Cryogenics in Space
- A review of the missions and technologies

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Since the first liquefaction of ^4He and the discovery of superconductivity by H. Kamerlingh-Onnes (1908 and 1911), cryogenics and its applications have come a long way. The continuous improvement of cryogenic equipment has made it easier and easier to achieve temperatures well below the liquefaction point of nitrogen (77 K), either by means of cryogens (liquid gases such as Xe, H_2, O_2, N_2, ^4He and ^3He) or by means of mechanical coolers. Cryogenic devices, such as sensors and cold electronics, have taken advantage of the progress made in materials science, thereby offering a reliable and effective solution to otherwise unsolvable problems.

In the last 15 years, several spacecraft have employed cryogenic equipment, mostly in the context of astrophysics missions, targeting the electromagnetic radiation emitted by celestial objects over a wavelength range that it is difficult to cover from the ground. Such missions include IRAS (Infrared Astronomical Satellite, launched in 1983), COBE (Cosmic Background Explorer, launched in 1989) and ISO (Infrared Space Observatory, launched in 1995). Several new missions are currently in preparation, including Herschel/Planck, SIRTF and the Next-Generation Space Telescope (NGST). In the higher temperature range, between 100 and 10 K, many missions are already operational or under development. They include military reconnaissance satellites (such as Helios), Earth-observation satellites (Spot) and meteorological spacecraft (MSG, Meteosat Second Generation), with infrared detectors operating at about 85 K.

Applications of cryogenics in space

The development, in-orbit commissioning, and operation of cryogenic instrumentation in space raises the level of mission complexity, risk and associated cost. Any application must then be justified on the basis of its specific return. In the case of scientific missions, the cryogenic detectors and related payloads are the only candidates for the accomplishment of the mission objectives, offering unmatched performance and unique advantages. In the case of other applications, such as telecommunications, the advantages offered by superconducting devices need to be evaluated against their development and operating costs, and compared with alternative technologies.

Cryogenic detectors for space applications

Cryogenic photon detectors offer two main advantages over conventional sensors:

– their much higher sensitivity (expressed by the Noise Equivalent Power or NEP, i.e. the amount of incident power required to achieve a signal-to-noise ratio equal to unity)
– the better energy resolution (expressed in terms of resolving power, i.e. the ratio $E/\Delta E = \lambda/\Delta\lambda$, with ΔE representing the full width at half maximum of the detector response to a monochromatic excitation of energy E).

Cryogenic detectors have driven the utilisation of cryogenics in space, determining the requirements in terms of operating temperature, temperature stability and architecture of the payload system. This trend is now well-established across the electromagnetic spectrum. Figure 1 provides a summary of the different detectors, including operating photon energy and temperature range. Table 1 provides an overview of other characteristics of the detectors, including typical power dissipations, array sizes and operating temperatures.

Applications involving the lower energy end of the electromagnetic spectrum (i.e. sub-millimetre wave and infrared) are the ones that benefit most from the utilisation of cryogenic detectors. Dramatic developments have recently taken place in infrared detector technology, driven mainly by the vast investments made by the US Department of Defense during the 1980s. Such developments embrace a very large spectral range, from the Near-IR (NIR, λ = 1 µm) to the Far-IR (FIR, λ = 200 µm), and have focused on low-background, high-sensitivity

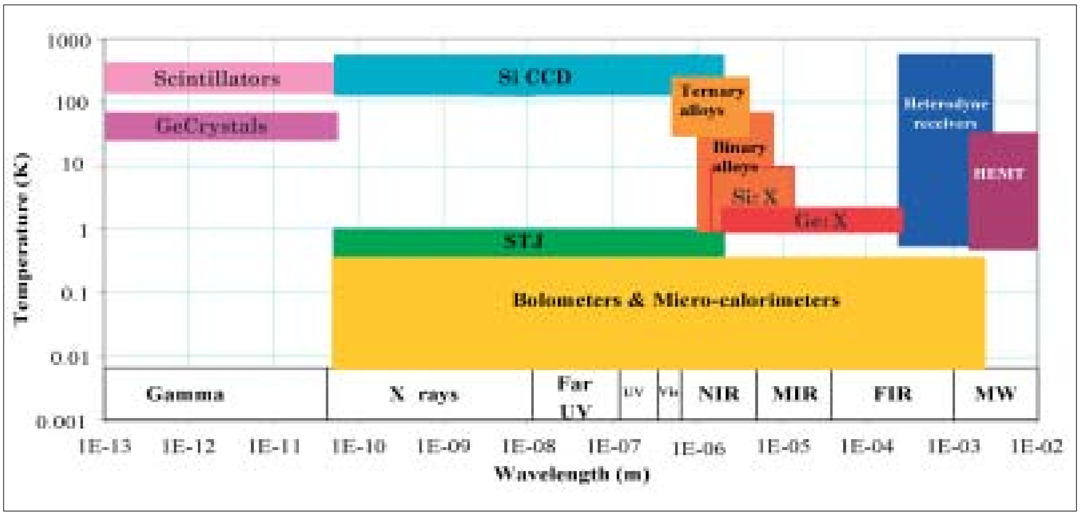

Figure 1. Overview of photon detectors and related operating temperatures. Note the extended sensitivity range of the cryogenic detectors, such as STJs and bolometers

Table 1. Main characteristics of photon detectors and SQUIDs

Detector type (pixel and array)	Temperature range (K)		Dissipation range (W)		Detector size		
	Min.	Max.	Min.	Max.	Pixel (µm)	Array (n x n)	Wavelength
Ge crystal	50	100	0	0	10 000	<10	Gamma
CCD	150-200	300	0.1	20	10-30	10^6	X-ray / Vis
STJs	0.01	1	10^{-9}	10^{-6}	20-50	$<10^3$	X-ray–UV-Vis-NIR
µ-Calorimeters	0.05	0.3	10^{-12}	10^{-11}	100	<100	X-ray
TESs	0.05	0.3	10^{-11}	10^{-9}	100	<100	X-ray-UV-Vis-NIR
Photo-conductors-NIR	30	100	0.01	0.02	30-50	10^6	NIR
Photo-conductors-MIR	2	20	0.01	0.02	50-100	$<10^4$	MIR
Photo-conductors-FIR	1	2	0.001	0.003	50-100	$<10^3$	FIR
Sub-mm bolometers	0.1	0.3	10^{-9}	10^{-8}	100-500	$<10^2$	Sub-mm
SQUIDs (LTS)	1	4	10^{-12}	10^{-11}	na	na	Read-out/accelerometer

and large-format arrays. IRAS used a total of 62 detector elements, while since 1995 large-format arrays for IR astronomy have been available with total pixel counts in excess of 10^6.

Astronomical observations in the far-infrared investigate objects that are colder than those observed in the visible or in the near-infrared, as blackbody radiation in the 30 – 300 µm wavelength range (emitted by bodies at temperatures ranging from 100 to 10 K). An example of such cold objects is the interstellar dust in our galaxy (at 20 – 30 K), as detected by IRAS in 1983, which both confirmed the existence of interstellar dust and detected its thermal emission. Photo-conductors represent the main detection technique use throughout the IR range. At low temperatures and low photon fluxes, the conductivity of these semi-conducting materials is influenced by the absorbed IR photons, which can ionise impurities and free charge carriers. Such photoconductors are typically operated at T < 3 K. In the case of Isophot, a broad-band photometer flown onboard ISO, Ge:Ga detectors were combined with low-noise CMOS integrating preamplifiers and multiplexers operating at 2 K to achieve a NEP of order 10^{-18} W/Hz$^{1/2}$.

Bolometers have also been used to detect sub-millimetre photons. Neutron-Transmutation-Doped (NTD) Ge detectors are well-established and operate at temperatures between 300 and 100 mK, with NEPs of order 10^{-17} W/Hz$^{1/2}$. Such devices will be used onboard ESA's Planck spacecraft.

