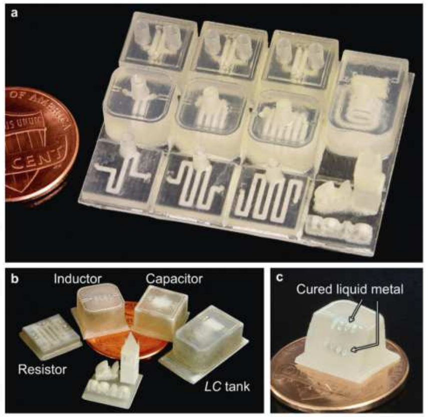
SiC fibers in aluminum laminate

Materials and illustration by applications

Electronics

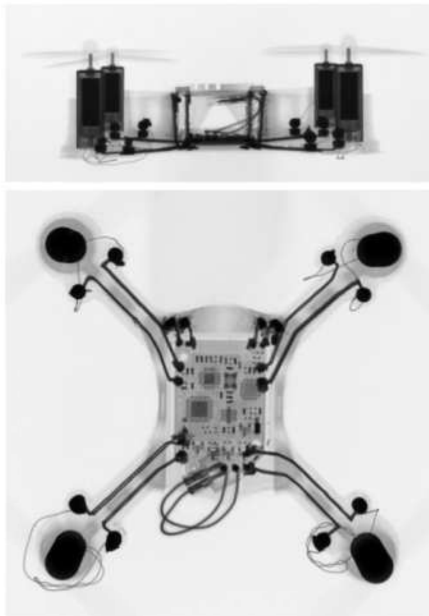


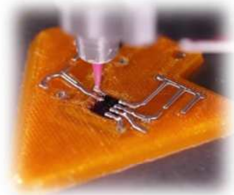
http://www.kurzweilai.net/3d-printing-basic-electronic-components

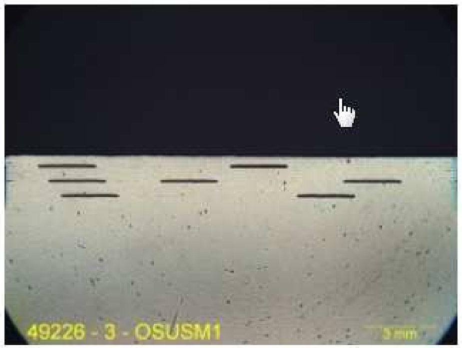


9000 € http://www.voxel8.co/printer/

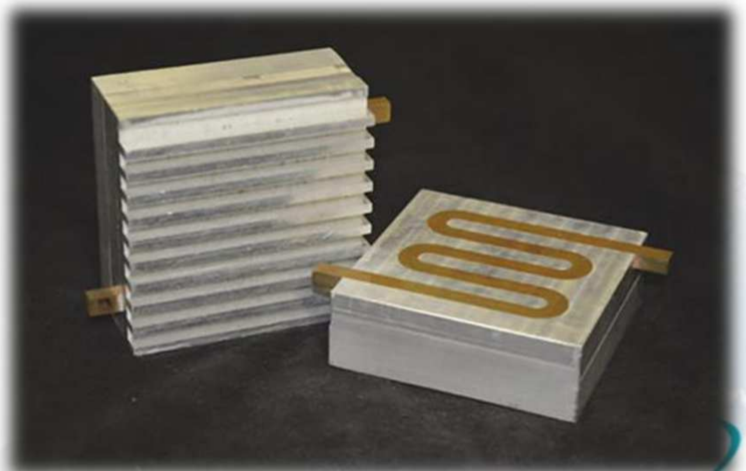
Printing	
Printing Technology	FFF, Pneumatic Direct Write
Build Volume	4" x 6" x 4" (10 cm X 15 cm x 10 cm)
Layer Resolution	200 microns
Filament Size	1.75mm
Pause / Resume Prints	Yes
Build Plate	Kinematically Coupled
Conductive Trace Width	250 microns
Software	
Hosted	Cloud
Supported Files	STL, PLY, OBJ, OFF, AMF
Connectivity	USB, WiFi
Supported Browsers	Chrome, Firefox
Materials	
Materials	PLA, Conductive Silver Ink
Resistivity	5.00×10^{-7} Ω-m
Silver Ink Cure Time	5 minutes





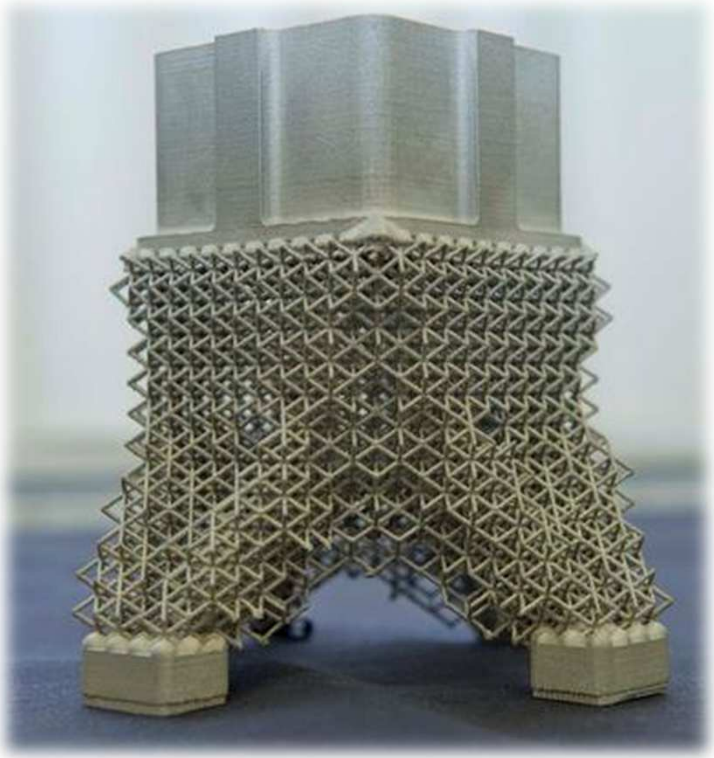


(PVDF) a polymer with piezoelectric properties, embedded in aluminum



http://fabrisonic.com/dissimilar-metals/

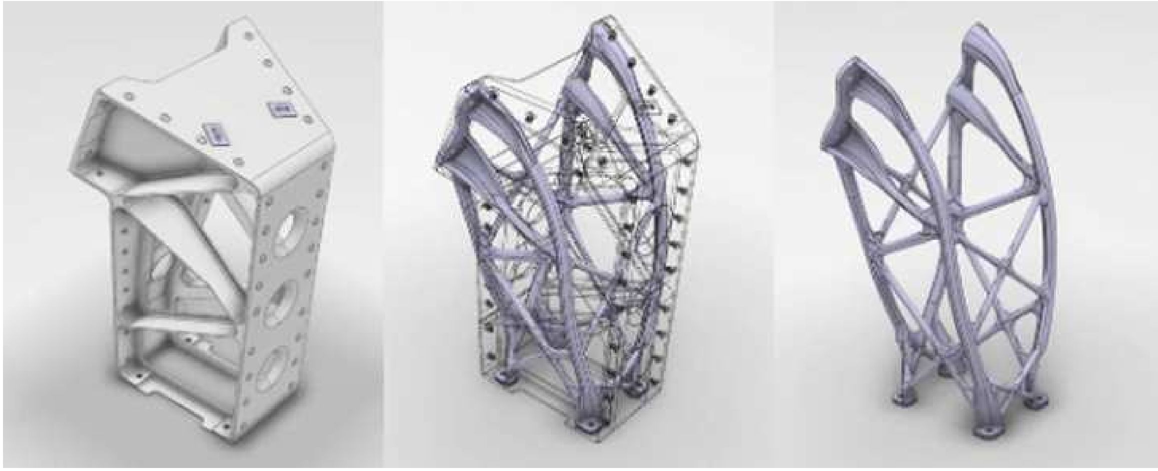
Space



http://www.esa.int/spaceinimages/Images/2014/11/One-piece_3D-printed

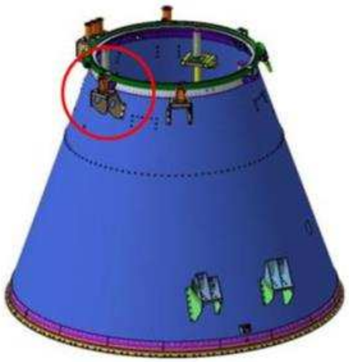
Bracket for satellite. Mass reduction
222 -> 164 g

https://airbusdefenceandspace.com/newsroom/news-and-features/airbus-defence-and-space-optimising-components-using-3d-printing-for-new-eurostar-e3000-satellite-platforms/



4 parts of aluminum
44 rivets.

1 part, 40% stiffer, 35% lighter
Qualified for space flight on E300



Adaptateur Charge Utile (ACU) of Space Launcher

Connector Support (original)
0.453kg
Assembled from 4 parts

Integrated solution	Topology Optimized	Topology Opt. II
0.385kg	**0.197kg**	**0.168kg**
- 15% weight	- 56% weight	- 63% weight
1 part	1 part	1 part (bionic design)

http://www.esa.int/spaceinimages/Images/2014/10/AM-produced_launcher_payload_connector

Materials and illustration by applications

Space – ESD PEKK from Stratasys

Figure 8 - Comparison of ABS-ESD7 and ULTEM 9085 resin to ESD PEKK in the on-edge build direction.

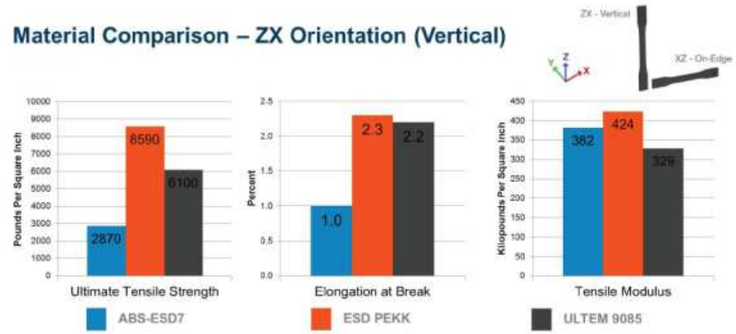


Figure 9 - Comparison between ABS-ESD7, ESD PEKK, and ULTEM 9085 resin mechanical properties in the vertical build direction.

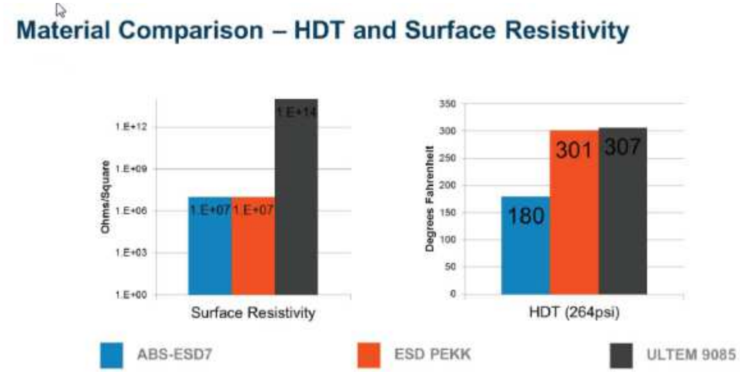
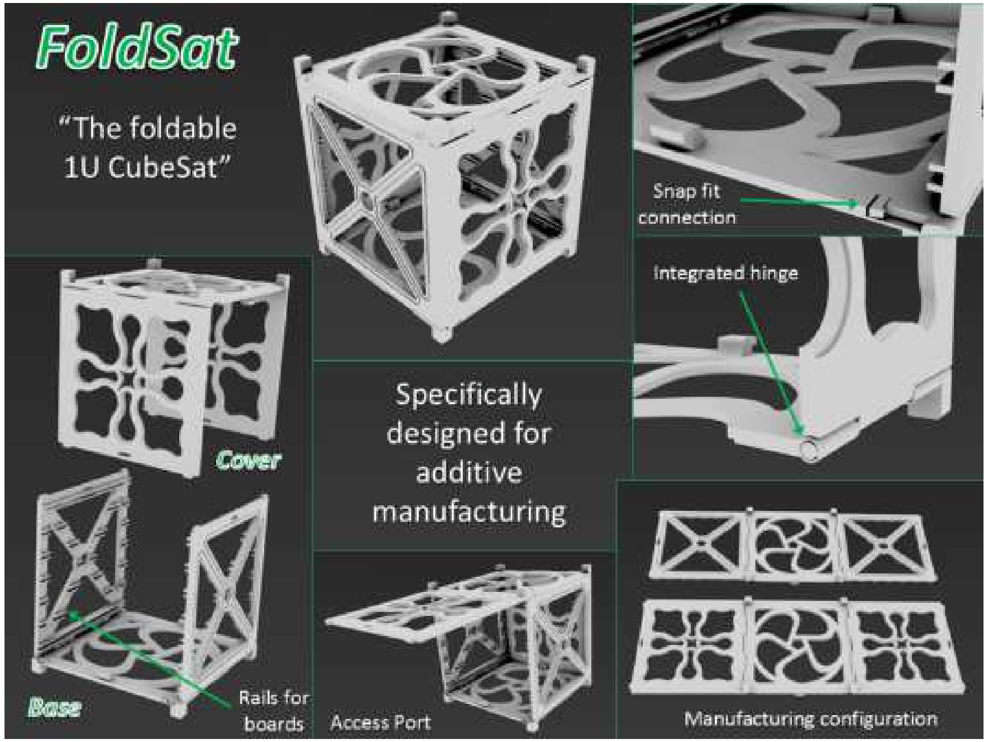


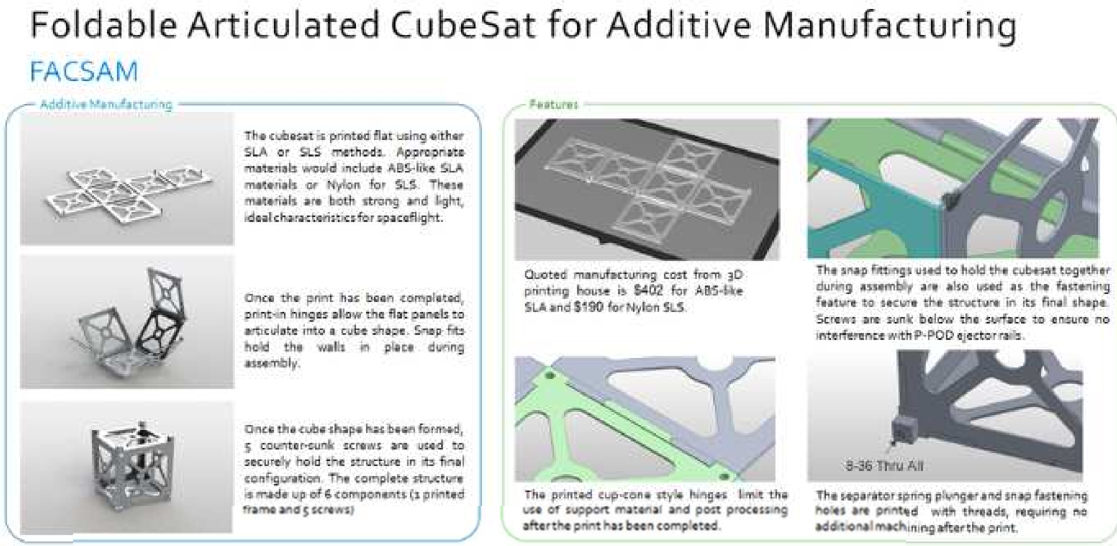
Figure 10 - Surface resistivity and heat deflection temperature comparisons between ABS-ESD7, ESD PEKK, and ULTEM 9085 resin.

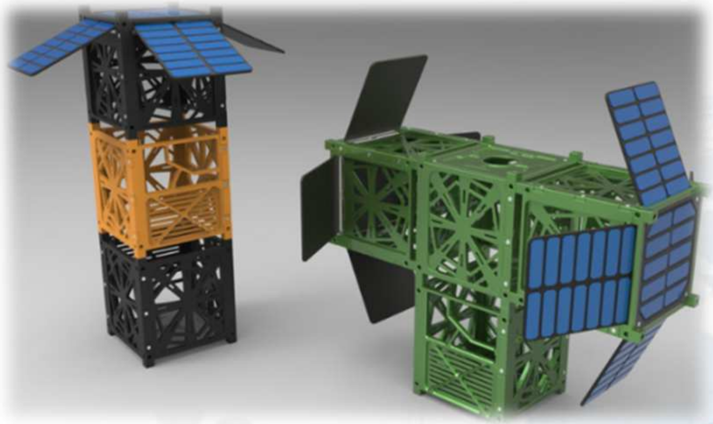
Electro-dissipative material

Materials and illustration by applications

Satellite AM design by “common” people



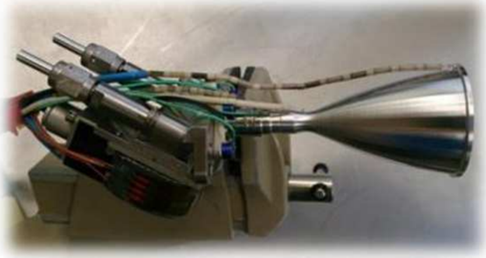




https://grabcad.com/challenges/the-cubesat-challenge/results

Other

Combustion chamber @ ESA
Platinum-Rhodium
1253°C – 32 min



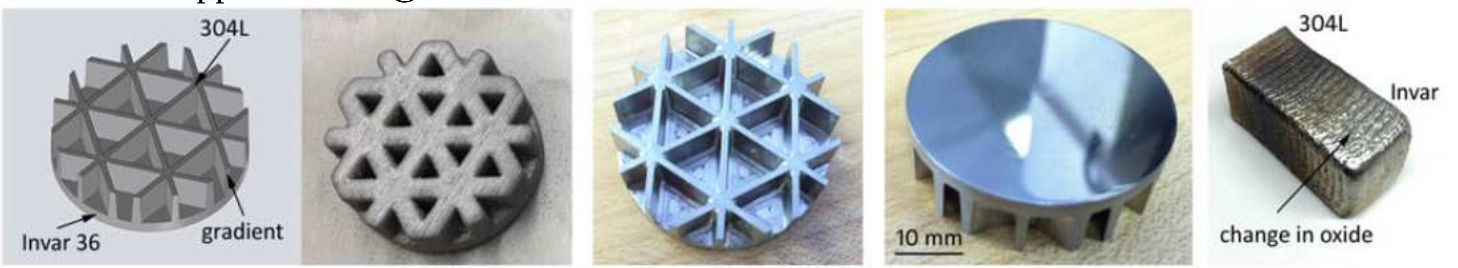
http://www.esa.int/Our_Activities/Space_Engineering_Technology/Hot_firing_of_world_s_first_3D-printed_platinum_thruster_chamber

CoCr fuel nozzle @ GE Aviation
20 parts combined in one design
Lifetime x 5, 25% weight reduction
100.000 parts in 2020

CoCr high pressure turbine blade @ GE Aviation

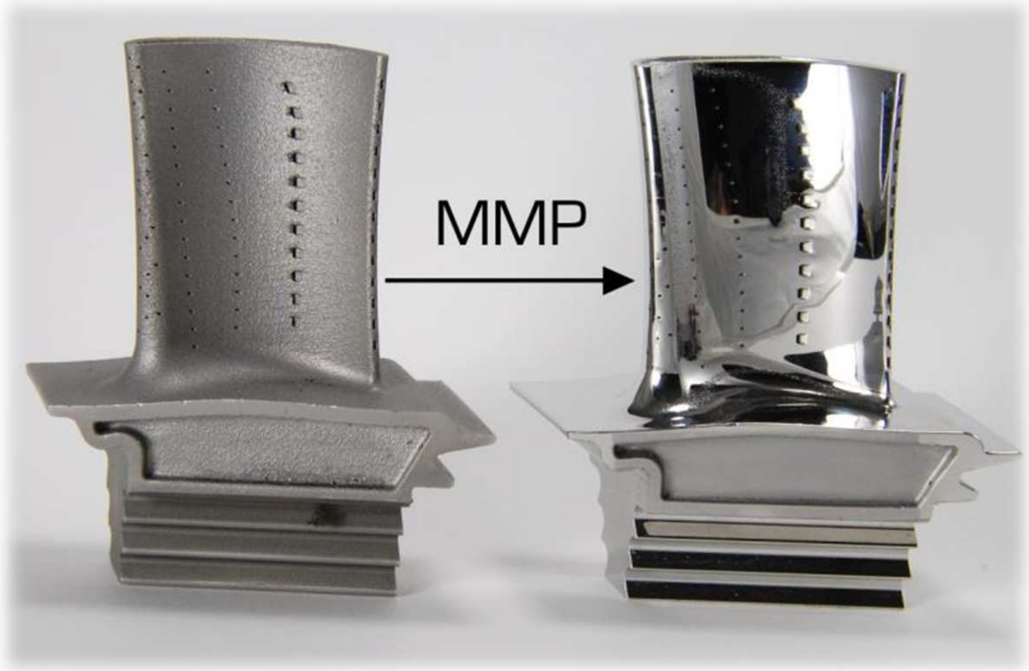
http://www.gereports.com/post/74545249161/blades-and-bones-the-many-faces-of-3d-printing

Invar for support mirror @ Nasa



http://www.nature.com/srep/2014/140619/srep05357/full/srep05357.html

AM Post process



http://www.microtekfinishing.com/microtek_aerospace.php

http://extrudehoneafm.com/additive-mfg/3216507

Mechanical properties of the SLM material after different heat treatments. WQ = water quenching. AC = air cooling. FC = furnace cooling. Treatment six to eight are well known titanium heat treatments [30]. Samples for treatment three were built in a different batch in which building errors are present, which led to premature failure of the components.

Nr.	T (°C)	t (h)	Cooling rate	E (GPa)	σ_y (MPa)	UTS (MPa)	$\varepsilon_{fracture}$ (%)
1	540	5	WQ	112.6 ± 30.2	1118 ± 39	1223 ± 52	5.36 ± 2.02
2	850	2	FC	114.7 ± 3.6	955 ± 6	1004 ± 6	12.84 ± 1.36
3	850	5	FC	112.0 ± 3.4	909 ± 24	965 ± 20	– (premature failure)
4	1015 followed by 843	0.5 2	AC FC	114.9 ± 1.5	801 ± 20	874 ± 23	13.45 ± 1.18
5	1020	2	FC	114.7 ± 0.9	760 ± 19	840 ± 27	14.06 ± 2.53
6	705	3	AC	114.6 ± 2.2	1026 ± 35	1082 ± 34	9.04 ± 2.03
7	940 followed by 650	1 2	AC AC	115.5 ± 2.4	899 ± 27	948 ± 27	13.59 ± 0.32
8	1015 followed by 730	0.5 2	AC AC	112.8 ± 2.9	822 ± 25	902 ± 19	12.74 ± 0.56

AM defect reduction

Murr, L. (2015). Metallurgy of additive manufacturing : Examples from electron beam melting. *Additive Manufacturing xxx*, xxx.e1-xxx.e14.

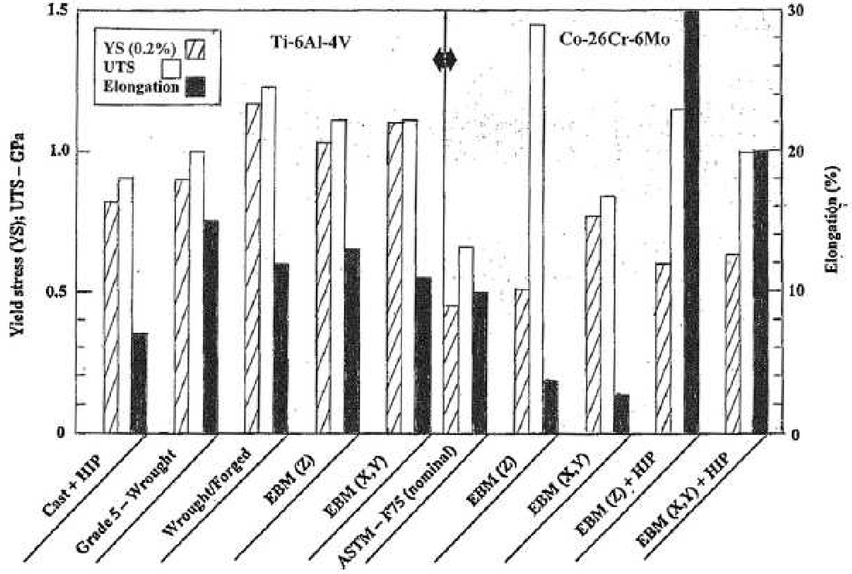
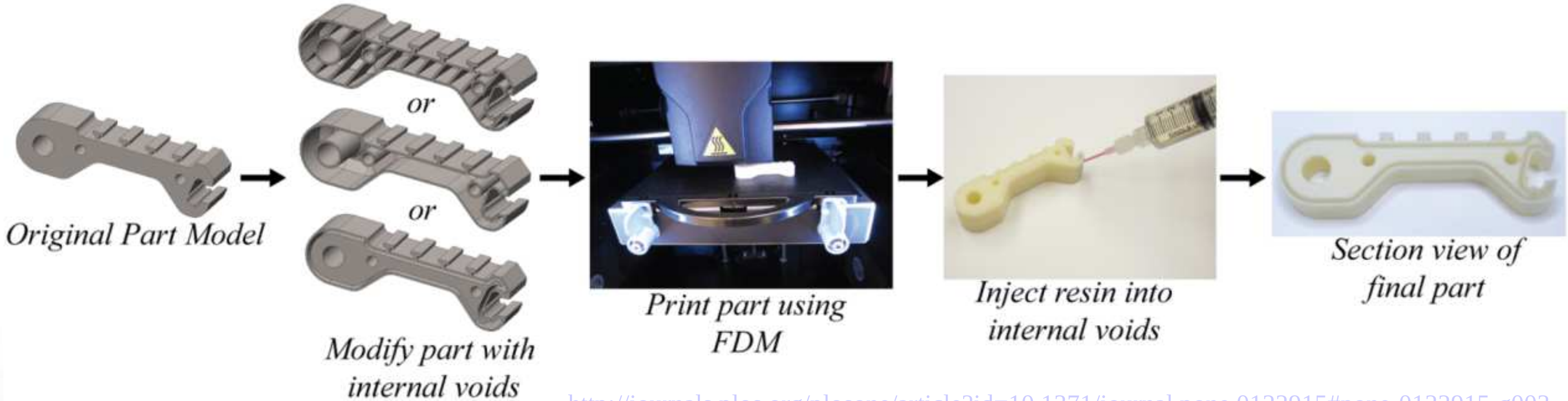
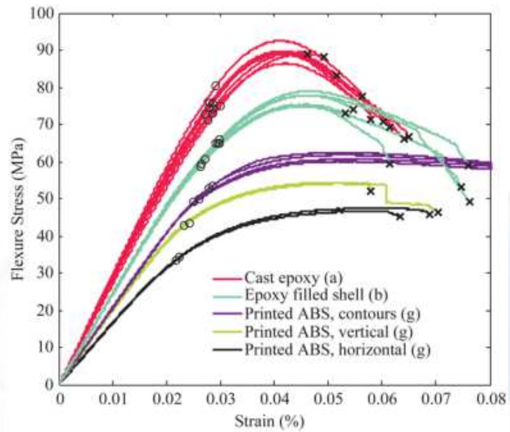


Fig. 15. Comparison of mechanical properties for commercial and EBM-fabricated and treated Ti-6Al-4V (left) and Co-Cr-Mo (Co-base superalloy). Commercial Co-Cr-Mo products are denoted by ASTM-F75 standard.





http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0122915#pone-0122915-g003

AM in-process control - LBM

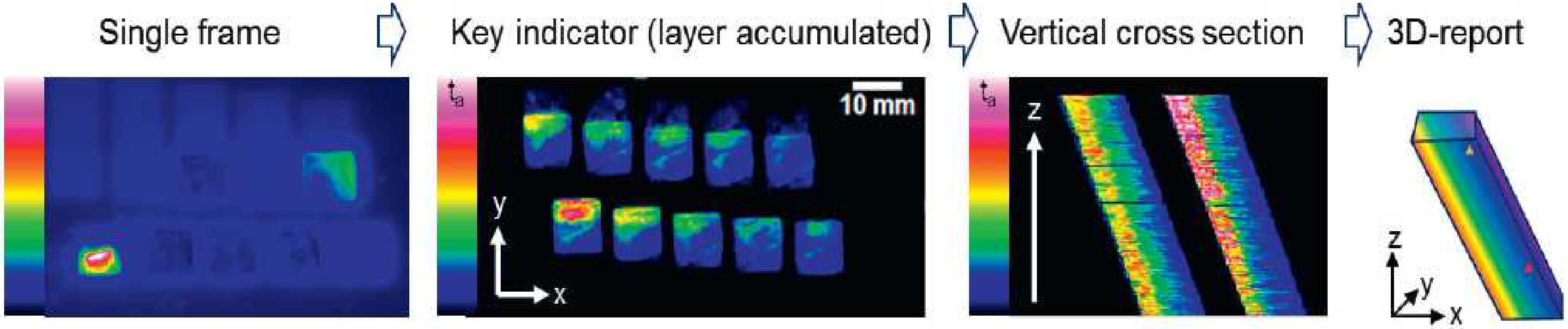


Fig. 2. Data processing to generate a visual quality report.

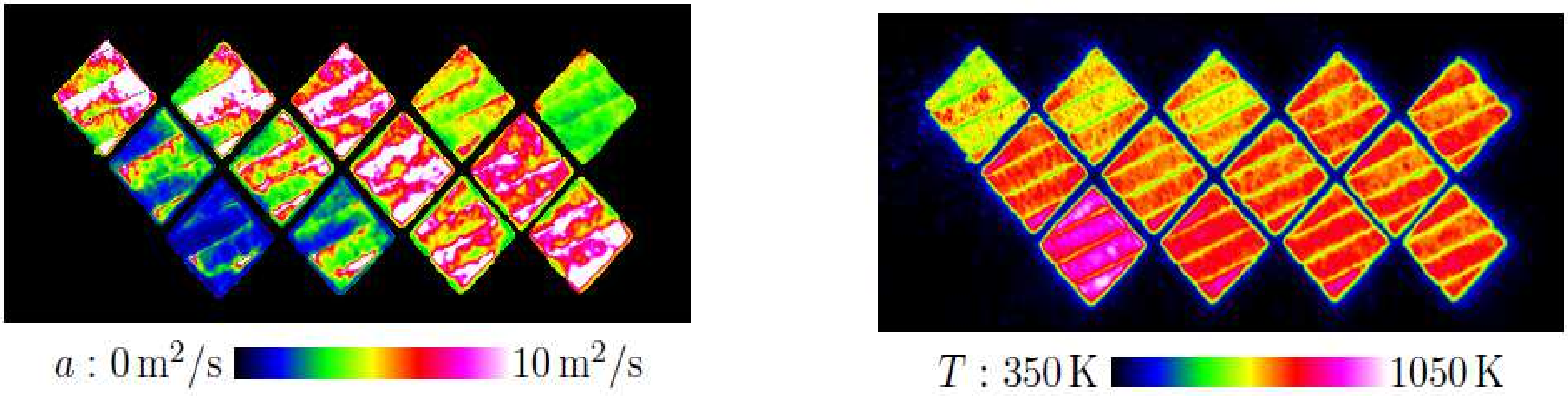
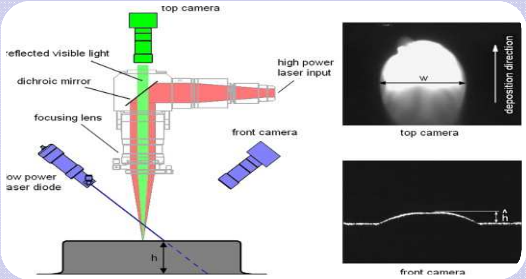
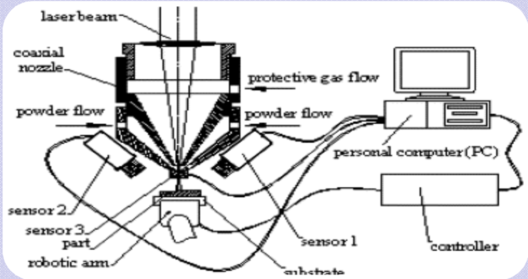


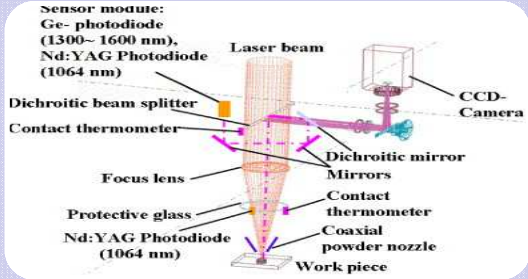
Fig. 4. Mapped key indicators for build height 3.6 mm: thermal diffusivity (left) and maximum measured temperature (right)

Krauss, H., Zeugner, T., & Zaeh, M. (2014). Layerwise Monitoring of the Selective Laser Melting Process by Thermography. *Physics Procedia*, 64-71.

AM in-process control - DED







Meltpool size control :

A camera films continuously the meltpool, coaxially with the laser. If the size increases, the power have to decrease and vice versa

Distance between deposit and nozzle :

An in-line scanning of the deposit is used to correct the distance deposit/nozzle

Temperature monitoring:

An IR pyrometer measures the temperature during process to correct laser power.

Optics and Lasers in Engineering
Volume 48, Issue 4, April 2010, Pages 478–485

Increased stability in laser metal wire deposition through feedback from optical measurements
Almir Heralić, Anna-Karin Christiansson, Mattias Ottosson, Bengt Lennartson

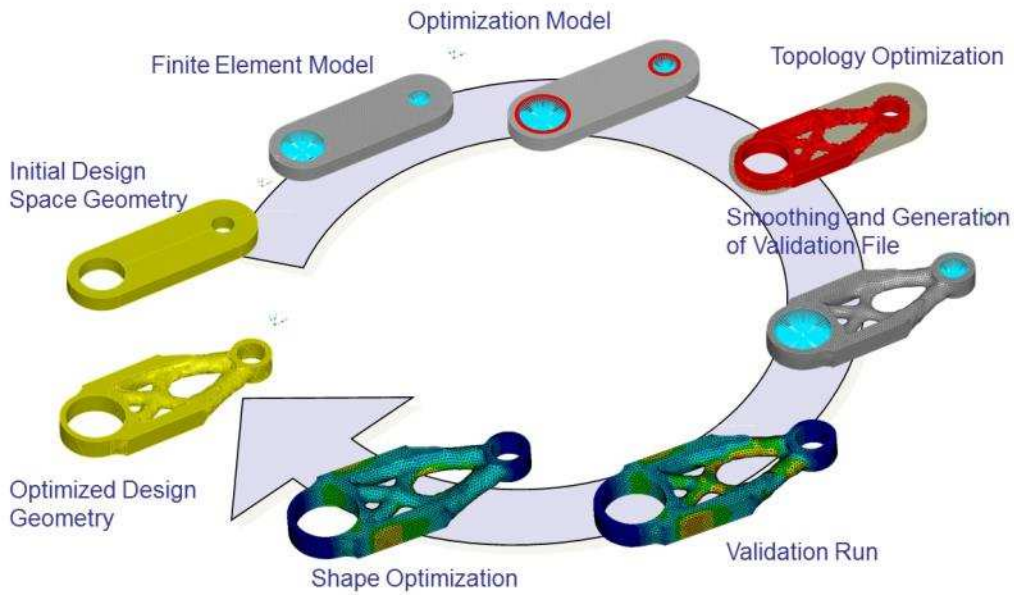
Optics & Laser Technology
Volume 36, Issue 6, September 2004, Pages 477–483

In-time motion adjustment in laser cladding manufacturing process for improving dimensional accuracy and surface finish of the formed part
Jichang Liu, Lijun Li

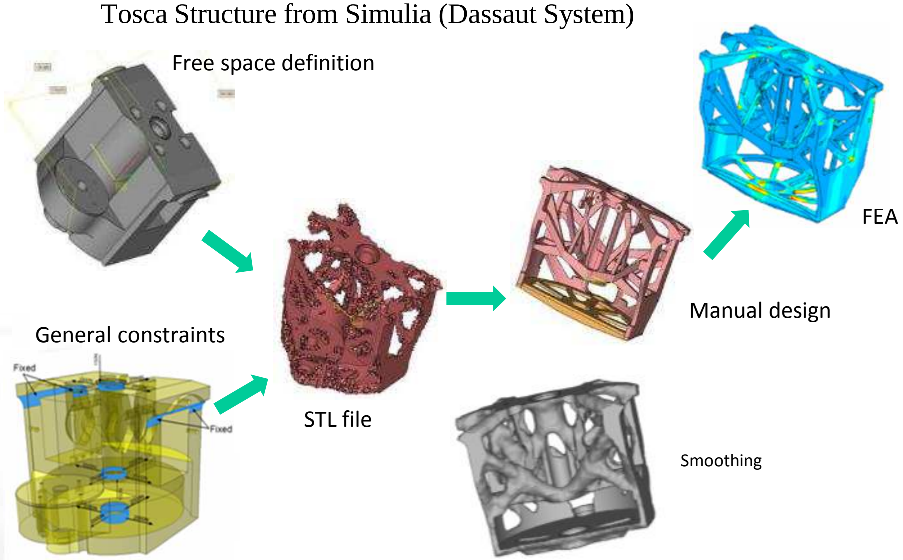
Available online at www.sciencedirect.com
SCIENCE DIRECT
Thin Solid Films 453–454 (2004) 477–485
thin solid films
www.elsevier.com/locate/tsf

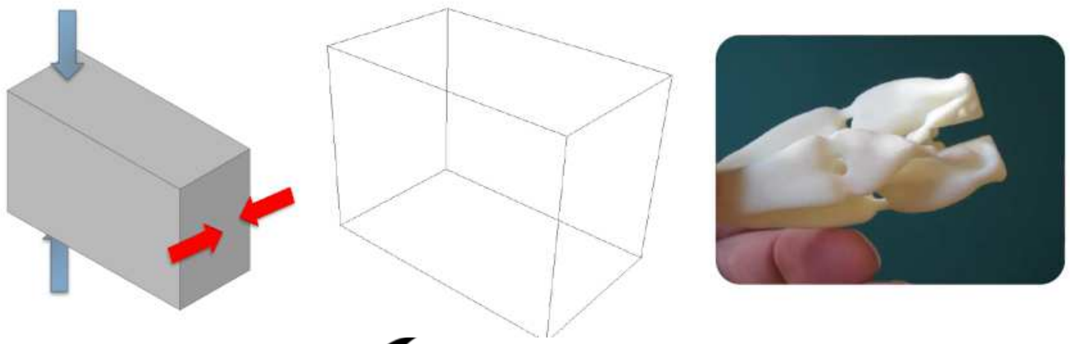
Optical monitoring of Nd:YAG laser cladding
M. Doubenskaia, Ph. Bertrand, I. Smurov*
Ecole Nationale d'Ingénieurs de Saint Etienne, 58 rue Jean Parot, 42023 Saint-Etienne Cedex 2, France

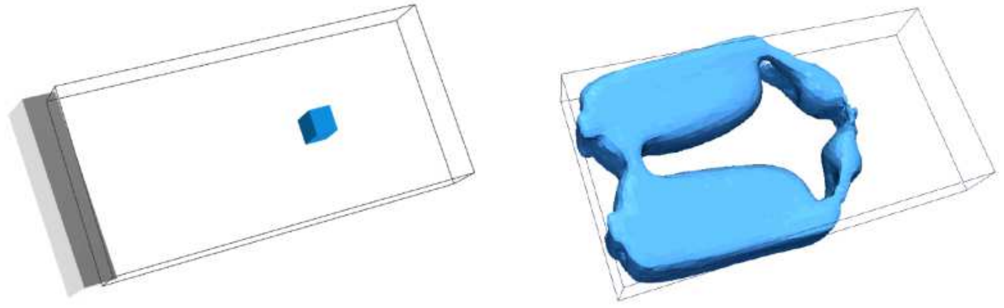
AM Modeling



Tosca Structure from Simulia (Dassault System)







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Ref.:

Get Involved / Technical Committees / Committee F42 / List of Subcommittees and Standards

Committee F42 on Additive Manufacturing Technologies

Staff Manager: Pat Picariello 610-832-9720

Subcommittees and Standards

Standards under the jurisdiction of F42

Each main committee in ASTM International is composed of subcommittees that address specific segments within the general subject area covered by the technical committee. Click on the subcommittee links below to see the title of existing standards for each subcommittee. Then, click on the resulting titles to see the standard's scope, referenced documents, and more.

F42.01 Test Methods
F42.04 Design
F42.05 Materials and Processes
F42.90 Executive
F42.91 Terminology
F42.94 Strategic Planning
F42.95 US TAG to ISO TC 261

http://www.astm.org/COMMIT/SUBCOMMIT/F42.htm

Subcommittee F42.01 on Test Methods

Showing results 1-3 of 3 matching ACTIVE standards under the jurisdiction of F42.01 **F42 Home**

F2971-13 Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing

F3122-14 Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes

ISO/ASTM52921-13 Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies

Showing results 1-4 of 4 matching Proposed New Standards under the jurisdiction of F42.01 **F42 Home**

WK49798 New Guide for Intentionally Seeding Flaws in Additively Manufactured (AM) Parts

WK49229 New Guide for Anisotropy Effects in Mechanical Properties of AM Parts

WK49230 New Guide for Conducting Round Robin Studies for Additive Manufacturing

WK49272 New Test Methods for Characterization of Powder Flow Properties for AM Applications

http://www.iso.org/iso/fr/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=629086

Normes et projets sous la responsabilité directe du ISO/TC 261 Secrétariat

Norme et/ou projet	Stade	ICS
ISO 17296-2:2015 Fabrication additive -- Principes généraux -- Partie 2: Vue d'ensemble des catégories de procédés et des matières premières	60.60	25.040.20
ISO 17296-3:2014 Fabrication additive -- Principes généraux -- Partie 3: Principales caractéristiques et méthodes d'essai correspondantes	60.60	25.040.20
ISO 17296-4:2014 Fabrication additive -- Principes généraux -- Partie 4: Vue d'ensemble des échanges de données	60.60	25.040.20
ISO/ASTM 52900:2015 Fabrication additive -- Principes généraux -- Terminologie	60.60	01.040.25 25.040.20
ISO/ASTM DIS 52901 Fabrication additive -- Principes généraux -- Exigences pour l¿achat de pièces en fabrication additive	40.60	25.040.20
ISO/ASTM NP 52902 Fabrication additive - Principes généraux - Artefacts d'essais	10.99	
ISO/ASTM DIS 52903-1 Fabrication additive -- Spécification normalisée pour la fabrication additive de matériaux plastiques à base d'extrusion -- Partie 1: Matières premières	40.20	25.040.20
ISO/ASTM CD 52903-2 Titre manque	30.99	25.040.20
ISO/ASTM DIS 52910 Pratique normalisée -- Guide de conception en fabrication additive	40.99	25.040.20
ISO/ASTM 52915:2016 Spécification normalisée pour le format de fichier pour la fabrication additive (AMF) Version 1.2	60.60	35.240.50 25.040.20
ISO/ASTM 52921:2013 Terminologie normalisée pour la fabrication additive -- Systèmes de coordonnées et méthodes d'essai	60.60	25.040.20

- 4. High level screening of AM design features – WP 1200 (TAS-I)

4. High level screening of AM design features

For each material associated with the related process, five families of parameters has been searched and analyzed:

- **PROCESS WITH MATERIAL MAIN CHARACTERISTICS**
- **QUALITY STANDARDS**
- **MAIN MISSION REQUIREMENTS (ECSS-Q-70-71A)**
- **MECHANICAL-THERMAL-PHYSICAL PROPERTIES**
- **APPLICATIONS HERITAGE**

4. High level screening of AM design features

For each one of Five families of parameters (30 parameters c.a.) other Seven class of materials: metal alloys and polymer, composite and ceramics parameters has been set (about 40 materials) for a total 1200 cells c.a.

- **Aluminium alloys**
- **Titanium alloys**
- **Stainless steel alloys**
- **Nickel super Inconel alloys**
- **Composite structures**
- **Polymers and PEEK**
- **Ceramics and Al2O3**

- **PROCESS WITH MATERIAL MAIN CHARACTERISTICS**
- **QUALITY STANDARDS**
- **MAIN MISSION REQUIREMENTS (ECSS-Q-70-71A)**
- **MECHANICAL-THERMAL-PHYSICAL PROPERTIES**
- **APPLICATIONS HERITAGE**

BENCHMARK OF A.M. MATERIAL & PROCESSES

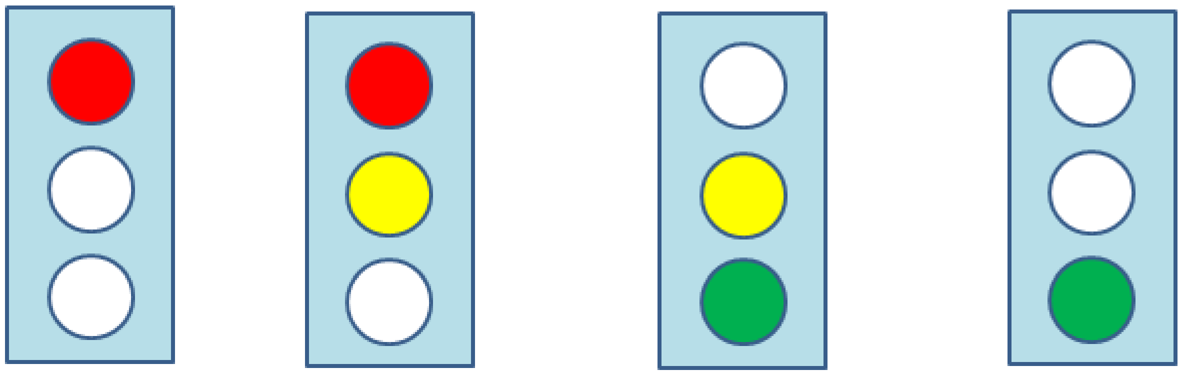
- The scope of this method is also to perform preliminary benchmark of A.M. material & processes respect what is required to a space application respect to the present data picture

- The presence of blank cell in the numerous matrix of the parameters provide an immediate picture of what has been found in this search and what is missing.

- As reference for each class of material one consolidate space material has been taken in the table

4. High level screening of AM design features

High level qualitative scale evaluations respect to suitability respect to spacecraft applications on the base of data available have been set in order to streamline the work to be performed in Task 3 and 4



Not adequate for space

Not adequate for space, at present, but promising in future

Adequate for space but development are needed

Adequate for space

➢ PROCESS WITH MATERIAL MAIN CHARACTERISTICS

1. Type of process
2. Max dimensions achievable for A.M. parts
3. Accuracy
4. Surface roughness
5. Minimal thickness
6. Ability for Bonding

POTENTIAL APPLICATIONS ON SPACECRAFT	MATERIALS OBTAINED BY ADDITIVE MANUFACTURING (A.M.)	A.M. Process	MAX Dimensions Volume	Accuracy [mm] (including distorions)	Roughness	Minimal thickness	Ability for bonding	Corresponding "traditional" material not obtained in additive manufaturing
Example of Al traditional alloy	Material also present for additive manufacturing	N.A.	up to several meters	0,05	[0.4 ; 3.2]	0.2mm	bonding Welding Screwing	Ti6AlV4 (annealed) Ti3AlV2.5 (T40) excluded from here presented characteristics
Potential S/C structures parts (i.e. brackets Secondary and Tertiary) antenna mechanics	Ti6Al4V (Arcam)	EBM	205 x 205 x 304 mm source : Sirris report	0,25 mm for small parts or 0,1 % source : Sirris report			machinability screwing welding ref.	
	Ti6Al4V ELI (Arcam)	EBM	205 x 205 x 304 mm source : Sirris report	0,25 mm for small parts or 0,1 % source : Sirris report				
	Ti Grade 2 (Arcam)	EBM	205 x 205 x 304 mm source : Sirris report	0,25 mm for small parts or 0,1 % source : Sirris report				
	Ti 64 (EOS)		400X400X400 ref. EOS			0,3 mm ref. EOS		
	TiAl6V4 (Renishaw)	LBM (SLM)						
	Ti6Al4V (Sciaky)	DED (EB or plasma with wire feed)	2500X2500X2500 mm source : www.sciaky.com;	1 mm ca. source : www.sciaky.com				
Shape memory alloy	TiNi							

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4. High level screening of AM design features

➢ QUALITY STANDARDS

1. Existing Standard applicable for Additive
2. Existing Standard for A.M. process
3. Existing Standard for A.M. material
4. Existing Standard for A.M. verification

			REF. STANDARDS OF "TRADITIONAL ALLOY "			REF. STANDARDS OF ADDITIVE "BORN" ALLOY			
POTENTIAL APPLICATIONS ON SPACECRAFT	MATERIALS OBTAINED BY ADDITIVE MANUFACTURING (A.M.)	A.M. Process				Standards for the powders	Standard specific to process the alloy in additive	Standard specific for the alloy in additive	Standard specific for test speciments in additive
Example of Al traditional alloy	Material also present for additive manufacturing	N.A.	AMS 4911 AMS 4928 AMS 9046	ASTM-B-265		N.A.	N.A.	N.A.	N.A.
Potential S/C structures parts (i.e. brackets Secondary and Tertiary) antenna mechanics	Ti6Al4V (Arcam)	EBM				ASTM-F-3049-14 general only for powder	ASTM-F-2924-14		
	Ti6Al4V ELI (Arcam)	EBM					ASTM-F-3001		
	Ti Grade 2 (Arcam)	EBM							
	Ti 64 (EOS)								
	TiAl6V4 (Renishaw)	LBM (SLM)							
	Ti6Al4V (Sciaky)	DED (EB or plasma with wire feed)							
Shape memory alloy	TiNi								

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			REF. STANDARDS OF "TRADITIONAL ALL MAIN REQUIREMENTS FOR AN "UNMANNED" SPACECRAFT															
POTENTIAL APPLICATIONS ON SPACECRAFT	MATERIALS OBTAINED BY ADDITIVE MANUFACTURING (A.M.)	A.M. Process	temperature range (i.e. T>-80°C ; T<+100°C)	Density (Kg/dm^3)	Outgassing in vacuum (i.e. CVCM, RML)	resistance to Radiation (up to 100 Krad)	Cleanliness (Particulate & Molecular)	ESD (conductive surfaces with proper passivation treatments)	CTE um/m*K^-1	Thermal conductivity	Static mechanical properties UTS Mpa YTS Mpa E Gpa (@20°C)	Fatigue strenght (Mpa)	Fracture Toughness strenght (Mpa·m)	resistance to corrosion and stress corrosion	creeping	Safety	Non Destructive Inspection (NDI) surface and volumetric defect suitability	surface treatments for thermal control
Example of Al traditional alloy	Material also present for additive manufacturing	N.A.	[illegible]	4,4 source : Spacecraft Sys. Eng. Fortescue @1991	N.A.		Compatible with optical application TBC	Compatible with several surface treatments	9 source : Spacecraft Sys. Eng. Fortescue @1991	130 W/m-K	UTM min900MPa YTS min800MPa E 110 source : Spacecraft Sys. Eng. Fortescue @1991	500 source : Spacecraft Sys. Eng. Fortescue @1991	75 source : Spacecraft Sys. Eng. Fortescue @1991				Good inspectability	Compatible with several surface treatments
Potential S/C structures parts (i.e. brackets Secondary and Tertiary) antenna mechanics	Ti6Al4V (Arcam)	EBM									UTM 1020 YTS 950 E 120 source : Sirris report	600 HIP, 1e7 cycles						
	Ti6Al4V ELI (Arcam)	EBM									UTM 970 YTS 930 E 120 source : Sirris report	600 HIP, 1e7 cycles						
	Ti Grade 2 (Arcam)	EBM									UTM 570 YTS 540 E not available source : Sirris report							
	Ti 64 (EOS)										UTM 1200 ± 50 YTS 1200 ± 50 E 110 ± 10 source : Sirris report							
	TiAl6V4 (Renishaw)	LBM (SLM)									UTM 1081 ± 30 YTS 1018 ± 40 E not available* source : Sirris report *E 111 ± 4 other producer							
	Ti6Al4V (Sciaky)	(EB or plasma with wire feed)																
Shape memory alloy	TiNi																	

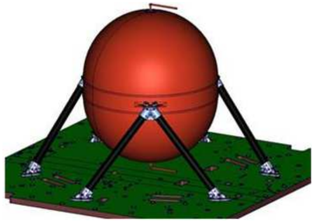
➢ MAIN MISSION REQUIREMENTS

1. Temperature range
2. Outgassing in vacuum
3. Resistance to Radiation
4. Cleanliness (especially for optical allocation)
5. Electrical charge and discharge (Compatibility with surface treatments)
6. Compatibility with surface treatments for thermal control
7. Resistance to corrosion (i.e. Atomic oxygen)
8. Safety
9. Fluid compatibility

4. High level screening of AM design features

➢ APPLICATIONS HERITAGE

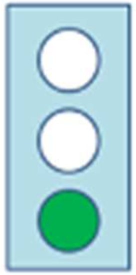
1. Heritage in Space
2. Heritage in Aeronautics
3. Heritage in Automotive
4. Heritage in Bio medics or others



			HERITAGE IN OTHER APPLICATIONS OF TRADITIONAL ALLOY NOT IN ADDITIVE	HERITAGE IN OTHER APPLICATIONS OF ALLOY IN ADDITIVE MANUFACTURING
POTENTIAL APPLICATIONS ON SPACECRAFT	MATERIALS OBTAINED BY ADDITIVE MANUFACTURING (A.M.)	A.M. Process	Space Aeronautics Automotive Medical Others	Space Aeronautics Automotive Medical Others
Example of Al traditional alloy	Material also present for additive manufacturing	N.A.	EXTENSIVE USE & HERITAGE IN AERONAUTICS & SPACE	N.A.
Potential S/C structures parts (i.e. brackets Secondary and Tertiary) antenna mechanics	TI6Al4V (Arcam)	EBM		AERONAUTICS (ENGINES BLADES & BRAKETS) WIDE USE IN MEDICAL APPLICATIONS
	TI6Al4V ELI (Arcam)	EBM		
	TI Grade 2 (Arcam)	EBM		
	TI 64 (EOS)			
	TIAl6V4 (Renishaw)	LBM (SLM)		
	TI6Al4V (Sciaky)	DED (EB with wire feed)		
Shape memory alloy	TINI			

4. High level screening of AM design features

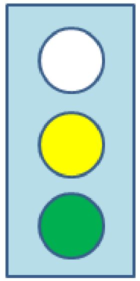
Titanium Alloys powder based processes:



- TiAl4V with EBM & Laser sintering powder based process
- Ti64V with EBM & Laser sintering powder based process

<u>For short time term application</u>

Titanium Alloy by EBM or WAMM wire processes:

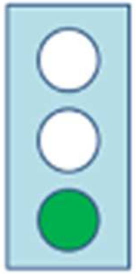


- TiAl4V with EBM or WAMM

Are very promising AM processes wire based process for large structure (in order of magnitude of meters) <u>For medium term application</u>

4. High level screening of AM design features

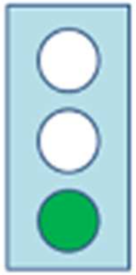
Aluminium Alloys powder based processes:



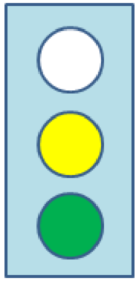
- AlSi10Mg AlSi7Mg0.6 with Selected Laser sintering by powder based process
- Then also AlSi12, AlSi7Mg with Selected Laser sintering by powder based process

<u>For short time term application</u>

INVAR & Nickel super alloys (particularly Inconel), Stainless steel and related powder based processes:



- INVAR is promising for spacecraft optical applications

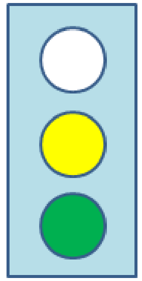


- Other Nickel super alloys (particularly Inconel) & Stainless steel are also promising for spacecraft applications in <u>medium term</u>, also if applications are limited : small component , propulsion (existing application for space in U.S.) Due to limited data available (despite in US Inconel is already used by Space X for propulsion system) a further proper investigation should be performed in dedicated additional study.

