

# Overview of European Space Cryogenic Missions and Developments in 2020 (and Beyond)

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## ABSTRACT

After almost 30 years of technological developments spearheaded by innovative institutes and companies and supported by national and international agencies, space cryogenics is now a mature engineering domain, embraced by instruments and payload designers. This state of affair leads to a multiplication of missions in various stages of development that require cryocooling solutions in various forms and sizes and with a vast array of specificities. It is an exciting time to be involved in space cryogenics.

After a rapid rundown of the major historical European space cryogenic missions, this paper describes the cryogenic aspects of European missions currently in-orbit, in development, or in preparation. The driving requirements will be spelled out as well as the associated baseline and alternative solutions.

Finally, the paper lays out the current landscape of space cryogenic developments in Europe.

## INTRODUCTION

Created in 1975, the European Space Agency has been involved since its beginnings in Cryogenic missions. InfraRed detection being a pressing need for Earth Observation, the spearheading missions originate from this domain. Picking up from CNES, then ESRO developments, ESA launched in 1977 the first Meteosat satellite. The spacecraft not only revolutionized weather forecasting for Europe, but was also the first incursion of Europe in Space Cryogenics: the MVIRI instrument used HgCdTe detectors cooled at 90K by a passive system. An important page of European, but also global Space Cryogenics, was turned in 1991 with the launch of ISAMS onboard UARS (NASA) and ATSR onboard ERS-1 (ESA) (Fig. 1). The University of Oxford (GB) and RAL (GB) designed a compact 80K split Stirling Cooler based on the clearance seal/diaphragm spring solution which virtually removed all rubbing surfaces from the mechanism: for the first time, the long lifetime Space Cryogenics dream became a reality. On the Scientific front, as described in C. Jewell paper [1], most of the early Research and Development effort for Cryogenics of the European Space Agency was devoted to the development of the Superfluid Helium Cooling for the Infrared Space Observatory which was launched in 1995.

The end of the 1990's and early 2000's saw in parallel the democratization of the long-life Stirling Oxford-Style Cooler for Space (more than 20 flight units delivered worldwide, Gibson [2]) and the multiplication of developments in the promising field of Pulse Tube Cooling. This period culminated in 2009 by the dual launch of Herschel and Planck. Those two ESA satellites symbolize the turning point that the technical field was going through: 1) Herschel was the last large European dewar-based cryogenic mission to date, while 2) Planck was the first in-orbit demonstration of a complex cryochain that combines passive cooling and closed-cycle cryocoolers to provide cooling from room temperature to <1 K.



**Figure 1.** ERS-1/ERS-2 (left) and ISO (right) illustrate the early steps of Europe in Space Cryogenics in the domains of Earth Observation and Science.

**Table 1.** List of European Cryogenic Missions launched since 2009. In green are the missions that will be tackled in the paper.

Acronym	Launch	Instrument	Agencies	Orbit	Cryo System and Requirement
Meteosat-10	05/07/2012	SEVIRI	EUMETSAT ESA	GEO	Passive cooling @ 85K
Metop-B	17/09/2012	IASI	EUMETSAT ESA	SunSync	Passive cooling @ 90K
GAIA	19/12/2013	FPA	ESA	L2	Passive Cooling @ 173K
Sentinel-2A	23/06/2015	MSI	ESA EC	SunSync	Passive Cooling @ 190K
Meteosat-11	15/07/2015	SEVIRI	EUMETSAT ESA	GEO	Passive cooling @ 85K
Sentinel-3A	16/02/2016	SLSTR	ESA EC EUMETSAT	SunSync	Active Cooling (ADS 50-80K cooler) @ 80K
EXM-TGO	14/03/2016	NOMAD	ESA	Mars Orbit	Active Cooling (RICOR K508) @ 88K
Meteosat-8 (IODC)	15/09/2016	SEVIRI	EUMETSAT ESA	GEO	Passive cooling @ 85K
Sentinel-2B	07/03/2017	MSI	ESA EC	SunSync	Passive Cooling @ 190K
Sentinel-5P	13/10/2017	TROPOMI	ESA NSO	SunSync	Passive Cooling @ 140K
Sentinel-3B	25/04/2018	SLSTR	ESA EC EUMETSAT	SunSync	Active Cooling (ADS 50-80K cooler) @ 80K
Metop-C	07/11/2018	IASI	EUMETSAT ESA	SunSync	Passive cooling @ 90K
CSO	19/12/2018	TBD	CNES	LEO	TBD
PRISMA	22/03/2019	Hyper-Spectral Camera	ASI	SunSync	Passive Cooling @ 185K

Following this ‘Golden Age’, what were the European Space Cryogenic missions that flew in the post 2009 period? What do the missions in development and in preparation look like?

## EUROPEAN CRYOGENIC IN-ORBIT MISSION PERFORMANCE

### Cryogenic Missions Launched since 2009

Table 1 lists all the European space missions with significant Cryogenic elements that have been launched since 2009.

The following points can be noted:

- With 14 cryogenics spacecraft launched, the last 10 years totals the same number of cryogenic missions than in the period 1999 – 2009.
- However, since 2009 only four actively cooled missions (cumulating seven flight coolers) were launched, whereas in the previous period, seven missions required mechanical coolers for a total of 16 flight mechanisms.
- In both periods, the bulk of the missions comes from the Earth Observation domain.

The significant discrepancy in the number of actively cooled missions between the two periods can be explained by two phenomena:

- 1) The 2000-2010 period corresponds to the end of major development cycles (Envisat, Herschel/Planck, Metop, MSG). Due to the time constants in the sector, follow-up missions (which also would require active cryocooling) were not launched in the decade that follows, but will be launched in the 2020's.
- 2) Technologically, this period corresponds also to the end of a cycle: from 2000 to 2010 the effort on Stirling Coolers was focused on industrialization, lifetime confirmation, and supplying the demand. Pulse Tube Cooler technology was maturing, but not yet qualified. The portfolio of ‘off-the shelf’ coolers was limited and hindered by the industrial reorganization that Astrium UK underwent in 1999 (move from Bristol to Stevenage).

