



New applications of Advanced Manufacturing Methods for space instrumentation and Systems of Nanospacecraft.

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Presented by P. Rochus, Scientific Director of CSL



Investigate blue-sky thinking in-line with the Agency's objectives

- **ESA's Basic Technology Research Programme (TRP)** enables researchers to explore new ideas from the very earliest stages, starting with the first time they ask themselves 'what would happen if...?' Technological progress is such a constant in our lives that it is easy to think of it as occurring automatically. In fact, making it happen comes down to ongoing human ingenuity, effort and most of all curiosity.
- This programme is there to investigate blue-sky thinking in-line with the Agency's objectives. A tentative idea is confronted with reality through proof-of-concept testing, then – if all goes well – comes confirmation that 'we've got something'.

Presentation plan

- Objectives of the project
- Advanced Manufacturing Methods
- Case studies description
- Current lessons
- Remaining work





Objectives of the project

- Why this project ?
 - Several advanced manufacturing technologies matured to a level compatible with space applications
 - They are well suited to space hardware since they are applicable to unique parts or small series
 - Nevertheless there is a need to better understand their optimal implementation within design and manufacturing chain
- Background of the project
 - SIRRIS is highly implied in additive manufacturing techniques for several years
 - SIRRIS and CSL participated in a similar project with KULeuven in 2003 (with Belgian funding)
 - *“New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation”* P. Rochus (CSL), J.-Y. Plessier (CSL), J.-P. Kruth (KUL), M. VanElsen (KUL), T. Dormal (CRIF), R. Carrus (CRIF), IAC-06-C2.8.05, International Astronautical Congress, Valencia, 2006 and Acta Astronautica 61 (2007) 352 – 359
 - TAS-F and ALMASpace are closely following all advanced technologies in order to improve the performances of their instruments and increase the fly-to-buy ratio of their development



Objectives of the project

- Partners of the project
 - CSL is the coordinator of the project and is largely experienced in the development and testing of flight hardware
 - SIRRIS is the technology provider, either based on in-house capabilities or via sub-contractors
 - TAS-F and ALMASpace are the case studies providers, defining the requirements and playing the role of « customers »
 - ESA participated in the selection
- Organisation of the project
 - Step 1: Review of the advanced manufacturing methods
 - Additive manufacturing, advanced joining techniques, advanced forming methods, coatings...
 - Presentation was given to all partners to emulate their imagination to provide case studies : **LBM, EBM, L Cladding, aerosol jet printing, LW, EW, Salt Dip brazing, ...**
 - Step 2: **Level 1 case study**
 - Reproduction of an existing part by advanced techniques in order to evaluate pro's/con's of the techniques and get some first experience
 - **Full testing of the case studies to verify the compliance to the main requirements**

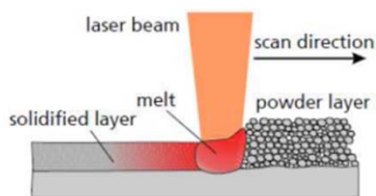
Objectives of the project

- Organisation of the project (cont'd)
 - Step 3: Level 2 case study
 - Design driven by application requirements i.e. designing the part and the manufacturing flow to maximise part performances
 - Full testing of the case studies to verify compliance to requirements
 - Step 4: Level 3 case study
 - Part design driven by the subsystem to which it belongs i.e. designing the part and the manufacturing flow to maximise the sub-system performances
 - Full testing of the case study to verify compliance to requirements
 - Step 5: Summary of all lessons learnt
 - Reporting all lessons learnt in order to better define the engineering process of designing and manufacturing a part in order to take full advantage of the advanced manufacturing techniques and minimise the risks

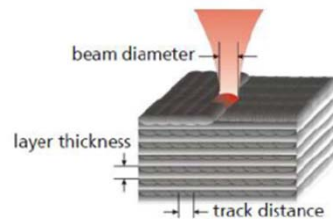
Advanced manufacturing methods

- Additive manufacturing techniques

- Material is added to the part and not removed from a raw block of material
- Part is built layer by layer (more common method)
 - Some techniques imply the direct injection of powder in the laser beam (laser cladding) allowing 3D building and repair of parts
- Power sources
 - Laser
 - Electron beam
- Materials available:
 - Polymers
 - Metals: aluminium, titanium, stainless steel ...
- Improvement of the techniques implies that the pure metal powder is directly melted to form the part (no binding material)
 - Ease manufacturing process and reduce risk (less steps)
 - Improve mechanical properties of material (almost full density)

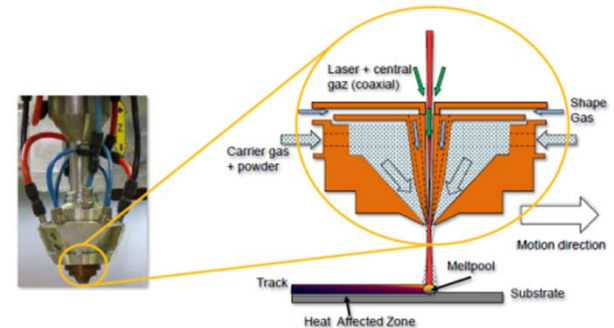


Pictures from ILT



Laser Beam Melting

Laser Cladding



Advanced manufacturing methods

- Advanced joining techniques

- Friction Stir Welding

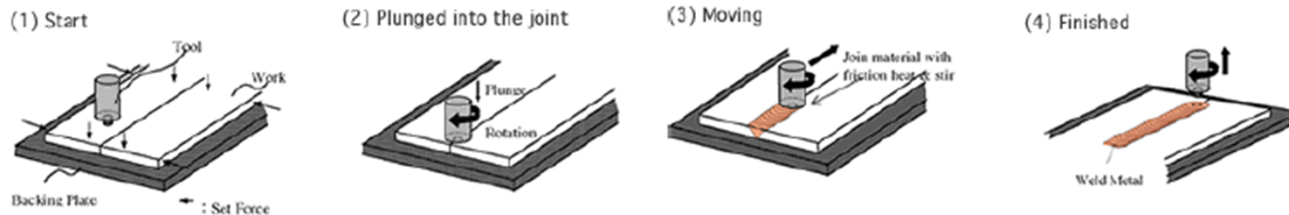
- Solid state welding ($T_{\text{welding}} \ll T_{\text{melting}}$)
- Available for Aluminium and alloys, Steels, Copper...
- Specific welding tool mounted on kind of milling machine