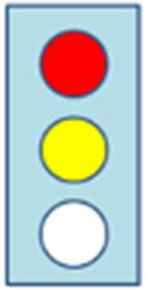
4. High level screening of AM design features

A.M. Polymers (particularly PEEK) and related processes:

- PEEK families are promising for spacecraft applications may be in also less than medium term as far the PEEK not in AM is already used in outer space application

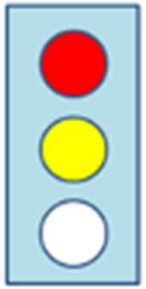


- In general for the polymers investigated very limited data has been found to evaluate compliance for spacecraft application. A further proper investigation should be performed in dedicated additional study; probably proper developments could make some A.M. polymers promising for spacecraft applications in medium/long term



Composite materials (e.g. metal matrixes, glass fibber) and related processes:

- Very limited data has been found to evaluate compliance for spacecraft application. A further proper investigation should be performed in dedicated additional study, it seems that in future proper developments could A.M. Composite materials & Ceramics in medium/long term



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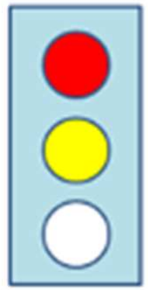
4. High level screening of AM design features

Regarding A.M. Ceramics (particularly AlO3) and related processes:

Very limited data has been found to evaluate compliance for spacecraft application. A further proper investigation should be performed in dedicated additional study, it seems that in future proper developments could Ceramics promising for spacecraft applications in medium/long term



- 5. Impact evaluation methodology– WP 2100 (TAS-F)

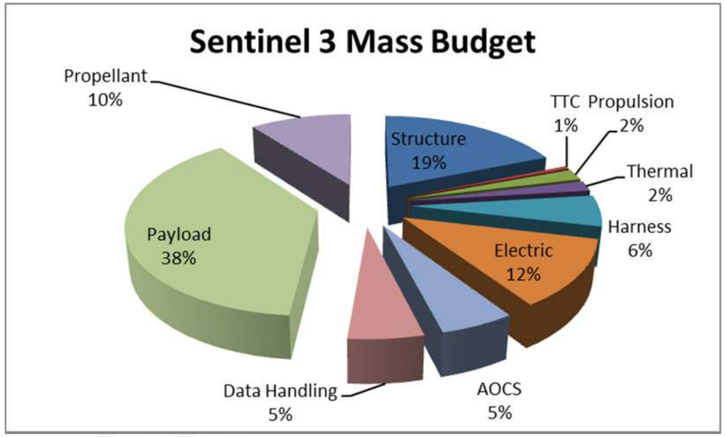
5. Impact Evaluation Methodology

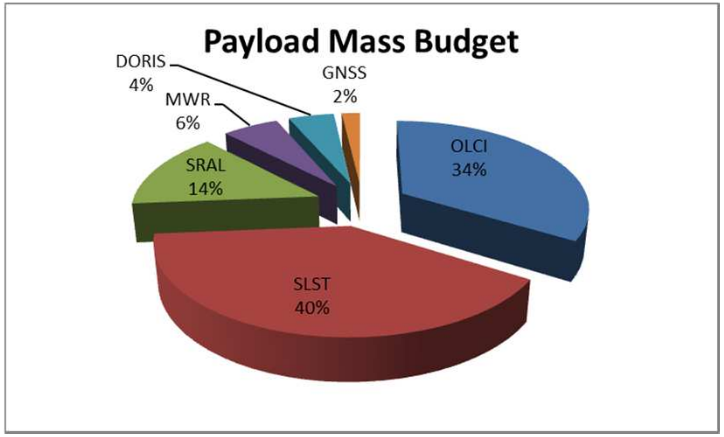
- WP2100 Output – AM-TASF-SYS-TN-001 issue 2
  - Definition of generic criteria to evaluate and compare AM at system level

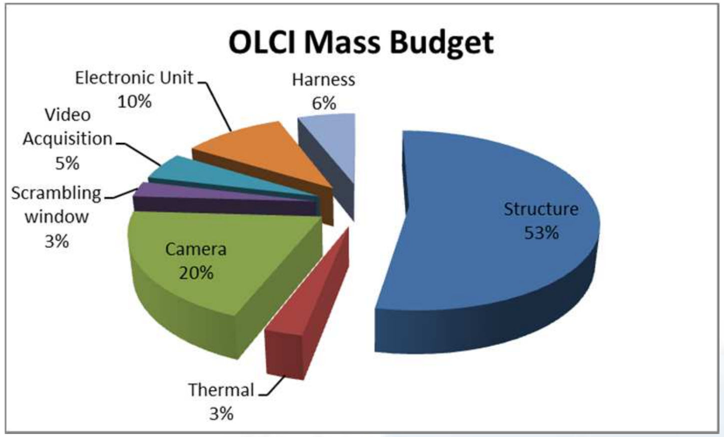
Criteria list definition →

The main selected criteria are
- Programmatic
- Performance
- Environment

- No independency of criteria
  - Ex mass

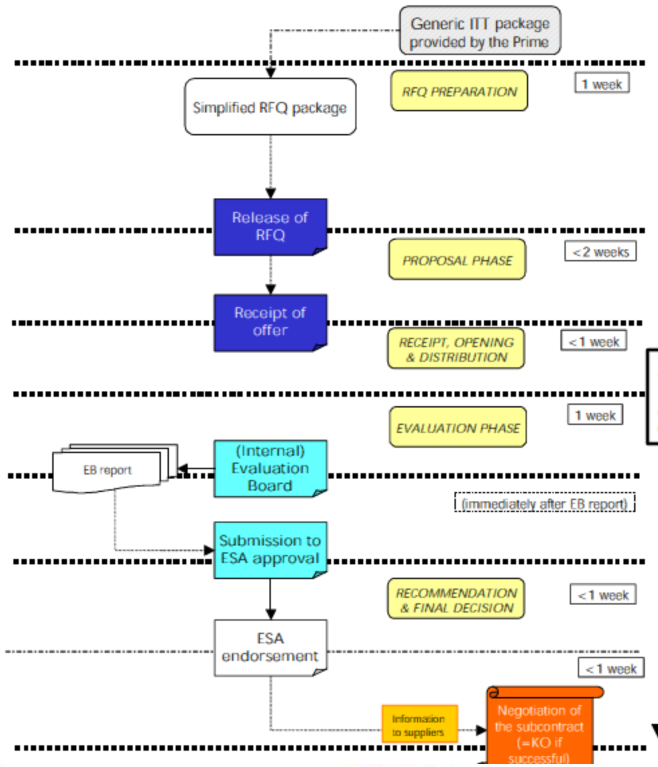


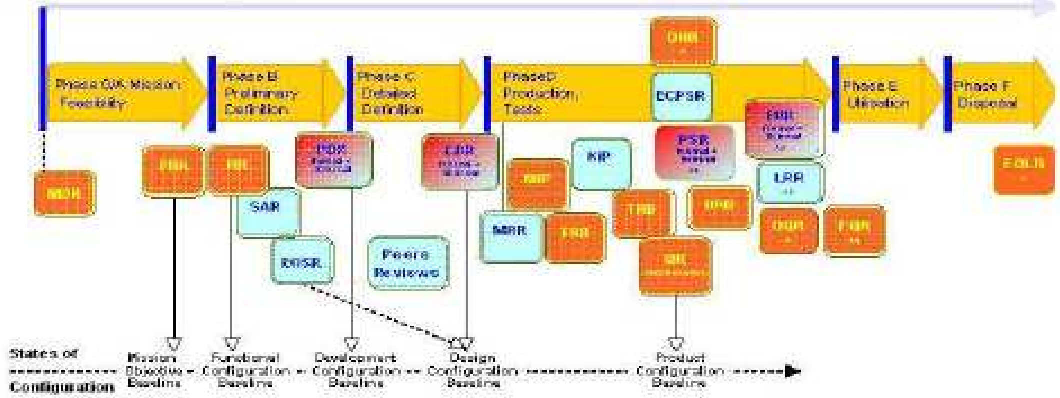




5. Impact Evaluation Methodology

- Programmatic criteria
  - Lead Time
    - Change of B/C/D phase
    - Equipment manufacturing & test
  - Life cycle cost
    - Engineering
    - production
  - AIT aspects
    - Integration
    - Test





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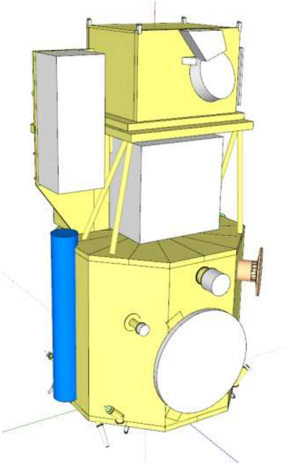
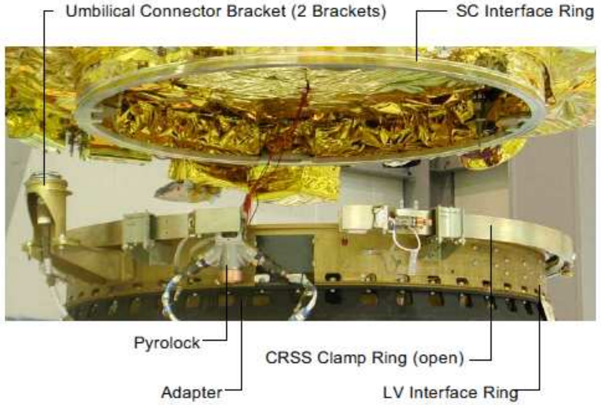
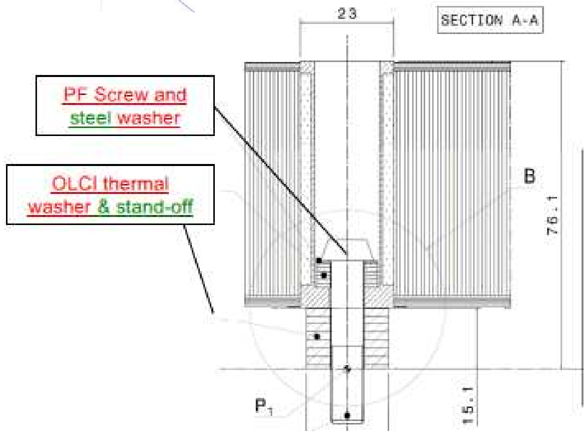
5. Impact Evaluation Methodology

- Performance criteria
  - Mass
  - Geometry
  - Interfaces
    - Example OLCI fixation
  - Reliability

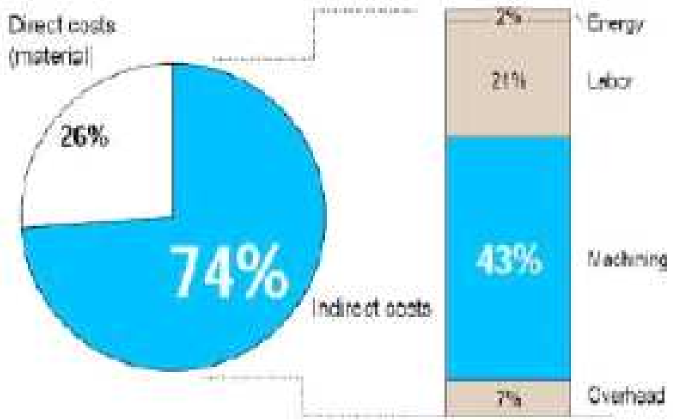






5. Impact Evaluation Methodology

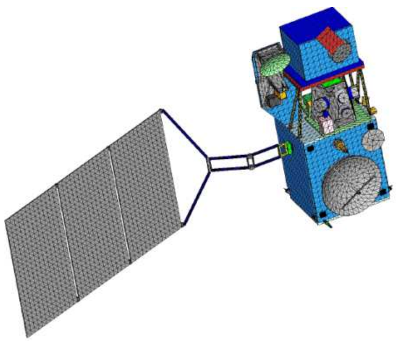
- Environment criteria
  - Material resource
  - Energy resource
  - Los compatibility



Applicable to Structure

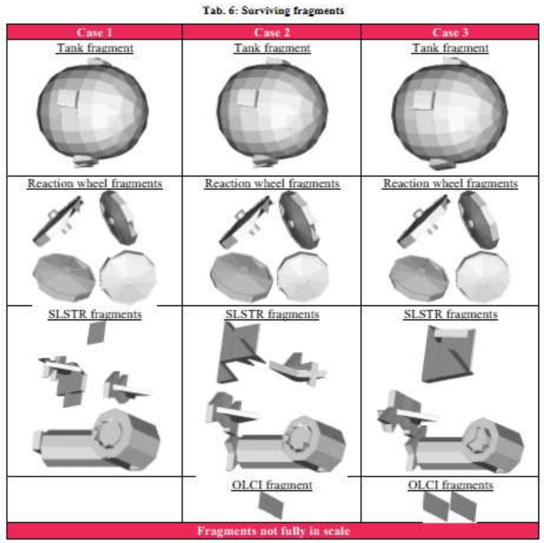
Additive Manufacturing cost estimations based on Stainless Steel

(reference Roland Berger Strategy Consultant)



SCARAB modelization

HTG S3 analysis



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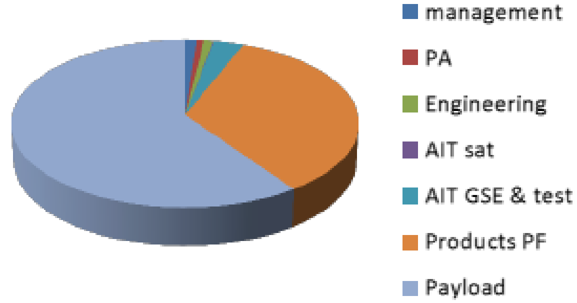
5. Impact Evaluation Methodology

- Weighting
  - Based on cost

PFM



FM

Payload cost includes engineering, manufacturing and test

Lead times includes equipment engineering cost & production cost → distributed on products

- Life cost includes satellite engineering + production cost

Score definition is :	Weight are applied :
1= risky, critical or AM interested non demonstrated 2 = slight advantage 3 = big advantage	1 = low priority 2 = medium priority 3 = high priority

5. Impact Evaluation Methodology

Criteria evaluation

1. Programmatic impact	AM	Weighted
Life-cycle cost	This refers to satellite and includes engineering activity. AM impact is considered as a big advantage as applicable to all mission duration. Note that satellite w heighting is very sensitive to PFM or FM. But payload is alw ays specific and represents a major part of the satellite cost.	9
Lead time	Relative to equipments, including equipement engineering and manufacturing and testing up to delivery for satellite integration. Weight refer to products. Potential risk of satellite schedule delay.	9
AIT tests	Includes AIT tests and GSE. This part w ill depend of satellite FM or PFM (acceptance or qualification tests).	3
AIT integration	Weight represents part of cost in the SC, includes ground support equipment, protection tool during integration, tubing support for ex. Reduction of pieces has a high positive impact on integration	4
2. Performance impact	AM	Weighted
Mass	Titanium & alu techno represent large % SC material. Weight is maximum according to snow ball effect.	9
Geometry	Volume and geometry are impacted by AM w ith pieces surface optimization. Weight is limited as threshold to change fairing configuration is important. Volume impact improvement can be used for global satelltie design and payload capacity.Raw material aspect is considered at enviromental level.	4
Interfaces simplification	Includes supports, interface removal, links betw een mechanical parts…	6
Reliability	impact of design margins and pieces number reduction.	2
3. Environmental impacts	AM	Weighted
Material resources	Advantage of AM is major through the process.	6
Energy resources	Energy resource is limited	1
Cleanspace	possibility to use AM for demisable structure to allow mission to be compliant w ith LOS. Mandatory at 2020. The cost impact to comply ot LOS for medium satellite size is major (refer to threshold effect).	6

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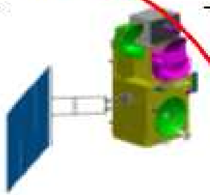
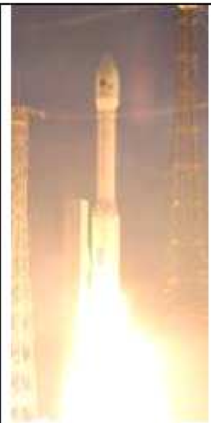
5. Impact Evaluation Methodology

- Criteria validity w.r.t Threshold
  - Launcher

Proteus 800	Prima
	
PL < 800kg/400W	PL < 1000kg/3kW
SC < 1500 kg	SC < 2000 kg
Life < 10 years	Life < 10 years

Launcher				
	Soyuz	**Vega-C**	**Rockot**	**PSLV**
Cost	1.6 Vega-C	Reference	0.8 Vega-C	1.2 Vega-C
Performance on Sentinel3 orbit	4300 kg	1800 kg	1250 kg	1500 kg

- Sentinel 3 = 1250 kg launch mass 815km/98°6
- If 30% satellite mass saving -> not sufficient for a step in launcher
  - Increase of payload capacity
- Launcher threshold exists but no real impact on criteria for S3

Criteria validity w.r.t Thresholds

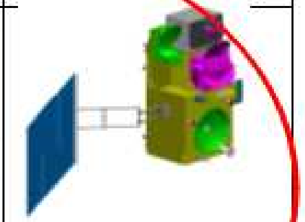
Cleanspace

Controlled re-entry

- + 200 m/s DV
  - Additional 60m/s for S3 = 35 kg propellant

Uncontrolled re-entry

- Casualty risk function (mass, volume, materials)

Proteus 100	Proteus 150	Proteus 500	Proteus 800	Prima
				
PL < 100kg/100W	PL < 170kg/150W	PL < 500kg/400W	PL < 800kg/400W	PL < 1000kg/3kW
SC < 200 kg	SC < 450 kg	SC < 1000 kg	SC < 1500 kg	SC < 2000 kg
Life < 5-7 years	Life < 10 years	Life < 10 years	Life < 10 years	Life < 10 years

And larger….

Sensitivity analysis

- PFM/FM

1. Programmatic impact	Score (1-2-3)	AM	Weight (1-2-3)	Weighted
life-cycle cost	3	This includes engineering activity. AM impact is considered as a big advantage as applicable to all mission duration.	3	9

- Orbit
- Rosetta mission price/kg wet mass > 1000 Sentinel 3 mission price/kg wet mass
  - Expensive PF & payload -> complex subsystem prop, TTC, AOCS, PDHT, power
  - Ratio payload/satellite mass Sentinel ~10* ratio payload/satellite mass Rosetta

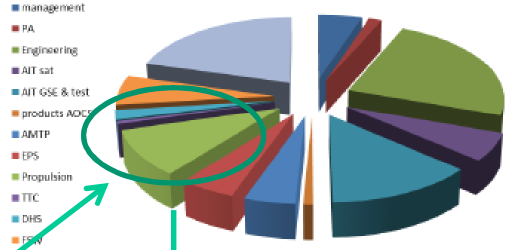
1. Programmatic impact	Score (1-2-3)	AM	Weight (1-2-3)	Weighted
Life-cycle cost	3	This refers to satellite and includes engineering activity. AM impact is considered as a big advantage as applicable to all mission duration. Note that satellite wheighting is very sensitive to PFM or FM. But payload is always specific and represents a major part of the satellite cost.	3	9
Lead time	3	Relative to equipments, including equipement engineering and manufacturing and testing up to delivery for satellite integration. Weight refer to products. Potential risk of satellite schedule delay.	3	9
2. Performance impact	**Score (1-2-3)**	**AM**	**Weight (1-2-3)**	**Weighted**
Mass	3	Titanium & alu techno represent large % SC material. Weight is maximum according to snow ball effect.	3	9

5. Impact Evaluation Methodology

- Sensitivity analysis
  - Propulsion
    - Very preliminary estimation of S3 with 4*PPS500

$$\frac{DV_{elec}}{DV_{chimique}} \approx 12.5$$

Sentinel 3 mass budget	reference hydrazine	electric propulsion
Platform		
Structure	228	228
TTC	6	6
thermal control	21	25
harness	65	66
Power	139	144
aocs	62	62
data handling	62	62
propulsion	24	36
Payload	441	441
Total dry mass	1048	1070
System margin	70	70
Hydrazine/Xenon	119	18
Satellite mass	**1237**	**1158**



Propulsion procurement increases

Mass -> Snow ball effect limited

Heaviest criteria: mass, lead time, life-cycle cost

Relative Robustness demonstrated through sensitivity analysis

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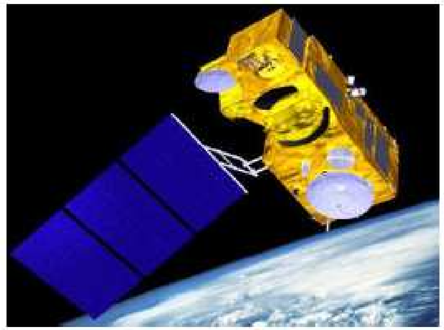
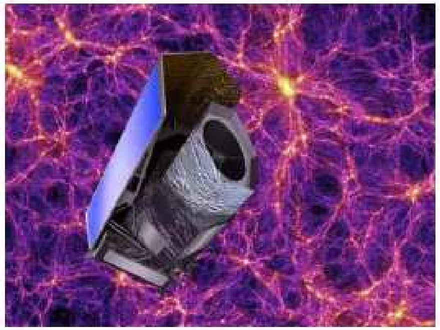
5. Impact Evaluation Methodology

- Two satellites selected as different as possible
  - Goal: to reveal synergy & application multiplicity
    - Sentinel 3A&B
      - Mature program
      - LEO
      - Optical payload
      - Small « series » effect / FM
    - Euclid
      - In design phase
      - Different maturity
      - L2 orbit
      - PFM
      - Science mission



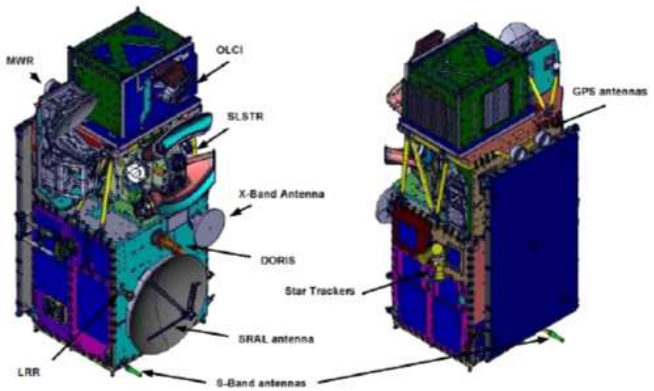


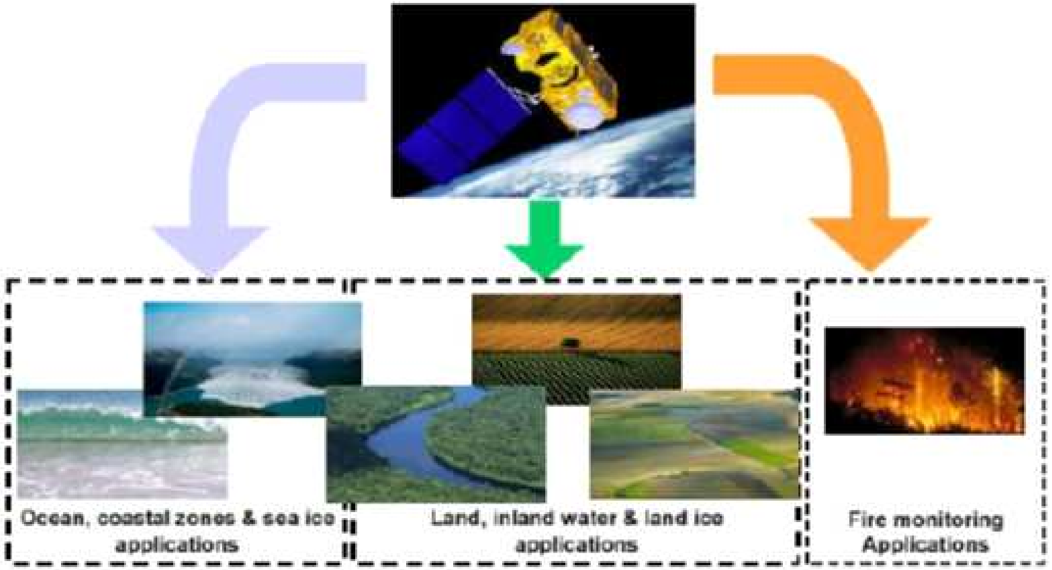
Qualitative then Quantitative evaluation on those 2 candidates

- 6. Application screening on Sentinel 3 satellite – WP 3100 (TAS-F)

6. Application screening on Sentinel 3 satellite

“ To assess the potential applications of AM techniques in manufacture & assembly



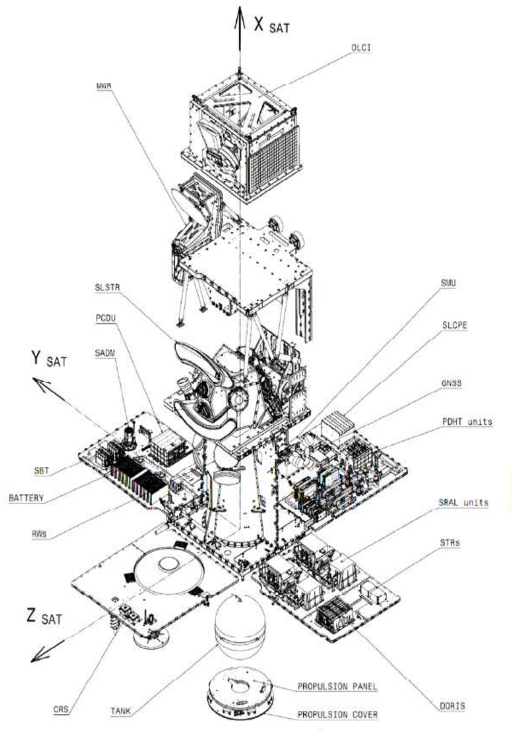


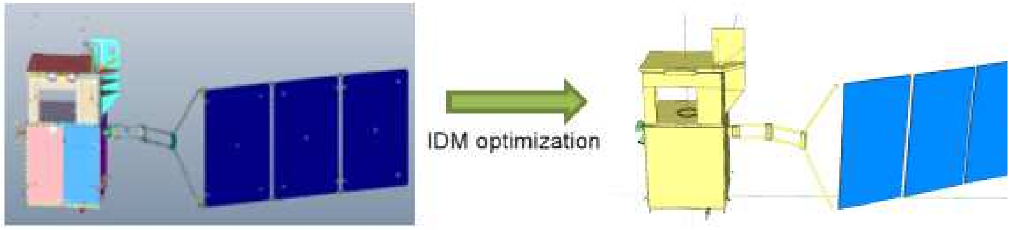
- SVM + PLM

OLCI SLSTR SRAL MWR

6. Application screening on Sentinel 3 satellite

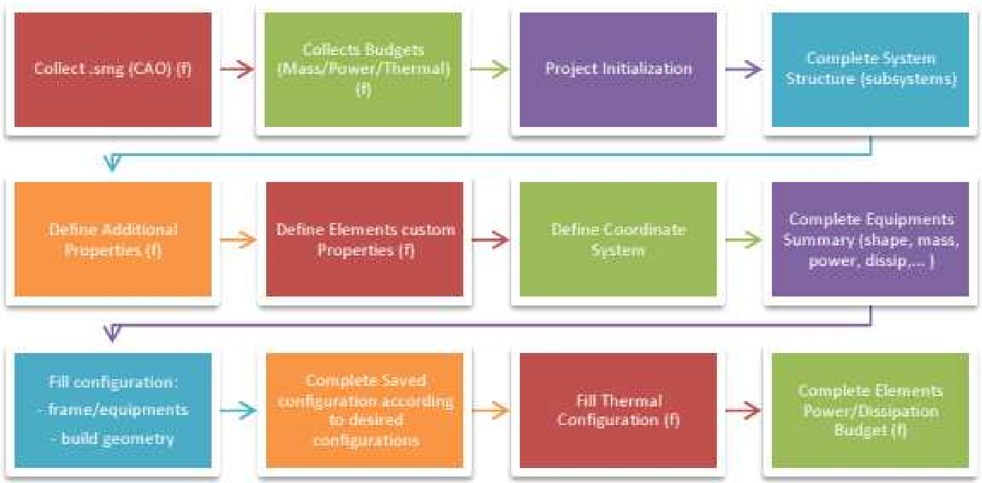
- Method
  - 1/ Mapping of satellite elements
    - First screening based on material
    - Through product tree
    - ranking
  - 2/ Redesign with IDM tool to take benefit of geometry





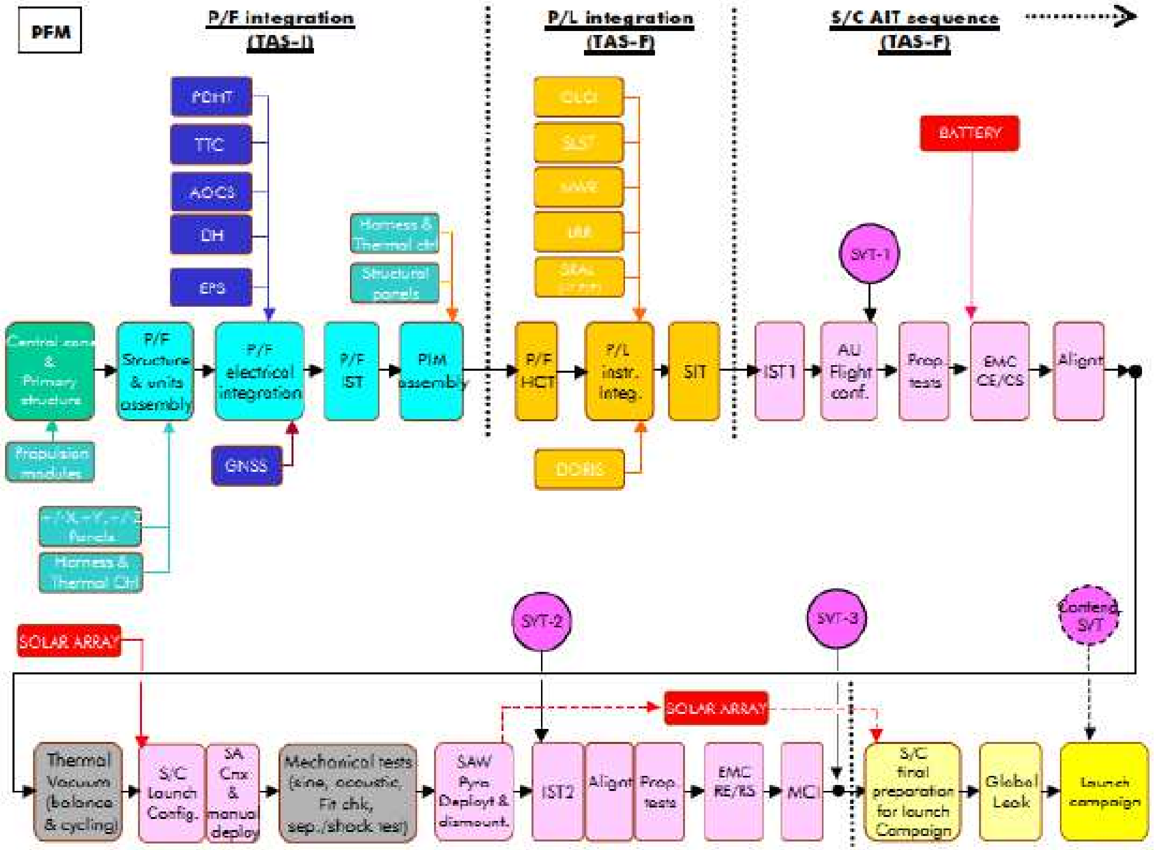
Sentinel 3 seen in Catia

Sentinel 3 seen in IDM



6. Application screening on Sentinel 3 satellite

- **Lifecycle**
  - Engineering
  - Modelization tool
  - Topological optimization
- **Lead Time**
  - At equipment level + integration
  - Suppression of forged mold
  - Change of procurement duration
- **Integration time**
  - Improvement / interfaces
  - Mockup



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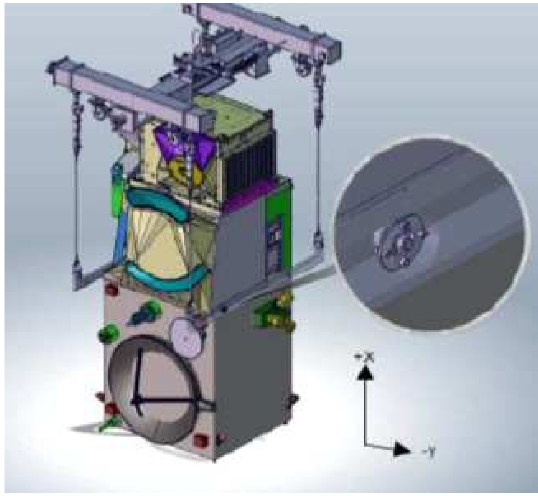
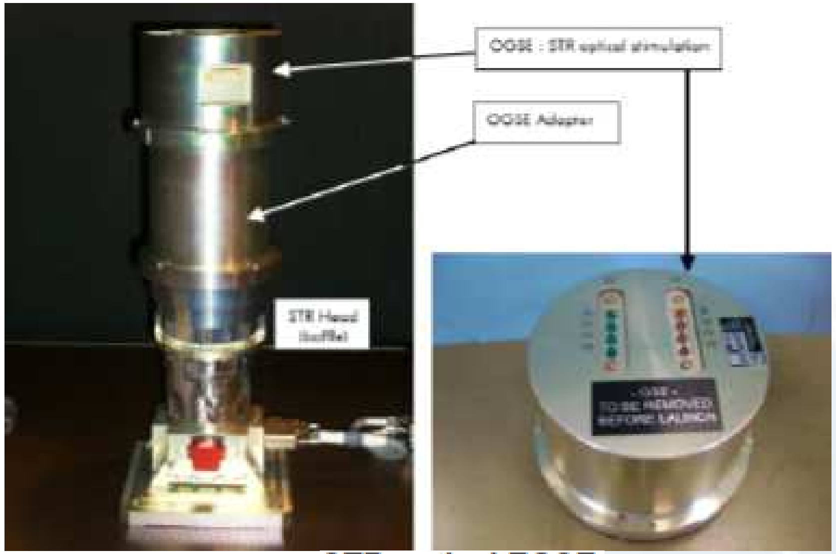
6. Application screening on Sentinel 3 satellite

- **AIT tests**
  - No major improvement
    - in AIT sequence:
      - Test duration.
    - In MGSE:
      - Ratio performance/price less interest,
      - Potential risk,
      - Containers due to large dimensions.
  - Interests mainly on:
    - Covers:
      - Custom made in live,
      - Light mass.
    - EGSE:
      - Specific to payload.



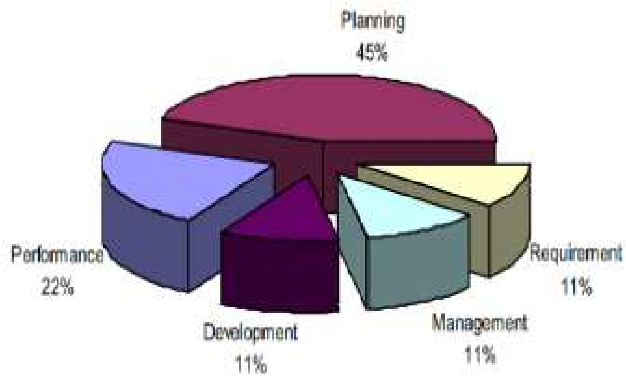
vertical Handling device



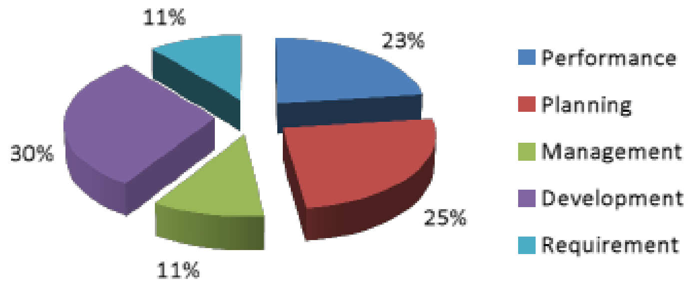
STR optical EGSE

6. Application screening on Sentinel 3 satellite

- Performance
  - Mass & power budget
    - Will be evaluated in next step
  - Geometry
    - To optimize interface reduction
    - Launcher accommodation
  - Interfaces
    - Functions sharing thermal/electric/structure
    - Supports integrations
  - Reliability
    - Design freedom
    - Prototyping
    - Possibility to increase robustness to default



Risk sharing (CDR reference)



Risk sharing (AM hypothesis)

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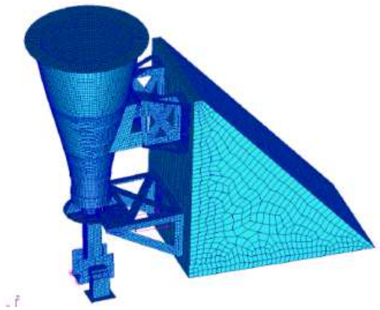
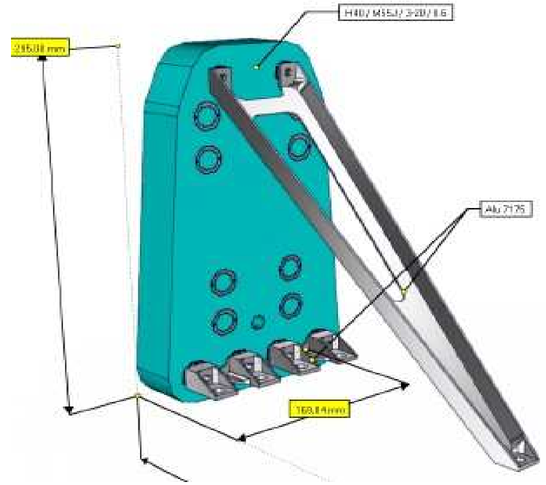
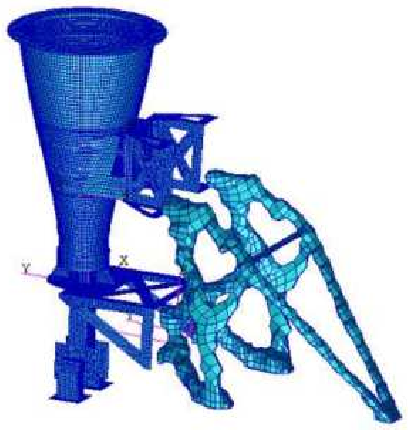
6. Application screening on Sentinel 3 satellite

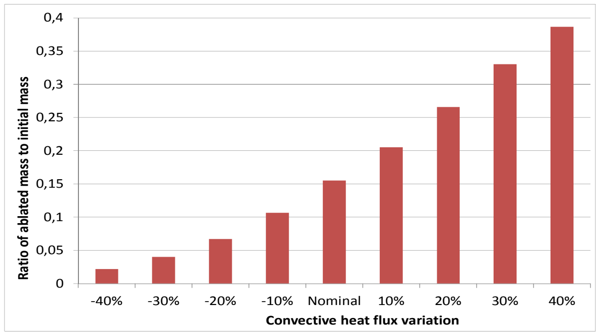
- Environment
  - Material resource:
    - Major AM improvement,
    - Bulk material savings,
    - Just needed quantity.
  - Energy resource:
    - Part indirect cost,
  - LOS compatibility:
    - Reducing number of debris,
    - D4D.







Break-up altitude, convective heat flux…



6. Application screening on Sentinel 3 satellite

- Ranking:
  - Weighting factor for the figures of Merit
  - Approach
  - Primary
  - Secondary
  - Tertiary

->

	SCORES										Total score	Weighting factor
this figure of merit ▶ ▼ this figure of merit compared to	Life cycle cost	Lead time	AIT aspects	Mass	Geometry	Interface	Reliability	Material resource	Energy resource	LOS compatibility	**Pi**	**Wi**
Programmatic												
Life cycle cost		-1	0	-1	1	-1	1	-1	1	-1	-2	9,5
Lead time	1		1	0	1	1	1	1	1	1	8	11,8
AIT aspects	0	-1		-1	1	0	1	0	1	0	1	10,2
Performance												
Mass	1	0	1		1	0	1	1	1	1	7	11,6
Geometry	-1	-1	-1	-1		-1	1	0	1	-1	-4	9,0
Interface	1	-1	0	0	1		1	1	1	1	5	11,1
Reliability	-1	-1	-1	-1	-1	1		-1	1	-1	-5	8,8
Environment												
Material resource	1	-1	0	-1	0	-1	1		1	0	0	10,0
Energy resource	-1	-1	-1	-1	-1	-1	-1	-1		-1	-9	7,8
LOS compatibility	1	-1	0	-1	1	-1	1	0	1		1	10,2
											Q = 42	100,0

6. Application screening on Sentinel 3 satellite

PRODUCT NAME ->	PT CODE								Items	Material	Life cycle cost	Lead time	AIT aspects	Mass	Geometry	Interface	Reliability	Material resource	Energy resource	LOS compatibility	Total
											9,5	11,8	10,2	11,6	9,0	11,1	8,8	10,0	7,8	10,2	
Platform	1	1																			
Structure	1	1	1																		
Primary Structure	1	1	1	1																	
central tube	1	1	1	1	1					composite; sandwich from with CFRP face-sheets and aluminium honeycomb	1	2	1	2	2	1	1	1	1	0	122,3
Shear webs	1	1	1	1	2					sandwich with CFRP face-sheets	1	2	2	2	1	2	1	1	1	0	134,6
upper/bottom deck panel	1	1	1	1	3					sandwich with CFRP face-sheets	1	2	2	2	1	2	1	1	1	0	134,6
SADM reinforcement	1	1	1	1	4				Solar Array Drive Mechanism Reinforcement	sandwich with CFRP face-sheets	1	2	2	0	2	2	1	1	1	0	120,4
brackets and cleats	1	1	1	1	5					metallic brackets/ Titanium inserts	1	2	1	1	1	2	2	1	0	0	113,7
Interface ring	1	1	1	1	6				Mass impact includes LV side	Al. Alloy	1	2	0	2	2	2	1	2	1	0	133,2
Secondary Structure	1	1	1	2																	
SVM panels	1	1	1	2	1					sandwich with Al. Alloy face-sheets	1	2	2	2	1	2	1	1	1	0	134,6
PIM panels	1	1	1	2	2					sandwich with CFRP face-sheets	1	2	2	2	1	2	1	1	1	0	134,6
brackets and cleats	1	1	1	2	3					Aluminium	1	2	1	1	1	2	2	1	0	0	113,7
Struts	1	1	1	2	4					CFRP tubes / Al. Alloy fittings	0	1	1	1	1	1	1	1	0	0	72,5
Tertiary Structure	1	1	1	3																	
Tank support	1	1	1	3	1					Al. Alloy	1	2	1	1	2	1	1	1	1	0	110,7
STR support	1	1	1	3	2				Star Tacker Support	Ti. Alloy / CFRP	1	1	2	2	1	2	1	2	1	0	132,7

6. Application screening on Sentinel 3 satellite

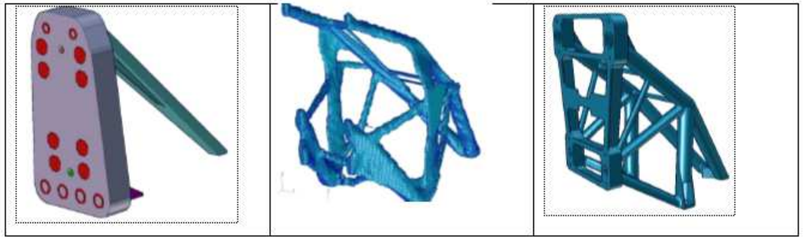
CSS support	1	1	1	3	3				Coarse Sun Sensors Support	Al. Alloy	1	2	1	0	2	1	1	1	1	0	99,1
RW support	1	1	1	3	4				Reaction Wheel Support	Metallic end part / CFRP	1	2	2	1	1	2	1	2	1	0	132,9
GNSS support	1	1	1	3	5				Global Navigation Satellite System Support	Al. Alloy	1	2	1	2	2	1	1	1	1	0	122,3
SADM support ->	1	1	1	3	6				Solar Array Drive Mechanism Support	Al. Alloy	1	2	1	1	2	1	1	1	1	0	110,7
LRR support	1	1	1	3	7				Laser Retro Reflector Support	Al. Alloy	1	2	1	1	2	1	1	1	1	0	110,7
RCT bracket	1	1	1	3	8				Reaction Control Thruster bracket	Al. Alloy	1	2	1	1	2	1	1	1	1	0	110,7
SRAL fixation	1	1	1	3	9				Synthetic Aperture Radar Altimeter support	Al. Alloy	1	2	1	2	2	1	1	1	1	0	122,3
SBA support	1	1	1	3	A				S-band Antenna Support	Al. Alloy	1	2	1	1	2	1	1	1	1	0	110,7
F & D support	1	1	1	3	B				Fill and Drain Support	Al. Alloy	1	2	1	2	2	1	1	1	1	0	122,3
DORIS support	1	1	1	3	C				Doppler Orbitography and Radiopositioning Integrated by Satellite Support	Al. Alloy	1	2	1	1	2	1	1	1	1	0	110,7
HRN & WG supports	1	1	1	3	D				Harness and WaveGuide Supports	Al. Alloy	1	1	2	1	1	1	1	1	1	0	100,0
Thermal Control	**1**	**1**	**2**																		
Radiators	1	1	2	1						data not available	1	1	2	1	2	2	1	1	1	0	120,1
Thermal doublers	1	1	2	2						aluminium	0	0	0	1	0	0	0	0	0	0	11,6
Interfillers	1	1	2	3						data not available	0	0	0	0	0	0	0	0	0	0	0,0
Heat pipes	1	1	2	4						Al alloy - filled with ammonia	1	2	2	0	2	2	1	1	1	0	120,4
Kapton Heaters	1	1	2	5						kapton	0	0	0	0	0	0	0	0	0	0	0,0
Thermistors	1	1	2	6						data not available	0	0	0	0	0	0	0	0	0	0	0,0
Clayborn heaters	1	1	2	7						data not available	0	0	0	0	0	0	0	0	0	0	0,0
Power	**1**	**1**	**3**																		
PCDU	1	1	3	1					Power Conditionning Distribution Unit	data not available	1	2	1	2	1	2	0	1	1	1	125,8
Battery	1	1	3	2					Li-Ion Battery Assembly	carbon lithium ion cells, fiber cell support plates, aluminium structure	1	2	1	2	1	2	0	1	1	1	125,8
SADM	1	1	3	3					Solar Array Drive Mechanism	data not available	1	2	1	1	1	2	1	1	1	0	112,8
Solar Array	1	1	3	4						data not available	1	1	2	1	0	2	0	0	0	0	75,6
TT&C	**1**	**1**	**4**						**Tracking, Telemetry and Command**												
S-band Antenna	1	1	4	1						GFRP, AL alloy, copper	1	1	2	1	0	2	0	1	1	0	93,4
S-band Transponder	1	1	4	2						data not available	0	0	0	0	0	0	0	0	0	0	0,0
DC / RF Harness	**1**	**1**	**5**																		
Supports	1	1	5	1						data not available	0	1	2	0	1	2	1	0	0	0	72,3
Connectors & backshell	1	1	5	2						twisted cable- Metallic backshell	0	1	2	0	1	2	1	0	0	0	72,3

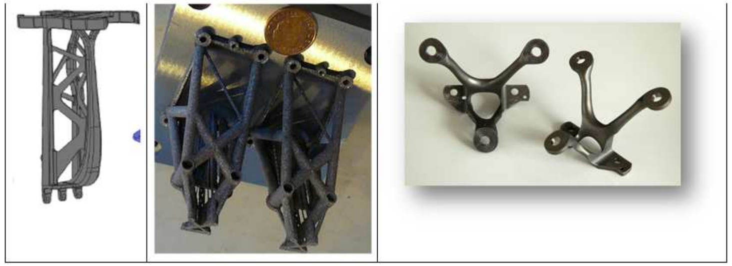
6. Application screening on Sentinel 3 satellite

