# Transient Thermal Model of the JWST MIRI Cryocooler

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## ABSTRACT

This paper describes a transient thermal model of the James Webb Space Telescope (JWST) Mid-Infrared Instrument (MIRI) cryocooler, including the active control loops in the cooler and lumped approximations of the MIRI and JWST observatory. The model predictions are compared with data from ground testing and initial flight operation.

## INTRODUCTION

The JWST MIRI cryocooler presents unusual challenge for transient modeling compared to smaller and more compact, single cycle space cryocoolers. In the JWST MIRI cryocooler system.[1-7] (shown in Figure 1), the MIRI focal plane is cooled by a hybrid Pulse Tube-Joule Thomson cooler. A Pulse Tube (PT) cryocooler precools the helium working gas of the JT cooler system to 18 K,

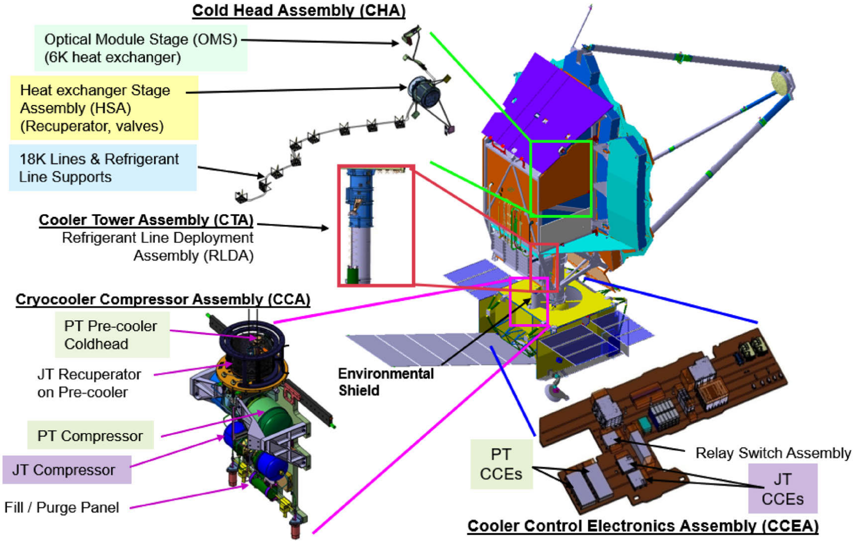

**Figure 1.** MIRI Cryocooler Subsystem

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then a Joule Thomson (JT) expansion cools the helium gas to below 6 K. The PT pre-cooler and the JT compressor are located on the spacecraft bus, which is remote from the 6.2K coldhead at the instrument. The thermal loads and thermal masses of the cooler are distributed between the bus, the instrument and the approximately 10 meters of tubing connecting them. In addition to 6 K cooling provided by a JT expansion, shield cooling is provided at intercepts by the cold return gas. The PT pre-cooler compressor and the JT compressor are powered and controlled by separate electronics which do not communicate with each other in real time.

The preferred temperature control approach does not add heat to the system with a control heater, but instead modulates the compressor drive such that the minimum refrigeration is provided to maintain the instrument temperature with bounds.

The distributed nature of the cooler, the two separate control electronics, and the active temperature control via refrigeration modulation presented challenges for transient temperature control.

## MODELING APPROACH

The transient thermal modelling approach was to build up a reduced order lumped model from sub-models of the cooler's functional blocks[4,5], which were then mapped to the cooler geometric regions and the spacecraft thermal interface to the cooler. This is distinct from the opposite approach of starting with a large Finite element approach (FEM) and reducing its order (which is sometimes done for passive thermal systems).

At its root the cooler is comprised of the following basic functional blocks:

- A compressor for the JT helium circuit, which defines the pressure and flowrate
- A precooler which defines the temperature of the helium as it leaves the spacecraft bus
- A pair of refrigerant lines which carry the helium between the bus and the instrument
- An actively cooled radiant shield around the instrument cooled by the JT return gas
- A JT cold head in the instrument consisting of a recuperator, a flow restriction and a heat exchanger interface to the instrument
- Temperature control with PT compressor drive control
- Temperature control with JT compressor drive control

These functional blocks are interconnected as shown in the block diagram shown in Figure 2. Overlaid on the block diagram are the additional simplified interconnection used in the lumped model approach.

