

# Spacecraft Cryogenic Developments and Perspectives at the European Space Agency

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## ABSTRACT

The successful launch of Herschel/Planck in 2009 was a significant milestone for Space Cryogenics in general and the European cryogenic community in particular: Europe, in collaboration with American partners, successfully put into orbit and operated sub-Kelvin instruments cooled by sophisticated cryochains. It was not only an engineering achievement leading to the collection of invaluable scientific data, but also the culmination of almost 20 years of space cryogenic developments by the different institutes, companies and agencies in Europe.

Since this turning point, space cryogenics Research and Development/Technology has never been so dynamic in Europe. The European Space Agency has been involved in over 80 activities ranging from PhD projects to qualification of new products. New satellites appeared with increasingly stringent requirements, e.g., low vibration/vibration free, increasing cooling power, lower detectors temperature.

This paper will describe the recent and current developments in the field of spacecraft cryogenics at ESA as well as the driving mission requirements in the Earth Observation and Science domains. The whole range of temperature (from 50mK to 200K) and technologies (coolers, heat switches, energy storage units) will be addressed. The in-orbit performances of the cryogenic subsystem for the agency's recently launched satellites (e.g. Sentinel 3) and the design and verification for cryogenic instruments currently in development (e.g. Meteosat 3rd Generation, Athena) will be touched upon as well.

Finally, the paper will lay out the current outlook in terms of missions and needs in the domain of cryogenics for spacecrafts.

## INTRODUCTION

Cryogenics for Space is as old as the space era itself: Sputnik 1, the first artificial satellite was launched in 1957 with a rocket, the Sputnik-PS, using Liquid Oxygen as the oxidizer. Techniques related to cryogenic fluid storage and on-ground oxygen liquefaction were used in and around the launch pad to contribute to this founding milestone.

As pointed out in the R.G. Ross[1], cryogenics in space followed closely the launch of Sputnik 1. After the first space dewars during the Apollo years, engineers and scientists rapidly saw the necessity to launch cryocoolers to cool experiments and focal planes, namely long life time closed-cycle cryocoolers.

This quest for multi-year cooling for space was in essence achieved with the launch at the beginning of the 1990s of the RAL (GB) and Oxford (GB) flexure-bearing dynamic gas seal linear Stirling coolers (Figure 1). This technological revolution spread around the world, and all the Stirling cycle-based space cryocoolers (and mechanical Joule-Thomson coolers) to this date possess the key technical features of this mechanism.

The European Space Agency was an early actor in the developments of space cryogenics by funding research and technology projects driven by the Infrared Space Observatory (ISO) mission launched in 1996. By the end of the 1990s and the beginning of the 2000s when it became clear that the stored cryogen solutions would slowly be replaced by mechanical coolers based architectures for all the temperature range, the agency focused its developments in the fields of linear compressors, Stirling and pulse tube coolers. This period culminated in 2009 by the launch of Herschel, the last stored cryogen satellite of the agency, but especially Planck (Figure 1) which featured a sophisticated cryochain of passive, sorption and mechanical coolers to cool detectors down to 100mK. This year also corresponds to the start of the endurance test of the Large Pulse Tube Cooler from Air Liquide (FR), which paved the way for its selection in 2012 as the cooling solution for the instruments of the last member of the Meteosat family, Meteosat Third Generation (MTG).

After those critical milestones, it was paramount for the European Space Agency, in order to remain on the forefront in the domain of cryogenics, to maintain this strategic capability, and to enable more and more demanding missions to not only sustain and adapt the qualified technology to answer short and medium-term needs but also to propose new types of developments and technology to fulfil tomorrow's requirements.

## SPACECRAFT CRYOGENICS DEVELOPMENT AT ESA

### Foreword on Technological Developments at ESA

As a space agency, one of the missions of ESA is to promote, provide guidance and provide financial support to research and innovation that can be used for space. The ultimate goals are to ensure the success of future space missions and enhance the world-wide competitiveness of European space industry.

