Design of a Flight Like Cryostat for 30-50 K Two-Stage Pulse Tube Cooler Integration

J. Tanchon[1], T. Trollier[1], P. Renaud[1], J. Mullié[2], H. Leenders[2], T. Prouvé[3], I. Charles[3], T. Tirolien[4]

[1]Absolut System SAS, 38170 Seyssinet Pariset, France
[2]Thales Cryogenics BV, 5626 DC, Eindhoven, NL
[3]University Grenoble Alpes, CEA INAC-SBT, 38000 Grenoble, France
[4]European Space Agency ESA-ESTEC, Noordwijk, NL

ABSTRACT

An ESA Technical Research Program (TRP - 4000109933/14/NL/RA) is run by a TCBV/CEA/AS consortium for the development, optimization and testing of a cryostat actively cooled by a 2-Stage High Reliability Pulse Tube cryocooler (presented in a companion paper). The interest of this concept is to allow the detector operation – for example Quantum Well IR Photodetector (QWIP) or Mercury Cadmium Telluride (MCT) detectors - at lower temperature, in the range of 40K-45K, for an overall input power similar to the one required by current Earth Observation programs.

Several cryostat concepts have been traded to optimize mechanical, thermal and electrical interfaces between the 2-stage cryocooler, the detector assembly and the external structure while minimizing the impact of 2 stage cooling on the Detector's Assembly Integration and Test phases.

For this project, an innovative supporting structure concept has been developed by Absolut System to offer a good compromise between thermal and mechanical performance. High performance flexible Thermal Links Assemblies (TLA) have been also optimized using our background developed for European on-going space projects (MTG, IASI-NG and others, presented in a companion paper).

This paper will present the conceptual study output, the detailed design phase including thermal and mechanical justification and the final design description of the cryostat. The outcomes of current manufacturing will be also presented.

INTRODUCTION

The space cryogenics sector is characterized by a large number of applications (detection, imaging, sample conservation, propulsion, telecommunications) that lead to various requirements (temperature range, microvibration, lifetime, consumption) that can be met by different solutions (Stirling or JT coolers, mechanical or sorption compressors). Recent years in Europe saw the development of coolers to meet Earth Observation mission requirements that can provide more than ~3 W of cooling power at an operational temperature around 50K [1][2]. Those single stage Stirling or Pulse Tube coolers have a no load temperature in the range of 30K with limited cooling power at 40K with reasonable rejection temperatures.

On the other end, the trend of focal plane cooling requirements for Earth Observation is to aim either at higher cooling power at current temperature levels (around 50K) due to the use of bigger detectors, or to lower the ultimate temperature to limit dark current or to use new detector types. For instance, the QWIP detectors seem promising but need to operate at 35 - 45K, which is not reasonably obtainable with the currently available coolers developed for Earth Observation.

In addition to detector cooling, this cooler can also be used in a multistage cooling system (e.g., Shield cooler). To satisfy this trend, one solution consists of using the current Pulse Tube and Stirling technologies in a double stage configuration to intercept parasitics at a higher temperature and to make cooling power available at lower temperature. This solution makes the most use of the existing technology building blocks (e.g., compressor) but requires mastery of the design/manufacturing/integration constraints linked to double stage cryocoolers used in cryostats.

In parallel to the development and the optimization of a 30-50K two-stage pulse tube cooler performed by TCBV and CEA/INAC [3], Absolut Ssystem focused on the system level analysis and the best way to improve the cryostat concept taking benefits of the two-stage cryocooler capability. This paper reports the activities performed on the target Cryostat from the system level trade-off to the manufacturing and integration of the final hardware going through justification analysis.

SYSTEM LEVEL TRADE-OFFS AND CONCLUSIONS FOR DETAILED DESIGN

Several aspects have been analyzed during the first phase of the development. The objective was to propose different cryostat concepts and to evaluate their performance for comparative study. The main aspects analyzed are: cryostat integration and accessibility (in particular detector's alignment constraints), thermal performance, mechanical robustness and stability regarding optical constraints, and orientation of the cold finger regarding gravity for ground testing.

