James Webb Space Telescope Mid-Infrared Instrument Cooler systems engineering

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ABSTRACT

On the James Webb Space Telescope (JWST), the Mid-Infrared Instrument (MIRI) is unique among the four science instruments in that it operates around 7K as opposed to 40K like the other three near infrared instruments. Remote cooling of the MIRI is achieved through the use of a Joule-Thomson (J-T) Cooler, which is precooled by a multistage Pulse Tube Cooler. The MIRI Cooler systems engineering is elaborate because the Cooler spans a multitude of regions in the observatory that are thermally and mechanically unique with interfaces that encompass a number of different organizations. This paper will discuss how a significant change to the MIRI Cooling System from a solid hydrogen Dewar to a Cooler was achieved after the instrument Preliminary Design Review (PDR), and it will examine any system compromises or impacts that resulted from this change so late in the instrument design. A general overview of the Dewar and the Cooler systems management, the roles of the systems teams in the different organizations, how the requirements are managed in such an elaborate environment, and the distinct design and Integration and Test (I&T) challenges will also be provided.

Keywords: JWST, MIRI, Dewar, Cooler, Lessons Learned

1. INTRODUCTION

Formerly known as the Next Generation Space Telescope (NGST), JWST is a follow-on mission to the Hubble Space Telescope. It is a large space telescope consisting of a deployable 6.5 m primary mirror and four science instruments: a Near-Infrared Camera (NIRCam), a Near-Infrared Spectrograph (NIRSpec), a Mid-Infrared Instrument (MIRI), and a Fine Guidance Sensor (FGS). The instruments are supported within the Integrated Science Instrument Module (ISIM). Equipped with these instruments, JWST offers unprecedented capabilities for observation and study of the history of the universe[1-3]. It involves international collaboration between NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA). The JWST development effort is managed by NASA's Goddard Space Flight Center (GSFC) with Northrop Grumman Space Technologies (NGST[**]) as the prime contractor for the telescope and the Space Telescope Science Institute (STScI) as the lead for mission operations and data processing after launch.

MIRI is a unique multifunctional instrument that will support all four of the JWST science missions: detecting and studying first light objects, studying the assembly of galaxies, observing the planetary systems and origins of life, and investigating the birth of stars. MIRI is a joint product of NASA GSFC and JPL, ESA, and the European Consortium (EC). In order to achieve its science objectives, MIRI will provide science data through coronagraphy, spectroscopy, and imaging between the wavelengths of 5 to 28 μm. Because of its high sensitivity to thermal infrared, MIRI needs a cooling system of its own to achieve an operational temperature of approximately 6K. This can not be achieved on the observatory through the passive methods used to cool the rest of the JWST, so the MIRI has been designed to include its own, dedicated cryogenic cooling system.

The MIRI Cooler provides cryogenic cooling for the initial cooldown and normal operation of the MIRI Optical Module (OM) and the Focal Plane Arrays (FPA) at a nominal temperature of 6.7 K[4-6]. The MIRI Cooler is a hybrid Cooler consisting of a Joule-Thomson (J-T) Cooler precooled by a multi-stage Pulse Tube Cooler. This hybrid configuration

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[**] From this point forward, NGST refers to the prime contractor Northrop Grumman Space Technologies

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allows remote cooling of the MIRI Instrument with the Cooler compressors and their electronics approximately 11 m from the Cooler's cold interface with the instrument. The Cooler is composed of components that reside in all three regions of the observatory. Figure 1 provides an overview of the Cooler components with respect to the Observatory architecture.