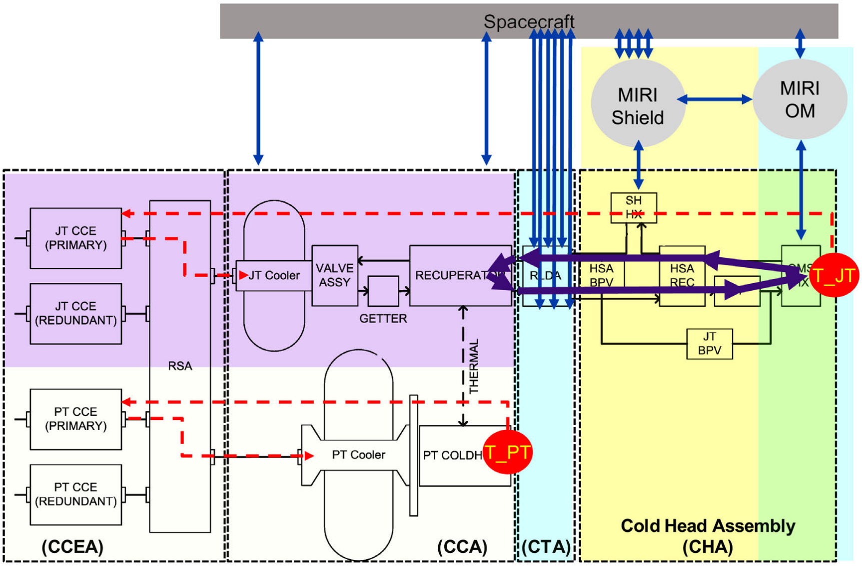

**Figure 2.** MIRI Cryocooler subsystem functional block diagram with key transient thermal model features overlaid. The red circles show the PT and JT temperature control points and refrigeration locations. The purple arrows show the helium supply and return. The blue arrows show passive thermal connection to the spacecraft

Selection of the software used for MIRI Cryocooler Transient Modeling was driven by the following key requirements:

- Needs to natively support lumped node transient thermal networks
- Needs to support heat advection (heat transport by fluid motion)
- Needs to be capable of including active cooling devices
- Needs to allow PID type feedback control of the active cooling devices
- Needs to allow customizable control loops
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- Needs to be in use and validated at Northrop Grumman, JPL and NASA Goddard

A "Commercial Off The Shelf" (COTS) software packages that accommodated lumped transient modeling with control logic and programable blocks were preferred over inhouse coding (e.g. Python, Matlab etc.) to avoid excessive validation and training upon handoff. C&R Technology's Sinda/Fluint Thermal Desktop[8] and Sinda/Fluint SINAPS were both considered. Although SINAPS is the simpler, more compact environment, Thermal Desktop (TD) was chosen due to its broad utilization in all three organizations interfacing with the cooler (NG, JPL, GSFC). Thermal Desktop is also used regularly NASA-wide for large, system level thermal models, so a simplified cooler model could easily be integrated into observatory level models.

A reduced order lumped element network model of the cooler and its thermal connections to the spacecraft was created in TD. The node and conductor properties were derived from other models and tests. The model evolved from a simple two node two conductor model (steady lift PT, steady lift JT, supply gas and return gas) with elements subsequently added as additional operating scenarios were simulated, as additional fidelity was required. In its final form at the time of final ground testing the model (Figure 3) consists of the following:

- 27 nodes (including four boundary conditions, four arithmetic nodes)
- 10 "one-way" conductors (modeling advection via helium gas flow)
- 24 'two way' conductors: (for conduction & radiation)
- 2 active heat loads (OM & CCA)
- 3 cryocooler heaters (Decontamination heaters)
- 2 active coolers (PT & JT)