- Electron beam welding

- Performed under vacuum
- Limits the power required for welding

- Salt dip brazing

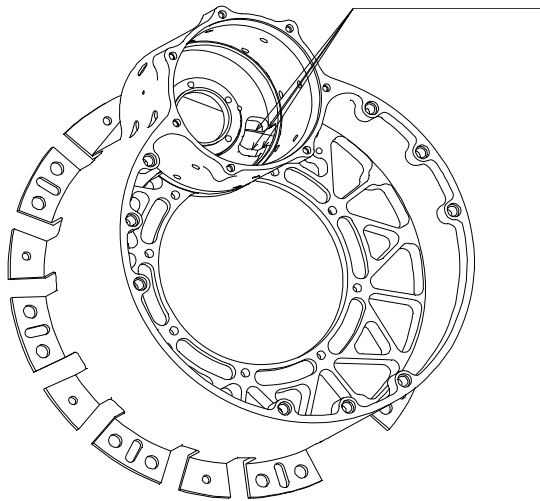
- Applicable to AA 6061
- Assembly of raw parts with additional of paste filled with aluminium powder at the joins
- Dipped in melted salt that melts the aluminium contained in the powder
- The melted aluminium enters the join gaps by capillarity
- The part is then heat-treated to the T6 standard



Friction Stir Welding

Case studies description

- Level 1 case study
 - 2 case studies selected:
 - Structural case for space mechanism (TAS-F)
 - Reaction/Momentum Wheel Housing Assembly (ALMASpace)



Structural case initial design

Reaction/momentum wheel housing manufactured by standard methods



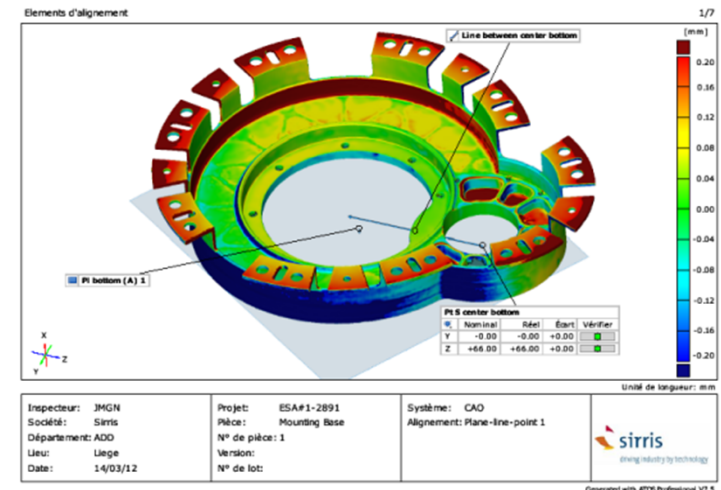
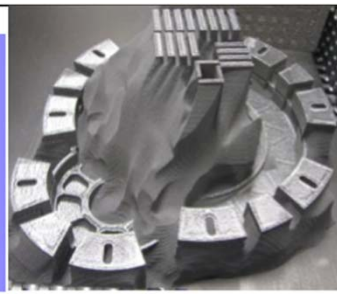
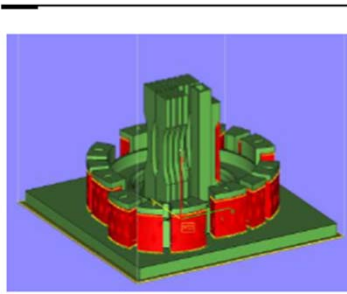
Case studies description

- Structural case for space mechanism
 - Main part of **a solar array drive mechanism**
 - Structural part containing mechanism elements : in the front side are mounted the balls bearing and the potentiometer, in the back side the collector and the stepper motor. So it is strongly loaded since being the link between solar panel and spacecraft.
 - Made of Titanium alloy Ti6Al4V
 - Selected method: Electron Beam Melting of Titanium
 - Advantages:
 - Well suited for large, massive parts in titanium
 - Reduced building time
 - No heat treatment required due to high temperature of the process (limited residual stresses)
 - Disadvantages:
 - Higher roughness
 - Less accuracy

Case studies description

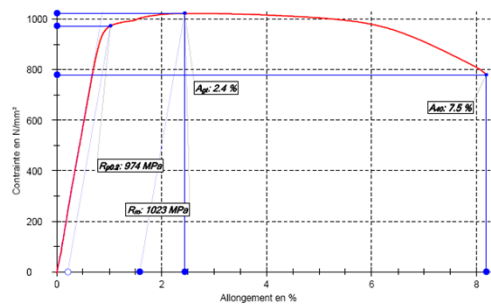
- Structural case for space mechanism (cont'd)
 - Building included **several samples for properties measurements** (density, strength, fatigue)
 - Several minor problems during building required several trials
 - Powder excessive charging
 - Processes interruptions
 - Post machining faces few problems
 - Post machining required for interface surfaces and fitting diameters
 - Legs vibration due to lack of support
 - Flatness not reached due to non-flat clamping surfaces
 - Question raised about the transfer of references between additive manufacturing and standard post-machining (similar to casting)