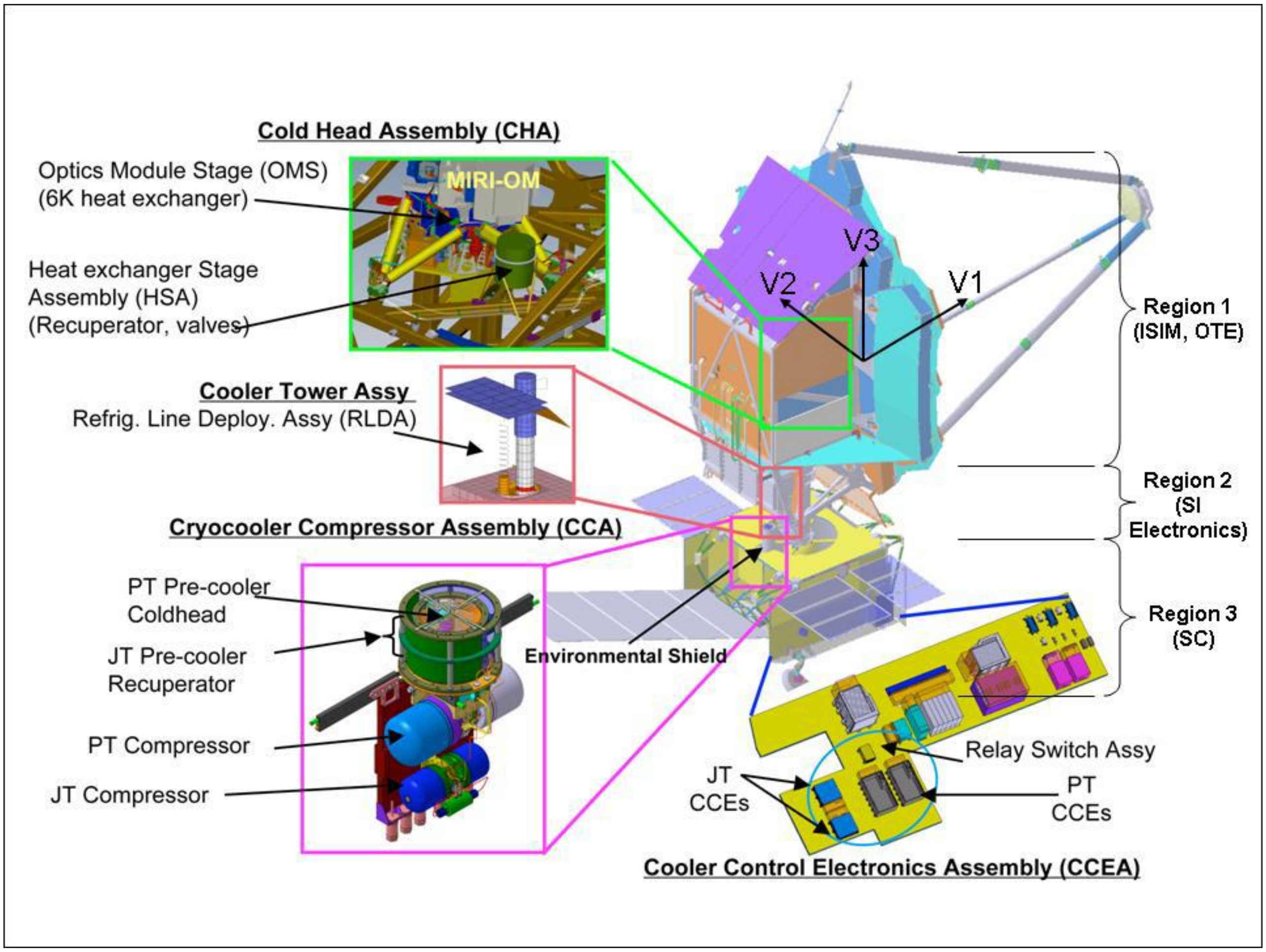

Fig. 1. Cooler Architecture Overview

The Cooler Compressor Assembly (CCA) refers to the compressors for the multi-stage Pulse Tube (PT) Cooler and the Joule-Thomson (J-T) Cooler. The Cooler Control Electronics Assembly (CCEA) consists of redundant control electronics connected through relay switches to each compressor. The relay switches provide the switching interface between the prime and redundant electronics boxes. The CCA and CCEA are mounted in the spacecraft (Region 3). All Cooler parts in Region 2, including the refrigerant lines and their field joints, are considered to be a part of the Cooler Tower Assembly (CTA). A portion of the refrigerant lines is wound into a coil to accommodate the deployment of the telescope and this coil is referred to as the Refrigerant Line Deployment Assembly (RLDA). The Cold Head Assembly (CHA) resides in the ISIM (Region 1) and consists of a Heat exchanger Stage Assembly (HSA) and an Optical Module Stage (OMS). The helium circulated in the refrigerant lines is cooled to 18 K by the CCA pre-cooler, and cooled down to 6K at the HSA, where the J-T isenthalpic process takes place. The last section of the refrigerant lines delivers the 6K cooling from the HSA to the OMS to provide the operational temperature for MIRI.

During the course of its design, MIRI has accommodated two different cryogenic systems. MIRI was first designed to operate using a hydrogen Dewar. Around the time of the MIRI Instrument and Dewar PDRs, through a series of studies to achieve mass savings on the JWST, it was decided by JWST management to switch to a cryocooler. This major change in the architecture has been implemented quickly. About two years after the switch, and one year after the Cooler design effort got underway in earnest, the Cooler went through significant management structural changes, which was a major effort. These changing architectural and management configurations, which are described in the remainder of this paper, have provided their own challenges, issues, and unique solutions.

2. DEWAR MANAGED BY ISIM

When the initial concept for the MIRI was developed in the late 1990's, the cooling for the detectors and optics was assumed to be provided by an active mechanical cooler, in particular, a Turbo-Brayton cooler similar to what is providing the cooling for the Hubble Space Telescope instrument NICMOS. In 1999, Goddard commissioned two studies (by Lockheed and Ball) to determine how the cooling for MIRI should be provided, by a mechanical cooler, or by a stored cryogen Dewar. At that time, the technological maturity of coolers capable of providing temperatures at or below 6K in space was judged to be too immature, and a stored cryogen (solid hydrogen) Dewar solution was base-lined for MIRI. In 2001, the development of the MIRI was officially shifted to a partnership between the Jet Propulsion Laboratory (JPL) and a European Consortium with the baseline approach of using a stored cryogen, solid hydrogen Dewar to achieve the required detector and optics temperatures[7].

The MIRI Instrument was developed through its successful Instrument Preliminary Design Review (PDR) in March of 2005 with the cooling being provided by a solid hydrogen Dewar (see Figure 2). The MIRI Dewar's initial concept was developed by Air Liquide under contract with the European Space Agency, but the responsibility for the Dewar was transferred to JPL after the initial MIRI concept ("Phase A") had been completed (early 2003). JPL selected Lockheed Martin Advanced Technology Center to design and build the MIRI Dewar. JPL managed the Dewar development contract, and provided the interface between the Dewar team and the rest of MIRI and the JWST to establish the interfaces and requirements for the MIRI Dewar.