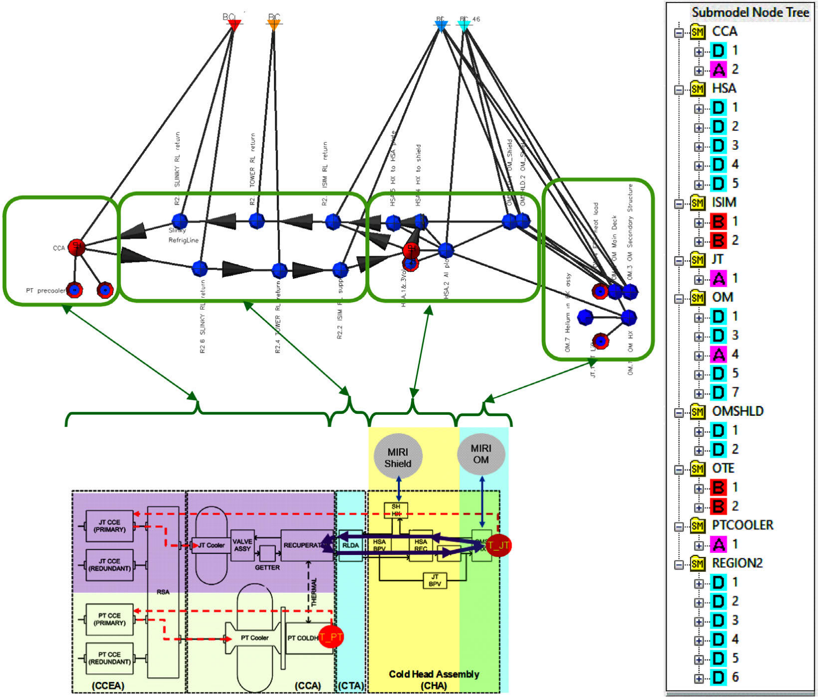
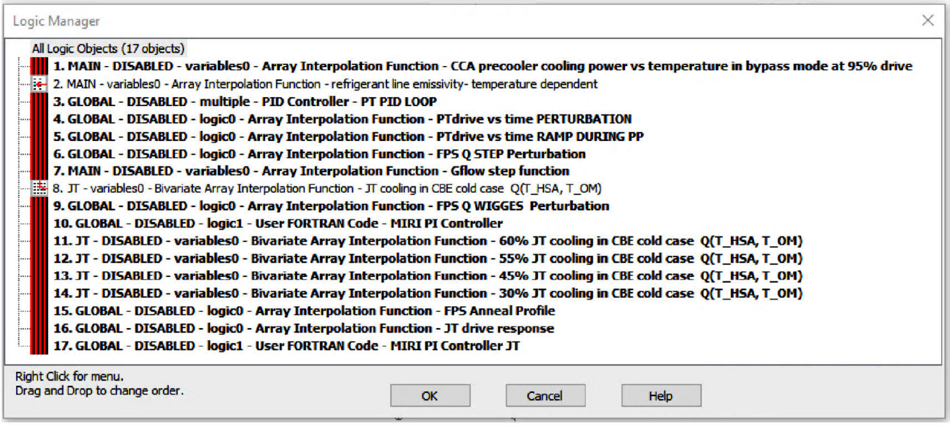


**Figure 3.** Transient Thermal model corresponding to the MIRI Cryocooler Subsystem functional block diagram.



All Logic Objects (17 objects)
1. MAIN - DISABLED - variables0 - Array Interpolation Function - CCA precooler cooling power vs temperature in bypass mode at 95% drive
2. MAIN - variables0 - Array Interpolation Function - refrigerant line emissivity- temperature dependent
3. GLOBAL - DISABLED - multiple - PID Controller - PT PID LOOP
4. GLOBAL - DISABLED - logic0 - Array Interpolation Function - PTdrive vs time PERTURBATION
5. GLOBAL - DISABLED - logic0 - Array Interpolation Function - PTdrive vs time RAMP DURING PP
6. GLOBAL - DISABLED - logic0 - Array Interpolation Function - FPS Q STEP Perturbation
7. MAIN - DISABLED - variables0 - Array Interpolation Function - Gflow step function
8. JT - variables0 - Bivariate Array Interpolation Function - JT cooling in CBE cold case Q(T_HSA, T_OM)
9. GLOBAL - DISABLED - logic0 - Array Interpolation Function - FPS Q WIGGES Perturbation
10. GLOBAL - DISABLED - logic1 - User FORTRAN Code - MIRI PI Controller
11. JT - DISABLED - variables0 - Bivariate Array Interpolation Function - 60% JT cooling in CBE cold case Q(T_HSA, T_OM)
12. JT - DISABLED - variables0 - Bivariate Array Interpolation Function - 55% JT cooling in CBE cold case Q(T_HSA, T_OM)
13. JT - DISABLED - variables0 - Bivariate Array Interpolation Function - 45% JT cooling in CBE cold case Q(T_HSA, T_OM)
14. JT - DISABLED - variables0 - Bivariate Array Interpolation Function - 30% JT cooling in CBE cold case Q(T_HSA, T_OM)
15. GLOBAL - DISABLED - logic0 - Array Interpolation Function - FPS Anneal Profile
16. GLOBAL - DISABLED - logic0 - Array Interpolation Function - JT drive response
17. GLOBAL - DISABLED - logic1 - User FORTRAN Code - MIRI PI Controller JT