Case studies description

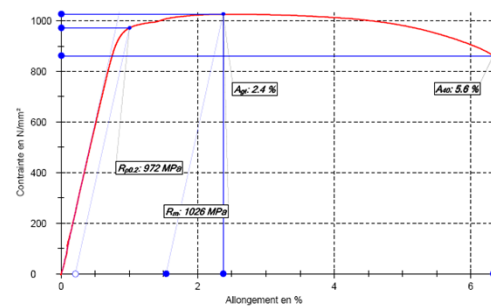


Case studies description

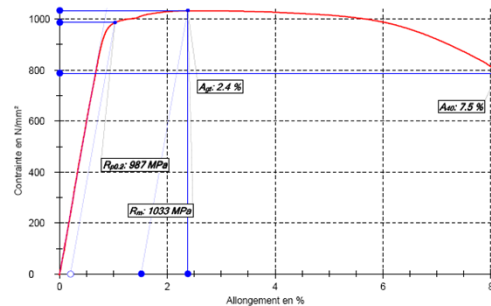
ADD113/1 Oz (JOB01)



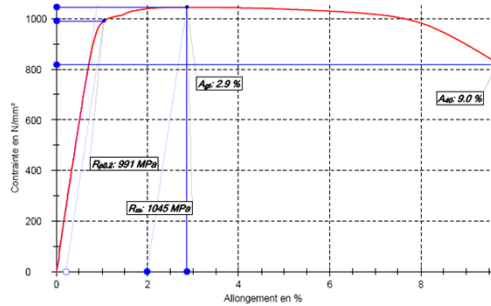
ADD113/2 Oz (JOB01)



ADD113/3 Oz (JOB01)



ADD113/4 Oz (JOB01)



Mechanical properties of vertical sample (building direction)

Index	Rp0.2 (Mpa)	Rm (Mpa)	Agt (%)	A40 (%)	Z (%)
ADD113/1	974	1023	2,4	7,5	39,6
ADD113/2	972	1026	2,4	5,6	33,4
ADD113/3	987	1033	2,4	7,5	40,5
ADD113/4	991	1045	2,9	9	39,2
ADD113 Oz (Arithmetic mean)	981	1032	2,5	7,4	38
Typical Ti6Al4V	880	950		14	36

- Rp0.2% Yield strength
 - Rm Ultimate strength
 - Agt Maximal uniform elongation under maximal load (elastic + plastic)
 - A40 Elongation at break
 - Z Necking measured after test
 - E Young Modulus
- Parameters definition**

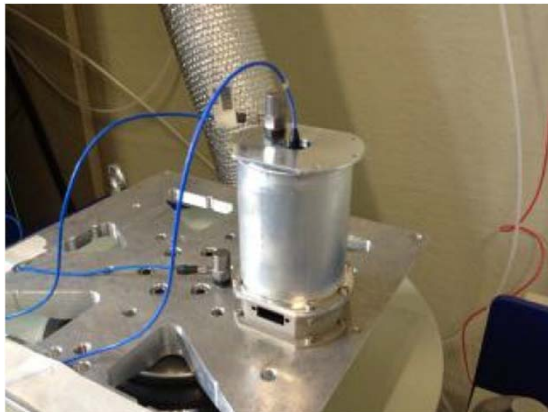
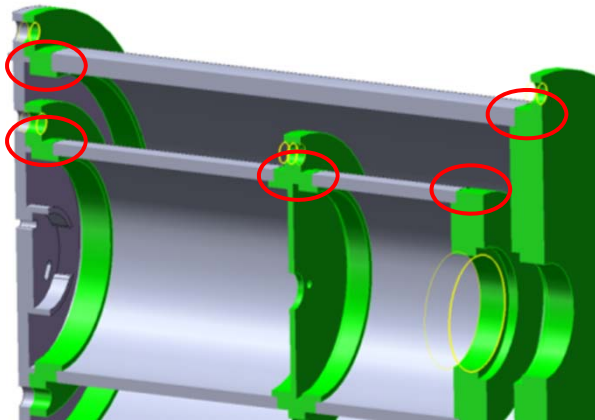
Case studies description

- Reaction/momentum wheel housing assembly
 - Contain the reaction/momentum wheel and its mechanism
 - Is composed of several parts to be assembled
 - Has to withstand the loads due to the launch and then to maintain in the correct position the rotating masses inside itself.
 - Originally manufacturing from block of materials
 - Goal: minimise the manufacturing complexity and time
 - Selected method:
 - Standard manufacturing + electron beam welding for the upper part
 - Laser beam melting of stainless steel for the base
 - Aluminium was not available at that time and stainless steel should be the closest in terms of manufacturing process
 - Post machining for the interface surface and for the mounting holes

Case studies description

- Reaction/momentum wheel housing assembly (cont'd)
 - Design was adapted for the welding
 - Standard tube diameters were chosen (for cost reduction)
 - Additional thicknesses and support at the level of the joints
 - Only problem reported was a deformation of the interface flange
 - Due to the proximity of the welding → post-machining would be necessary
 - Could be use-as-is in the application
 - Base made by laser beam melting didn't face major problem
 - Only parameters adaptation (hull and core) was required to minimise delamination
 - Post machining required for interface surfaces and fitting diameters
 - Legs vibration due to lack of support
 - Flatness not reached due to non-flat clamping surfaces
 - Question raised about the transfer of references between additive manufacturing and standard post-machining (similar to casting)

