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Power Requirements and Energy Recovery in Stirling and Pulse Tube Cryocoolers for Space Missions

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Abstract. Space cryocoolers permit cryogenic cooling of space-based astronomy instruments and a range of other sensors and detectors across electromagnetic wavelengths. This study investigates the energy requirements and performance of various cryocooler designs, with a focus on Stirling, pulse tube, and Stirling pulse tube cryocoolers (SPTCs). These systems are essential for missions requiring high reliability, minimal vibrations, and efficient cooling. The Stirling cryocooler utilizes a displacer to transfer heat efficiently, while the pulse tube cryocooler achieves low vibration by eliminating moving parts at the cold end. The SPTC integrates advantages from both systems, offering high efficiency and minimal thermal noise, making it particularly suited for next-generation space missions. Key aspects analyzed include power requirements, cooling efficiency, and energy recovery mechanisms. Innovations such as displacers for energy recovery and advanced phase shifters are highlighted, demonstrating their impact on improving system performance. Comparative evaluations reveal the operational trade-offs between different cryocooler types, emphasizing the importance of design choices for specific mission requirements. The study investigates in further detail the SLSTR cryocooling instrument on-board Sentinel-3 and pulse tube systems in the James Webb Space Telescope, and discusses the design considerations undergone to permit their long-term reliability and precision. Despite advancements, challenges remain in optimizing energy usage and further reducing thermal noise. This work consolidates knowledge on cryocooler technology, providing a foundation for future research and development. By addressing current limitations and exploring novel energy recovery methods, the study paves the way for more efficient and reliable cryogenic systems in space exploration.

1. Introduction

Cryogenic cooling plays a vital role in enabling high-performance instrumentation in space missions across disciplines such as astrophysics, Earth observation, and planetary science. From radio receivers to far-infrared detectors to X-ray microcalorimeters, many scientific instruments operate at cryogenic temperatures to reduce thermal noise, improve signal-to-noise ratios, and stabilize thermally sensitive components. The emergence of cryocoolers has revolutionized this capability by eliminating the need for expendable cryogens, thus supporting longer mission durations and reducing system mass and complexity. Space cryocoolers have now become integral components in flagship missions such as the James Webb Space Telescope (JWST) [1], Planck [2], and Hitomi (Astro-H) [3], where their reliability and performance directly enabled the scientific data obtained from these groundbreaking space missions.

Two of the most commonly used cryocooler architectures flown in space are Stirling cryocoolers and pulse tube cryocoolers (PTCs). Stirling cryocoolers offer high thermodynamic efficiency by implementing a closed-cycle regenerative process with a moving displacer to achieve gas compression and expansion [4]. Meanwhile, PTCs eliminate all moving parts at the cold end, substantially increasing reliability and reducing vibrational interference at the cold head, which is an important consideration for sensitive optical instruments to be integrated at this surface [5]. In recent years, hybrid systems such as Stirling-type pulse tube cryocoolers (SPTCs) have emerged, combining the efficiency of Stirling systems with the low-maintenance architecture of PTCs [6, 7, 8]. These systems are being increasingly adopted for missions where strict power budgets, minimal mechanical wear, and long-term thermal stability are mission-critical [9].

Despite the advances in cryocooler technologies, key challenges remain in optimizing power consumption, improving energy recovery mechanisms, and tailoring thermal architectures for varying mission profiles. With CubeSats and small satellites entering domains traditionally dominated by flagship missions, there is a growing demand for compact, power-efficient cryogenic systems. This study provides a brief overview of state-of-the-art Stirling and PTC performance in space, including case studies from current and past missions [1, 2, 3, 10], and explores how energy recovery innovations, such as displacer-based expansion energy recovery [6, 11] and phase-tuning techniques [5, 12], can enhance cryocooler efficiency.