**Figure 4.** TD Logic Objects for cooler valve states, temperature control loops, and instrument perturbation.

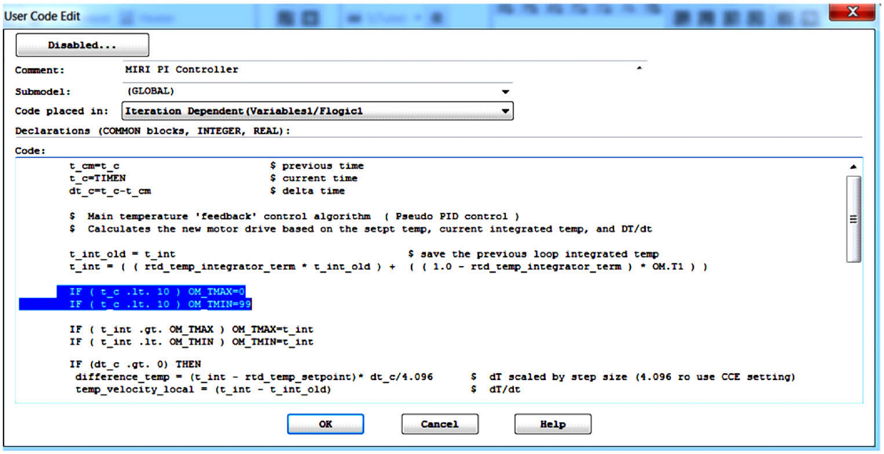
The two active coolers are implanted as controlled heaters with refrigeration (lift) being negative heat. The JT cooler node is an arithmetic node implemented as a bivariate table of data generated from a separate anchored model of lift vs inlet temperature, outlet temperature and drive level. The PT cooler node is a simi-lar arithmetic node with its lift similarly implemented as a table generated from a separate anchored model.

The advection (heat transport by the flow helium) is modeled with TD "one-way conductor" conductors which conduct equivalent to mdot*Cp*dT only in the direction of flow. The boundary layer thermal resistance for heat transfer through tube wall was modeled as external thermal resis-tance conductors in series with the thermal path to the wall.

The cooler's operational modes, and instrument thermal perturbations were implemented in TD Logic Objects (Figure 4), including:

- Cooler's Valve states
- Cooler's Heater states
- Cooler's PT and JT temperature control states
- Cooler's PT and JT maximum drive states

There is a separate control loop for the PT and JT cooler, and these loops do not communicate with each other. The cooler's temperature control approach uses a PID control loop to modulate the compressor drive voltage in response to the measured temperature difference from a set-point. The PID algorithm was ported from the cooler electronics software into Thermal Desktop's pseudo-Fortran, virtually verbatim (Figures 5 & 6). TD Logic Objects define which control loops are active in each cooler mode.



Comment: MIRI PI Controller

Submodel: (GLOBAL)

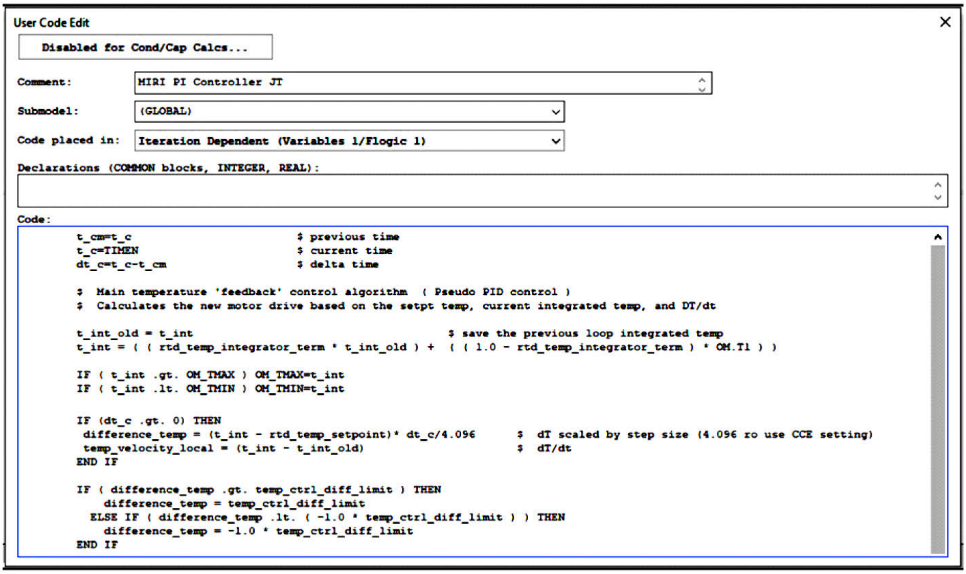
Code placed in: Iteration Dependent(Variables1/Flogic1