Case studies description



Case studies description

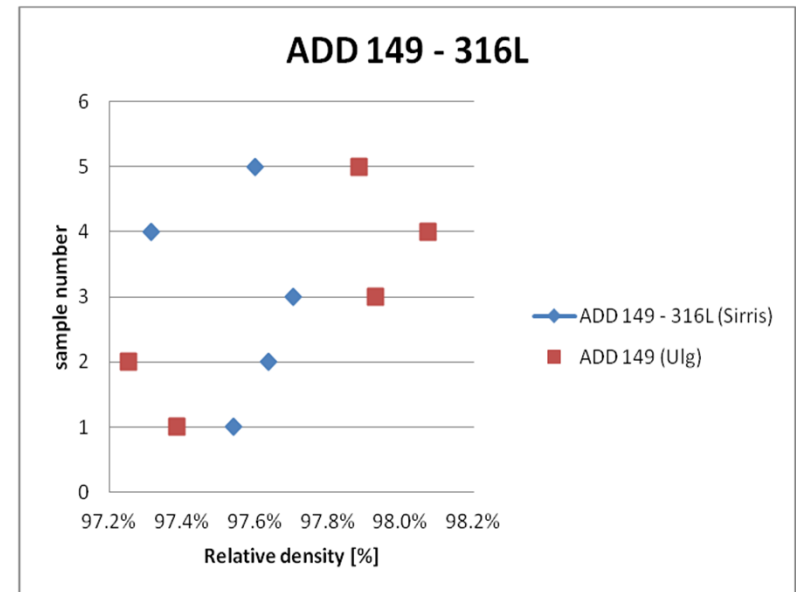
Main EUT	I eigenfrequency	II eigenfrequency
Beginning	1480	-
Middle	1480	1780
End	1477	1785
Secondary EUT	I eigenfrequency	II eigenfrequency
Beginning	1460	1760
Middle	1460	1760
End	1531	1764

Eigenfrequencies of a reference model (Secondary) and of the built model (Main) before and after random and shock testing performed at ALMASpace

Relative density along the height of a sample (bottom to top → 1 to 5)
Measurements by SIRRIS and by ULg

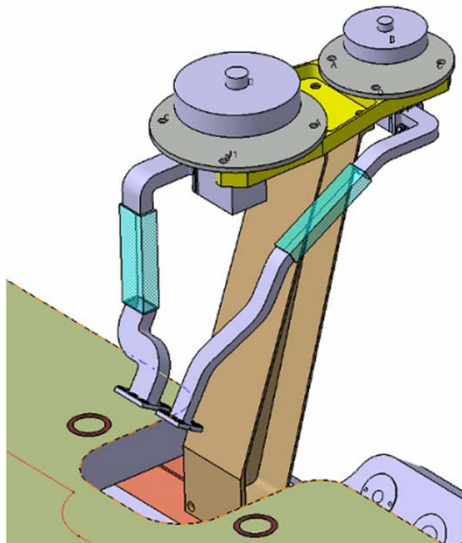
Index	Rp0.2 (Mpa)	Rm (Mpa)	Agt (%)	A40 (%)	Z (%)	E GPa
ADD132/1	318	354	2,4	3,6	41,8	89
ADD132/2	448	552	10	10,6	29,2	122
ADD132/3	380	472	8,9	9,5	15,9	108
ADD132/4	387	482	11,9	15,9	18,9	120
ADD132/5	384	485	11,7	13,6	22,7	163
ADD132/6	427	535	8,6	9,7	20	136
ADD132 Oz (Arithmetic mean)	405	505	10	12	21	130
Typical AISI316L	290	560		50		193

Mechanical properties of vertical sample (building direction)



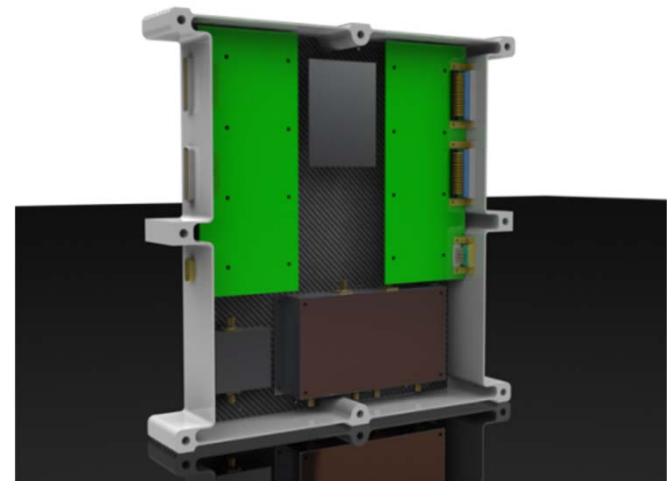
Case studies description

- Level 2 case study
 - 2 case studies selected:
 - Antenna support (TAS-F)
 - ALMASat-class Microsatellites Modular Tray (ALMASpace)