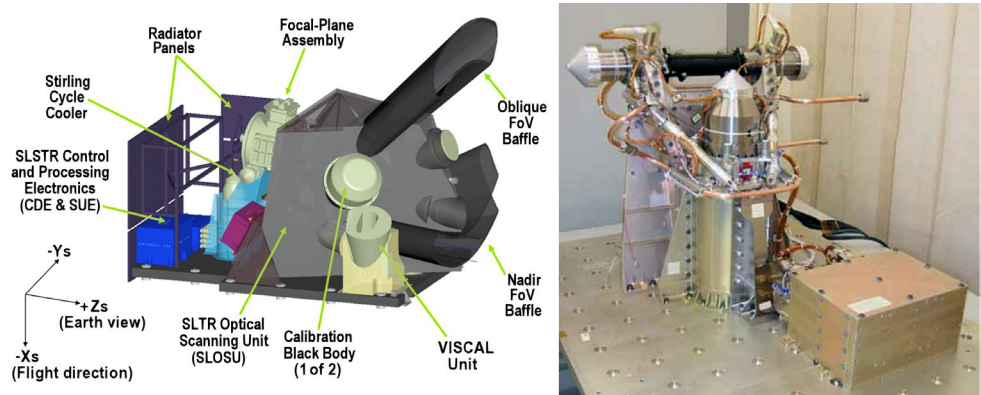
To illustrate these points, the following two in-orbit missions are discussed in more detail: 1) Sentinel 3, the latest launched ESA spacecraft with Active Cryocooling, and 2) Sentinel 5p, the latest (nonrecurrent) launched ESA spacecraft with Passive Cryocooling.

**In-Orbit Performance of Sentinel 3**

SENTINEL-3 is a European Earth Observation satellite mission developed by ESA as part of the European Commission’s Copernicus program. The main objective of the SENTINEL-3 mission is to measure sea surface topography, sea and land surface temperature, and ocean and land surface color with high accuracy and reliability to support ocean forecasting systems, environmental monitoring and climate monitoring. The mission definition is driven by the need for continuity in provision of ERS, ENVISAT and SPOT vegetation data, with improvements in instrument performance and coverage.

The four main instruments are Ocean and Land Colour Instrument (OLCI), SAR Radar Altimeter (SRAL), Microwave Radiometer (MWR) and Sea and Land Surface Temperature instrument (SLSTR). As the only Cryogenic instrument of the suite, SLSTR from Leonardo (IT) will be the subject of the next paragraphs.

The SLSTR instrument is a high accuracy radiometer, which represents the successor of the (A)ATSR family. It is comprised of two elements: the SLSTR Optical Scanning Unit (SLOSU) and the Control&Processor Electronics (CPE). The SLOSU (Fig. 2) includes the Detection Assembly (DA), which contains the Focal Plane Assembly (FPA) and the Cryocooler System (CCS), Coppo [3].



**Figure 2.** The schematic of the SLOSU (left – courtesy Leonardo) shows the Cryocooler System location (right – courtesy Airbus DS ltd) used to achieve the ~85 K detector temperature.

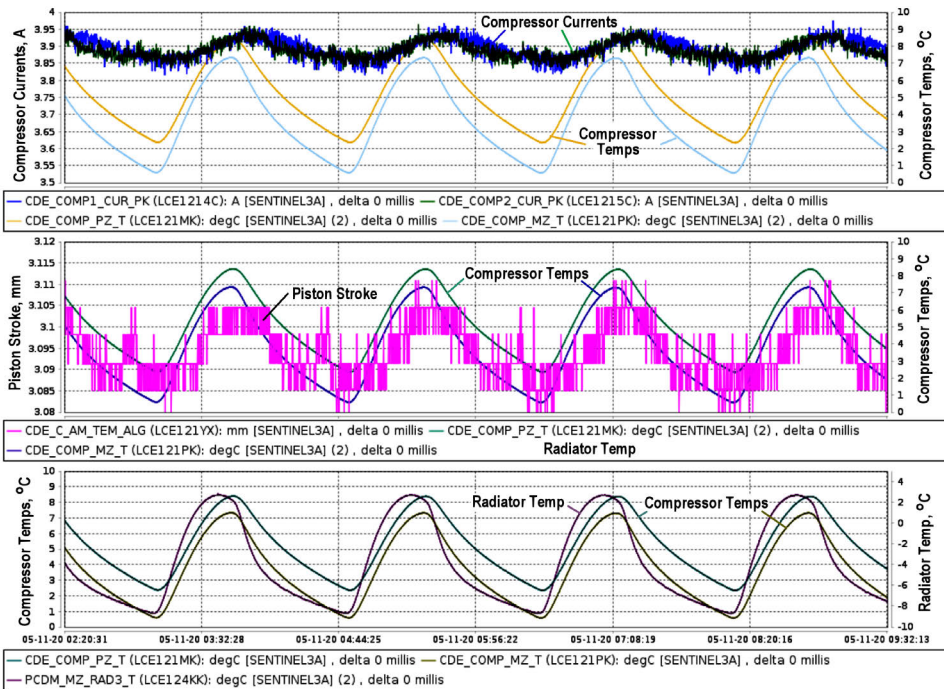
Within the FPA, the IR and the SWIR channels are accommodated onto a cryogenic optical bench cooled at 85K by a pair of head-to-head 50-80K Stirling Coolers from Airbus DS Ltd (GB). The main design features related to cryogenics are the following:

- The two 50-80K Coolers are mounted onto a Cryocooler Support Structure that provides a suitable thermal and mechanical environment for the System as well as a cunning accommodation of the moving parts to passively mitigate exported vibrations.
- The Cooler Drive Electronics from CRISA (ES) possesses the following functions: active launch lock, position control loop for compressor and displacer, cold tip temperature control and active microvibration cancellation.
- The Cold Tips of the Stirling Coolers are connected to the FPA InfraRed Optical Bench via two High Purity Aluminum Thermal Link Assemblies.
- The IR OB is supported by GFRP struts and enclosed in a Low Emissivity Can, which in flight is connected to deep space via the so-called venting snorkel. On ground, the entire FPA can be evacuated for ground testing purposes.