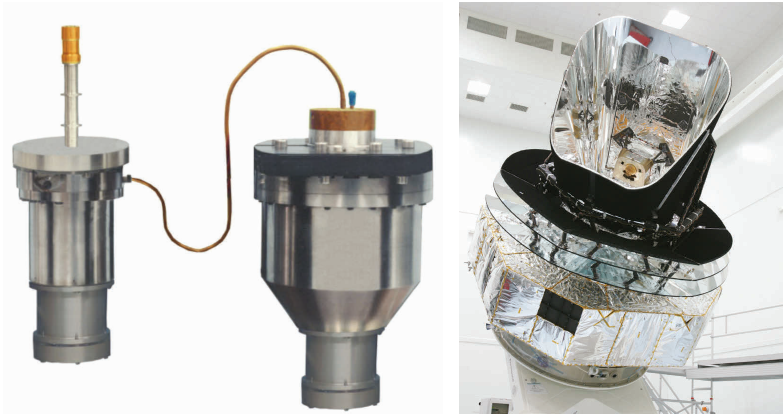
In order to achieve those objectives, the agency has at its disposal an array of Research & Development programs that will depend on the type of application (e.g. Earth Observation, Science, Telecommunication), the type of activity (e.g. PhD, de-risking, spin-in and spin-out) and target Technology Readiness Level (TRL).

Schematically speaking, the technology development approach at ESA can be summarized as follows:

- New development ideas are identified by specialists within ESA and proposed to the community via the Technology Research Program (TRP) plans (every 2 years). Those development proposals are typically pioneering with a low starting TRL as they are meant to cover needs beyond the immediately identified missions. The tender is open competition within Europe and the final product shall reach the level of a breadboard functionally verified in laboratory environment (TRL4). The budget comes from the mandatory contribution of all the ESA member states.
- Once the TRL4 is achieved, there are two possibilities:
  - The idea is picked up by a member state to support its industry by increasing the TRL to greater than TRL 5 via the General Support Technology Program (GSTP, optional program of ESA).
  - The technology is deemed interesting by a mission and its maturity is increased via domain specific developments (e.g. Earth Observation with EOPP, Science with CTP etc.).

Aside from this mainstream path, the agency also fosters innovation via the subsidies of PhDs and PostDoc (Networking/Partnering Initiative - NPI) or thanks to bottom-up projects coming from inventors or developers themselves (Innovative Triangle Initiative - ITI).

In order to achieve better-coordinated research and development activities among all the European space sector actors, a process of harmonization on the topic of cryogenics and focal plane



**Figure 1.** The launch of Oxford University ISAMS 80K cooler (left) at the beginning of the 90s and of Herschel Planck (right) in 2009 correspond to two major milestones in European Space Cryogenics.

cooling has been put in place since 2001. Every ~6 years all the stake holders on the topic (agencies, institutes, and industries) are involved in a common process to identify the new trends, agree on promising development subjects and choose the most efficient way to implement them. The last harmonization round on Cryogenics occurred in 2012, and the next one is planned for 2019.

### Development Drivers in Cryogenics at ESA

As already mentioned, the European Space Agency has been active in the domain of space cryogenic developments almost since its creation. Before examining the current trends that motivate the development choices since 2009, one can find summarized hereafter the development drivers until that date:

- In the 1970s and 1980s, the cryogenic technology program was led by ISO: Superfluid He Dewar technologies, porous plug etc.
- In the 1980s and the first half of the 1990s, the focus was the development of the Stirling coolers and their lifetime demonstration.
- In the second half of the 1990s, the developments for Herschel/Planck on Joule-Thomson and subKelvin coolers began and the first studies on European space pulse tube cold fingers were initiated.
- At the beginning of the 2000s, the development of European pulse tube coolers began, with the Medium Pulse Tube Cooler followed by the Large Pulse Tube Cooler. On the science front, major missions that did materialize (XEUUS that became later on IXO then Athena) or not (Darwin) were driving the innovation (50mK cooler, Helium JT Sorption Cooler).