In the sub-millimetre-wavelength range, heterodyne receivers provide very high sensitivities up to frequencies as high as 500 GHz. Several laboratories have shown that receivers based on Superconductor-Isolator-Superconductor (SIS) devices (such as Nb-based Superconducting Tunnel Junctions) offer better performance than the conventional Schottky-diode-based systems. Operating temperatures are of order 2 K. At frequencies η > 500 GHz, the so-called Hot-Electron Bolometers (HEBs) compete with SIS and Schottky diodes for the next generation of heterodyne receivers (e.g. on ESA's Planck and Herschel missions). In such devices, the incoming radiation excites the electron population, thus determining changes in the resistance of the device, according to a non-linear behaviour, used for mixing the signal voltage with the local oscillator voltage. Operating temperatures range from 70 K (2 deg, InSb HEBs) to 0.3 K (NIS HEBs).

In the NIR (at wavelengths between 1 and 5 µm), other photo-conductors are used, mainly PtSi, HgCdTe and InSb. Over the last decade, the introduction of two-dimensional InSb arrays has drastically changed the field of IR astronomy, with a 1 k x 1 k pixel array based on hybrid technology. These detectors have operating temperatures ranging between 77 and 35 K and have already been used onboard the Hubble Space Telescope.

A new generation of photon detectors is represented by Superconducting Tunnel Junctions (STJs) and Transition Edge Detectors (TESs), both photon-counting in the visible and NIR, with intrinsic spectroscopic capability.

Table 2. Summary of cryogenic space programmes (Space Science)

Mission	Application	Type/Class	Launch year	Cryogenic system
IRAS (NASA,NIVR,SERC)	Science / IR	Satellite (surveyor)	1983	^{4}He cryostat
COBE (NASA)	Science / IR	Satellite (surveyor)	1989	^{4}He cryostat
ISO (ESA)	Science / IR	Satellite (observat.)	1995	^{4}He cryostat
SFU (ISAS/NASDA/MITI)	Science / IR	Instrument (IRST)	1995	^{4}He cryostat + ^{3}He SC
MSX (BMDO,US)	MP/UV to FIR	Satellite (observat.)	1996	sH_2 cryostat
HST (NASA)	Science / NIR	Instrument (Nicmos)	1997	sN_2 cryostat
WIRE (NASA)	Science / IR	Satellite (surveyor)	1999	Dual, sH_2 cryostat
STEP (ESA)	Science / FP	Satellite		^{4}He cryostat
Astro-E (ISAS, NASA)	Science / X	Satellite (observat.)	2000	sNe + ^{4}He cryost.+ADR
INTEGRAL (ESA)	Sci. / Gamma	Instrument (observ.)	2001	Stirling cooler
SIRTF (NASA)	Science / IR	Satellite (observat.)	2002	^{4}He cryostat
Submillimetron (ASC)	Sci. / Sub mm	ISS telescope	> 2004	^{4}He cryost. + ^{3}He SC
XEUS (ESA)	Science / X	Instrument (observ.)	2005	Stirling cool. + ADR
Herschel (ESA)	Science / IR	Satellite (observat.)	2007	^{4}He cryost. + ^{3}He SC
Planck (ESA)	Science / FIR	Satellite (surveyor)	2007	H_2 & ^{4}He JT + DR
NGST (NASA)	Science / NIR	Satellite (observat.)	2008	Passive rad. + cooler
Constellation-X (NASA)	Science / X	Satellite (observat.)	2008-10	Astro-E like / coolers
ARISE (NASA)	Sci. / Radio	Satellite (VLBI)	2008	Cryo-cooler + H_2 JT
DARWIN (ESA)	Science / IR	Satellite (VLBI)	>2009	Cryo-cooler + H_2 JT
TPF (NASA)	Science / IR	Satellite (VLBI)	2010	Passive rad. + cooler.
Rosetta (ESA)	Sci. / Comet	Instrument (probe)	2003	Stirling cooler

FP = Fundamental Physics
MP = Multipurpose mission (defence + science)

Table 3. Summary of cryogenic space programmes (Applications / Technology).

Mission	Application	Type/Class:	Launch year	Cryogenic system
Meteosat 1–7 (ESA/EUM.)	Meteo.	P/L	1977-97	Passive radiator
ERS (ESA)-1/2	Earth Observat.	P/L (ATSR)	1991/1995	Stirling cooler
CRISTA (DARA, D)	Earth Observat.	P/L (STS-66/85)	1994/97	^{4}He cryostat
MSG-1/2(ESA/EUMETSAT)	Meteo.	P/L (Seviri)	2000/2002	Passive radiator
ENVISAT 1 (ESA)	Earth Observat.	P/L (MIPAS/AASTR)	2001	Stirling cooler
Metop (ESA/EUM./NOAA)	Meteo.	P/L (IASI)	2001	Passive radiator
MSG-2 (ESA/EUMETSAT)	Meteo.	P/L (Seviri)	2002	Passive radiator
USMP/LPE (NASA)	Technology	P/L (STS-52)	1992	^{4}He cryostat
SHOOT (NASA)	Technology	P/L (STS-57)	1993	^{4}He cryostat
HTSSE I–II (NRL/USAF)	Technology	P/L (ARGOS)	1993-1999	Stirling cooler
STRV-1B (DRA)	Technology	Mini-satellite	1994	Mechanical cooler
IN-STEP/CSE (NASA)	Technology	P/L (STS-63)	1995	Mechanical cooler
BETSCE (NASA)	Technology	P/L (STS-77)	1996	H_2 Stirling+JT+ Sorpt.
MIDAS (NASA)	Technology	P/L (STS79/MIR)	1996	Mechanical cooler
CheX (NASA)	Techn./MS	P/L (STS-87)	1997	^{4}He cryostat
ISS / Bosch (ESA)	Techn./TLC	P/L (ISS)	> 2005	Mechanical cooler
LTMPF (NASA)	Techn./MS	P/L (ISS)	2003	^{4}He cryostat
FACET (NASA/JPL)	Technology	P/L (STS)	< 2003	sCO_2+sNe cryostat
UARS (NASA)	Atmosphere	P/L (CLAES/ISAMS)	1991	sNe cryostat/ Stirling
Landsat 7 (NASA)	Earth Observat.	P/L (MISR)	1999	Passive radiator
Terra (NASA)	Earth Observat.	P/L (MODIS)	1999	Stirling cooler.
Aqua (NASA)	Earth Observat.	P/L (CERES)	2000	Stirling-PTR + passive
Aura (NASA)	Earth Observat.	P/L (HIRDLS)	2002	Stirling-PTR + passive

P/L = Payload/instrument onboard a satellite / STS / ISS
MS = Materials Science
STS = Space Shuttle flight
TLC = Telecommunications

STJs have operating temperatures ranging between 0.5 and 0.1 K, depending on the superconductors used (typically Nb, Al, Ta), responsivities of order 10^4 e^-/eV, resolving powers of order 10 at λ = 500 nm and maximum count rates of order 10^4 events/s. TESs operate at about 0.1 K, also have very conspicuous responsivities, comparable energy resolutions and a maximum count rates of order 10^3 events/s. Both STJs and TESs can operate over a large photon energy range, with very interesting performances in the UV and X-ray regions. The key benefits of such devices are the much higher detection efficiency (close to 100%), the photon counting and intrinsic spectroscopic capability, and the good imaging resolution (with individual pixels of order 20 µm). In the case of STJs, an energy resolution of 15 eV at 6 keV has been demonstrated, while TESs have achieved even better results (a few eV's at 6 keV).