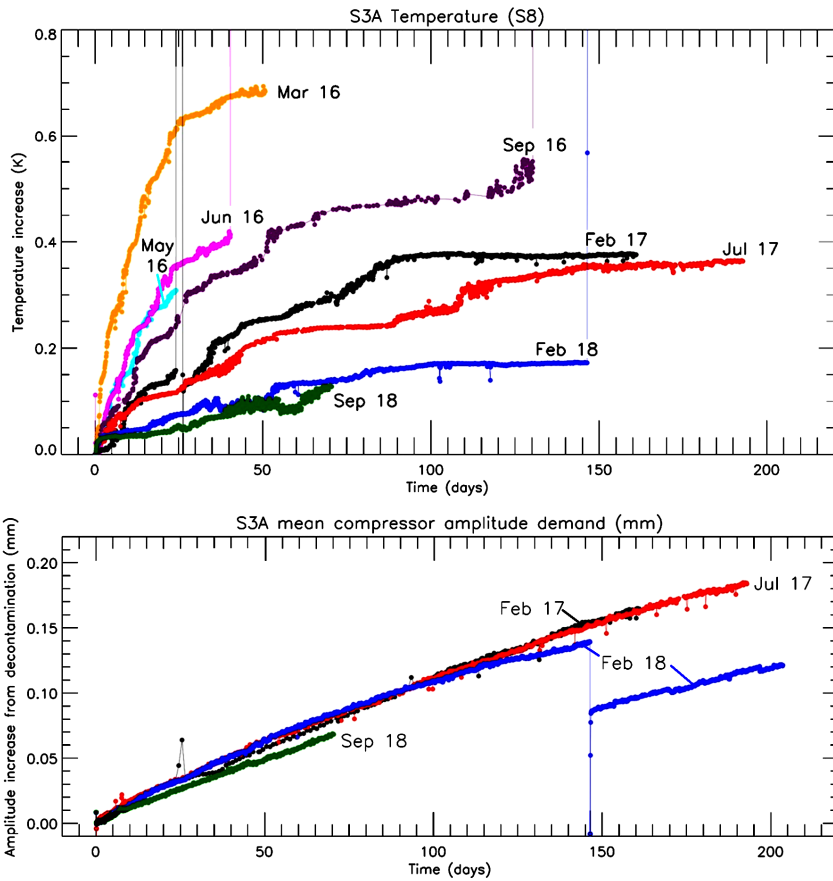
Launched the 16<sup>th</sup> of February 2016, SLSTR on Sentinel 3A has been performing exceptionally well [4][5][6]. There have been no major anomalies, and availability gaps are due to ground station issues, maneuvers, calibration observations or decontamination. It is interesting to note that due to early CDE blips, which caused impromptu transitions to STANDBY mode, it has been decided to disable the vibration control loop of the cooler system, without impact on the performance of the instrument.

The Cryocooling System performs nominally. In beginning of life conditions, the thermal model correlation has been verified with in-orbit data. When applying the thermal environment reported in telemetry to the FPA Thermal Model, the expected heat load on the cold tip at ~80K was around 1.84W. This was compared to the heat load measured in-flight derived from the compressor stroke and only a small discrepancy of 4% (within the uncertainties of the exercise) was obtained (~1.77W at 80K was estimated in flight).

The short-term behavior of the cryocooling system as described in Figure 3 is typical. On the bottom panel we see that the radiator picks up a little bit of sun before the satellite enters eclipse, thus its temperature varies sensibly during the orbit (from -8°C to 2°C). This 10°C temperature excursion is damped to 5°C at



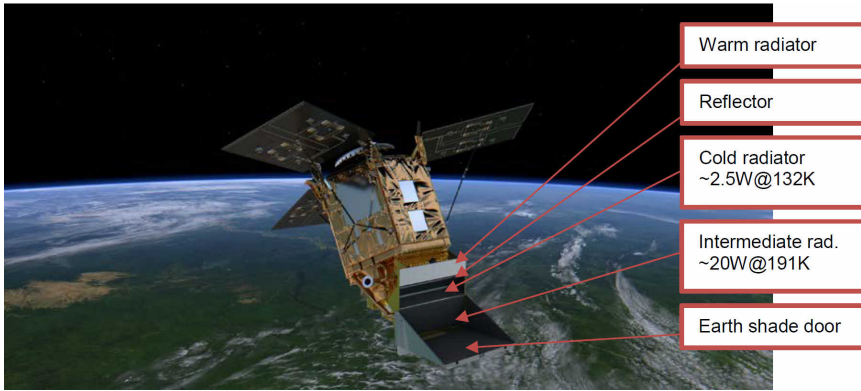
**Figure 3.** Examples of in-orbit data of daily variation of compressor currents, compressor temperatures, piston stroke, and compressor radiator temperature.



**Figure 4.** The curves coming from [5] present the effect of contamination on the cryo-system: (Top) Increase of the detector temperature compared to the initial temperature between each decontamination sequence. (Bottom) Increase in compressor stroke between each decontamination sequence.

the compressors/displacers level. The variation of interface temperature of the cooler affects slightly its efficiency, and — as the cold tip temperature is actively controlled in closed loop on the piston stroke to maintain a target temperature — this variation of efficiency is reflected on the piston stroke and currents: when the coolers get hotter, the stroke increases.