After intensive trade-off, Concept 4 surrounded by the border in the Figure 1, has been selected. This concept offers a good compromise between the thermal performance, mechanical aspects and integration of the components. The main advantages of this configuration are:

- Very compact Optical Cold bench. The optical cryostat is split from the cold head cryostat. Both sub-assemblies are thus optimized in term of volume, and mass.
- Design with cold fingers downward. The parasitic losses of the cold finger will be representative of flight conditions.
- Distance required between the 2 sub-assemblies limited due to the direct coupling between cold head cryostat and optical bench (limited thermal links length).
- Radiative and conductive loads intercepted by cryocooler 1st stage.
- Cold shield implemented after mounting of all internal components (better accessibility)

The main design driver identified is the mechanical behavior of the supporting structure which could be critical and required detailed analysis. At a lower level, some trade-offs have been conducted regarding the component selection like the "Thermal link concepts and material selection", the "Radiative insulation selection" or the "Supporting structure concept".

Thermal link concepts and material selection

The thermal links required for this project are critical for thermal performance, mass, stiffness and mechanical loads. To answer these requirements with the best compromise, different materials have been studied. The material to be selected for the thermal links shall combine:

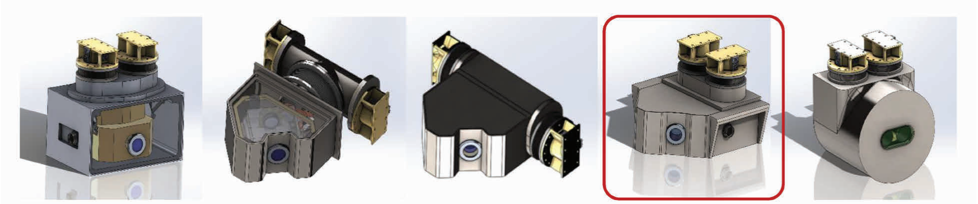

Figure 1. Different cryostat concepts considered

- an excellent thermal conductivity at ambient temperature.
- a low density.
- a low Young modulus (low stiffness).

To evaluate the best candidate for the thermal links, we utilize the ratio between the thermal conductivity and the density of the different interesting materials in our operating temperature range. As can be seen in the Figure 2, the Pyrolytic Oriented Graphite (POG) is the best candidate in the 75K-160K temperature range while the 5N aluminium is the best candidate in the 40K-75K temperature range. Both materials offer a very low Young modulus.

The aluminium will be used for the 2nd stage thermal links operating in the 30-50K temperature range and the POG will be used for the 1st stage thermal link operating in the 100-160K temperature range.

The two thermal links are made with thin aluminium and POG foils staked together and thermally and mechanically connected on the extremities to 1080 aluminium grade end-fittings (see Figure 3). The specific coupling processes have been developed by Absolut System and qualified for European space programs. The typical foils thickness is in the range of 50 µm to 70 µm.

Radiative insulation selection

The radiative loads on the thermal shield represent a significant part of the parasitic heat losses for the complete cryostat. For most of the cryostat, low emissivity coatings are used to limit the

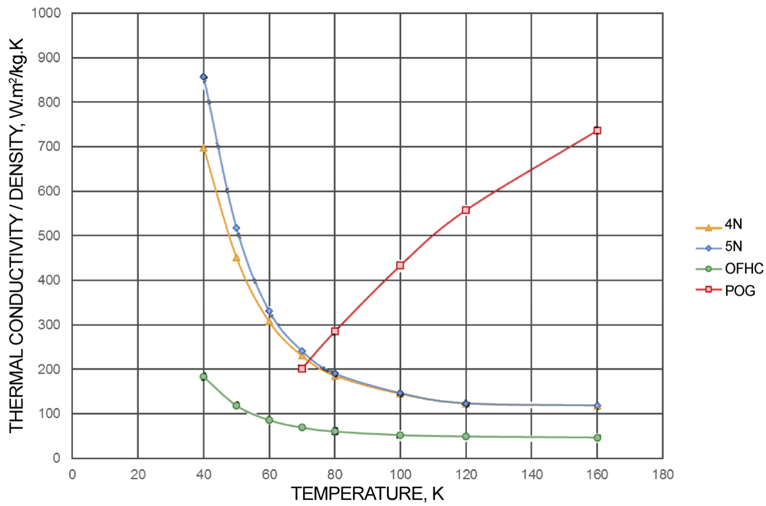

Figure 2. Ratio between thermal conductivity and density for pure aluminium, OFHC copper and POG

