# Mid-Infrared Instrument Cryocooler on James Webb Space Telescope: Cooldown, Commissioning, and Initial Performance

**Konstantin Penanen[1], Kimberly Banks[2], David Breda[1], Bradley Moore[1], Bret Naylor[1], Michael Petach[3], Analyn Schneider[1], Kalyani Sukhatme[1], Mark Weilert[1]**

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[2]Goddard Space Flight Center, Greenbelt, MD
[3]Northrop Grumman Space Systems, Redondo Beach, CA

## ABSTRACT

The focal plane modules and the optical bench of the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST) require temperatures below 7K to operate. While other, near-IR, instruments in the Observatory are cooled passively, MIRI cryogenic components are cooled by a dedicated distributed 4-stage hybrid Pulse Tube/Joule-Thomson mechanical cryocooler, spanning all of the Observatory's regions. The MIRI cryocooler is designed to meet stringent heat lift, thermal stability, power draw, exported vibration, and reliability requirements. Cryocooler components stowed for launch are designed to be released as part of the JWST deployment sequence. Cryocooler pneumatic and thermal control configurations are progressed through a coordinated sequence as the Observatory is cooled. Here, we describe the initial stages of MIRI cryocooler commissioning and present functional performance results after the first five months on orbit.

## INTRODUCTION

NASA's flagship infrared observatory, James Webb Space Telescope, launched on December 25, 2021, from the European overseas equatorial spaceport in Kourou, French Guiana, on top of an Ariane 5 rocket. JWST's focal plane is partitioned between four major instruments, all residing inside the Integrated Science Instrument Module (ISIM): NIRCam, NIRSpec, FGS/NIRISS, and MIRI. Of these, NIRCam, NIRSpec, and FGS/NIRISS cool passively. MIRI is the only instrument that requires active cooling. This is needed in order to bring MIRI's arsenic-doped silicon focal plane arrays (sensitive to longer, 5-27μm, wavelength range) to the required ~6.4-6.7K operational temperatures. Besides the detector arrays, the entire MIRI optical bench is cooled to below 7K. The thermal environment for MIRI is provided by a dedicated mechanical cryocooler, the subject of this article.

To support the initial cooldown and transition to science operations on site at the JWST Mission Operations Center (MOC), a MIRI cryocooler commissioning team was assembled. The team was comprised of personnel from the Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), and the Space Telescope Science Institute (STScI). A remote team of subject matter experts from NGSS, JPL, and GSFC, heavily drawn from the implementation team, participated in commissioning data reviews and was on standby to address any anomalies.

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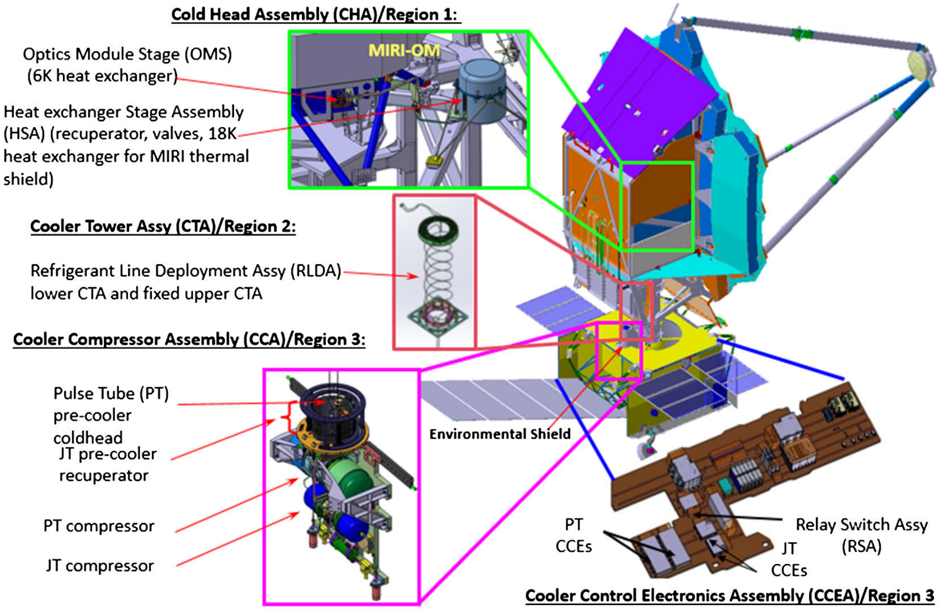

**Figure 1**. Location of the MIRI Cryocooler components throughout the JWST Observatory.

As described elsewhere [1-3], the MIRI Cryocooler is a hybrid 4-stage cooler consisting of a three-stage Pulse Tube (PT) precooler and a single Joule-Thomson (JT) stage (see Figure 1). The thermo-mechanical unit is partitioned into a Cooler Compressor Assembly (CCA), placed in the Spacecraft bus, with dedicated radiators extracting heat at near room temperature, and Cooler Cold Head Assembly (CHA), co-located with the MIRI instrument optical bench, which includes the JT constriction and gas-flow switching. The CCA houses the three-stage PT precooler driven by a linear compressor, and a JT circulator, driven by another linear compressor. The Cooler Control Electronics Assembly drives the compressors, provides telemetry and commanding functionality, and operates valves, heaters, accelerometers, and temperature and pressure sensors. The CHA provides a cooling interface to the optical bench and focal plane modules at the 6K Heat eXchanger (6K HX), and an interface to the MIRI shield, at near 20K. The Heat exchanger Stage Assembly (HSA), a part of the CHA, houses the flow control solenoid and pressure-actuated valves, and the JT cooling stage. Both the HSA and the PT precooler employ counterflow heat exchangers (recuperators). The CHA and the CCA are connected by the refrigerant lines that run along the telescope tower and along telescope and instrument metering structures. The lines accommodate telescope tower deployment with a coiled segment called Refrigerant Line Deployable Assembly (RLDA), stowed and contained for launch.

Organizationally, MIRI is a 50/50 ESA/NASA partnership, with JPL and MIRI European Consortium responsible for the deliveries. MIRI EC delivered the instrument optical bench assembly and the associated electronics. JPL delivered the MIRI Focal Plane System (focal plane modules, focal plane electronics, and focal plane harnesses), the MIRI Cryocooler, and ISIM-resident application software for all MIRI subsystems. Northrop Grumman Space Systems (NGSS) is the key industrial partner for the Cryocooler, responsible for the overall cryocooler design, build, and technical performance. The RLDA, the HSA hexapod, the piloted cryogenic valve, and parts of cooler electronics were built by JPL; GSFC built sections of the refrigerant lines and line supports. GSFC also built the MIRI Optical Module (OM) radiative shield, an integral part of the MIRI thermal design. Acceptance testing for the MIRI cryocooler at the subsystem level was conducted at JPL.