After those years of development, the sector of Space Cryogenics in Europe reached a critical turning point at the end of the first decade of the 2000s:

- The technology of long lifetime space cryocoolers has been extensively flight proven and diversified with the two options – Stirling and pulse tube – being available in Europe.
- A European spacecraft having temperature stage requirements in the whole temperature range from room temperature to subKelvin has been successfully designed, tested and operated in orbit.

Now that those fundamental challenges have been addressed, the following aspects are driving the cryogenics developments at the European Space Agency:

1. To propose a complete portfolio of long lifetime active coolers catering to the needs of all classes of missions (small, medium, large) in all the relevant temperature ranges (40 to 150K).
2. To identify technologies that can answer new types of challenging requirements (e.g. Vibration Free Cooling).

3. To look for optimized cryogenic architecture using the already developed cryocoolers by proposing advanced integration solutions (e.g. multiple-stages, cryogenic heat switches).
4. Specifically for science, to close the gaps of a full active cryochain down to 50mK.
5. Finally, to promote innovation by revisiting technologies which began their developments decades ago or opening entirely new domains of developments.

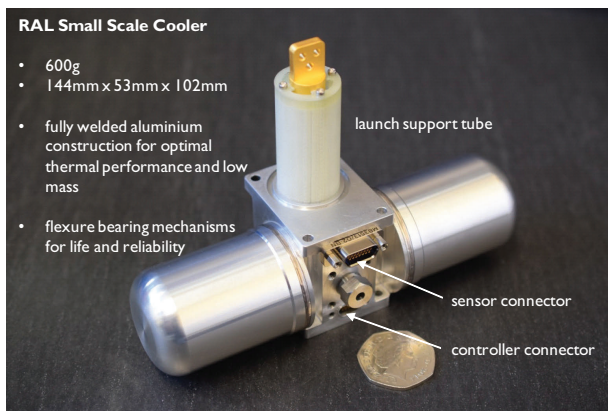
### Objective 1: To expand the portfolio of 40-150K coolers

A recurrent and sustained need for space cryogenics comes from Earth Observation missions that require cooling for the Thermal Infrared (50-90K) or Short Wave Infrared (~120-150K) detectors. In addition to the target temperature, the missions are now more and more diverse in terms of class (small, medium, large) or architecture. It is strategic for Europe to propose – if possible – multiple active cooling solutions in all format.

- *TRP - Small Scale Cooler (RAL - GB)*: In order to answer the need of smaller operational missions that require classical space lifetime and reliability with a more compact form factor, a prototype of 620g linear Stirling Cooler (Fig. 2) providing 0.5W at 77K (22W input) has been designed, manufactured and tested (TRL 4).
- *EOPP – High Power Stirling Cooler (Airbus DS – GB)*: To capitalize on the large heritage of the BAe/ADS 50-80K coolers, a larger version that could answer the needs of Meteosat Third Generation (2W at 50K) was prototyped (TRL 4).
- *GSTP – Low Vibration Stirling Cryocooler Unit Engineering Model (TAS UK/RAL/Honeywell Hymatic - GB)*: A new consortium has been put together to propose a new range of Stirling cooler products based on the experience of RAL (Cold Finger), Honeywell Hymatic (Compressor) and TAS UK (Electronics). The first product (planned to reach TRL 6 by mid 2019) is a 3Wat 50K Stirling cooler using the Honeywell compressor developed for HEC.
- *Proposal - Low Noise Miniaturized very high frequency Pulse Tube cooler (TBD)*: This proposal for development aims to develop another compact cooler (~750g) geared towards SWIR applications.
- *Proposal – Microcooler for Miniaturized Experiments (TBD)*: Unlike the other developments, this item will cover the needs of interplanetary experiments where the lifetime needs to be moderate, but where the volume and power consumptions are the driving parameters. The typical solution would be rotary stirling cooler with a guaranteed lifetime.