Antenna support preliminary design

Modular tray CAD model



Case studies description

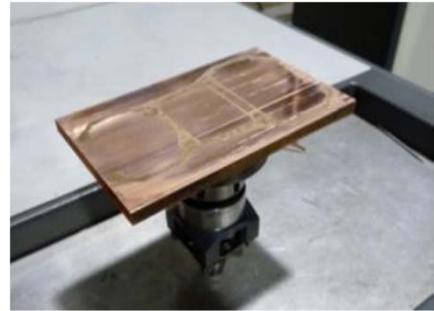
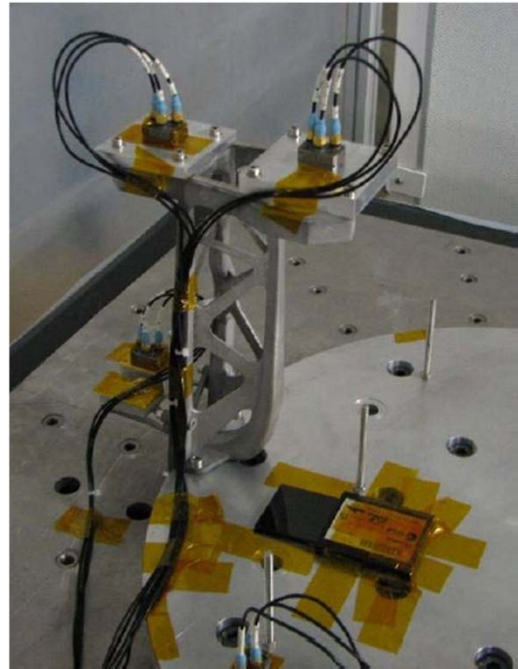
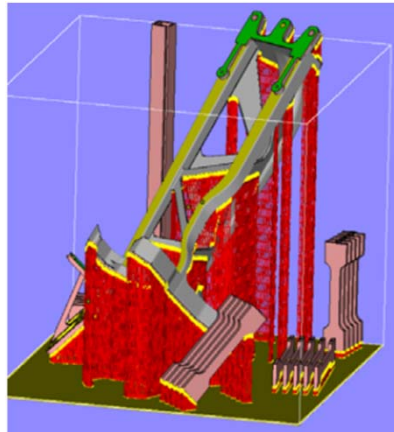
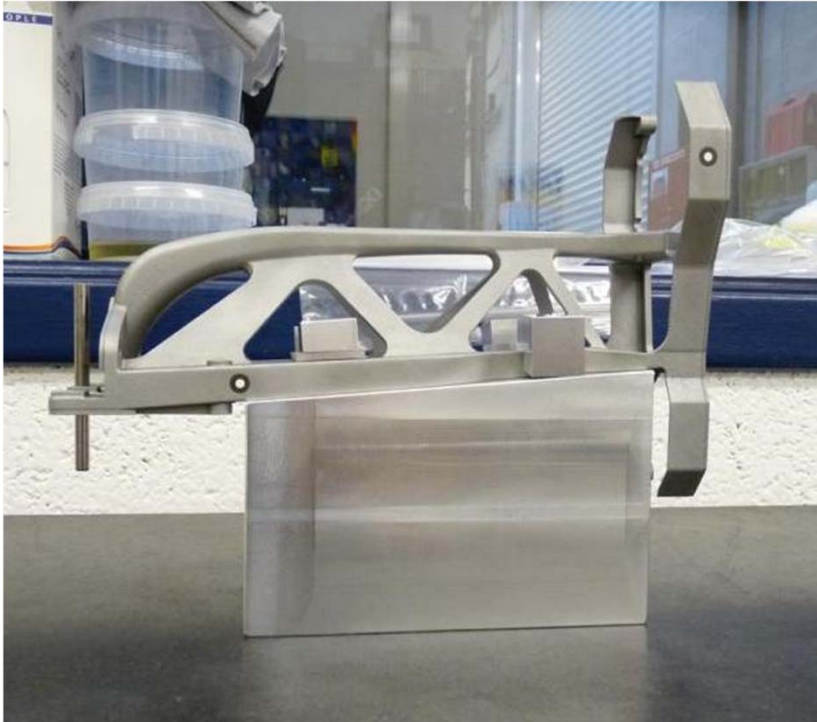
- Antenna support
 - Supports 2 antennas
 - Is connected to the satellite main frame
 - Some constraints for the routing of the waveguides
 - Only preliminary design exists
 - Goal: design a structure to support the antennas with minimal mass and sufficient stiffness and strength
 - Selected method:
 - Design by topological optimisation
 - Manufacturing in aluminium by laser beam melting
 - Post machining for interface surfaces and holes

Case studies description

- Antenna support (cont'd)
 - Topological optimisation goal: obtain the correct stiffness by minimising the mass
 - Optimisation parameters such as to limit intermediate density elements
 - Part is re-drawn manually for further analyses (strength analysis) and manufacturing

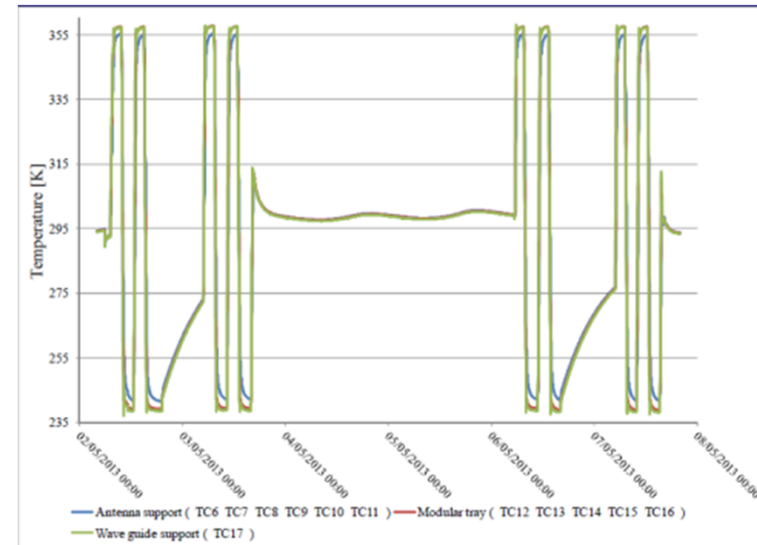


Case studies description



Case studies description

- Vibration test at CSL
 - Low level sine performed before and after each high level
 - High level sine up to 20g, up to 100 Hz
 - No variation before-after high level in all axes
 - First eigenfrequency at 165 Hz (Computations at 143 Hz and 212 Hz depending on the interface conditions)
 - Cleanliness control indicates still some particles coming out of the tubes
- Thermal cycling at CSL
 - 8 cycles performed under vacuum between -30°C and +80°C
 - No contamination detected during test
 - No problem reported

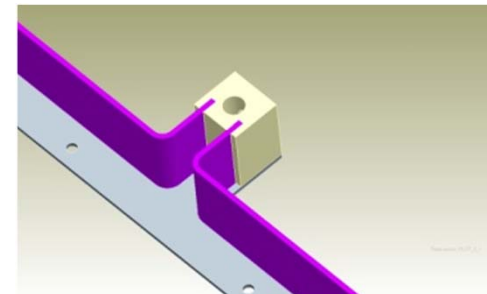
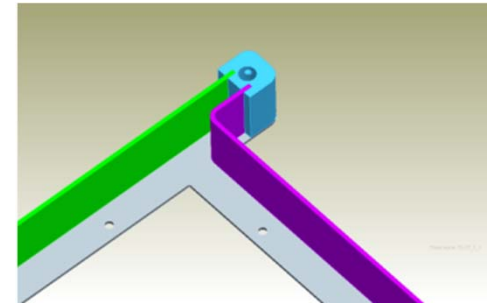
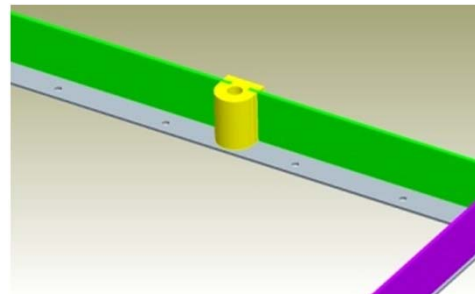
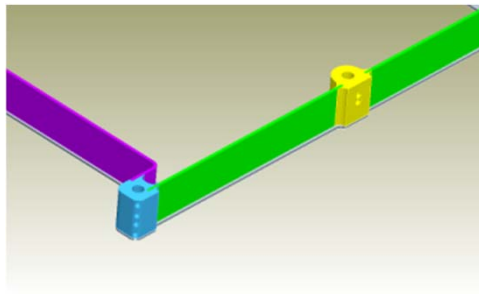