## MIRI CRYOCOOLER OPERATIONS AND COMMISSIONING OVERVIEW

At the start of commissioning after launch, the cryocooler is configured to decontaminate the refrigerant lines and the JT constriction while MIRI cools passively till MIRI reaches ~100K. Helium cooled by

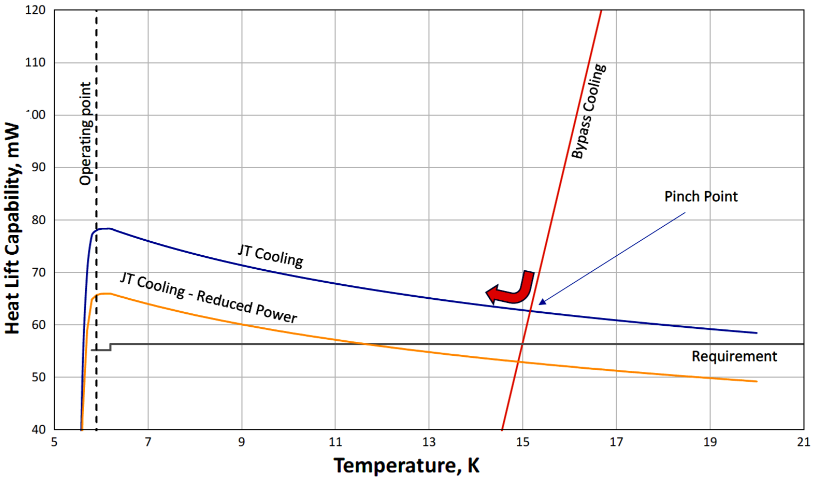

**Figure 2**. Notional Heat Lift Capability vs. Temperature curve. PT precooler capability drops precipitously near ~15K. Transition from bypass cooling to JT cooling is achieved by actuating cryogenic valves to force the flow through the JT constriction near the point of lowest heat lift capability: "Pinch Point."

the PT precooler is then circulated through the 6K HX, bypassing the JT constriction, to cool MIRI to ~15K (see Figure 2). To achieve further cooling, the gas is forced through the JT constriction. Cryocooler 'Pinch Point' is defined as the minimum point on the heat lift capacity vs. temperature curve, where the cooler is transitioned from the bypass cooling to JT cooling. For the MIRI Cryocooler, via its characterization and acceptance testing, this Pinch Point was chosen at ~15K. After the Pinch Point traverse, the JT cooling further cools MIRI to its operating temperature of ~5.9K at the 6K HX. MIRI cryocooler then maintains this steady state through the science operations, subject to a reduced power allocation.

## MIRI CRYOCOOLER TELEMETRY

The MIRI Cryocooler generates several dozen key housekeeping telemetry elements out of a suite of over 2000 telemetry items. These include temperatures throughout the thermo-mechanical unit and electronics, compressor waveform telemetry, JT loop pressure, as well as command and telemetry diagnostics and status. The cadence of telemetry downlink is specified in ISIM and Spacecraft filter tables. During cryocooler-centric operations, real time telemetry is available as frequently as once per 4 seconds for critical telemetry elements. In nominal operations, real time housekeeping telemetry is updated once every ~60 seconds. Housekeeping telemetry is also stored on board, at higher rates, and is generally downlinked when high-rate communication is available. Mission-phase-specific alarm values have been provided by the design team to alert any out-of-nominal conditions.

## MIRI TELEMETRY MONITORING

During Observatory Commissioning, Cooler real-time telemetry is monitored from the JWST MOC at STScI. Cryocooler commissioning team personnel were on-site continuously, with additional subject-matter personnel added during cryocooler-specific activities. To lessen the in-person presence at the MOC in the midst of the COVID pandemic, a reliable remote monitoring facility was also established at JPL. Display pages of telemetry items, along with their alarm status, were available. In addition, a custom MIRI Cryocooler graphical representation with key status and telemetry items was available (see Figure 3).

## MIRI CRYOCOOLER OPERATIONS PLANNING

JWST and MIRI operations have been exercised on the ground through an extensive test campaign [4]. The highest fidelity testbed for exercising the cooler hardware components is the MIRI System Testbed at JPL, where a flight-like Cryocooler and thermal representations of the MIRI Shield and the MIRI optical bench assembly with a functional stand-in for Focal Plane System, are also present. Mission

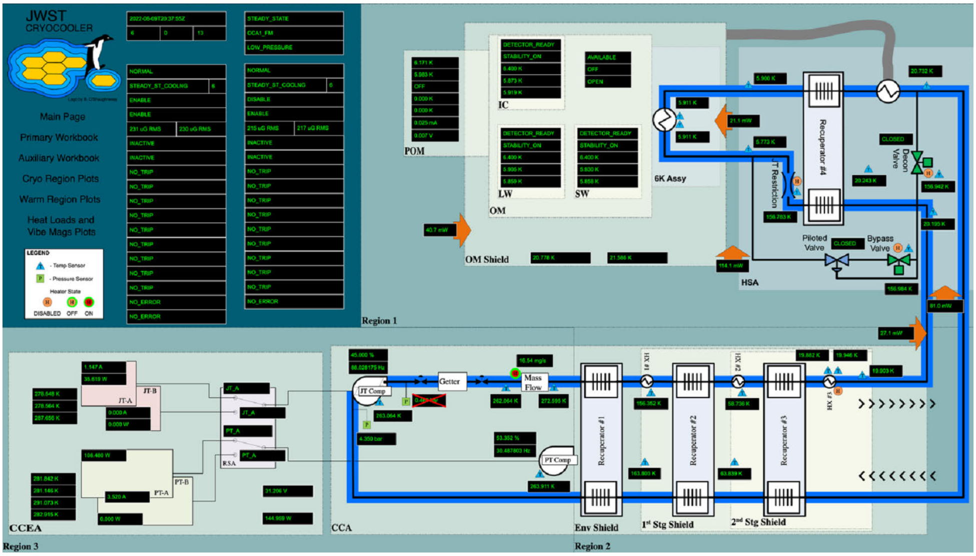

**Figure 3**. Cryocooler-centric MIRI telemetry display (“heatmap”). The snapshot captures Cryocooler and MIRI condition during science operations, with actively temperature-controlled focal plane arrays and Cryocooler interface to MIRI optical bench controlled at 5.9K. Active path of the working fluid, through the JT constriction, is shown in blue. Large orange arrows indicate heat flows. Housekeeping telemetry for the cryocooler control electronics assembly is also displayed. The logo graphics is by B. O’Shaughnessy.

operations products, such as standard operating procedures and prepared scripts, have been developed in the testbed and validated in ISIM, Spacecraft, and Observatory integration and test.