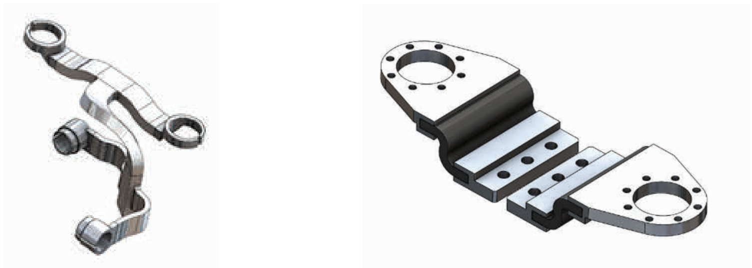

Figure 3. CAD views of the high purity aluminium thermal link on the left and POG thermal links on the right

radiative coupling between the warm side and the cold side with very good results. However, the low emissivity coatings are not as easy to produce and the final emissivity is not always expected.

The best candidates for the low emissivity coatings are aluminium, gold and silver with a high purity grade metallized coating. If we consider the surface contamination and manufacturing discrepancy, the “typical” emissivity of the coatings need to be corrected for the worst case analysis. For gold coating, the emissivity range is between 0.03 and 0.05 which increases the uncertainty of thermal analysis by a factor 2.5.

The low emissivity coatings are a very efficient solution to reduce radiative coupling between the surfaces but are very sensitive to surface contamination and in particularly to ice contamination. A thin layer of ice on the thermal shield will induce a direct degradation of the emissivity of the coating because ice tends to absorb in the IR wavelengths and scatters in visible wavelengths.

As detailed by R. G. Ross [4], very thin deposited films of contaminant gases can significantly influence the emissivity of coated surfaces such as polished gold or aluminum. It has also been demonstrated that the water-ice film has a very strong impact on the sample emissivity. The emissivity of the polished metal surface increases initially by a factor 2 per micrometer of water-ice thickness and finish by a factor close to 1 for water-ice thickness greater than 20 μm. For a polished gold surface, a water-ice film thickness of approximately 1.0 μm would be expected to increase the emissivity up to 0.06-0.1 and thus greatly increase the radiative loads.

Several aspects of R. G. Ross [4] are interesting. For metallic surface with a temperature below 250K, the “Surface Residence Time” of water molecule is several years, and the surface film of water is immobile when temperature reaches 100K. Thus, once water is trapped on a cryogenic surface, it is very difficult for it to leave and migrate to another surface.

The second interesting aspect of this paper is that it suggests that using multi-layer insulation (MLI) is much better than a single low-emissivity surface in controlling the effects of contamination. The MLI will be less sensitive to water-ice contamination due to the number of layers which act like a stacked series of radiation shields operating from environment temperature down to cryogenic temperature. The “equivalent” emissivity of MLI blanket is in the range of 0.001 to 0.01 for a space qualified MLI which will then provide, in worst case conditions, 6 to 10 times better thermal performance than a gold coating. However, MLI is generally not recommended in optical cryostats which are sensitive to surface contamination. Polyimides used in MLI blanket are a source of water vapor. This material is known to retain water and have a saturation temperature of 152K. As a result, this material should not be used where it has a view factor with optical elements below 152K.

In our case, the optical configuration is very favorable. The thermal shields will cryopump most of the water vapor and then decrease its partial pressure. When the water is trapped onto a cold surface (temperature below 150K), the molecules are fixed and will not migrate to other surfaces. The emissivity degradation mainly impacts the intermediate cold shield but it is far less critical with a two-stage cryocooler configuration compared to a single stage cooler which is directly impacted by the emissivity degradation. We concluded that the MLI is a very good candidate to limit the contamination sensitivity on the cryostat while reducing the radiative losses.