Case studies description

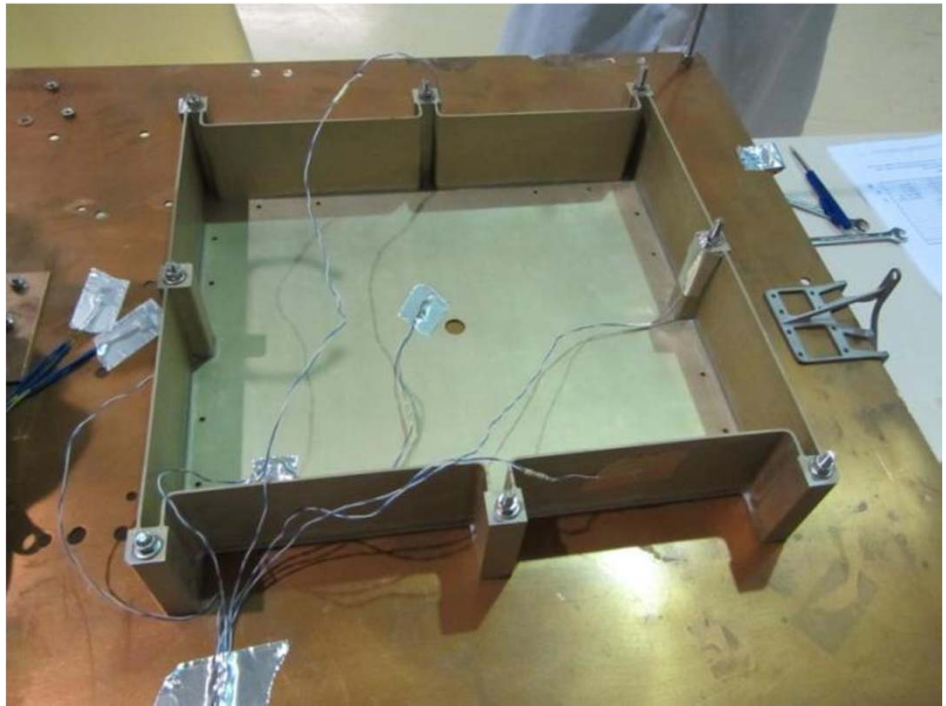
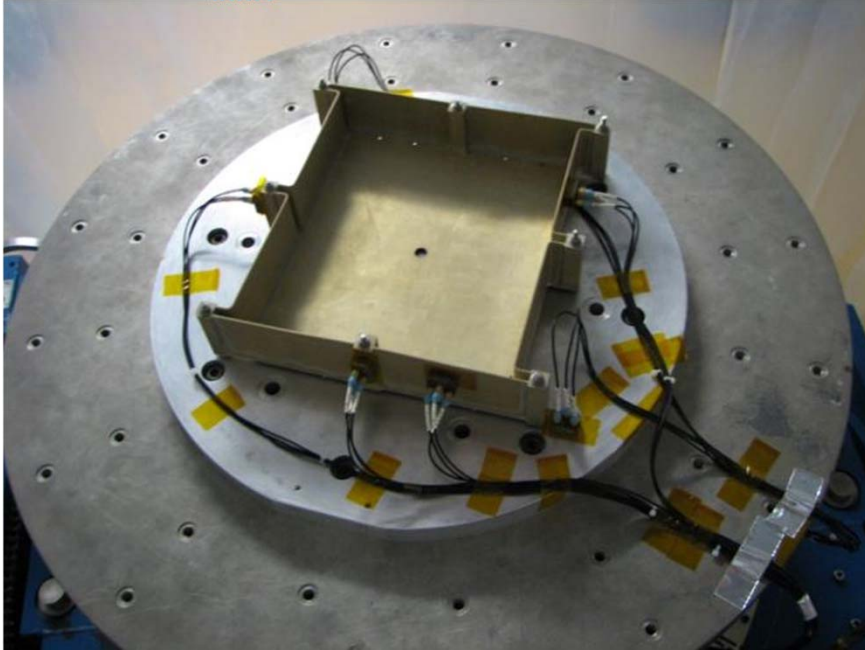
- Modular tray
 - Part of nanosatellite structure – stack of such trays constitutes the satellite
 - Each tray contains sub-systems
 - Solar panels are mounted on external surfaces
 - Current trays manufactured from raw material → complex, time and scrap consuming manufacturing
 - Goal: find a way to manufacture at low cost a small series of trays with minimum changes
 - Selected method:
 - Manufacturing of elements by standard manufacturing methods
 - Assembly by salt dip brazing

Case studies description

- Modular tray (cont'd)
 - Design submitted to AML (Fr – specialist of salt dip brazing) for decomposition
 - Material is aluminium alloy 6061T6
 - Manufacturing of elementary parts by AML
 - Assembly and paste application by AML
 - Brazing process by AML
 - Heat treatment to reach T6

