

Manufacturing and Testing of a Flight-Like Cryostat for 30-50K Two-Stage Pulse Tube Cooler

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ABSTRACT

The consortium of Thales Cryogenics BV, CEA-SBT and Absolut System developed a flight-like cryostat integrating a two-stage 30-50K pulse tube cryocooler under the auspices of an ESA Technical Research Program (TRP - 4000109933/14/NL/RA). One of the objectives of this project was to develop the key technologies, e.g., the two-stage cryocooler and the cryostat components, and also to demonstrate by test that such a configuration is a very good option for a conventional Earth observation instrument using a single stage cryocooler.

Furthermore, the use of a two-stage cryocooler in a dedicated two-stage cryostat offers the possibility to operate the detectors at a lower temperature, which is of interest for a Quantum Well Infrared Photodetector (QWIP) or Mercury Cadmium Telluride (MCT) infrared detectors operation in the 40K-45K temperature range for an overall input power similar to the one that is required in current Earth Observation Infrared instruments.

This paper presents the final cryostat architecture, the manufacturing and elementary tests performed on the different components (thermal links, supporting structure, cryocooler...) and the end-to-end tests performed on the Equipped Cryostat. Finally, the performance measured on our two-stage cryostat will be compared to a conventional cryostat architecture.

INTRODUCTION

The space cryogenics sector is characterized by a large number of applications (detection, imaging, sample conservation, propulsion, telecommunications etc.) that produce different requirements (temperature range, micro vibration, lifetime, consumption etc.) that can be satisfied by different solutions (Stirling or JT coolers, mechanical or sorption compressors etc.). Recently in Europe, the developments of coolers to meet Earth Observation mission requirements has produced different solutions that are capable of providing more than ~3W of cooling power at an operational temperature of approximately 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 available at 40K for reasonable ambient rejection temperatures.

On the other end, the trend in focal plane cooling requirements for Earth Observation is to aim at higher cooling power at current temperature levels (around 50K) due to the use of bigger detector matrices, or to lower the temperature to limit dark current or to use new detector technologies. For instance, the QWIP detection solution seems very promising but needs to operate at a temperature around 35 - 45K, which may not be reasonably obtainable with the currently available coolers developed for Earth Observation.

In addition to detector cooling, this type of 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 the detector cooling power available at a lower temperature. This solution makes use of existing component building blocks (e.g. compressor) but requires the mastering of the design/manufacturing/integration constraints linked to double stage cryocoolers used in cryostats.

This paper reports the activities performed regarding the manufacturing and testing of the Equipped Cryostat following the design and analysis outcomes presented in previous Cryocoolers 19 paper [3].

EQUIPPED CRYOSTAT DETAILED DESIGN

The detailed design of the cryostat has been performed after an intensive evaluation study. Several aspects have been analyzed during the first phase of the development to define the optimal configuration of the Equipped Cryostat. The main aspects evaluated were: the cryostat integration and accessibility (in particular detector's alignment constraints), the thermal performances, the mechanical robustness and stability regarding optical constraints, the orientation of the cold finger regarding gravity for ground testing.

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

The core of the Equipped Cryostat is composed of a cold box structure where the dichroic optics are mounted to split the beam towards the two infrared detectors mounted on the cold box. With the innovative design of the supporting structure, the cold box is part of the supporting structure including warm interface and struts (see Figure 1). Thus, no screwed interfaces are implemented on the optical/mechanical path between the mechanical reference and the detectors. Only a single monolithic metallic part ensures this function.

On the back of each detectors, the high purity aluminium thermal link is mounted. This thermal link has been adapted to maintain a uniform temperature while reducing the temperature gradient and the overall mass. With the specific manufacturing process developed and qualified by Absolut System for thermal links [4], the thermal link's shape is free of constraints and can be designed with an 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 <40K.

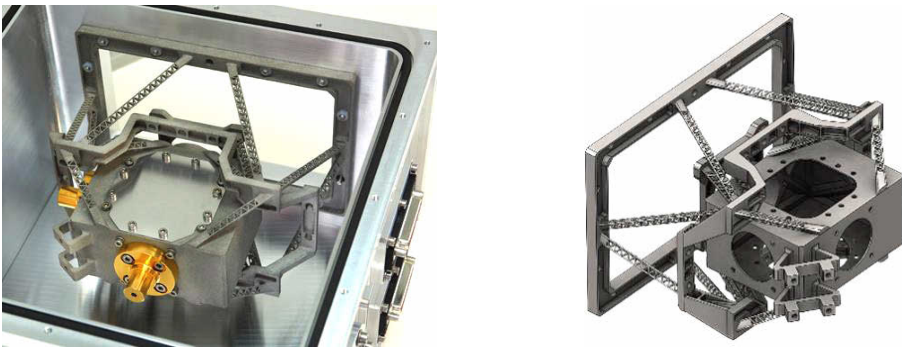


Figure 1. Innovative monolithic supporting structure made with additive manufacturing