Supporting structure concept

One of the most critical components highlighted in the study is the supporting structure. The overall design of the system and its optimization is strongly driven by this component. The primary function of the mechanical supporting structure is to ensure a robust positioning of the optical components against mechanical and thermo-mechanical loads including the high stability of the structure during cool-down, thermal cycling, and mounting/dismounting.

The other aspect in the design of the supporting structure is to reduce the conductive losses through the supports. Ti6Al4V Titanium alloy and composite materials like Glass-Fiber Reinforced Plastic (GFRP) are the best candidates for this function. However both don’t offer the same level of performances. GFRP is a good candidate considering its mechanical and thermal performance. GFRP is 10 times better in terms of thermal conductivity, 2 times better in terms of density and 3 times better in term of Yield limit (in fibers directions) than Ti6Al4V. However, this material is difficult to implement because it is ortho-tropic, and thus the mechanical properties are significantly different with the direction of the load. When the load is applied perpendicular to the fibers, the Yield limit drops down to 100 MPa which is considerably low. Furthermore, the material requires specific design due to the complex manufacturing process. It is then difficult to get the optimal shape, fibers orientation and thickness due to the manufacturing constraints.

To obtain a robust supporting structure while minimizing the thermal conductive heat losses, an innovative solution has been proposed using 3-D lattices in titanium alloy (Ti6Al4V) produced with an Additive Manufacturing (AM) process. The combined use of Titanium alloy and the particular structure of the lattice (see Figure 4) makes the supportive structure very stiff and with a low thermal conductivity.

Following the mechanical analysis, the optimal shape has been selected for the lattice structure, and a good mechanical performance has been reached. As a first comparison, with the same conditions, the first Eigen mode of the concept with lattice design is above 300 Hz with a thermal conductance 45% lower than with composite blades.

To validate this concept, some breadboard samples have been designed and produced with several dimensions to evaluate the robustness of the manufacturing process. A baseline design has been selected for the lattice, and the mechanical and thermal analyses have been updated using these inputs.

DESIGN DESCRIPTION OF THE EQUIPPED CRYOSTAT

After optimization of the design regarding thermal and mechanical analysis, the detailed design of the target cryostat has been validated by the project team during the Critical Design Review Process. The manufacturing and assembling processes started following this design review.

The core of the target cryostat is composed with a Cold Box system where dichroic optics are mounted to split the entrance beam towards the two infrared detectors attached on the cold box (see Figure 5 and 6). With the innovative design of the supporting structure, the cold box is directly part of the supporting structure including warm interface and struts. Thus, no screwed interfaces are implemented on the optical/mechanical path between the mechanical reference and the detectors. A single monolithic metallic part ensures this function.

On the back of each detector, the high purity aluminium thermal link is mounted. This thermal link shape has been adapted to optimize the temperature homogeneity while reducing the temperature gradient and the overall mass. With the specific manufacturing process developed and qualified by Absolut System for thermal links, the thermal link's shape is free of constraints and can be designed with extremely complex routing, shape or interfaces. The other extremity of the thermal link is attached directly on the second stage of the cold tip operating at 40 K.