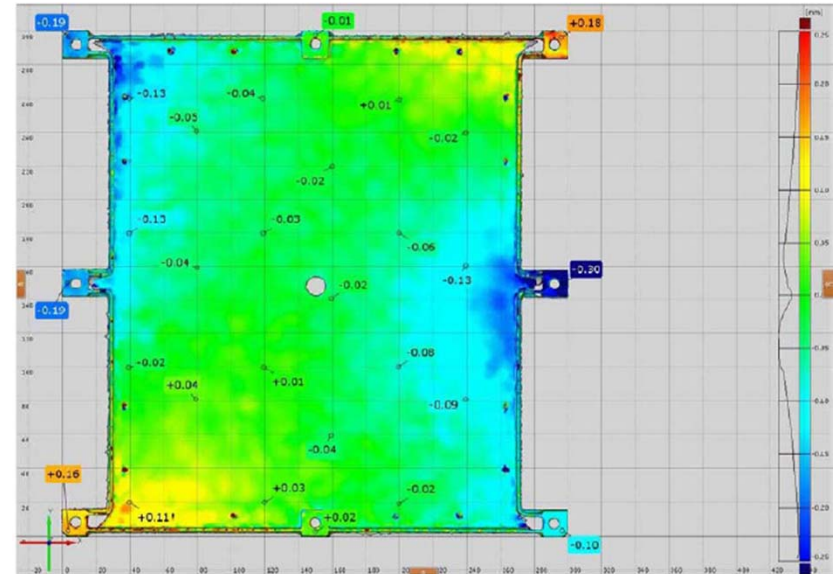


Case studies description



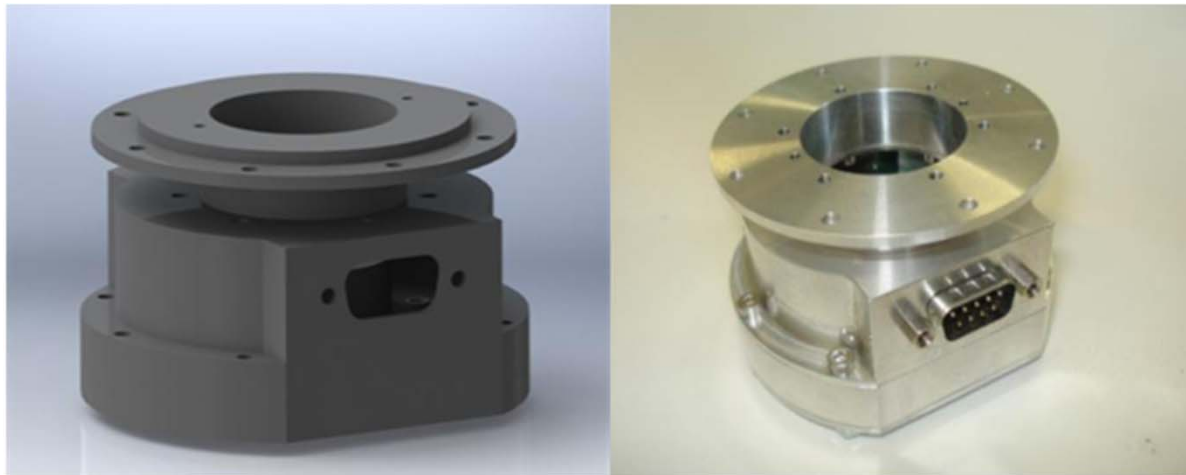
Case studies description

- Measurements
 - Some dimensional error (probably not linked to the process itself)
 - The errors generated some mounting difficulties in vibration that finally generated some permanent deformation
 - No impact on the ability to mount it is a stack or to mount sub-systems
- Vibration test at CSL
 - Low level sine performed and compared with standard tray → minimal difference observed
- Thermal cycling at CSL
 - 8 cycles performed under vacuum between -30°C and +80°C
 - No contamination detected during test
 - No problem reported



Case studies description

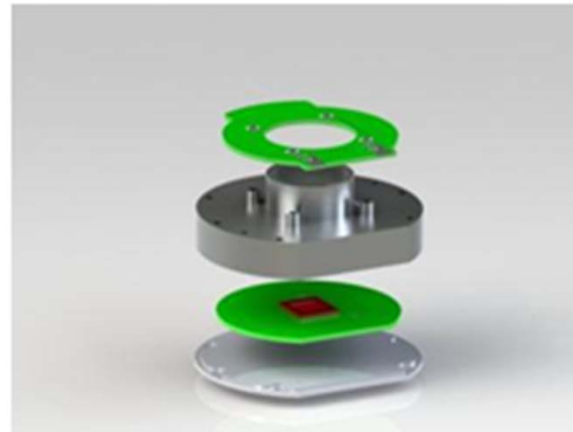
- Level 3 case study
 - 1 case study selected:
 - Sun sensor housing (ALMASpace)



Sun sensor current design

Case studies description

- Sun sensor
 - Assembly including:
 - Commercial optical sub-system
 - Power conditioning PCB
 - Optical detector on proximity electronics PCB
 - Structure ensuring stiffness, strength and alignment