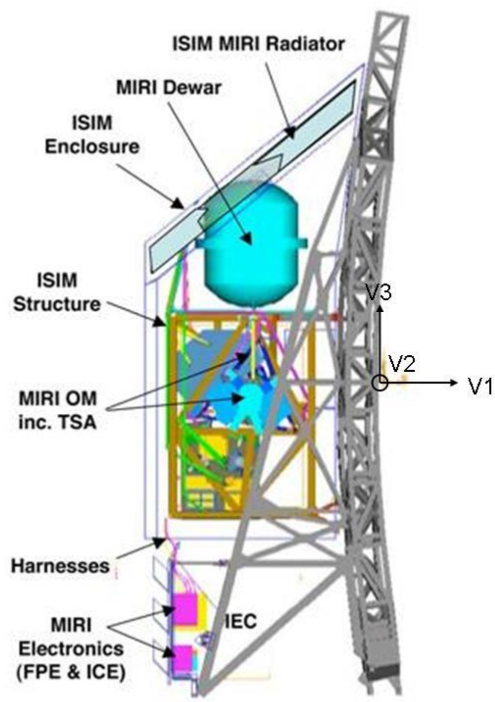

Fig. 2. MIRI Dewar Interfaces

Physically, the MIRI Dewar was located close to the MIRI Optical Module (OM), in the JWST Integrated Science Instrument Module (ISIM). Because of available volume constraints, the very large Dewar (about 250kg) was mounted to the ISIM bench at the "top" of the ISIM (see Figure 2) about 1 meter away from the MIRI (OM), and many meters above the JWST launch interface. The cooling for the MIRI OM (Optics and detectors) was provided through a mechanical Thermal Strap Assembly (TSA) that mounted on one side to a simple, bolted interface on the deck of the MIRI OM, with the other side attached to the warm side of thermal switches mounted inside the Dewar. The thermal switches provided the isolation necessary between the hydrogen cryogen and the MIRI OM during the launch and initial cool down phases of the JWST mission[8]. The MIRI Dewar's vent valves were controlled by the JWST avionics to allow for the vents to be opened as soon after launch as possible. The Dewar Control Electronics (DCE), located inside the MIRI Focal Plane Electronics (FPE) box, read the telemetry from the Dewar. The final critical interface for the MIRI Dewar was the vent line that had to be routed to vent the sublimating vapor outside of the ISIM enclosure without placing undesirable forces or torques on the JWST Observatory. Figure 3 provides an overview of the Dewar interfaces.