2. Cryocooler Technologies for Spaceflight

2.1. Stirling Cryocoolers

Stirling cryocoolers operate based on a closed regenerative thermodynamic cycle in which a piston and displacer drive periodic compression and expansion of helium gas. The regenerator is typically made from a porous material such as stainless steel mesh and stores and transfers heat between the hot and cold ends of the cycle allowing for enthalpy transfer. The system undergoes two isothermal processes (expansion and compression) and two isochoric (constant volume) heat transfers [13]. The primary appeal of Stirling cryocoolers lies in their relatively high thermodynamic efficiency and compact design, making them particularly suitable for missions with moderate cryogenic demands (typically between 40 K and 90 K, as a single-stage unit).

Spaceflight-qualified Stirling cryocoolers often incorporate linear compressors, flexure-bearing suspensions, and hermetically sealed chambers to improve reliability and minimize mechanical wear [4, 14]. As discussed, one challenge associated with these systems is the presence of moving parts at both ends, which can introduce vibrations detrimental to sensitive instruments integrated at the cold end. To mitigate these effects, many systems use dual-opposed piston configurations that cancel out net vibrations. Applications include Earth observation instruments like the SLSTR on Sentinel-3, where long-term thermal stability, low mass, and modest cooling power are essential. The balance of efficiency and simplicity has made Stirling cryocoolers a standard technology in low-Earth orbit (LEO) remote sensing payloads [15].

2.2. Pulse Tube Cryocoolers (PTCs)

Pulse tube cryocoolers operate without any moving parts at the cold end, relying instead on pressure oscillations generated by a compressor and phase tuned by inertance tubes or orifices [13]. This phase lag allows the regenerator to effectively absorb heat from the warm gas and transfer it to the cooler gas during the cycle, enabling net cooling at the cold end [5].

As discussed, the absence of moving parts in the cold head enhances mechanical reliability, reduces wear, and eliminates vibrational interference. These advantages make PTCs a preferred solution for space telescope instruments, including the Mid-Infrared Instrument (MIRI) onboard the James Webb Space Telescope (JWST), where achieving very low temperatures (5–7 K) is critical for infrared sensitivity [1]. However, PTCs generally require higher input powers than Stirling coolers for equivalent cooling capacity, particularly at moderate temperatures. Still, the benefits of low maintenance, extended lifetimes, and adaptability to multi-stage designs have firmly established PTCs in the toolkit of cryogenic space systems.

2.3. Hybrid Stirling-Type Pulse Tube Cryocoolers (SPTCs)

Stirling-type pulse tube cryocoolers (SPTCs) seek to merge the thermodynamic strengths of the Stirling cycle with the cold end low vibration pulse tube. This configuration leverages the energy efficiency of the Stirling process while preserving the no-moving-parts advantage of the pulse tube at the cold tip. The result is a system capable of achieving low temperatures with higher thermodynamic efficiency and lower vibrational signatures than conventional Stirling machines [6].

SPTCs are particularly attractive for space missions where long life, minimal vibration, and precise thermal stability are critical, but where the extremely low temperatures of multi-stage PTCs are not

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required. They are yet to be flown in space, however, and research in SPTCs continue to increase the technology in Technology Readiness Level (TRL) [9].

3. Energy Recovery and Thermodynamic Optimization

3.1. Displacer-Based Recovery

At low power budgets, recovering energy from the expansion phase of the working gas can improve overall cryocooler efficiency by reducing net input power. Displacers at the warm end of the pulse tube or regenerator can harness mechanical or acoustic work from the residual pressure differential generated during gas expansion. This recovered energy, typically lost in conventional PTCs, can be redirected to assist in compression or drive auxiliary thermal management subsystems [13, 11].