## CRYOCOOLER OPERATION IN SAFE HAVEN MODE; COOLER FAULT MONITORING AND RESPONSE

The MIRI Cryocooler is designed to handle its own faults (for example, over/under temperature, overcurrent), and can operate autonomously in case telemetry is disrupted or lost. However, loss or interruption of power to the compressors would result in a time-consuming effort to restore the thermal operating environment for MIRI, as well as for the rest of the instruments in ISIM. Observatory fault response therefore accommodates maintaining cryocooler power through low-risk Observatory Safe Haven (fault response) events. MIRI Cryocooler power remained uninterrupted throughout commissioning.

A fault commonly observed in ground testing was a so-called “knock trip”. Both JT and PT compressors carry an accelerometer that is capable of detecting low-level vibration synchronous with the compressor drive, and is also capable of detecting sharp asynchronous shocks. In response to significant shock events, the compressor drive is lowered (attenuated) moderately. Repeat shock events bring the compressor into standby, where the telemetry is retained, but compressor drive and heaters are disabled.

Designed to respond to an inadvertent piston stroke or centering excursion, the accelerometers also react to external sources of shock. One source of such shock events is thermal settling of the cryocooler structure, including its composite environmental shield. The event is well characterized and understood, based on ground testing. It is not considered anomalous, and a standard recovery procedure has been put in place and practiced. During commissioning, as of this writing, the PT compressor has experienced three attenuation events, and the JT compressor has experienced one. There were no transitions to standby. The compressors were not driven at the time of shock-inducing Observatory deployments early in commissioning.

## LAUNCH, DEPLOYMENTS, AND POWER-ON

MIRI, as other instruments, remained powered off at launch. Limited indications of MIRI Cryocooler environment were available through spacecraft-monitored temperature sensors at the cryocooler compressor assembly heat rejection interfaces. Following launch, a number of highly choreographed Observatory deployments were performed. Of particular note, deployments with critical cryocooler performance implications were the launch vehicle separation, extension of the Deployable Tower Assembly, the release of the Cooler Jitter Attenuation Assembly, the release of the cryocooler compressor assembly launch locks, and the deployment of the Spacecraft radiators, all uneventful. The first opportunity to ascertain the health of the cryocooler following launch and deployment came with the power-up of the Cooler electronics on Day 10 of the mission.

## INITIAL PASSIVE COOLDOWN AND DECONTAMINATION

In the initial stages of Observatory cooldown, thermal exchange was dominated by passive radiative cooling, as expected. Critical to instrument optical performance, and to eventual low-temperature thermal performance, was the management of volatile contamination, primarily water ice, at the external surfaces of the instruments. MIRI, tucked away in ISIM and under a dedicated thermal shield (MIRI Shield), was the slowest instrument to cool passively. However, cryocooler refrigerant lines that snake from the spacecraft, along the tower, and into ISIM, have low thermal mass and are exposed. To avoid line external contamination, the MIRI cryocooler was configured to circulate gas at a low rate, with thermostatic (bang-bang) temperature control aimed at maintaining the lines (and the HSA) temperature above the water band (see Figure 4). This circulation also aimed at mitigating any internal contamination settling at the JT constriction and the flow passages within the cryogenic valves. The circulating helium passed through a getter in the compressor assembly, to scrub the gas of any residual volatiles. In this stage of operation, minimal power (approximately 3 W) was drawn by the JT compressor, with the PT compressor remaining off. The circulating gas did not reach the MIRI optical bench; the flow was bypassed through an open latched decontamination bypass valve located within the HSA.

During cooldown through the water band, the MIRI focal plane modules were heated by integral heaters, in order to establish a temperature gradient that drives water ice off. The decontamination heater power is negligible in comparison to other thermal drivers throughout the cooldown.

Following the decontamination stage, the MIRI cryocooler JT compressor was stopped, and the PT compressor was brought up to an intermediate power (~25% of maximum), which eventually cooled the

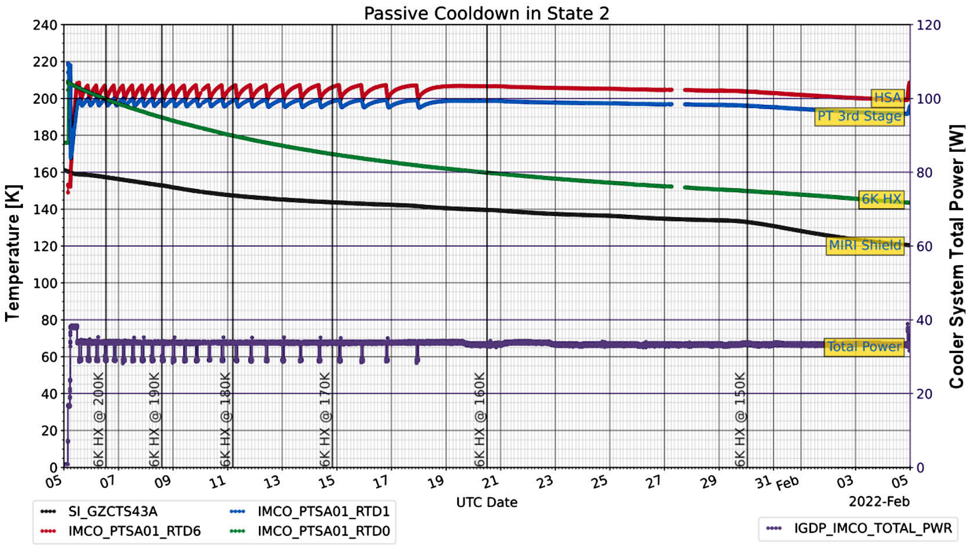

**Figure 4**. MIRI Cooldown through Water Band during Observatory commissioning. MIRI OM temperature (green) and MIRI shield (black) are cooling passively. The heat exchanger stage assembly (red) and the third stage of PT precooler (blue) are kept near 200K. Crycooler total power (purple, right axis) reflects the tare power, power to the JT compressor, and power to the heaters at the HSA. Time is indicated as Day of Year (DOY) in 2022, in Coordinated Universal Time.