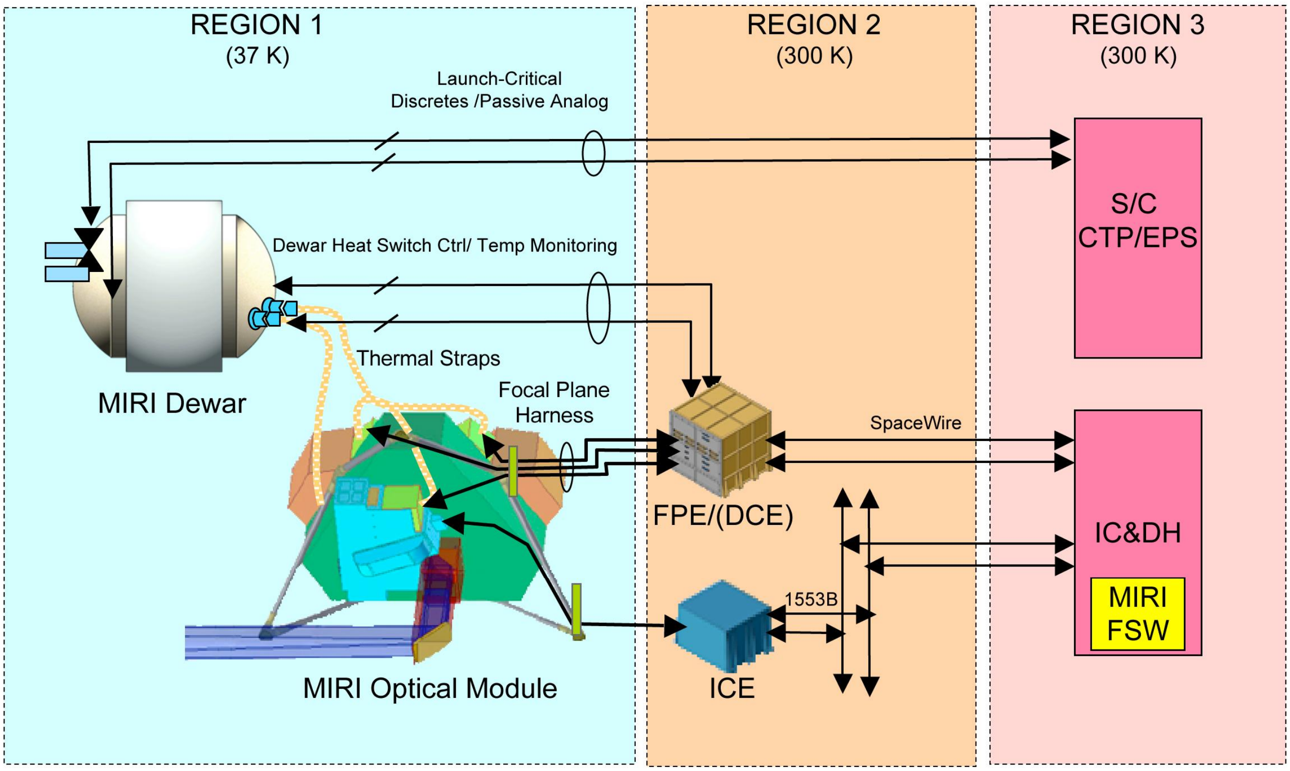

Fig. 3. Dewar Interfaces Overview

In parallel to MIRI's development of its concept and preliminary design with a Dewar providing cooling, NASA Headquarters started the Advanced Cryocooler Technology Development Program (ACTDP) in late 2001 managed by JPL. The ACTDP was a technology development program for developing enabling technology for long life cryogenic space-based observatories needing 6K temperatures. The requirements for the program were focused on three potential initial projects: JWST (MIRI), Constellation-X, and the Terrestrial Planet Finder. The final goal of the program was to bring the competitively selected Cooler technologies to TRL-6: subsystem model or prototype demonstration in a relevant environment.

Overall mass problems within the JWST became an issue in early 2005 and around this time the progress in the development of the ACTDP Coolers had shown that mechanical coolers could provide the needed 6K remote cooling required by MIRI. In order to resolve the JWST mass issue, a trade study was initiated that considered all viable options including replacement of the Dewar with a mechanical cooler. In conclusion of the trade study, the JWST directed MIRI to switch to a mechanical Cooler, two weeks after the MIRI Dewar and Instrument PDRs. Because the interfaces between the MIRI Dewar and the MIRI OM had been designed as very simple bolted interfaces on each end, the change to the MIRI Cooler did not impact the thermal or mechanical design of the MIRI OM beyond some minor changes to the detector thermal straps. The constraint imposed by needing to use the existing interface to the MIRI OM has not been a significant impact to the Cooler's design.

The other interfaces required by the MIRI Cooler (in the spacecraft for the compressors and the Cooler Control Electronics Assembly, in the Tower for the Cooler refrigerant lines, and inside the ISIM for the various components of the Cooler Cold Head Assembly) impacted elements of the JWST that at the time of the switch to the Cooler were not as mature as the MIRI OM. Thus, the design of the Cooler and the design of the JWST elements that interface with the Cooler, and the interfaces between these elements have been proceeding together.

3. COOLER MANAGED BY ISIM

After the Dewar-Cooler replan, the number of interfaces had increased by a large amount overall. The Cooler compressors and their electronics could not be supported within ISIM like the Dewar because of the large amount of heat generated by the compressors, as well as exported vibration issues from the compressors. This meant that the compressors needed to be isolated from the instruments and remote cooling needed to be provided to MIRI. The electronics could not be within the ISIM enclosure for thermal and EMI/EMC reasons, and because the electronics needed to be located close to the compressors they were driving. Given these restrictions, the MIRI cooling system now spans almost the entire height of the observatory crossing all three regions of the telescope. This multi regional hardware clearly has more complex and more intricate interfaces than the Dewar. Regions 2 and 3 now have the majority of the interfaces to the MIRI cooling system; where as Region 1 has a minimal amount, in contrast to the Dewar.