PDHT	**1**	**1**	**6**						**Processing Data Handling Transmitter**												
PDHU Assy	1	1	6	1					Data Storage & Handling unit Assembly	data not available	2	1	1	2	1	2	0	1	1	0	113,3
TWT	1	1	6	2	1				Travelling Wave Tube	Al. Alloy	1	1	1	1	1	2	1	1	1	0	100,9
EPC	1	1	6	2	2				Electrical Power Conditioning	data not available	2	1	1	1	1	2	0	1	1	0	101,7
XBA Assy	1	1	6	3					X-Band Antenna Assy	data not available	1	1	2	1	0	2	0	1	1	0	93,4
AOCS	**1**	**1**	**7**						**Attitude and Orbit Control Subsystem**												
CSS	1	1	7	1					Coarse Sun sensors	data not available	0	0	0	0	0	0	0	0	0	0	0,0
Magnetometer	1	1	7	2						data not available	0	0	0	0	0	0	0	0	0	0	0,0
STR optical head	1	1	7	3					Star Tarcker head	data not available	0	1	2	0	1	2	1	0	0	0	72,3
MTB	1	1	7	4					Magneto Torquer Bar	data not available	0	0	0	1	0	0	0	0	0	0	11,6
RW	1	1	7	5					Reaction wheel	data not available	1	2	1	1	1	1	1	1	1	2	122,0
CRS	1	1	7	6					Coarse Rate Sensors	data not available	0	0	0	0	0	0	0	0	0	0	0,0
Propulsion	**1**	**1**	**8**																		
Tank	1	1	8	1						Shell Titanium alloy	1	2	1	1	1	1	1	1	1	2	122,0
Thrusters	1	1	8	2					1 N Thruster	Alloy	1	2	1	0	1	1	1	1	1	1	100,2
Latch Valves	1	1	8	3						data not available	1	1	0	0	0	0	1	1	1	0	47,9
Ergol filter	1	1	8	4						titanium body & pleates metallic screen electron beam welded	1	1	0	0	0	0	1	1	1	0	47,9
SAPT	1	1	8	5					Standard Accuracy Pressure Transducer	data not available	1	1	0	0	0	1	0	1	1	0	50,2
FDV	1	1	8	6					Fill and Drain Valve	titnanium seat, ceramic ball	1	1	0	0	0	0	0	1	1	0	39,1
Tubing & supports	1	1	8	7					Supports tubing	titanium	1	1	1	1	1	2	1	1	1	0	100,9
Trimming orifice	1	1	8	8						data not available	1	1	0	0	0	1	1	1	0	0	51,2
GNSS	**1**	**1**	**9**						**Global Navigation Satellite System**												
GNSS antenna	1	1	9	1						data not available	1	1	2	1	0	2	0	1	1	0	93,4
GNSS electronic	1	1	9	2						data not available	0	0	0	0	0	0	0	0	0	0	0,0
Data Handling	**1**	**1**	**A**																		
SMU	1	1	A	1					Satellite Management Unit	data not available	2	1	1	0	0	1	0	0	0	0	52,1

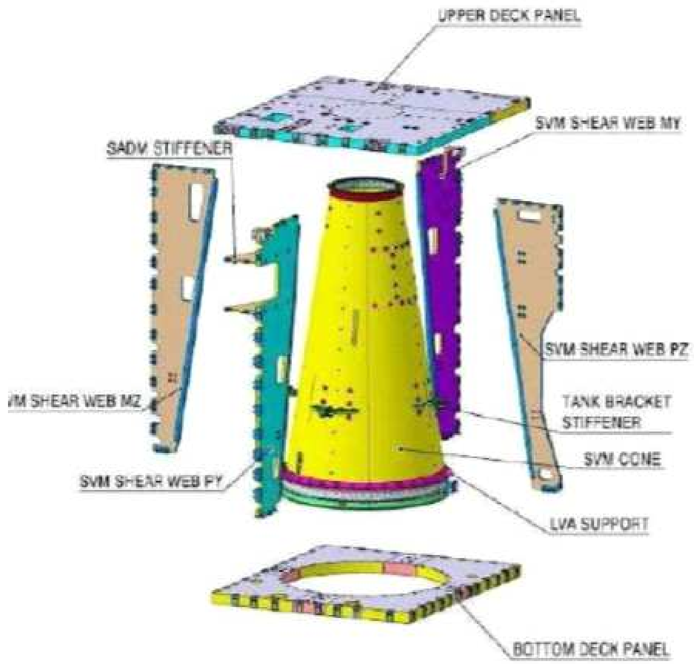
6. Application screening on Sentinel 3 satellite

- High ranking applications
  - Primary Structure
  - Secondary structure





TTC   Star Tracker   Antenna



Lateral panel:
Aluminium Honeycomb +
Alu face-sheets

CFRP sandwich

IF ring
aluminium

CFRP+alu honeycomb

  - Integration of thermal control management
    - Embedded heat-pipes
    - Interest of material adaptation with specific CTE
    - Geometry adaptation to increase dissipation

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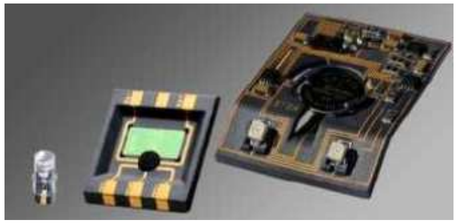
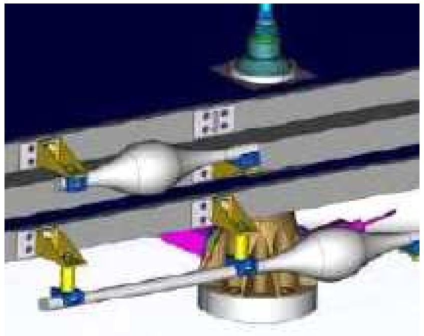
6. Application screening on Sentinel 3 satellite

Adele hinge

- High ranking applications
  - Mechanism
    - AM simplification
    - Reduction of pieces number
  - Power PCDU
    - Applicability to dissipative elements (PDHU, SMU)
  - TTC Waveguide
  - Harness

SADM Mockup



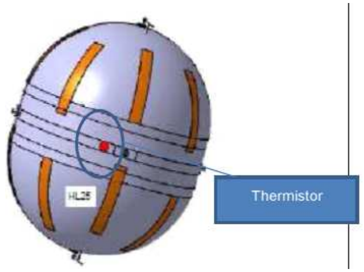


S3 Inter-panel harness

6. Application screening on Sentinel 3 satellite

- High ranking applications
  - Propulsion
    - Platform sandwich panel
      - Aluminium alloy honeycomb
      - Aluminium alloy skin
    - 4 supporting mounting structure
      - Titanium
      - Attachment tank to thrust cone
  - Propulsion Tank
  - Tubing

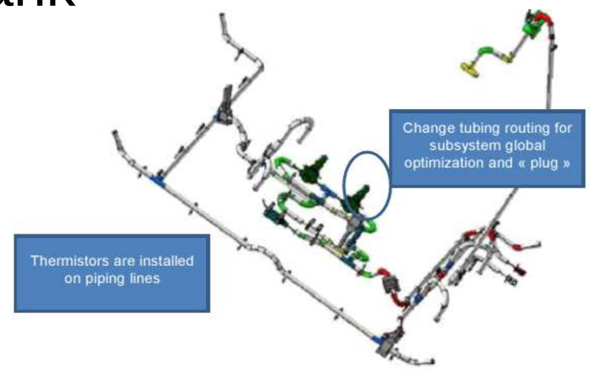
Lateral panel: Aluminium Honeycomb + Alu face-sheets



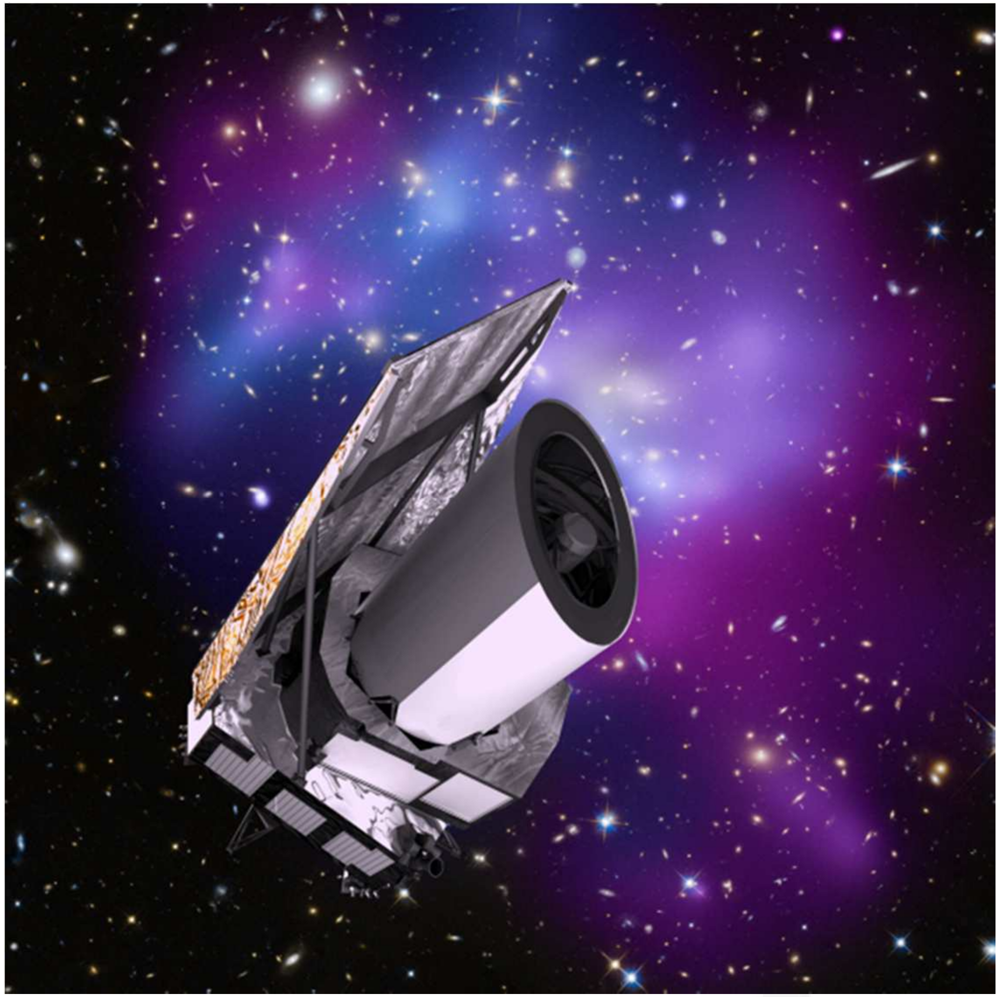
CFRP sandwich

IF ring aluminium

Nozzle (Safran)

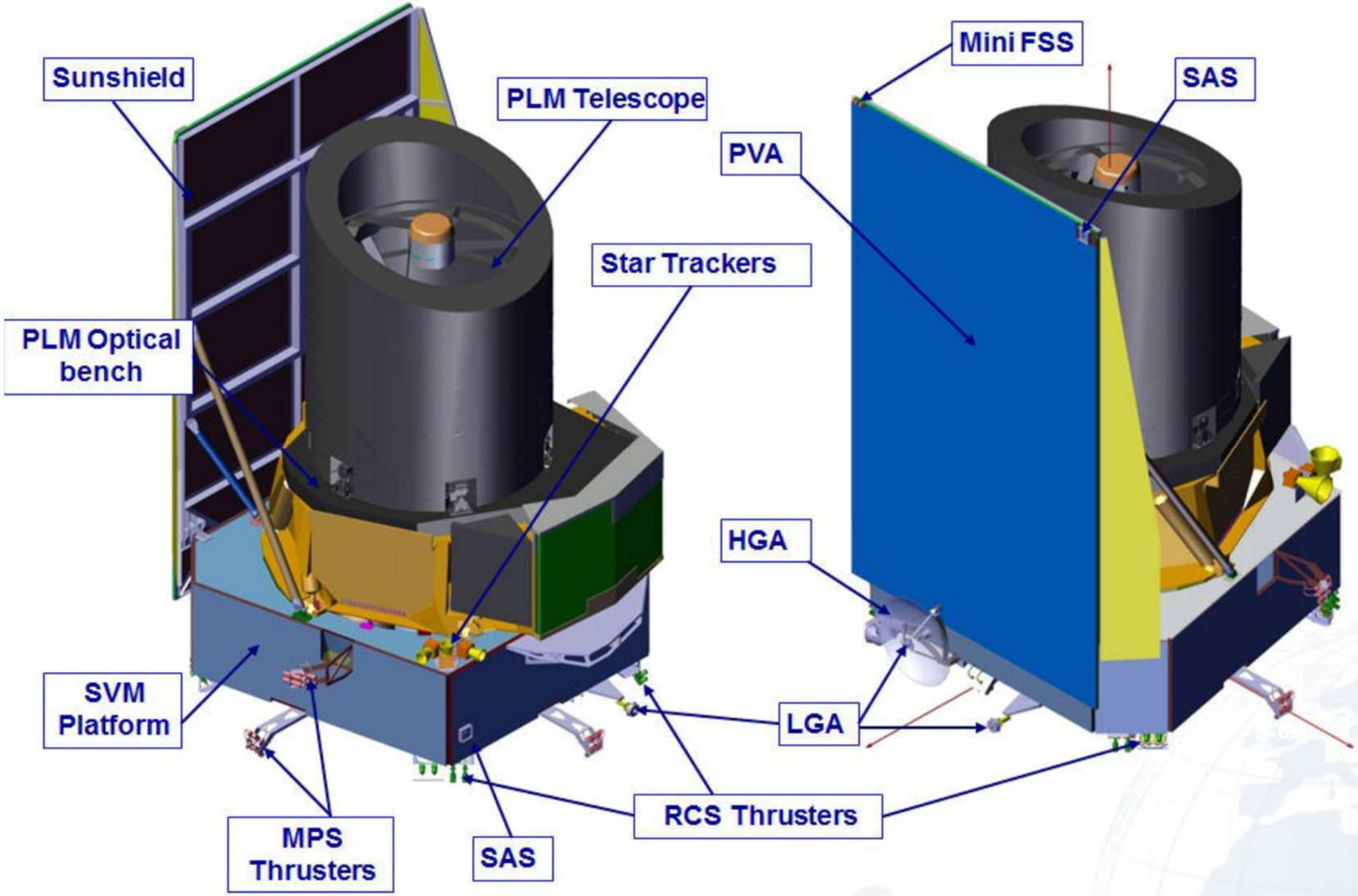


- 7. Application screening on Euclid satellite – WP 3200 (TAS-I)



EUCLID SPACECRAFT

Euclid is the next medium-class mission of ESA's Science Programme, to be implemented and launched by 2020. The objective of Euclid is to elucidate the geometry and the nature of dark energy and dark matter.



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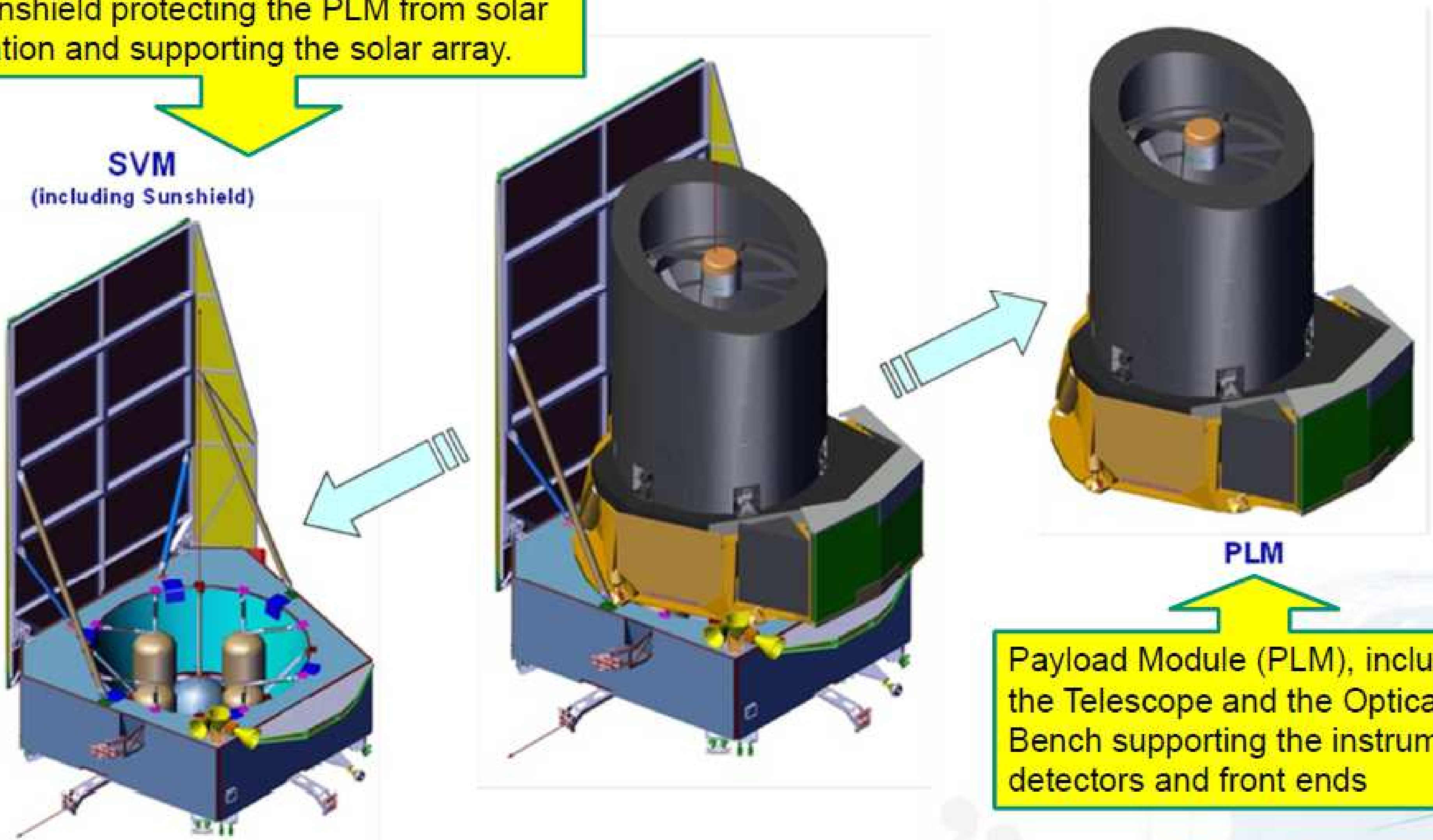
EUCLID SPACECRAFT

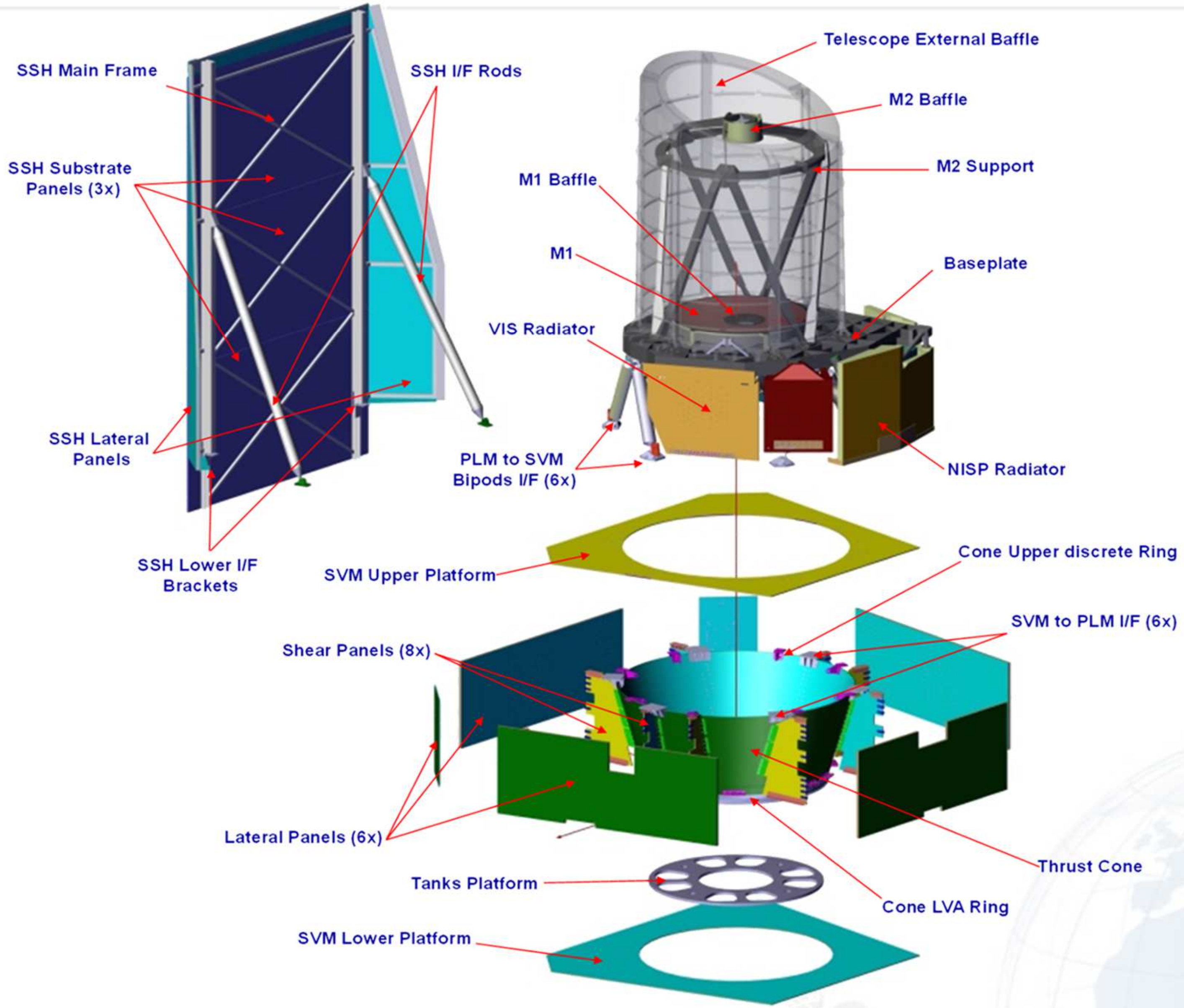
Service Module (SVM) comprising the spacecraft platform with its subsystems and a Sunshield protecting the PLM from solar radiation and supporting the solar array.

The EUCLID spacecraft is composed of:



Payload Module (PLM), including the Telescope and the Optical Bench supporting the instrument detectors and front ends

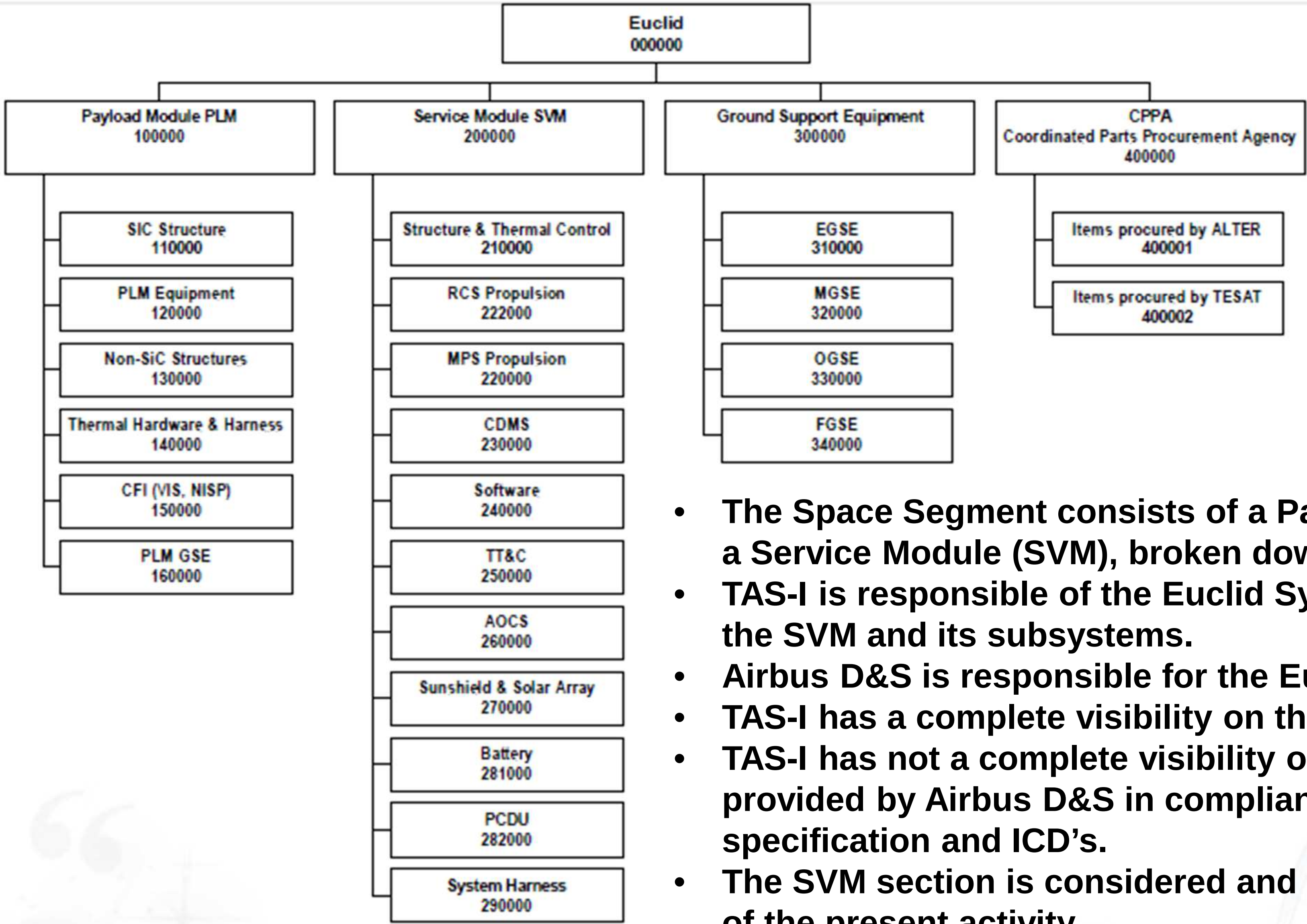
EUCLID PLM mechanical architecture



EUCLID programmatics

MILESTONES	DATES
Phase B2 Kick-off	T0
S/C SRR	T0+7M
S/C PDR	T0+12M
PHASE C/D KICK OFF	T0+12M
S/C CDR	T0+53M
S/C QR	T0+66M
S/C FAR	T0+76M

Euclid product tree



- **The Space Segment consists of a Payload Module (PLM), and a Service Module (SVM), broken down into subsystems.**
- **TAS-I is responsible of the Euclid System spacecraft and of the SVM and its subsystems.**
- **Airbus D&S is responsible for the Euclid PLM.**
- **TAS-I has a complete visibility on the SVM part of Euclid.**
- **TAS-I has not a complete visibility of the design of PLM that is provided by Airbus D&S in compliance with the dedicated specification and ICD's.**
- **The SVM section is considered and screened for the purpose of the present activity.**

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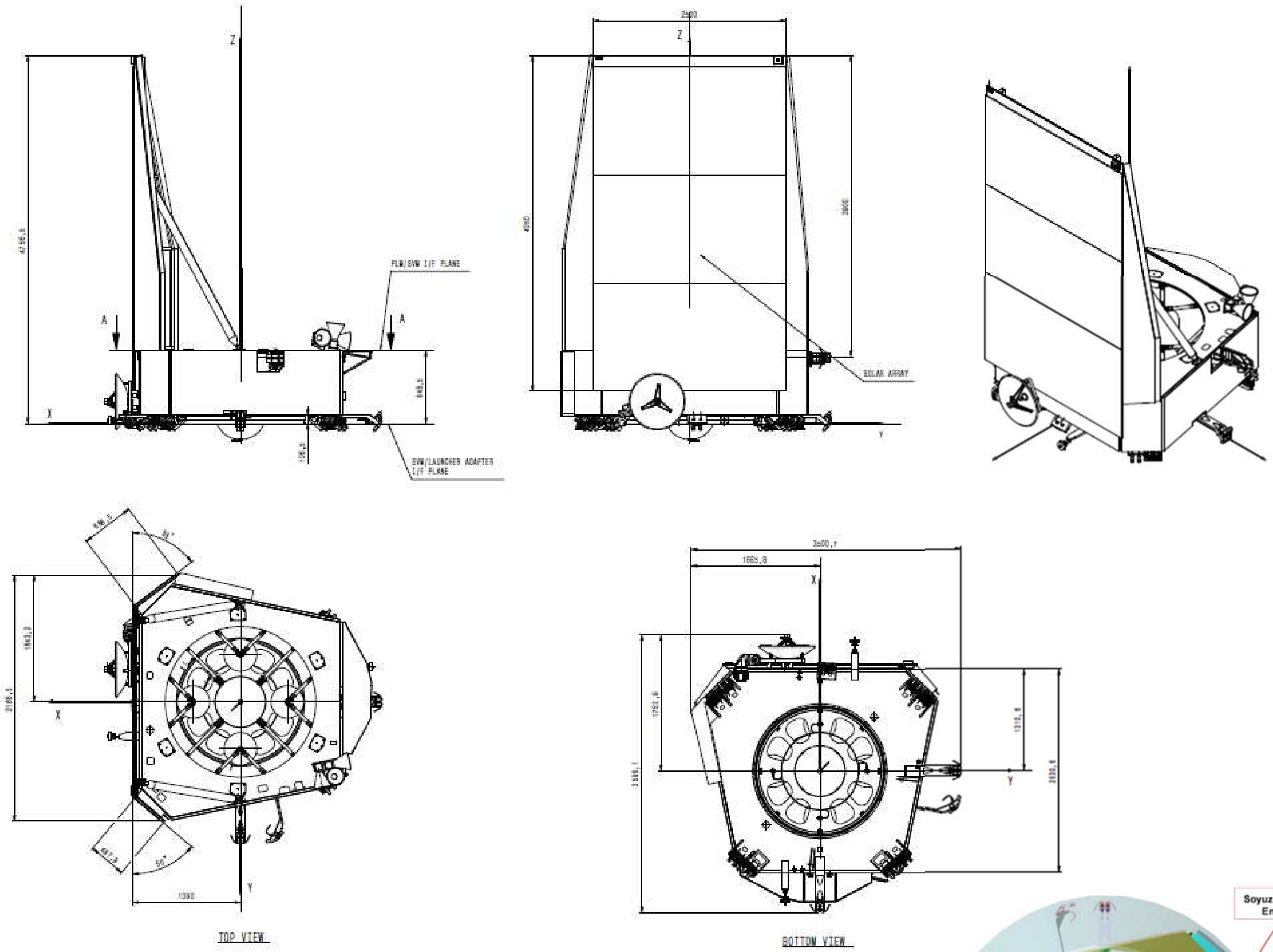
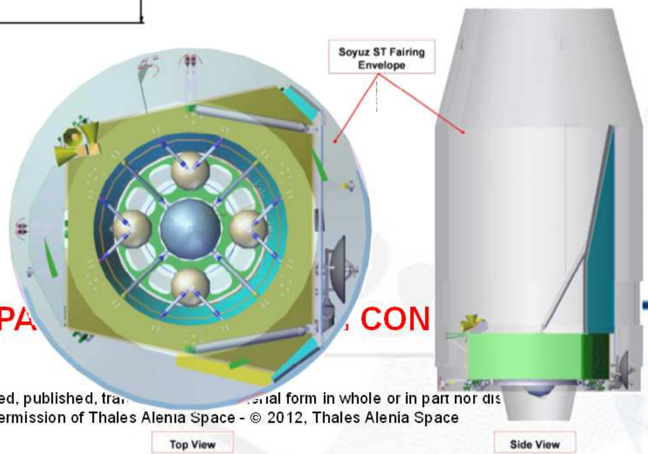
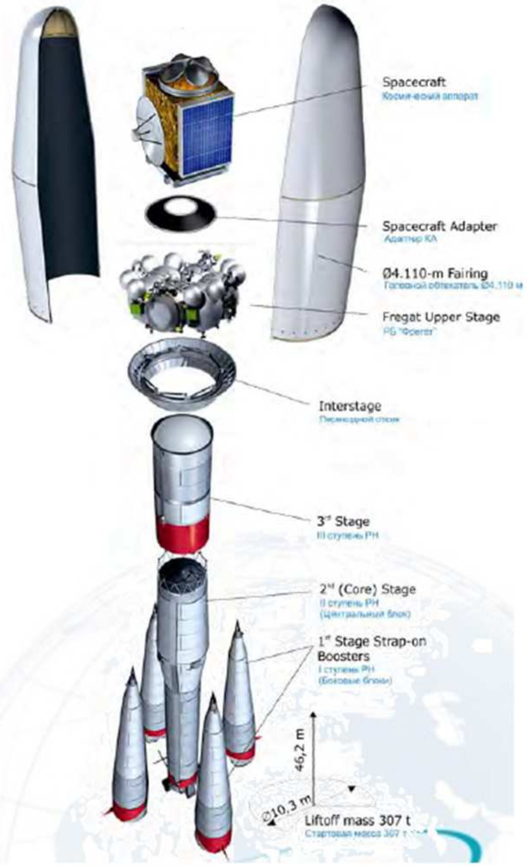
EUCLID satellite: geometric characteristics

The geometric dimensions of the Euclid SVM shape are =
3,6m * 3,5m * 4,7m (x*y*z)

The Launcher selected for the Euclid Satellite is **SOYUZ ST 2-1B**.





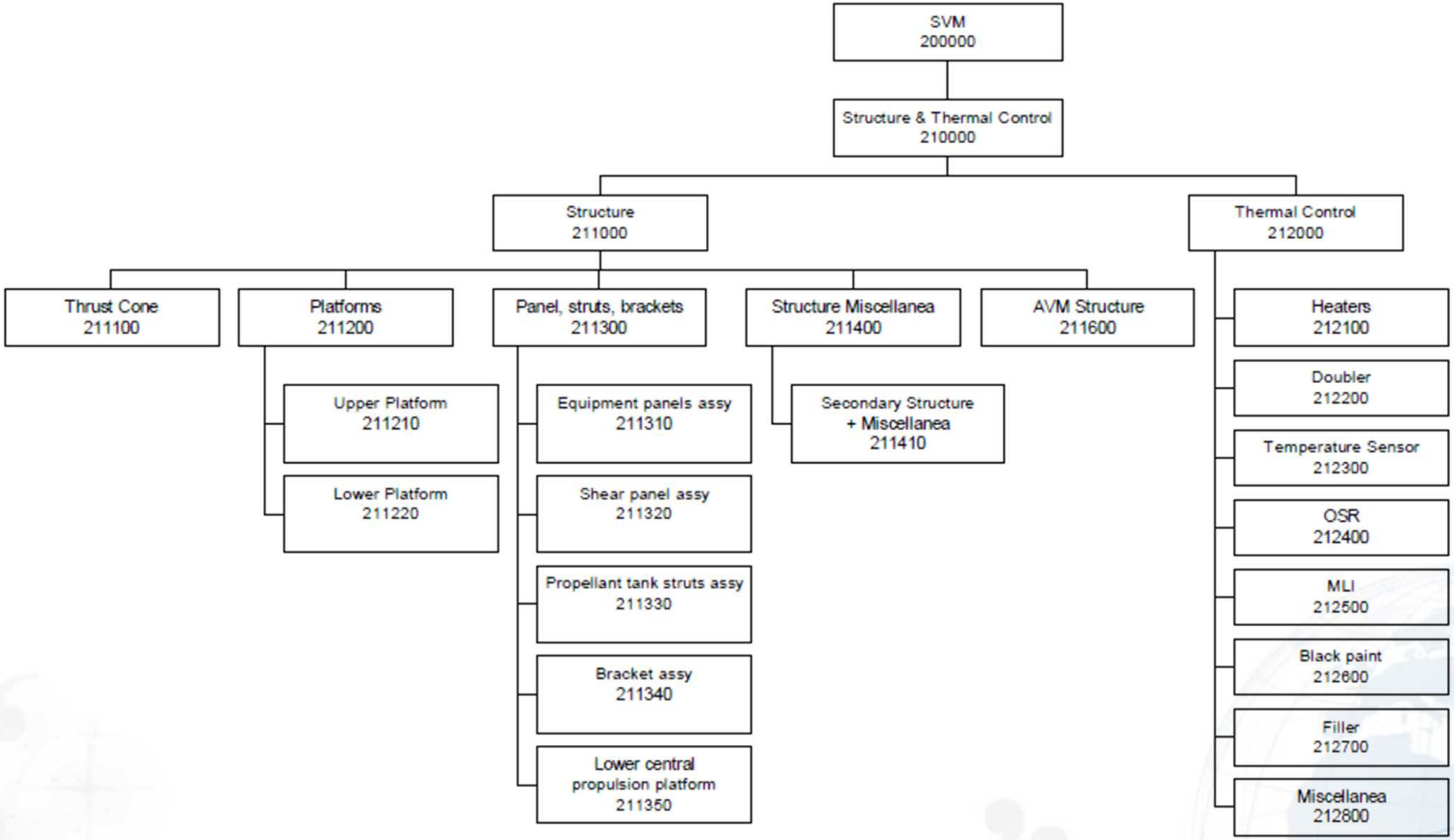


Mass budget

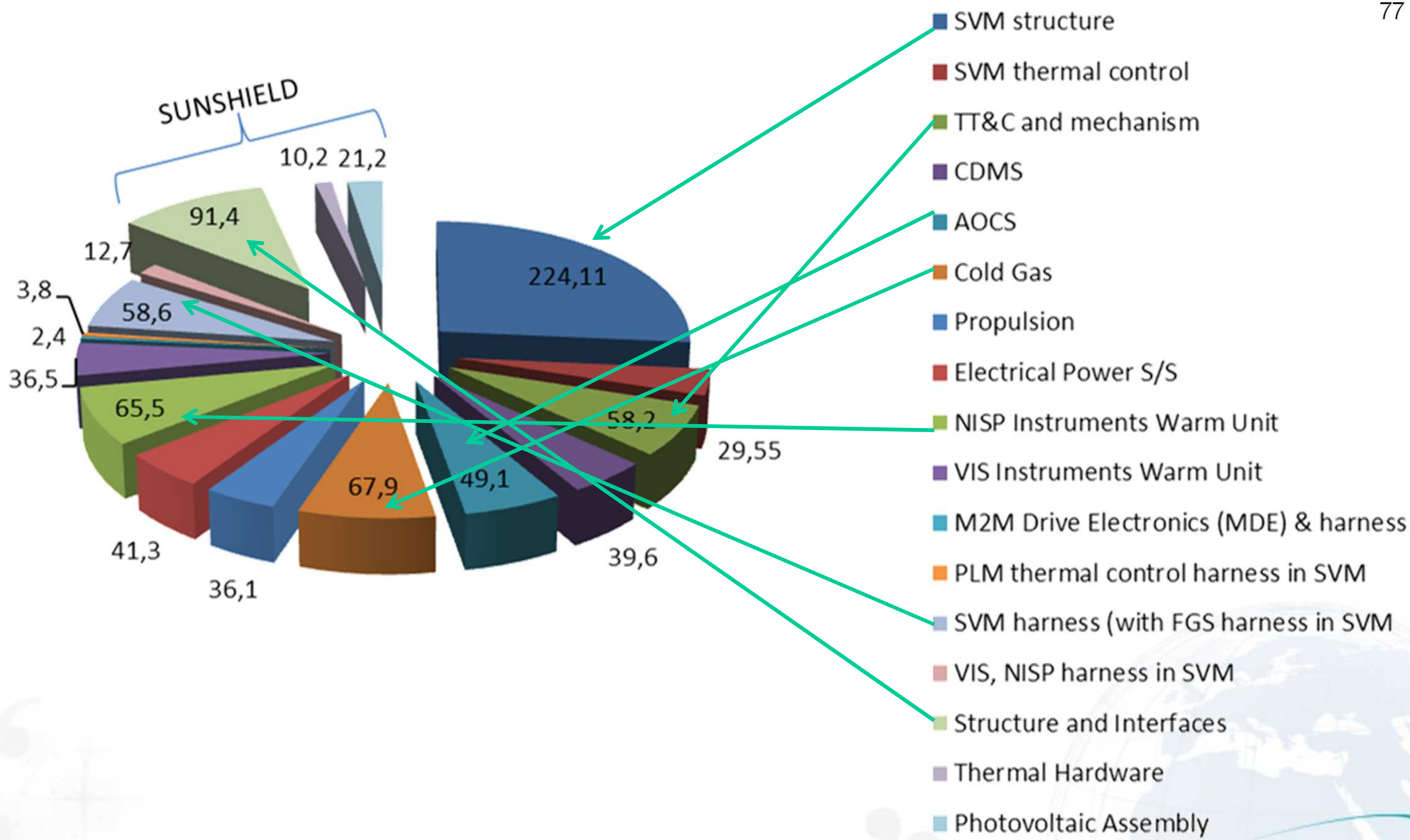
Spacecraft Module	Best Engineering Estimate [kg]	Margin [%]	Margin [kg]	Current Mass [kg]
SVM				
SVM Structure	179,0	15,0%	26,9	205,9
SVM Thermal Control	27,4	15,0%	4,1	31,5
TT&C	54,4	13,1%	7,1	61,5
CDMS	34,8	5,0%	1,7	36,5
AOCS	45,0	5,0%	2,2	47,2
Micro Propulsion System	67,0	6,9%	4,6	71,6
Reaction Control System	46,5	8,3%	3,8	50,4
Electrical Power Subsystem	24,4	4,2%	1,0	25,4
NISP Instruments Warm Units	59,0	6,8%	4,0	63,0
VIS Instruments Warm Units	26,8	30,6%	8,2	35,0
M2M drive electronics (MDE) Assembly	2,7	20,0%	0,5	3,2
FGS Assembly	5,3	20,0%	1,1	6,4
PLM thermal control harness in SVM	2,0	20,0%	0,4	2,4
SVM harness	67,7	20,0%	13,5	81,2
VIS, NISP harness in SVM	15,4	20,0%	3,1	18,4
Radiation Shielding	5,8	20,0%	1,2	6,9
Total SVM	**663,1**	**12,6%**	**83,5**	**746,6**
Sunshield				
Structure and interfaces	63,9	14,0%	8,9	72,8
Thermal hardware	13,0	20,0%	2,6	15,6
Photovoltaic assembly	15,7	0,1	1,5	17,1
Miscellaneous	1,2	0,2	0,2	1,4
Total Sunshield	**93,8**	**14,1%**	**13,2**	**107,0**
PLM				
PLM System (part of R-PLM)	563,2	10,7%	60,0	623,3
VIS and NISP harness (part of R-PLM)	27,2	0,1	2,8	30,0
TOTAL R-PLM	*590,5*	*10,6%*	*62,8*	*653,3*
VIS units in PLM	80,5	21,7%	17,5	98,0
NISP units in PLM	86,1	10,3%	8,9	95,0
FGS units in PLM	5,0	18,9%	1,0	6,0
Total PLM	**762,1**	**11,8%**	**90,2**	**852,3**
Total Spacecraft dry mass	**1519,0**	**12,3%**	**186,9**	**1705,9**
System margin on CFIs				0,0
System margin				**141,5**
PLM System margin (10%)				***65,7***
System margin excluding PLM (10%)				***75,8***
Total Spacecraft dry mass with margin				**1847,4**
Propellant (including pressurant mass) (2% margin included)				126,1
Cold Gas				65,7
Balancing Mass				45,0
Separated launch mass				**2084,2**
Adapter Mass				135,0
Total Launch Mass				**2219,2**
Requirement				**2160,0**
Margin for 135 kg LVA				-59,2
Maximum Mass for Lighter LVA				75,8

Euclid product tree

The screening of the EUCLID parts is based on the Product Tree that provides overview over Spacecraft main breakdown structure into successive levels of hardware items.



Mass budget



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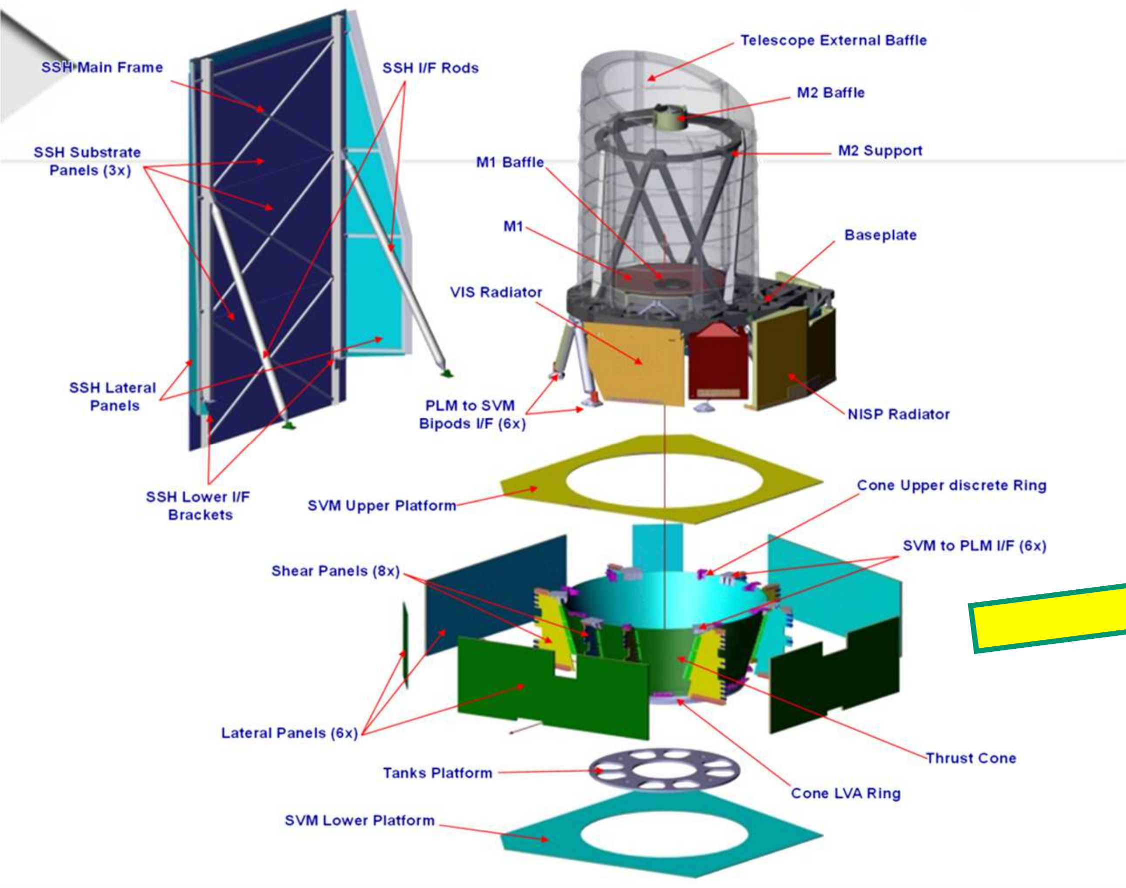
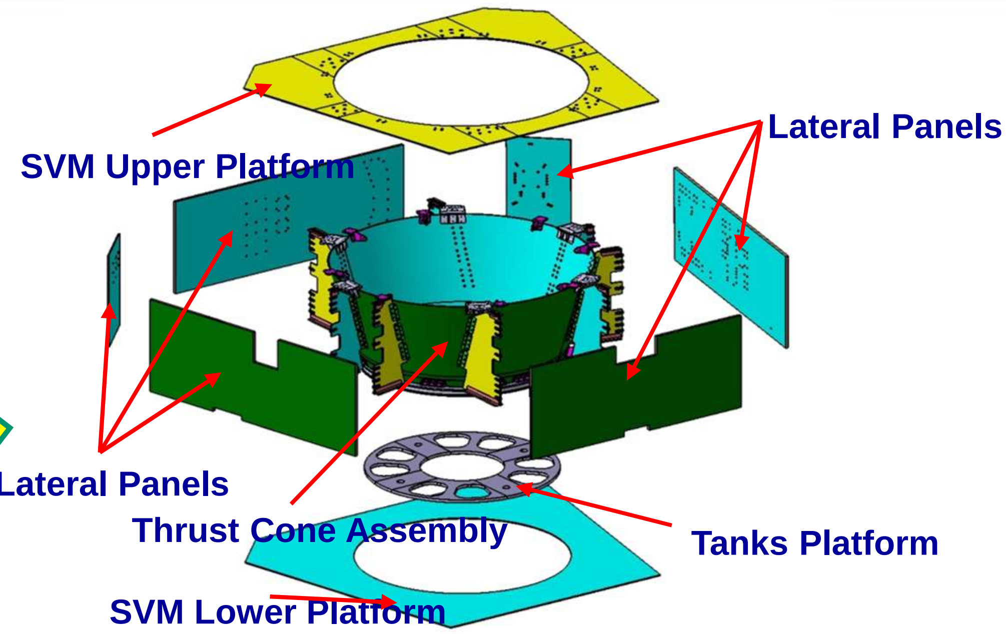
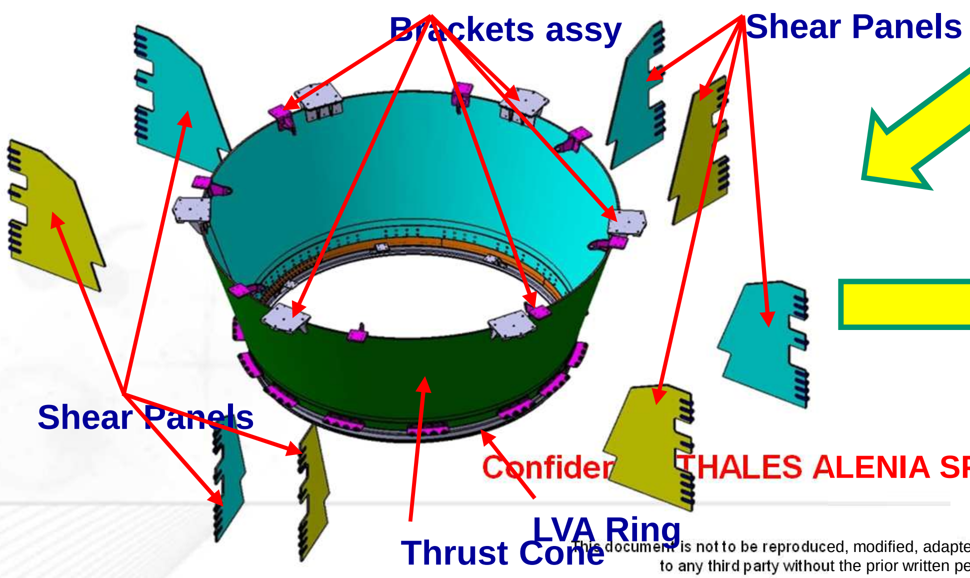
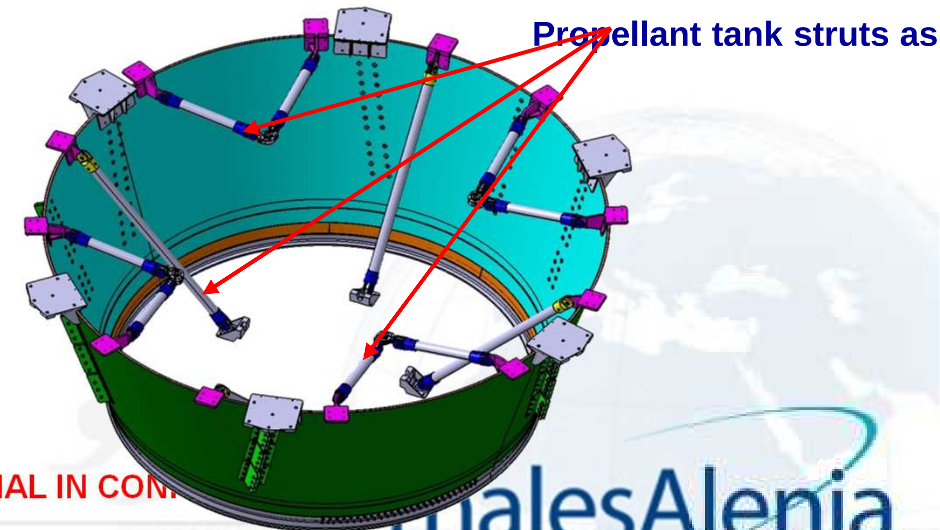
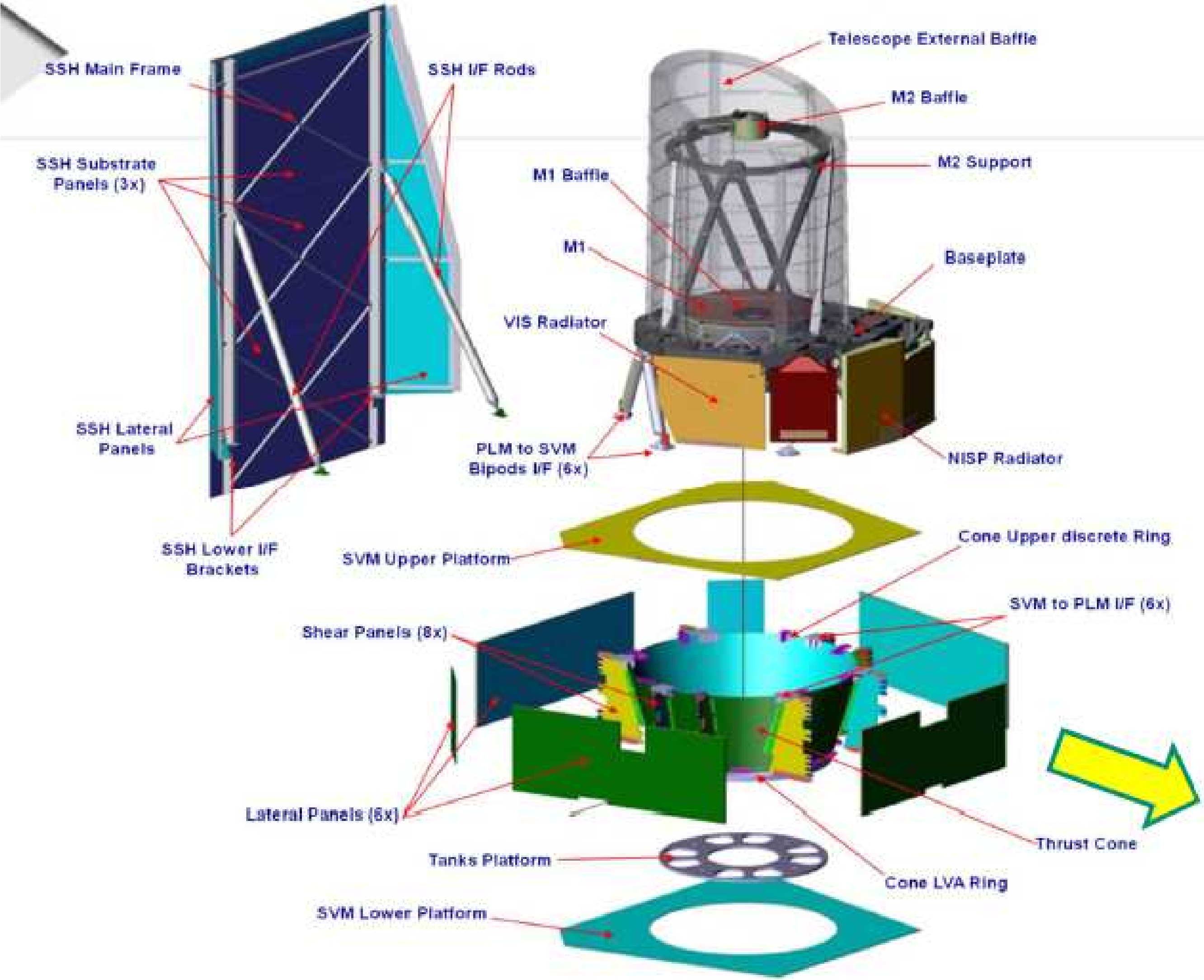