The long-term behavior, as shown on the top of Figure 4, needs to be described by a dedicated study that will include model correlation. However, the behavior shown can be explained by contamination. The accumulation of contaminants onto the Optical Bench would increase its emissivity, which translates into an increase of heat load on the system. This higher heat load affects the gradient between the OB and the Cold Tip and — due to the fact that the reference point for the active control loop of the coolers is the cold tip temperature and not the OB or detector — leads to a small increase of the detector temperature. At each decontamination sequence, this increase of emissivity is cured and the temperature of the detector decreases. The rate of increase of this temperature from one decontamination to another slows down, which is typical of contamination effects (outgassing following an exponential curve). The bottom of Figure 4 can be explained by the effect of contamination on the stroke of the pistons. Because the data presented begin one year after launch, the initial outgassing phase is passed; this explains why the stroke degradation slope does not vary much from one sequence to the other.



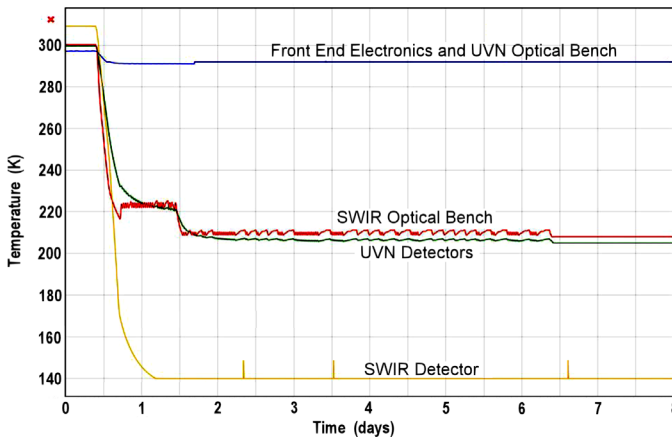
**Figure 5.** This artist view of Sentinel-5P shows how the radiant cooler looks like after opening of the Earth shade door, which protects from contamination and limits heat losses during launch.

### In-Orbit Performances of Sentinel-5P

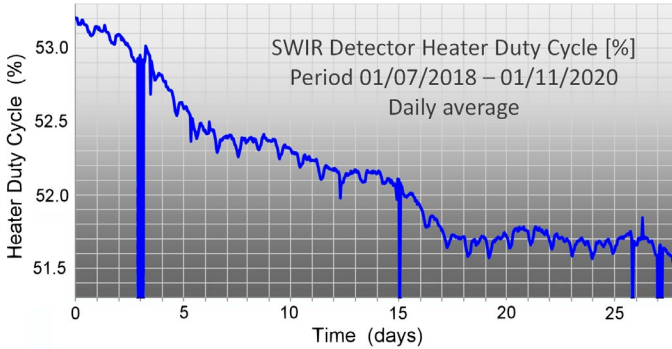
Sentinel-5 Precursor (shown in Fig 5) —the fruit of the collaboration between ESA, the European Union and the Netherlands Space Office —is the first Copernicus mission dedicated to monitoring the atmosphere. The sole instrument, TROPospheric MONitoring Instrument (TROPOMI), performs atmospheric measurements with high spatial resolution to be used for air quality and climate monitoring & forecasting. TROPOMI 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 205 K for the UVN detectors and SWIR optical bench, and cooling down to 140 K for the SWIR detector, Zevenbergen [7].

Sentinel 5-P was launched the 13<sup>th</sup> of October 2017. As shown on the top-left of Figure 6, following a 3-week decontamination period, the Earth Shade door opened on November 7, 2017. The coldest stage of the radiant cooler reached its target temperature in merely 16 hours. As it can be seen on the middle curves, the week of thermal commissioning was devoted to the fine-tuning of the active thermal control of the intermediate stage. The radiant cooler was pronounced commissioned on the 13<sup>th</sup> of November 2017 and has maintained outstanding performance to this date. In particular, the temperature stabilities obtained are excellent and well beyond the requirements (e.g. 10mK peak to peak is obtained on the SWIR detector for 80 mK required).

Another remarkable performance of TROPOMI's radiant cooler is its long-term behavior. As presented in Figure 7, the head room for active thermal controllability of the cold radiator decreased by less than 2% in 2.5 years. This should guarantee the required temperature and stability far beyond the 7-year mission.



**Figure 6.** Temperature of the radiant cooler from launch until the end of the thermal commissioning. Zero days is midnight, November 7, 2017.



**Figure 7.** Long-term evolution of the SWIR detector Duty Cycle (courtesy Airbus DS NL)

**EUROPEAN CRYOGENIC MISSIONS IN DEVELOPMENT**

Even though it is clear that new types of uses are appearing on the horizon (e.g. In Situ Resource Utilization, RBO/ZBO), most of space cryogenics applications concern either Earth Observation or Scientific focal plane cooling. The paper next examines the European missions currently on the books in these two domains.

**Earth Observation Cryogenic Missions in Development in Europe**

As alluded to in the first part of this paper, we can see in Table 2 that the 2020’s decade will see the launch of the newest generation of two important families of European Earth Observation Satellites: Meteosat Third Generation, and MetOp-SG. Those two sets of spacecraft will require 24 flight models of cryocoolers. Along with these two heavyweights, Copernicus Expansion — which began its implementation in 2018 — brings the total to three missions that require cryogenics, including one that needs mechanical coolers.

**Table 2.** List of European Cryogenic Earth Observation Missions in study or development. In green are the three missions that will be addressed in the paper.