From a thermodynamic perspective, the potential for energy recovery can be analyzed by comparing the ideal Stirling cycle to real processes with internal recovery stages. The net work W of the Stirling cycle is given by:

$$W = Q_H - Q_C, \tag{1}$$

where Q_H is the heat rejected at the hot end and Q_C is the heat absorbed at the cold end. In a regenerative system with recovery, a portion Q_{rec} of the expansion work can be utilized, effectively reducing the required external work:

$$W_{\text{net}} = (Q_H - Q_{\text{rec}}) - Q_C. \tag{2}$$

This becomes especially useful in multi-stage configurations, where the enthalpy difference between successive stages can be harvested through inter-stage pressure modulation. The instantaneous power available from a displacer moving gas through a regenerator of cross-sectional area A and velocity v under a pressure difference ΔP is:

$$\dot{W}_{\text{rec}} = A\, v\, \Delta P. \tag{3}$$

Mechanical implementation of such recovery often requires non-linear valves, tuned displacer kinematics, or feedback-regulated pistons. These components must be optimized to avoid introducing phase mismatches or parasitic thermal loads. Experimental studies have demonstrated recovery gains up to 10–15% of total input work under idealized laboratory conditions, offering promising avenues for future flight systems [6].

0.1 Phase Control and Inertance Tuning

In pulse tube cryocoolers and hybrid SPTCs, effective phase control is essential for ensuring a favorable thermodynamic lag between pressure $P(t)$ and mass flow rate $\dot{m}(t)$. This phase lag maximizes the regenerator's ability to transfer enthalpy and allows for net heat pumping at the cold end. Without sufficient phase separation, the acoustic power within the tube is dissipated inefficiently [5].

The key governing equation for phase shift in an inertance tube is derived from fluid dynamic impedance analysis. The pressure drop ΔP across an inertance tube of length L, diameter d, and density ρ can be approximated under laminar oscillating flow as:

$$\Delta P = \frac{8\mu L}{\pi d^4}\dot{m}(t) + j\omega\rho L\frac{\dot{m}(t)}{A}, \tag{4}$$

where μ is the dynamic viscosity, A is the cross-sectional area, and ω is the angular frequency of oscillation. The imaginary part introduces a time-dependent phase shift, critical to synchronizing pressure and flow waveforms.

The inertance tube effectively behaves like an acoustic inductor, while the gas reservoir acts as a capacitor. This forms an acoustic RC circuit, and the resulting phase angle ϕ between pressure and flow can be tuned by adjusting the length and volume of the components:

$$\tan(\phi) = \frac{\omega R_g V_r}{Z}, \tag{5}$$

where R_g is the gas constant, V_r is the reservoir volume, and Z is the characteristic impedance of the system [13].

In multi-stage coolers, maintaining independent phase control for each stage is critical to preventing thermal backflow and achieving stable cold tip operation. This is especially relevant in hybrid architectures, where inertance tuning must be coordinated with the displacer's stroke and phase reference.

Advanced implementations include variable-orifice or actively modulated inertance tubes to allow in-situ tuning. These are increasingly used in laboratory and prototype systems for spaceflight applications where environmental and mission changes (e.g., orbital eclipse, instrument load variation) require real-time optimization.

4. Spaceflight Cryocoolers: Case Studies

4.1. MIRI (JWST)

The Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST) required unprecedented cooling performance for a space observatory, targeting an operational temperature of 6.7 K and achieving a measured 5.9 K for optimal detector performance. To achieve this, a hybrid pulse tube cryocooler and JT system was developed by Northrop Grumman, consisting of a warm-stage compressor located in the spacecraft bus, an intermediate stage to reach 18 K, and a Joule-Thomson (JT) stage to reach the final 6 K temperature. The coldest stage used helium gas as the working fluid, expanded through a JT valve at low pressure. The cryocooler was connected to the focal plane via a roughly 10-meter-long high-conductance heat pipe that minimized vibration transfer from the compressor and accommodated JWST's large deployable architecture [1].

During initial operation, the total input power peaked at 245 W during the long cooldown phase, reflecting the thermal inertia of MIRI's optics and baffles. Once equilibrium was reached, power consumption stabilized between 145–170 W in science mode. The design prioritized ultra-low vibration and long operational life, achieved by separating the mechanical components from the science instruments and employing no moving parts at the cold tip. The 4-stage PTC-JT architecture demonstrated a significant advancement in space cryocooler integration, overcoming the challenges of long-distance thermal transport and intermittent orbital heat loads while preserving high detector sensitivity in the 5–28 μm spectral range.