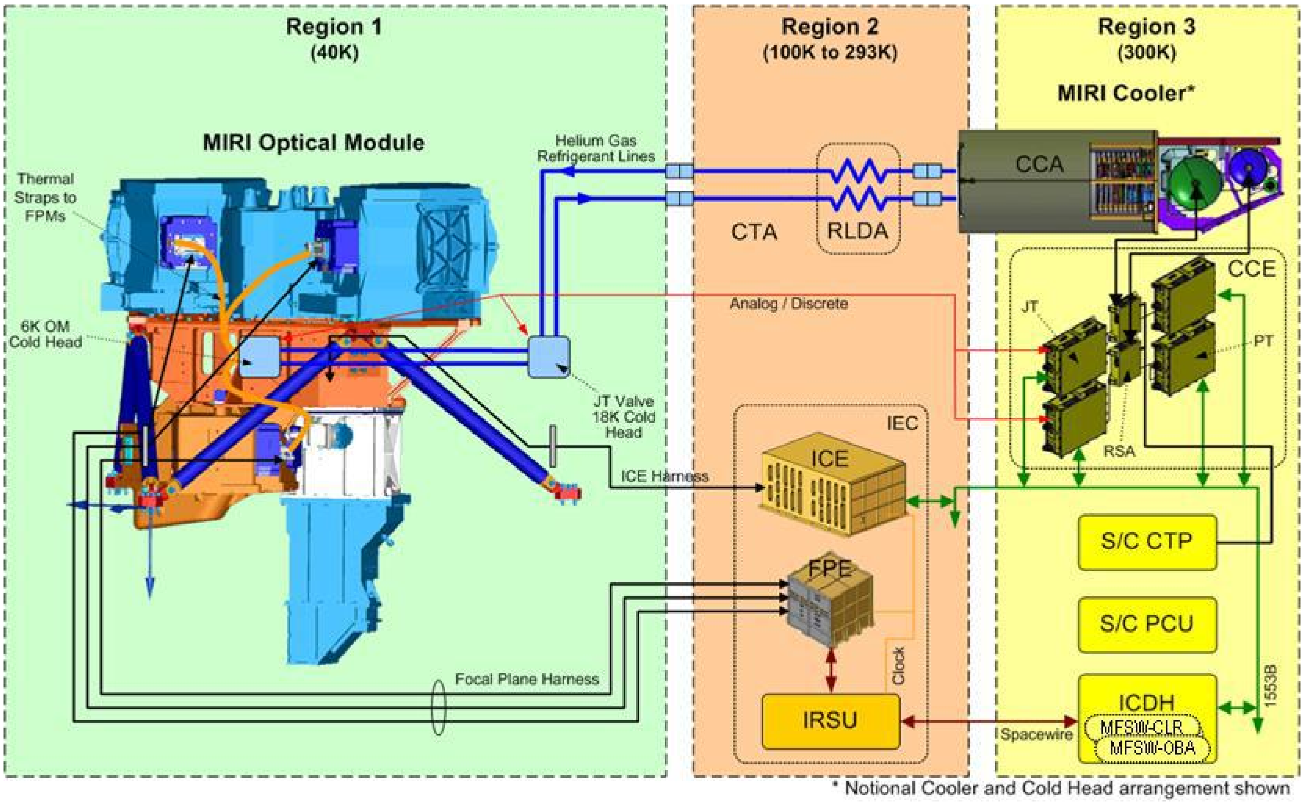

Fig. 4. Cooler Interface Overview

Starting in Region 3, the cooler has many mechanical interfaces to the spacecraft. The compressors (CCA) are mounted on the +V3 side of the spacecraft completely inside the JWST launch support structure. The CCA's exported vibration and the telescope's mechanical response is dampened by a spacecraft provided vibration isolation system. A cut out is accommodated on the +V3 side of the spacecraft to penetrate into Region 2. An environmental shield that interfaces to the sunshield is implemented to retain the thermal performance of the telescope. Because of the high demand for power to accomplish 6K cooling, the spacecraft provides a maximum of approximately 500W of bus power. The heat generated by the compressors from cooling the instrument requires a heat rejection system consisting of a dedicated radiator and a heat pipe transport system, all of which have to be accommodated mechanically and thermally by the spacecraft. The radiator was originally deployable, but then redesigned to be fixed to the spacecraft panel. The cooler electronics are mounted on the +V2 panel of the spacecraft. They do require a significant amount of panel space to expel their heat to space. The electronics require direct electrical interfaces to the spacecraft as well for power and communication. The harnesses that connect the electronics to the compressors and to the spacecraft bus are also accommodated within this region.

Region 2 interfaces are fewer than the interfaces in Region 3, but are not any easier to accommodate. To be able to route along the deployable tower the refrigerant lines are coiled and supported by the tower at the top of the RLDA before penetrating thermal shields in the JWST as the lines are routed towards Region 1. The CTA is partially exposed to space for part of this run, which creates thermal and environmental interfaces that can not be characterized easily. A field joint is necessary before entering into Region 1 that is supported on the ISIM structure and is thermally isolated.

Once it is inside ISIM in Region 1 the interfaces are reduced and become less complicated. The lines are mounted on the ISIM structure with thermal isolators. They are shielded from space by an SLI/MLI enclosure around ISIM. The line routing is simple to both the 6K and 18K heat exchangers. The 18K heat exchanger (HSA) is supported by three thermally isolated interface points to the ISIM structure. The 6K stage is a simple, bolted interface to the deck of the MIRI OM. This is the same interface as was designed initially for the Dewar heat strap. All of these interfaces are highlighted in Figure 4.

Even though there were drastic architectural changes after the transition to the Cooler, the management and technical organization changed very little initially. ISIM was the ultimate customer with JPL managing the Cooler contract. The cooler was obtained from the ACTDP program with the competitive selection made to procure the Cooler from Northrop Grumman Space Technologies. The ACTDP program helped advance the development of the Cooler such that the transition to the MIRI Cooler had little impact to the rest of the observatory in terms of technology development. Even though the management and technical teams at GSFC and JPL did not change, there were now new players added to the MIRI cooling systems development team; the NGST cooler team and the NGST prime contractor. The technical and management teams of these two groups had to be involved in the development of all of the new interfaces. Now that a substantial portion of the interfaces lay within the spacecraft, the JWST prime contractor had to assume a larger role in the accommodations of the cooler. NGST was now the spacecraft contractor and the cooler contractor at the same time, however, under two separate contracts. Therefore, there was no direct route of communications between the Cooler team and the NGST prime contractor, hence delaying progress. Not having a direct path of communication affected the technical aspects of the development.

The document flow was not as straight forward for this option because of the management organization as well, which also reflected on the design and other technical aspects of the program. The binding documents between ISIM, JPL and the Cooler contractor, which were requirements for the Region 1 hardware, were fed down through the ISIM level documents. This was a simple and straight forward task. However, the requirements that were binding between the cooler, spacecraft, and the optical telescope element, which were requirements for Region 2 and 3, took a convoluted path. Since the cooler was an ISIM component at that time the requirements had to flow between these elements through the ISIM documentation. So the ISIM documents added a layer of bureaucracy that hindered the implementation and development of requirements, as well as the daily work that is associated with it. This also allowed for strenuous requirements traceability and left open the possibility for unavoidable mishaps. To simplify the interfaces between JPL and the Cooler, JPL chose from the beginning to have one binding document for the cooler contract and combined all necessary requirements into a cooler specifications rather than having the cooler team sift through multiple documents to find pertinent requirements.