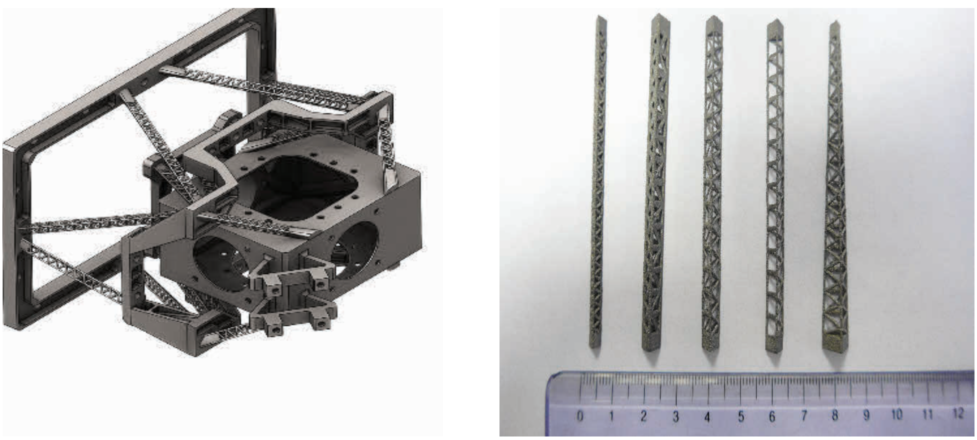

Figure 4. Overview of the monolithic supporting structure (left) and Ti6Al4V lattice breadboards manufactured using AM process (right)

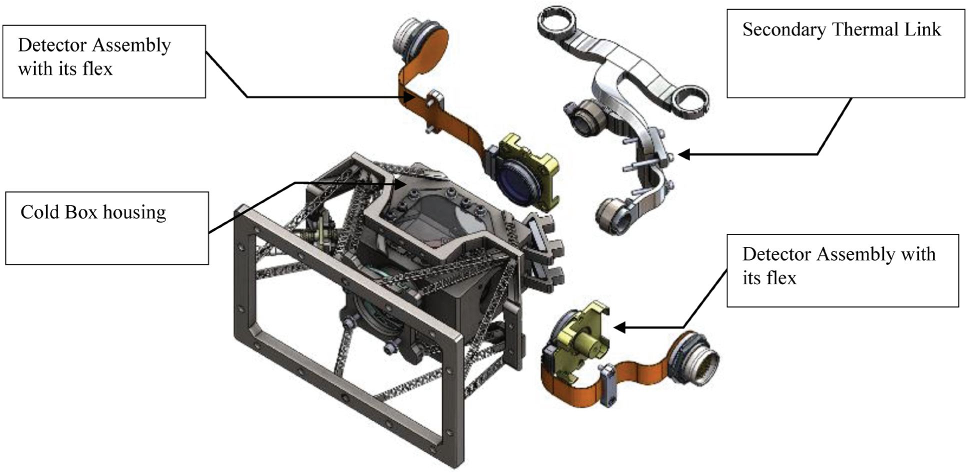

Figure 5. Exploded view of the cold box assembly

In order to minimize the parasitic heat fluxes on the detectors and on the cold box, a baffle assembly is required. The different parts of the baffle are made using aluminium alloy to offer the best compromise between mass, thermal conductivity and mechanical performance. The external surfaces will be covered with MLI blanket and the internal surface black coated. Following thermal optimization, the cold window is mounted on the baffle at the intermediate temperature (in the range of 100 K). The baffle will be black coated on its internal face. The external face will be covered with MLI blanket as per the cold shield.

The cold box is surrounded by an aluminium thermal shield to intercept radiative heat losses. The thermal shield is separated in 4 main parts in order to implement the thermal shield after final