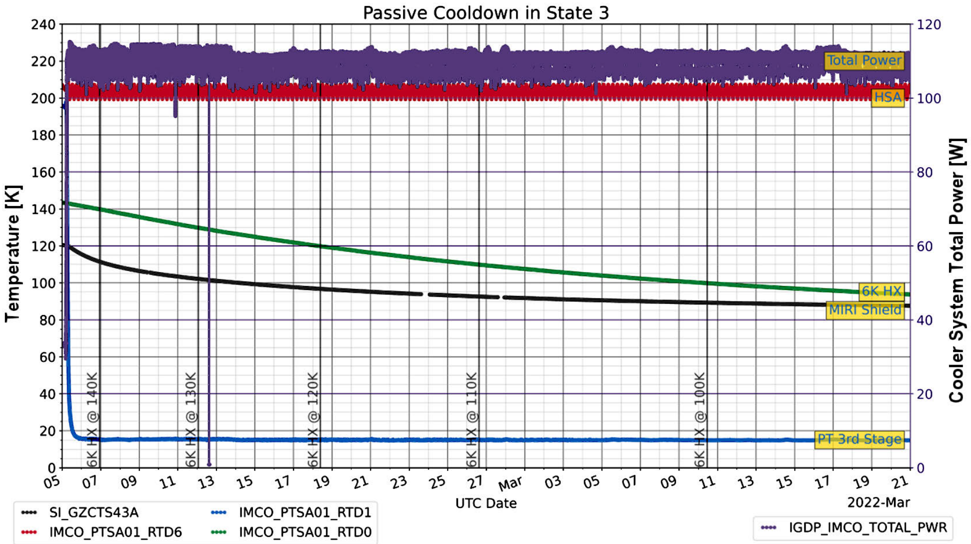

**Figure 5.** Continued passive cooldown of MIRI OM (green) and OM Shield (black). PT compressor is operated at an intermediate power. The temperature of the HSA (red) is thermostatically controlled near 200K. Cooler system total power (purple) varies due to heater power changes.

3rd stage of the PT precooler to ~15K (See Figure 5). The HSA thermostatic control remained on, to maintain the valves and JT constriction within the HSA warmer than the rest of the JT circulation loop. The system remained in this state for several weeks, until the other JWST instruments cooled off sufficiently to be able to start assessment of the Observatory optical performance and any effect that cryocooler compressors may have on it.

## BYPASS COOLDOWN

Once the initial assessment of the telescope optical performance was successfully achieved, the MIRI Cryocooler transitioned into bypass cooldown (See Figure 6). In this mode, the gas precooled by the PT stages is forced to flow through the 6K HX. The decontamination bypass valve is closed, while the Joule-

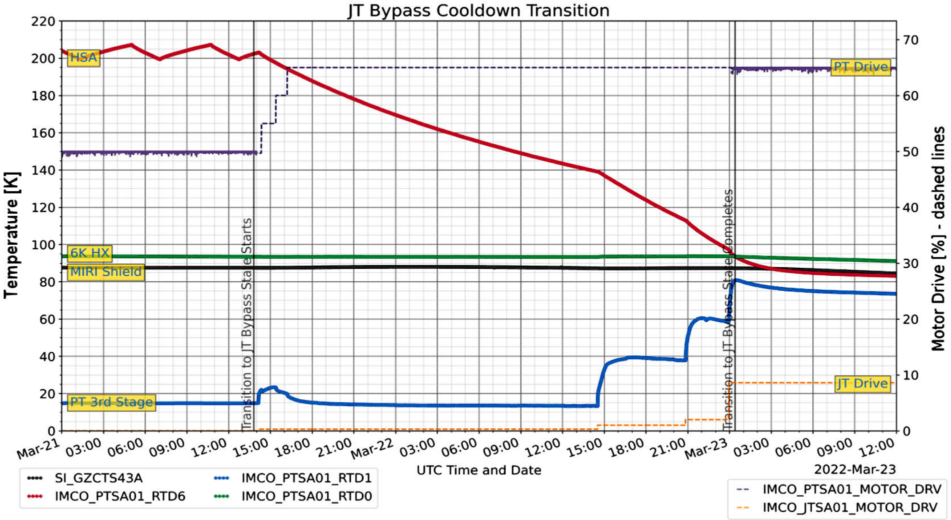

**Figure 6.** Initial 72 hours of JT Bypass transition. HSA thermostatic control (red) is turned off; PT precooler power is increased (purple dashed line), and JT circulation is slowly resumed (orange dashed line). Active cooling of MIRI OM (green) and MIRI Shield (black) begin.

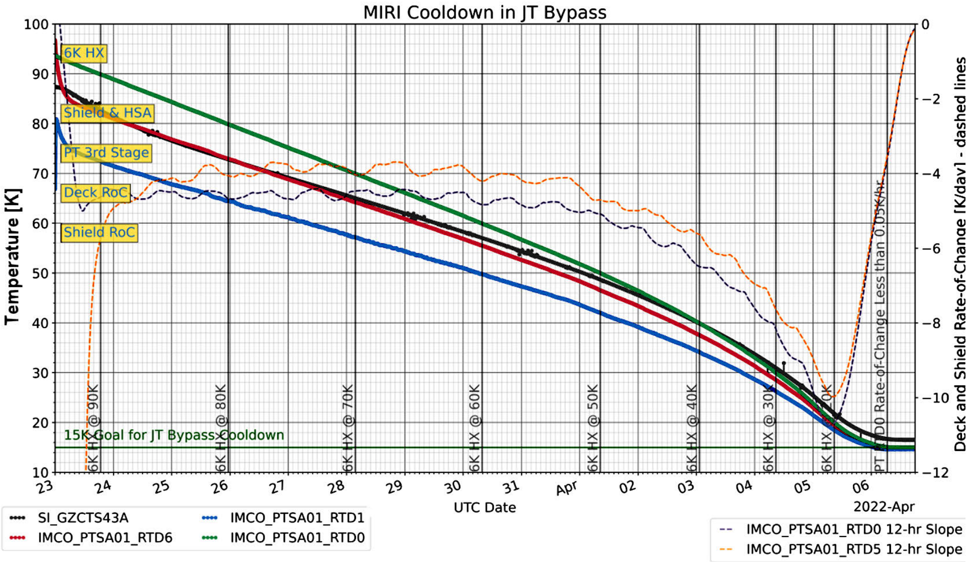

**Figure 7.** Completion of JT Bypass Cooldown. Temperatures of MIRI OM (green), MIRI Shield (black) and PT third stage (blue) trend to JT bypass goal. Temperature rates of change for MIRI OM (orange dashed line) and MIRI Shield (blue dashed line) are also shown.