### Objective 2: To develop cryocoolers for new types of challenging requirements

Cooling power, cold tip temperature or technical budgets (mass, power) are the traditional drivers for cryocooler development. Nevertheless, missions constantly push the boundary of technology



**Figure 2.** The development of the RAL Small Scale Cooler illustrates the effort of ESA to expand the cooling solutions to all classes of satellite.

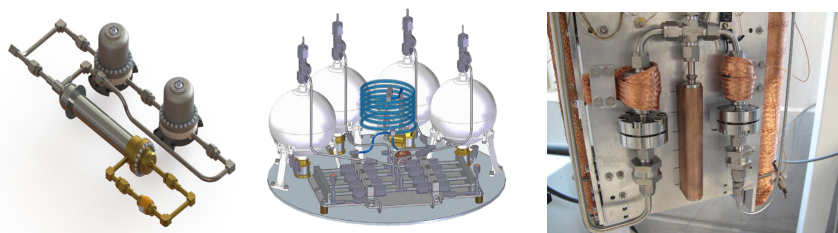
and new requirements end up driving the thermo-mechanical design or even the feasibility of an instrument. The typical example is the exported micro vibrations: the force exported by the current generation of cryocoolers are in the order of tenths of a Newton thanks to cunning compensation algorithms and careful manufacturing of the mechanisms. This extremely low level of micro vibrations is not sufficient for missions. This leads to sophisticated accommodation solutions, which are add mass and complexity to the cryogenic subsystem.

- *TRP – Development of a 40-80K Vibration Free Cooler (Absolut Sytem - FR)*: In order to cope with missions that have more and more stringent pointing requirements, Absolut Sytem is developing a ‘Vibration Free’ (at low frequency) cooler based on the Reverse Turbo Brayton Cycle (Fig. 3). The breadboard, which will provide >1.1W at 40K (180W input) will be tested by the end of 2018 (objective TRL 5).
- *TRP – Development of a 40-80K Vibration Free Cooler (Active Space-PT)*: In parallel to the activity previously mentioned, another SME proposed to investigate the possibility to provide vibration free cooling at ~77K using a Sorption based Nitrogen Joule Thomson cooler (Fig. 3). The predicted performance of this cooler is 1.5W at 80K and will be tested by Q4 2018 (objective TRL 5).
- *CTP – Hydrogen Sorption Cooler (University of Twente – NL)*: Motivated by the Darwin science mission that needed totally vibration free 4K cooling, the University of Twente developed and tested to TRL5 an H<sub>2</sub> Sorption cooler able to provide 35mW at 14.5K (Figure 3).
- *Proposal – Cryocoolers operational at Cryogenic temperatures (TBD)*: In some applications, passive cooling to cryogenic temperature is feasible but active cryocooling is necessary to reach the ultimate temperature required by the detector. It is in theory more efficient thermodynamically to use bithermal machines at the lowest temperature and can potentially simplify architectures (no need of having a warm enclosure in a cold payload). The proposal is to develop a cryocooler that can operate at temperatures lower than 77K.

### Objective 3: To propose solutions for advanced cryogenic architectures

In order to satisfy potential short/medium term increase in cooling power demands without jeopardizing the recent qualification efforts on cryocoolers, one straightforward solution is to optimize the thermal architecture of cryostats. Some conceptual solutions are discarded early on in projects because technological bricks are missing, or their integration is judged too risky.

- *TRP – 2-Stage Cooler for 30-50K Detector Cooling (TCBV - NL)*: Building on the recent development of the LPTC, this project not only brought a double stage pulse tube cryocooler (1.49W@42K and 3.03W@105K for 160W input power) to TRL6 but also demonstrated with a flight like 2-Stage Cryostat designed by Absolut System that such architecture can lead to a decrease of 10K of the detector compared to a standard 1-stage design.
- *TRP – Cryogenic Heat Switch in the 30 to 80K temperature range (LIDAX - ES)*: The advantage of being able to disconnect the OFF cryocooler to an application has been identified since the beginning of space cryogenics. This simple idea is difficult to apply in practice,



**Figure 3.** Three developments tackling the challenge of Vibration Free Cooling: the Reverse Turbo Brayton developed by Absolut System (left), a Nitrogen Sorption Cooler from Active Space (center) and the H<sub>2</sub> Sorption Cooler manufactured and tested by the University of Twente (right).



the item having challenging and conflicting requirements. The Spanish company LIDAX is developing a passive differential CTE-based mechanism that can answer the need of typical Earth Observation Cryostat architecture. The addition of this element shall decrease by more than 15% the consumption of a cryocooler with respect to the architecture without a heat switch. The TRL 5 shall be reached Q2 2019.