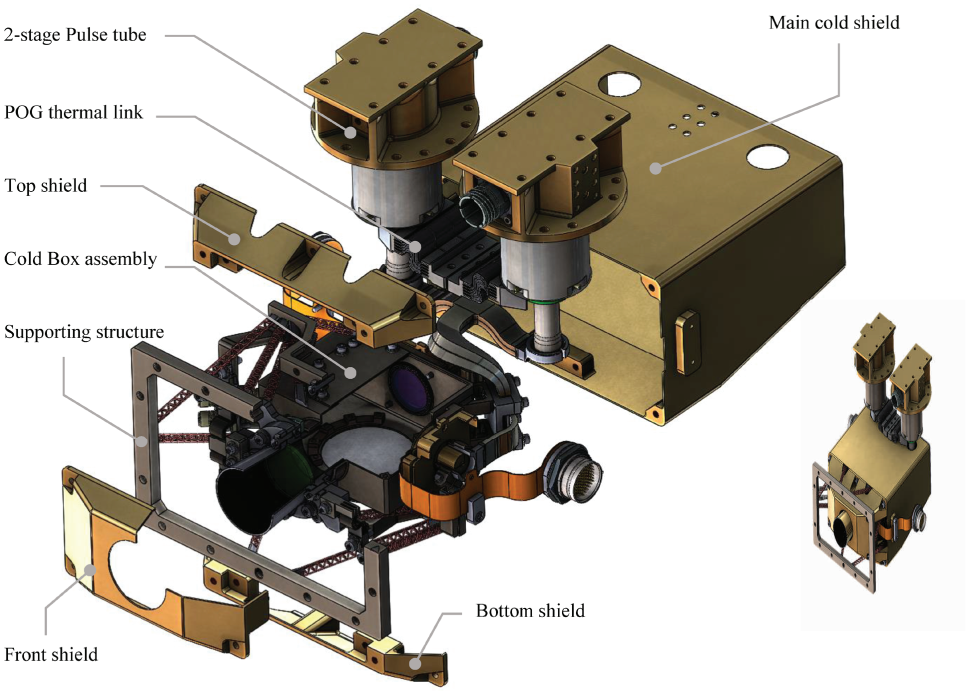

Figure 6. Exploded view of the optical bench assembly and assembled view in miniature

integration and alignment of the detectors. The thermal shield is attached mechanically onto the supporting structure intermediate interface. This intermediate interface is implemented between the warm flange at room temperature and the Cold Box in the 40 K temperature range. The back of the thermal shield is thermally coupled to the second stage of the Pulse tube cold head through POG thermal links. Around this thermal shield, MLI blankets are implemented to lower radiative heat losses.

The cryostat housing is made with several components. The main part is the housing of the cryostat and the other components are mainly the covers which ensure the vacuum tightness after assembly of all internal components. The cryostat housing is a massive part made with aluminium alloy. The use of titanium alloy is possible to improve the stiffness and to lower the mass. On the front side of the cryostat, the front cover is equipped with the entrance window. This cover is mounted on the same mechanical interface as the supporting structure to have the same mechanical reference for optical chain alignment (see Figure 6).

On the top and on the back, two covers are screwed after assembling of the sub-system inside the housing. The sides of the cryostat are used for hermetic feedthroughs. 4 hermetic feedthroughs have been implemented: 2 for the video harnesses and 2 for sensors and heaters. The 4 connectors are mounted on the cryostat using intermediate plates which are easier to change or adapt during development process than the re-machining of the cryostat.

THERMAL AND MECHANICAL ANALYSIS

To predict the thermal and mechanical performance of the target cryostat FEM, modelling has been run supported by an elementary breadboard tests. Two models have been developed to perform the validation of the design. The first is dedicated to the thermal modeling, including radiative modeling and the second one, more detailed, to check the mechanical behavior of the cryostats and particularly, the supporting structure (see Figures 7 and 8).

Using these models, the thermal analysis of the cryostat has been studied for different operating condition with the objectives to evaluate the parasitic heat losses and to validate the thermal balance with cryocooler capability.