Thomson bypass valve (JT bypass) remains open; the thermostatic control of the HSA is stopped. The rate of radiative cooling for MIRI had slowed substantially as the temperature of the OM had reached ~90K, and the effect of active cooling was dramatic.

A late change to the planned operation in this bypass mode was necessitated in response to the launch vehicle clamp band unplanned release anomaly. During anomaly resolution before launch, the cryocooler was tested successfully at room temperature to rule out any gross damage, but it was not possible to test it out fully. In order to mitigate risk of any latent damage during commissioning, this late change was implemented.

The initial concept of operation had the cryocooler power turned up to the maximum allowed by the PT compressor capability (still within power allocation) to achieve the fastest cooldown. Compressor drive required in operation subsequent to bypass cooling had been determined to be substantially lower, because of heat load and performance margins that remained available.

Rather than applying full rated power to the PT compressor, a decision was made to limit the power during bypass cooling to be consistent with the minimum power needed in the approach to pinch point (see below) and then in the transition through the pinch point. This approach added several days to the cooldown timeline, but avoided an unnecessary risk of stressing the compressor (See Figure 7).

Before using the updated concept on flight hardware in commissioning, the new bypass cooldown sequence was fully validated in a dedicated MIRI System Testbed run at JPL.

Due to the durations involved, MIRI on-ground testing did not fully exercise either the passive cooling or bypass cooling stages. The testbed testing at JPL did validate cooling rates at several intermediate temperatures and allowed thermal model correlations. Bypass cooldown duration, with the adjusted cooldown power, was estimated ahead by the Observatory thermal team. As performed timeline was a close match to these predicts.

## APPROACH TO PINCH POINT

By design, bypass cooldown of MIRI was aimed at a 15-20K temperature floor. At the lower end, the temperature was limited by the tested capability of the MIRI shield hardware. Operationally, the PT compressor was configured to operate in a temperature control mode, with the goal temperature at 15K.

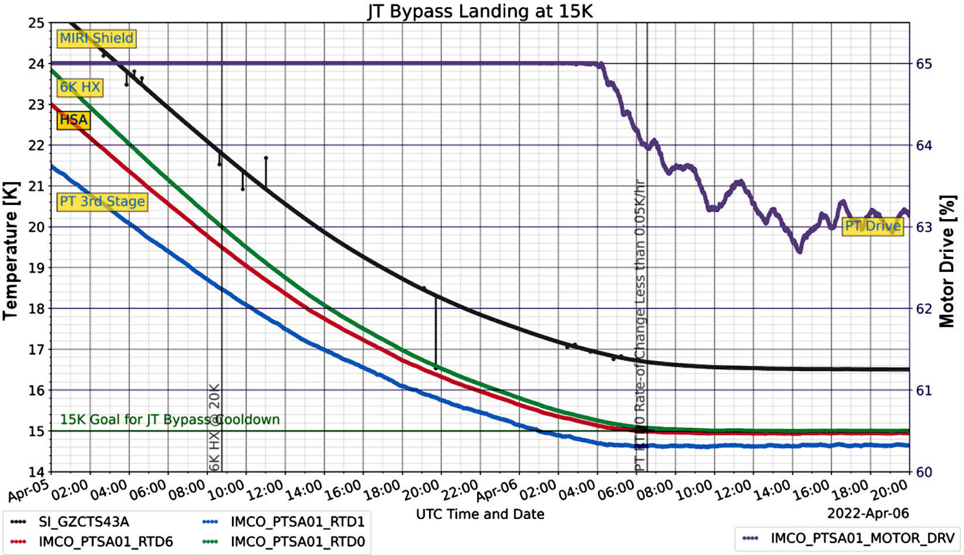

**Figure 8.** Approach to Pinch Point at completion of JT bypass cooldown. As the temperature control implemented in Cooler electronics lowers the PT compressor drive (purple), MIRI OM (green), MIRI shield (black), the HSA (red), and the PT precooler third stage (blue) all stabilize.

In the temperature control scheme, the drive to the PT compressor is varied based on temperature feedback from a sensor at the 6K HX (See Figure 8). As the goal temperature is approached, the drive is lowered. Once the pre-established stability criteria are met, the cryocooler operational environment is assessed. In particular, the parasitic heat loads on the optical module, as well as the heat loads on the MIRI shield and refrigerant lines are measured. This thermal balance point is also an opportunity to assess the on-orbit performance of the cryocooler thermo-mechanical unit, by measuring the power required to achieve cooling at a given temperature. Both the loads and the heat lift performance were consistent with ground testing performance.

## PINCH POINT TRANSITION AND COOLDOWN

Closing the JT bypass valve and increasing compressor drive to force helium through the JT constriction is the most active portion of MIRI cooldown. It is also the most choreographed, after having been performed 25 times in ground testing at the Cryocooler level and in the JWST integration and test campaign, on flight and flight spare MIRI cryocooler hardware. The time sensitivity of these operations comes from the negative slope of the heat lift vs. temperature curve characteristic to cryocoolers relying on the Joule-Thomson effect (see Figure 2). Any delay in completing all the steps required to establish continuous cooling has the potential of needing to re-configure the cryocooler back into bypass cooling mode and starting again, causing disproportional delays and incurring additional valve operations. The on-orbit pinch point transition was uneventful and consistent with ground testing (see Figure 9). The PT compressor power is increased to provide cooling margin during this transition. The solenoid JT bypass valve is then closed, with confirmation provided by an observed JT loop pressure change. JT compressor power is then set higher to generate the pressure drop needed to induce JT cooling.

The inverted heat lift curve and decreasing heat capacity of the optical bench results in accelerated cooling as the temperature is lowered. This trend is arrested near the eventual science operation temperature (5.9 K at the 6K HX), where the heat lift is again slowed, and parasitic loads rise. In the pinch point cooldown, the PT compressor power is programmed to decrease as the temperature lowers. This helps avoid runaway cooling and any JT loop instability that was observed early in ground testing. Once the OM temperature cools below 5.4 K, JT compressor drive is lowered to slow down the cooling as the instrument approaches operational temperature.