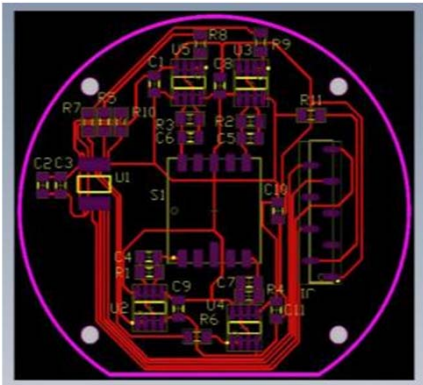
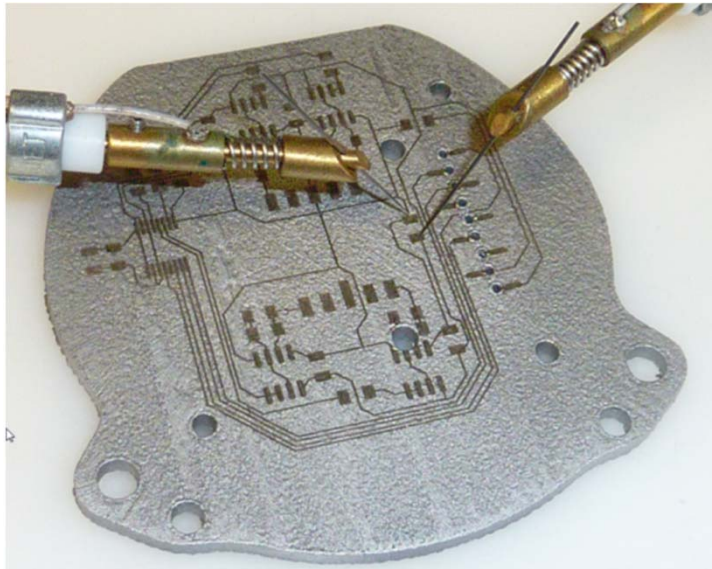
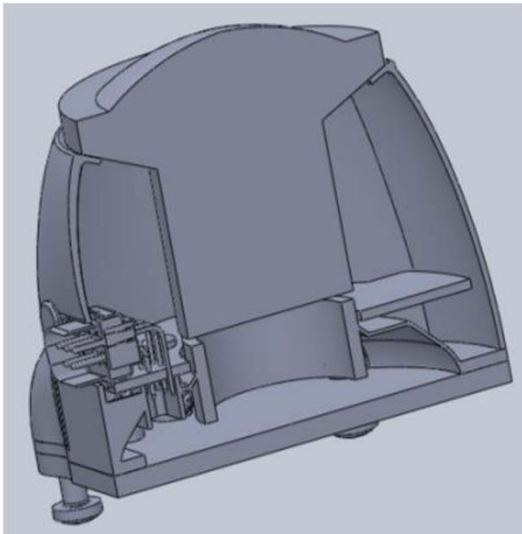
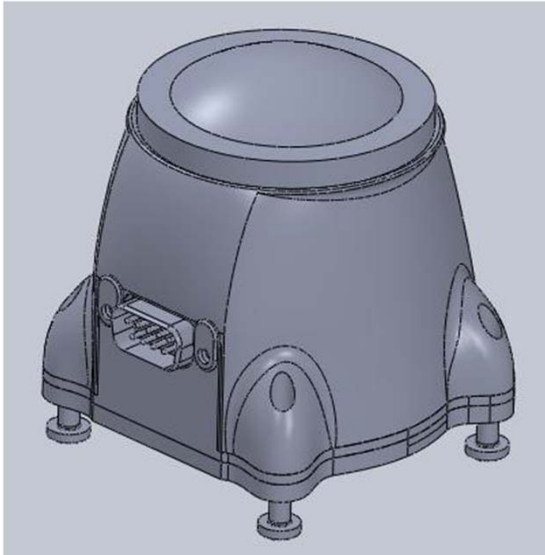




Case studies description

- Sun sensor (cont'd)
 - Structure is re-drawn to take advantage of additive manufacturing methods
 - Support mean of the optical sub-system is optimised (closer to cog) and the optical sub-system is measured by 3D measurement machine (fringe projection) to accurately know the geometry and ensure correct fitting close to optical (heavy) elements
 - Power conditioning PCB used as is (no improvement possible)
 - Optical detector PCB removed and optical detector and proximity components directly mounted on the back plate where the circuit is “printed” by aerosol jet printing
 - Aerosol jet printing allows printing of powder material (in binder) by projection (like ink jet printer)
 - The powder is sintered afterwards with a laser allowing a very local heating
 - In this application, a insulating under-layer is applied (by more classical method) to avoid short-circuit

Case studies description





Components realized this week



Case studies description

- It will be then tested in vibration, thermal cycling and performances





Current lessons

- The project up to now is a success
 - We have learnt a lot of things about these techniques
 - Some of the case studies have prolonged their life after the project
- The current lessons can be summarised:
 - The work in a team between the customer, the designer and the manufacturer is important for these techniques
 - The designer has to change its way of thinking linked to standard manufacturing
 - The advanced methods (and particularly the additive manufacturing) are (currently) not the final solution, post machining remains an essential step of the manufacturing to reach the final tolerances and surface properties
 - Post-machining steps shall be taken into account at the design phase in order to optimise/minimise them
 - How to transfer references ?
 - Are all tolerances necessary?
 - What are the really useful interfaces ?
 - Is the structure stiff enough where I plan post-machining ?
 - Despite the improved confidence and repeatability of the building methods, the mechanical properties reached shall be verified by addition of samples in the process



Remaining work

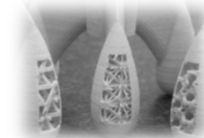
- Level 3 case study will be finished in one month
- The information received in this project is huge and the lessons learnt numerous
- Everything will be reported in a final report and in the definition of guidelines in the way the engineering approach shall be changed in order to optimally use these advanced techniques
- These methods are surely the future of space hardware manufacturing
- We are all eager to continue the development of these techniques



Thank you for your attention

Possibilities

- Integrated functions (hinges, snap-fit's, springs)
- Compliant mechanisms
- Internal channels
- Lightweight parts (topology optimization)
- Bi-materials
- Variable density (graded or controlled porosity)
- Functionality graded material (optomechanics, 3 different Ti alloys with 3 specific functions: impact resistance, fatigue and creep)
- Internal structures for
 - maximum weight reduction with minimal strength reduction
 - local variation of lattice types --> graded porosity, intended anisotropy,
 - shock damping, vibration reduction
- Integrated electrical circuit
- New technologies available soon : Laser induced forward Transfer (LIFT), Two-photon polymerization the femtosecond (10⁻¹⁵ sec) laser systems



Stay informed



Still limitations

- Costs of current technologies,
- Cost (and limitation) of raw materials
- Lack of open standards
- Quality control and repeatability
- Certification of process and materials
- New materials to be developed
- Accuracy and surface quality enhancements required
- Material structure depends on the process and thermal aspects
- Still needs to finalize the systems with classical manufacturing tools and the interface has to be optimized (Tooling points)