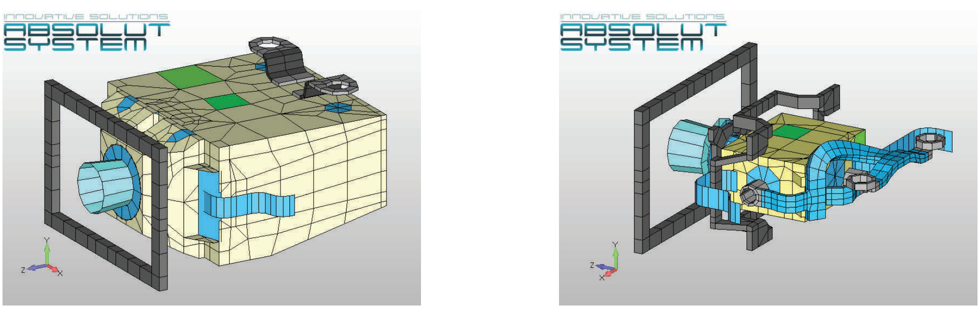

Figure 7. Thermal model of the cryostat

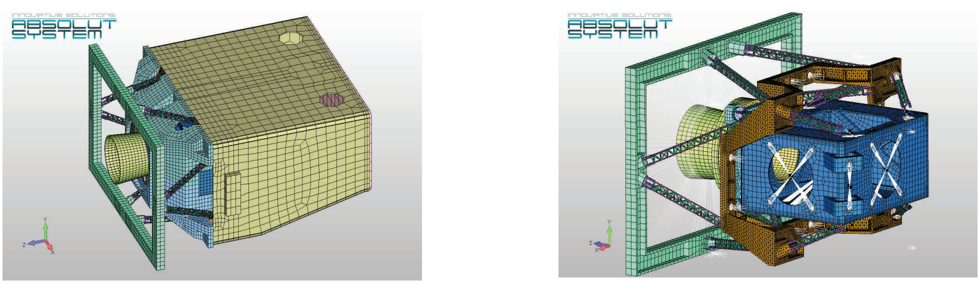

Figure 8. Overview of the meshing of the complete cryostat used for FEM analysis

In parallel, the 3-D lattice has been tested using breadboard test to evaluation the thermal conductance of the elementary structure. This test was important to decrease the uncertainty related to the contribution of the supporting structure on the conductive heat losses.

After several iterations, the thermal losses of the complete cryostat have been evaluated and are reported in the Table 1. We can see that a significant portion of the losses are from the redundant cold head. The other significant contribution is coming from the radiative load on the cold shield. Considering these outputs and the project margin philosophy, the final cooling capacity required on the cryocooler is: 1095 mW@ 42K and 2648 mW@126K.

Regarding the mechanical analysis, the cryostat and associated components has been modelled with a very refined model including a representative modelling of the 3-D lattice supporting structure. The objective was to evaluate the stress in the structure when the cryostat is submitted to mechanical environmental tests (sine and random loads) (see Figure 9). One critical parameter in the dynamic response prediction of structural components is the hypothesis made on the amplification factor. To give more consistency in our analysis, the supporting structure has been produced and submitted to sinus sweep at low level to refine our initial hypothesis (initial Qfactor = 50 and measured at 40). Following these considerations, the stress analysis in sinus and random reported positive margins on all the components. The stress in the elementary beams of the lattice contains a comfortable Margin of Safety.

MANUFACTURING AND ASSEMBLING PROCESS

The final configuration of the test cryostat has been simplified compared to the flight-like design. The aim of the tests is to validate the different performances and for this reason, the redundant cooler will not be implemented. Other simplifications have been made on the optical chain where dummy detectors equipped with temperature sensors and heaters will be used for the thermal test campaign or the entrance window which is replaced by a plain aluminium disk black coated. With the exception of these simplifications, we kept the design of the optical bench as close as possible to the flight-like design. The supporting structure, the thermal links, the cold shield and other components critical for performance validation are fully representative. The MLI blanket will be made with conventional MLI using spacer. This MLI should be replaced for flight with a blanket made with embossed foils far less critical in term of particulate contamination. Figure 10 shows the different components during their integration in the ISO5 environment.

Table 1. Summary of Thermal Losses Analysis

Heat fluxes in mW	**Intermediate stage 126 K**	**Cold stage 42 K**
Internal dissipation		
IR sensors	0	220.0
Conductive heat fluxes		
Supporting structure	147.0	99.6
Wiring - heaters	117.3	47.6
Wiring - sensors	43.3	4.9
Video harness	183.4	183.4
Redundant cold finger	1425.1	294.3
Radiative heat fluxes		
External radiation on the cold shield	434	-
Internal radiation with the cold shield	-	18
Radiation on the baffle	436	-
Radiation from the cold windows	-	15.6
Radiation on the Video Harness	30	30
Total of parasitic heat losses on each stage	**2816.1**	**693.4**
Total net heat load on each stage	**2122.7**	**913.4**