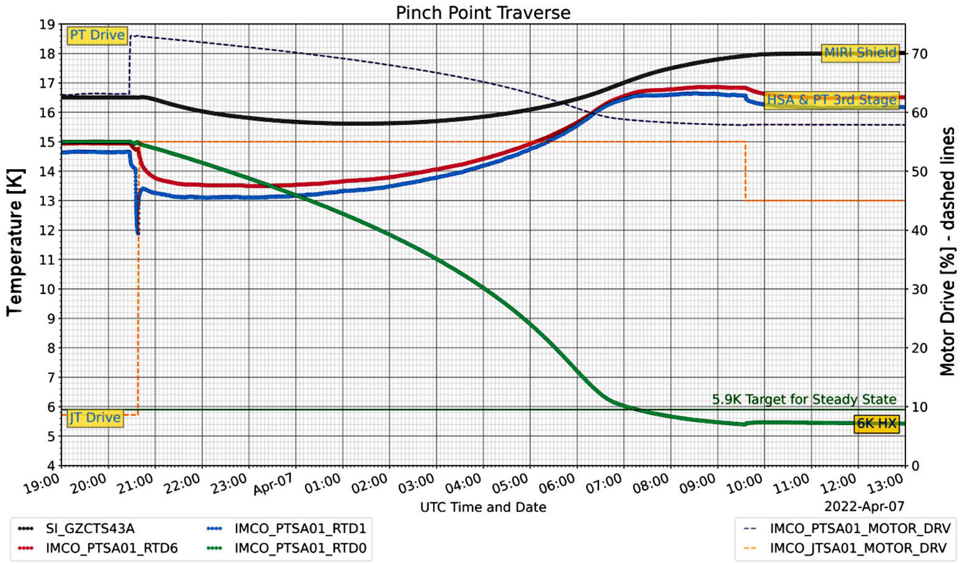

**Figure 9.** MIRI Cryocooler Pinch Point traverse during commissioning. As the JT bypass valve is closed and flow is driven through the JT constriction (orange dashed line), the OM (green) cools, while the HSA and MIRI shield (red and black) warm up. PT compressor drive (purple dashed line) is algorithmically lowered as the OM temperature drops.

## INSTRUMENT CONDITIONING AND CHECKOUT

Once the instrument reached 7K, MIRI detector and mechanism checkouts were initiated. These involved several thermal dissipation events associated with filter and grating wheel checkout and run-in, contamination control cover operation, MIRI pick-off mirror heater checkout, and initial detector anneal characterization. In this period, the MIRI cooler remained in the pinch point cooldown mode, to moderate the impact of large temperature excursions (see Figure 10).

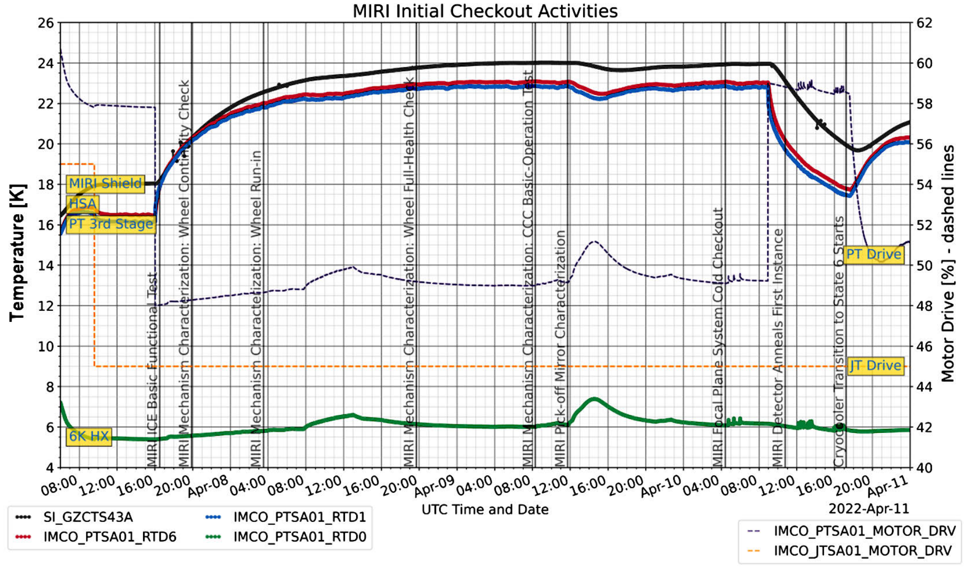

**Figure 10.** MIRI OM (green), PT Third Stage (blue), HSA (red) and OM Shield (black) during high-powered MIRI checkout. JT drive (orange dashed line) and PT drive (purple dashed line) are also shown. PT compressor drive remains algorithmically tied to OM temperature.