In-flight T [K]	Lifetime	Orbit	Status
3	290 dd	Near Polar	Post-ops.
1.4 - 1.6	305 dd	Near-Earth	Post-ops.
1.8	840 dd	HEO	Post-ops.
0.3	30 dd	LEO	Post-ops.
< 8	600 dd	LEO	Post-ops
60	700 dd	LEO	Post-ops.
< 7.5	120 dd	LEO	Postops/loss
1.8	180 dd	LEO	Not approved
0.065	730 dd	LEO	Loss
85	2-5 yr	HEO	Development
1.4	2.5 yr	Earth trailing	Development
0.1-0.3	tbd	LEO	Study
0.05 – 0.3	> 10 yr	LEO	Study
0.3 & 1.74.	5 yr	Sun-Earth L2	Development
0.1 & 20	460	Sun-Earth L2	Development
4 – 40	5-10 yr	Sun-Earth L2	Study
0.05	3-5 yr	Sun-Earth L2	Study
20	tbd	HEO	Study
4	tbd	L2 / Earth trailing	Study
30	5 yr	L2 / Earth trailing	Study
80	10 yr	Heliocentric	Development

In-flight T [K]	Lifetime	Orbit	Status
90		GEO	Post-ops./ops.
80	2 yr	LEO	Operations.
2.5-12	10 dd	LEO	Post-ops.
75-85	7 yr	GEO	Development
80	5 yr	LEO - Polar	Development
100	5 yr	Sun-synchr.	Development
75-85	7 yr	GEO	Development
2.2	> 6 dd	LEO	Post-ops.
< 2.2	> 6 dd	LEO	Post-ops.
70-80	3 yr	Sun-synchr.	Loss / ops.
80	3 yr	GTO	Post-ops.
65	8 dd	LEO	Post-ops.
10	< 1 dd	LEO	Post-ops.
80	> 8 dd	LEO	
1.6	> 6 dd	LEO	Post-ops.
77	> 1 yr	LEO	Development
1.6	180 dd	LEO	Development
19	> 6 dd	LEO	Development
16/80	1.5 yr	Near-circular	Post ops.
90	5 yr	Sun-synchr	Operations
80	5 yr	Sun-synchr.	Operations
60-85	6 yr	Sun-synchr.	Development
65	5 yr	Sun-synchr.	Development

Fundamental physics and planetary sciences can also benefit from the utilisation of cryogenic detectors. One example are SQUID (Superconducting Quantum Interference Devices) based gravity gradiometers, to be used for low-altitude Earth and planetary missions. In addition to mapping the intensity of the gravitational forces, these sensors can be used to verify the well-known 'Equivalence Principle', which postulates the coincidence of gravitational and inertial mass. This issue is being addressed in the feasibility studies of several different space missions, including STEP (ESA) and LISA (NASA). SQUID-based accelerometers are the only ones capable of achieving the required accuracy. So far, SQUID devices based on low-temperature superconductors are favoured, with operating temperatures around 4 K. SQUIDs based on high-temperature superconductors (HTS) are also being investigated, in view of their ability to operate at about 77 K.

Scientific missions: a review

Scientific missions dominate the present scenario for cryogenics applications in space due to the advantages offered by cryogenic detectors over conventional sensors. This short review is organised in chronological order, starting with IRAS, the first 'cryogenic mission', which flew in 1983. Mission in the operations (or post-operations) phase, missions presently under development, and missions under study are grouped in different sections. Tables 2 and 3 provide a summary of all non-military space missions that involve cryogenics.

- Missions in operation/ post-operation

IRAS (Infrared Astronomy Satellite) was the first scientific satellite based on cryogenic instrumentation. Launched in January 1983 as a joint project by the United States, the United Kingdom and the Netherlands, its mission was to map the entire sky at IR wavelengths, from 8 to 120 µm. The satellite was equipped with a 0.6 m telescope cooled with liquid helium to about 4 K. The focal-plane assembly was located at the Cassegrain focus, at about 3 K. It contained the survey detectors (based on 62 photo-conductive elements made from four different materials), a low-resolution spectrometer and a chopped photometric channel.

COBE (Cosmic Background Explorer) was developed by NASA's Goddard Space Flight Center to measure the cosmic background radiation. This satellite was launched in November 1989 and operated for about 10 months in survey mode. It carried three instruments: a FIR Absolute Spectrometer (FIRAS), a Differential Microwave Radiometer (DMR) and the Diffuse IR Background Experiment (DIRBE), operating at wavelengths between 1.25 and 240 µm. FIRAS and DIRBE operated at 1.6 K, cooled by a 650 litre, superfluid helium cryostat.

ISO (Infrared Space Observatory) was developed by ESA and operated at wavelengths from 2.5 to 240 µm between November 1995 and May 1998, in a highly elliptical orbit. This satellite (Fig. 2) was based on a cryostat containing about 2200 litres of superfluid helium and on a 0.6 m-diameter telescope, feeding four instruments (an infrared camera, a photometer and two spectrometers) working in different wavelength ranges. The four instruments made use of different photo-conductors based on InSb, Si and Ge and operating between 1.8 and 10 K.

Figure 2. The ISO (Infrared Space Observatory) spacecraft, fully integrated and ready for transport to the launch facilities. The solar panels shield the satellite from direct Sun illumination. The cryostat is fixed to the Service Module via the struts visible in the lower part of the picture

- Missions under development

Several spacecraft presently under development will make use of cryogenic instrumentation (Tables 2 and 3).

Planck is the third medium-size mission (M3) in ESA's Horizon 2000 scientific plan. Its main objective is to map the temperature anisotropies of the Cosmic Microwave Background (CMB) over the whole sky, with a sensitivity ($\Delta T/T$) of $2x10^{-6}$ and an angular resolution of 10 arcmin. Such goals require bolometers operating at 0.1 K, HEMT at 20 K and a low-emissivity, cooled telescope (60 K). The cryogenic system proposed for Planck is based on pre-cooling to 60 K by passive radiators, cooling to 20 K with a H_2 Joule-Thomson Cooler (adsorption compressors), cooling to 4 K with a He Joule-Thomson cooler (mechanical compressors), and final cooling to 0.1 K with an open-loop Dilution Refrigerator. The nominal mission lifetime is 15 months.

Herschel (formerly known as FIRST – Far-Infrared and Submillimetre Telescope) is the fourth Cornerstone mission of Horizon 2000. It is dedicated to astronomical observations in the far-infrared and sub-millimetre wavelength range, from 85 to 600 µm. Herschel is a multi-user observatory, based on a superfluid helium dewar at 1.65 K and on a ^{3}He sorption cooler delivering a base temperature of 0.3 K. The scientific goals will be achieved with three instruments operating between 0.3 and 2 K. Herschel is presently scheduled for launch in 2007 and its He dewar is designed for a mission lifetime of 3.5 year. Due to the commonality in technologies, science objectives and final orbit (around the second Lagrangian point of the Sun-Earth system), ESA has decided to develop Herschel and Planck together, and to launch them with a single Ariane-5 flight. Detailed engineering assessments are in progress.

SIRTF (Space Infrared Telescope Facility) is the fourth member of NASA's family of 'Great Observatories'. It is designed to perform imaging and spectroscopy in a large wavelength range, from 3 (NIR) to 180 (FIR) µm via a 0.85 m-diameter, helium-cooled telescope. The detectors' temperature is 1.4 K, while the cryogenic system is optimised (passive radiation and efficient use of helium gas enthalpy) to make use of only 360 litre of superfluid He, for a minimum lifetime of 2.5 years. SIRTF is currently in the development phase and is scheduled for launch in May 2002. Thanks to a number of trade-offs, it has been possible to drastically reduce the mission costs by selecting a solar orbit and limiting the satellite mass to about 900 kg.

Finally, among the missions under development, we would like to mention Integral (International Gamma-Ray Astrophysics Laboratory) as an example of utilisation of space-qualified Stirling cryo-coolers. Integral is a medium-size ESA science mission dedicated to spectroscopy and imaging between 15 keV and 10 MeV. The spectro-meter on the spacecraft is based on about 30 kg of germanium detectors maintained at a temperature of 85 K. The satellite is scheduled for launch in 2001.