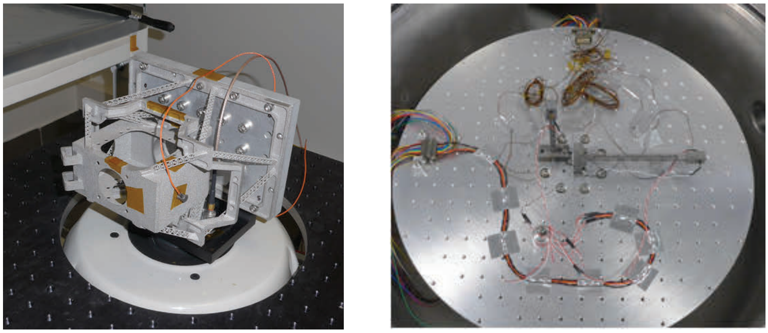

Figure 9. Elementary breadboard test: structural test of the supporting structure on the left and thermal conductance characterization of the elementary struts on the right

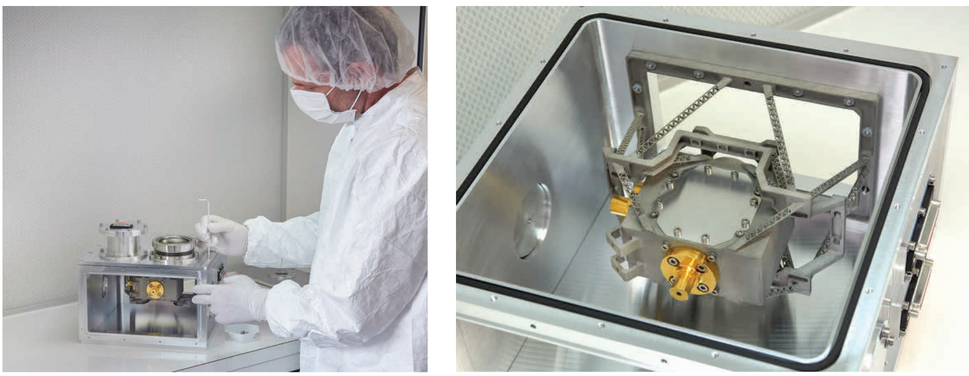

Figure 10. Picture of the optical bench during integration and integrated into the cryostat housing in Absolut System premises

CONCLUSIONS AND OUTLOOK

A flight-like cryostat has been designed by Absolut System and is under assembly prior testing. This cryostat is designed to take benefits of a high efficiency two-stage coaxial pulse tube cooler to operate infrared detectors in the 40 K temperature range with the same input power budget than conventional single stage coolers. An innovative supporting structure has been developed, manufactured and tested in order to offer a robust and efficient structure. A monolithic design with high thermal and mechanical performance has been designed which simplify the mechanical path and reduce drastically the number of parts and screwed interfaces. Most of the parts of this demonstration cryostat have been manufactured and are under assembly. The final test will run this summer after integration of the two-stage pulse tube cooler.

ACKNOWLEDGEMENTS

This development is performed in the frame of ESA Technical Research Program - 4000109933/14/NL/RA.

The authors thank ESA for their funding and technical supports during this development, and Thales Alenia Space for their technical supports regarding cryostat system engineering and peer review.

REFERENCES

1. T. Trollier, J. Tanchon, J. Buquet et al. « Design of a Large Heat Lift 40 to 80 K Pulse Tube Cryocooler for Space Applications," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 75-82
2. S. Watson, "Design and development of a high power stirling cooler," *European Space Mechanisms & Tribology Symposium*, ESMATS 2013
3. P. Bruins, T. Prouvé, I. Charles, T. Trollier, J. Tanchon, J. Mullié, T. Benschop, « A 30-50 K Dual-Stage Pulse Tube Space Cooler," *Cryocoolers 18*, ICC Press, Boulder, CO (2015), pp. 33-37
4. Ross, R.G., Jr., "Cryocooler Load Increase due to External Contamination of Low-E Cryogenic Surfaces," *Cryocoolers 12*, Springer US (2003), pp. 727-736.