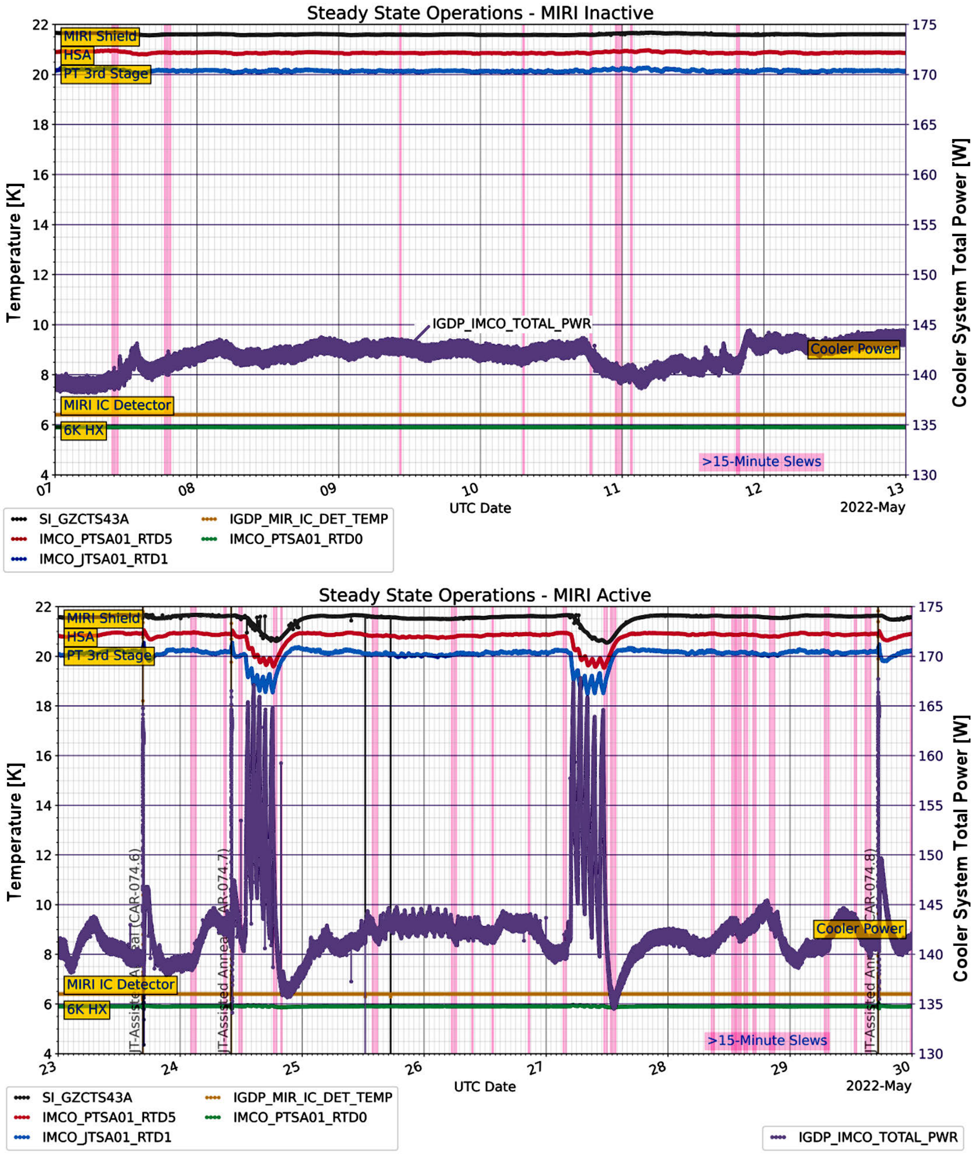

**Figure 11**. MIRI temperatures while MIRI inactive (top) and active (bottom) - 6K OM (green), Imager focal plane module IC detector (tan), PT precooler (blue), HSA (red) and MIRI shield (black). Compressor total power is shown in purple. Power variation in bottom graph is due to active temperature control reacting to energy pulses due to MIRI OM mechanism operations.

## STEADY STATE TRANSITION

Once the instrument mechanism checkout was successfully completed, the MIRI cryocooler was transitioned into Steady State operation mode. Here, the cooler PT electronics again exercise a temperature control algorithm that closes the feedback loop between the 6K HX readings and PT compressor drive (see Figure 11). The temperature control loop has a time constant of tens of minutes to hours, with complex heat load and heat lift interplay between cryocooler, optical bench, and MIRI shield components. MIRI thermal control had been exercised with representative heat loads and heat load variations in ground testing, and is now performing on orbit as expected.

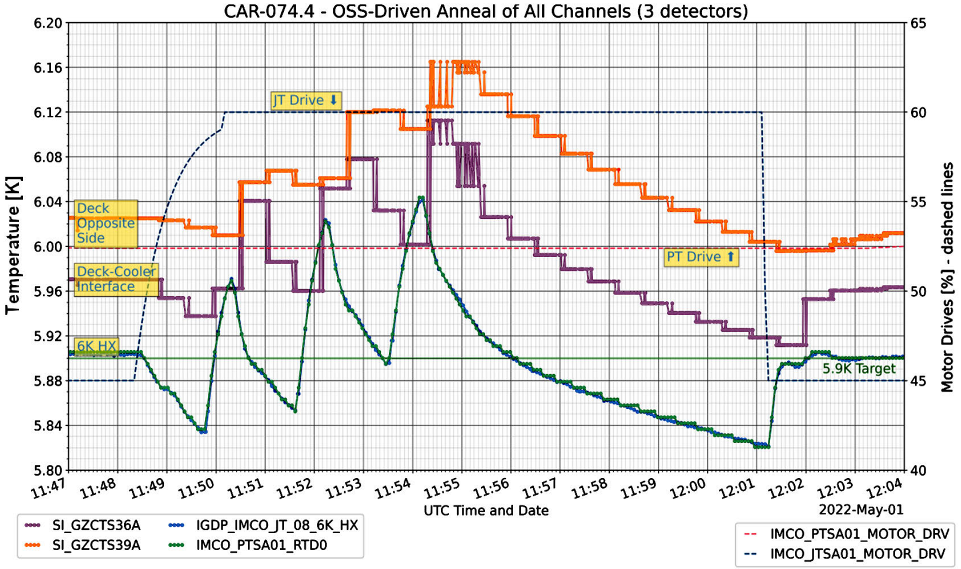

**Figure 12.** Representative 3-detector anneal. Temperatures at several locations on MIRI OM is shown - Cooler 6K HX (green), OM deck at Cooler interface (purple), and Deck, opposite to Cooler interface (orange). JT compressor drive (blue dashed line) is increased to provide heat lift that removes the heat impulse due to anneals.

## JT-ASSISTED ANNEALS

MIRI focal plane arrays experience undesired image persistence due to cosmic rays and bright object exposures. To mitigate these, MIRI FPMs undergo anneals, during which the detectors are heated to ~20K for several tens of seconds to help dissipate charges within the array (see Figure 12). This results in several tens of Joules of thermal energy that reaches the optical bench through heat links. Because the timing of these events and energy dissipation in them is highly predictable, the cryocooler exercises a sequence of steps that greatly reduces the recovery time compared to the default temperature control algorithm. These anneals and the JT-assisted recovery sequence were tested on the ground and adjusted as part of on-orbit commissioning. The parameters were confirmed to be as expected and only minor adjustments were needed.

## CRYOCOOLER ENVIRONMENT

Cryocooler performance relies heavily on its compressor-assembly heat rejection system performance (see Figure 13). The CCA rejects heat through a number of heat pipes to a pair of dedicated radiators. The heat pipe interfaces were equipped with an array of spacecraft-provided thermostatically-controlled heaters, to provide make up heat at the lower range of the allowable flight temperatures. Due to low thermal loads and efficient cooler operation, the power dissipation of the cryocooler remained low enough for some of the thermostatic controls to remain engaged. The Cryocooler experienced a high of 271K at the PT compressor during pinch point transition; it operates with its reject temperatures between ~260K and 268K at the beginning of life in Steady State science operations, consistent with the predictions.