The main challenge of the verification of a cooler that spans all three regions of the observatory is having an end-to-end test-as-you-fly I&T program. The I&T approach that overcomes this issue is outlined in Figure 5. In general, the approach has been that all components go through unit level qualification at the vendor. During higher levels of assemblies, flight models are used wherever can be, and flight spares are used elsewhere. This way hardware that interfaces or depends on a cooler component to have a flight representative test can accomplish just that. MIRI thermal tests at the ISIM level flight I&T, for example, use the flight CHA and the cooler spare CCA, in order to have a representative test. At the observatory level, the flight RLDA is also used to have as much of the flight components as possible to have the test more realistic. Similarly, the flight spare cooler CCA is used at the Observatory level testing to characterize the cooler performance in a flight like environment. In the case of the MIRI Cooler, this issue is no different than the rest of the observatory where a full observatory thermal test is not possible, because of the shear size of the telescope. However, the overall organization of the MIRI Cooler under ISIM further complicated the situation because ISIM had to be involved with the I&T activities of the spacecraft and be active in the verification that takes place at all levels of JWST development.

As the design and development slowly progressed it became more apparent that this management of the MIRI Cooler under ISIM was not the most optimum. Certain changes had to be made. The progress needed to be more efficient, interfaces needed to be simplified, and the unnecessary communication paths had to be eliminated. It was obvious that there were many parties involved that did not have direct control over one another.