SSH Main Frame
SSH I/F Rods
SSH Substrate Panels (3x)
SSH Lateral Panels
SSH Lower I/F Brackets
Telescope External Baffle
M2 Baffle
M2 Support
M1 Baffle
M1
Baseplate
VIS Radiator
PLM to SVM Bipods I/F (6x)
NISP Radiator
SVM Upper Platform
Cone Upper discrete Ring
SVM to PLM I/F (6x)
Shear Panels (8x)
Lateral Panels (6x)
Thrust Cone
Tanks Platform
Cone LVA Ring
SVM Lower Platform

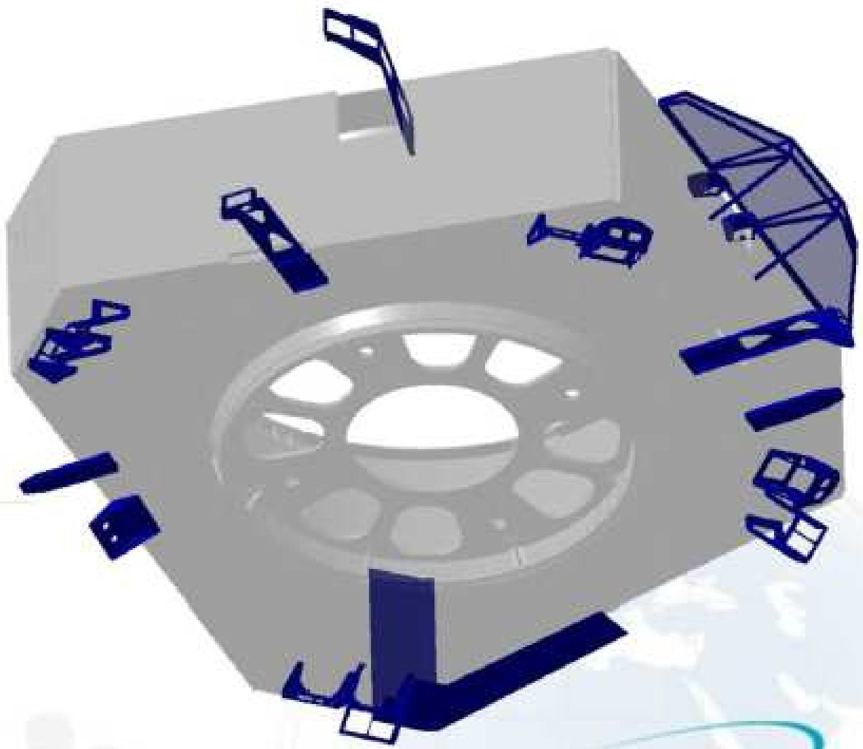

SVM Upper Platform
Lateral Panels
Lateral Panels
Thrust Cone Assembly
Tanks Platform
SVM Lower Platform

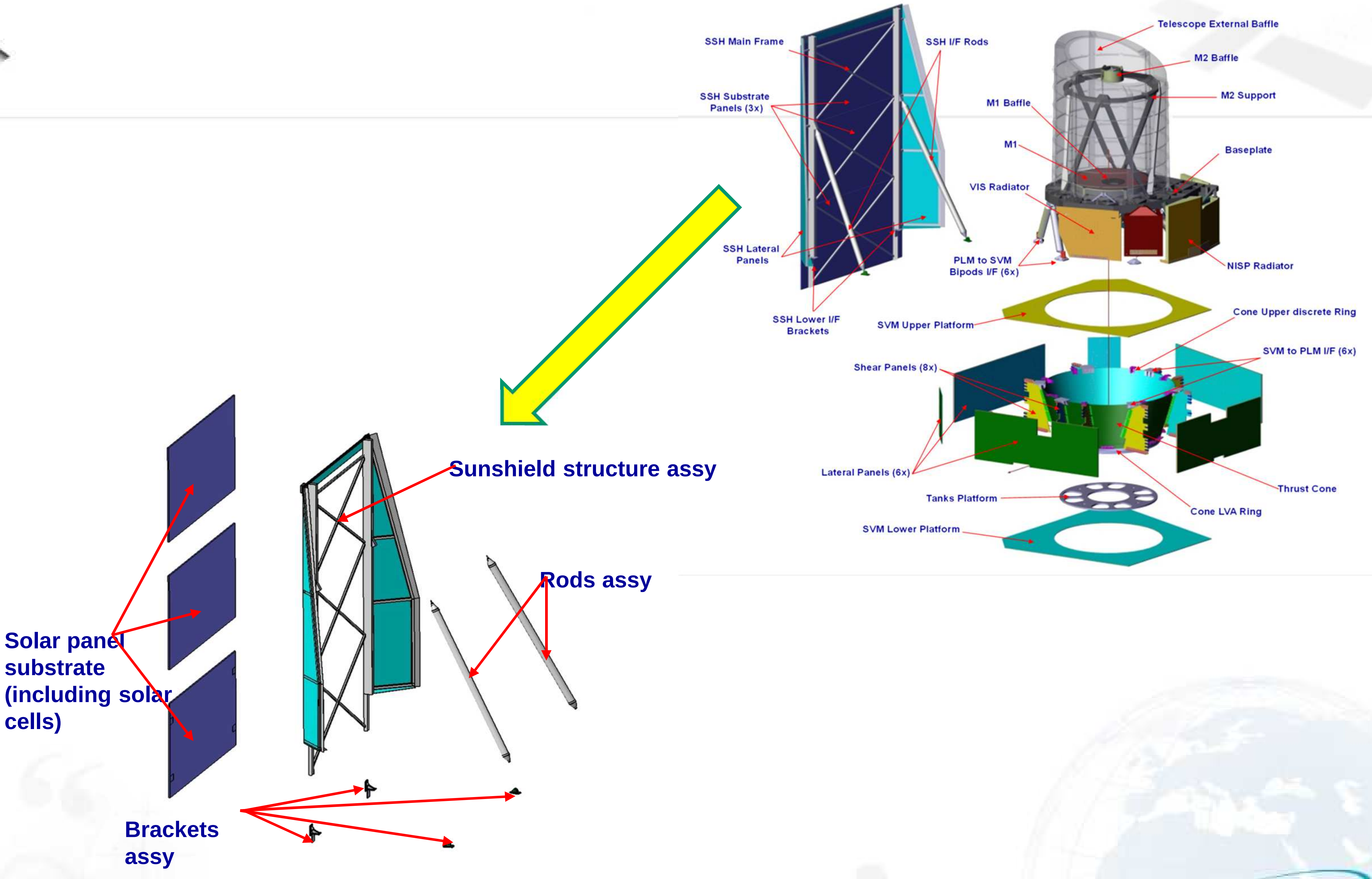

Brackets assy
Shear Panels
Shear Panels
Thrust Cone
LVA Ring


Propellant tank struts as

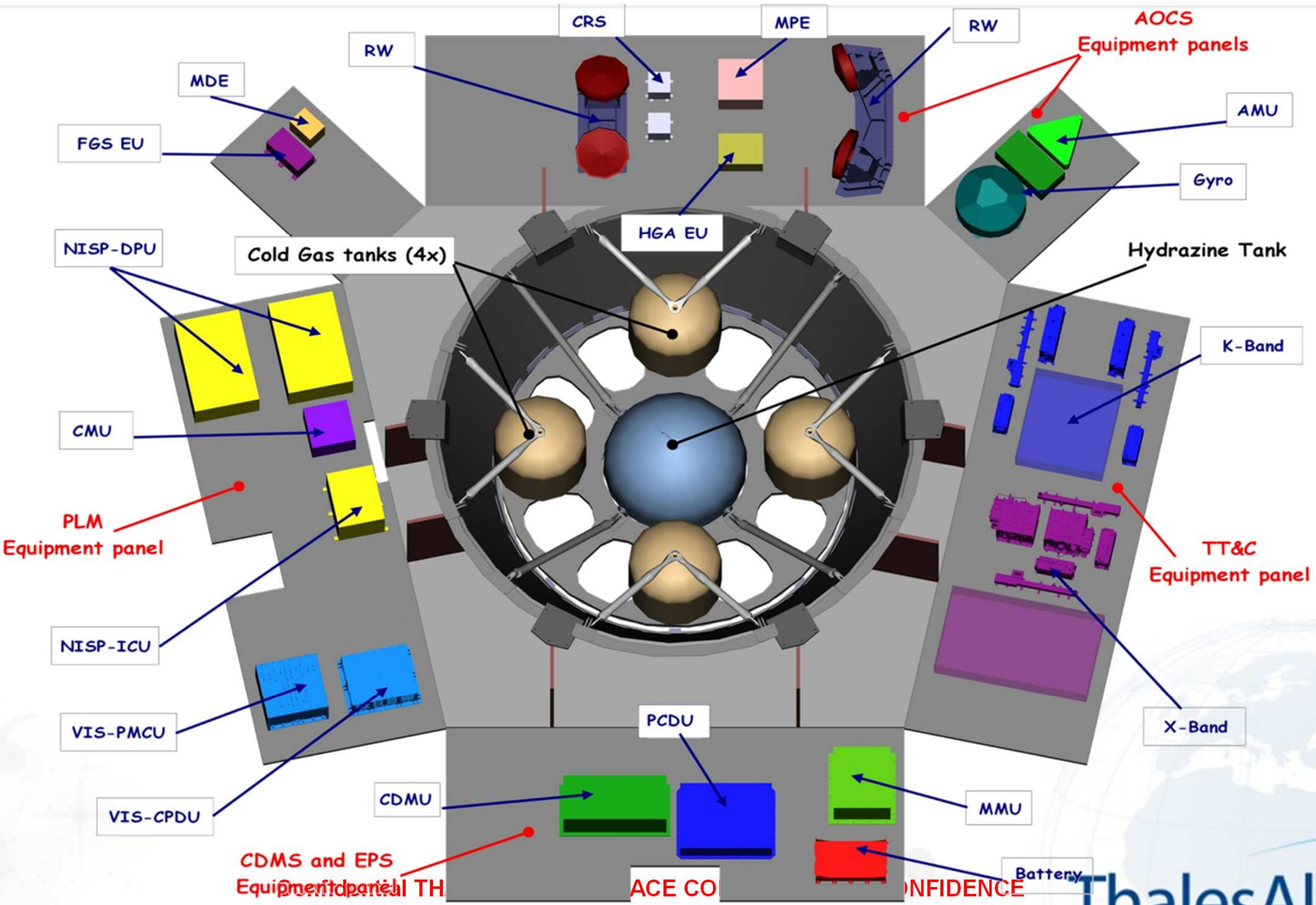


Secondary structure assy (blue components)




SSH Main Frame
SSH I/F Rods
SSH Substrate Panels (3x)
SSH Lateral Panels
SSH Lower I/F Brackets
Telescope External Baffle
M2 Baffle
M2 Support
M1 Baffle
M1
Baseplate
VIS Radiator
PLM to SVM Bipods I/F (6x)
NISP Radiator
SVM Upper Platform
Cone Upper discrete Ring
SVM to PLM I/F (6x)
Shear Panels (8x)
Lateral Panels (6x)
Thrust Cone
Tanks Platform
Cone LVA Ring
SVM Lower Platform
Sunshield structure assy
Rods assy
Solar panel substrate (including solar cells)
Brackets assy

Equipments accommodation on SVM



EUCLID satellite ranking

The five criteria identified for the selection of the most suitable parts to be manufacture through RMFG techniques in the context of the present study are:

Programmatic	
	• Life cycle cost
	• Lead time
	• AIT aspects
Performance	
	• Mass
	• Geometry
	• Interface
	• Reliability
Environment	
	• Material resource
	• Energy resource
	• LOS compatibility

EUCLID satellite ranking

this figure of merit ▶ ▼ this figure of merit compared to	SCORES										Total score	Weighting factor
	Life cycle cost	Lead time	AIT aspects	Mass	Geometry	Interface	Reliability	Material resource	Energy resource	LOS compatibility	**Pi**	**Wi**
Programmatic												
Life cycle cost		-1	0	-1	-1	-1	0	1	1	1	-1	9,8
Lead time	1		1	-1	-1	-1	1	0	1	1	1	10,3
AIT aspects	0	-1		-1	-1	-1	0	-1	1	1	-3	9,3
Performance												
Mass	1	1	1		0	0	1	1	1	1	6	11,6
Geometry	1	1	1	0		0	1	0	1	1	5	11,3
Interface	1	1	1	0	0		1	1	1	1	6	11,6
Reliability	0	-1	0	-1	-1	-1		0	1	1	-2	9,5
Environment												
Material resource	-1	0	1	-1	0	-1	0		1	1	1	10,3
Energy resource	-1	-1	-1	-1	-1	-1	-1	-1		-1	-8	8,0
LOS compatibility	-1	-1	-1	-1	-1	-1	-1	-1	1		-6	8,5
											Q = 39	100,0

For each criterion, a score varying between 0 and 2 (higher is better) is given.
In order to determine the weighting factor of the above described five figures of merit, the following approach was followed:
Each figure of merit (A) is compared to each other (B) according to the following rules
A is more relevant than B → +1 point awarded
- A and B are equally relevant → 0 point awarded
- A is less relevant than B → -1 point awarded

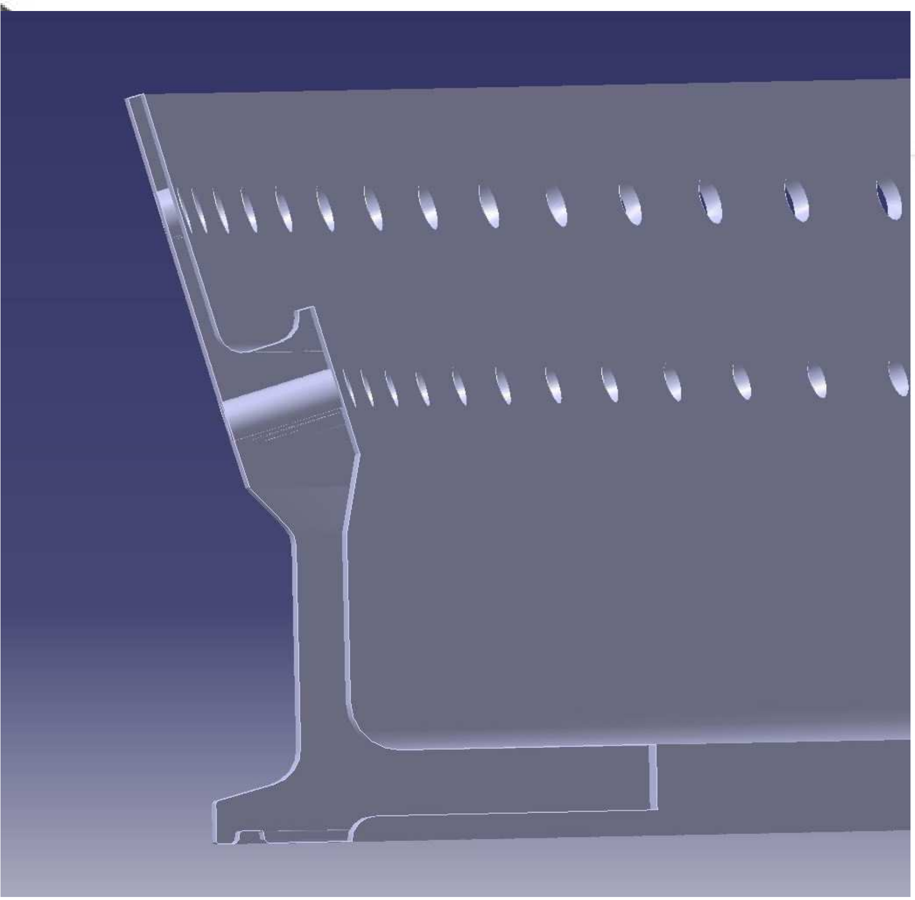
The total amount of points (Pi) collected by each figure of merit (i) is calculated The table below summarizes the process and the results.

EUCLID satellite ranking

Item Number						Item	Material	Life cycle cost	Lead time	AIT aspects	Mass	Geometry	Interface	Reliability	Material resource	Energy resource	LOS compatibility	TOTAL
								9,8	10	9,3	12	11	12	9,5	10	8	8,5	
0						**EUCL**												
2						**SVM**												
2	**1**					**Structure and Thermal Control**												
2	1	1				Structure												
2	1	1	1			Central Thrust Cone Assembly		2	2	2	1	2	3	0	1	1	0	146,1
2	1	1	1	2		PLM Bracket		1	2	2	1	1	2	2	0	0	0	108,4
2	1	1	1	2	1	Upper IF Brackets	Titanium	1	2	0	2	2	1	0	2	0	0	108,4
2	1	1	1	2	2	Internal IF Bracket	Titanium	1	2	0	2	2	1	0	2	0	0	108,4
2	1	1	1	3		Upper IF discrete ring	AA7075 T7351 - Aluminium Alloy	1	2	0	2	2	1	0	2	0	0	108,4
2	1	1	1	4		LVA Ring		1	1	0	0	1	1	1	2	1	0	81,9
2	1	1	1	4	1	LVA IF ring	AA7075 T7351 - Aluminium Alloy	1	2	0	2	2	1	0	2	0	0	108,4
2	1	1	1	4	2	Doubler	AA7075 T7351 - Aluminium Alloy	1	2	0	2	2	1	0	2	0	0	108,4
2	1	1	3			Panels, struts, brackets												
2	1	1	3	1		Lateral Panels (6x)		1	1	1	0	0	1	0	2	2	0	77,6
2	1	1	3	2		Shear Panel (8x)		1	1	1	0	0	1	0	2	2	0	77,6
2	1	1	3	4		Radial Rod (RCS tank)		1	2	1	1	0	2	1	0	1	0	92,8
2	1	1	3	5		Tank Rod (MPS tank)		1	2	1	1	0	2	1	0	1	0	92,8
2	1	1	4	6		Secondary structure - Brackets												0
2	1	1	4	6	1	RW Bracket	AA7075 T7351 - Aluminium Alloy	1	2	0	1	2	0	0	2	0	0	85,2
2	1	1	4	6	8	CMU Supports	AA7075 T7351 - Aluminium Alloy	1	2	0	1	2	0	0	2	0	0	85,2
2	1	1	4	6	9	STR Supports	AA7075 T7351 - Aluminium Alloy	1	2	0	1	2	0	0	2	0	0	85,2
2	**3**					**CDMS**	Data Not Available											0
2	5	8				K-Band HGA Assembly	Data Not Available											0
2	5	8	1			ARA (antenna reflector)	Data Not Available	1	2	2	1	1	2	1	1	1	0	123,7
2	6	8	1	2		FGS PEM (incl. Box)	Data Not Available	1	1	1	2	1	2	0	2	1	0	115,7
2	**7**					**Sunshield & Solar Array**												0
2	7	1				Sunshield Structure		1	2	2	1	1	2	1	1	1	0	123,7

ASSY in orange

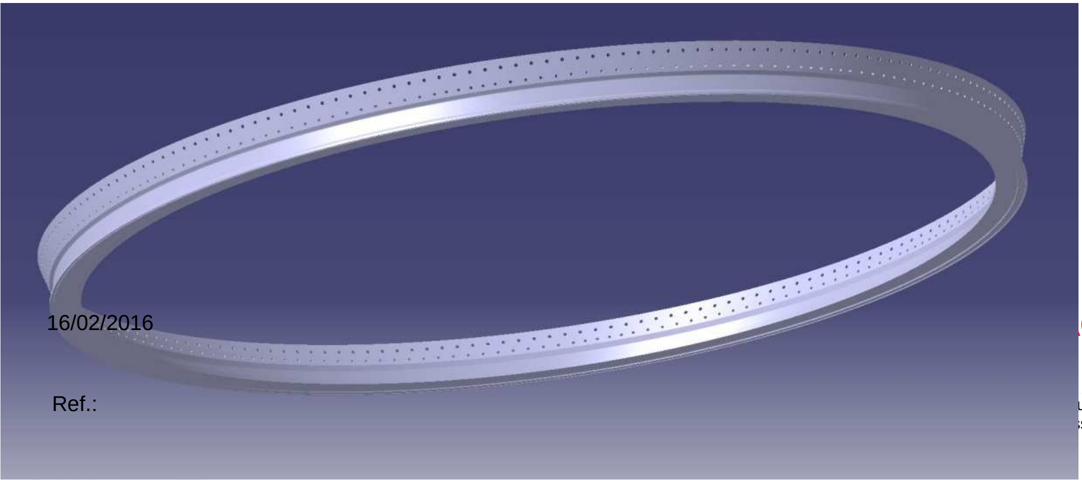
[from 0 = (no/very limited applicability)
to 2 = (high applicability / advanced (component level)



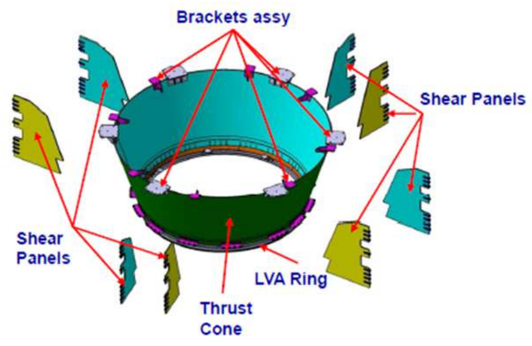
LVA (Launch Vehicle Adapter Ring)

Improvement can be mostly seen on:

- **Lead time:** AM process generically reduces manufacturing logistics from MRR to delivery
- **AIT aspects:** not significant
- **Mass:** redesign can significantly reduce the mass w.r.t. the machined part. The topological optimisation of this part can hypotisise a mass saving of 20%
- **Geometry:** redesigned part modify the geometry without significant advantages on the physical architecture of the s/c
- **Interface:** improvement can be seen if the brackets are included together other parts

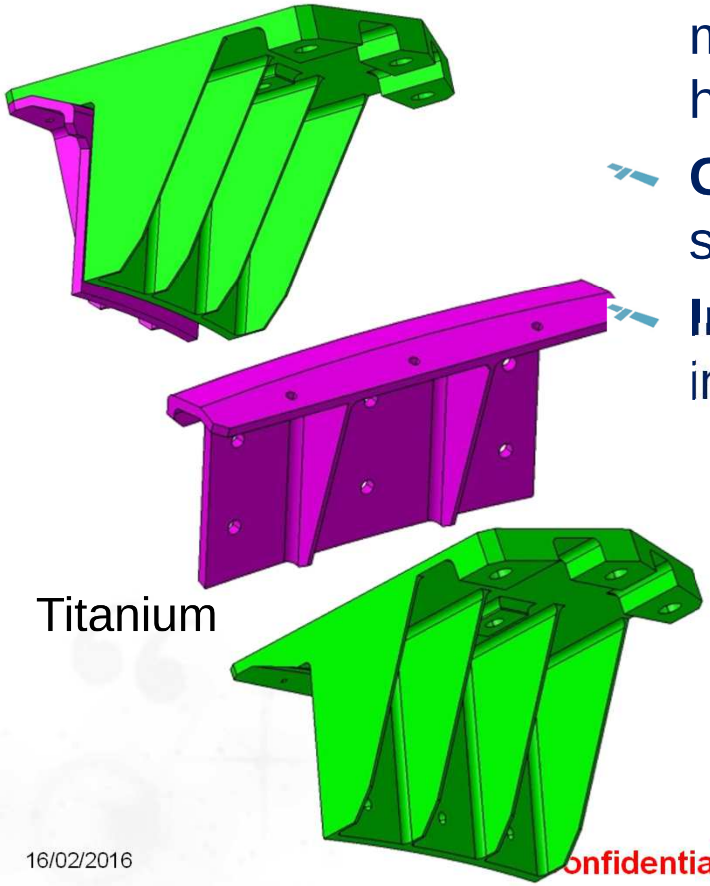


EUCLID satellite selected part: PLM bracket assy

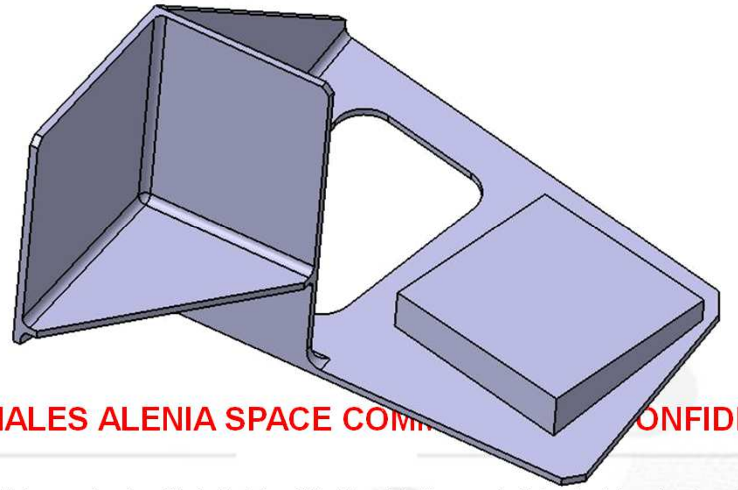


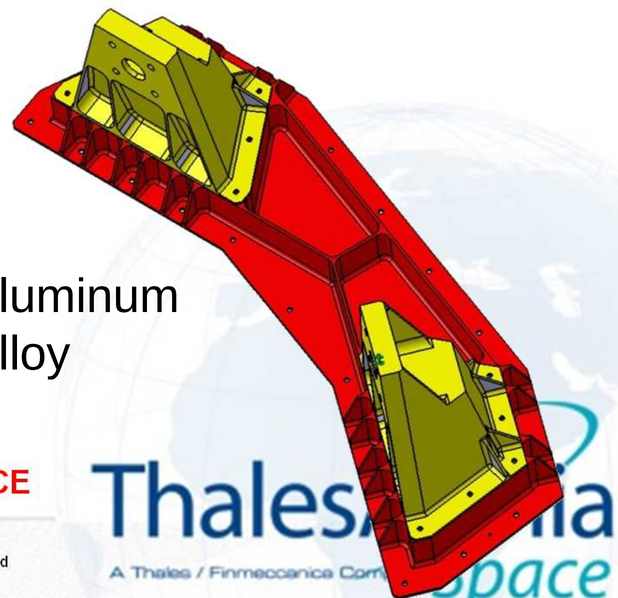
Improvement can be mostly seen on:

- **Lead time:** AM process generically reduces manufacturing logistics from MRR to delivery
- **AIT aspects:** not significant
- **Mass:** redesign can significantly reduce the mass w.r.t. the machined part. The topological optimisation of this part can hypotisise a mass saving of 20%
- **Geometry:** redesigned part modify the geometry without significant advantages on the physical architecture of the s/c
- **Interface:** improvement can be seen if the brackets are included together other parts



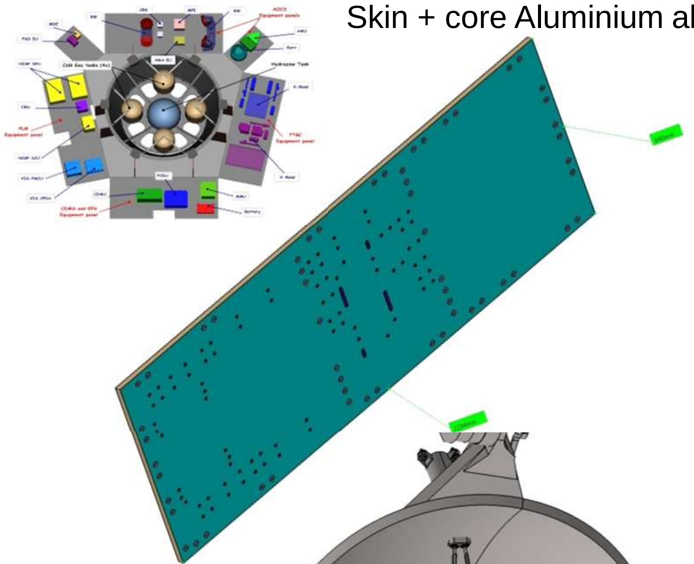
Titanium



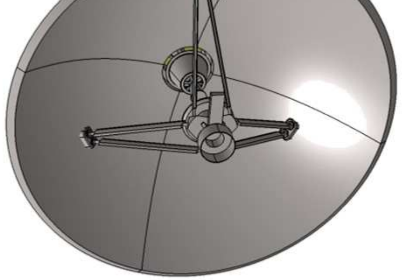


Aluminum Alloy

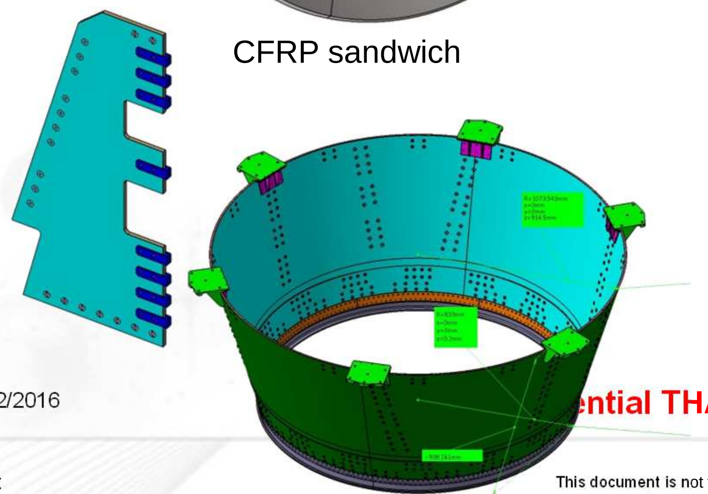
EUCLID satellite selected part: lateral panel



Skin + core Aluminium alloy



CFRP sandwich



skin CFRP-core Aluminum alloy

RUAG replaced the sandwich panel by aluminium frame:

- Replacement of Sentinel-3 panels with frames has a negligible impact on the global stiffness of the satellite structure
- Thermal function can be embedded in the frame if needed
- Harness can be routed inside the frame structure
- Overall mass impact of the frames concept is limited and potentially recovered by optimization runs

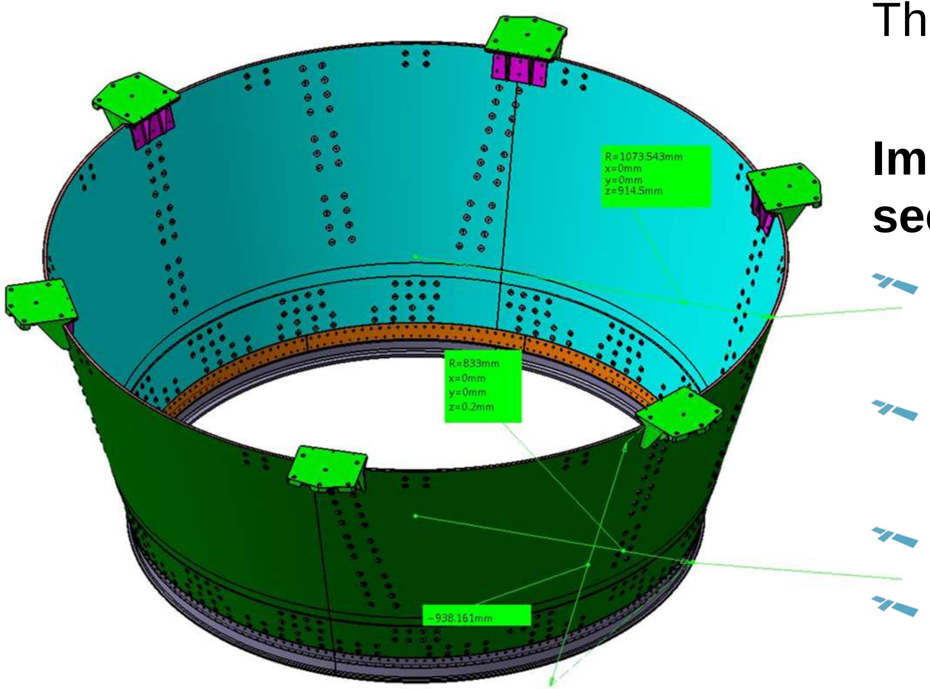
- **Improvement for the Euclid equipment panels can be mostly seen on:**
- **Lead time:** AM process generically reduces manufacturing logistics from MRR to delivery
- **AIT aspects**
- **Mass**
- **Geometry**
- **Interface**
- **Reliability**

Available data does not allow a quantification of the impacts

EUCLID satellite selected part: central thrust cone assy

RUAG replaced the sandwich panel by aluminium frame

The same solution can be adopted by the Euclid panels



skin CFRP-core Aluminium alloy

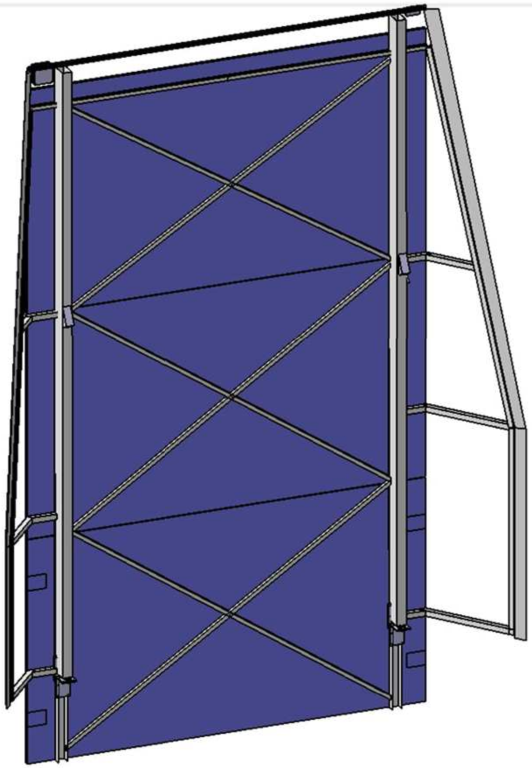
Improvement for the Euclid thrust cone can be mostly seen on:

- **Lead time:** AM process generically reduces manufacturing logistics from MRR to delivery
- **AIT aspects:** sensibly improved if parts can be manufactured already assembled
- **Mass:** to be assessed
- **Geometry and Interface:** can be improved if the PLM brackets could be included, even partially

EUCLID satellite selected part: antenna reflector

- **Improvement can be mostly seen on:**
- **Lead time:** AM process generically reduces manufacturing logistics from MRR to delivery
- **AIT aspects:**
- **Mass**
- **Geometry**
- **Interface**
- **Reliability**
- **Material resource**
- **Energy resource**
- **LOS compatibility**

EUCLID satellite selected part: Sunshield structure

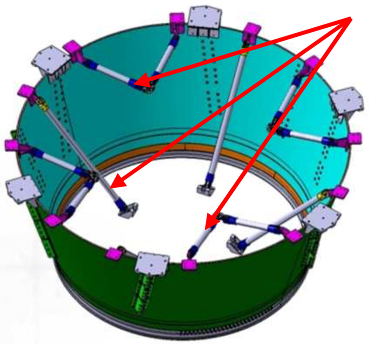


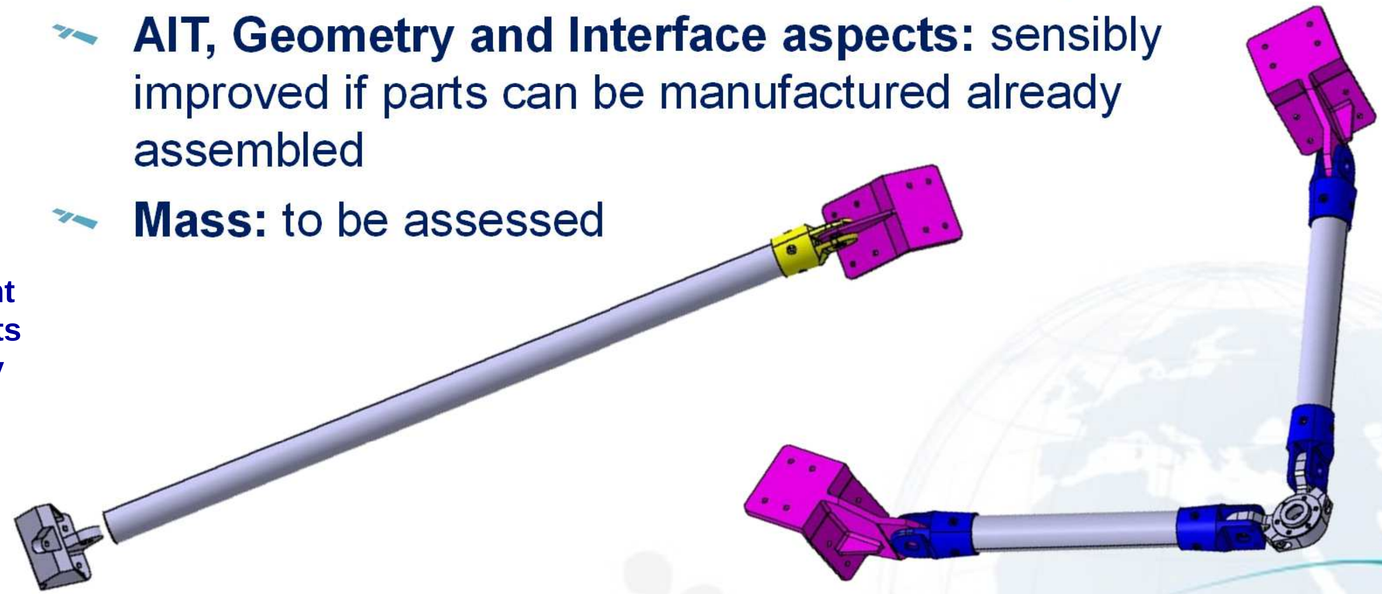
RUAG replaced the sandwich panel by aluminium frame

The same solution can be adopted by the Euclid sunshield substrate panels

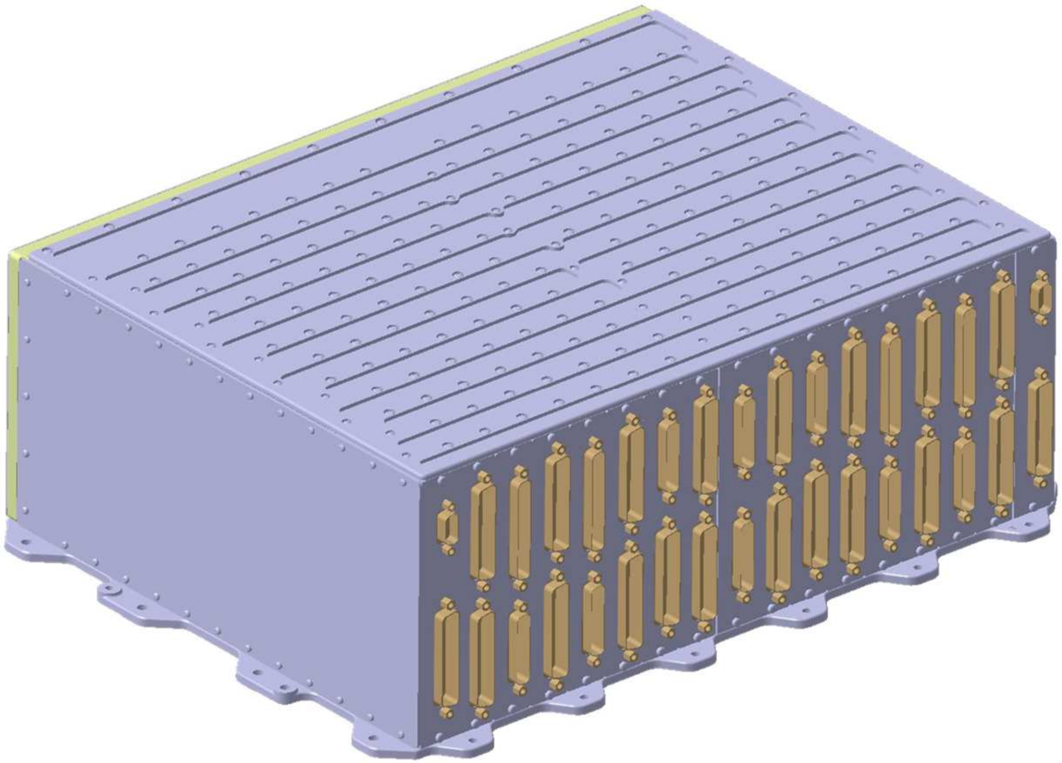
Improvement for the Euclid support structures can be mostly seen on:

- **Lead time:** AM process generically reduces manufacturing logistics from MRR to delivery
- **AIT, Geometry and Interface aspects:** sensibly improved if parts can be manufactured already assembled
- **Mass:** to be assessed





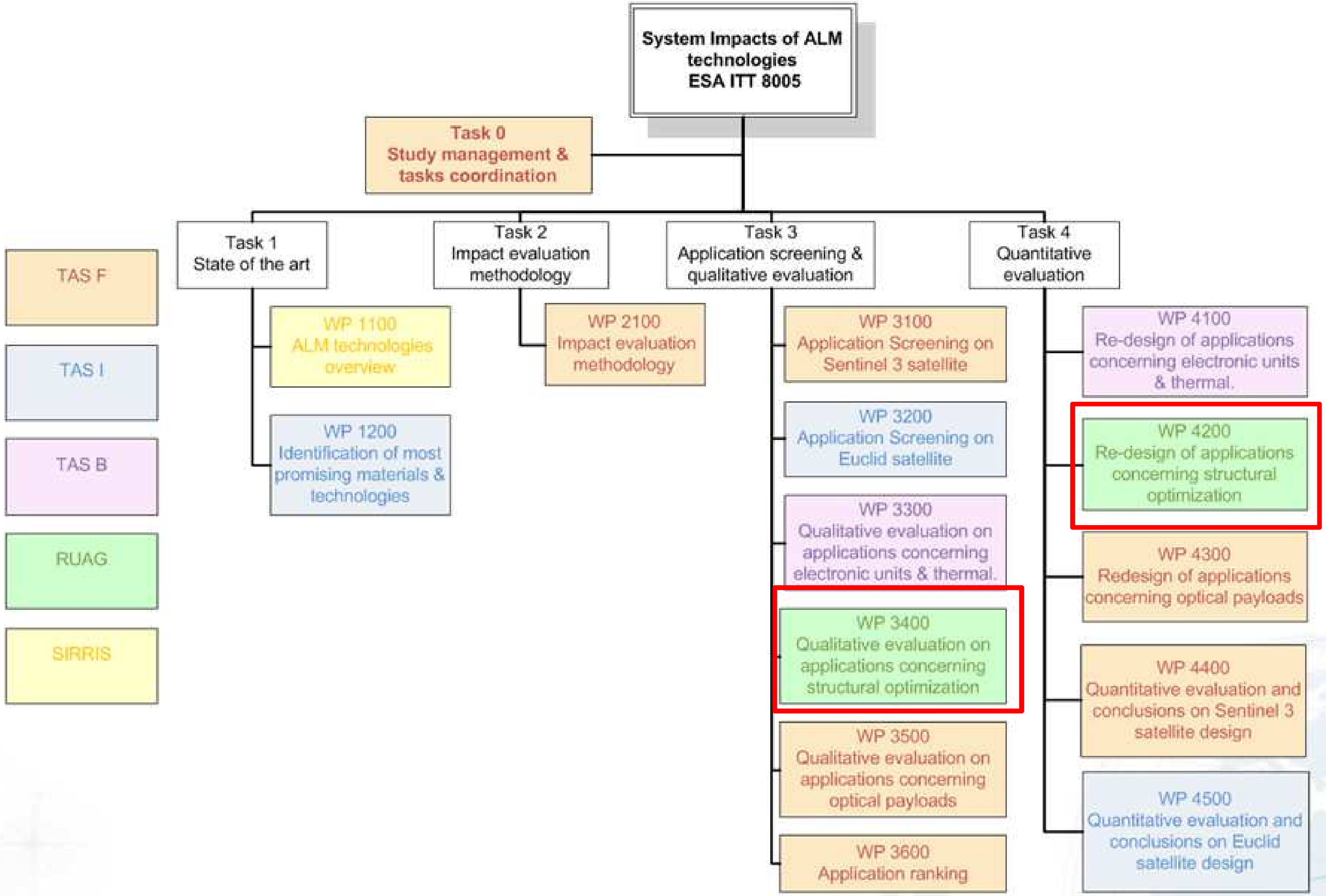
EUCLID sat. selected part: Power Control and Distribution Unit PCDU



- **Improvement can be mostly seen on:**
- **Lead time:** AM process generically reduces manufacturing logistics from MRR to delivery
- **AIT aspects**
- **Mass, Geometry, Interface:** possible improvement can be derived from the redesign of the metallic case
- **Reliability**
- **Material resource**
- **Energy resource**
- **LOS compatibility**

- 8. Structural optimisation – Quantitative evaluation on applications and redesign activities – WP 3400/4200 (RUAG-Switzerland)

- RUAG scope of work (WP 3400; WP 4200)



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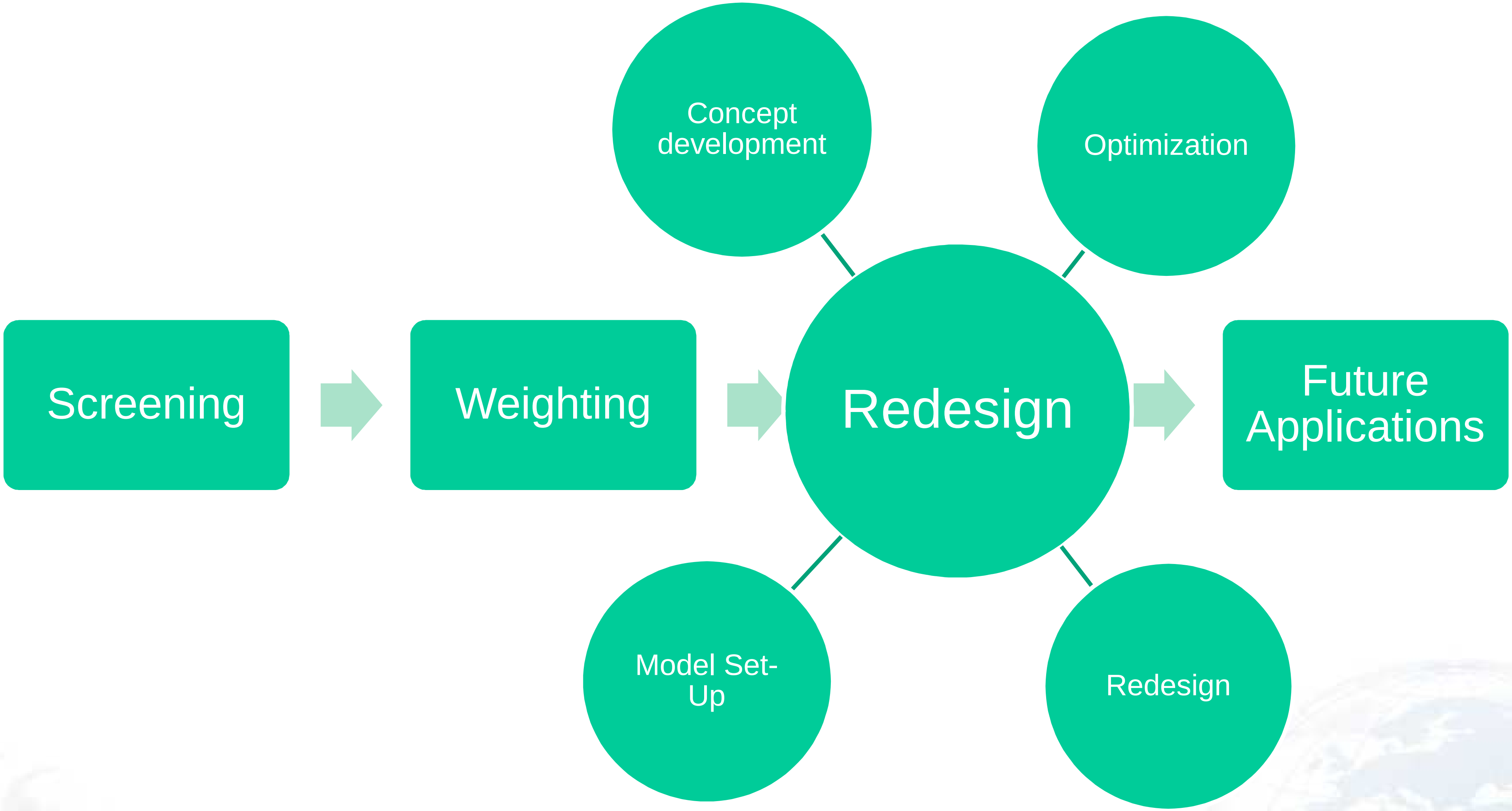
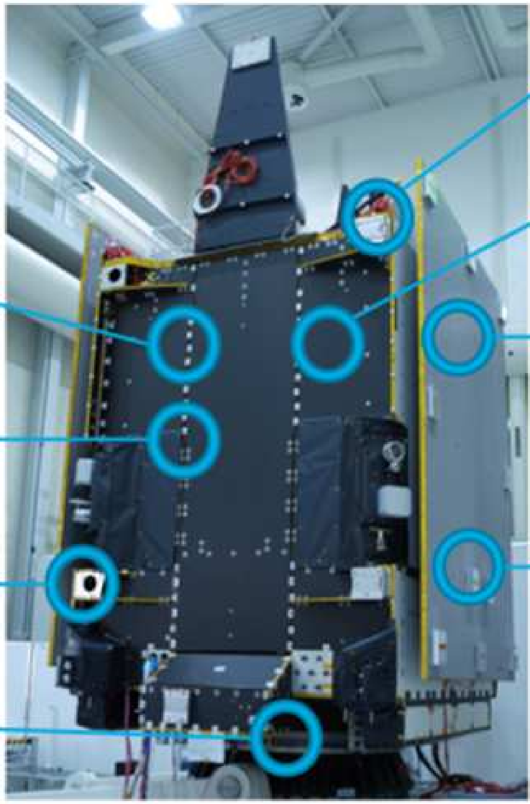
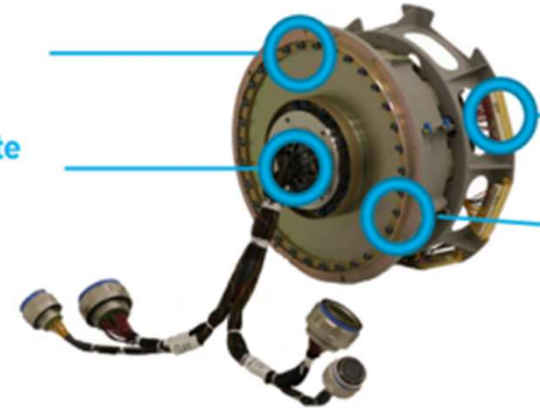
Summery - Flow of activities RUAG work packages