- Missions under study

NGST (Next-Generation Space Telescope) is considered the successor of the Hubble Space Telescope. The programme calls for a 6 to 8 m-diameter, passively cooled telescope to minimise thermal self-emission and enable observations to be made in the NIR and Medium-IR (MIR) from 1 to 30 µm. The scientific objectives for NGST are the study of galaxies, stars and planet formation and the study of the chemical and geometrical evolution of the Universe. The so-called 'NGST Yardstick Mission' (a mission design developed by NASA, academia and industry since starting in 1996) baselines a deployable 8 metre telescope, passively cooled below 50 K. The science instruments are an NIR camera, an NIR low-resolution spectrograph and a MIR camera-spectrograph combination. The first two instruments operate at 30 K (passive radiator cooling), the third one makes use of either an active cooler or solid H_2 to achieve a base temperature of about 8 K. ESA is also involved in the NGST project with a financial participation of some 15%. The telescope should be launched in 2008.

XEUS (X-ray Evolving Universe Spectroscopy mission) is the potential follow-on mission to the ESA XMM Cornerstone (launched at the end of 1999). The mission aims to place a permanent X-ray telescope in orbit by exploiting the facilities available on the International Space Station (ISS) and by ensuring significant growth and evolution potential. The main features of the proposed observatory are the very large telescope aperture and the utilisation of cryogenic detectors in two narrow-field imaging spectrometers (respectively TESs and STJs). The cryogenic design would be based on Stirling mechanical coolers, combined with ADR systems in order to extend the mission lifetime beyond what is achievable with consumable cryogens.

Darwin (Infrared Space Interferometry Mission) is a Cornerstone candidate in the ESA 'Horizon 2000 Plus' science plan. Its goal is to detect terrestrial planets in orbit around other stars and to allow high-resolution imaging in the medium infrared, between 5 and 30 µm. Interferometry would be carried out over a 50 – 500 m baseline, including six free-flying 1.5 m telescopes. Both the telescopes and the focal-plane detectors would be cooled to about 20 – 30 K. A similar mission is being studied in the USA, namely the Terrestrial Planet Finder.

Earth Observation and Meteorology satellites

The field of Earth observation (i.e. the remote sensing of our planet from space for civilian purposes) has grown considerably in importance over the last 10 – 15 years. Several missions have been developed with the objective of monitoring the Earth's natural environment and studying natural phenomena related to the planet's water cycle. Cryogenics are required because of the use of detectors capable of imaging the Earth's surface in the near- and medium-infrared (typically operating around or just below 100 K). Due to the low-altitude orbits of these satellites, the large thermal flux emitted by the Earth often precludes the utilisation of purely passive thermal control, obliging us to make use of mechanical coolers.

ESA's Earth Observation Programme is based on a number of missions for the monitoring of our planet's atmosphere, oceans and land. The ERS-1 and ERS-2 satellites (ESA Remote Sensing Satellites) were developed to provide information on the Earth and its environment and were launched in 1992 and 1995, respectively. The IR Along-Track Scanning Radiometers (ATSRs) embarked on ERS-1 and ERS-2 were equipped with Stirling-cycle coolers (from Oxford University) to maintain the focal-plane assembly at about 100 K.

The Meteosat Second Generation (MSG) continues the legacy of the previous Meteosat missions, with greatly improved performance. Three satellites (MSG-1 to 3) are being procured by ESA on behalf of Eumetsat to guarantee uninterrupted coverage from 2000 to 2012. Onboard MSG-1, two instruments have focal-plane assemblies operating at low temperatures – the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) and the Geostationary Earth Radiation Budget (GERB) radiometer – and both are cooled by passive radiators to operate at about 80 K.

Envisat-1 is a large multidisciplinary mission, dedicated to study of the Earth and its atmosphere with both science and application objectives. Three instruments onboard this spacecraft (due for launch in autumn 2001) require cryogenic temperatures in order to operate, namely MIPAS, AATSR and SCIAMACHY. MIPAS is a Fourier-transform spectrometer operating in the 4 to 16 µm wavelength range and using photo-conductive and photo-voltaic HgCdTe detectors. The optics and detector assembly are cooled to 70 K by a pair of Stirling-cycle coolers. The AATSR is an IR-visible radiometer whose focal-plane assembly is cooled to 80 K by another pair of Stirling coolers. Finally, SCIAMACHY is an imaging spectrometer operating between 0.2 and 2.4 µm; it uses silicon and InGaAs detectors passively cooled to temperatures ranging between 235 and 130 K.

ESA, Eumetsat, CNES and NOAA are co-operating in the development of MetOp (Meteorological Operational), a new generation of weather satellites. MetOp will continue part of the ERS mission, complement the results provided by Envisat and support scientific investigations as well as weather forecasts. MetOp, presently undergoing development, will carry similar instruments to Envisat, with similar cryogenic requirements.

Technology-validation missions
A number of cryogenic space missions have been dedicated to the validation of specific technological issues (see Table 3). This is the case for payloads flown on research satellites and on the Space Shuttle, or to be flown on the International Space Station (ISS).

Others
- Telecommunications
The recent progress in High-Temperature Superconductors (HTS) has opened new perspectives for the fabrication of radio-frequency (RF) super-conducting devices, such as filters, delay lines, resonators and antennas. These devices provide the capability to improve the performance of telecommunications satellites, which needs to be traded off against the increased system complexity by implementing a cryogenic system onboard the spacecraft.

- Sample storage
The long-term storage of biological samples requires cryogenic temperatures. On the ground, this is achieved by using liquid nitrogen. For the ISS, ESA is developing a cryogenic freezer (Cryosystem) for the cooling down to and long-term storage of biological samples at –180ºC. The cooling system consists of mechanical coolers.

In addition, cryogenic applications in the near future may include:
– zero-loss storage of cryogenic propulsion fuels for long-term missions (e.g. a Mars mission)
– liquefaction of propellant produced on the Moon or Mars
– use of low-temperature electronics with increased performance
– energy storage using superconductive devices (similar systems are already under development for ground applications).

Cryogenics and spacecraft engineering
The following paragraphs provide a summary of the engineering issues associated with cryogenics in space.

Architecture of cryogenic spacecraft
A spacecraft is usually composed of a Service Module (service bus) and a Payload Module (Fig. 3). The Payload Module carries one or more instruments that process signals coming from the Earth (e.g. for Earth observation, meteorological or telecommunications applications) or from space (e.g. for astronomy). The instruments can either have their own optics, or share a common unit (e.g. main telescope). The presence of cryogenic installations has a strong impact on the architecture of a spacecraft or of an instrument, the key factors coming into play being as follows:

- A cooler needs to be used (i.e. cryogens, radiators, mechanical coolers). The cooler must have a heat lift compatible with the satellite's size and the available power resources.
- The low-temperature equipment must be properly supported, insulated from the room-temperature satellite bus, and protected from solar and/or Earth radiation. The lower the operating temperature, the higher the demands on the thermal insulation.
- The cold parts have to be accessed (e.g. optical access to the detectors, signal wires, temperature sensors and heaters) and wiring needs to be routed between the cold payload and the satellite bus for further processing (analogue/digital conversion, data handling) before transmission to Earth via telemetry.
- Cryogenic ancillary equipment needs to be used to operate the cryogenic payload (e.g. heat links, heat switches, filters, thermometry).
- System testability (instrument performances and payload cooling system) is likely to have an impact on the payload architecture.
- The complete system must survive the vibrations induced by the launcher: this requirement has a strong impact on both the cooler and instrument designs (e.g. a compromise is required between the large support cross-section required for the launch, and the thermal-insulation requirements).
- The cooler has to operate in zero gravity for several years.
- The payload needs to be built with materials compatible with both the space and cryogenic environments.
- The lifetime (or MTBF, mean time between failures) of the equipment should be compatible with and preferably exceed the mission duration.