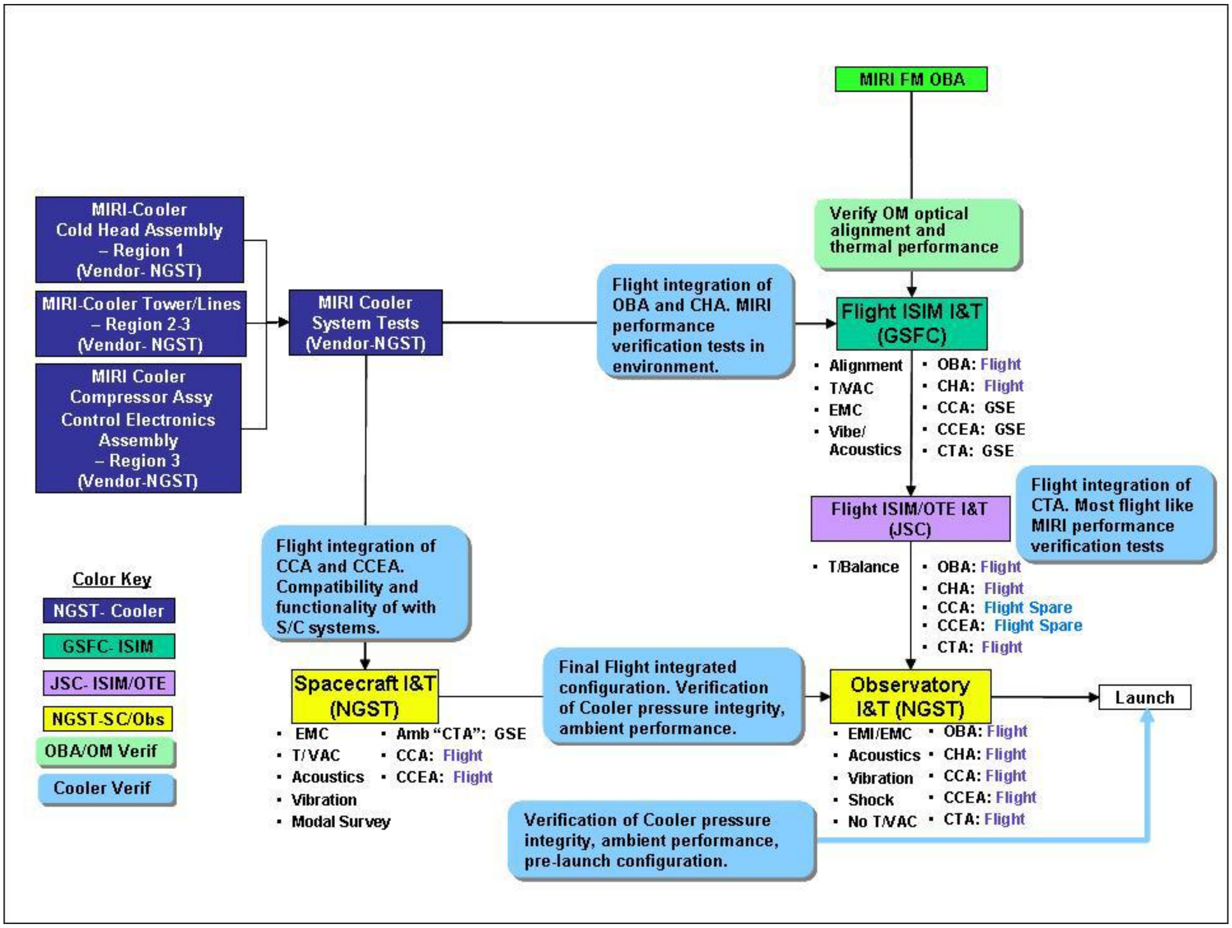

Fig. 5. MIRI Cooler I&T Flow

4. COOLER MANAGED BY OBSERVATORY

A new trade study was opened in early 2007 to look into simplifying the technical and management organization for the MIRI Cooler. This would mean another replan and replans come with their own risks. In order to avoid further delays and risks, the trade study was geared towards finding the most optimal way to achieve maximum efficiency in the development of the cooler without effecting the cooler TRL development. In all options, the ISIM role would be minimized as it was recognized that it had the least amount of interfaces and did not need any involvement in the decision making process of the other interfaces. Towards the end of May 2007, a team of affected stakeholders determined the MIRI Cooler development should be tied to the Observatory rather than to the ISIM because the Observatory to Cooler interfaces are more numerous and complex. The reorganization would tie the Cooler development more directly and cleanly with the Cooler accommodations work within the Observatory.

This new organization simplifies things. A single point of contact, management, and technical overview, is established. The new organizational baseline retains JPL for Cooler contract management and technical oversight. The JPL Cooler manager becomes a direct report of the GSFC Observatory manager, who is the Contracting Officer's Technical Representative for the NGST-Prime contract. Since the observatory holds responsibility for both the Cooler and NGST prime, the interfaces within the spacecraft and around the OTE can be dealt more directly and internally to some degree. The JPL Cooler Manger is supported directly by the GSFC Observatory Cooler SE who coordinates the accommodation efforts within the ISIM. NGST-Prime's Observatory Systems Engineering organization is responsible for leading the Cooler accommodation within the Observatory's Optical Telescope Element (OTE) and the Spacecraft Element (SCE) and works directly with the NGST Cooler Manager. Figure 6 describes the organizational layout in detail.

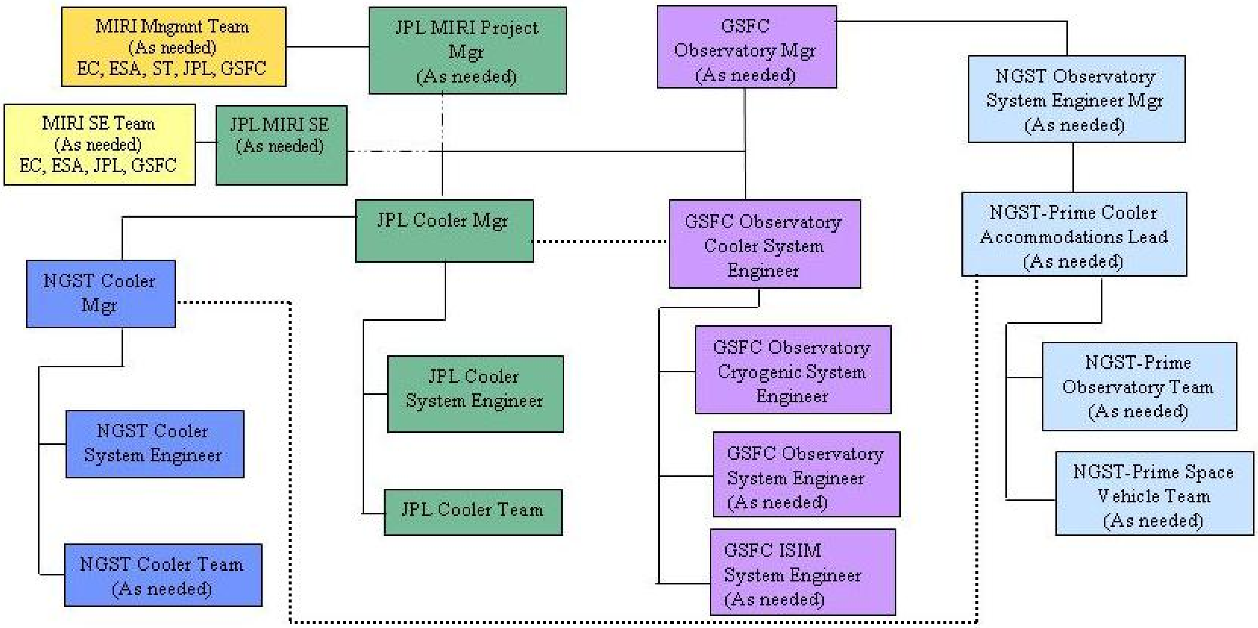

Fig. 6. Cooler Organizational Chart

The overall Cooler architecture and location with the JWST is primarily the same as it was when under the ISIM effort as described in the previous section.

One significant change under the reorganization was that the Cooler parent requirements would no longer be controlled under the ISIM in the MIRI instrument interface requirements documentation. This simplifies the requirement flow by eliminating ISIM requirements in between the Cooler and NGST prime. All requirements needed to transition into observatory controlled documents. The implementation of the flow was a time consuming process as a new requirements flow down needed to be agreed upon by all interfaces. Out of the definition of the flow, a few new requirement documents needed to be created, and we took this opportunity to clarify previously vague requirements.

During this time, the responsibility of certain components was transferred to ensure a cleaner well defined interface. The responsibility for the HSA support (originally ISIM responsibility) was transferred to the JPL Cooler team allowing the support to be designed along with the HSA. The Observatory, who is responsible for accommodating the Cooler electronics and compressors within the Spacecraft, took responsibility for the harnesses between the cooler electronics and the compressors (initially a Cooler deliverable) to aid in the overall accommodation.