Mission	Passive Cooling	Cryocoolers	Launch Date	Remark
MTG	Regular temperature	Need: 2.8W@50K (LPTC)	Q4 2022(I) Q4 2023(S)	6 Satellites with 2FM each.
MicroCarb	Radiator protected by a parabolic baffle to reach 150K	No	2021	CNES Mission
MetOp-SG A	Regular Temperature	METimege: ~3W@55K (HEC) IASI-NG: ~3.1W@75K (LPTC)	2023	3 Satellites ME Timege CFI from DLR IASI-NG CFI from CNES
Shalom	2 Stage Radiator 140-180K	No	2024	Italian-Israeli mission
Trishna	Regular temperature	~2W at 60K (2xLPT6510)	2025	CNES-ISRO mission
CO2M	Baffled 2-stage radiator to reach 150K on the detector	No	2025	Part of High Priority Copernicus Missions
LSTM	200K for the SWIR	Need ~3W at 65K (LPTC)	2027	Part of High Priority Copernicus Missions
TRUTHS	Passive Cooling at 150K for HSI	Active cooling at 60K for CSAR	2028	ESA/UKSA Mission
CHIME	170K	No	2028	Part of High Priority Copernicus Missions
Polaris Hosted Arctic Imager	Regular temperature	~90K	TBD	Infrared observation of the poles via HEO
LOCUS	Regular temperature	~100K	TBD	Rejected Earth Explorer 10 proposal, can reappear. Needs a miniaturised Cryocooler
TANGO	Regular temperature	COTS with IDCA at 150K	2024 (if selected)	Part of the SCOUT initiative, 16U spacecraft.

Lastly, one can note that the promise of (very) small satellites requiring cryogenics seems to have finally come to fruition with missions like TANGO or LOCUS.

### Example of Cryogenic EO Mission in Development in Europe: MTG

Meteosat Third Generation is the next-generation of European operational geostationary meteorological satellite system undertaken in the frame of a cooperation agreement between ESA and EUMETSAT. It is composed of two types of satellites:

- 1) Four imaging Satellites (MTG-I) embarking two optical payloads (Flexible Combined Imager and Lightning Imager) and one communication payload (DCS&SAR). FCI and DCS&SAR are continuation of MSG mission.
- 2) Two sounder Satellites (MTG-S) embarking two sounding payloads: the InfraRed Sounder (IRS) and the Copernicus Sentinel 4 UVN.

The main features of the two types of Spacecraft are described hereafter:

- MTG-I, prime TAS-F (FR):
  - Total mass ~3.6t, FCI mass ~450kg.
  - Total power budget ~2.2kW, FCI power consumption ~500W.
  - 3-axis Stabilized GEO platform.
  - HgCdTe Detectors to be cooled at 58K
  - Lifetime requirement: 8.5 years.
  - First launch: Q4 2022.
- MTG-S, prime OHB (DE):
  - Total mass ~3.8t, IRS mass ~500kg.
  - Total power budget ~2.2kW, IRS power consumption ~800W.
  - 3-axis Stabilized GEO platform.
  - HgCdTe Detectors to be cooled at 55K
  - Lifetime requirement: 8.5 years.
  - First launch: Q4 2023

In the years 2004-2005, the Pre-phase A studies conducted within ESA based upon the high level user needs identified Cryogenics (~3W at 50K) as one of the technological drivers. That prompted the launch of two technological development activities: the Large Pulse Tube Cooler of ALAT (FR) and the High Power Stirling Cooler of Airbus DS ltd (GB). In 2012, the LPTC of ALAT was selected as the technical baseline to cool down the detectors of both FCI and IRS.

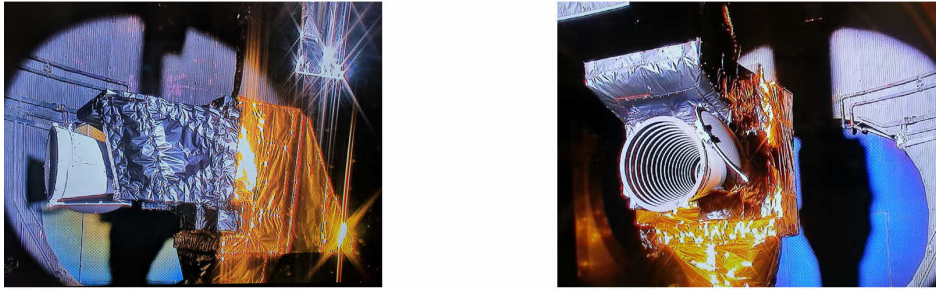
In addition to the Cryocooler System, for which you can find more details in the paper of T. Wiertz [8], the following building blocks are key elements of the cryogenic architecture (common for IRS and FCI):

- Both FPAs are accommodated into Cryostats coming from Frentech (CZ) covered with Physical Vapour Deposited Gold coating that guarantees an emissivity lower than 0.027.
- The cryocoolers in cold redundancy are connected to the detectors and cold optics via High purity aluminium Thermal Link Assemblies from Absolut System (FR).
- The Coolers are connected to radiator assemblies provided by Iberespacio (ES) in order to guarantee the required interface temperatures (0°C for FCI and -10°C for IRS).
- In order to mitigate the effect of the little exported microvibrations coming from the coolers, they are accommodated on sophisticated Cryocooler Structures that include Elastomeric Suspension Elements.

At the time of writing of this paper (January 2021), the status of the hardware is as follows:

- All the Cryocooler Units for both FCI and IRS have been manufactured and tested and exceed cryogenic commitments by a significant margin (between +6 and +10% more efficient than the EMs). The solar vacuum testing is illustrated in Figure 8. The microvibration performance is also excellent and consistent across all coolers thanks to the significant manufacturing efforts deployed by TCBV (NL).
- The PFM of the first FCI has been assembled and is being tested in order to be delivered to the satellite in 2021. The Detector Chain and Electronics Assembly has been characterized which confirms the excellent behavior of the PFM Cryocooler System.