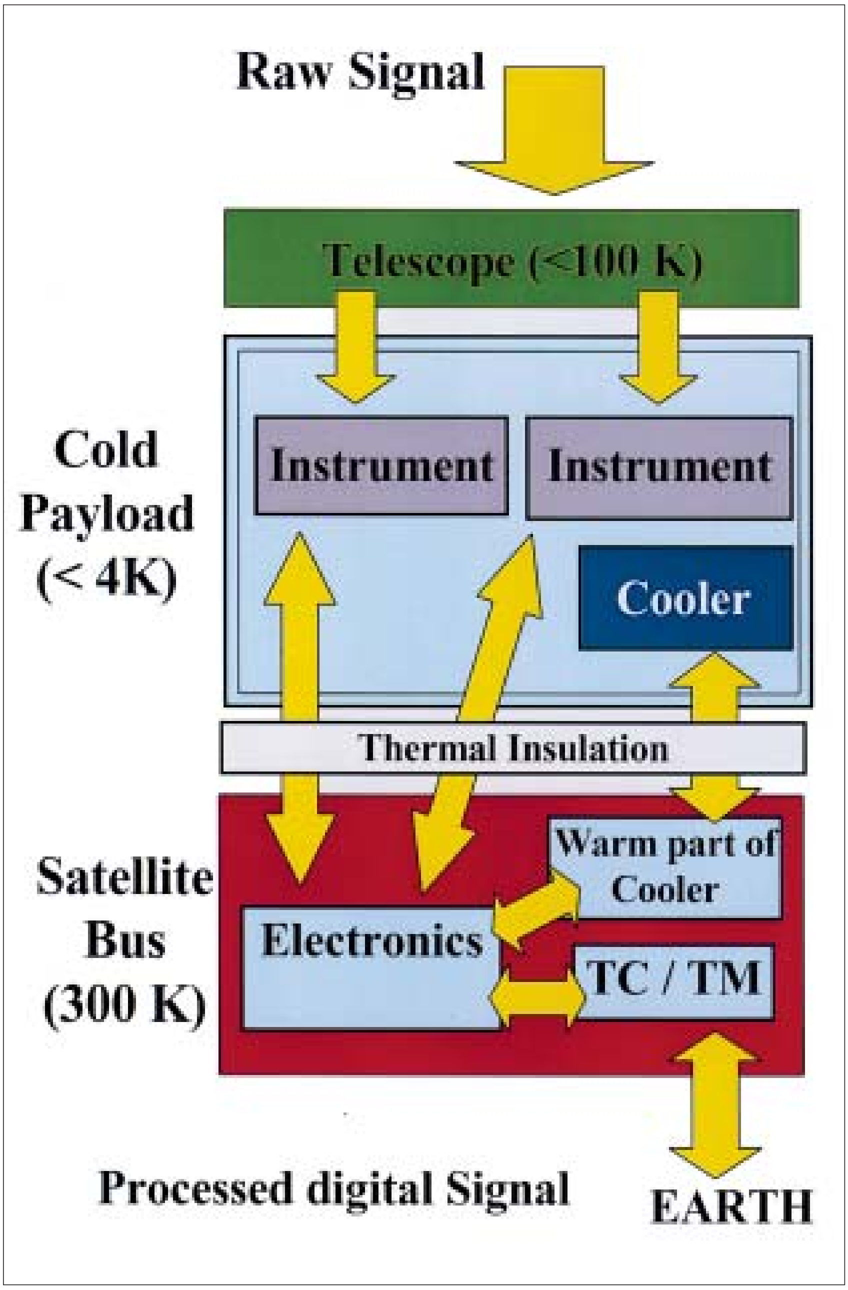

Figure 3. Typical architecture of a cryogenic satellite for space science. Three main sections can be identified: the telescope (cooled below 100 K), the Payload Module with focal-plane detectors maintained below 4 K, and the Service Module, maintained at room temperature

Space coolers

- Principle of cooling systems for space

Coolers provide a cold heat sink, by removing the heat in the cold area and dissipating it in the warm area. In the case of a satellite isolated in space, the energy will be finally radiated to space. The cooling process is well described by elementary thermodynamics: either the energy is directly radiated to space (via radiators), or some work has to be performed to pump it from a cold to a warm level where it can be more easily radiated away.

Such a heat-pumping operation can be achieved using an open- or closed-cycle configuration. The open cycle corresponds to the use of stored cryogens, where the work is performed on the ground before the mission by a liquefier. The cold heat sink is provided by the evaporation of liquid or solid cryogens. In this case there is no energy to radiate, but gas is released. The lifetime of the system is thus governed by the heat losses and by the mass of cryogen that can be flown.

The closed cycle relies on the use of mechanical coolers, where the work is done continuously during operations (Fig. 4). Existing space coolers can provide about 1 W of cooling power in the temperature range 50 – 100 K (Stirling coolers, pulse tubes), about 100 mW in the range 15 – 20K (double-stage Stirling), or a few mW at 4 K (Joule-Thomson). Very-low-temperature coolers (e.g. ^{3}He cryo-sorption refrigerators, dilution, ADR) rely on the pre-cooling systems mentioned above to achieve even lower temperatures (typically between 100 mK and 1 K).

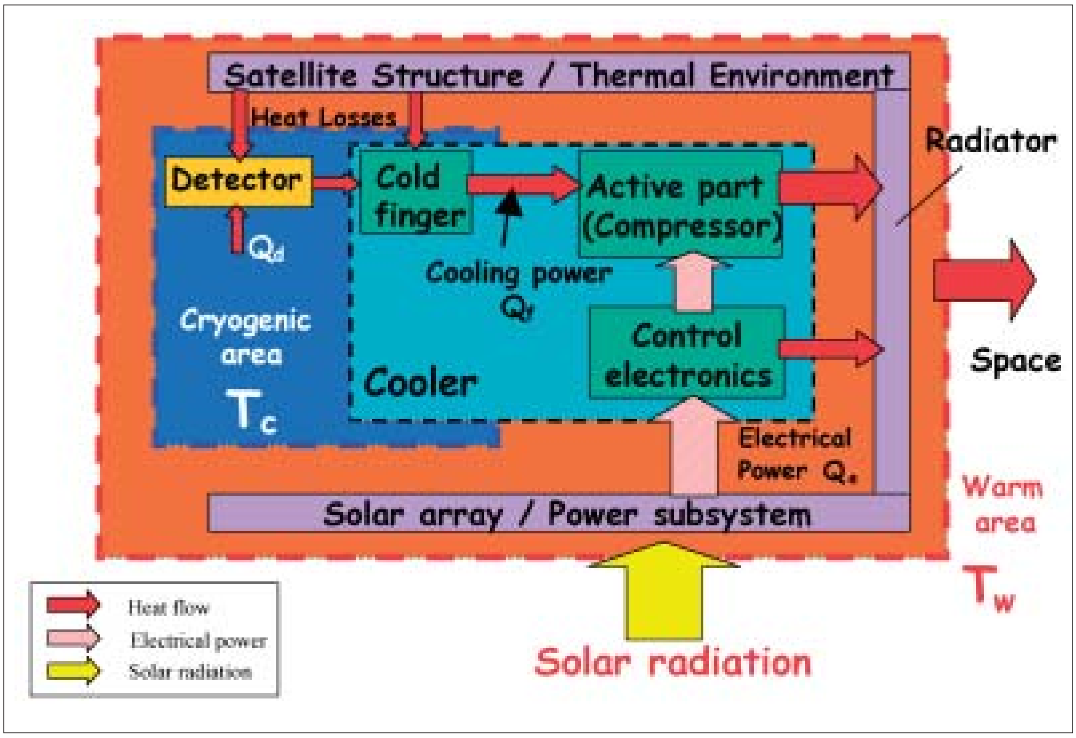

Figure 4. Schematic of a space cooler. Its cold end is interfaced to the focal plane (detectors), while its active part and control units are linked to the satellite structure and ultimately to the radiators. The heat load is minimised by thermally isolating the cryogenic area from the rest of the system

In all cases, some electronics is required to monitor the temperature, maintain it constant, or drive the cooler mechanisms. For higher temperature systems (T > 50 K), a single stage can be sufficient. For lower temperature systems, multiple-stage coolers or a chain of various types of coolers have to be used.