Declarations (COMMON blocks, INTEGER, REAL):

Code:

```
       t_cm=t_c                          $ previous time
       t_c=TIMEN                         $ current time
       dt_c=t_c-t_cm                     $ delta time

       $  Main temperature 'feedback' control algorithm  ( Pseudo PID control )
       $  Calculates the new motor drive based on the setpt temp, current integrated temp, and DT/dt

       t_int_old = t_int                                      $ save the previous loop integrated temp
       t_int = ( ( rtd_temp_integrator_term * t_int_old ) +  ( ( 1.0 - rtd_temp_integrator_term ) * OM.T1 ) )

       IF ( t_c .lt. 10 ) OM_TMAX=0
       IF ( t_c .lt. 10 ) OM_TMIN=99

       IF ( t_int .gt. OM_TMAX ) OM_TMAX=t_int
       IF ( t_int .lt. OM_TMIN ) OM_TMIN=t_int

       IF (dt_c .gt. 0) THEN
        difference_temp = (t_int - rtd_temp_setpoint)* dt_c/4.096      $  dT scaled by step size (4.096 ro use CCE setting)
        temp_velocity_local = (t_int - t_int_old)                      $  dT/dt
```

**Figure 5.** TD implementation of PT cooler PID temperature control loop.



Comment: MIRI PI Controller JT

Submodel: (GLOBAL)

Code placed in: Iteration Dependent (Variables 1/Flogic 1)

Declarations (COMMON blocks, INTEGER, REAL):

Code:

```
        t_cm=t_c                          $ previous time
        t_c=TIMEN                         $ current time
        dt_c=t_c-t_cm                     $ delta time

        $  Main temperature 'feedback' control algorithm  ( Pseudo PID control )
        $  Calculates the new motor drive based on the setpt temp, current integrated temp, and DT/dt

        t_int_old = t_int                                      $ save the previous loop integrated temp
        t_int = ( ( rtd_temp_integrator_term * t_int_old ) +  ( ( 1.0 - rtd_temp_integrator_term ) * OM.T1 ) )

        IF ( t_int .gt. OM_TMAX ) OM_TMAX=t_int
        IF ( t_int .lt. OM_TMIN ) OM_TMIN=t_int

        IF (dt_c .gt. 0) THEN
         difference_temp = (t_int - rtd_temp_setpoint)* dt_c/4.096      $  dT scaled by step size (4.096 ro use CCE setting)
         temp_velocity_local = (t_int - t_int_old)                      $  dT/dt
        END IF

        IF ( difference_temp .gt. temp_ctrl_diff_limit ) THEN
            difference_temp = temp_ctrl_diff_limit
          ELSE IF ( difference_temp .lt. ( -1.0 * temp_ctrl_diff_limit ) ) THEN
            difference_temp = -1.0 * temp_ctrl_diff_limit
        END IF
```

**Figure 6.** TD implementation of JT cooler PID temperature control loop.

## COMPARISON OF MODEL TO DATA AND USE OF THE MODEL

The Transient Model was compared with cooler data during Instrument Level ground test. The cooldown was of course easily matched. The more stressing scenario is when the cooler is in temperature control in steady state. Figure 7 shows a comparison of the measured 6K heat exchanger temperature compared to the transient thermal model during a defined heat temporal profile (which labeled CBE cold "FPS hammer" and "Anneal" ), compared to Thermal Desktop Model. The model to data agreement was within +/-30mK for relevant perturbations. As shown in Figure 7 this level of agreement was adequate to allow the transient model to be used to optimize the PID parameters of the cooler's control loop as shown in Figure 8. The performance of the cooler during thermal perturbation of instrument calibration in flight (Figure 9) shows that the PID parameters optimized with the transient thermal model are effective at maintaining the desired thermal stability at the 6K interface to the MIRI instrument.