A baffle assembly is required to limit the parasitic heat fluxes on both detectors and the cold box. The different parts of the baffle are made of Aluminium alloy to offer the best compromise between mass, thermal conductivity and mechanical performances. The external surfaces are covered with MLI blankets and the internal surface is coated black. Following the thermal optimization, the cold window has been mounted on the baffle at an intermediate temperature (in the range of 100K). The baffle is coated black on its internal face. The external face is covered with MLI blankets 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 into 4 main parts to implement the thermal shield after final integration and to allow for 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 40K temperature range. The back of the thermal shield is thermally coupled to the second stage of the pulse tube cold head through POG (Pyrolytic Oriented Graphite) thermal links. Around this thermal shield, MLI blankets are implemented to reduce parasitic radiative heat losses.

One of the most critical components for a 40K flight cryostat is the supporting structure because of the thermal performance and the mechanical robustness constraint. During the design phase, an innovative supporting structure concept has been proposed using TA16V4 lattice produced using an Additive Manufacturing process. A breadboard has been presented in a previous paper and the final part based on a monolithic concept of the complete supporting structure has been manufactured and successfully undergone an environmental test campaign.

The overall design of the Equipped Cryostat is presented in the Figure 2. This design offers a good compromise between the thermal performance, mechanical aspects and integration of the components. The main advantages of this configuration are:

- To offer a compact Cold Optical Bench decoupled from the Cryocooler assembly. The optical cryostat is split from the cold head cryostat using high performance thermal links. Both sub-assemblies are optimized separately and mounted and tested in parallel. This aspect eases the integration and test of the stated components
- To operate with the cold fingers oriented downward to the gravity vector. The parasitic losses of the cold finger will be representative of flight conditions during the ground test campaign.
- To limit the distance required between the 2 sub-assemblies. The compactness of the design optimizes the performance of the flexible thermal links.
- To absorb the radiative and conductive parasitic heat losses on the cryocooler 1st stage. An active cold shield is used as a cold bus to absorb and distribute the losses on the 1st stage of the cooler. The parasitic heat losses on the second stage (operating at less than 40K) are thus limited.

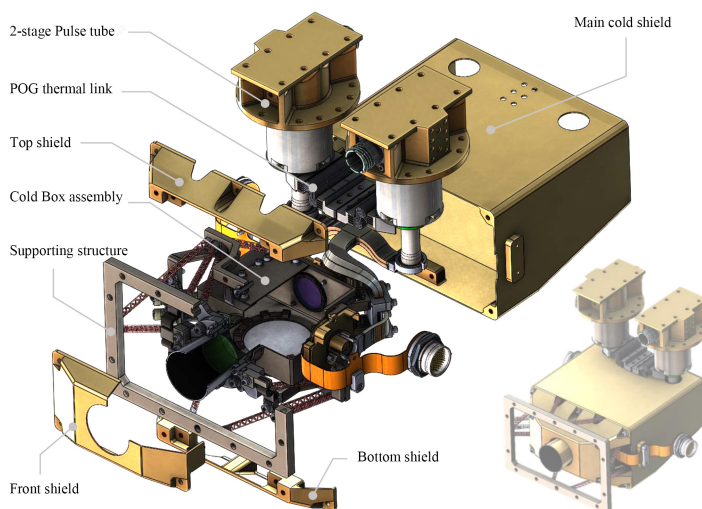


Figure 2. Exploded view of the Optical Bench Assembly and assembled view in miniature

- The cold shield is mounted on a low thermal conductivity structure supporting the 40K components to facilitate the integration of the optical components with the rigid and dis-mountable active cold shield.

A product tree of the Equipped Cryostat is presented in Figure 3 together with the lower level components present in the cryostat, such as the dummy detectors, the thermal links, the optical bench assembly and the cold box. The Equipped Cryostat contains two cold finger interfaces on top; the cryocooler is installed on one side and next to it the dummy cold finger is installed. Since no active detector is available for this program, the cryostat is equipped with two dummy detectors. For redundancy purposes the cryostat can accommodate two cryocoolers. However for the frame of the development program, only one cryocooler is manufactured, therefore the second cold finger interface is equipped with a dummy cold finger which fully represents the parasitic heat losses.