- *TRP – Breadboarding of a Cryogenic Gas Loop Heat Switch for Earth Observation Missions (ALAT – FR)*: An interesting take on the Cryoswitch idea is to use the gas of the cryocooler itself as the thermal link between the application and the cold tip. Air Liquide Advance Technology will investigate this solution with the objective of reaching TRL4 in 2019.
- *ITI – Energy Storage Unit (Active Space – PT)*: When the mission imposes a varying thermal environment on the passive or active cryocooling system (e.g. slew of agile satellite) or when there is an operational necessity to switch the cooler off and maintain a cold temperature, having an Energy Storage Unit can be advantageous. Active Space in collaboration with the University Nova de Lisboa designed such item and pushed it to TRL3 [2].

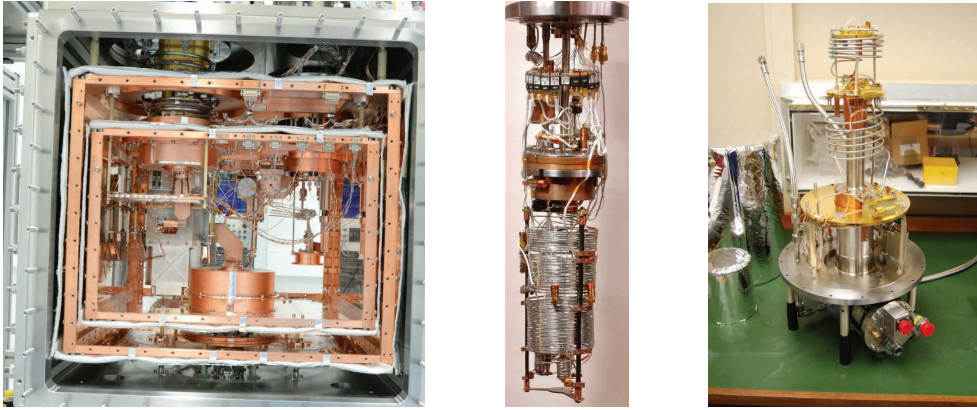
#### Objective 4: To answer the need of upcoming Science missions

Science missions have always been one of the incentives for developments in cryogenics. Unlike the Earth Observation domain where it is possible to find trends that can guide future activities, Science needs are directly linked to the selected mission. Two ESA missions in the Science domain will need cryogenics in the medium term: Athena and Ariel (see Figure 4).