Optimised Lifting Brackets
Customised honeycomb
Sandwich Panel Edge Inserts
Integrated Heat Pipes
Sandwich Panel Spool Inserts
Equipment Support Brackets
Optimised Thermal Doublers
Interface rings/adapters

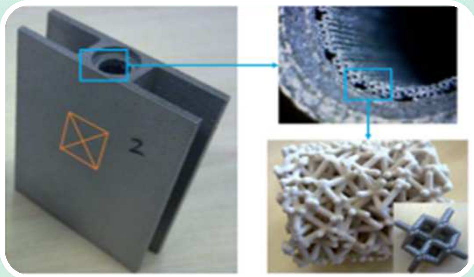

Reduced interfaces
Connector Brackets
Integrate cables
Mass optimised design

- Main identified fields of action for structural applications and mechanisms:

Mechanical/Physical Performance	Integration of function

Mechanical/Physical Performance

Source RUAG



Source thermacore

Source CalTech.edu

Stiffness

- Optimize structural parts to achieve better performance in terms of stiffness
- Reduce mass
- Design for dimensional stability by adapting the part stiffness

Thermal performance

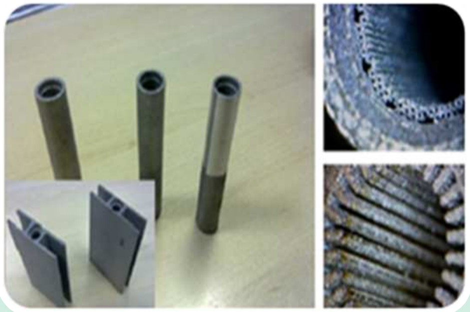
- Optimize heat transport within a part
- Improve heat pipe thermal performance by implementing a porous capillary wick

Multi material properties

- Combine two or more materials in a single part to implement domains of specific mechanical and physical properties
- Coatings
- Electrical conductivity

Integration of Functions

Source mms



Source thermacore

Source DuPont

Wiring

- Reduce effort for cable routing
- Make ty-bases and stand-offs obsolete
- Reduce AIT effort

Structural part with integrated Heat Pipes

- Directly include complex shaped, printed heat pipes in structural parts
- Reduce AIT effort
- Potential for mass saving

Conductive elements/ Grounding network

- Reduce AIT effort
- Conductive ink
- Heater elements
- Grounding network

Weighting of identified fields of action

Together ahead. RUAG

	Structural parts											
1. Programmatic impact	Wiring		Brackets; Cleats		Conductive elements/ Grounding network		Integration of Thermal functions		Inserts/Core elements		Rings/Adapters	
Life-cycle cost	0	For recuring projects no update of design and manf' assumed	0	For recuring projects no update of design and manf' assumed	0	For recuring projects no update of design and manf' assumed	0	For recuring projects no update of design and manf' assumed	0	For recuring projects no update of design and manf' assumed	0	For recuring projects no update of design assumed
Lead time	3	potential reduction in lead time; less machining effort	6				6	e.g			9	lead time compared to forgings can be reduced significantly
		AIT; test on ...le level	0				6				0	usually no test on ring/adapter level
AIT integration	6	integration effort reduced since features are already included	3	integration effort reduced since features already included;	6	integration effort reduced since features already included (e.g. grounding network printed...)	9	integration effort reduced significantly since features are already included	0	no impact identified	3	integration effort can be reduced due to integration of elements (e.g. MLI stand-offs, Ty-bases...)
2. Performance impact	W				Conductive elements/ Grounding network				Inserts/Core elements			
Mass	3	mass saving in combination with topology optimisation	9	significant mass saving in combination with topology optimisation	0			...ue to ...d	3	m... with topology optimisation		topology optimisation
Geometry	9	Wiring removed from top surface; more space for equipment	6	reduction of design space feasable; less interfaces	0	no impact identified	6	reduction in design space space feasable (module concept; compare with TAS-B proposal)	0	no impact identified	3	reduction of design space feasable
Interface simplification	3	some potential to reduce the number of interfaces (no Stand Off's)	3	some potential to reduce the number of interfaces (monolithic parts)	3	some potential to reduce number of interfaces (e.g. grounding network directly printed)	9	number of interfaces can be significantly reduced (module concept)	3	some potential to reduce the number of interfaces (depending on the design)	3	some potential to reduce the number of interfaces (depending on the design)
Realiabilty	0	no impact identified	0	no impact identified	0	no impact identified	0	no impact identified	0	no impact identified	0	no impact identified
3. Environmental impact	Wiring		Brackets		Conductive elements/ Grounding network		Thermal functions		Inserts/Core elements		Rings/Adapters	
Material resources	0	limited	6	amount of "machined away" material reduced	0	limited	6	amount of "machined away" material reduced	6	amount of "machined away" material reduced	9	amount of "machined away" material reduced significantly
Energy resources	0	limited	0	limited	0	limited	0	limited	0	limited	0	limited
Cleanspace	0	parts will not reach ground	0	parts will not reach ground	0	parts will not reach ground	0	parts will not reach ground	0	parts will not reach ground	3	AM design to prevent bulk material that poses a potential risk to reach ground during re-entry
Weighting	27		33		15		45		15		36	

Wiring

Brackets & Cleats

Conductive Elements/ Grounding Network

Integration of Thermal Functions

Inserts/Core Elements

Ring/Adapters

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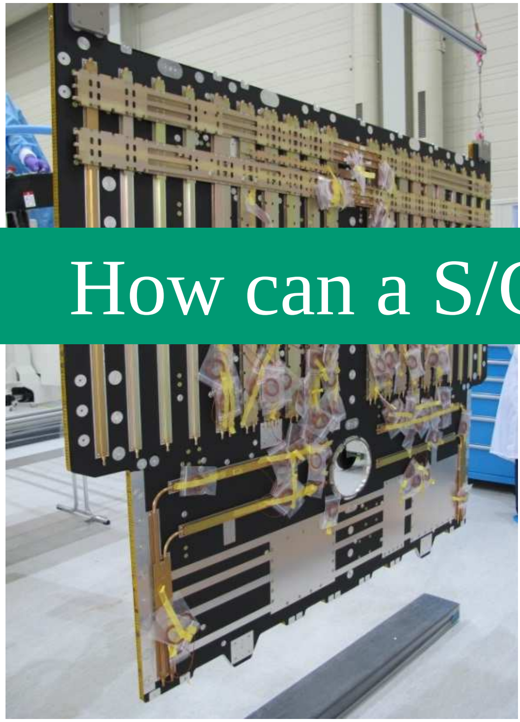
Weighting of identified field of action

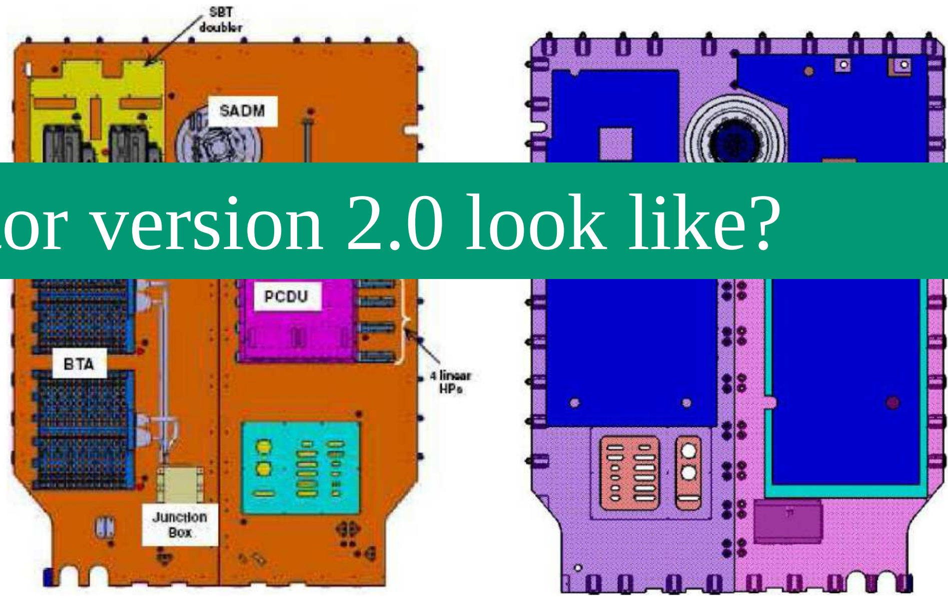
	Structural parts											
1. Programmatic impact	Wiring		Brackets; Cleats		Conductive elements/ Grounding network		Integration of Thermal functions		Inserts/Core elements		Rings/Adapters	
Life-cycle cost	0	For recuring projects no update of design and manf assumed	0	For recuring projects no update of design and manf assumed	0	For recuring projects no update of design and manf assumed	0	For recuring projects no update of design and manf assumed	0	For recuring projects no update of design and manf assumed	0	For recuring projects no update of design assumed
Lead time	3	potential reduction in lead time; less machining effort	6	lead time can be reduced; no forgings/plates required	3	potential reduction in lead time lead time of conductive elements	6	e.g. lead time can be reduced; lead time heat pipes...	3	lead time can be reduced no semi finished products needed	9	lead time compared to forgings can be reduced significantly
AIT tests	3	potential reduction in AIT; test on integrated module level	0	no impact identified	3	potential reduction in AIT; test on integrated module level	6	test on module level	0	no impact identified	0	usually no test on ring/adapter level
AIT integration	6	integration effort reduced since features are already included	3	integration effort reduced since features already included; interfaces reduced	6	integration effort reduced since features already included (e.g. grounding network printed...)	9	integration effort reduced significantly since features are already included	0	no impact identified	3	integration effort can be reduced due to integration of elements (e.g. MLI stand-offs, Ty-bases...)
2. Performance impact	Wiring		Brackets		Conductive elements/ Grounding network		Thermal functions		Inserts/Core elements		Rings/Adapters	
Mass	3	mass saving in combination with topology optimisation	9	significant mass saving in combination with topology optimisation	0	no impact identified	3	mass savings seen feasable due to integration of functions and reduction of interfaces	3	mass saving in combination with topology optimisation	6	mass saving in combination with topology optimisation
Geometry	9	Wiring removed from top surface; more space for equipment	6	reduction of design space feasable; less interfaces	0	no impact identified	6	reduction in design space space feasable (module concept; compare with TAS-B proposal)	0	no impact identified	3	reduction of design space feasable
Interface simplification	3	some potential to reduce the number of interfaces (no Stand Off's)	3	some potential to reduce the number of interfaces (monolithic parts)	3	some potential to reduce number of interfaces (e.g. grounding network directly printed)	9	number of interfaces can be significantly reduced (module concept)	3	some potential to reduce the number of interfaces (depending on the design)	3	some potential to reduce the number of interfaces (depending on the design)
Realiabilty	0	no impact identified	0	no impact identified	0	no impact identified	0	no impact identified	0	no impact identified	0	no impact identified
3. Environmental impact	Wiring		Brackets		Conductive elements/ Grounding network		Thermal functions		Inserts/Core elements		Rings/Adapters	
Material resources	0	limited	6	amount of "machined away" material reduced	0	limited	6	amount of "machined away" material reduced	6	amount of "machined away" material reduced	9	amount of "machined away" material reduced significantly
Energy resources	0	limited	0	limited	0	limited	0	limited	0	limited	0	limited
Cleanspace	0	parts will not reach ground	0	parts will not reach ground	0	parts will not reach ground	0	parts will not reach ground	0	parts will not reach ground	3	AM design to prevent bulk material that poses a potential risk to reach ground during re-entry
Weighting	27		33		15		45		15		36	

Based on the weighting done in WP3400, the highlighted two applications were subjected to further re-design activities.

How can a S/C radiator version 2.0 look like?

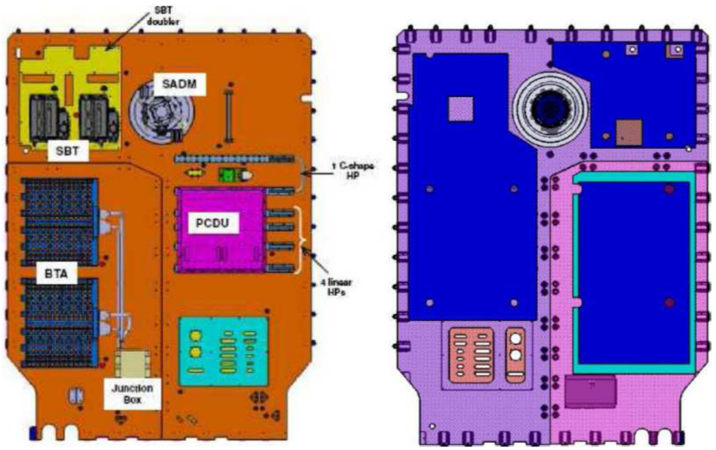


Heat pipe network on SGEO Payload Radiator (source RUAG)

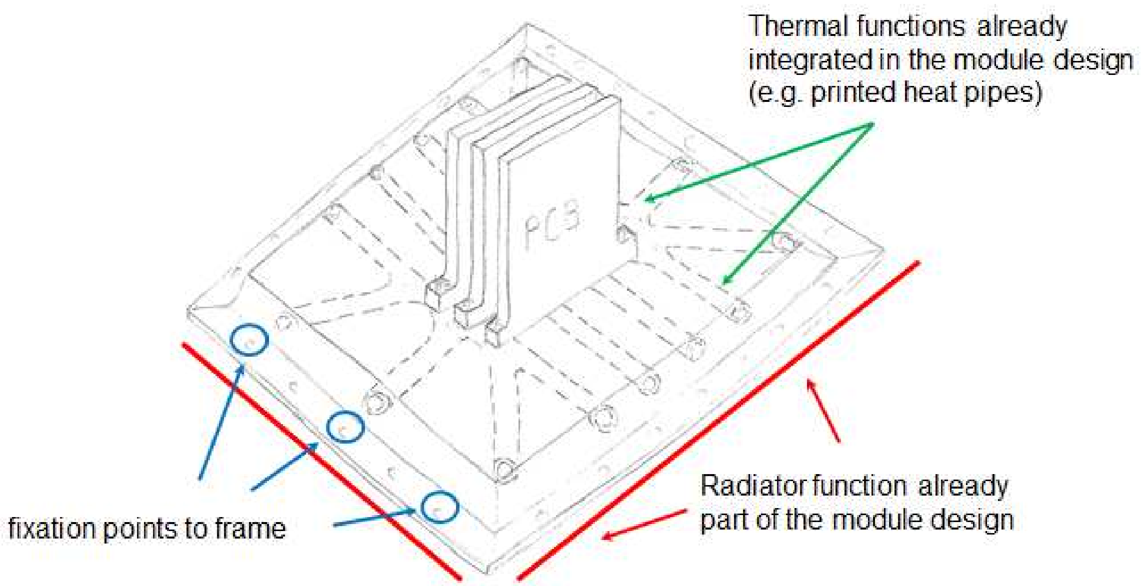


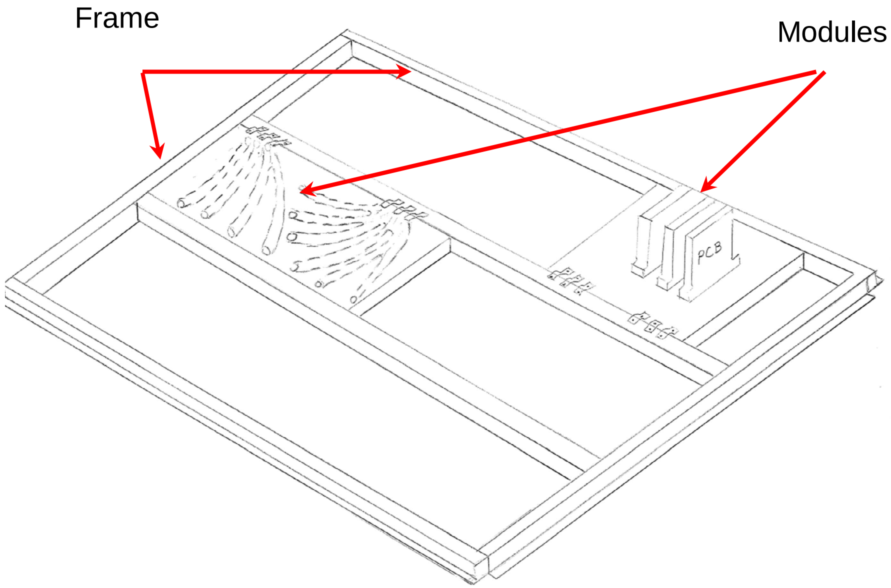
Sentinel 3 - +Y panel thermal control

Modular Radiator (Frame Concept)



- Radiator panel replaced by a frame where modules are positioned onto according to system needs
- Combine and merge the functions of the equipment housings and a the conventional radiator structure on module level





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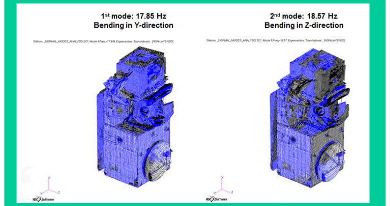
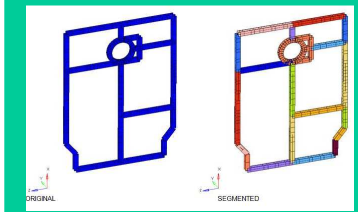
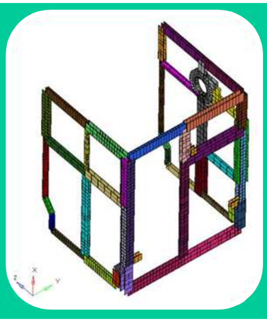
Modular Radiator – Sequence of activities



- Sensitivity Analysis on S/C level



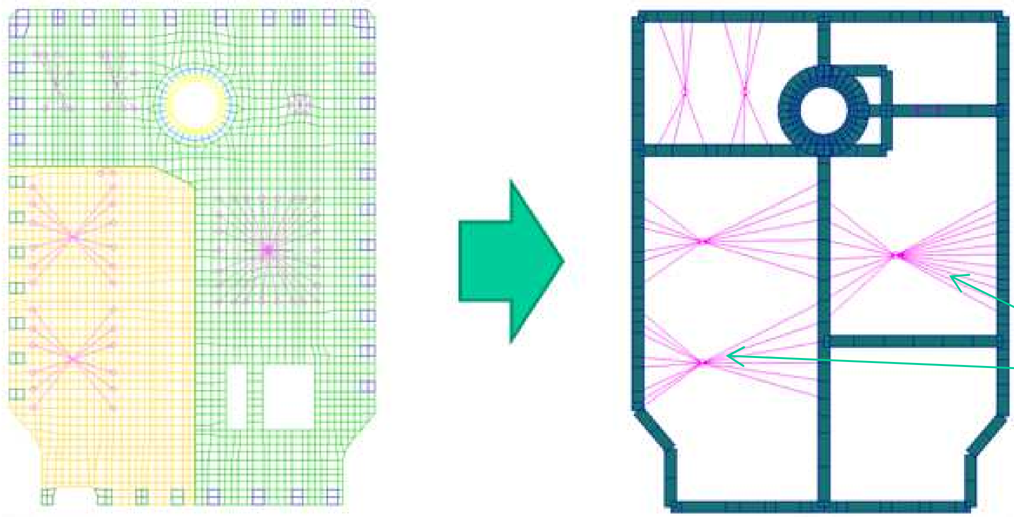
- Segments created to allow the software to do a size optimization



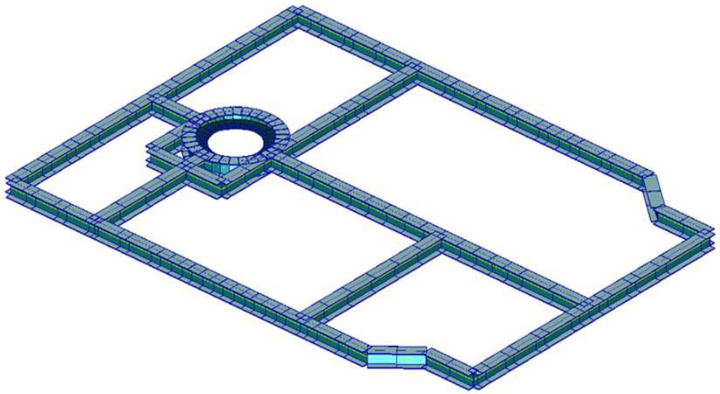
- Run optimization (various iterations)

Modular Radiator – Sensitivity Analysis

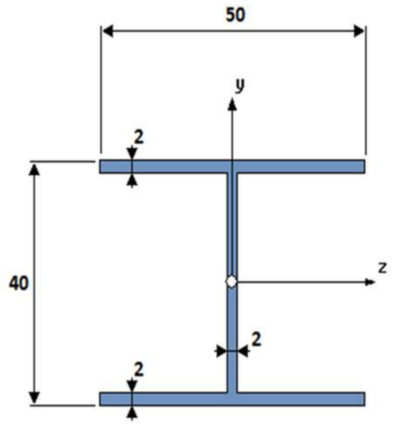
- Modelling Detail – Example PY Panel



- Beam lay-out defined to envelope the Sentinel 3 equipment lay-out (some smaller adoption taken)
- Equipment mounted with RB3 elements
- Mass increased by 15%



- I-Beam cross section



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Ref.:

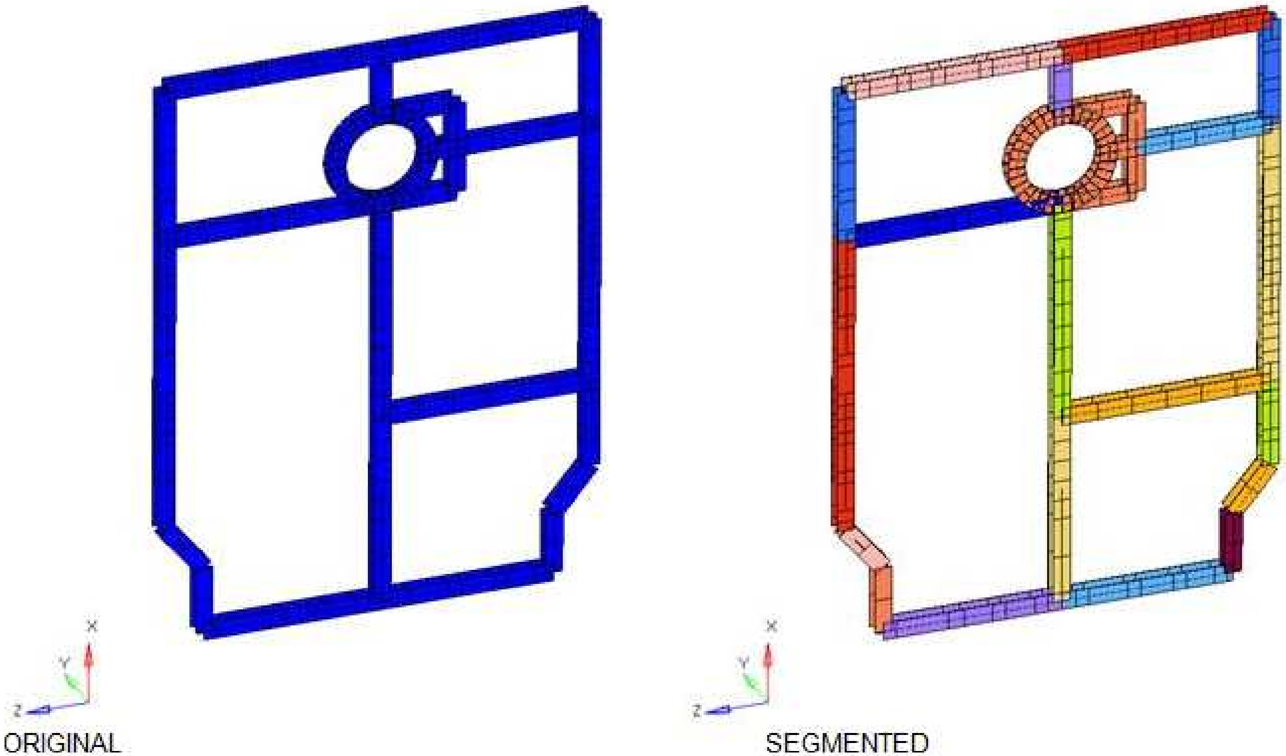
Modular Radiator – Sensitivity Analysis - Summary

	Original design	Frame concept PY	Frame concept PY & MY	Frame concept MZ, PY & MY
Delta mass	-	+6.9 kg	+10.5 kg (3.6 + 6.9) kg	+12.7 kg (2.2 + 3.6 + 6.9) kg
1st mode	17.85 Hz bending in Y-direction	17.79 Hz (-0.3%) bending in Z-direction	16.98 Hz (-4.9%) bending in Z-direction	14.85 Hz (-16.8%) bending in Z-direction
2nd mode	18.57 Hz bending in Z-direction	17.97 Hz (-3.2%) bending in Y-direction	17.80 Hz (-4.1%) bending in Y-direction	15.59 Hz (-16.0%) bending in Y-direction

- Replacement of PY and MY radiator panels with frames has a negligible impact on the global stiffness of the Sentinel-3 satellite structure
- When three panels are replaced, the frequency drop is higher but still limited and could be recovered by stiffening the frames and/or the primary structure
- Primary structure is the main contributor to the S/C stiffness
- Overall mass impact of the frames concept is limited and potentially recovered by optimization runs

Modular Radiator – Size Optimization – General Aspects

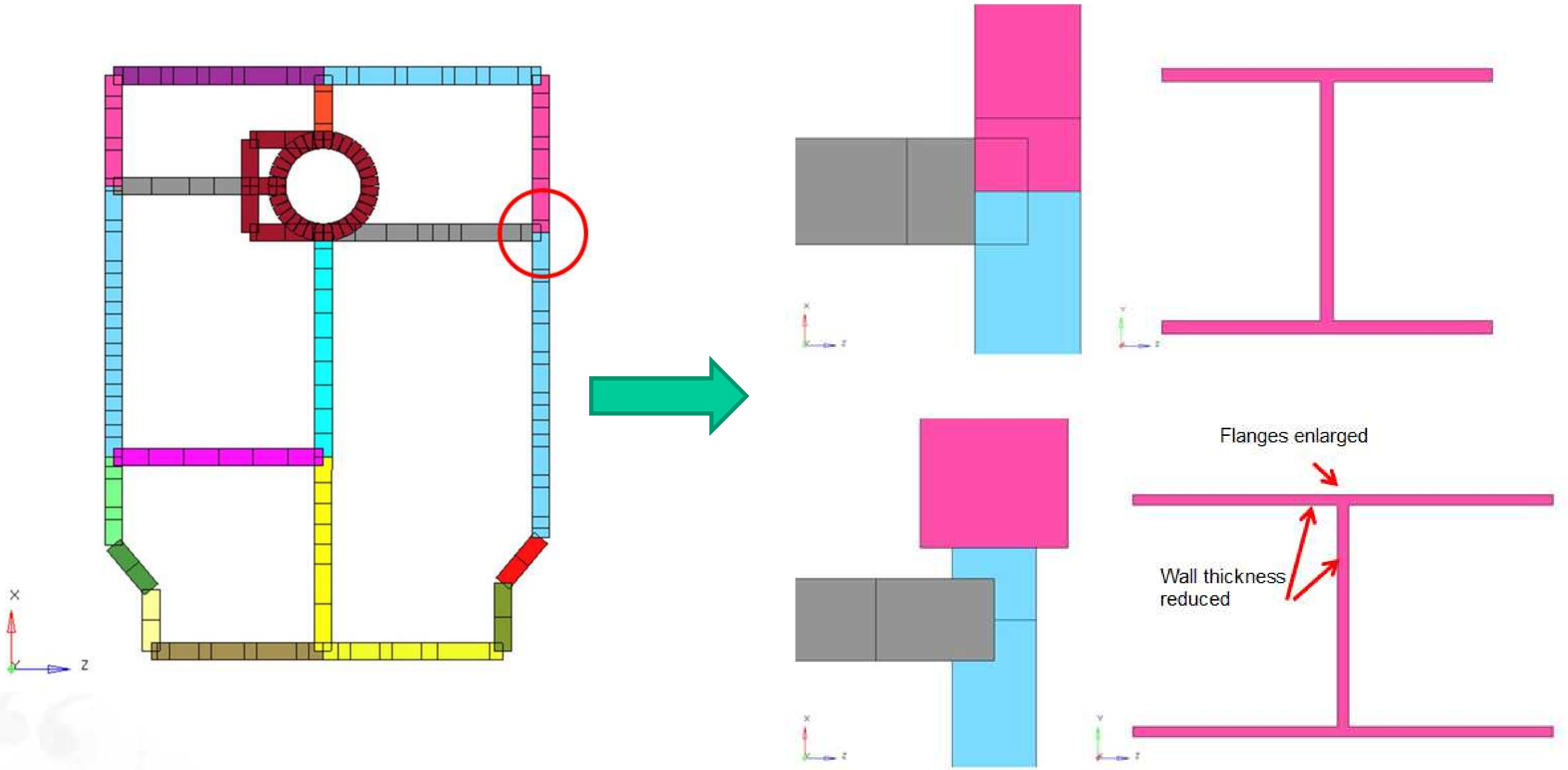
- Beam design from the sensitivity analysis segmented to allow the software to do a size optimization (size of Beam Flanges, Web Height…)



- Each color represents a different physical property card (example PY frame)

Modular Radiator – Size Optimization – Results

Together ahead. RUAG



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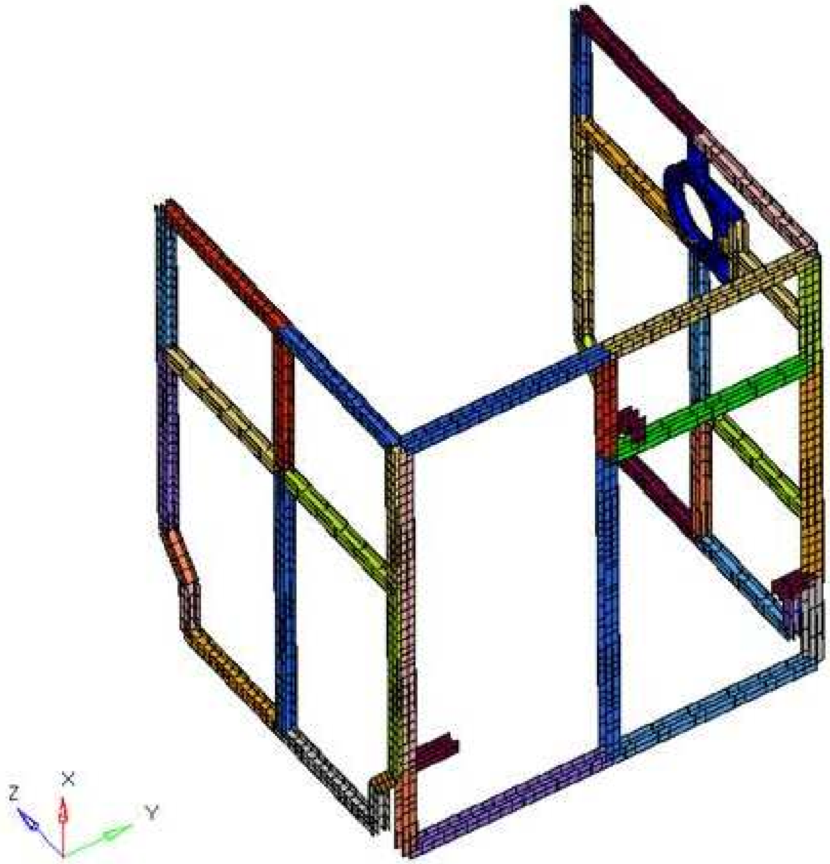
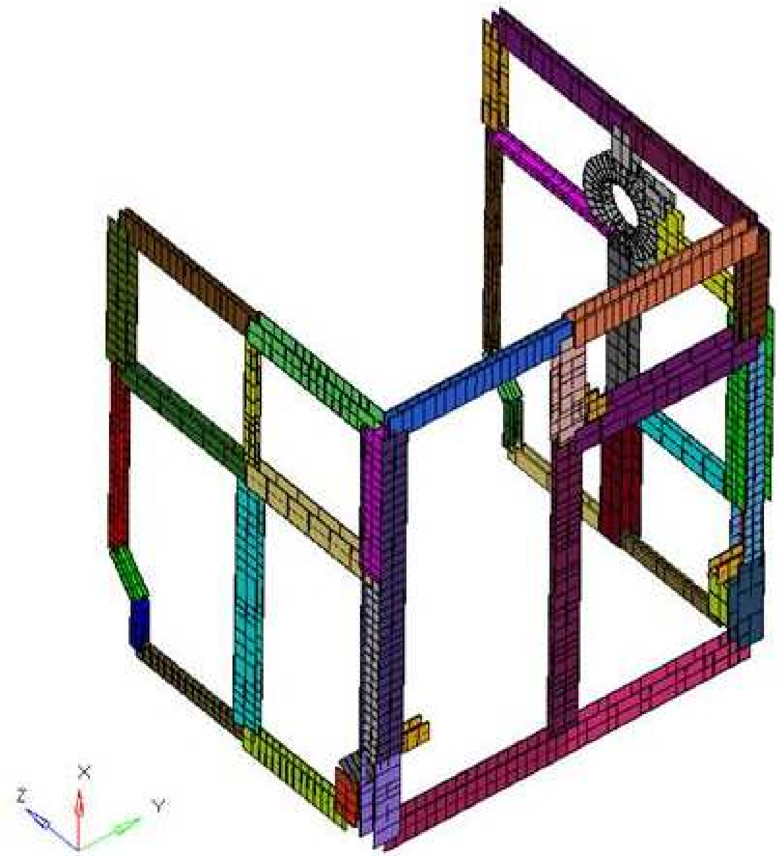
Modular Radiator – Size Optimization – Results



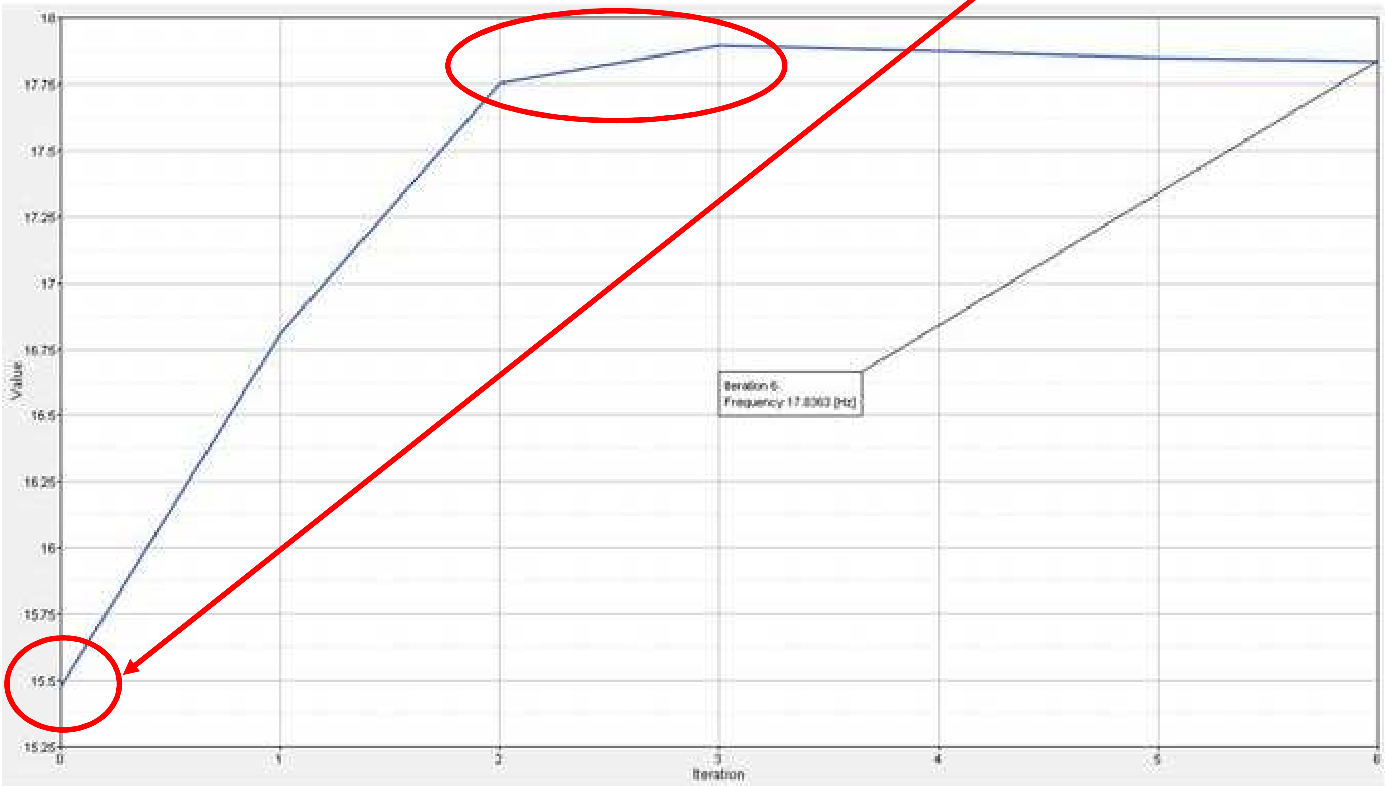
optimized



non-optimized

Modular Radiator – Size Optimization – Results

Trop in frequency can be recovered

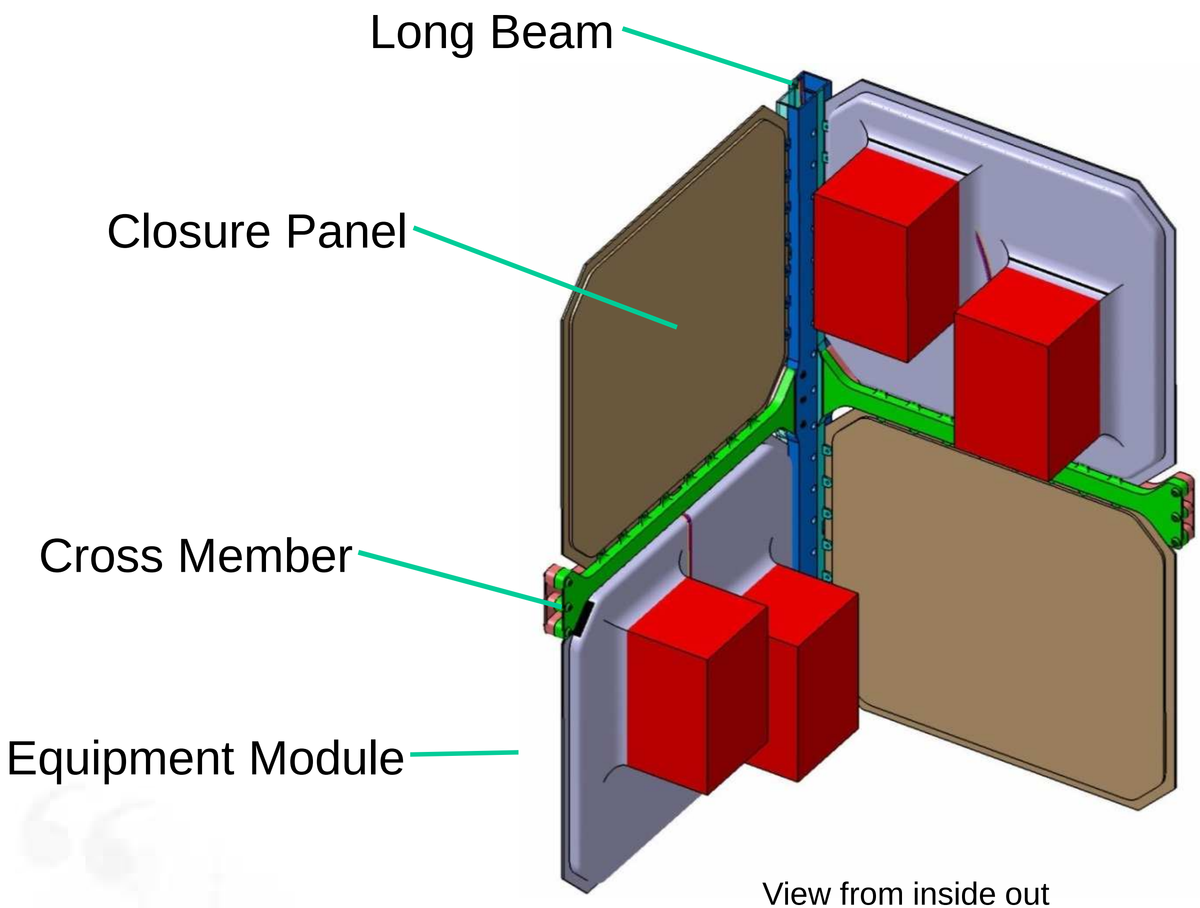


- Frequency trop and mass increase can be recovered by employing size optimization on the radiator frame

Modular Radiator - Design Concept

Together ahead. RUAG

- Design Concept for Frame without thermal function



View from inside out

- Mechanical interfaces between equipment modules and the frame can be limited to a few standardized connection points to simplify the interface
- Equipment modules can be developed, assembled and tested individually, before integration into the satellite structure.

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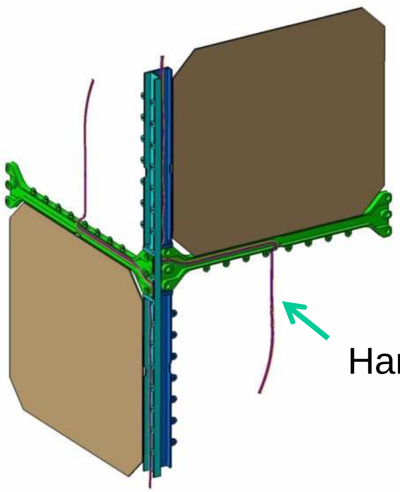
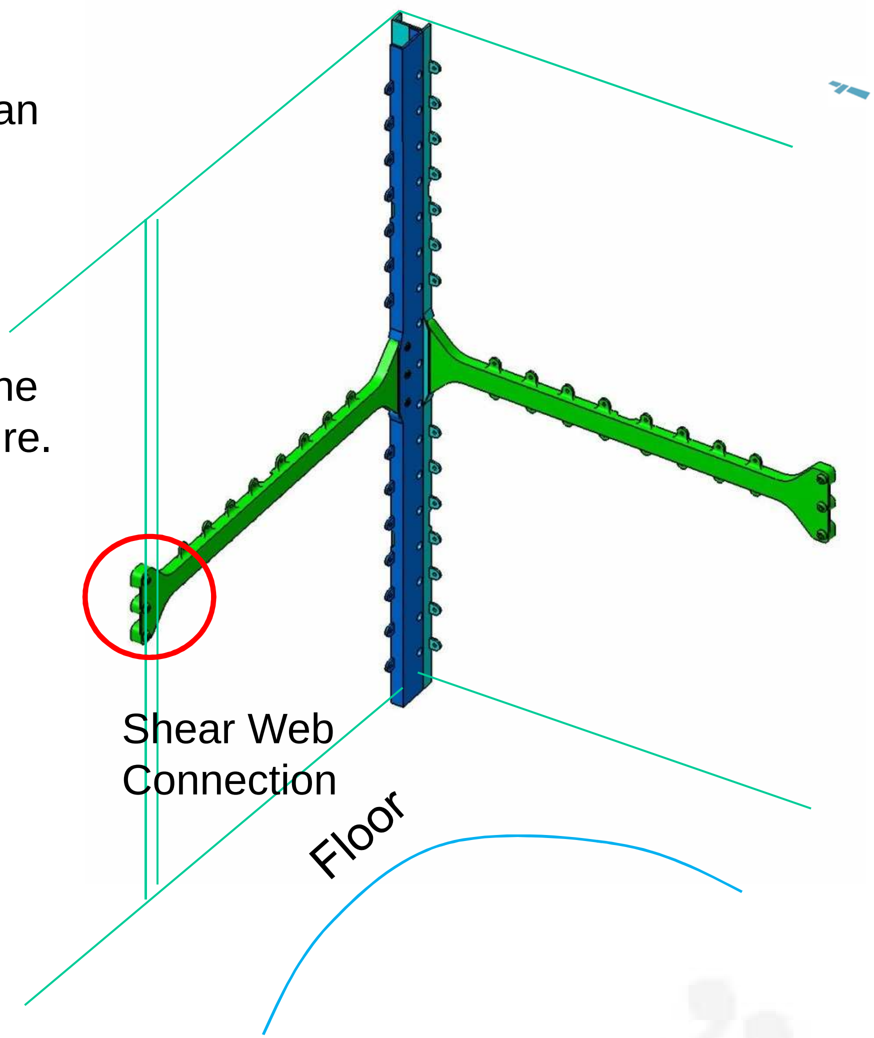
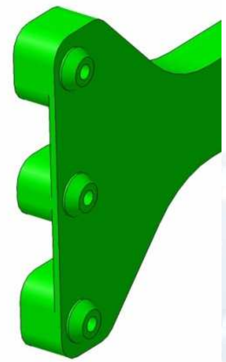
Assembly and Integration concept

- Frame members are made from 2 parts, an inner and an outer part.
- Just the inner part will be mounted to the satellite structure at this stage.
- Harness can be routed in the inside of the Frame Structure.





- For the Frame Structure, conical connections guarantee accurate positioning of the parts and a high load transfer capability.



- Closing of profiles

Modular Radiator – Programmatic Impact

Lead Time Impact

- Positive Impact on lead time expected
- Manufacturing of frame vs. lead time of classical sandwich panel radiator a ratio of 70 vs. 110 days was predicted

Effort for Design and Analytical Verification

- By using standardized elements and methods (e.g. attachment points, Web developed for a certain load rang…) benefits are seen conceivable

AIT Effort

- RUAG does not have access data related to system integration, but a positive impact is expected

Modular Radiator – Performance aspects

Interface

- Reduced number of interfaces on module level
- Standardized elements for frame; members as well as attachment points

Geometry

- Realize more compact parts, especially on module level
- In the frame harness and piping can be integrated, more space for equipment available

Reliability

- Standardized elements and analysis methods have positive effect on reliability

Modular Radiator – Environmental impact

Material resources

- Less scraped material from machining
- Net shaped parts realized in case machining of interfaces is necessary

Energy resources

- Substantial amount of energy is consumed during the production of the powder and the build process
- Less semi finished products have to be produced

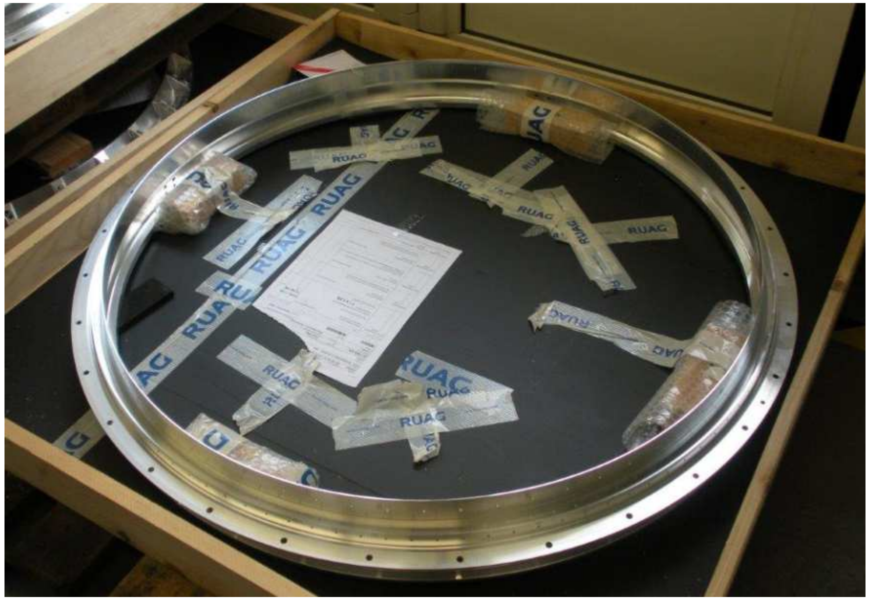
LOS compatibility

- No massive bulk material accumulations
- Risk reduced that parts are reaching the ground after atmospheric re-entry

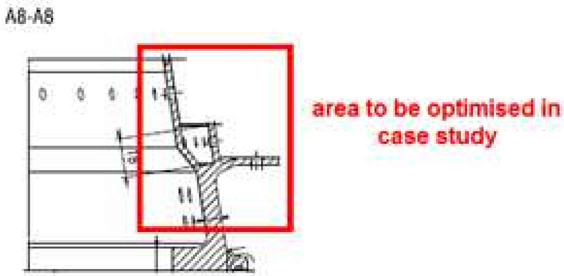
Modular Radiator – Outlook

- Repeat the exercise having element based volumes, using classical Topology Optimization
- Dimension the beams also against strength (von Mises stress) and repeat the optimization.
- Expand the concept beyond the secondary structure panels and include also the primary structure into the optimization considerations. What does this mean on the overall satellite design.
- Develop a concept for modules or sub-modules.
- Elaborate in further detail the design concept of the module, sub-module and frame element attachment points and create a kind of design catalogue.
- Try to run a Topology Optimization on a complete Panel defined with volume element.
- Look on a concept, where the radiator frame has thermal functions.
- Interface management – How to specify? Who is responsible for what?
- Testability, process verification, capability to set material properties and the correlation with the FEM model.
- Manufacturability – How an end-to-end manufacturing can be realized ?

- Sentinel 3 LVA ring was identified as a very promising field of application for AM technologies. This involves a topology optimized design.