Some key requirements and characteristics of the cryostat, detectors and overall Equipped Cryostat are listed below:

- Detector dissipation total: 110 mW per detector 220 mW
- Cold box temperature: 50 K
- Detector temperature: < 45 K
- Detector diameter: 30 mm
- Qualification temperature: -35 °C to +45 °C
- Detector electrical interface: 91 pins circular connector
- Cryostat Envelope: 300 x 290 x 250 mm
- Cryostat Mass excluding cryocoolers: < 16 kg
- Equipped Cryostat Mass including cryocoolers : < 29 kg

MANUFACTURING AND ASSEMBLY OF THE EQUIPPED CRYOSTAT

The final configuration of the test cryostat has been simplified as compared to the flight-like design. The redundant cooler unit is not implemented for this study. Other simplifications have been made on the optical chain where dummy detectors are equipped with temperature sensors and

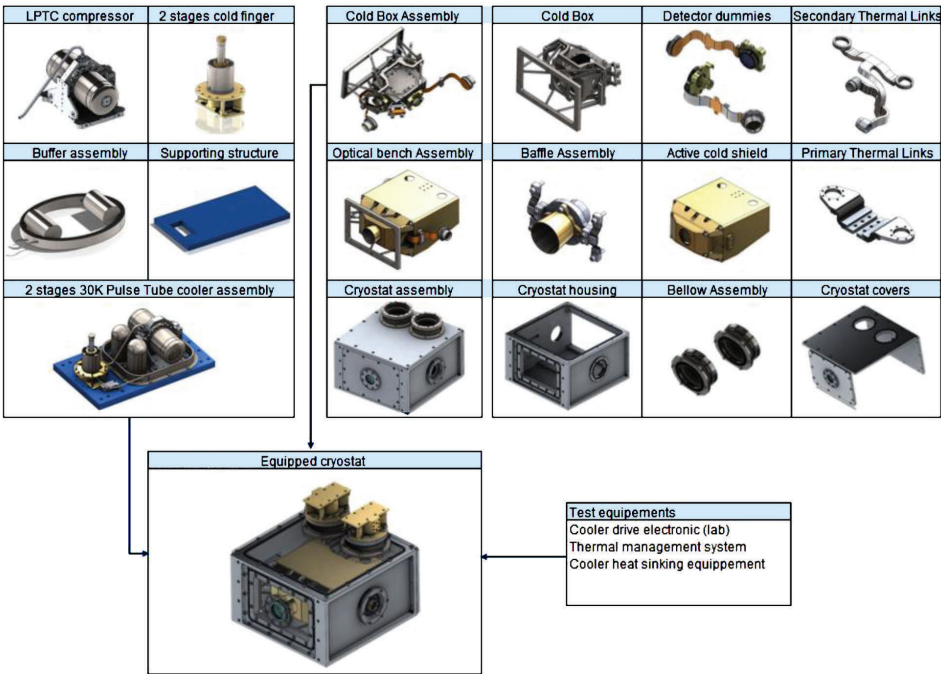


Figure 3. Overview of the components breakdown

heaters used for the thermal test campaign. The entrance window 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 is fully representative, the thermal links, the cold shield and other components critical for performance validation are also fully representative. The MLI blanket is made with conventional MLI using spacers. This MLI should be replaced for flight with a blanket made with embossed foils which are far less critical in terms of particulate contamination.

The video harness is not part of the dummy detectors assembly. To simulate the conductive and radiative loads on these harnesses, an additional dissipation is applied either on the detector itself in nominal mode or on the active cold shield in the case of heat intercepted configuration. For a heat intercepted configuration, most of the heat losses is absorbed by the active cold shield and thus the heat flux going onto the second stage is reduced. However the total length of the harness if fixed (due to signal attenuation concern). In this configuration the first stage is thus more loaded but with the advantage to reduce significantly the load on the second stage of the cooler. This configuration is particularly adapted with two-stage cryocooler configuration offering important cooling capacity on the first stage. The performances of the two-stage cryocooler are reported in Table 1.

The different pictures presented in the Figure 4 to Figure 6 shows the different steps of the integration of the Equipped Cryostat up to the final test configuration in the Figure 7.