- *CTP – 15K Pulse Tube Cooler Engineering Model (ALAT - FR)*: In order to satisfy the shield cooling and Joule-Thomson precooling function of the X-IFU instrument of Athena, Air Liquide Advance Technology is developing a pulse tube (intercepted with active phase shifting) able to provide ~300mW at 15K for 300W input power. The whole cryocooling system (including Electronics) will be manufactured and tested; the mechanism will reach TRL6 by end of 2019.
- *CTP – 2K Cooler Engineering Model (RAL – GB)*: The penultimate stage of the X-IFU cooling chain needs to be around 2K. Capitalizing on the Planck 4K Cooler experience, RAL is developing a <sup>3</sup>He Joule Thomson cooler (30mW@2K) that shall reach TR6 by the end of 2019 with an associated electronic that will reach TRL4.
- *CTP – Detector Cooling System (CNES/CEA – FR)*: The purpose of this activity is to demonstrate the capability in Europe to cool a focal plane down to 50mK using a chain of active cooler from room temperature. This project led by CNES will build a Cryostat representative to what is planned for the X-IFU instrument and perform an end to end test using coolers (15K, 2K and SubKelvin) coming from other ESA developments.
- *ITIs – Closed Cycle Dilution Demonstrator and Sorption Based Circulator (Institut Neel – FR and University of Twente – NL)*: The back-up solution for the subKelvin stage of X-IFU is an adaptation of the Planck dilution into a closed-cycle system. This promising technology has reached TRL4 in 2 separated ITIs: the first one was devoted to the Closed Cycle Dilution itself, and the second one was devoted to the <sup>3</sup>He Sorption circulator (developed by University of Twente).
- *CTP – Neon Joule-Thomson Cooler for Ariel (RAL – GB)*: The detectors of the Spectrometer of the Ariel mission have to be cooled at around 40K. RAL is adapting its Planck/2K JT technology to accommodate this need using Neon as working fluid. The full system shall reach TRL5 by end of 2019.
- *Proposal – V-Grooves compatible High efficiency MLI (TBD)*: Multi-Layer Insulation is avoided in V-Grooves assemblies because the shape and the specularity of the external layer impairs the V-Groove effect. One could think of having the best of both world by developing a special MLI that can avoid those issues.

#### Objective 5: To constantly foster innovation

In addition to answering mission needs coming up in the near or farther future, the role of the agency is also to stimulate innovation. It is crucial to give industry the opportunity to work on more fundamentals developments.



**Figure 4.** A large development effort is dedicated to the preparation of Athena. The CRY1 of the DCS (left – courtesy CEA) includes a PT15K and the Hybrid ADR. The CCDR from Institut Néel (center) is the back-up for the Sub-K stage. The cold plumbing of the 2K cooler can be seen the right (RAL)

- *TRP – New Generation Compressor (TCBV – NL):* Building on the lessons learned coming from the recent developments, the latest improvement in material and manufacturing techniques, TCBV will prototype a new generation of compressor that shall be better than the available compressors in terms of mass, efficiency and micro vibrations. The design shall be scalable to all classes of compressor, but the demonstrator built in this project will target ~60W input power class cooler (e.g. to provide cooling at 120K).
- *TRP – New Generation Cold Finger (TBD):* Similarly to the previous TRP, this project aims at revisiting the design of cold fingers considering all the latest advances.
- *NPIs and ITIs – Space Optical Cryocooler developments (Lumium/University of Pisa – NL/IT):* Optical cryocooling for space is the typical example of technology that is potentially ground breaking, but requires fundamental developments to meticulously alleviate the possible show-stoppers and improve its Technology Readiness Level. Two PhDs have been subsidized to do development work on the topic of the cooling medium crystal and an ITI examined the first system level challenges to develop an optical cooler for Space.
- *NPIs/ITIs – Microcryogenic Coolers and Cold Tips (University of Twente/Kryoz/Dutch Space - NL):* The combination of Sorption Compressors and Micro JT cold tips has been investigated through multiple projects. This type of cooler could answer the very specific need of vibration free on-chip cooling or distributed on-chip cooling. TRL5-6 was achieved on the micro-cold tip. [3]

## RECENT AND UPCOMING ESA MISSIONS INVOLVING CRYOGENICS

The Space Cryogenics landscape is primarily shaped by missions. In this section, we will cover some of the missions that are currently relevant to the cryogenic sector in Europe.

### Sentinel 3 – the latest launched ESA spacecraft with Active Cryocooling

Sentinel 3 is a Copernicus fleet of satellites whose objective is to measure sea surface topography, sea and land surface temperature, and ocean and land surface color. The Sea and Land Surface Temperature instrument (SLSTR) requires detectors cooled to 85K. This requirement is met thanks to a Cryocooler System (CCS) composed of two head-to-head 50-80K Stirling Coolers provided by Airbus DS that cool down an Infrared Bench accommodated inside a cryostat thermally insulated from the rest of the payload. In terms of performance, an active vibration control loop permits to limit the exported below 300mN and the Cryocooler System was expected to cool down the focal plane below 89K end of life (heatload 2W) with a consumption lower than 75W [4].