Conventional machined Sentinel-3 LVA ring (source RUAG)

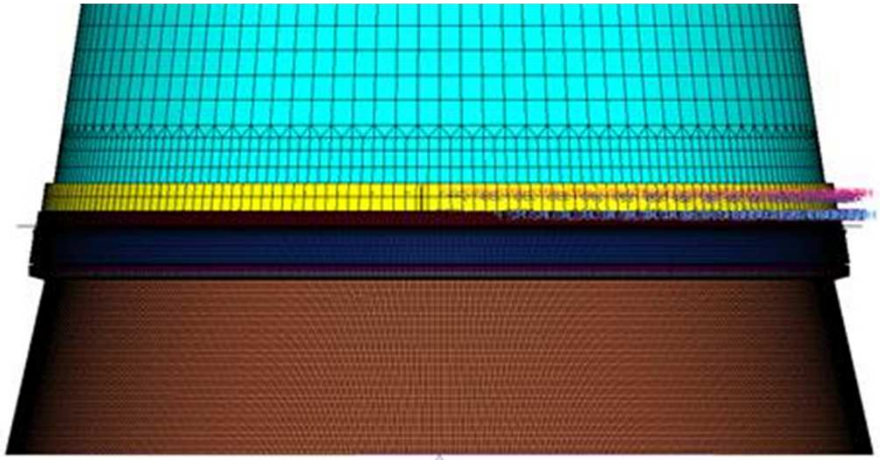


Sentinel-3 cone with mounted LVA ring (source RUAG)

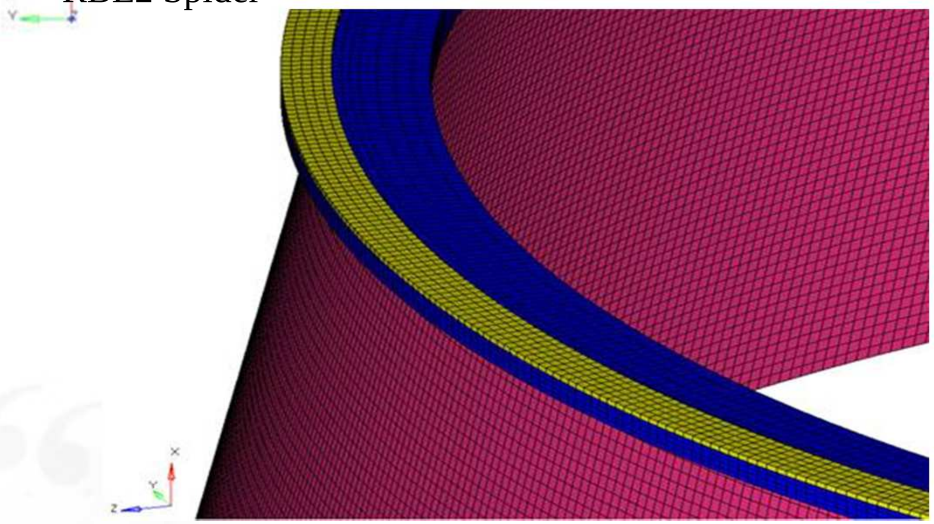
Ring/Adapters- S3 LVA ring – Modelling

Together ahead. RUAG

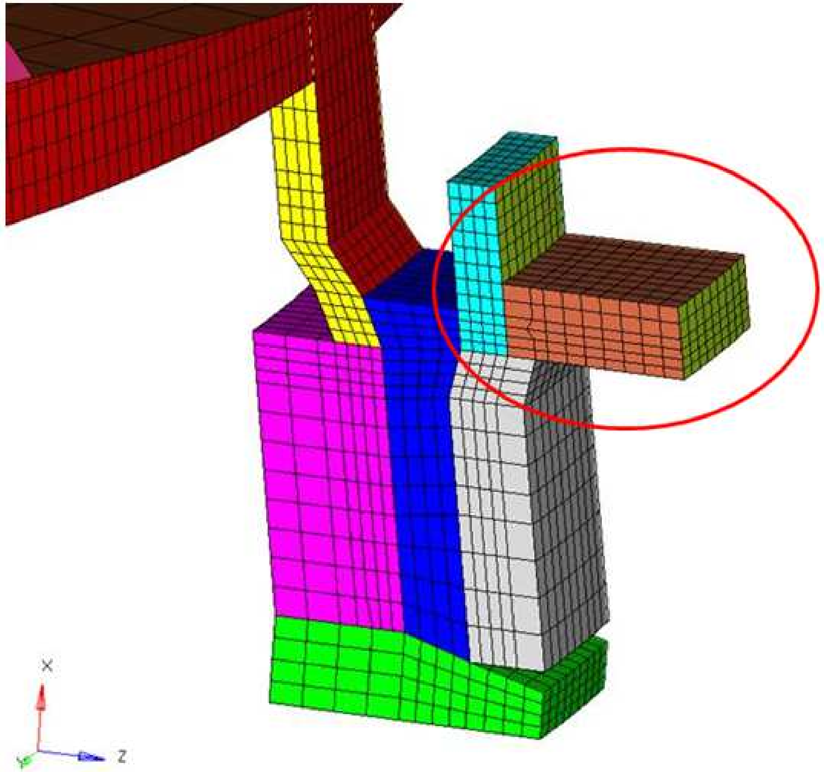
- clamp band radial pressure applied
- design variable for optimization was expanded
- original design kept for lower floor flange and interface area to launcher adapter



Simplified S3 FE on Adaptor; the Adaptor is clamped though RBE2 Spider



Yellow solid elements - contact area with the adaptor (merged contact nodes)



design variable

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- Design Variable: Element densities with-in design space. Original S3 LVA web and fork volume was expanded in order not to limit the optimization by the initial design except for the lower floor flange and the interface area to the launcher adapter.

- Responses: The following responses were chosen for the analysis:
  - Volume fraction
  - Eigenfrequency

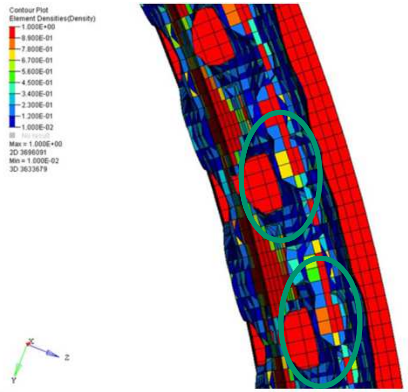
- Constraint: The following constraints were set:
  - Volume fraction – upper boundary 70% of the original volume (unexpanded volume); roughly 20% of expanded volume
  - Yield stress of used material
  - No manufacturing constraints introduced so far

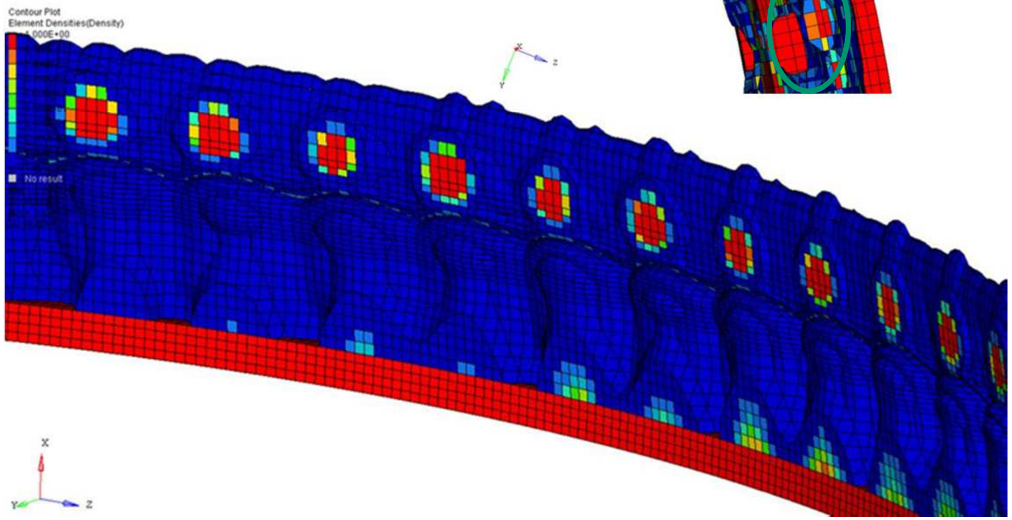
- Aim: The aim of the optimization is the maximization the first global S/C Eigenfrequency.

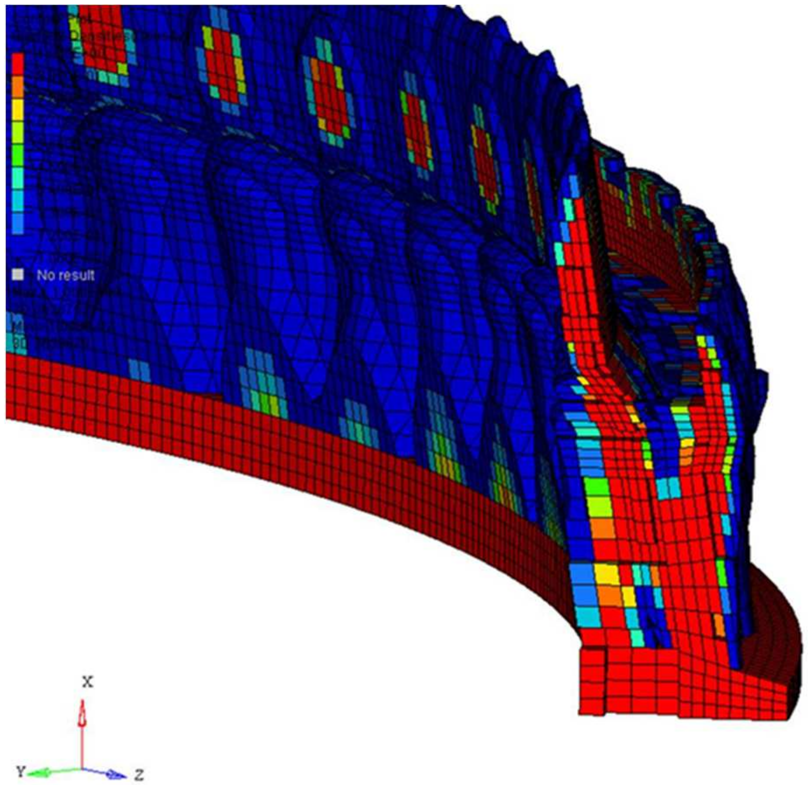
Ring/Adapters- S3 LVA ring - Results

- The optimized design first global S/C frequency equal to 14.08 Hz against the original 13.83 Hz
- Around 70 % of the original non-expanded volume kept
- 3.7 kg instead of 5.2 kg ➡ around 30% mass saving
- design mainly driven by the stiffness - analysis of the QSL and clamp band pressure just reveals maximum Von Mises stresses in the order of 70MPa

Interface Ring - Optimization results







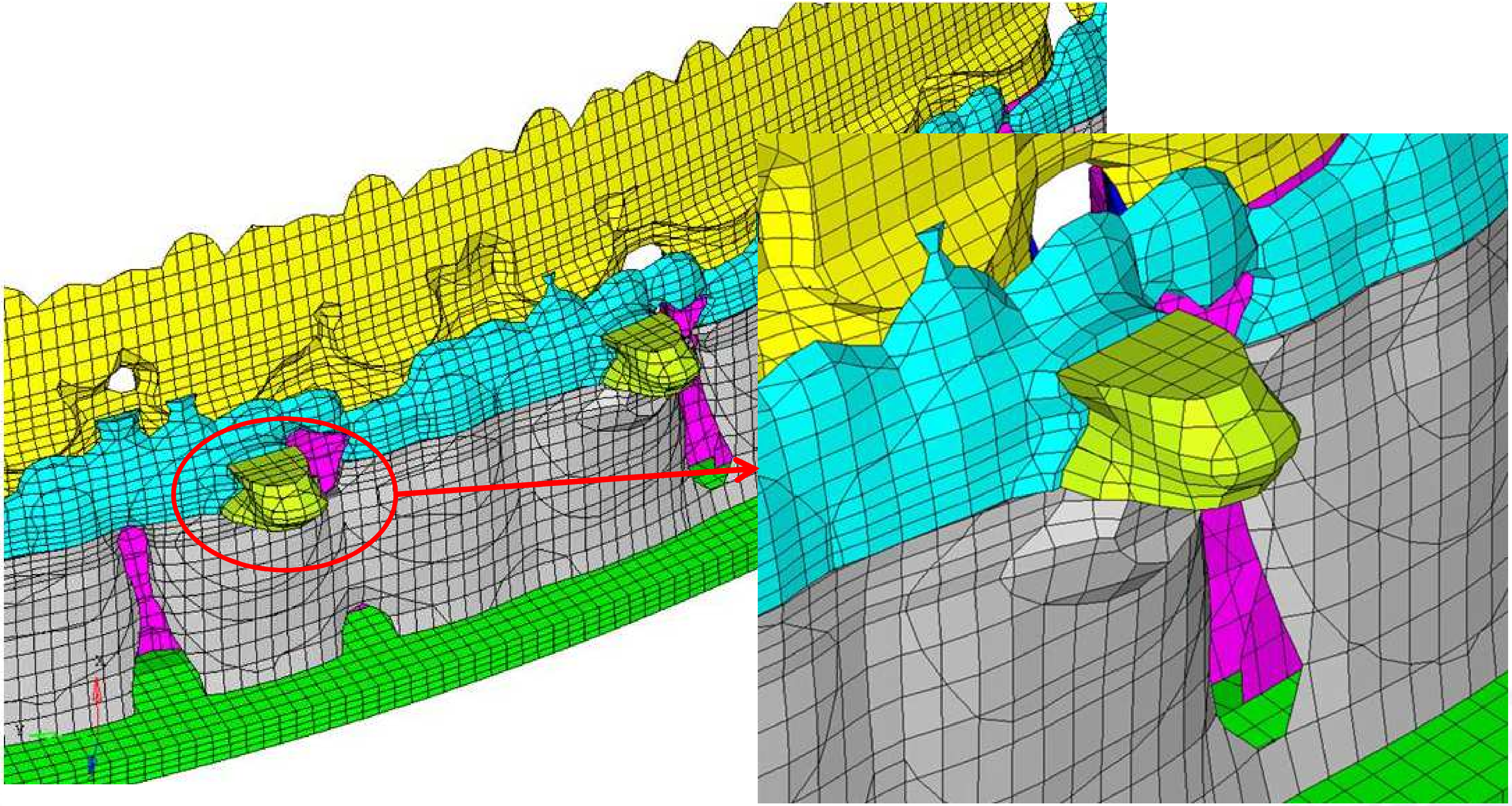
Section A:

- Columns shaped reinforcements; holes volumes in between the columns-shaped reinforcements
- red solid elements have 100% of original density

Interface Ring – Optimization results

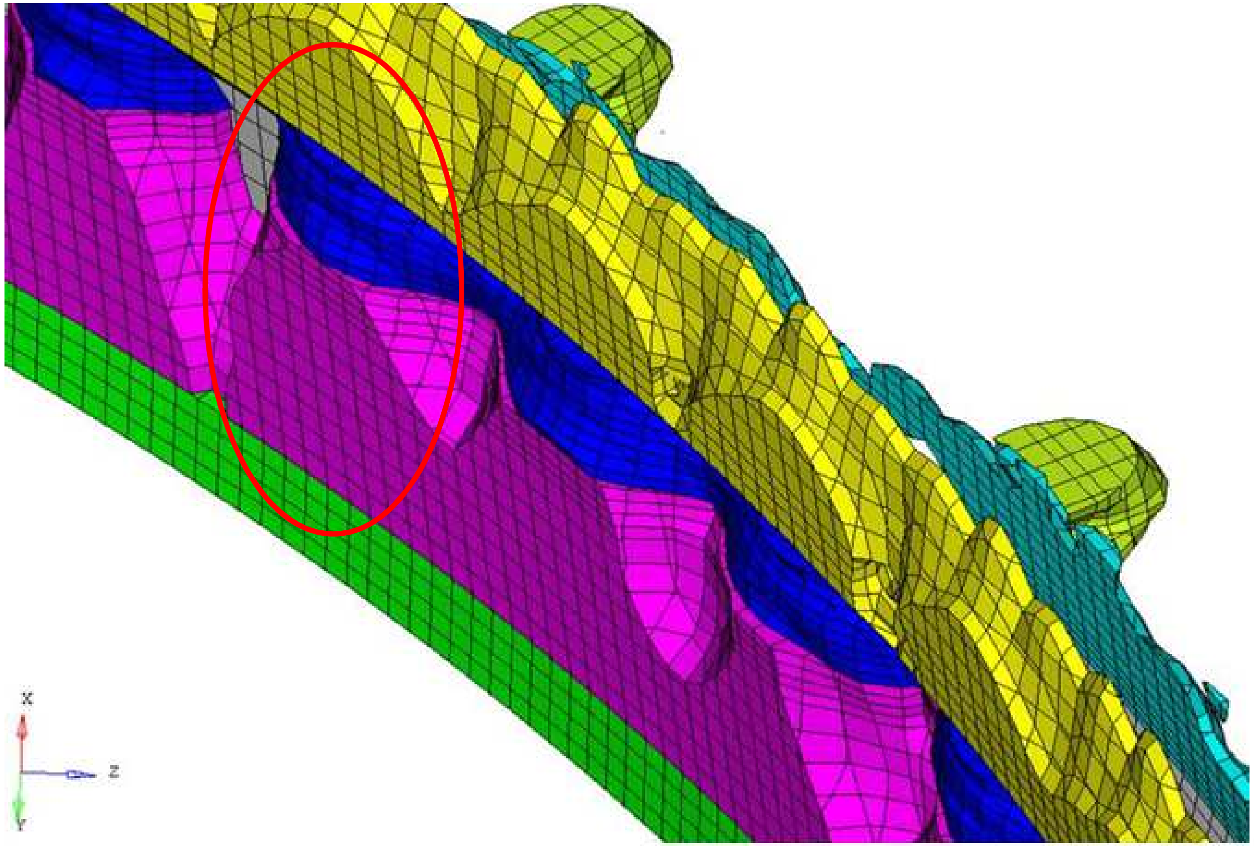
- Flange to Lower Floor is included in the design volume

Interface Ring – Optimization results



- Lower Floor Flange is reduced to finger-like supports

Interface Ring – Optimization results



- Columns shaped reinforcements design is still valid

Lead Time Impact

- Positive Impact on lead time expected
- 3 – 4 weeks instead of 24 – 30 weeks

Effort for Design and Analytical Verification

- When design and analysis methods are established, a similar development effort is expected compared to a conventional designed ring.

AIT Effort

- Similar AIT effort compared to the conventional ring expected

Interface Ring – Performance aspects

Interface

- No significant impact identified

Geometry

- Due to optimization and AM manufacturing technologies more compact designs are deemed possible

Reliability

- No significant impact identified

Interface Ring– Environmental impact

Material resources

- Less scraped material from machining
- Net shaped parts realized in case machining of interfaces is necessary

Energy resources

- Substantial amount of energy is consumed during the production of the powder and the build process
- No finished products have to be produced

LOS compatibility

- No massive bulk material accumulations
- Risk reduced that parts are reaching the ground after atmospheric re-entry

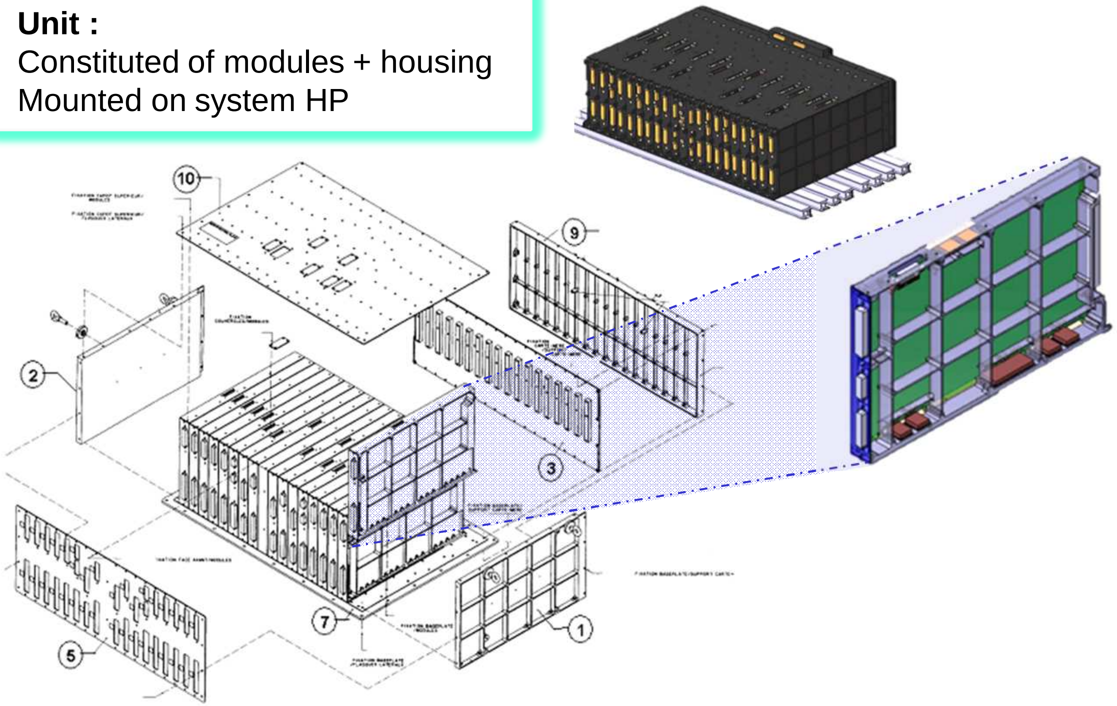
- A study of the influence of the Cone to Fork fixation (currently a simple rigid spider) shall be carried out with the connection modelled more realistically.
- Another interesting aspect to be studied is the design of the connection of the CFRP cone to the LVA ring.
- It would be interesting to increase the thickness of the design volume for the fork even further, e.g. to 9mm.
- Over fluxes at the LVA interface due to QSL loads (e.g. launcher load cases, transportation) to be included in future optimisation runs.
- How can be the interface to the launcher modified wrt. to achieve a design for additive manufacturing.

- 9. Electronic units & thermal application - Quantitative evaluation on applications and redesign activities – WP 3300/4100 (TAS-B)

9. Electronic units & thermal application

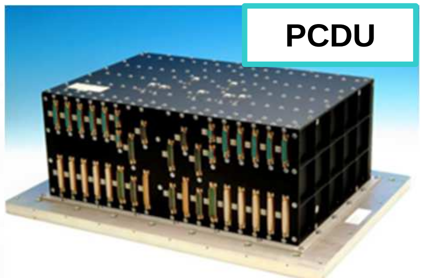
Electronic unit structure

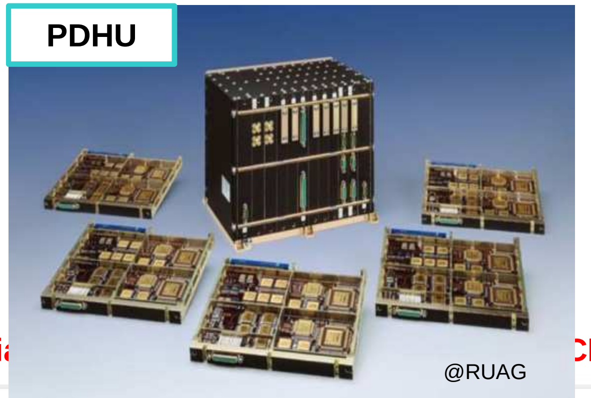
Unit :
Constituted of modules + housing
Mounted on system HP

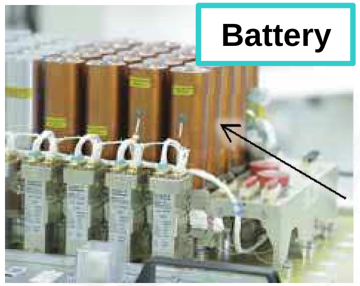


Module :

- PBA (PCB with electronic components)
- Metallic frame + stiffeners
- Dissipative/heavy components reported on structure
- Connectors







Electrochemical cells

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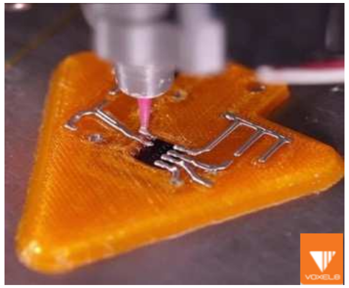
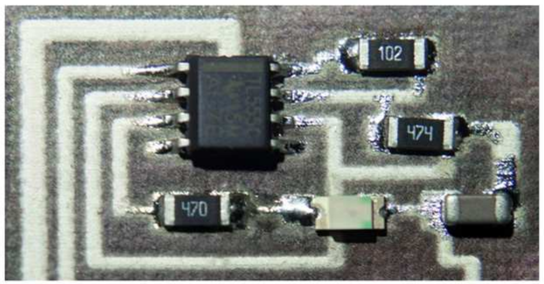
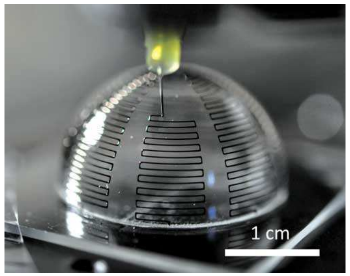
9. Electronic units & thermal application

AM applications : Electronics printing





Close up of a surface mount circuit printed straight onto paper



Advantages

- Circuitry in 3D instead of 2D : geometry DoF + 3D routing
- Building blocks
- Mechanically interesting (no PCB bending)
- Printing of heaters with resistive ink or print circuitry with conductive ink on structure
- Easy instrumentation with printing of sensors
- Direct electrical insulation while manufacturing

Disadvantages

- Maturity level is low (even if used for smartphone antennas or very small sensors)
- Specific materials needed - space qualification
- Not applicable to power electronics (or processors) nor components with numerous connectors (evolution)
- Need to ensure contacts in case of shocks and vibrations
- Heat management ?

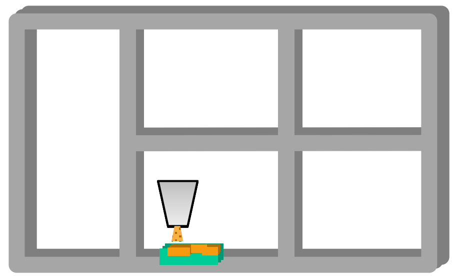
9. Electronic units & thermal application

AM applications : Mass savings and Thermal management

Reduce the mechanical structure to a minimum thanks to lattice structures and topological optimization

Electronic components : Power increases while size decreases

→ heat flux density becomes a concern in almost every electrical application



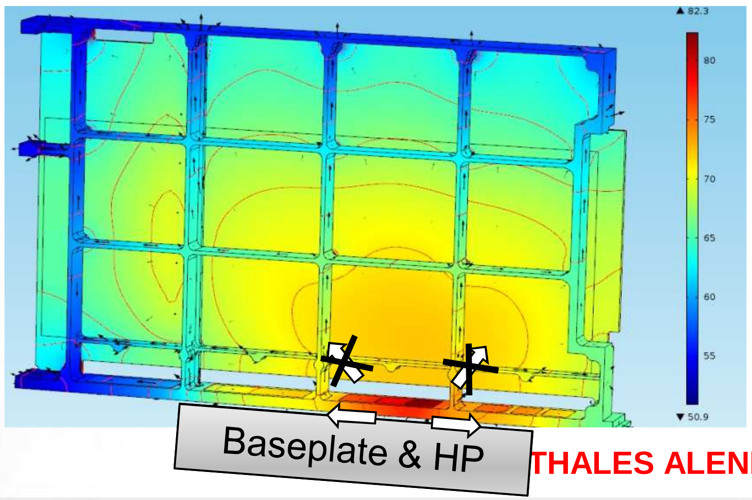
Reduce contact resistance

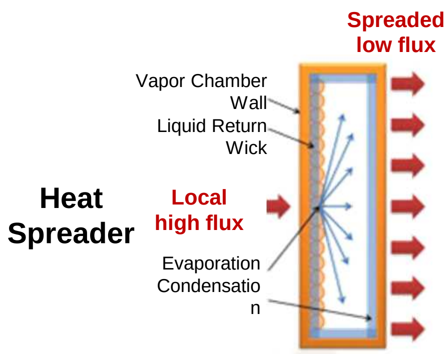
Conduction through metallic structure <> structure mass savings

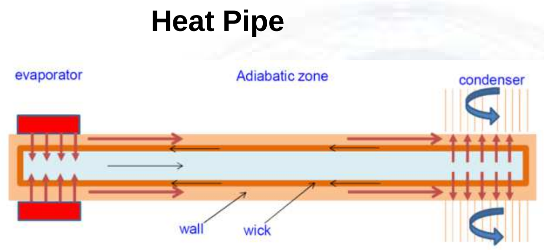
→ Highly dissipating components at closest from cold source

→ Limiting interfaces reduces contact resistance

→ Need to integrate thermal functions inside mechanical structure to drive heat







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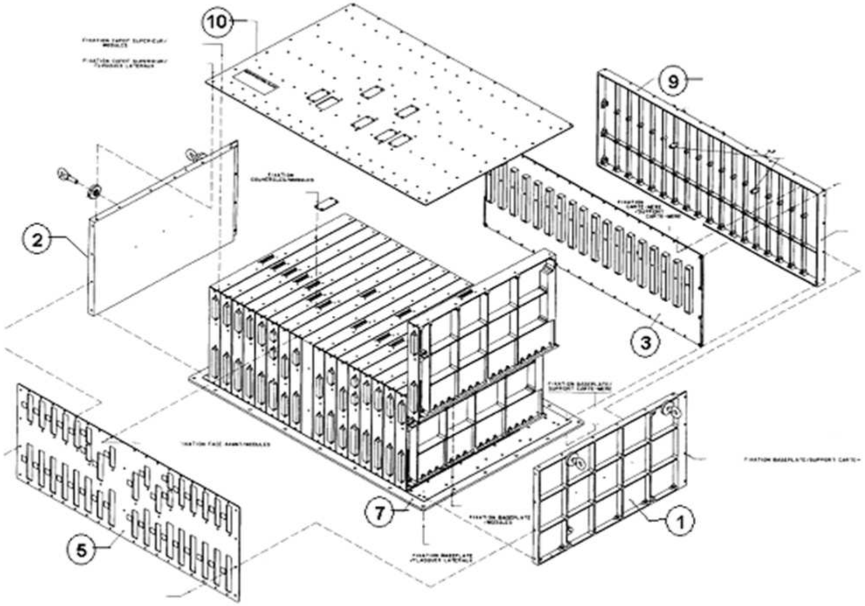
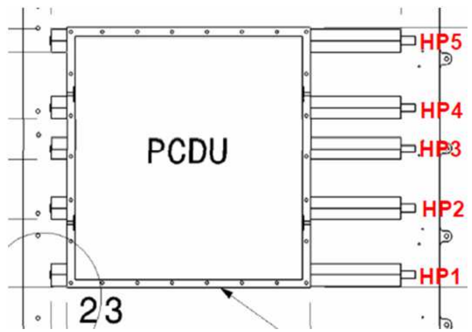
9. Electronic units & thermal application

PCDU Thermal model

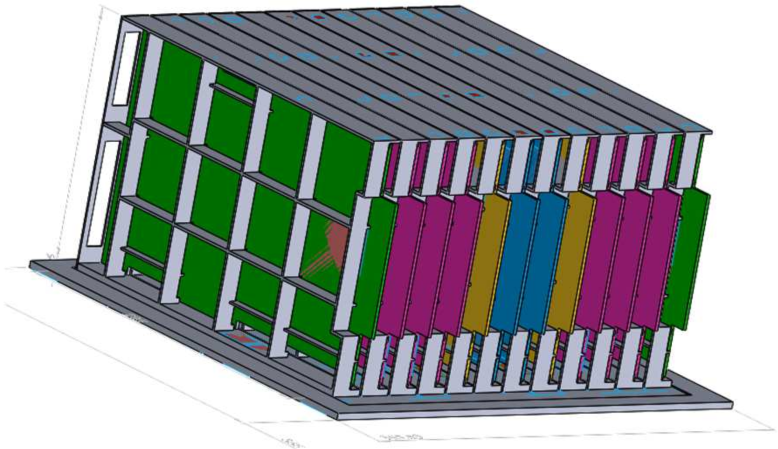


Mass of the PCDU : 15.5 kg
Structure/total mass ratio : 50%



connectors

LxWxH 345x355x200 mm

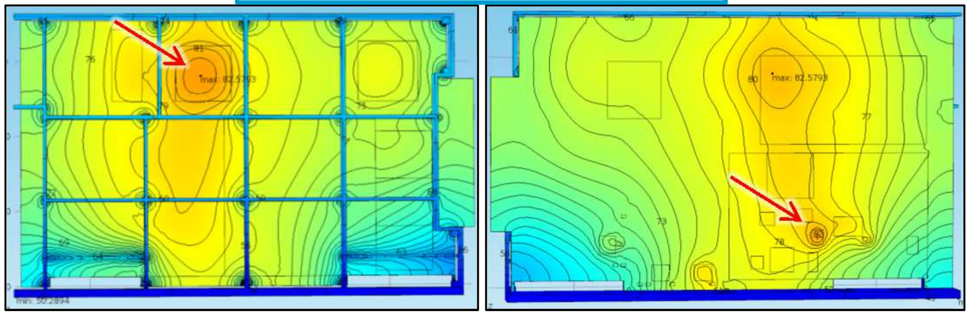


Sentinel 3 PCDU dissipations	
Module	Dissipated heat (W)
PYRO 1	3,92
DISTRI 1	1,96
DISTRI 2	1,96
DISTRI 3	10,9
POWER 1	53,32
TMTC 1	7,854
TMTC 2	1,86
POWER 2	47,64
DISTRI 4	1,96
DISTRI 5	1,96
DISTRI 6	1,96
PYRO 2	0,908
TOTAL	136,2

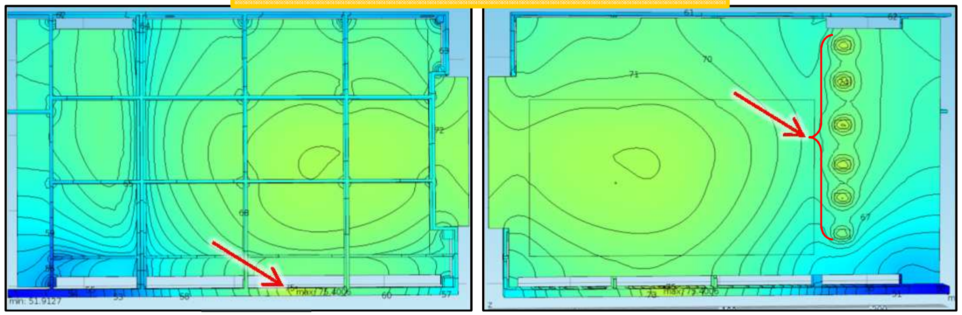
9. Electronic units & thermal application

Reference case

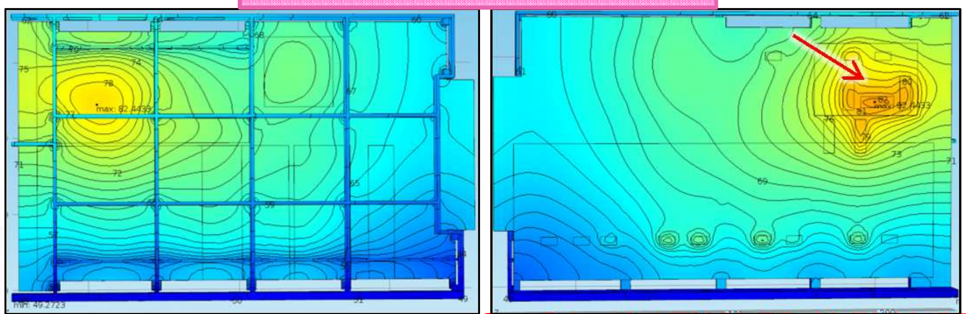
TMTC Tmax = 82,6°C

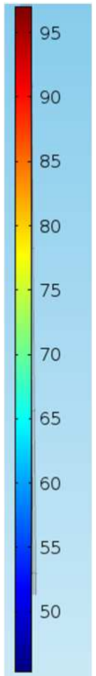


POWER Tmax = 75,3°C



DISTRI Tmax = 82,4°C





Critical modules :

- TMTC 1 - hot spots
- POWER 1 - high P_{diss} (>50W)
- DISTRI 3 - hot spots
- are close to each other

Conditions :
Tmax (PCB) < 85°C
max flux < 4 W/cm²
mean flux < 1 W/cm²

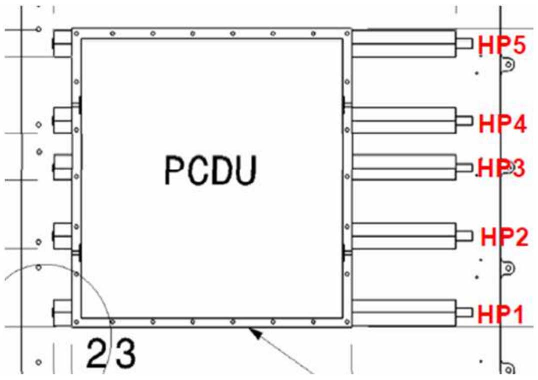
	Global	HP n°1	HP n°2	HP n°3	HP n°4	HP n°5
max flux (W/cm²)	0,871	0,345	0,706	0,869	0,871	0,564
mean flux (W/cm²)	0,253	0,130	0,275	0,339	0,343	0,176

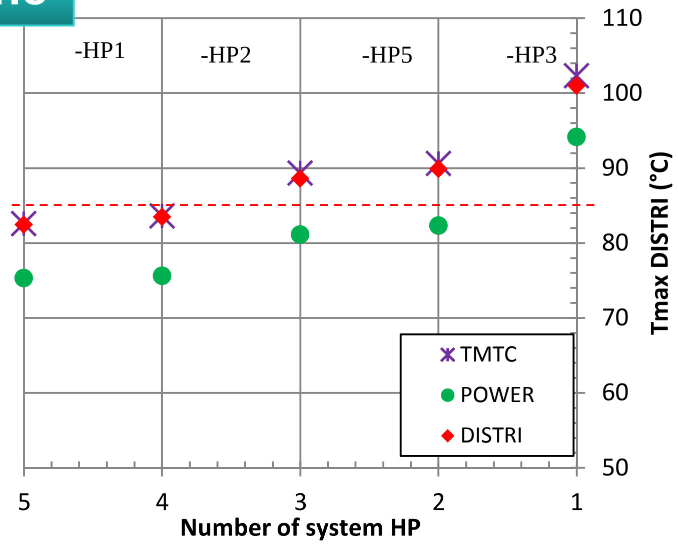
→ large margin on HP fluxes but very thin margin on T

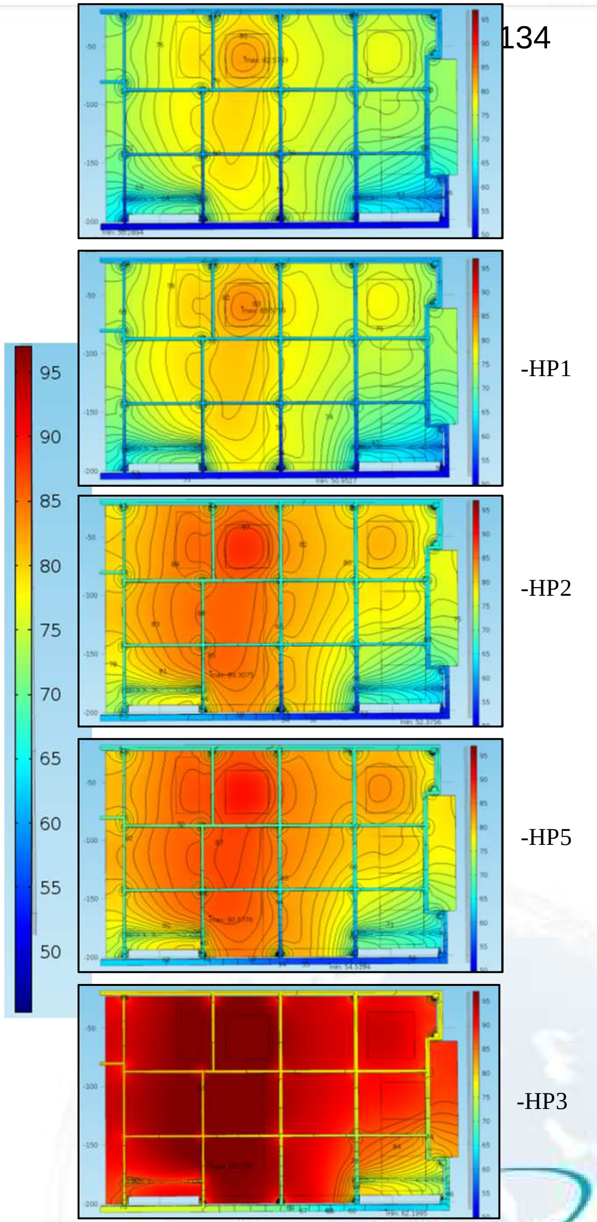
→ remove HP and manage heat locally

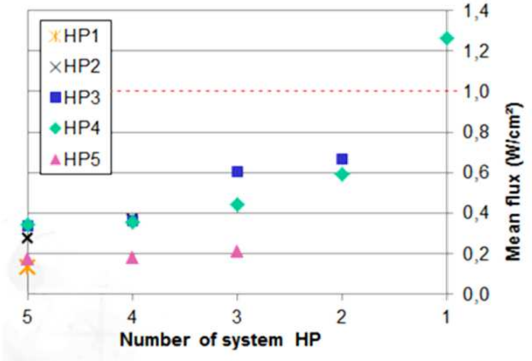
9. Electronic units & thermal application

Remove system HP one by one

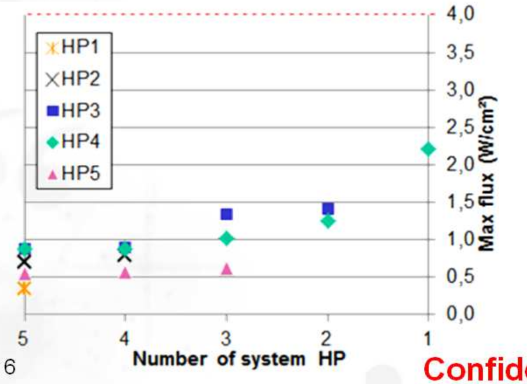








HP1 and HP5 can be removed almost without impact



To respect heat flux criterion at least 2 HP are necessary + a redundant third one

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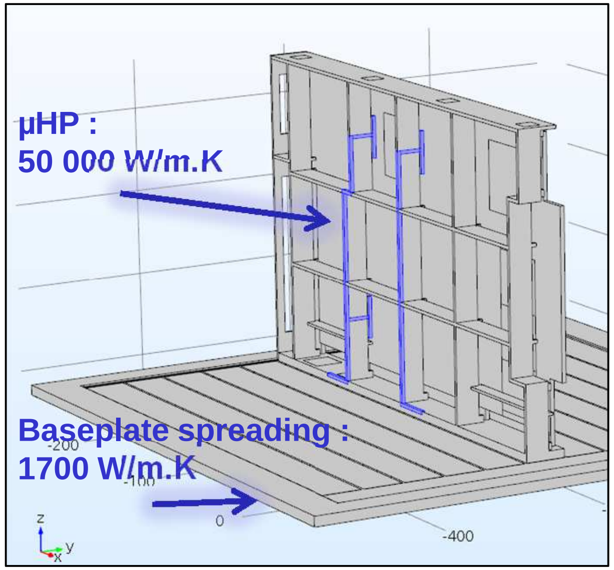
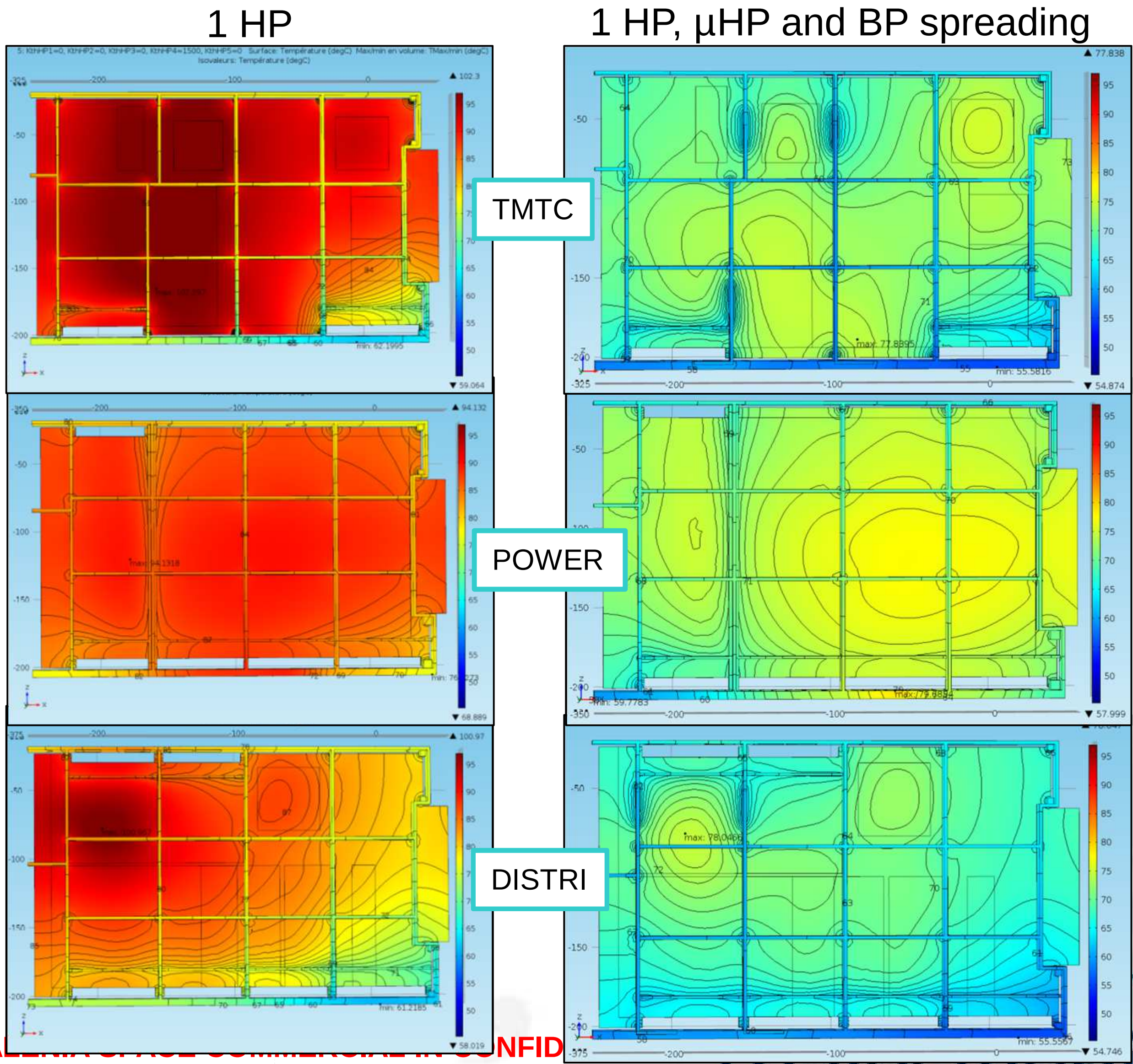
Addition of two-phase thermal functions





9. Electronic units & thermal application

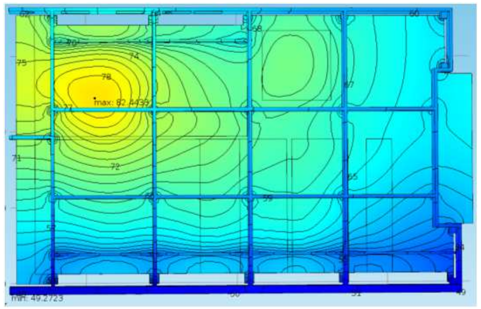
Unit resizing

"Height is limited because of heat conduction through the metallic structure"

Equal surface & power density

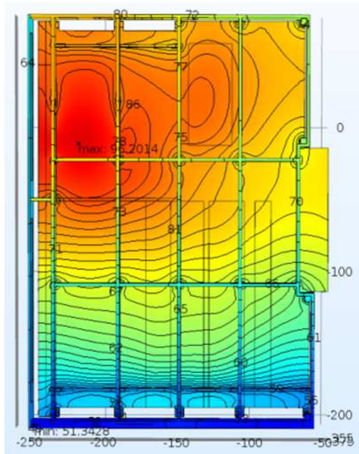
BP spreading and µHP keeps T_{max}<85°C with only 1 system HP

5 HP

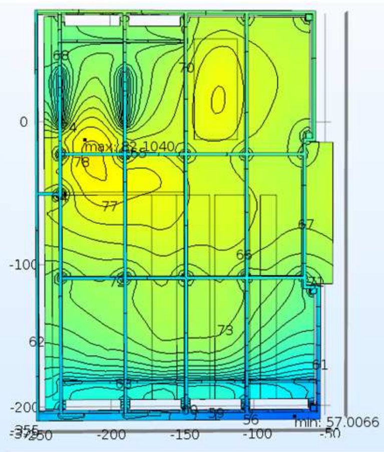


294 x 186 mm

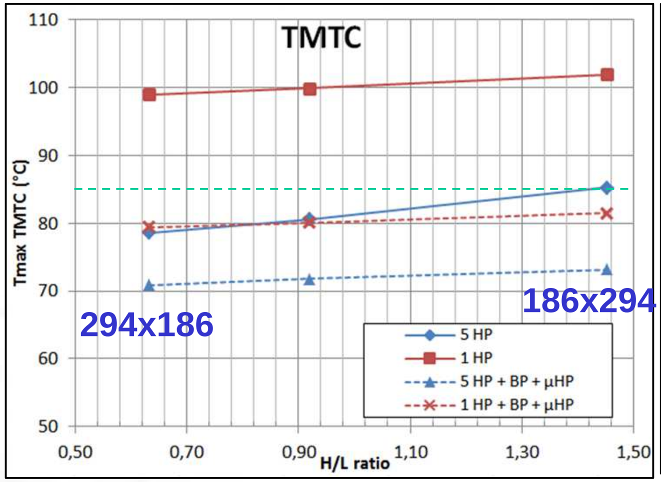
5HP

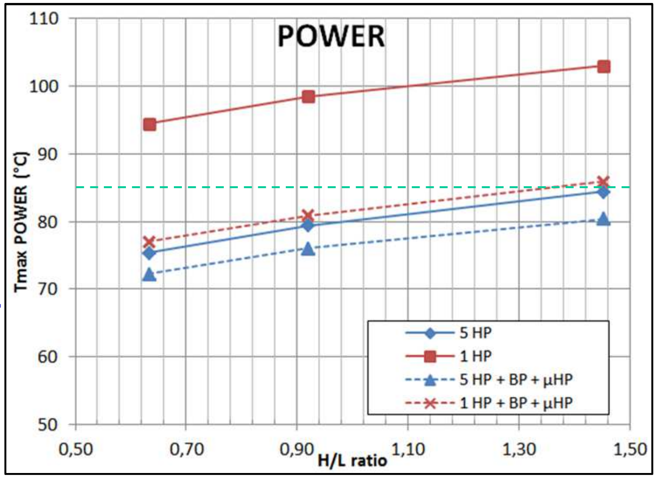


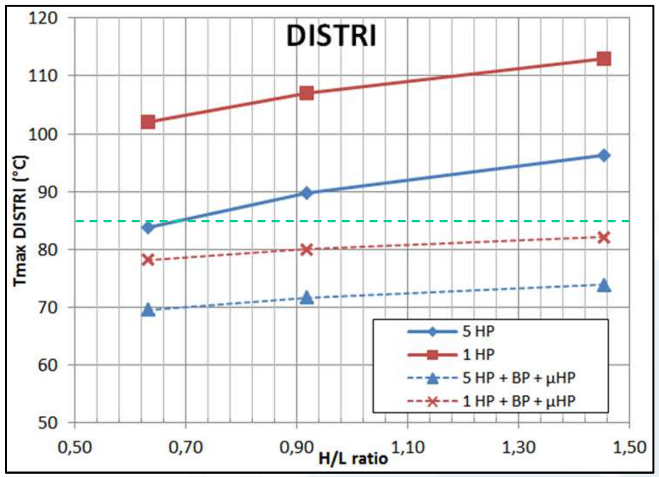
1 HP, µHP and BP spreading



186 x 294 mm



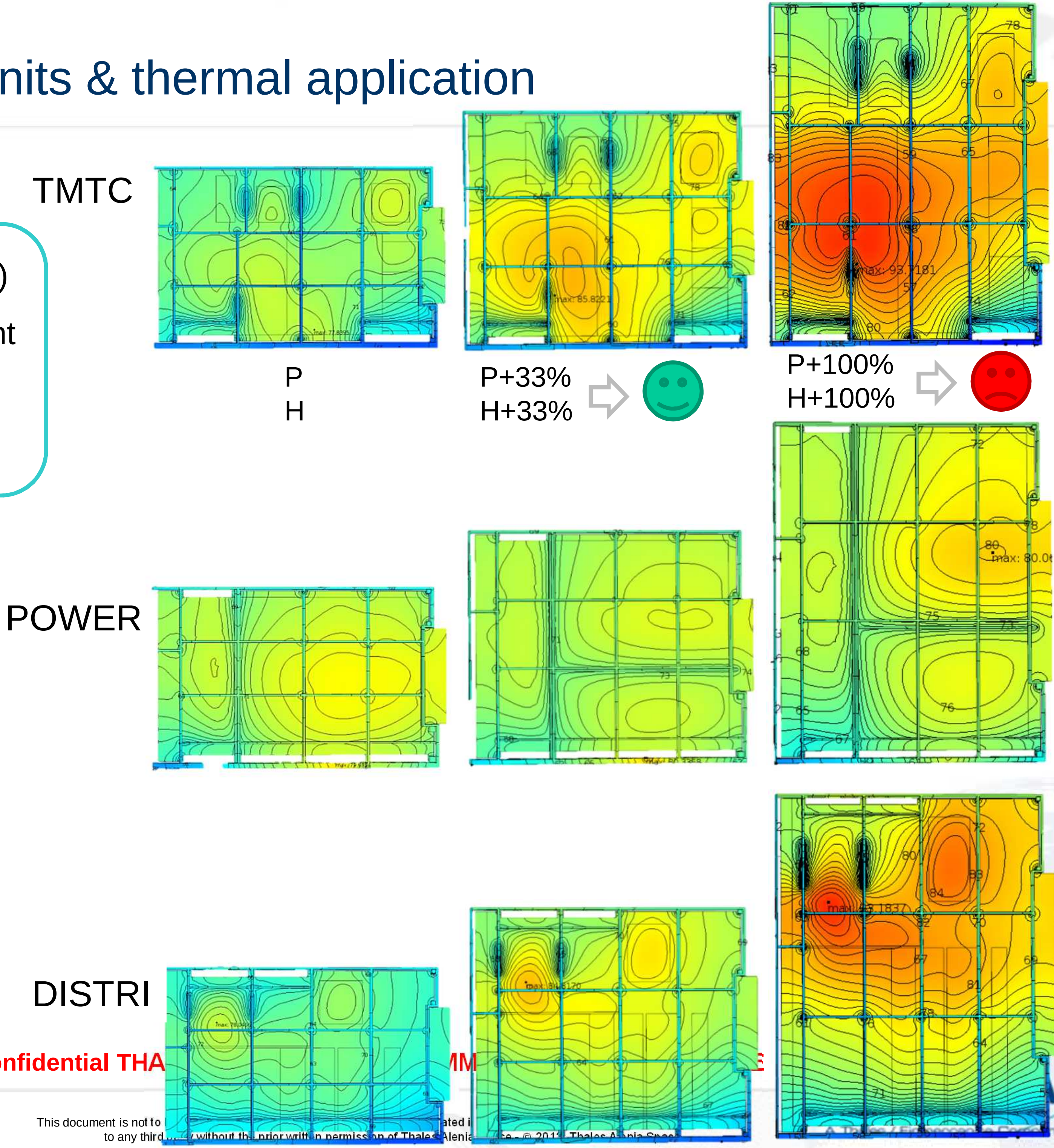




9. Electronic units & thermal application

Merge modules

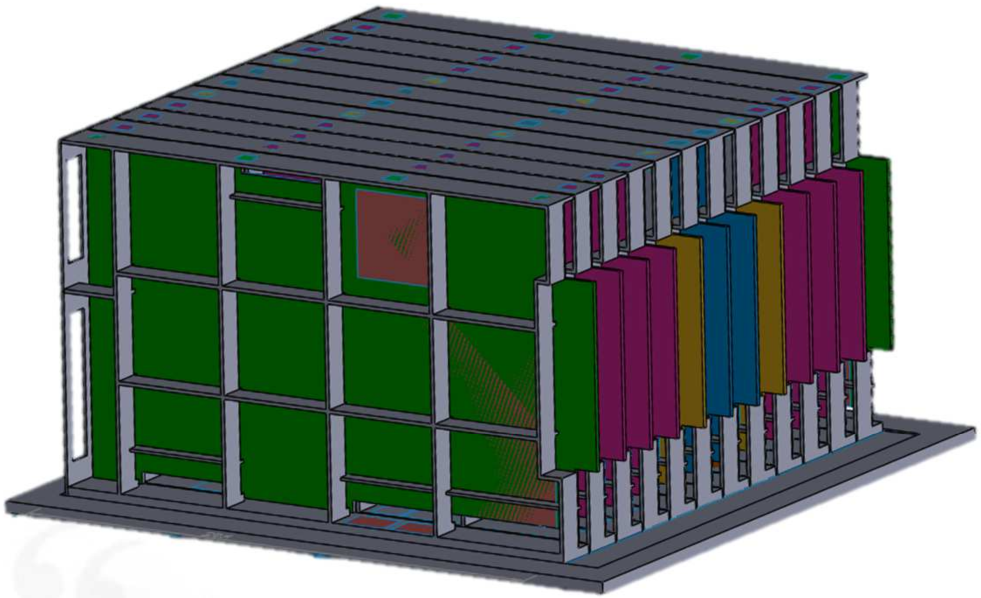
- remove 3 modules (-25%)
- increase power and height
- use BP spreading + µHP
- 1 system HP



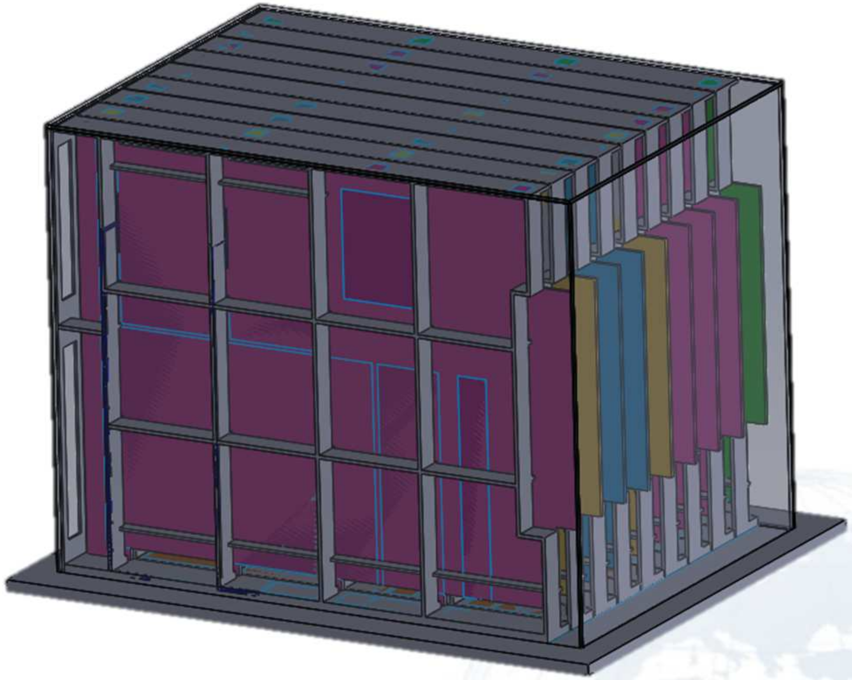
9. Electronic units & thermal application

New CAD file

12 modules
345 x 355 x 200 mm



9 modules
345 x 265 x 264 mm



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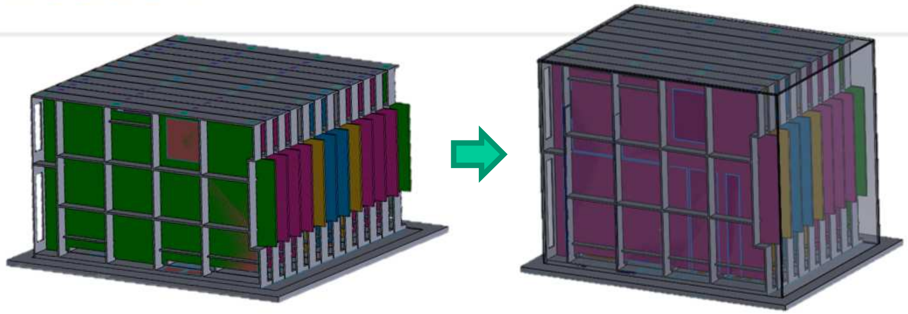
9. Electronic units & thermal application

Impacts : Mass

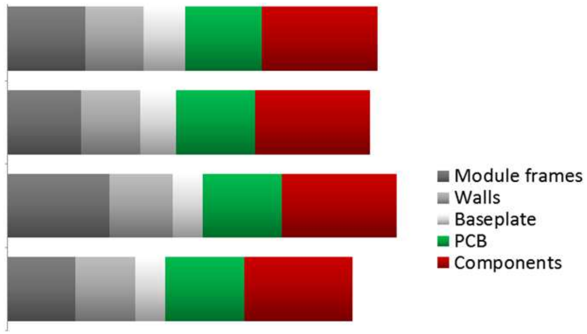


Heat management with micro heat pipes/spreading :

- higher equipment
- reduce number of modules

Mass of components remains the same (electrical function). A few connectors to motherboard can be spared.