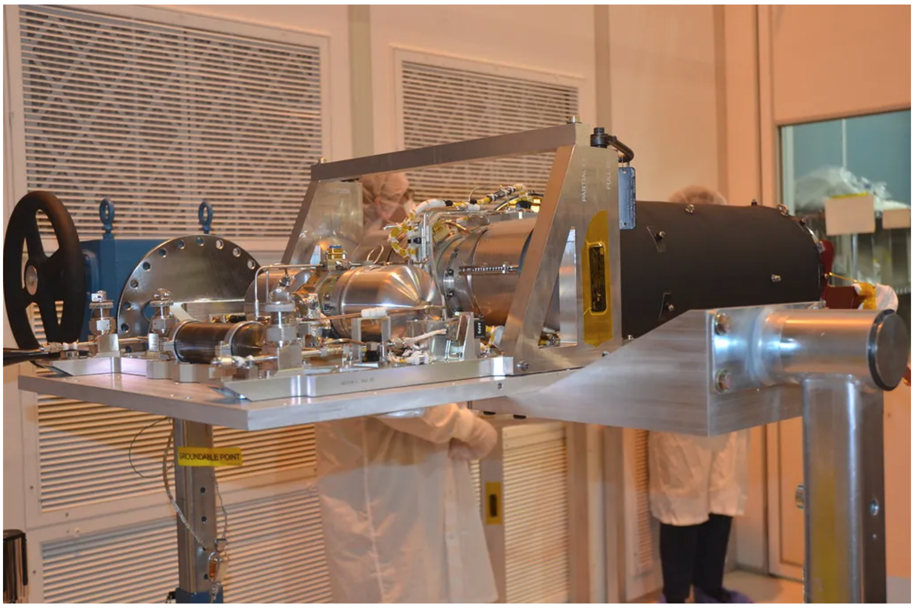

Figure 1. JWST's MIRI instrument cryocooling system. Image credit: NASA/JPL, reproduced from [16].

4.2. Planck Space Telescope

The Planck mission, launched by ESA in 2009, was designed to map the anisotropies of the cosmic microwave background (CMB) with high precision. To achieve the necessary detector stability and sensitivity, Planck employed a cascade of cryogenic systems, including passive radiative cooling down to $\sim$50 K, followed by active cooling using a hydrogen sorption cooler (down to 20 K), a mechanical Stirling cooler (to 4.5 K), and finally a closed-cycle dilution refrigerator for sub-Kelvin cooling. This configuration allowed the High Frequency Instrument (HFI) bolometer arrays to operate at 0.1 K, making it one of the coldest temperatures ever achieved in space [2].

The total cryogenic chain required over 350 W during cooldown, including power for compressors, valves, and radiators. The 20 K sorption cooler used reversible metal hydride beds to cycle hydrogen gas through a JT valve, while the 4 K stage was maintained using mechanical compressors with high reliability and minimal microvibrations. The dilution refrigerator combined ^{3}He and ^{4}He isotopes in a continuous flow system, producing stable temperatures below 100 mK. The complexity of this system underscored the importance of multi-technology cryogenic integration and set a benchmark for future cosmic microwave background missions such as LiteBIRD and CMB-S4.

4.3. Astro-H (Hitomi)

The Astro-H (Hitomi) satellite, developed by JAXA and launched in 2016, featured one of the most sophisticated cryogenic systems for X-ray astrophysics. Its Soft X-ray Spectrometer (SXS) required a stable operating temperature of 50 mK to achieve its 4–7 eV energy resolution goals. This was enabled through a 2-stage Stirling cryocooler that cooled the SXS dewar to 4.5 K, combined with a subsequent adiabatic demagnetization refrigerator (ADR) for sub-Kelvin temperatures [3]. The Stirling units were driven by linear compressors, and their compact inline design allowed integration with minimal heat leakage and vibration.