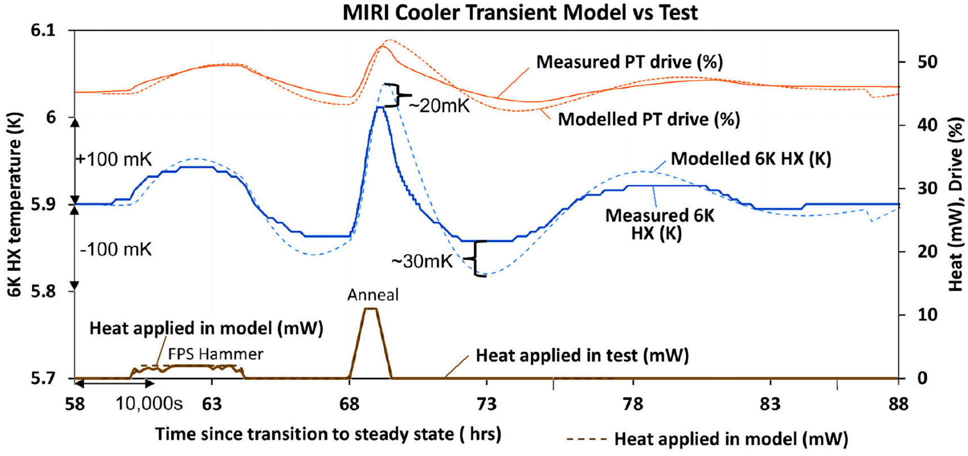


**Figure 7.** Optimization of the MIRI Cryocooler's PID parameters using the transient thermal model.

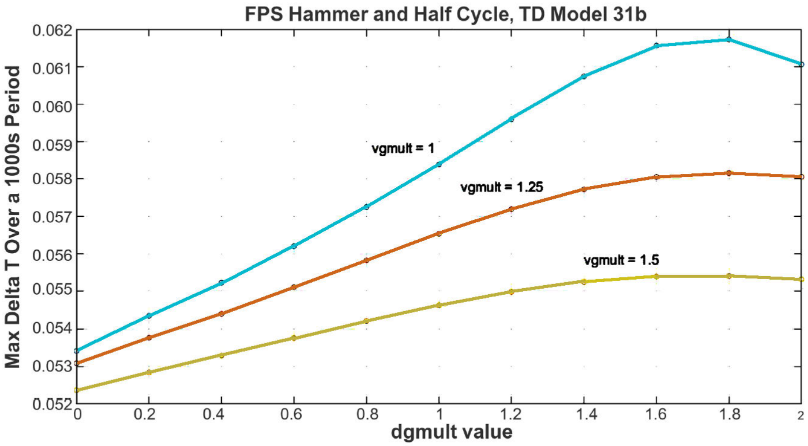


**Figure 8.** Parametric optimization of the cooler PID parameters in the transient thermal model.

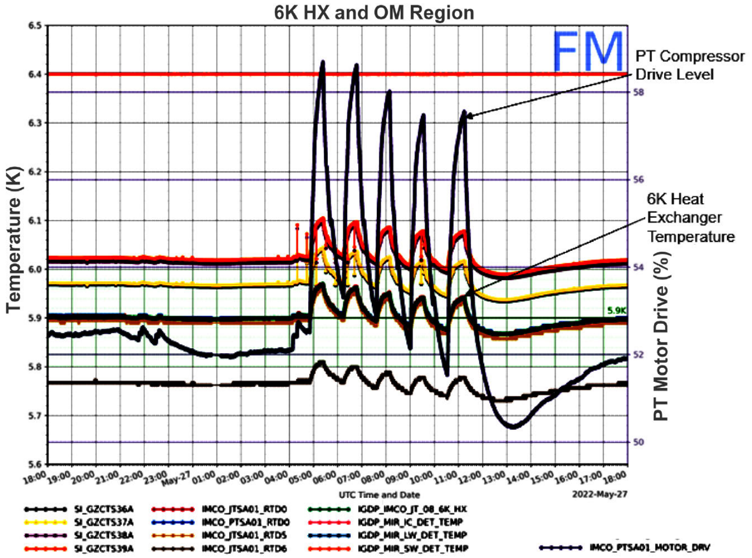


**Figure 9.** Data from the commissioning phase showing MIRI Cryocooler temperature control during calibration lamp thermal perturbations.

## CONCLUSION

A lumped parameter, reduced order transient thermal model of the JWST MIRI cryocooler was developed and implemented in Thermal Desktop. This relatively simple model is sufficient for capturing the JWST MIRI cryocooler's transient thermal performance in the JWST spacecraft environment, both in constant drive mode and temperature control mode. The model predicts the system transient behavior when under temperature control, and as used to optimize the PID param-eter of the coolers control loop. A simple temperature control approach with separate PID loops for PT and JT compressor drive, using these optimized parameters, has demonstrated the ability to maintain the required thermal stability of the coolers interface to the MIRI instrument.

## ACKNOWLEDGMENT

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