- Types of cooler

Radiators are the most efficient, simplest and more reliable space coolers. They are based on the fact that all objects emit infrared radiation in proportion to their surface area S, emissivity ε, and the fourth power of their temperature T, and on the fact that the deep-space environment is very cold (black body at T_0 = 2.73 K). The net cooling power is thus:

$$Q_{rad} = \sigma\ S\ F\ \varepsilon\ (T^4 - T_0^4) \approx \sigma\ S\ F\ \varepsilon\ T^4$$

where σ is Stefan's constant and F≈1 is the shape factor. Radiators are efficient above 100 K, but have limited performances at low temperatures (where the parasitic loads through the insulation increase) and also have size-related limitations (it is usually difficult to mount more than a few m^2 on a spacecraft). Figure 5 shows the actual performance of satellite radiators against the theoretical heat-rejection capabilities. Another limitation of

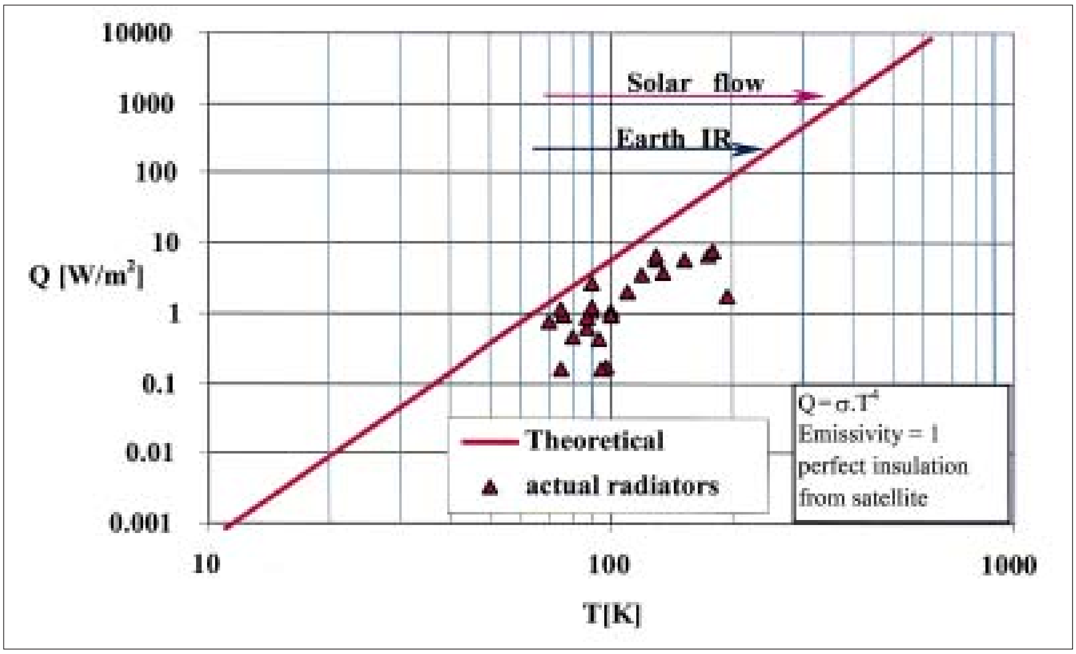

Figure 5. Radiator heat lifts as a function of temperature and area. Actual radiators deviate from theoretical expectations due to the actual emissivities of their surfaces. In practice it is difficult to run a passive radiator at T< 60 K, even in orbits far away from Earth

radiators is their orientation: they need to be shaded from solar radiation (1.4 kW/m^2), and from the Earth's infrared and albedo radiation (about 300 W/m^2 for the Earth), and to look towards deep space in order to radiate efficiently. This is a severe limitation that can be managed only by constraining the spacecraft's attitude and manoeuvring, together with careful baffle and shield design to reject the unwanted radiation. In addition, it is often necessary to have multiple-stage radiators, thereby increasing their complexity.

There is therefore a lower limit to the temperature and cooling power that can be achieved with radiators. For low Earth orbits (e.g. Earth-observation satellites), the temperature limit is about 100 K, with a cooling power lower than 1 W/m^2. For geostationary orbits (at 36 000 km, e.g. telecommunication satellites), the temperature limit can be reduced to 75 – 90 K. For far-away orbits (e.g. Lagrangian points), the Earth radiation constraint vanishes, and the radiator architecture becomes simpler, with lower temperatures and better performances. In the case of Planck, it is expected to have a cooling power of about 2 W and a temperature of about 50 K; in the case of NGST or Darwin it is estimated to have a cooling power of 200 mW at about 35 K.

A stored-cryogen cooler is composed of a cryogen tank, a vacuum vessel (isolating the cryogen tank before and during launch), filling and venting lines, heat shields/multi-layer insulation, and some interface or volume for instrument accommodation. In the absence of gravity, the fluid needs to be maintained inside the tank by a phase separator (based on capillary forces, or the fountain effect for superfluid helium). For ground dewars, the cryostat neck is normally used as a filling and venting line in addition to supporting the inner cryogen tank. Due to the dynamic loads present during the launch, space dewars are not compatible with this architecture. A separate venting line is used to use the gas enthalpy efficiently to cool the shields, and to release the gas without applying momentum to the spacecraft. In space, it is also possible to cool the whole vacuum vessel by radiation to space and by the venting line (as opposed to on the ground, where the tank must be at room temperature to avoid condensation). The ISO vacuum vessel, once in space, was at 110 K; the Herschel vessel is expected to be at 77 K, and that of SIRTF at 5 K. In addition, the bath equilibrium pressure is not 1 bar as on the ground, but it is vented to the vacuum of space. This allows a pump on the cryogen bath and the use of solid cryogens, which require no phase separator. The proper design of the exhaust nozzle allows tuning of the base temperature (vapour pressure) of the cryogen bath by adjusting the pressure drop. The volume of cryogen to be carried depends on the mission's duration and on the heat input. The choice of the cryogen depends on the base temperature required. The cryogens available do not provide a continuum of temperatures, but rather discrete values in different ranges. The most widely used are superfluid or supercritical helium, solid H_2 and solid Ne. An overview of the choices made for different missions is presented in Table 4. For low-temperature systems, to optimise the cryogen mass it is more interesting to use a bi-cryogen system, such as N_2 and He, or H_2 and He.

Table 4. Cryostat/cryogen choices for a number of spacecraft

Mission	Cryogen
IRAS, COBE, ISO, Herschel, SIRTF	Superfluid ^{4}He
IBSS, STEP	Supercritical ^{4}He
WIRE	Solid H_2
XRS on ASTRO-E	Solid Ne
NICMOS	Solid N_2

In a mechanical (or active) cooler, mechanical work produced by moving parts is transformed into refrigerating power. There are many ways to classify active coolers. The most widely used is to distinguish between regenerative cycles (Stirling, pulse tube, Gifford coolers) and recuperative cycles (Joule-Thomson or Brayton coolers). The regenerative coolers are based on a pressure wave generated by a compressor (usually mechanical), and a cold finger, using a mobile (Stirling, Gifford) or a fixed (Pulse Tube) regenerator. The heat is extracted at the cold end when the gas expands, and rejected at the warm end when the gas is compressed. The recuperative cycles use the enthalpy difference between high- and low-pressure gas. The Brayton-cycle coolers use a cold turbine to expand the gas, whereas the Joule-Thomson coolers use the expansion through an orifice, and the properties of real gas to get the cooling effect. Being irreversible, the Joule-Thomson cooler (normally coupled to Stirling units) is less efficient than the Brayton type, but is simpler.