The cryocooler system consumed approximately 300 W and included redundant compressor systems to ensure long-term reliability over the expected multi-year mission lifetime. The SXS was shielded by multiple thermal isolation stages and vibration isolation mounts to maintain spectral integrity. Unfortunately, the mission was lost shortly after launch due to an attitude control failure, but the cryogenic system performed nominally up to that point. The technology demonstrated on Hitomi served as the basis for the XRISM (X-ray Imaging and Spectroscopy Mission), launched in 2023, continuing Japan's legacy in advanced cryogenic X-ray instrumentation, as well as opening doors in space-based Very Long Baseline Interferometry in the radio astronomy domain [17, 18].

Table 1 provides an overview of cryocoolers deployed in key space missions.

Table 1: Cryocooler Performance Summary from Key Space Missions

Mission	**Cooling Temp (K)**	**Input Power (W)**	**Type**	**Reference**
JWST (MIRI)	5.9	145–245	4-stage PTC-JT	[1]
Planck	0.1	350+	Sorption + JT	[2]
Astro-H	4.5	300	2-stage St + JT	[3]
SPICA	16	90	Multi St + JT	[10]
SLSTR (Sentinel-3)	85	90	Stirling	[15]

5. Discussion

The suitability of a cryocooler for a given space mission is dictated by a multidimensional set of requirements beyond just target temperature. These include input power constraints, thermal load variability, mass and volume budgets, mechanical complexity, long-term reliability, and acceptable vibration levels. For instance, Earth observation missions in low Earth orbit may prioritize lightweight, modest-temperature cryocoolers with high duty cycles, while deep space or cosmology missions may demand ultra-low temperatures and extreme thermal stability. Hybridized cryocoolers, especially Stirling-type pulse tube cryocoolers (SPTCs), are increasingly attractive in this context, as they allow different thermal stages to be independently optimized, enabling more efficient thermal load handling across a wide dynamic range. Their hybrid architecture merges the robustness of pulse tube designs with the tunability of displacer-driven phase control, making them ideal for mid-to-low temperature missions requiring minimal maintenance over multi-year lifetimes [19].

Looking ahead, emerging cryocooler designs are incorporating several innovations aimed at improving adaptability and integration. These include active vibration suppression systems, fault-tolerant and redundant compressor configurations, and real-time feedback electronics to tune phase relationships and inertance settings based on changing mission conditions. As CubeSats and microsatellites begin to carry more sophisticated payloads, such as quantum sensors or IR telescopes, there is a growing push to miniaturize cryocooler subsystems while preserving core performance characteristics. Energy recovery strategies, including displacer-based work harvesting and inter-stage heat regeneration, could prove critical for enabling such platforms by reducing net power demands. Additionally, scalable architectures that allow parallelization of cold stages or swap-in modularity could usher in a new era of customizable, mission-adaptive space cryogenics.

6. Summary

Stirling and Stirling-type pulse tube cryocoolers have demonstrated remarkable adaptability and efficiency across a broad spectrum of space missions, from moderate-temperature Earth observation instruments to sub-Kelvin cosmology payloads. Their ability to balance thermodynamic performance with mechanical simplicity and long operational lifetimes makes them ideal candidates for both current and next-generation observatories. As future missions target more stringent thermal requirements, such as ultra-low temperatures for infrared detectors or long-duration stability for quantum payloads, energy-efficient architectures with finely tuned phase control will become increasingly vital. Hybrid systems that integrate Stirling compression with pulse tube expansion offer a promising compromise, minimizing vibration while enabling multi-stage flexibility. Moreover, recent advancements in displacer-based energy recovery and adaptive inertance tuning show potential to reduce cryocooler power consumption by up to 20%, enhancing mission viability for power-limited platforms such as CubeSats and interplanetary probes. These developments underscore the critical role of cryogenic engineering in extending the scientific reach of space exploration.

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