Table 1. Two-Stage 30-50K Cryocooler Performance

Pinput [W]	1 st stage		2 nd stage	
	Cooling power [W]	Temperature [K]	Cooling power [W]	Temperature [K]
180	3.0	98.3	1.0	33.0
160	3.0	100.6	1.63	42



Figure 4. Thermal links (5N aluminium on the left and POG in the center) and optical bench (right picture)

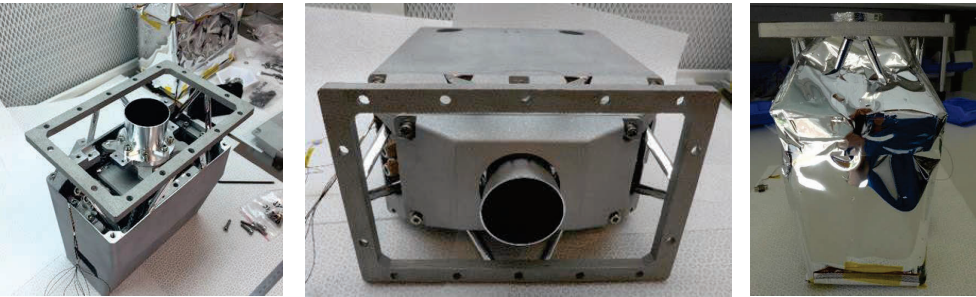


Figure 5. Optical bench with active cold shield with MLI blankets

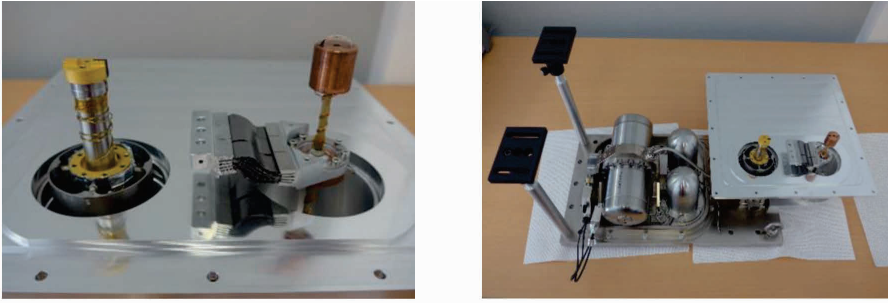


Figure 6. Cryocooler assembly with POG thermal link and cryostat top flange

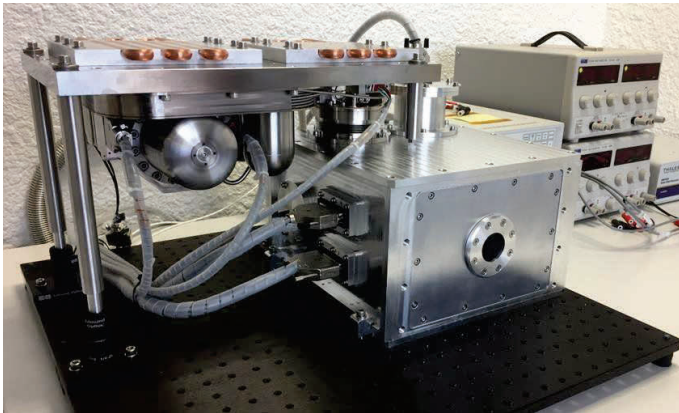


Figure 7. Equipped Cryostat including 30K two-stage pulse tube cryocooler

PERFORMANCE TESTS RESULTS OF THE EQUIPPED CRYOSTAT

Objective of the End-to-End Tests and Test Conditions

The main objective of the test campaign performed on the Equipped Cryostat is to demonstrate the thermal performance of IR instrument using a two-stage cryocooler instead on a single stage cryocooler. The test sequence of the Equipped Cryostat is performed at atmospheric pressure in order to avoid the use of thermal vacuum chamber. The Equipped Cryostat is oriented in order to get the cold finger vertical with cold tip facing down (no gravity effect). During the test sequence, the warm-end flange temperature is controlled to the desired test value by chilled water flowing into a cold plates attached to the cooler supporting structure. The end-to-end test sequence is based on the operating temperature measurement of the dummy IR detectors for different load cases:

- “NO-LOAD”: no dissipation applied on the cryostat and redundant cold finger
- “OFF-state”: both detectors not powered but with representative parasitic heat losses (redundant, harnesses...)
- “DET ON”: both detectors powered and with representative parasitic heat losses (redundant, harnesses...)
- “INTERCEPT”: Intercept of the conductive losses through the video harness on the 100K stage (same condition than for DET ON for the other loads)