The main difference between ground and space coolers lies in the lifetime required. A lifetime of 5 years is a typical requirement for most space applications, which means that friction between moving parts must be minimised. This has led to the development and qualification of coolers based on the 'Oxford compressors': this compressor uses a linear drive, while the leak tightness of the compressed volume is guaranteed by a tight clearance seal (about 10 µm). A diaphragm spring is then used to maintain an alignment compatible with such a small gap, whilst still allowing the axial motion of the piston. Life tests as long as 8 years have been performed with this system and many such coolers are currently flying in space.

Another important limitation for space coolers is the electrical power demanded. A typical power allocation for a cryo-cooler is between 50 and 200 W. Most mechanical coolers (typically based on the Stirling cycle) have an efficiency of order 2 – 5% of the ideal Carnot cycle, implying a cooling power of a few mW at 4.2 K with an input power of about 100 W. Figure 6 provides a summary of the Coefficients Of Performance (COPs) of different active coolers as a function of temperature, in the form of the ratio between cooling power and absorbed electrical power. The COP is compared to the efficiency of the ideal Carnot cycle.

Mass also represents a critical parameter in the evaluation of space coolers, typically being limited to 100 – 150 kg. In addition, coolers should not generate vibrations degrading the performance of the sensitive detectors that they are supposed to cool down. Vibrating forces are generated as reaction to moving masses within the cooler, and such forces may cause elastic deformation of the instrument structure, either affecting its alignment or causing electrical interference in the form of micro-phonic pick-up.

To date most of the mechanical coolers proposed for space applications are based on the Stirling cycle or on the Joule-Thompson expansion, but more recently Pulse Tube Refrigerators (PTRs) have been proposed as an interesting alternative, due to their lack of moving parts and the reduced vibration level. Most of the development effort is concentrated on improving the efficiency of such coolers. A small PTR developed by Lockeed-Martin in collaboration with NIST (USA) has been flown onboard the Space Shuttle (mission STS-90), delivering 50 mW at 100 K, with an input power of order 10 W (COP = 0.005). TRW (USA) has also delivered several PTR units, including a system used in the AIRS instrument, to be flown onboard the Aqua (formerly EOS-PM) mission, with a cooling power of 1.75 W at 55 K (Table 3).

Finally, we should mention that a closed-cycle, hydrogen sorption cooler is being developed by JPL (USA), with the potential to offer a vibration-free alternative to mechanical coolers for the 50 – 20 K temperature range; such an approach is presently baselined for ESA's Planck mission.

- Very-low-temperature coolers (T < 1K).

In many scientific satellite applications it is

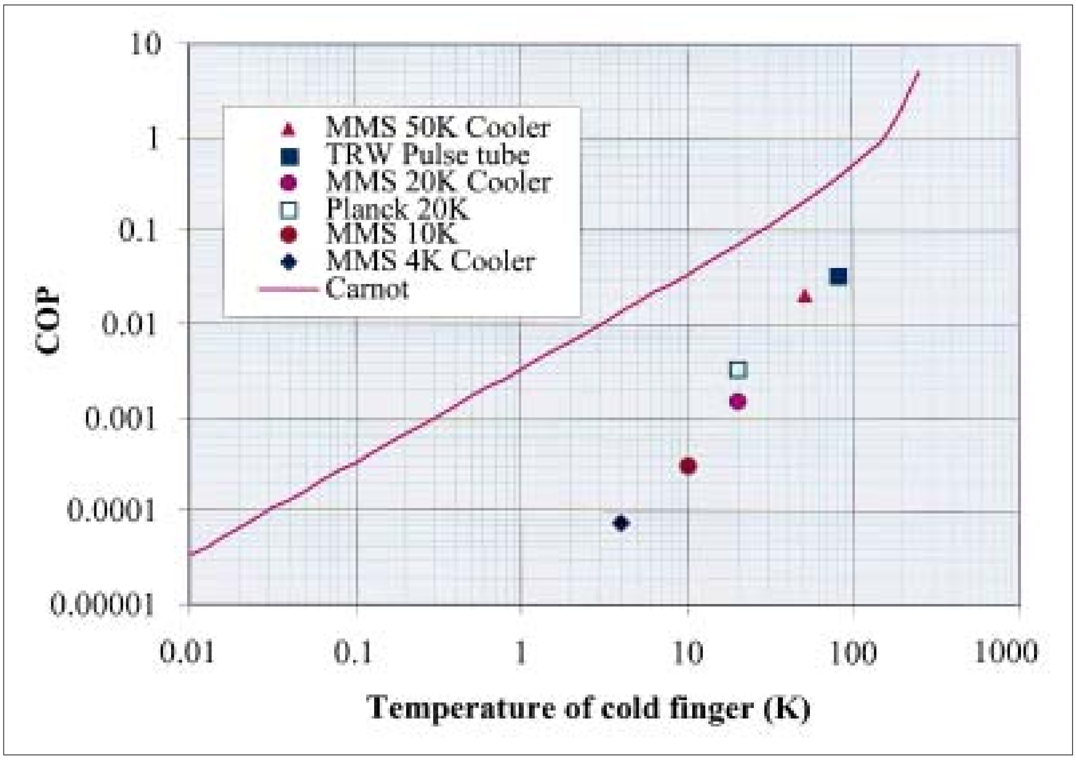

Figure 6. Coefficients Of Performance (COPs) of different coolers. The solid line represents the efficiency expected from an ideal Carnot cycle. The typical efficiency achieved at 10 to 20 K is of order 0.001

necessary to achieve even lower temperatures, well below 1 K. Such a temperature range can be achieved by using closed-cycle ^{3}He sorption coolers (down to 250 mK), by Dilution Refrigerators (50 mK) and by Adiabatic Demagnetisation Refrigerators (50 mK).

He sorption coolers offer interesting performances, due to the simplicity of their operation, the lack of moving parts, and the possibility to work in a closed cycle configuration with an efficient duty cycle (^{3}He condensation phase vs. hold time at base temperature). Their typical cooling power is of the order 10 µW at 300 mK. Sorption coolers have already been flown on balloons (Boomerang, Maxima, Archeops), on sounding rockets and on the SFU satellite (IRST - Infrared Space Telescope instrument). Sorption coolers will be used for the SPIRE and PACS instruments onboard Herschel (Table 2).

Dilution Refrigerators, based on the quantum-mechanical properties of ^{3}He – ^{4}He mixtures, are routinely used on Earth to achieve temperatures below 100 mK, with cooling powers exceeding 100 µW. This technique is now being adapted for space applications and it is planned to be flown on Planck (cooling power of order 0.1 µW). The absence of gravity and running the conventional mixture circulation in space are the main challenges of such a development. The proposed approach avoids the use of circulation pumps by working in open-loop mode, thus requiring a very large amount of gas mixture and offering a lifetime limited by the gas reservoirs. Alternative techniques may combine the capillary liquid confinement with a closed-loop system based on cryo-sorption pumps.

Adiabatic Demagnetisation Refrigerators have already been used on sounding rockets and scientific satellites (Astro-E). They produce base temperatures of 50 – 100 mK by reducing the entropy associated with the electronic spins of the atoms of paramagnetic salts. Forcing the electronic spins to align in a single direction via a magnetic field of a few Tesla reduces the entropy. Cooling powers of about 10 µW are achieved. ADRs offer very low base temperatures with simple operation and good duty cycle efficiency. The main challenges presented are the need for large magnetic fields (implying large currents and potential EMI issues) and for high-performance and high-reliability thermal switches. The use of an ADR system is baselined by ESA for the future XEUS mission (Table 3).

Solid-state coolers, analogous to Peltier elements but operating below 1 K, are also being investigated. They are based on metal-insulator-superconductors, which provide cooling of the lattice by relying on phonon-electron coupling and removing the hottest electrons present in the normal metal electrode of the device. Cooling of membranes from 0.3 K to 0.1 K has already been achieved. Such coolers are being developed with the aim of building self-cooling detectors (bolometers or STJs) with simpler pre-coolers (e.g. ^{3}He sorption coolers).