**Figure 8.** (Left) The FCI STM solar vacuum testing in 2018 at ESTEC demonstrated the performance of the Cryogenic System. (Right) The STM of the IRS has been vacuum tested in August 2019. The cryogenic performance was demonstrated during the IA DEA EM test in 2018.

- The AIT of the PFM of the Detector Electronics Assembly and Interferometer Assembly (IA DEA) of IRS is ongoing. The EM testing held in 2018-2019 demonstrated the adequacy of the cryogenic design.

**Example of Cryogenic EO Mission in Development in Europe: Trishna**

The Thermal infrared Imaging Satellite for High-resolution Natural resource Assessment (TRISHNA) is a cooperation between CNES (FR) and ISRO (IN) with the objective to monitor at a global scale:

- Ecosystem stress and water use (i.e. monitoring of energy and water budgets of the continental biosphere, evapotranspiration)
- Coastal and inland waters (mesoscale, sub mesoscale dynamics, processes)

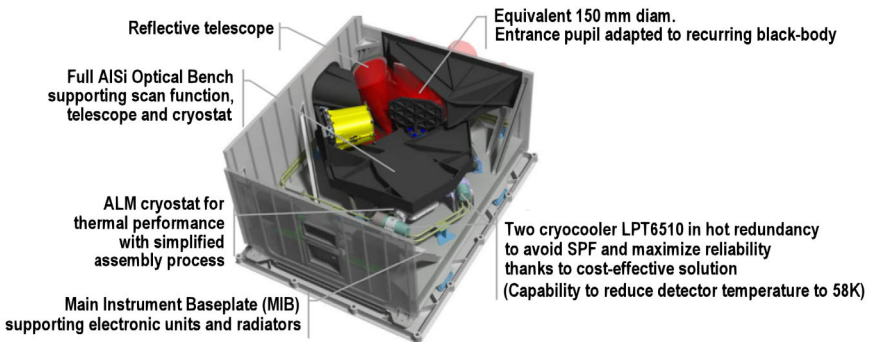
The TRISHNA payload is composed of:

- The VNIR-SWIR instrument under ISRO responsibility.
- The TIR instrument under the CNES responsibility.

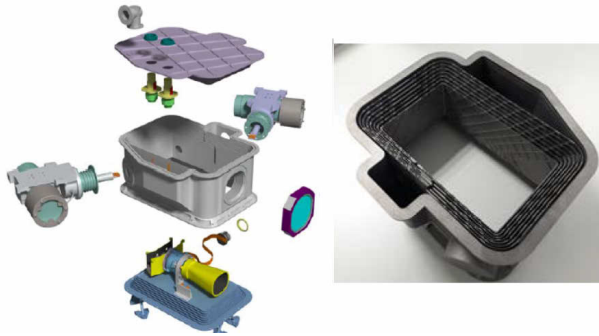
The key features of this medium sized satellite are described hereafter:

- Total mass: ~1t (<295kg for the TIR instrument)
- Solar Array sizing: ~2kW (<265W for the TIR instrument)
- Launch year: 2025.

Airbus DS (FR) was awarded the contract for the TIR instrument development in April 2020 and proposes a concept (Figure 9) that allies innovation and cost effectiveness. In particular, Focal Plane cooling (58 K required for the detector) is provided by two LPT6510 coolers from TCBV (NL) in hot redundancy, and the Cryostat is additionally manufactured. One of the underlying concepts of the ALM Cryostat design proposed by Airbus (Figure 10) is to have a single monolithic piece of titanium bridge from the Instrument optical bench interface to the detector interface, thus simplifying mounting and alignment.



**Figure 9.** The compact TRISHNA IR instrument is based on a full AISi design for the optical bench and the telescope.



**Figure 10.** The ALM Cryostat (left) is made out of three different pieces and shall guarantee  $<1\text{W}$  of parasitics on the detector. A first BB of the Cryostat (right) has been manufactured. Court. Airbus DS

### Example of Cryogenic EO Mission in Study in Europe: TANGO

Twin ANthropogenic Greenhouse gas Observers (TANGO) is part of ESA's SCOUT initiative, which embraces the 'New Space' paradigm to develop reduced budget (30MEURO) Earth Observation Research Missions. Two ideas motivate ESA to pursue this approach:

- 1) The possibility to compliment classical institutional missions with high revisit times constellations,
- 2) The opportunity to easily and quickly demonstrate in-orbit technologies.

In the case of TANGO, one of the objectives of the mission is to complement Sentinel 5 and Copernicus CO<sub>2</sub>M observation for the verification of the Paris agreement and global stock takes. Some of the other goals are (Pastena [9]):

- NO<sub>2</sub> observations at high spatial resolution,
- Exploit the use of CO<sub>2</sub>/NO<sub>2</sub> ratio observations to estimate CO<sub>2</sub> emissions from offshore NO<sub>2</sub> sources,
- Demonstrate a distributed monitoring system that can pave the way to future larger constellations allowing for enhanced coverage and temporal resolution.

TANGO is based on two push-broom spectrometers each flying on the ISIS (NL) 16U CubeSat platform. One of the spectrometer concerns CO<sub>2</sub> monitoring and requires a cutoff wavelength at 1.6 micrometers. If the detector selected is HgCdTe based, it will need cooling at around 150 K. However, unlike comparable bigger missions like CO<sub>2</sub>M or Sentinel 5, passive cooling cannot be an option due to the limited volume available and the fact that the satellite relies on forward motion compensation (pitch maneuver to improve observation quality). Consequently, it is very likely that, if selected, TANGO will rely on microcooler(s) (potentially with IDCA) for its focal plane cooling.