The dissipation applied for these different load cases are summarized in the Table 2. These different tests are performed with the nominal operating condition determined during design phase for the cryocooler:

- Input power at cryocooler compressor level = 123 W

Table 2. Dissipations Applied for the Different Load Cases During Test Sequence

Heaters	Heater / dissipation	Load cases			
		NO-LOAD	OFF SATE	DET ON	INTERCEPT
Dummy detector 1	Heater_det_1	0	91.5 mW	201.5 mW	165 mW
Dummy detector 2	Heater_det_2	0	91.5 mW	201.5 mW	165 mW
Dummy redundant 1st stage	Total heat load	1380mW	1484 mW	1483 mW	1467 mW
	Heater load_1st	0	104 mW	103 mW	87 mW
	Parasitic	1380mW	1380 mW	1380 mW	1380 mW
Dummy redundant 2nd stage	Total heat load	0	201 mW	197 mW	207 mW
	Heater load_2nd	0	27 mW	23 mW	33 mW
	Parasitic	174mW	174 mW	174 mW	174 mW
Video harness intercept 1	Heater_video_1	0	0	0	139.5 mW
Video harness intercept 2	Heater_video_2	0	0	0	139.5 mW

- Warm-end temperature = 20 °C
- Cryostat temperature = room temperature (20-22 °C)

As a reference for the test evaluation, the summary of the thermal losses analysis for the nominal operating case (DET ON), is reported in the Table 2. The heat fluxes expected for each stage are in the range of 0.8W@34K and 2.34W@103K.

Tests Results

The End-to-End tests of the 30-50K Equipped Cryostat have been run at Absolut System premises over a one month period. During this period the different cases have been tested with very good results and consistency regarding expected performances.

NO-LOAD:

The first load case run corresponds to the no-load conditions of the cryostat. This test is very useful to evaluate the conductive and radiative heat losses of the cryostat. The heat fluxes absorbed by the cooler on each stage are evaluated using there temperature measurement and the thermal mapping performed during the cryocooler acceptance test. In this conditions, the cooling power evaluated on the cryocooler is as follows:

- 1st stage: 2190 mW (102.5K on the 1st stage)
- 2nd stage: 478 mW (29.8K on the 2nd stage)

These heat fluxes correspond to the total of the parasitic heat losses of the cryostat with the dummy redundant but without any dissipations on the heaters. In these tests conditions, the minimum temperature reached on the detectors is in the range of 30K (31.2K for Detector 1 and 30.5K for Detector 2).

OFF-STATE:

For this test, dissipations on the redundant cold finger are applied on each stage to simulate the parasitic heat losses of a real cold finger. A dissipation on the detectors is also applied to simulate the conductive losses through the video harness (~90mW/detector). In this conditions, the cooling power evaluated on the cryocooler is as follow:

- 1st stage : 2368 mW (104.5K on the 1st stage)
- 2nd stage : 677 mW (33.1K on the 2nd stage)

In these tests conditions, the minimum temperature reached on the detectors is in the range of 34.5K (35.2K for Detector 1 and 34.1K for Detector 2).

DET-ON:

This test correspond to the nominal operating conditions where the detectors are powered. For this test, the dissipation of the 2 detectors are applied and combined with the OFF-STATE conditions. In this conditions, the cooling power evaluated on the cryocooler is as follow:

- 1st stage : 2180 mW (103.18K on the 1st stage)
- 2nd stage : 849 mW (35.6K on the 2nd stage)

In these tests conditions, the minimum temperature reach on the detectors is in the range of 38K (38.5K for Detector 1 and 37.1K for Detector 2). As we can see on the Table 3, the expected heat fluxes on the first stage and second stage of the cooler is very close to the measured performances (5-6% discrepancy). This discrepancy includes all the measurement uncertainties, thermal model uncertainties and cooler fit function uncertainties.

HEAT INTERCEPT:

This test corresponds to the nominal operating condition (DET ON) but where the video harness are connected on the active cold shield to intercept heat flux going through the harness onto the detectors. This flux is important on the second stage thermal balance and this configuration should show a decreasing of its temperature. In this conditions, the cooling power evaluated on the cryocooler are as follow:

- 1st stage : 2409 mW (105.0K on the 1st stage)
- 2nd stage : 815 mW (35.2K on the 2nd stage)

In these tests conditions, the minimum temperature reach on the detectors is in the range of 37.2K (37.9K for Detector 1 and 36.6K for Detector 2).