	L (mm)	H (mm)	Modules	Mass (kg)		Contributions
345x355x200 mm	**294**	**186**	**12**	**15,50**		
	244	224	12	15,20	**-2%**	
	194	282	12	16,31	+5%	
345x**265**x264 mm **shorter HP**	294	247	**9**	**14,44**	**-7%**	



integration of thermal functions

topological optimization

additive manufacturing

electronic units

→equipment is lighter

→equipment can be even lighter

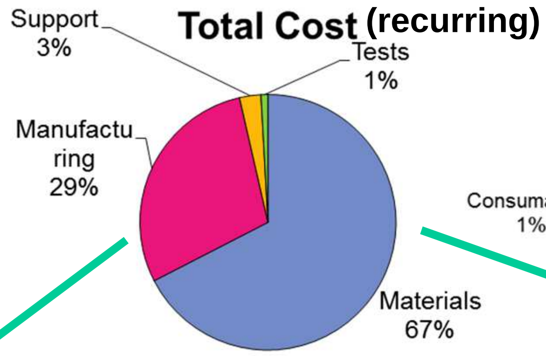
structure weight ↘

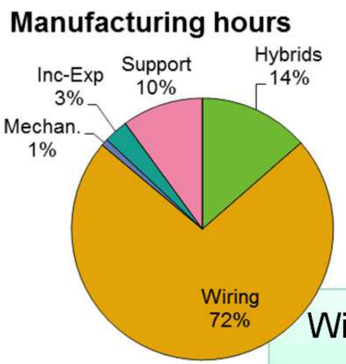
more compact and lighter spacecraft

9. Electronic units & thermal application

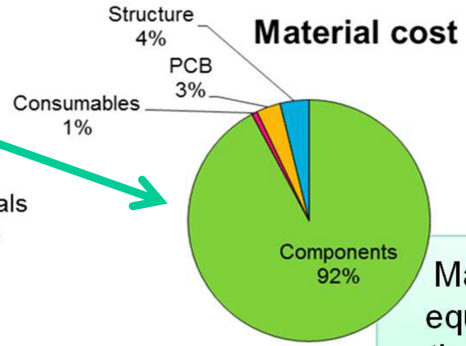
Impacts : Costs

Structural parts are assigned to a subcontractor





Wiring is the main contributor in the manufacturing hours



Material is the main contributor in the equipment cost, especially because of the amount of electronic components.

1 module structure machined ~ a few hundred euros (recurring)

Same structure in AM costs between 5000 and 10 000 € (according to AM manufacturer)

- 1 module AM increases unit price by ~1,5%
- 2-phase thermal functions are quite expensive

→+3-5% per module

→equipment is more expensive

if the number of modules is reduced by 25% + limit components reported on structure : Manufacturing hours reduced by 10% → 3% saving in global cost

→-1% per module

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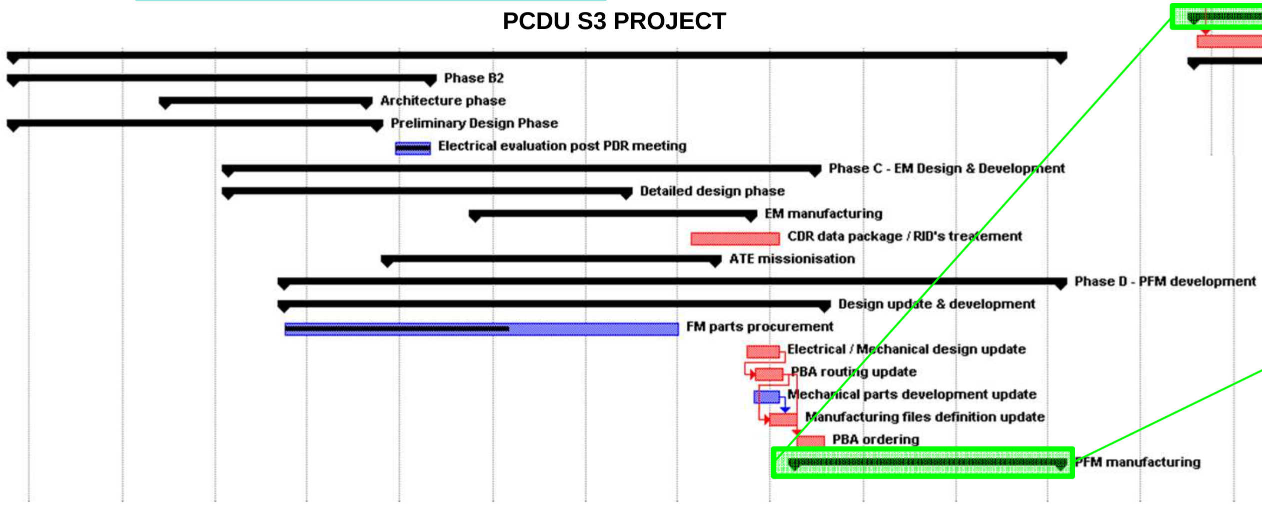
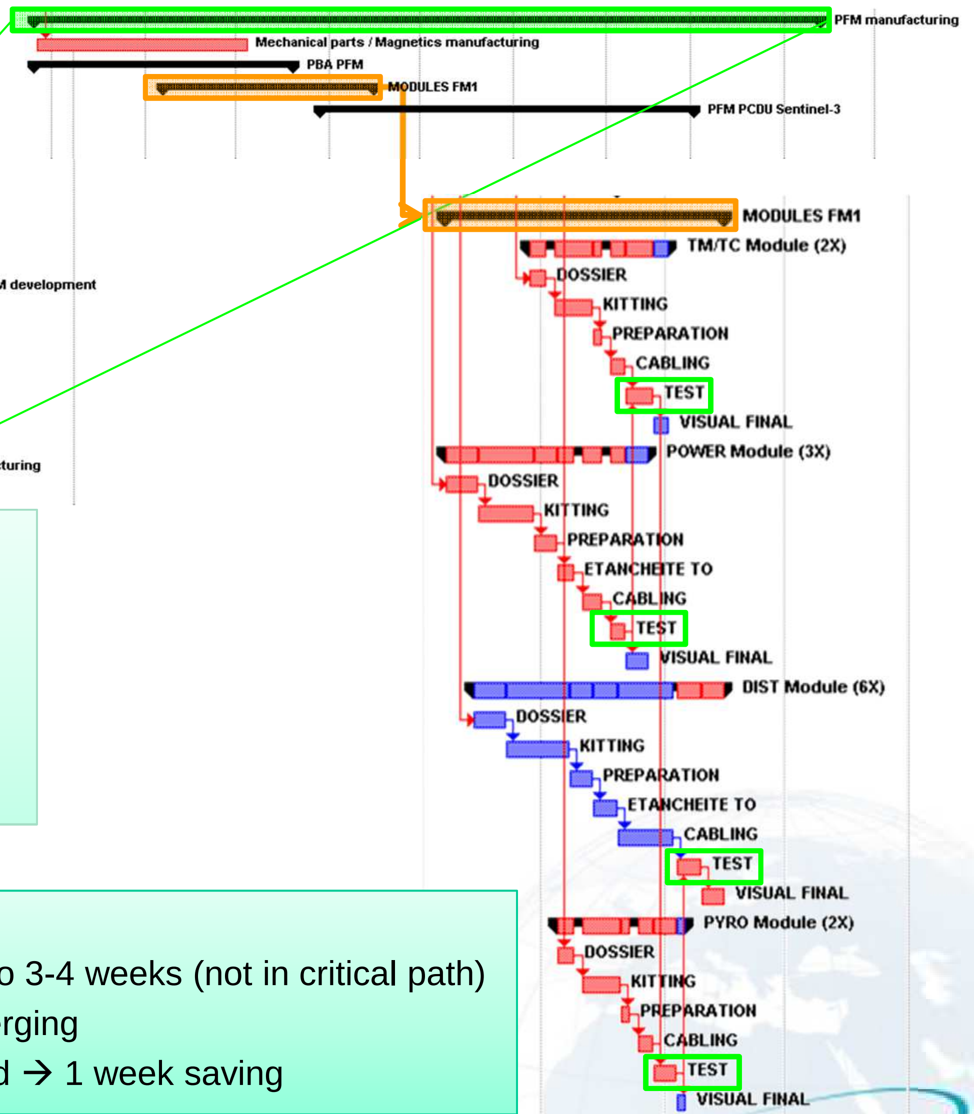
9. Electronic units & thermal application

Impacts : Planning





Non-recurring :

- thermal aspects have to be taken into account earlier in the project
- design time of the AM-thermal parts ? interaction with subcontractors :
  - AM manufacturer (writing CNC program for machining requires currently ~40h/module)
  - 2 phase solutions provider

Recurring :

- manufacturing time of the AM-thermal parts is estimated to 3-4 weeks (not in critical path)
- modules parallel manufacturing → no time saving with merging
- testing phase for each module (sequential) will be reduced → 1 week saving

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9. Electronic units & thermal application

Impacts : Environment

- Material

Raw material saving with AM is around 90% (printing of supports not taken into account)

L (mm)	H(mm)	Modules	Material amount (cm³)		Material savings with AM
			Aluminium block	Module	
294	186	12	1093,7	100,45	91%
244	224	12	1093,1	94,47	91%
194	282	12	1094,2	130,78	88%
294	247	9	1089,3	115,75	89%
294	372	9	1640,5	131,79	92%
294	297,6	9	1312,4	121,83	91%

- Energy

For aluminium in comparison with titanium, the machining energy levels are much lower.

energy to manufacture an aluminum block + bulk machining

VS

fusion of metal powder by a laser + surface machining

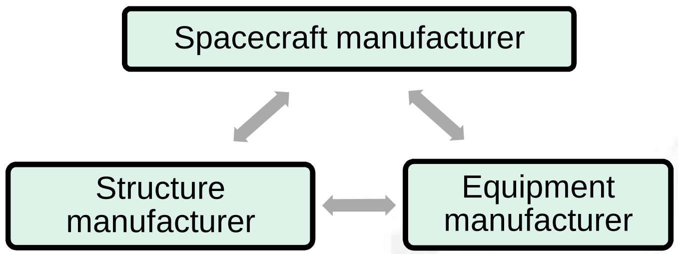
- LOS

minimizing PCDU mass should limit the probability of ground impact.

The use of topological optimization should help in that way.

Conclusion (1/2)

- Thanks to AM, heat management with micro-thermal functions inside the structure seems efficient
- If 3 modules (25%) are removed by merging with others:
  - Mass saving of 7% is achievable at equipment level and could be improved with topological optimization
  - Manufacturing hours can be reduced by ~10%
  - Planning can be slightly reduced (1 week)
  - Unit cost is estimated to increase by 6 to 12%
- Price of AM / thermally functional part is unknown and can be quite expensive
- Final benefit might be more perceptible at system level (less HP, lighter unit) than at equipment level which is more expensive
- Importance of interactions



Conclusion (2/2)

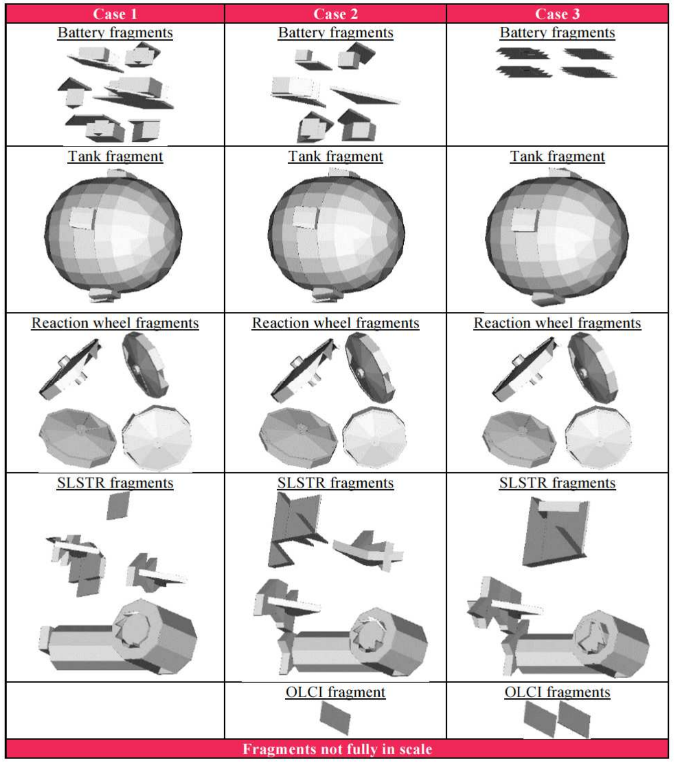
To apply additive manufacturing to dissipative electronic equipment, these aspects have to be integrated or mastered:

- Designers must be formed to design for additive manufacturing
- Part quality assessment (with post-treatment) and standardization
- Reliable thermal function integration (THERMAM project)
  - powder removal, internal surface treatment
  - reliable sealing to ensure to hold internal pressure and avoid leaks at all costs
- Testing 3D tortuous 2-phase systems designed for 0g is tricky
- Integrate a thermal optimization in the AM design, just as topological optimization for mechanical performance. → first level of thermal design, before adding the two-phase thermal function which could eventually be avoided
- State of Mind change : “AM parts are too expensive” but it can lead to cost savings that counter-balance (launch ~50€/g)
  - By 2020, AM cost should be divided by two

- 10. Quantitative evaluation on Sentinel 3 satellite design - WP 4400 (TAS-F)

10. Quantitative evaluation on Sentinel 3 satellite design

- **Criteria : SDM Compliance**
  - 1/ 2T LEO satellite (Sentinel 3) -> orbit change to natural re-entry in 25 years
  - 2/ following step : casualty risk computation
    - HTG evaluation of survival pieces
    - Casualty area computation
    - Compliance with 10-4
  - 3/ if NC -> controlled re-entry
    - Drastic satellite design change
- For S3A&B, result is ~1:11200
- => Impact of AM through "generic" LEO S/C
- Using CNES Tool " Debrisk"



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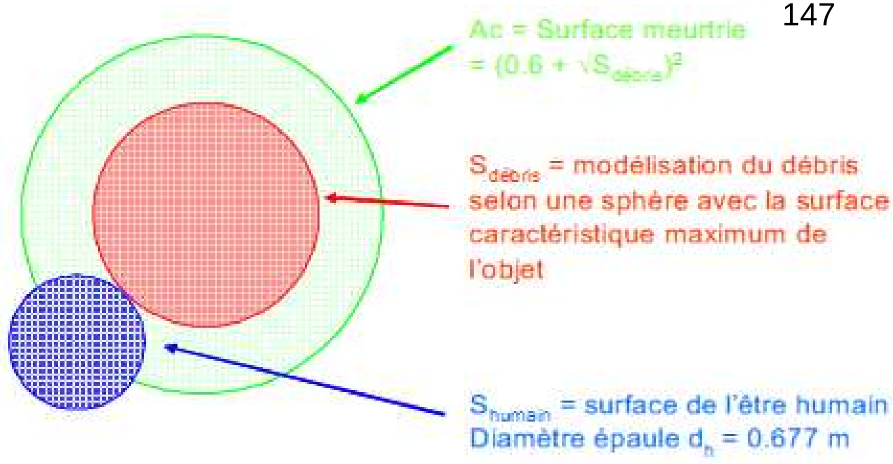
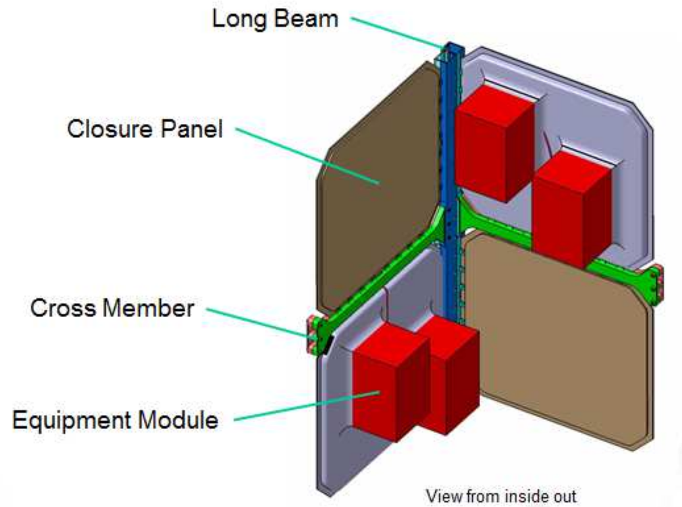
10. Quantitative evaluation on Sentinel 3 satellite design

- SDM Compliance for natural re-entry
  - 1/ Reduction of surviving elements
    - D4D guideline: to expose as soon as possible
  - 2/ Reduction of number of survival pieces
    - 1 single piece goal



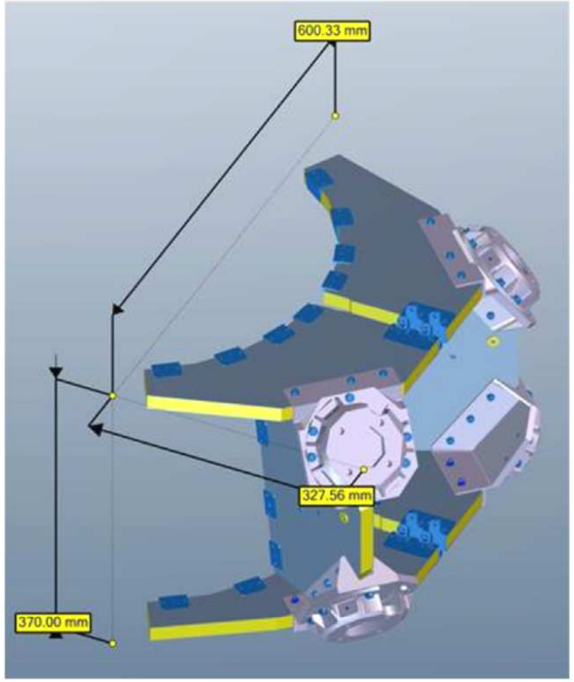
  - 1/ Reduction of surviving elements
- For elements that could demise, problem if separation at low altitude
  - Demise though heat flux exposure
  - => separation of lateral panel / hole



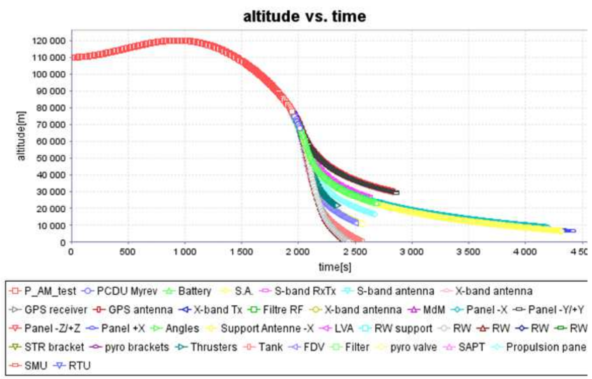
RUAG Panel Modular Concept

10. Quantitative evaluation on Sentinel 3 satellite design

- SDM Compliance for natural re-entry
  - 2/ Reduction of number of survival pieces

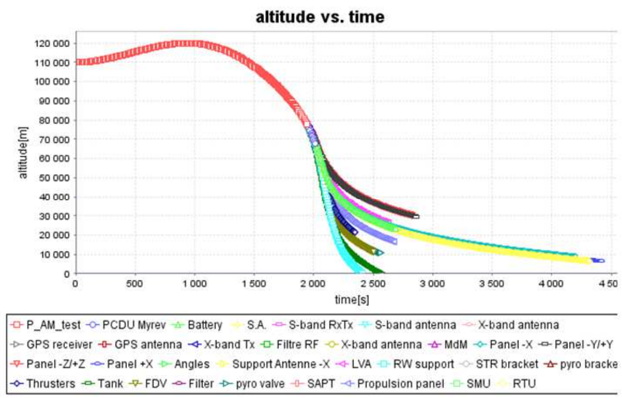


Case 1 : 4 RW re-entry



Casualty area = = 2,3 m2

Case 2 : RWs+support in titanium AM (1 piece)



Casualty area = 1,1 m2

Conclusion: Positive impact of AM on SDM

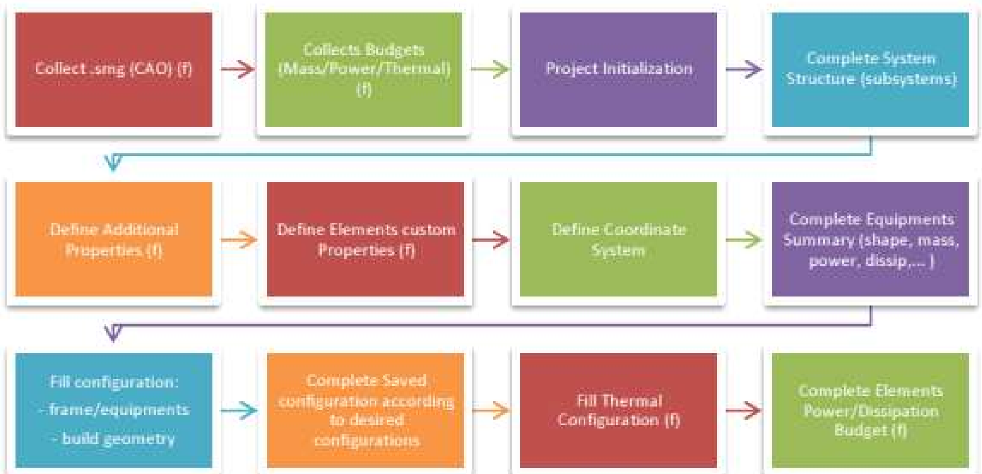
Warning: threshold effect wrt active debris removal

10. Quantitative evaluation on Sentinel 3 satellite design

- Method
  - 1/ Step 1 = introduction of redesigned elements
    - RUAG
    - TAS-B PCDU & application to dissipative units
    - TAS-F Optical bench re-design
    - All ready manufactured TAS support/pieces
  - 2/ Step 2 = Redesign with
    - IDM tool to take benefit of geometry
    - Extrapolation of topological optimisation.

Sentinel 3 seen in Catia

Sentinel 3 seen in IDM



10. Quantitative evaluation on Sentinel 3 satellite design

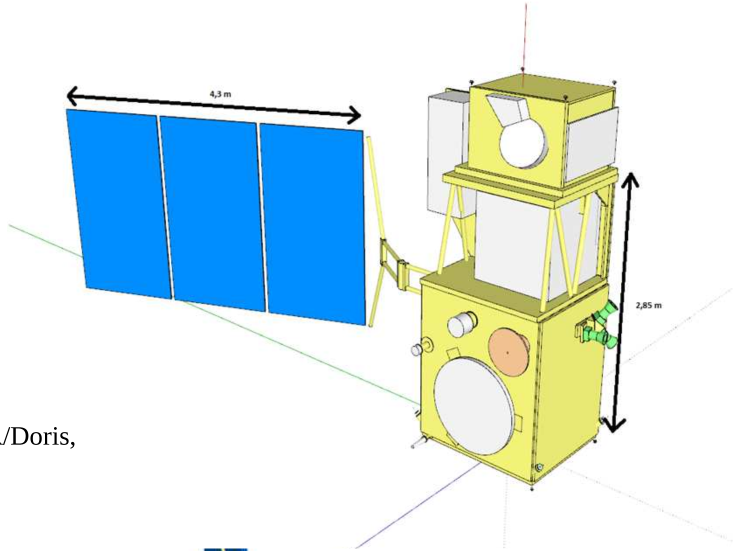
- Step1
  - Same configuration with 4 redesigned applications
    - TAS-B PCDU & application to dissipative units
      - Verification of PCDU accommodation
      - 7% on PCDU

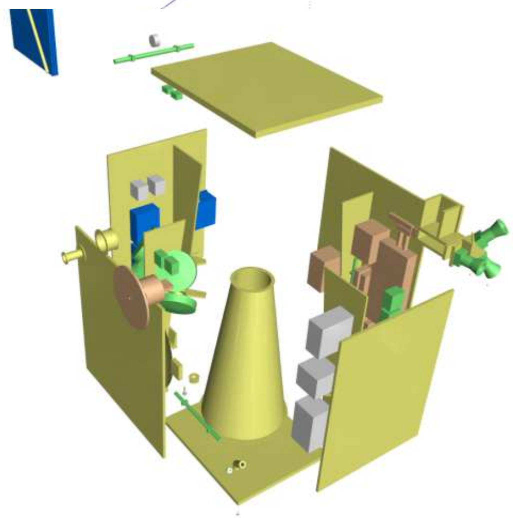
→ Electronics GNSS/STR/Doris, SMU, OEU, PDHU

    - RUAG panels & LAR I/F Ring
    - TAS-F OLCI Optical Bench

S, X, GPS, Doris, SRAL

      - -8.5%
    - All ready manufactured TAS support/pieces





Company	Parts	Mass Saving factors
TAS-F	ARABSAT main reflectors fitting (see 3.4.2.2 fig 3-18)	20 %
TAS-F	Ku Horn support for telecom satellite	57 %
TAS-F	Tubing support in PA12 (Polyamide) for Iridium next	69 %
TAS-I	Spacecraft antenna-reflector sustainer	25 %
TAS-I	Star tracker sensor bracket	46 %
TAS-I	Equipment mechanics	30 %

→ S, X, GPS, Doris, SRAL

→ LRR & Doris support

→ & RW support

→ SADM

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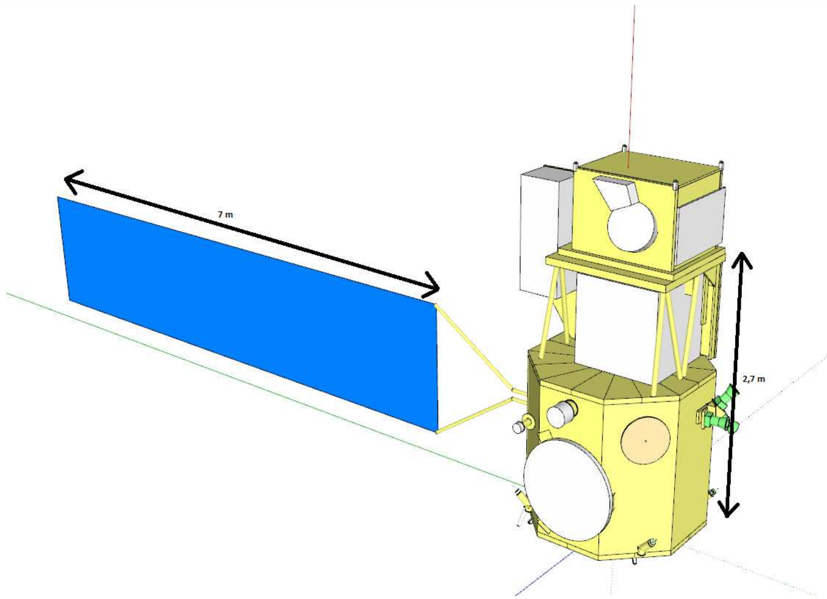
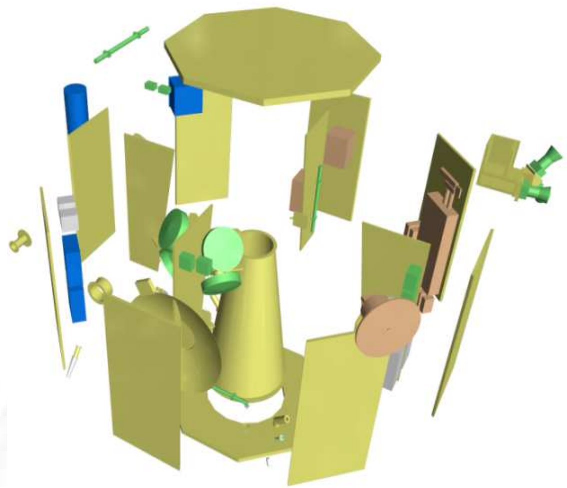
Step2

Geometrical optimization:

- To fit into Vega fairing,
- To try to optimize AOCS configuration,
- SA “3D printing”:
  - Verification of PCDU accommodation,
- 20% mean value reduction mass due to topological optimization.



  - Lower maturity / Step 1



10. Quantitative evaluation on Sentinel 3 satellite design

- Mass budget
  - Step 1
    - Wet mass – 52kg
  - Step 2
    - Wet mass – 94 kg
- Power budget
  - No impact

		Reference	Step 1	Step 2
▼	**Plateform**	Including margin [Kg]	Including margin [Kg]	Including margin [Kg]
+ -	**Subsystem**			
▼	Structure	165,46	149,96	146,92
▼	Propulsion	22,64	21,72	18,50
▼	Power	138,39	131,95	126,61
▼	AOCS	61,74	60,17	60,17
▼	TTC	6,16	5,76	5,67
▼	PDHT	44,45	41,58	40,89
▼	Data Handling	17,43	16,21	16,21
▼	Harness	64,79	64,79	64,79
▼	Thermal Control	21,00	20,62	17,03
▼	Fixation	5,32	5,32	5,32
Total mass without system margin		**547,37**	**517,29**	**536,33**
System margin		**584,29**	**552,19**	**572,51**
▼	**Payload**	Including margin [Kg]	Including margin [Kg]	Including margin [Kg]
+ -	**Subsystem**			
	Structure	49,46	48,21	38,62
▼	OLCI	148,93	144,20	144,20
▼	SLST	175,64	175,64	175,64
▼	SRAL	62,03	58,49	56,20
▼	MWR	25,21	25,21	25,21
▼	DORIS	20,54	19,25	18,83
▼	LRR	0,38	0,38	0,30
▼	GNSS	8,07	7,61	7,31
Total mass without system margin		**490,22**	**475,96**	**466,30**
System margin		**523,29**	**508,07**	**497,75**
▼	Balacing mass	11,20	11,20	0,00
System		Including margin [Kg]	Including margin [Kg]	Including margin [Kg]
Total dry mass without system margins		**1048,79**	**1004,46**	**968,41**
Total dry mass including system margins		**1118,78**	**1071,46**	**1033,74**
Total propellant mass		**119,40**	**114,36**	**110,31**
Total wet mass including all margins		**1238,19**	**1185,82**	**1144,05**

10. Quantitative evaluation on Sentinel 3 satellite design

MCI

Reference

REF		Stowed BOL	
		Without margins	*With margins*
COG_x	[mm]	1509,44	1511,65
COG_y	[mm]	7,89	2,03
COG_z	[mm]	-23,60	-27,54

Step 1

REF		Stowed BOL	
		Without margins	*With margins*
COG_x	[mm]	1509,44	1511,65
COG_y	[mm]	7,89	2,03
COG_z	[mm]	-23,60	-27,54

Step 2

STEP 1		Stowed BOL	
		Without margins	*With margins*
COG_x	[mm]	1504,49	1507,16
COG_y	[mm]	7,08	7,39
COG_z	[mm]	-10,03	-9,06

		Reference	**Step 1**	**Step 2**
Configuration		Deployed EOL	Deployed EOL	Deployed EOL
		With margins	*With margins*	*With margins*
Ixx_S3	[kg.m²]	**1714,0**	**1708,5**	**2640,9**
Ixy_S3	[kg.m²]	58,3	-14,7	152,3
Ixz_S3	[kg.m²]	55,7	-17,9	56,3
Iyz_S3	[kg.m²]	58,3	-14,7	152,3
Iyy_S3	[kg.m²]	**1404,2**	**1332,2**	**1131,4**
Iyz_S3	[kg.m²]	-85,9	-62,0	-13,6
Izx_S3	[kg.m²]	55,7	-17,9	56,3
Izy_S3	[kg.m²]	-85,9	-62,0	-13,6
Izz_S3	[kg.m²]	**2805,3**	**2774,3**	**3500,7**

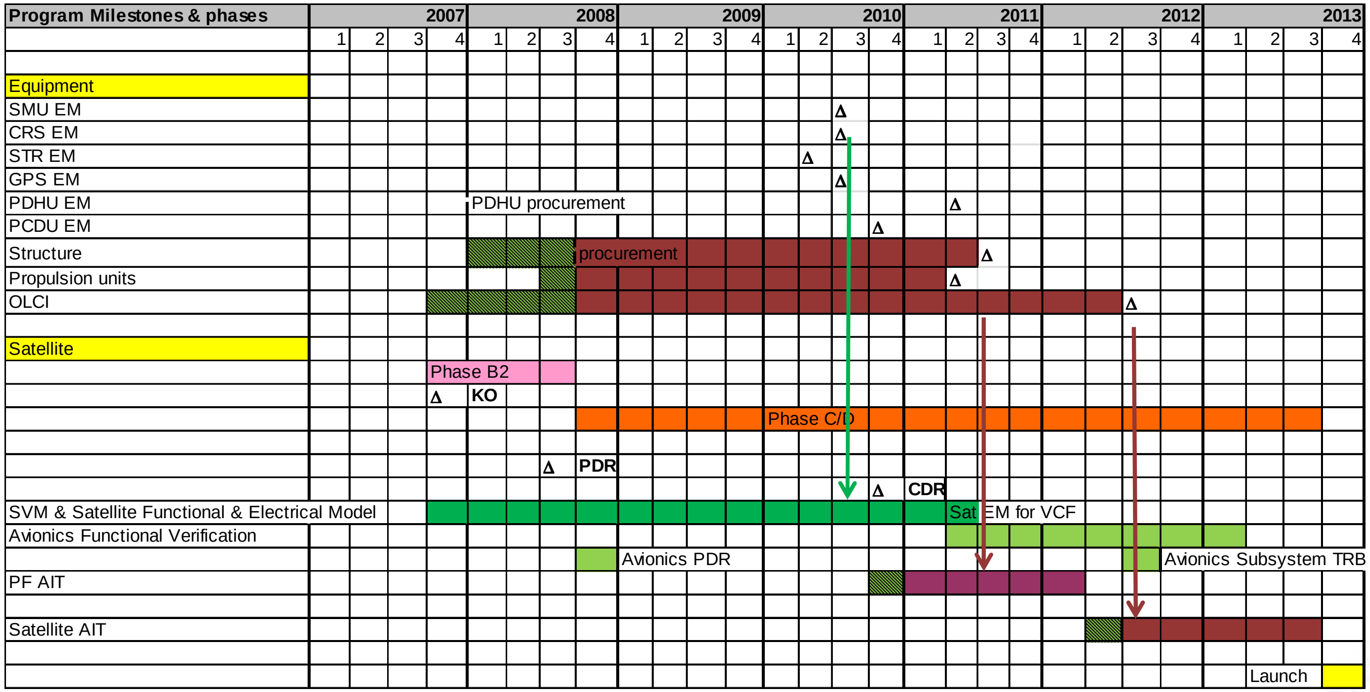
Goal : descope wheels configuration

- Need 20% inertia reduction to keep AOCS performance
- Cdg still in conformance with Launcher requirement

10. Quantitative evaluation on Sentinel 3 satellite design

Programmatics – Schedule

Sentinel 3A Reference (CDR status)



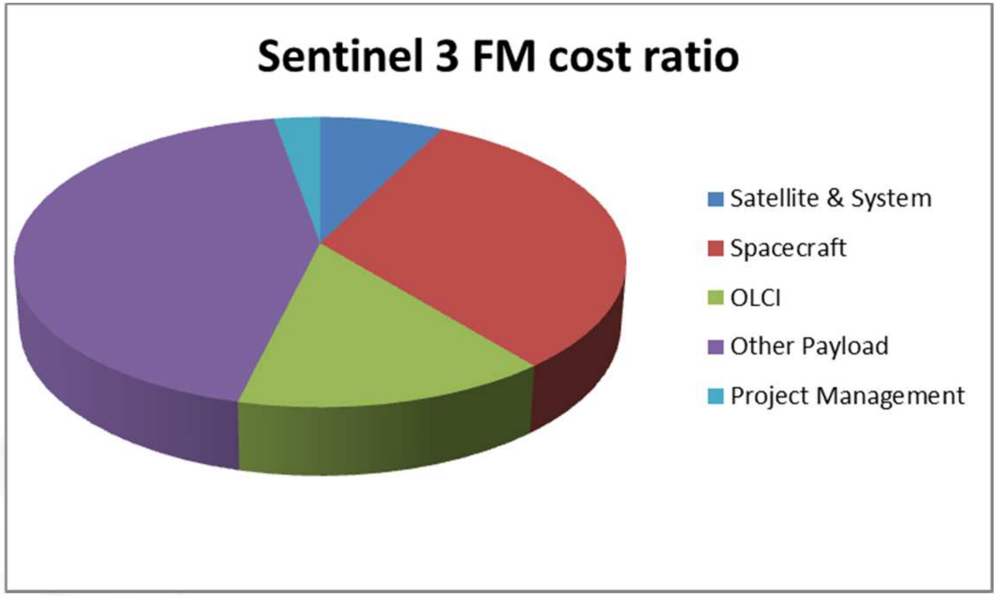
- Improvement mainly on lead time (no forged model, …)
- Integration time

Small schedule improvement

Schedule driven by Payload & Avionics

10. Quantitative evaluation on Sentinel 3 satellite design

- Programmatics – Cost
  - 3 axes
    - Improvement at Sentinel 3 satellite level of re-designed applications
    - Risk reduction at very beginning of a satellite program
    - Impact of satellite mass reduction



- FM satellite => Payload > 50%
- Study addresses SVM & OLCI

10. Quantitative evaluation on Sentinel 3 satellite design

Programmatics – Cost – axe 1

Lead Time	Provision	Improvement due to Additive manufacturing process	AM gain percentage (%)
Structure	Reference PECT	RUAG evaluation - ~30% manufacturing duration	0,09
PCDU, PDHU	Reference PECT	TAS-B evaluation - 2 weeks	0,00
Supports structure	Reference PECT	TAS-F evaluation from manufactured support- ~ 20%	0,01
TOTAL			**0,11**

Life cycle cost	Provision	Improvement due to Additive manufacturing process	AM gain percentage (%)
PF Mechanical activities engineering	S/C mechanical activities	S/C mechanical analysis improvement with topological optimization	0,01
Thermal & harness (TBC) routing activities - generic embedded functions	SVM activities	activities at equipment level	0,03
OLCI activities	Optical bench product	TAS-F evaluation	0,05
TOTAL			**0,09**

Integration	Provision	Improvement due to Additive manufacturing process	AM gain percentage (%)
integration preparation	equivalent AIT team activities	AM mock-up to optimize integration process at end of B2 phase - 20% improvement	0,01
Propulsion integration	equivalent AIT team activities	AM with thrusters & tubing embedded with no realignment -	0,01
equipments & supports integration	equivalent AIT team activities	minimization of interfaces - 50% improvement integration time	0,00
Structure & harness integration	equivalent AIT team activities	AM manufacturing as needed during integration process	0,00
TOTAL			**0,03**
		TOTAL	**0,22**

10. Quantitative evaluation on Sentinel 3 satellite design

Programmatics – Cost – axe 2

Technical risks	Provision	Improvement due to Additive manufacturing process	AM gain percentage (%)
General low maturity of satellite design, and of verif.&AIT approach, leading to quotation uncertainties for own share	10% of own share (service module only)	20% reduction as verif & AIT approach secured with AM mock-up at early program stage	0,10
Non recurrent activities for Payload	10% of payload ingeneering activities	topological optimization improvement for mechanical analysis. Remaining 8% of payload ingeneering	0,03
Additional analysis to ensure AOCS performances with specific mission modes	Additional AOCS analysis	No reduction is considered at this stage even if AM could improve knowledge of MCI at early stage of the program	0,00
Extra engineering and AIT activities in case of unexpected behavior of SVM parts during environmental sequence	Additionnal 10 people full time over 2 months for anomaly resolution and delta analysis	Subsystem integration function at lower level will move this risk to procurement. Risk reduction of 20% is quoted at satellite level.	0,03
TOTAL			0,16

Programmatic risks	Provision	Improvement due to Additive manufacturing process	AM gain percentage (%)
Schedule risk at Service Module integration level: schedule recovery actions, more AIT personnel, 3 shifts (in addition to schedule elongation costs costed)	10% of S/C AIT manpower costs	5% of S/C AIT manpower costs considering AM design "integration oriented"	0,13
Schedule risk at satellite level: extension of schedule duration for the whole 3-month planning margin due to late deliveryfor example	3 months of AIT manpower costs	no significant impact of AM on satellite system test but risk reduction at integration and in equipement delivery compensated by additional complexity of multifunctions applications	0,00
TOTAL			0,13

Purchasing risks	Provision	Improvement due to Additive manufacturing process	AM gain percentage (%)
General low maturity of overall design, and of verification&AIT approach, leading to quotation uncertainties for purchased share	10% of final expected purchased share	margin estimated reduced due to 5% applied to SMU and structure	0,19
Uncertainties on market conditions, currencies and obsolescence, leading to higher purchase SVM costs (+ ITAR problems)	10% for uncertainty and for obsolescence	minor improvement due to lead time reduction	0,01
Provision for potential change notice generated by TAS-F and source of over costs on sub-contracted equipments.	5% of final expected purchased share	reduced to 2% for structure and SMU considering possible very late design definition as soos as interfaces are not changed	0,11
TOTAL			0,31
		TOTAL	0,60

10. Quantitative evaluation on Sentinel 3 satellite design

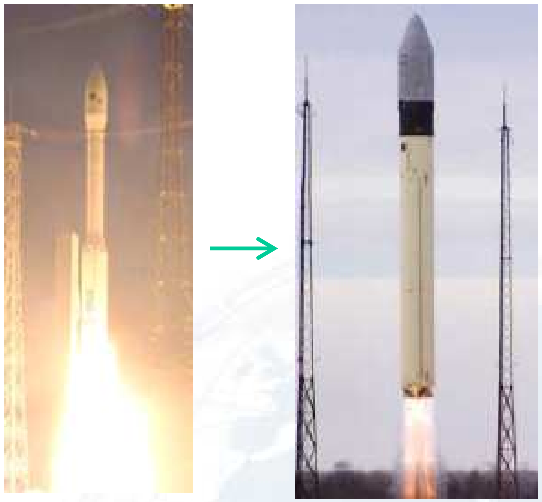
Programmatics – Cost – axe 3

Reduction of launched mass

Technical hypothesis	Provision	Improvement due to Additive manufacturing process - low hypothesis	AM gain percentage (%)	Improvement due to Additive manufacturing process -high hypothesis	AM gain percentage (%)
Single launch on Vega	reference launched mass = 1238 kg	launch cost function of updated launched mass 1186 kg - Step 1	0,87	Step in launcher capacity - Possible use of Rockot	4,15
Single launch on Vega	reference launched mass = 1238 kg	launch cost function of updated launched mass 1144 kg - Step 2	1,58	Step in launcher capacity - Possible use of Rockot	4,15

Increase of Payload

Technical hypothesis	Provision	Improvement due to Additive manufacturing process - low hypothesis	percentage (%) for price of kg payload launched
equivalent launched mass => Payload additional mass	Equivalence Payload cost/ mission cost . Payload mass ref = 441 kg	Possibility to increase Payload mass of 42 kg - Step 1 (same cost/payload mass ratio)	-4,54
equivalent launched mass => Payload additional mass	Equivalence Payload cost/ mission cost . Payload mass ref = 441 kg	Possibility to increase Payload mass of 79 kg - Step 2 (same cost/payload mass)	-7,94



Conclusion: Cost saving

Major effect is "snow ball effect" of dry mass reduction

GSTP/ARTES for AM

- Structure:
  - G61A-021QT: Primary Structures made by additive manufacturing (proposed)
- Thermal function in structural parts:
  - G61A-027MS: Development of embedded thermal functions in structural parts using 3D printing (proposed)
- Mechanism:
  - G61A-033MS: Development of a Compliant Mechanism Based on additive Manufacturing (proposed)
- Material:
  - GSTP 6.2: Net shape processing by SLM of aluminium alloys with high silicon content for low thermal expansion applications (proposed)

GSTP/ARTES for AM

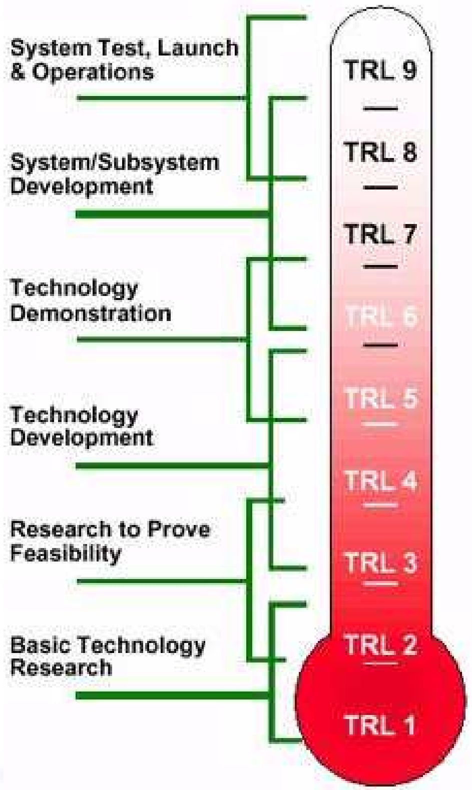
- RF function in structural parts:
  - G61A- 029ET: Development of one single part integrating waveguide filter, bends, couplers, supporting structures made by additive Manufacturing (proposed)
- RF Hardware:
  - G61A-035ET: Evaluation and consolidation of additive Manufacturing processes and materials for the manufacturing of RF hardware (proposed)
  - 15.ITT.30: Additive manufacturing of large focal arrays (intended)
  - 15.ITT.38: Miniaturised Ka band beam formatting network (intended)
- Propulsion Hardware:
  - G627-004QT: investigation into additive layer manufacturing for engine structural component (initiated in 2014)

GSTP/ARTES for AM

- Space hardware:
  - 15.1.QM.14: Development and test of additive manufactured space hardware – evaluation in term of mass, interface, environment impact and cost (completed)
- Verification methodology:
  - 15.1.QM.18: Verification methodology for parts made by additive manufacturing (issued)

Technology Readiness Level

Technology Readiness Levels definition	Expected model philosophy for full qualification
TRL 1 **Basic principles observed and reported** Transition from scientific research to applied research. Essential characteristics and behaviour of systems and architectures. Descriptive tools are mathematical formulations or algorithms.	Conceptual Design, Feasibility study, Preliminary Design 2 BB, 1 EM, 1 PFM
TRL 2 **Technology concept and/or application formulated** Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.	Feasibility study, Preliminary Design 2 BB, 1 EM, 1 PFM
TRL 3 **Analytical and experimental critical function and/or characteristic proof-of-concept** Proof of concept validation. Active R&D is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.	Preliminary Design 2 BB, 1 EM, 1 PFM
TRL 4 **Component/subsystem validation in laboratory environment** Standalone prototype implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.	Preliminary Design 1 BB, 1 EM, 1 PFM



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Technology Readiness Level

- PCDU: TRL 3
- Frames radiator/LVA: TR 2
- Optical bench: TR 2 (invar), 1 (ceramic)
  - Objective of the proposed pre-development activities is to reach TR4 including breadboarding activities in addition to more generic activities

Next activities – applications (recall)

- PCDU:
  - Part quality assessment with post treatment (manufacturing reproducibility, reliability,…)
  - Training for AM design
  - Thermal optimisation (topology) – might avoid the two-phase thermal function
  - Heat pipe integration (powder removal, surface treatment, testing orientation – wick structure without grooves, mechanical pressure resistance with removal of the heat pipe orientation constraint)
- LVA:
  - Definition improvement (ring attachment to the adjacent parts)
  - Mechanical analysis
  - Breadboarding
- Framed radiator:
  - Topology optimisation on a complete frame
  - Concept study of the module and submodule => equipment supplier to be associated to this study
  - Thermal and electrical function of radiator frame
  - Breadboarding
  - Concept applicable to primary structure (TBC)

Next activities

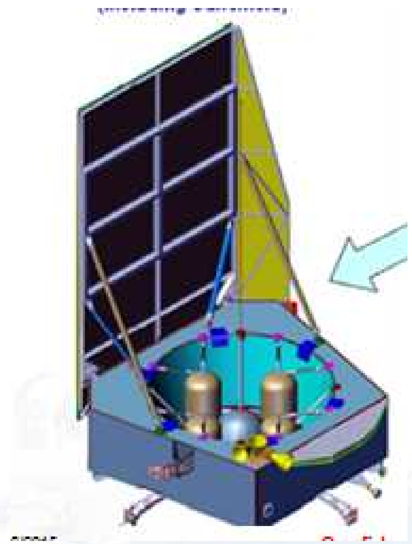
- General:
  - Interface/multifunction management => multifunction integration imposes multi-disciplinarity (thermal, electrical, RF functions embedded in mechanical parts)
    - Design of a next generation mini/micro-platform using AM to the maximal extent with multifunction integration
  - Topologic optimisation not limited to mechanical optimisation (thermal, thermal distortion,…)
    - In relation with aim B of the ESA AM roadmap, dedicated to the design tool (refer to document ESA/IPC(2015)82)
  - Design compatibility with Space Debris Mitigation requirements
    - In relation with aim B of the ESA AM roadmap
  - Development of a design tool suite for AM including in particular CAD design (lattice structure)
    - Aim B13 of the ESA AM roadmap

Next activities

- General (following):
  - Normalisation (ECSS) for design/material supply/processing /post-processing/qualification capabilities
  - Inspection, testability (samples – tensile static test- tomography)
    - In relation with aim F of the ESA AM roadmap (F04: NDI for AM manufactured parts)
  - Investigation of the reliability and reproductibility/transferability
    - Aim D10 of the ESA AM roadmap
  - Compatibility of surface with cleanliness requirements
    - Aim E06 of the ESA AM roadmap

- 11. Quantitative evaluation on Euclid satellite design – WP 4500 (TAS-I)

Quantification of ALM impacts are quantified through the following aspects:

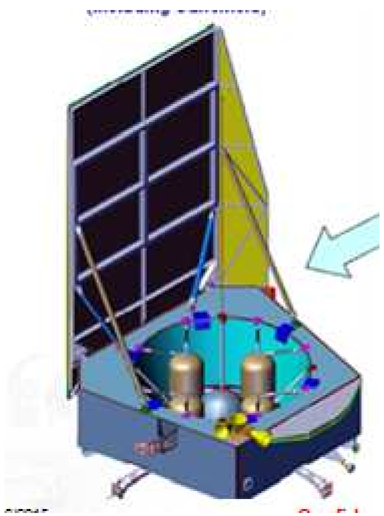


8.