### Science Cryogenic Missions in Study or Development in Europe

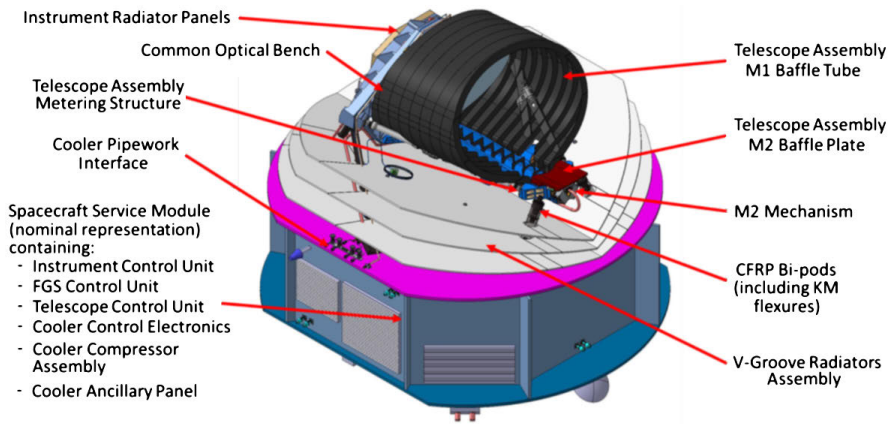
Table 3 lists the Cryogenic missions in the Science domains that are currently in development or envisaged. It has to be noted that it is very likely that this list will expand based on the new call from ESA for Scientific missions, Voyage 2050, will happen in 2021. It is expected that several of the proposed mission concepts will require cryogenic cooling.

### Example of Cryogenic Scientific Mission in study in Europe: ARIEL

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) mission (Fig. 11) has just been approved for implementation (ph. B2/C/D) in the frame of the ESA Cosmic Vision M4 program. It will perform a spectroscopy survey of hundreds of transiting planets, spanning different planetary sizes, a range of equilibrium temperatures and orbiting a variety of stellar types. As explained in the ARIEL Definition Study Report [10], multiple methods—amongst with the transit and the eclipse methods—are used to probe the atmosphere of the exoplanets, using the wide wavelength coverage (1.95  $\mu\text{m}$  to 7.8  $\mu\text{m}$ ) of the Ariel IR Spectrograph (AIRS).

**Table 3.** List of European Cryogenic Scientific Missions in study or development. In green are the two missions that will be addressed in the paper.

Mission	Cooling Needs	Launch Date	Remarks
Euclid	Passive cooling at 100K	2022	Cosmic Vision M2 L2 orbit
JUICE	Passive cooling at 90K	2022	Cosmic Vision L1 Part of MAJIS instrument
PLATO	Passive cooling at ~170K	2026	Cosmic Vision M3 L2 orbit
Ariel	Telescope at <70K and AIRS detectors <42K	2029	Cosmic Vision M4 L2 orbit
ATHENA	Cooling chain down to 50mK for XIFU instrument Passive cooling 170K for WFI	2031	Cosmic Vision L2 L2 orbit
SPICA M5	Cooling chain down to 50mK, Telescope at <8K	2032	Has been withdrawn from the Cosmic Vision M5 competition L2 orbit
Theseus	Active Cooling @ 90K	2032	Cosmic Vision M5 competition LEO orbit
Envision	Active Cooling @ 110K	2032	Cosmic Vision M5 competition Venus Orbit. IDCA solution
QPPF	15K vibration free Cooling	TBD	Concept study



**Figure 11.** The ARIEL Spacecraft and its main payload elements (court. Ariel Mission Consortium).

From the Thermal and Cryogenics point of view, the driving requirements coming from the ARIEL Payload are the following:

- The aluminum mirrors need to be maintained at a temperature < 70K in operation,
- The FGS Detectors need to be maintained at a temperature <70K in operation,
- The Cold Optics for both AIRS and the FGS need to be maintained at a temperature <60 K in operation
- The AIRS detectors need to be maintained at a temperature <42K in operation.

To tackle those challenging requirements, ARIEL uses a thermal architecture “à-la Planck”:

- The Cold Payload Module is mounted on a warm Service Module but is thermally decoupled using a set of three V-Grooves and low conductivity BiPods.
- The remaining parasitics coming from the SVM and the internal dissipations of the Cold PLM are rejected to space using a large surface area covered with a high-emissivity coating: the upper surface of the third V-Grooves, the Telescope Baffle, and the dedicated Instrument Radiator mounted on top of the Optical Bench.

- In order to achieve the 42K required for the AIRS detectors, a Neon Joule-Thomson Cooler from RAL STFC (GB) is baselined. This cooler draws his heritage from the He Joule-Thomson Cooler from Planck, with modernized mechanisms and an adapted cold plumbing due to the different working fluid.

As explained in the paper of G. Morgante [11], this design shows comfortable margins toward the temperature levels requested. However the following challenges are still anticipated:

- Management of the interfaces: as is typically the case in ESA Science projects, the responsibility of the Payload elements has been shared between numerous parties. This leads to a high number of interfaces in technically sensitive parts (e.g. V-Grooves and BiPods, between the cryoharness and all the PLM elements).
- Effect of Sun Illumination: being a Cryogenic PLM, the Payload Module of ARIEL is sensitive to sun intrusion. Missions phases like ascent and maneuvers need to be carefully analyzed to ensure that no fragile parts exceed their temperature limits.
- Neon Joule-Thomson Cooler Development: even though the risk for the development of the cooler is considered relatively low due to the expertise of the RAL team and the direct heritage of a flight proven cooler, the upcoming Engineering Model testing planned in the second half of 2021 will be crucial to demonstrate the Technology Readiness Level necessary at this stage of the project.