## CRYOCOOLER EXPORTED VIBRATION

Cryocooler compressor and pulse tube motion generates periodic disturbance (jitter) at the cooler drive frequencies (~30Hz for PT and ~90Hz for JT), and at their harmonics. While MIRI, with its longer wavelength range, is not particularly sensitive to jitter, the potential effect on near-infrared instruments was a concern. A number of design mitigations and a dedicated jitter characterization test on the ground were implemented. On-orbit wavefront and line of sight jitter measurements showed no measurable impact from cooler operations, including during JT-assisted anneal compressor drive increases.

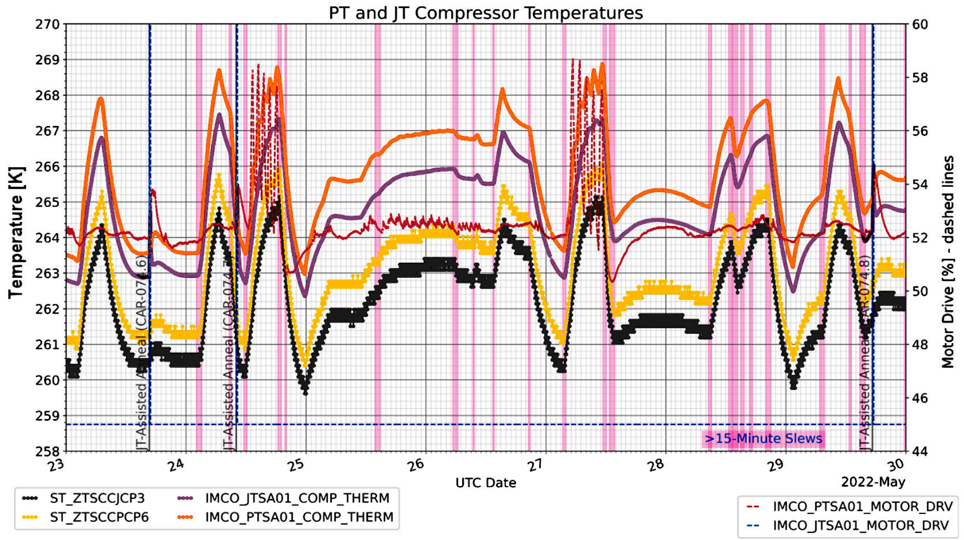

**Figure 13.** Temperatures at Cooler heat rejection interfaces during Steady State operations. JT compressor body (purple), PT compressor body (orange), heat pipe interfaces (yellow and black). Compressor drive is also shown - PT (dashed red) and JT (dashed blue).

## CRYOCOOLER PERFORMANCE AND POWER CONSUMPTION

Key performance parameters for the MIRI Cryocooler, codified in the subsystem requirement set, are the minimum acceptable heat lifts at its 6K HX and 18K interfaces, under worst case heat rejection environments, and subject to power allocations. The cryocooler is also required to meet temperature stability at short (1000 second) and long (24 hour) time scales when subjected to specified load variations.

The beginning-of-life heat loads are substantially lower than the heat lift requirement; the heat rejection interfaces likewise run at substantially lower temperatures than the worst case. Consequently, the power consumption achieved during cooldown and in steady state is substantially lower than the allocation. The thermal stability requirement is also met (see Figure 14).

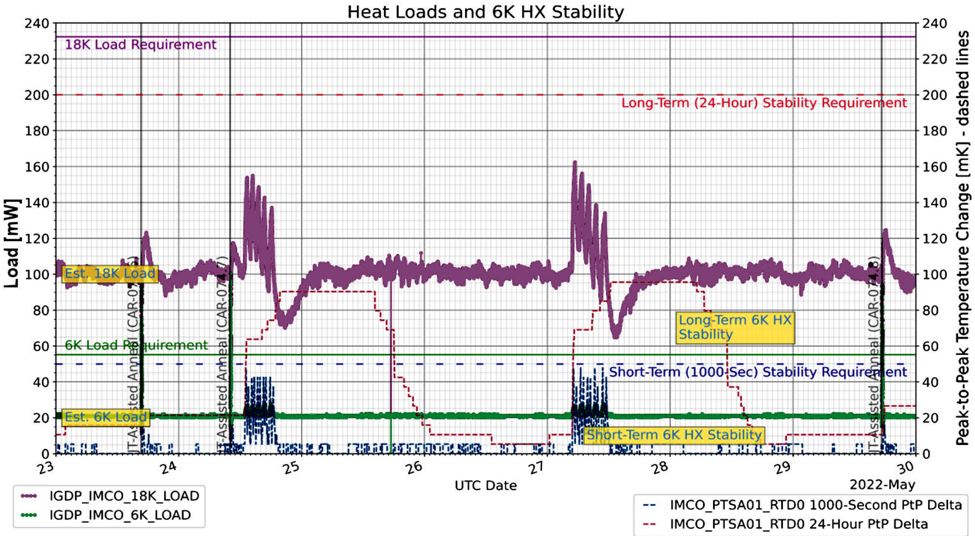

**Figure 14.** Estimated heat loads and heat load requirements at the 6K (Optical Module) interface (green) and at 18K conductive and radiative interfaces (purple) in steady state operations. Also shown are typical achieved short term (1000 seconds) and long term (24 hour) temperature stability trends vs. their requirements (blue and red dashed lines).

The cooldown power allocation was 475W, with the maximum power draw seen in cooldown of 245 W during the Pinch Point traverse.

Steady state operation is achieved with maximum draw of 180 W during JT-assisted anneal, and maximum of 170W (145W typical) during MIRI observations. This compares to a 400W allocation.

We note that the MIRI cryocooler is operated based on knowledge and experience acquired in its ground testing. The concept of operation was designed to remain robust to a variety of contingencies.

## CONCLUSIONS

JWST launch, Observatory deployments, arrival at L2 and cool down, and the start of instrument operations in commissioning were a complicated interplay, technically and organizationally, of a large dedicated JWST team. Successful MIRI cryocooler commissioning described in this article was only possible because every step in this interplay was completed flawlessly. The overall cooler performance to date falls within the modeled and tested range of pre-flight predicts. Throughout commissioning, no deviations from the prepared procedures were needed, and the MIRI cryocooler commissioning established the on-orbit performance baseline, both for key performance parameters (efficiency, power draw, temperature stability, etc.), as well as for the housekeeping telemetry items. A number of these parameters will be watched regularly for any adverse trends.

## ACKNOWLEDGMENT

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