Quantitative evaluation method setting

Quantification of impacts are quantified through the following aspects:

- **Mass, geometry**
  - redesign
  - propellant saving and needed components
  - Improved buy-to-fly ratio
- **Thermal aspects**
  - Improve thermal efficiency by embedding coolant
  - Improve thermal interfaces
- **Life cycle**
  - Improvement of all life cycle process including design, rawing/baseline management, PDM, ICD, lead time



…and then time/Cost saving

Quantitative evaluation of ALM mass saving impacts

- Mass reduction on components impact Inertial properties of spacecraft

  1) Quantitative Recalculation of Total dry mass

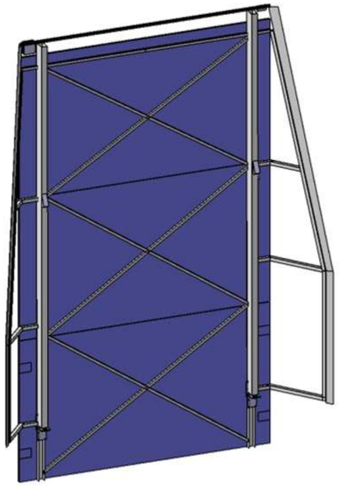
  2) Quantitative Recalculation Inertial Moments & C.o.G.

- Quantitative_Evaluation of Impact on
  - Euclid launch cost to Earth orbit
  - Euclid transfer orbit system to Lagrange point: needed propellant and tanks
  - Euclid Attitude Control operations: RCS needed propellant, tanks (6,25 year nominal life)
- Possible saving (qualitative) on primary structure due to subsystem mass saving

  Are to be considered thermal inertial aspects as consequences of mass savings

Quantitative evaluation of ALM assemblies versus PDM life cycle

- An assembly produced by several parts can be produced in a single components
- Evaluation of Impact on
  - Estimation on savings due to reduced complexity parts trough:
    - design,
    - drawings,
    - documentation management,
    - configuration baseline management,
    - Purchasing
    - …



EUCLID quantitative evaluation proposed focus 3 of 3

Quantitative evaluation of ALM buy-to-fly impacts

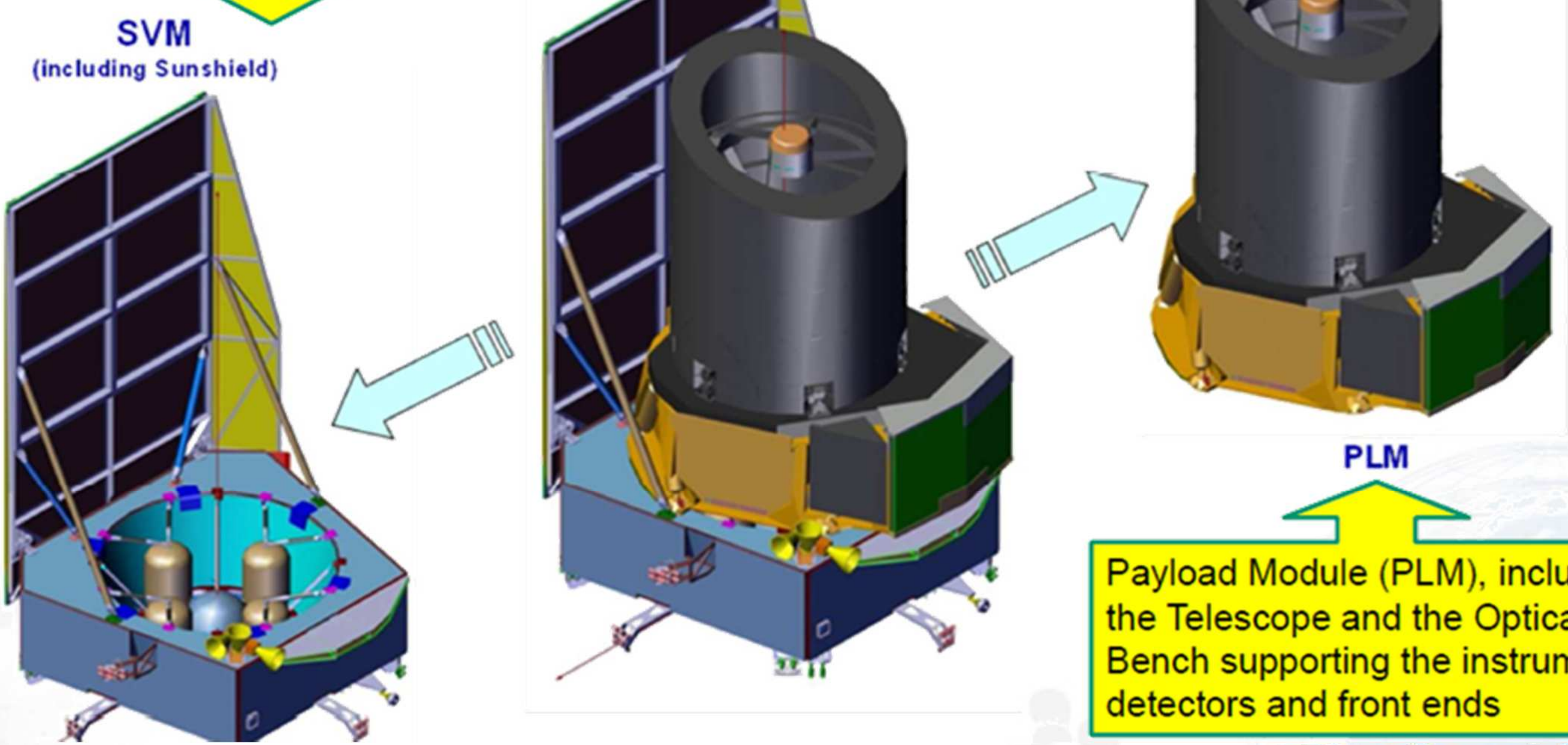
- Bulk Metal material reduction estimation on ALM components respect traditional machining

- Evaluation of Impact on
  - Quantitative estimation of material waste reduction

Quantitative evaluation

The EUCLID spacecraft is composed of:

Service Module (SVM) comprising the spacecraft platform with its subsystems and a Sunshield protecting the PLM from solar radiation and supporting the solar array.



Payload Module (PLM), including the Telescope and the Optical Bench supporting the instrument detectors and front ends

Quantitative evaluation

The EUCLID quantitative application consists to evaluate the results of the application screening and qualitative evaluations performed in the task 3 of the study logic and then implement them to EUCLID satellite.

The qualitative evaluations are concentrated on the following aspects:

- structural optimization and mechanisms (proposed by RUAG)
- electronic units and thermal integration (proposed by TAS-B)
- optical payloads (proposed by TAS-F)

Since no optical payloads are present in the EUCLID SVM element, the qualitative evaluations performed on optical payloads are not applicable to EUCLID in the frame of the present study.

Therefore the evaluations considered are only those relevant to structural optimization-mechanisms and electronic units with thermal integration.

Quantitative evaluation

The Euclid spacecraft has been analysed and the parts that have been considered worth for Additive Manufacturing listed and ranked. The parts selected with the higher score are functionally listed below: :

- Structural parts
  - LVA Ring
  - PLM bracket assembly
  - STR Supports
- Electronic equipment
  - PCDU
- Sandwich Panels
  - Lateral equipment panels
  - Shear panels
  - Thrust cone
  - Antenna reflector
- Support structure
  - Sunshield structure
  - Rods

SELECTED PARTS
Antenna reflector
Central Thrust Cone
STR Supports
Electronic Box (PCDU)
Lateral panel
LVA Ring
Upper IF discrete ring
PLM bracket assembly
radial rod (RCS tank) &MPS tank rod
Shear panel
Sunshield structure

Quantitative evaluation

Part	Sub-part	Material	Unit mass	Q.ty	BEE (kg)	Margin (%)	Margin (kg)	Current Mass [kg]
Antenna reflector	Reflector assy	CFRP sandwich	1,21	1	1,21	0,2	0,242	1,452
Central Thrust Cone		skin CFRP-core Aluminum alloy			17,6	0,15	2,6	20,3
	Nominal Skin + Reinforced Skin	M55J/EX1515 (45º,0º,-45º,90º)s	7,35	2	14,7	0,15	2,2	16,9
	Sandwich Adhesive	EX1516	0,71	2	1,4	0,15	0,2	1,6
	Core	AA-3/16-5056-0.007 32kg/m3	1,27	1	1,3	0,15	0,2	1,5
	Reinforced Core	AA-3/16-5056-0.007 32kg/m3	0,22	1	0,2	0,15	0	0,3
RW Bracket	CMU Supports	AA7075 T7351	1,5	2	3	0,15	0,45	3,45
STR Supports	Star Tracker bracket	AA7075 T7351	1,75	1	1,75	0,15	0,26	2,01
Electronic Box (PCDU)				1	18,7	0,04	0,75	19,45
Lateral panel								
	Equipment Panel +X	skin+core Aluminum alloy		1	6,19	0,15	0,93	7,12
	Equipment Panel +Y	skin+core Aluminum alloy		1	5,85	0,15	0,88	6,72
	Equipment Panel -X	skin+core Aluminum alloy		1	5,41	0,15	0,81	6,23
	Equipment Panel -Y	skin+core Aluminum alloy		1	6,15	0,15	0,92	7,08
	Equipment Panel +X-Y	skin+core Aluminum alloy		1	1,37	0,15	0,21	1,58
	Equipment Panel +X+Y	skin+core Aluminum alloy		1	1,37	0,15	0,21	1,58
LVA Ring					14,9	0,15	2,23	17,08
	LVA IF ring	AA7075 T7351	13,5	1	13,5	0,15	2,02	15,52
	Doubler	AA7075 T7351	0,17	8	1,36	0,15	0,2	1,56
Upper IF discrete ring		Titanium	4,37	1	4,37	0,15	0,66	5,02
PLM bracket assy								
	Upper IF Brackets	Titanium	1,8	6	10,8	0,15	1,62	12,42
	Internal IF Bracket	Titanium	0,53	6	3,2	0,15	0,48	3,68
Radial rod (RCS tank) &MPS tank rod	RCS Tank Struts assy	CFRP-fittings Aluminum alloy			2,26	0,15	0,34	2,6
	MPS Tanks Struts assy	CFRP-fittings Aluminum alloy			3,28	0,15	0,49	3,78
Shear panel	Shear Panels Assembly	skin CFRP-core Aluminum alloy		8	7	0,15	1,05	8,05
Sunshield structure	Support Structure				38,8	0,15	5,89	44,64
	Rods	CFRP						
	Rods end fittings	Titanium						
	Rods brackets	Aluminum alloy						
	Substrate Panels	CFRP	7,15	3	21,5	0,11	2,31	23,76

Quantitative evaluation

The evaluation and quantification of the impacts deriving from the application of the additive technologies to Euclid parts can be based on different aspects:

- Redesign based on what has been proposed by RUAG on structural parts foresees:
  - to replace the sandwich panel by aluminum frame and
  - optimize the design of the LVA ring

  This solution can be applied on the similar Euclid honeycomb panels with both skin and core in Aluminium alloy. They are:
  - Lateral equipment panels (skin and core in Aluminium alloy)
  - SVM tank platform (skin and core in Aluminium alloy)

- Redesign based on what has been proposed by TAS-B for thermal/electronic parts.

- Impact on mass, power, MCI/MoI and Configuration aspects.

- The following table summarizes the impacts deriving from the proposed redesigns based on Sentinel parts and their application to the analogue parts on Euclid:

Quantitative evaluation

The following table summarizes the impacts deriving from the proposed redesigns based on Sentinel parts and their application to the analogue parts on Euclid:

Redesign activities	Ruag: from CRFP panel to ALM modular framed panel	Ruag: from traditional to ALM design LVA ring	TAS-B: from traditional PCDU to ALM heat pipes in PCDU	TAS-F: optical bench in ALM
Quantitative results on Sentinel redesigned parts (in synthesis)	1) impact on mass panel +15% for each equipment 2) impact on mass panel structure -30% 3) cost reduction TBD% 4) Lead time reduction -63% TBC	1) mass reduction -30% 2) cost impact: TBD% 3) Lead time impact from 30W down to 4W TBC	1) mass reduction -7% 2) cost increase +3% 3) dimensions reduction on footprint -30% 4) dimension height increase + 50% 5) Lead time impact TBD%	N/A
Applicability to EUCLID parts	Structural analyses performed on Sentinel are assumed valid also for Euclid applications: 1) apply to all 6 equipment panel 2) apply to SVM Lower & upper platform including shear panels and on thrust cone Assembly	1) YES: Same factors can be applied to Euclid LVA ring	1) YES on PCDU TBC dimension versus envelope available 2) On all other electronic equipment box by applying a conservative mass reduction of -15%	NA
Quantitative impact assessment on Inertial EUCLID properties	1) Mass saving 2) C.o.M. impact 2) MoI impact	1) Mass saving 2) C.o.M. impact 2) MoI impact	1) Mass saving 2) C.o.M. impact 2) MoI impact	NA
Quantitative technical impact assessment on EUCLID Mission	1) Launch propellant saving 2) Orbit manoeuvres propellant saving 3) ACS propellant saving 4) Propellant tanks savings 5) Additional payload	1) Launch propellant saving 2) Orbit manoeuvres propellant saving 3) ACS propellant saving 4) Propellant tanks savings 5) Additional payload	1) Launch propellant saving 2) Orbit manoeuvres propellant saving 3) ACS propellant saving 4) Propellant tanks savings 5) Additional payload	NA

Quantitative evaluation

The different impacts on the EUCLID mass can be summarized as follows:

		SVM OPTIMISED MASS [kg.]	SVM ORIGINAL MASS [kg.]	SAVING [kg.]
A	RUAG panels	764,4	746,6	-17,8
	RUAG ring	741,5		5,1
B	TAS-B	718,8		27,8
C	RUAG + TAS-B	713,7		32,9
D	RUAG + TAS-B + all	678,0		67,8

A) Structural redesign: impact on mass

- The implementation of the mass impacts identified by RUAG by replacing honeycomb panels with ALM modular framed panel has the following impacts:
  - the average panels mass saving corresponding to 50%
  - the masses of the equipment installed on the optimized panels increase of 15% (to account for the additional equipment support).
- These values has been applied to the Euclid honeycomb panels with both skins and core in Aluminium (i.e. Lateral equipment panels and SVM tank platforms).
- Applying this redesign on the EUCLID Aluminium panels and equipment installed on them, the overall mass increases of **17,8 kg**., from 746,6 kg. to 764,4.
- The implementation of this redesign to EUCLID does not represent an advantage in terms of mass budget.
- The RUAG redesign of the LVA ring generates a mass saving of 30%: the application of this value to the EUCLID LVA ring generates a mass saving of **5,1 kg**.

B) Redesign of electronic equipment: impact on mass

- The optimisation proposed by TAS-B foresees to save 7% of the total mass of the PCDU by redesigning the electronic metal case and merging 3 modules.

- The application of this approach to Euclid PCDU as well as all the other electronic boxes dissipating more than 15 W (as per TAS-B recommendation) saves 27,8 kg.

C) Impact on mass budget considering RUAG + TAS-B redesign:

The combined RUAG + TAS-B cases means to considers:

- the redesign of the metal cases of the electronic boxes and saving 27,8 kg. (see point B above)
- the redesign of the LVA ring with a mass saving of 5,1 kg, (see point A above). In order to maximise the mass saving, the RUAG redesign of the honeycomb panels is not considered since it generates an increase of mass of 17,8 kg. ((see point A above).
- The EUCLID items impacted by the redesign are those in the rows coloured in yellow (LVA ring redesigned by RUAG) and in orange (TAS-B redesign) in the figure 10-6 below.

D) Impact on mass budget considering RUAG + TAS-B redesign approach and redesigning ALL the remaining screened parts

In addition to the EUCLID structural and electronic parts, a further evaluation exercise has been done including:

- All the EUCLID parts candidate for Additive Manufacturing identified in the Euclid screening
- This exercise is based on the hypothesis that all these parts will be made with additive manufacturing and therefore redesigned to better exploit the additive manufacturing capabilities.
- These parts have different characteristics and therefore their potential mass saving is strongly dependent to their functions and geometrical complexity.

D) Impact on mass budget considering RUAG + TAS-B redesign approach and redesigning ALL the remaining screened parts

- The following table reports some examples of parts (not belonging to EUCLID but derived from experience made by the Thales companies) redesigned for additive manufacturing and their resulting mass savings:

COMPANY	PART	MASS SAVING
TAS-F	ARABSAT main reflectors fitting (see 3.4.2.2 fig 3-18)	20 %
TAS-F	Ku Horn support for telecom satellite	57 %
TAS-F	Optical baffle	18%
TAS-F	Adel'light hinge	30 %
TAS-F	Tubing support in PA12 (Polyamide) for Iridium next	69 %
TAS-I	MDPS support bracket	22 %
TAS-I	Spacecraft antenna-reflector sustainer	25 %
TAS-I	Star tracker sensor bracket	46 %
TAS-I	Equipment mechanics	30 %
Thales	Cold Plate for Liquid Cooling	25 %

- These examples demonstrate that the mass saving values obtained after a generic redesign/topological optimization process vary from 18% to 69% and that is dependent on function and shape.
- In order to calculate the theoretical mass saving derived from the application of the additive manufacturing techniques to all the EUCLID candidate parts, it has been conservatively assumed a generic mass saving value of **20%.**

D) Impact on mass budget (continued)

Applying this saving to all those EUCLID candidate parts, in addition to those considered in the above RUAG + TAS-B exercise (that leads to a mass saving of 32,9 kg.) it is possible to have a theoretical additional mass saving that can be interpreted in two different ways:

- The first hypothesis is based on the application of the generic 20% of mass saving to all the remaining candidate parts except for all the honeycomb panels for which a redesign means an increase of mass. In this case the mass saving is 67,8 kg.

- The second hypothesis is based on the application of the generic 20% of mass saving to all the remaining candidate parts, including all the honeycomb panels. In this case the mass saving is 108,6 kg.

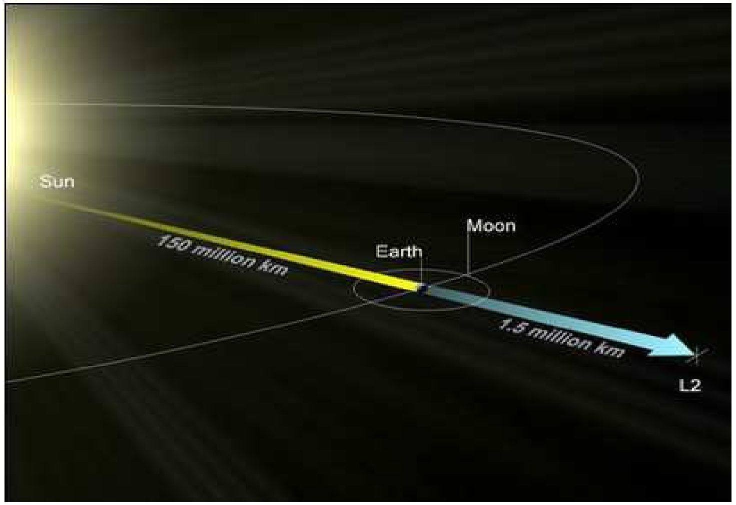
Fuel AOCS budget & launcher evolution

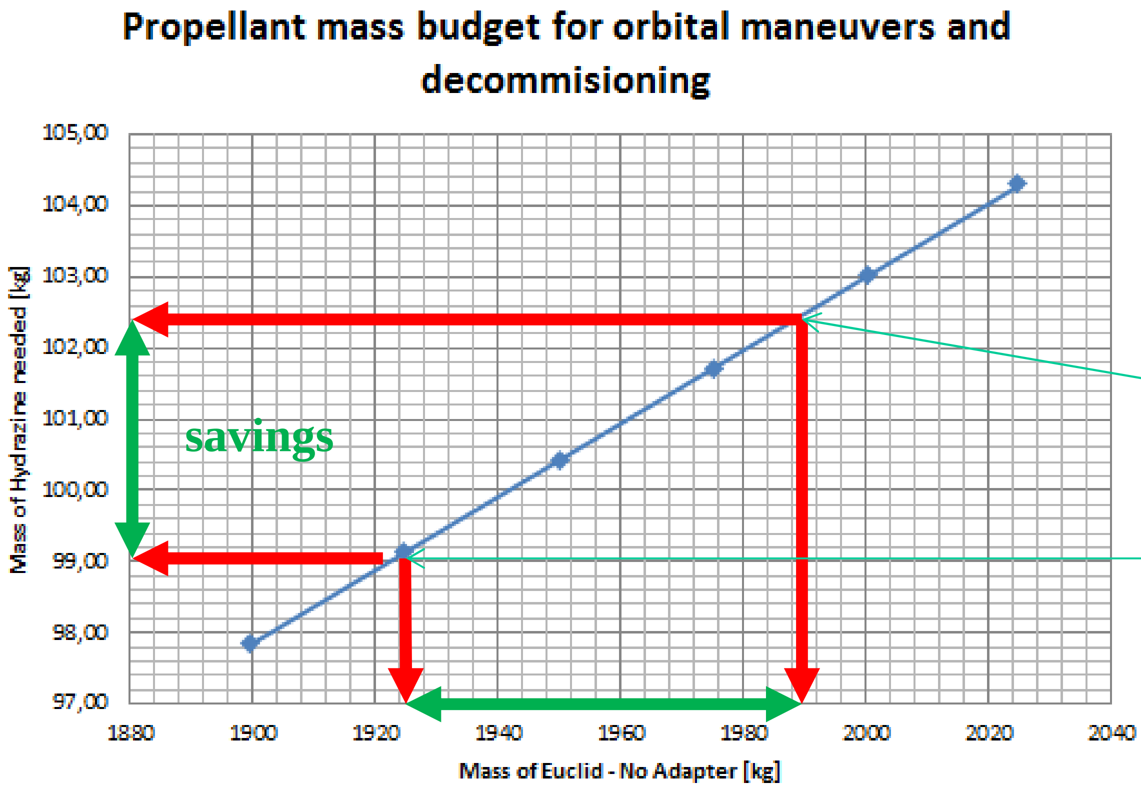
- **The Euclid mission requires high energy maneuvers being the final destination the Lagrangian Point L2, several Delta V maneuvers are planned**
- **A mass saving on the spacecraft produce a saving of propellant needed for the Orbit control system because the energy to provide to the spacecraft is proportional to its mass.**
- **This is obviously valid also for the launcher propellant in charge of the earth orbit insertion. Al propellant saving can be traduced directly to cost saving (launcher change)**

11. Quantitative evaluation on Euclid satellite design

Fuel AOCS budget & launcher evolution

1. Orbit control system evolution (from Earth to L2, L2 station keeping, decommissioning)

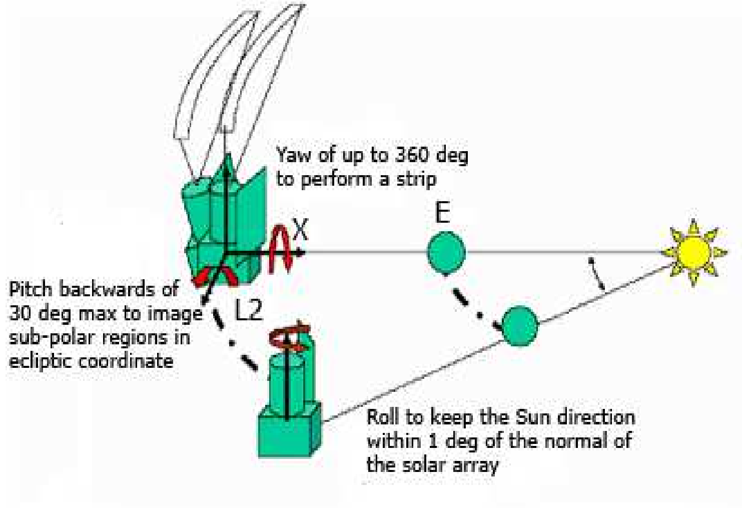




		SVM OPTIMISED MASS [kg.]	SVM ORIGINAL MASS [kg.]	ALM SAVING [kg.]	Ballast mass [Kg]	FINAL SAVING [kg.]
A	RUAG panel	764,4	746,6	-17,8		
	RUAG ring	741,5		5,1		
B	TAS-B	718,8		27,8		
C	RUAG + TAS-B	713,7		32,9	+14	-18,9
D	RUAG + TAS-B + all	638,0		108,6	+23	-83,65
E	RUAG + TAS-B + all	678,0		67,8	+18	-49,8

- Fuel AOCS budget & launcher evolution

1. Attitude control system evolution (1 of 2)



Most of the ACS maneuvers or Euclid:

- ACS maneuvers (by reaction wheels) to compensate the Hydrazine thruster misalignment during orbital maneuvers (L2 insertion)
- ACS maneuvers (by cold gas thrusters) to compensate the solar radiation disturbances in L2 (6 years life)
- ACS maneuvers (by cold gas thrusters) to re-point the spacecraft in L2 for scientific observation (6 years life)

- Fuel AOCS budget & launcher evolution

1. Attitude control system evolution (2 of 2)

- A mass saving on the spacecraft produce also reduction on Moment of Inertia of the spacecraft. The energy needed for a pure repointing attitude maneuvers is proportional to the MoI of the spacecraft.
- Being most of the Euclid ACS maneuvers compensation respect to perturbations (solar radiation or misalignments of Hydrazine thruster during Orbital manoeuvres and station keeping during scientific observation) the possible ACS propellant savings are very complex to evaluate: the smaller MoI change also the dynamic behaviour of the S/C manoeuvres (more "agility" of the spacecraft and more sensitivity respect to external perturbations like solar radiation disturbances or thruster misalignment), if saving any, could be very marginal. A very complex evaluation is considered out of the scope of present study.

11. Quantitative evaluation on Euclid satellite design

MCI budget evolution

		SVM OPTIMISED MASS [kg.]	SVM ORIGINAL MASS [kg.]	ALM SAVING [kg.]	Ballast mass [Kg]	FINAL SAVING [kg.]
A	RUAG panel	764,4	746,6	-17,8		
	RUAG ring	741,5		5,1		
B	TAS-B	718,8		27,8		
C	RUAG + TAS-B	713,7		32,9	+14	-18,9
D	RUAG + TAS-B + all	638,0		108,6	+23	-83,65
E	RUAG + TAS-B + all	678,0		67,8	+18	-49,8

Baseline Configuration

Mass Properties based on Current Mass values	Without Balancing Mass	With Balancing Mass
Mass and CoG Coordinates wrt System Reference Frame	1897.71 kg	1942.71 kg
Xg [m]	-0.045	-0.014
Yg [m]	0.030	0.004
Zg [m]	1.192	1.184
Moment of Inertia in the SRF [Kg*m²]		
Ixx	4985.6	5075.0
Iyy	5211.0	5315.1
Izz	1688.6	1817.1
Ixy	77.0	138.5
Ixz	136.7	88.6
Iyz	-22.8	19.3
Static Unbalance [mm]		53.86
Balancing Mass [kg]		45.0

RUAG+TAS-B Configuration

Mass Properties based on Current Mass values	Without Balancing Mass	With Balancing Mass
Mass and CoG Coordinates wrt System Reference Frame	1823.68 kg	1882.68 kg
Xg [m]	-0.057	-0.015
Yg [m]	0.030	0.000
Zg [m]	1.205	1.193
Moment of Inertia in the SRF [Kg*m²]		
Ixx	4847.8	4949.4
Iyy	5051.7	5190.6
Izz	1605.2	1763.9
Ixy	78.0	146.6
Ixz	182.6	119.4
Iyz	-21.5	23.2
Static Unbalance [mm]		64.30
Balancing Mass [kg]		59.0

RUAG+TAS-B+TAS-TO Configuration

Mass Properties based on Current Mass values	Without Balancing Mass	With Balancing Mass
Mass and CoG Coordinates wrt System Reference Frame	1774.59 kg	1842.59 kg
Xg [m]	-0.063	0.014
Yg [m]	0.031	-0.006
Zg [m]	1.227	1.213
Moment of Inertia in the SRF [Kg*m²]		
Ixx	4817.8	4942.9
Iyy	5012.3	5168.6
Izz	1562.5	1749.4
Ixy	72.2	154.6
Ixz	183.5	112.0
Iyz	-21.0	34.1
Static Unbalance [mm]		69.95
Balancing Mass [kg]		68.0

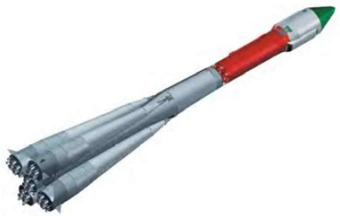
RUAG+TAS-TO Configuration

Mass Properties based on Current Mass values	Without Balancing Mass	With Balancing Mass
Mass and CoG Coordinates wrt System Reference Frame	1814.77 kg	1877.77 kg
Xg [m]	-0.059	-0.014
Yg [m]	0.030	0.004
Zg [m]	1.212	1.200
Moment of Inertia in the SRF [Kg*m²]		
Ixx	4845.6	4942.9
Iyy	5042.4	5168.6
Izz	1592.6	1749.4
Ixy	73.3	154.6
Ixz	181.5	112.0
Iyz	-20.5	34.1
Static Unbalance [mm]		66.10
Balancing Mass [kg]		63.0

Fuel AOCS budget & launcher evolution

Launcher evolution

- Fregat stage
- Launcher stages



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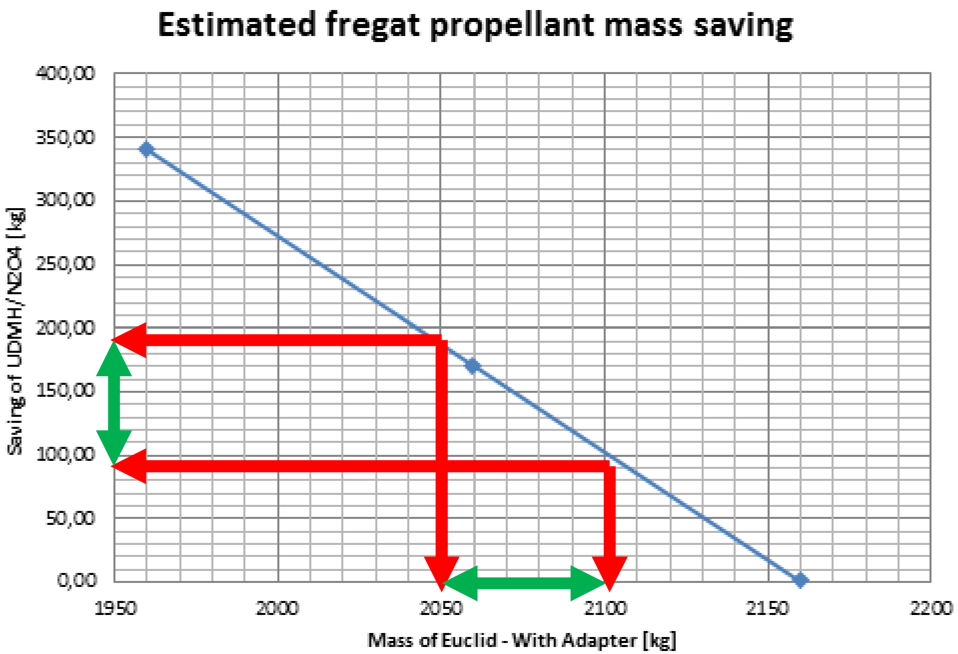
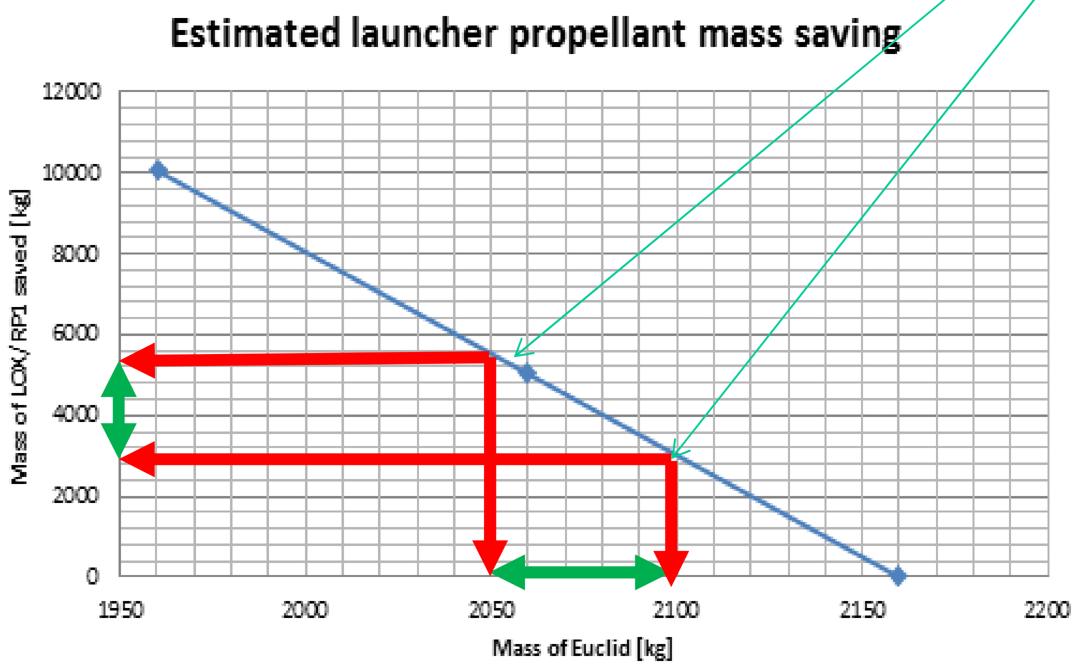




ThalesAlenia Space
A Thales / Finmeccanica Company

- Fuel AOCS budget & launcher evolution synthesis

- Estimated propellant savings for mass saved (on SVM) on Sentinel Spacecraft by ALM

  - **Orbit Control System** onboard the spacecraft for L2 insertion and decommissioning) saving respect the 130 Kg of Hydrazine are marginal for 100 Kg of mass saved (5 kg c.a. of saved Hydrazine respect to 100 Kg of SVM mass saved)
  - **Attitude control system:** complex evaluation needed for Euclid, probably minor saving respect the 60 Kg Nitrogen propellant foreseen at the present status.
  - **Fregat delta V= 3190 m/sec** : saving for 100 Kg of SVM mass saved are in the order of 170 kg of saved propellant
  - **Launcher** : saving for 100 Kg of SVM mass saved are in the order of magnitude of 5000 kg of saved propellant on launcher

- Interface, geometry, reliability evolution

- Change of geometry for Euclid due to ALM seems not possible being the S/C strongly constrained to special mission:
- Dimension of the payload are not under TAS-I control, payload dimensions and geometry are fixed.
- The dimensions of the Solar shield are fixed, being also the solar shield the panel surface constrained by total electrical power needed.
- Dimension in height of SVM are mainly constrained by propellant thanks dimension (Hydrazine and Nitrogen). The estimated reduction of Hydrazine (<5kg) do not justify smaller tanks.

Reliability evolution

- Due to present ALM solutions no major impact on reliability are envisages.
  - In case of assembly of more pars that by ALM redesign reduce the number of parts of the assembly, than an increase of reliability could be foreseen.
  - In case the TAS-B solution could lead to decrease of max Hot junction temperature of electronic components, than an increase of reliability is foreseen. The quantitative evaluation of this impact is complex and could be a future activity

11. Quantitative evaluation on Euclid satellite design

- Environmental & Space Debris Mitigation evolution

- **Euclid mission is not foreseen for re-entry in atmosphere being in L2, than should be not subjected to Space Debris Mitigation rules.**

Environmental & Space Debris Mitigation evolution

The environmental "green" impact could be led by:

Waste reduction and the smaller pollution to manufacture S/C parts in ALM

The buy to fly by ALM is optimized and waste reduced. In TAS-I experience the buy to fly of equipment mechanics in ALM pass from 1 to 10 c.a. for traditional CNC machining (up to 10 Kg of metal for 1 Kg of finished parts for electronic equipment's according TAS-I experience) with a strong reduction by ALM 1 to 2 or better values machining (also better than 2 Kg of metal to obtain 1 Kg of finished parts for electronic equipment's according TAS-I experience)

As example In case of 100 Kg of equipment about the 20-30% is the part of aluminum alloy mechanical boxes and frames (in TAS-I experience) than the for 20-30 Kg of finished mechanics are needed 200-300 Kg of bulk aluminum material in case of traditional CNC machining.

For 20-30 Kg of finished mechanics are made by ALM, 40-60 Kg c.a. of powder aluminum material could be sufficient instead 200-300 Kg c.a. by CNC (as order of magnitude).

The positive impact on environment is also to all the life cycle of the saved material since the origin.

The smaller pollution in atmosphere due to the smaller propellant (some tons for 100Kg saved mass) needed to launch the spacecraft in Earth Orbit

The smaller Hydrazine propellant to be produced for Orbit Control System of the spacecraft (<5kg c.a. for 100Kg saved mass)

The smaller documentation/energy needed to manage, on a S/C development, less parts and then less PDM activities thanks to ALM assembly.

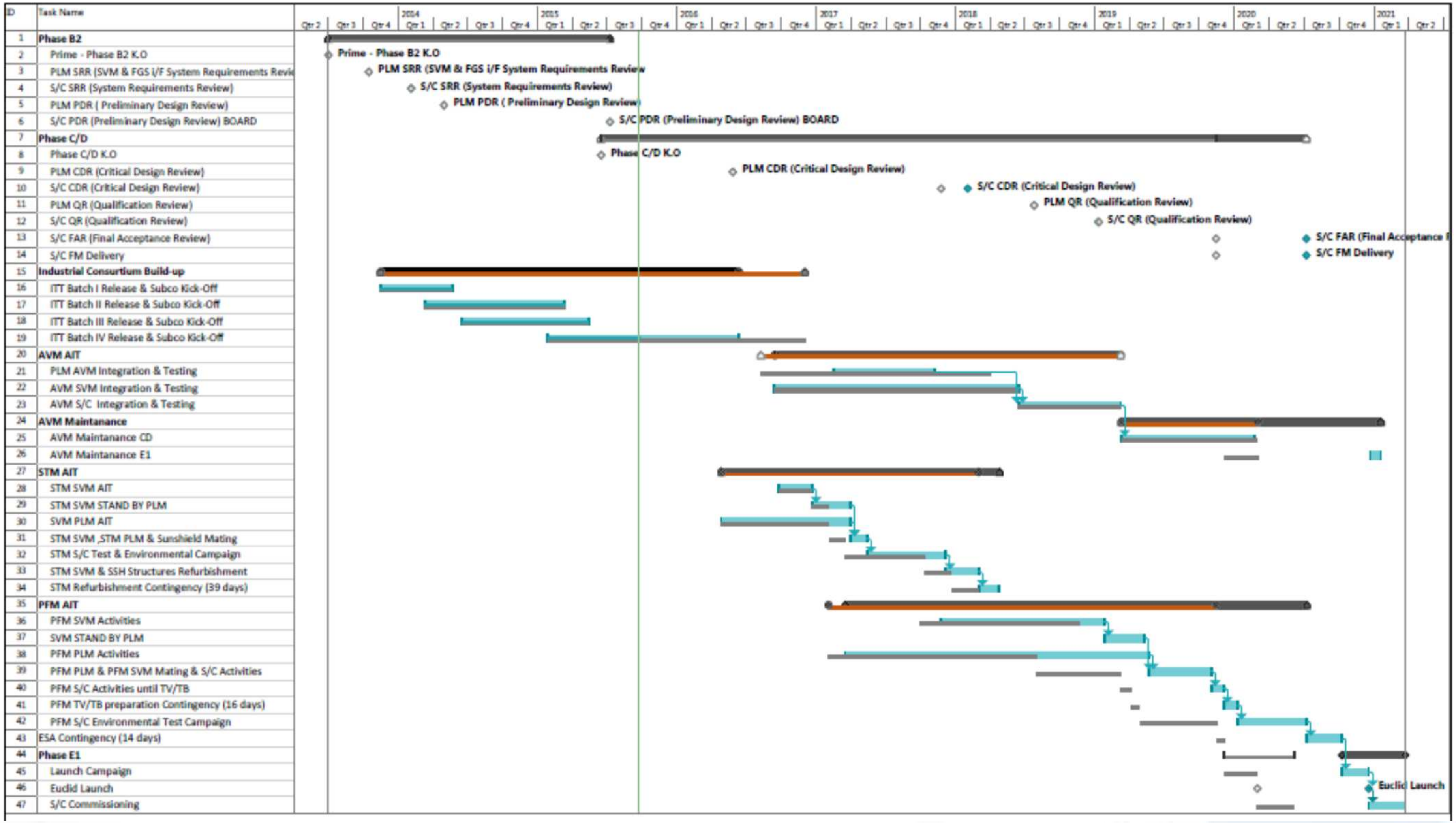
Cost evolution

- **Cost evolution as % respect to SVM mission cost development is <2"%**
  - cost savings due to Replacing Spacecraft panels with ALM modular framed panel
  - cost savings due to ALM LVA ring
  - cost savings due to traditional PCDU to ALM heat pipes in PCDU
    - this is not recognized as cost savings at unit level
    - cost savings at system level
  - cost savings due to Hydrazine savings derived from ALM mass savings
- Possible cost savings due chipper heavier adapter imply a possible cost savings < 0,5% according information available
- The potential cost savings on launcher due to potential propellant savings are not under TAS-I control. Other launchers options should be evaluated (possible future activity)

- Schedule evolution
- **No disruptive major schedule savings are present on Euclid mission due to ALM introduction as defined in present study.**
- On the mission critical path is present the payload development and the electronics equipment which are not impacted in the development duration by ALM according the solutions in the present study.
- Anyway the lead time reductions also of the ALM parts identified in present study are promising.
- A possible promising optimization is introduced if by ALM in case STM MAIT campaign could be anticipated in the program schedule.
- This STM anticipation lead to an anticipated harmonization and confidence of the loads given to the sub systems for design to the CDR. This fact leading to a reduction of potential overdesign (mass & cost) as well of the risks. This is a complex analyses for quantitative evaluation, out of the scope of present study, but possible subject of future activities.

11. Quantitative evaluation on Euclid satellite design

Schedule evolution



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Overall synthesis evolution

Overall synthesis evolution

The mass savings on present Euclid configuration led to new CoM with two scenarios:

- **Scenario A)** new ballast mass are needed to ensure CoM centering
- An increase of the ballast mass has been calculated and reduce the mass savings obtained by ALM.
- Impact on frequencies of S/C should be assessed due to lighter mass with respect the same stiffness, as well thermal issues.

- Overall synthesis evolution

- **Scenario B)** a new allocation of SVM units may reduce (or avoid) the increase of ballast mass and optimize the ALM savings.

- Being the present exercise performed on already Euclid defined spacecraft architecture , a new allocation for Euclid equipment's is in principle possible but out of the scope of present work. The present allocation of Euclid equipment's take in account also of thermal issues (more dissipative units are placed on the cold side of Euclid), than a new allocation should imply a thermal analyses assessment.

- **<u>This fact is a clear indication that ALM (to be convenient) should enter in as input of preliminary phase of architecture definition</u>.**

- Overall synthesis evolution

- The SVM mass savings and new MoI lead to main 4 scenarios:

- **Scenario 1)** Keep the full S/C mass and use the saving for and Additional Payload instrument in order to have additional scientific return by the mission. Possible additional payload of 49,8 Kg (case E) and 89 KG (case D). This is a purely exercise, the feasibility of and additional payload allocation in the present Euclid Architecture should be verified with more data on the payload also in term of volumes, power, data resources.

- Overall synthesis evolution

- The SVM mass savings and new MoI lead to main 4 scenarios:

- **Scenario 2)** Take the Cost saving for chipper a more massive (135kg instead 80kg) S/C adapter versus Fregat (mass of chipper adapter is 135 KG instead of light adapter in CFRP of mass 80kg) keeping the near the same total S/C max mass

- Overall synthesis evolution

- **Scenario 3)** Take all the mass saving, with all cost savings (<2% respect to S/C activities):
  - AOCS propellant saving <5Kg for the 49,8 Kg (case E) and 89 KG (case D)
- Upper stage and launcher propellant savings and then cost savings: not under TAS-I control, other launchers options should be evaluated (possible future activity)
  - The mass savings implies MoI reductions that could lead to chipper inertia wheels selection and possible cost savings:
    - Not true for Euclid because , the 49,8 Kg (case E) and 89 KG (case D) savings of present study do not imply enough MoI reduction to justify a cheaper inertia wheels selection.

Overall synthesis evolution

- **Scenario 4)** Take the mass saving, except the AOCS propellants savings :

- Life elongation for more propellant availability for AOCS and upper stage
  - Partially true for Euclid because additional propellant for baseline Orbit maneuvers (Fregat and hydrazine) do not imply longer life for Fregat propellant (only additional margins), may imply a bit longer life for hydrazine needed for orbital maneuvers of station keeping in L2. Life depend also of availability of Nitrogen for ACS see point b on following.
  - Not true for Attitude control system, , the 49,8 Kg (case E) and 89 KG (case D) savings of present study seems do not imply a elongation of ACS life (Nitrogen for cold gas)

- Launcher propellant savings and then cost savings
  - not under TAS-I control, other launchers cheaper options should be evaluated (possible future activity)
  - The mass savings implies MoI reductions that could lead to cheaper inertia wheels selection and possible cost savings:
    - Not true for Euclid because , the 49,8 Kg (case E) and 89 KG (case D) savings of present study do not imply enough MoI reduction to justify a cheaper inertia wheels selection.

Conclusions

1) On Euclid the ALM has been applied on SVM which is about the half of Euclid S/C (P/L is not under TAS control), quantitative results are promising but no disruptive on technical and program savings

2) Application of ALM is promising for Spacecraft application but a clear indication is that ALM should enter in as input of preliminary phase of any S/C architecture definition

Technology readiness level and required preliminary development

- Euclid is foresee to be launched in 2020 and CDR is planned in 2018, then some ALM technologies/application with adequate TRL can be candidate for evaluation for Flight on Euclid mission.
- If case, a proper acceptance criteria and negotiation shall be agreed with ESA for ALM parts, being also ECSS for ALM space application in progress but not still fixed.
- Considering TAS experience on parts manufactured in ALM by TI64 and AlSi alloys, several brackets present in Euclid spacecraft can be envisaged for an activity of re-design by topological optimization for ALM and going to a flight worthiness evaluation **(starting TRL5-6)** (see some following figure)
- The others ALM solution proposed in the present study (panel with ALM and heat pipe by ALM in the electronic equipment units) seems having very low TRL and need a time development not fitting the Euclid schedule for a Flight implementation.
- While, having TAS-I, experience on equipment units mechanics designed and manufactured in ALM, a screening to identify if some Euclid electronic equipment mechanics can designed in ALM for potential flight application on Euclid may be done. In that case, a proper acceptance criteria and negotiation shall be agreed with ESA for ALM parts also taking in account all program issue, risks and efforts. <u>This could be a future activity.</u>

Possible future activities

A. Develop Flight parts or equipment in ALM for Euclid Mission
B. The STM anticipation lead to an anticipated harmonization and confidence of the loads given to the sub systems for design to the CDR. This fact leading to a reduction of potential overdesign (mass & cost) as well of the risks. Perform the complex analyses for quantitative evaluation
C. Environmental impact: traduce in a quantitative environmental footprint saving (CO_2, H_2O savings) the saving due to ALM on spacecraft mission. All quantitative evaluation could extrapolated on all foreseen space mission in the planet in the future years.
D. Screening for Material and processes in ALM promising for space applications: continuation of WP1200

- 12. Wrap-up