### Example of Cryogenic Scientific Mission in Study in Europe: ATHENA

Selected in 2014 as the second Large Class mission in the frame of ESA's Cosmic Vision, ATHENA—Advanced Telescope for High-ENERgy Astrophysics—will be an X-ray telescope designed to address the Cosmic Vision science theme “The Hot and Energetic Universe” [10]. For European Space Cryogenics, this ambitious and extremely challenging mission is shaping up to drive the community for the coming years as Herschel/Planck did in the 1990's and early 2000's.

To achieve the mission's science objectives, Athena carries a payload capable of spatially-resolved X-ray spectroscopy and deep wide-field X-ray spectral imaging with performance greatly exceeding that offered by current X-ray observatories. Its instrumentation will consist of a cryogenic X-ray spectrometer called the X-ray Integral Field Unit (X-IFU), and a Wide Field Imager (WFI). The main characteristics of the spacecraft are the following:

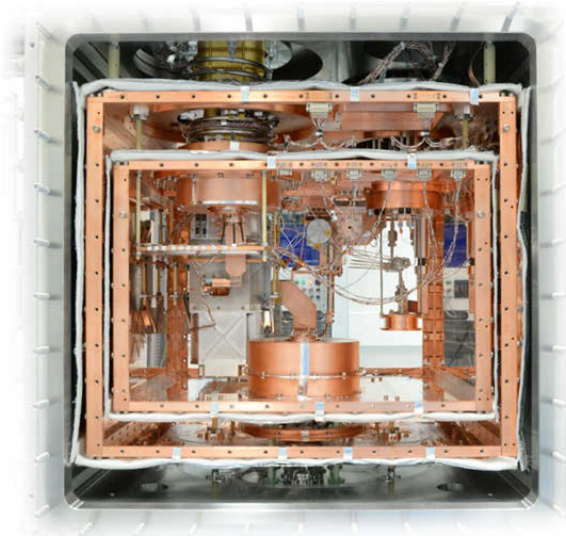
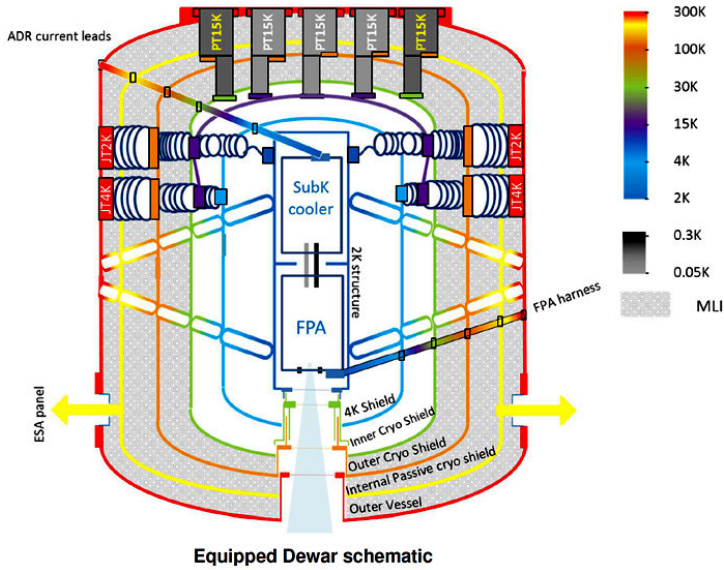
- Total mass: ~7t
- Power budget: ~8kW
- Focal length: 12m
- Surface area of the X-ray mirror: 1.5m<sup>2</sup> through combining 600 Silicon Pore Optics modules to be maintained at 20°C +/-5°C
- Mass of the Science Instrument Module: ~2.4t
- Dissipation inside the Science Instrument Module: ~5kW.
- Launch year: 2031

From the Cryogenic point of view, X-IFU represents one of the most challenging instruments to be launched. In order to guarantee the 50 mK temperature required by the Transition Edge Sensor detectors, the following architecture is envisaged by CNES (FR):

- Outer Vessel at 300 K
- Internal Passive Cooling at 200 K
- Outer Cold Shield at 80 K
- Inner Cold Shield at 30 K
- 15K JT Precooling stage
- 4K Stage
- 2K Stage
- 2K core (with 300 mK and 50 mK stage)

Those temperature stages are obtained thanks to a cooling-chain (Fig. 12) which is single-point-failure tolerant (except for the Sub-K cooler):

- 4x PT15K Coolers (24 kg and 300 W each)
- 2x JT4K Coolers
- 2x JT2K Coolers
- Hybrid He-3 Sorption Cooler / ADR



**Figure 12.** The concept of the active cooling chain as depicted on the left has been demonstrated thanks to the Detector Cooling Chain CTP (right) from CEA (FR). Court. CNES and CEA

In order to achieve the required technological maturity, ESA has been in the last 10 years funding developments corresponding to each stage of the Cryochain as well as an end-to-end demonstrator.

### CONCLUSION AND LINK TO THE DEVELOPMENTS

As described in this paper, the coming years promise to be exciting for European Space Cryogenics. Indeed, cryogenic missions have never been so ambitious, numerous and diverse.

In the space sector, technology developments need to be one step ahead of the missions: Technology Readiness Level can make or break projects. With a standard financial commitment, a brand new

development takes ~10 years to reach TRL 6, 5 years if it is the evolution of a product. It is therefore necessary to prepare today the technological development of missions that will be launched in 2040 – 2050.

What are the main topics of ESA led development activities?

- Completing the portfolio of qualified cooler systems for Large (MTG-like) to Small (TANGO-like) missions.
- Capitalize the lessons learned of 15 years of developments by preparing the next iteration of better & cheaper coolers.
- Prepare the future Earth Observation or Science challenges by developing Vibration-Free Cooler for Space (e.g. Reverse Turbo Brayton, Laser Cooler, Sorption Cooler).
- Embrace the New Space paradigm and develop methods to increasingly use COTS coolers on Space missions.

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