Sentinel 3a was launched the 16 of February 2016 and the satellite has been operating flawlessly since that date. In terms of in-orbit performance, after two years the cryogenic subsystem performs as expected:

- After 2 years in Orbit, the detectors are maintained at around 86K.
- The heatload seems to be very close to the 2W characterized on-ground.
- Contamination is well under control thanks to the design of the Cryostat (2 to 1 decontamination sequences per year, as anticipated).

Sentinel 3b was launched the 25th of April 2018, and the first cool-down of the focal plane points to the same behavior of the Cryocooler System as Sentinel 3-a.

### **Sentinel 5-p – the latest launched ESA spacecraft with Passive Cryocooling**

The instrument TROPOMI on Sentinel 5-P features a three stage radiant cooler. This cooler offers room temperature cooling for the instrument Front End Electronics and UVN optical bench, cooling down to 205K for the UVN detectors and SWIR optical bench, and cooling down to 140K for the SWIR detector [5].

Sentinel 5-P was launched the 13th of October 2017, and after the critical phase of the opening of the cooler door in November 2017, the Radiant cooler permitted all the target temperatures to be attained after one week of cool down.

One half year after the launch, the outstanding points concerning the Cryogenic and Thermal control subsystem are the following:

- Temperature levels and stability requirements are met.
- There is sufficient residual margin on all actively thermally controlled channels to ensure temperature stability of complete instrument over complete lifetime and beyond.

### **Meteosat Third Generation – the first ESA satellite that will embark Pulse Tube Coolers**

Meteosat Third Generation is a twin meteorological satellite concept based on 3-axis stabilized geostationary platforms. The MTG fleet will be composed of six satellites:

- Four imaging Satellites (MTG-I) embarking the Flexible Combined Imager (FCI) as main instrument [6].
- Two sounder Satellites (MTG-S) embarking the InfraRed Sounder (IRS) as main instrument.

Both FCI and IRS instruments require detectors to be cooled at around 55K. In 2012, the Large Pulse Tube Cooler of Air Liquide has been selected to fulfil this need. The other challenges related to cryogenics are the following:

- The number of satellites in addition to the long storage and lifetime requirements (respectively 10 and 8.5 years) of this operational missions lead to very stringent PA/QA requirements.
- Particularly on the Interferometer instrument, the micro vibrations requirements are extremely challenging. Few hundredths of Newton are expected at the base of the cryocooler support system.
- Considering the low temperature of the detectors, the size of the focal planes and the cold redundancy concept retained, the necessary cooling performances are close to the limit of the capability of the Large Pulse Tube Cooler.

The first MTG-I satellite is planned to be launched at the end of 2021. The Structural Thermal Model (STM) of the FCI instrument is currently undergoing Thermal Balance Test at ESTEC. Amongst other objectives, this test will permit to correlate the thermal behavior of the Cryostat and to verify that the thermal control system of the cryocoolers permits to guarantee the specified interface temperature of the cold finger (around 0°C) during the whole mission. A first test at Cryostat level showed encouraging results with respect to the performance of the cryostat and the LPTC.

MTG-S1 is set to be launched at the beginning of 2023. The cold part of the IRS instrument is on the verge of being vacuum tested (at engineering model level) to correlate the thermal model and verify the cryogenic margin of the system.



### ATHENA – The first ESA led mission to feature an active Cryochain down to 50mK

ATHENA is a Class L (Large) ESA Science Mission that will study the hot universe thanks to its two instruments: the Wide Field Imager (WFI) and X-Ray Integral Field Unit (X-IFU) (see Figure 5).

One of the many challenges of the mission is the thermal control of the focal plane of the X-IFU instrument: in order to reach the ground breaking performances that characterize this X-Ray observatory, the X-IFU uses a detection array of 3840 Transition Edge Sensors (TES) that need to be cooled at 50mK.