SENSITIVITY TO INPUT POWER:

Finally the last tests performed consisted in measuring the sensitivity of the detector’s temperature to the electrical input power applied on the cryocooler. The nominal operating case is for 123 W applied on the compressor and tests at 103 W, 143 W and 183 W have been performed to support potential instrument design. The evolution of the detector’s temperature is reported in the Figure 8. We can see that the two detectors can operate between 34K and 41K depending of the input power allowed at cryocooler level.

CONCLUSIONS AND OUTLOOK

A flight-like cryostat has been designed and manufactured by Absolut System. This cryostat is designed to take benefits of a high efficiency two-stage coaxial pulse tube cooler in order to operate

Table 3. Summary of Thermal Losses Analysis for the Nominal Case (DET ON)

Heat fluxes in mW	Intermediate stage 103 K	Cold stage 34 K
Internal dissipation		
IR sensors	0	220.0
Conductive heat fluxes		
Supporting structure	83	84
Wiring – heaters / sensors	104	41
Video harness	-	183
Redundant cold finger	1286	197
Radiative heat fluxes		
External radiation on the cold shield	416	-
Internal radiation with the cold shield	-	18
Radiation on the baffle	449	-
Radiation from the cold windows	-	31
Radiation on the Video Harness	-	30
Total net heat load on each stage	2338	804

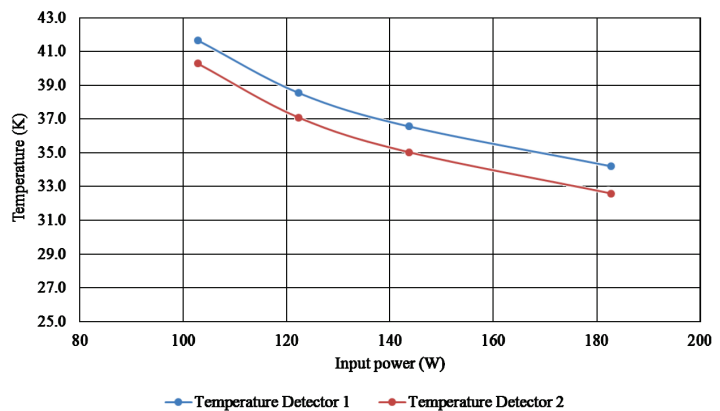


Figure 8. Evolution of the detector temperature for different cryocooler electrical input power

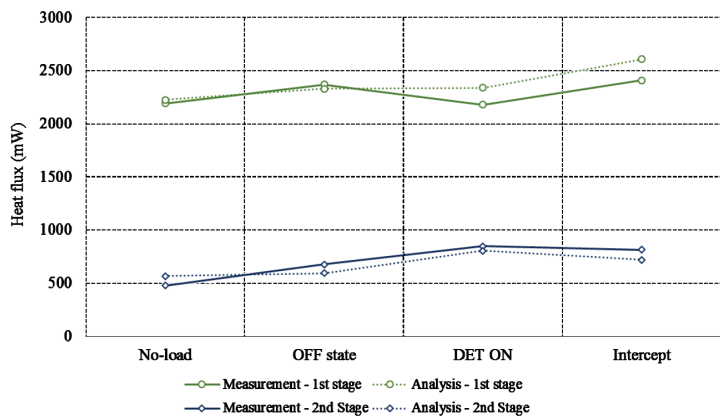


Figure 9. Comparison of the heat fluxes measured during test sequence and predicted performance

infrared detectors in the 40K temperature range with the same input power budget than conventional single stage coolers.

The Equipped Cryostat demonstrated very good thermal performances and detectors have reached a temperature of 36K with 123W input power at compressor level. This performance is very good regarding single stage cryostat concepts which operate typically 15-20K higher in temperature with the same operating conditions.

An innovative supporting structure has been developed, manufactured and tested in order to offer a robust and efficient cryogenic structure. A monolithic design with high thermal and mechanical performances has been designed which simplify the mechanical path and reduce drastically the number of parts and screwed interfaces.

Different tests have been performed on the Equipped Cryostat in order to validate the performances of the system and to improve the understanding of the thermal balance. Several points regarding the heat losses allocation are difficult to analyze properly due to the lack of temperature sensors, but good consistency of the overall thermal balance has been found. Figure 9 compares the measurement with the expected performances for the different tests.

We demonstrated during this test sequence that the results are very reproducible and over a long test period which means that the cryostat is not sensitive to contamination and particularly in this concept where MLI is used on the 1st stage. Some additional tests with 180W of input power have been performed and a temperature of 31K has been reached on detector dummy.

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