Thermal insulation and ancillary equipment

- Insulation technology for space

The goal of thermal insulation is to limit the heat loads on the cold stage to a level compatible with the cooler’s heat lift. Given the limited COP of space coolers, minimisation of the heat load is crucial to meeting the mission requirements. In space, conductive and radiative coupling represent the loss mechanisms to be reduced by thermally insulating the cold stages, which includes the use of low conductive supports, Multi-Layer Insulation (MLI) and shielding (e.g. V-groove shields).

- Ancillary cryogenic equipment for space

Cryogenic ancillary equipment plays a critical role during ground testing and must be adapted and qualified for space utilisation. The key items required onboard spacecraft are: high-thermal-conductivity links; heat switches; high-heat-capacitance devices; space-qualified temperature sensors; pressure, level and flow meters; cold filters/windows; cryo-mechanisms (e.g. choppers, filter wheels, grating devices); special paints and coatings; cryogenic cables and wiring.

Key technologies

Present situation and future needs

On the basis of the needs highlighted in the preceding sections, a number of critical technologies have been identified. The main issues involved and the envisaged development needs are outlined below.

Passive Radiators (in the 100 to 40 K range) play a major role on scientific satellites, thereby reducing the requirements imposed on active cooling systems. They need to guarantee high emissivity at low temperature (see role played by micro-cavities), while the related thermal isolation technology requires improvements. Design as well as testing tools are required.

Active Cooling Systems (between 100 and 50 K) are slowly moving from the pioneering phase of technology demonstrators to a mature commercial phase. Owing to the lack of a large customer base, the existing space-qualified coolers are very expensive (order of a million Euro) and quite heavy. In addition they remain a major source of vibration and their efficiency needs to be improved.

20 K coolers also have an important role to play as pre-cooling stages within more articulated and lower-base-temperature cryogenic systems. The Stirling-cycle-based coolers are not easily accommodated onboard spacecraft, while Joule-Thompson coolers are less efficient but more flexible, allowing the use of radiative pre-cooling. Modularity and cooling-power scalability are also important qualities to be pursued. Cryo-sorption-based systems represent an attractive alternative to be explored.

2 to 4 K coolers should provide larger cooling power (> 50 mW) in view of supporting lower temperature stages. Absence of (or low) vibration levels is also required in applications involving very-low-temperature coolers, sensitive detectors and high-accuracy spacecraft pointing and/or positioning (e.g. astrophysical observatory).

Very Low Temperature (VLT) coolers (T < 1 K) are becoming more and more important to space missions due to the use of very sensitive cryogenic detectors. A large effort is required to develop closed-loop, space-qualified coolers (such as ADR, DR, Sorption Coolers) providing sub-Kelvin temperatures and offering reliable performances and long lifetimes.

Miniaturisation also represents an important trend, since it should allow the reduction of heat losses, power consumption and sensitivity to vibrations. New activities are aimed at verifying the possibility of using micro-machining technologies to develop both active and solid-state miniature coolers.

Finally, ancillary equipment and devices should not be neglected. These include: high-conductivity thermal busses (e.g. heat pipes) and connections; low-thermal-conductivity and orbital disconnect supports; heat switches (important also for VLT coolers); cryo-mechanics; temperature-stabilisation devices and low-temperature measurement techniques.

Technology road-map

In Table 5 we have summarised the key areas to be explored in the future to produce significant advances in the field of cryogenics for space applications. The content of the table reflects what has been discussed in the previous sections, with the addition of considerations on the development time-scale and on the temperature range involved with each specific technology. The overall time scale considered is limited to the next 10 – 20 years.

ESA, within its Technology Research Programme, its General Support Technology Programme and certain specific projects, is active in most of the areas indicated in the table. Potential advantages are offered by improved co-operation between ESA and other institutions of the European Union (e.g. in the field of materials science, such as advanced composites).

The smallness of the market for cryogenics for space applications (e.g. qualified mechanical coolers) has meant high costs and has drastically reduced the number of suppliers. To improve the situation, it is necessary to promote the maximum possible compatibility between space and ground products, thus widening the potential market base. To this end, future development activities should include the space qualification of cryogenic systems largely based on or derived from Commercial Off-The-Shelf (COTS) units, originally developed for ground-based applications.

Conclusions

The field of cryogenics has made remarkable progress over the last 15 years, moving from laboratory prototypes to commercial applications in several areas. Such progress, coupled with the advanced performance offered by cryogenic and superconducting devices, has triggered a virtuous cycle of ever-growing initiatives and new applications.

Reliability and simplicity of operation have made it possible to use cryogenics in space, albeit at the price of additional complexity and higher cost. Continuous improvements have resulted in longer lifetimes and reduced risk, with a number of design solutions, from cryostat- to mechanical-cooler-based systems, capable of covering a large range of instrument base-temperature requirements.

The use of cryogenically cooled devices on spacecraft, such as photon detectors, has brought unprecedented results, especially in the field of space science. Over the last 10 to 15 years, several missions have demonstrated that these devices can outperform any competing technology.

An emerging trend is the development of complete cryogenic payloads, in which the use of cryogenic devices is extended to both the front-end electronics (e.g. low-noise amplifiers

Table 5. Technology road-map for cryogenics in space

Area	Critical technologies	Time (yr)	T (K)
Coolers	High-efficiency, low-T passive radiators	>5	<60
	Improved-efficiency, large-size dewars	>5	<4
	Low-vibration, high-COP Stirling coolers	>10	<10
	High-COP, space-qualified PTR	>10	4-80
	Space-qualified compressors based on turbines	>10	<10
	High-COP, miniaturised active coolers	>15	<50
VLT	Optimisation of space-qualified ADR	>5	<0.1
	Development of closed-loop DR	>10	<0.1
	Space qualification of sorption coolers.	>2	<0.5
	Solid state coolers based on NIS devices.	>10	<0.3
Thermal Insulation	Orbital disconnect supports.	>5	<10
	Very low emissivity coatings.	>2	<50
	Improved V-groove shields.	>2	<100
Ancillary Equipment	Cryogenic heat pipes for Space.	>5	<10
	Cryogenic heat switches for Space.	>10	<10
	IR absorbing paints.	>10	<10
	Space thermometry/in-flight calibration.	>10	<4
	Pressure / level / flow meters.	>5	<4
	Cryo-mechanisms (e.g. filter wheels).	>5	<10
	Cryo-optics, large area cooled mirrors.	>5	<50
	Cryogenic wiring for low amplitude signals.	>5	<10
	High heat capacitance devices.	>2	<10
	Testing facilities (e.g. vibrating table at low T).	>2	<10
Materials	High Temperature Superconductors films/wires.	>5	>80
	Low Temperature Superconductors devices.	>5	<10
	Advanced composite materials for cryogenics.	>10	300-1

and input multiplexers) and back-end electronics (e.g. output multiplexers and superconducting digital electronics), in addition to the more traditional detectors and optics applications. The development of cryogenic payloads for space calls for a system approach, involving the complete spacecraft design from the outset of the project. Clear examples are set by several space-science observatories that are built around their cryogenic tanks, or by the crucial role played by spacecraft geometry and by mission control in the case of passively cooled instruments.

Several technologies need to be improved to extend the application of cryogenics in space, including active mechanical coolers, thermal-insulation techniques and the miniaturisation of equipment, with the goal of reducing heat losses, as well as the sensitivity to vibrations. The development of high-conductivity thermal busses and connections (e.g. heat pipes), low-conductivity or disconnect supports, heat switches, temperature-stabilisation units and low-temperature measurement techniques, are all necessary to improve cryogenic payloads further.

In this article we have discussed the dominant space-engineering trends and the guidelines along which cryogenic technologies are expected to develop in the next 10 years. The importance assigned to it by the leading space organisations indicates that cryogenics is going to play a strategic role for many future space missions.