The technical solution pursued by CNES who is the prime of the X-IFU instrument, is a Russian doll cryostat architecture actively cooled by a cascade of eleven coolers separated in 6 temperature stages. The current baseline features:

- Five 15K Pulse Tube Coolers provided by ALAT to actively cool two thermal shields and precool the Joule-Thomson Coolers.
- Two 4K <sup>4</sup>He Joule Thomson Coolers provided by JAXA based on the Astro-H Heritage.
- Two 2K <sup>3</sup>He Joule Thomson Coolers provided by RAL or JAXA,
- An Hybrid Adiabatic Demagnetization Refrigerator composed of two stages: 300mK and 50mK. The 300mK stage is provided by a <sup>3</sup>He Sorption cooler based on Herschel heritage. The 50mK stage is an ADR that permits to reach the 0.5microW at 50mK requirement.

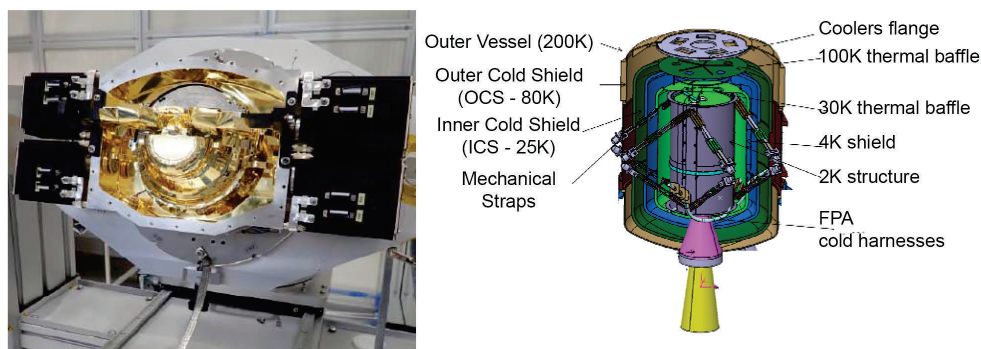
Before the launch planned for 2028, the whole European and international space cryogenic community will be mobilized to make this milestone mission a success.

### CONCLUSION AND FUTURE TRENDS IN SPACE CRYOGENICS

After the first revolution that represented the flight demonstration of long lifetime space cryo-coolers at the beginning of the 90s, space cryogenics development in Europe has embraced new challenges coming from the democratization of the technology.

The number of missions using or intending to use cryogenics in the near future has never been so high, which explains why the research and development in the sector needs to be dynamic. From the ESA perspective, the medium term will be covered by completing the portfolio of Stirling/pulse tube coolers.

The next revolution in space cryogenics for traditional missions might come through the successful development of Reverse Turbo Brayton cooler compatible with Earth Observation needs. On the paper, this type of cooler possesses advantages that open up a range of new possibilities: vibration free cooling below 1000Hz, decent thermodynamic performances in the whole temperature range, potential for distributed and remote cooling, low parasitics for a OFF cooler. If the manufacturing hurdles which characterize this class of cooler (small dimensions, delicate balancing, sophisticated recuperator to meet the high efficiency etc.) are overcome in the current TRP, the family can be expanded to high capacity coolers (e.g. for Zero Boil-off) and for temperatures below 30K.



**Figure 5.** Two very different cryostatss: on the left, we see Engineering Model of the FCI Cryostat (courtesy TAS-F), on the right, one of the concept for the X-IFU cryostat (courtesy of CNES).

Beyond the traditional space missions, a new type of market is appearing at the horizon. The so-called 'NewSpace' or 'Space 4.0' is the concept that small satellite constellations will be used to compliment the traditional institutional operational missions. In that optic, it is likely that cheap, but less lifetime demanding, miniaturized cryocooling options will be necessary in the future. One mission of the agency in the field of cryogenics development will be to accompany our industrial partners to define the product assurance and verification approach necessary to get 'flight-worthy' coolers without impairing the low price point.

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