It was decided to separate the MIRI Cooler interface control software application in the ICDH from the rest of the MIRI instrument flight software. The MIRI instrument flight software was much further along in the design process at this time and had already been tested. Separating the two applications in two different modules assured the Cooler application had no impact on the rest of the MIRI flight software.

The I&T and verification approach of the Cooler System is primarily the same as when the Cooler was under the ISIM. The Cooler verification will be done prior to delivery by the Cooler contractor. The overall Cooler System verification will be lead by the JWST prime contractor with a support team including the Cooler team and the ISIM.

The decision to reorganize the Cooler effort to the Observatory was made the end of May 2007. At this time, the Cooler team was working towards a System Requirements Review (SRR) in September 2007. There was not enough time to fully implement the reorganization and it was decided to delay the official reorganization until after the SRR, starting in fiscal year 2008, rather than to delay the SRR. We felt that it was acceptable to hold the SRR because the design requirements were understood and identified. The reorganization was simply changing where these requirements were being flowed from.

Between June and October of 2007, we focused on establishing a Cooler Management Plan to define the overall management set-up, commitments and roles and responsibilities under this new MIRI Cooler organization baseline. We also began drafting the new interface requirements documentation.

We believe this reorganization to the Observatory incorporated significant improvements to the organization and implementation of the overall Cooler effort to mitigate the issues experienced under previous baselines. The move to the Observatory effort has been fully implemented and the Cooler team has been operating under this organization for over a half a year. The MIRI Cooler PDR was the first review under the Cooler-Observatory organization.

5. LESSONS LEARNED

The MIRI Dewar development was very challenging because of the required lifetime (5 years and 6 months), the very slow cooldown of the host Observatory (3 months to cool from about 300K to near 40K), and the connection to an external optical bench that needed to be cooled after launch. Also, the Ariane 5 launch vehicle provided the additional challenge of needing to meet a more than 3 day long launch hold (78 hours). All of these thermal and lifetime requirements had to be met while keeping the mass of the Dewar within it allocation and without impacting any of the other Observatory systems (like the attitude control system which could be impacted by the Dewar venting). By working closely with all of the impacted other MIRI and JWST Observatory elements, the Dewar team was able to design a Dewar system that met all of these requirements in a balanced fashion.

The MIRI Cooler System offers unique challenges from previous flight programs with Coolers in that it must span all three regions of the Observatory with remote cooling located at the instrument 10+ meters away from the compressors in the Spacecraft. With this challenge, it is important that the management of the Cooler effort is in synch with the overall mission objectives, such that there are no substantial impacts to the Cooler development.

Through each transition of the MIRI cooling system, the team continuously tried to improve the overall process and gained a valuable collection of lessons learned from these experiences. Some of these lessons were learned from the non ideal implementation of solutions and others learned from a successful process. These lessons learned, as provided below, may be tailored to fit any given system to effectively arrive at an optimal design solution:

- Taking advantage of the work that has been previously done will save time in implementing a new approach. When MIRI was directed to switch from a Dewar to a Cooler, much of the work that had been done with respect to the Dewar contract was reused to establish the Cooler contract. Not only were the contractual documents (like the deliverable document list, the applicable documents list, and parts of the statement of work) transferable from the Dewar development to the Cooler development, much of the flow down of upper level requirements, and interface requirements related to the MIRI OM established for the Dewar could be applied to the Cooler without any modification.
- It is helpful to implement contracts in phases tied to the development phases of the hardware. Because the Dewar contract was only implemented through the Dewar PDR, the financial liability associated with stopping the contract was minimized.
- Keeping simple interfaces allows for parallel development of both sides of the interface without large impacts to one another in a major redesign activity. Since the interface of the Dewar with the MIRI OM had been kept very simple, the replan did not effect the instrument development and testing of the two components.
- Participation of all parties is crucial in the early stages of development. Throughout the initial study between the Dewar and the Cooler a greater spacecraft involvement would have been beneficial in identifying the interfaces sooner, minimizing the impact to the development. It is never too early to get all parties talking to each other and to ensure that the communication paths are developed between all organizations.
- It is beneficial to have alternatives to your baseline available. In this case, the ACTDP program was in place and helped the decision to explore mass savings with the use of a Cooler. If the Cooler technology development had been less than TRL-4 and if the projected TRL-6 levels were farther off than 2007, the option to implement a Cooler would not have existed.
- Examine the level of complexity in the system's interfaces and locate your system under the organization where the interfaces are most numerous and complex. This way the system will have greater visibility with the

appropriate teams. Having most of your interfaces controlled by another subsystem that you don't have any control over, leads to oversight of issues, lagging the development.

- Create a management plan to define the overall management set-up, commitments and roles and responsibilities under any organization. Having all parties sign up to a plan that is definitive, ensures that all responsibilities are distributed properly and nothing will fall through the cracks. This also provides a good reference to revert back to when issues arise.
- Evaluate each specific interface and determine the cleanest way to define where one's interface begins and another's ends. Assigning the responsibility for analysis, design, and manufacturing to the appropriate party/parties helps insure that design intent is/are maintained. Select the party, which is in direct need of a component as the designer, such that the design can be more freely optimized to obtain a more robust system.
- Evaluate the system schedule and determine the appropriate time to implement any necessary changes to the organizational structure or management ensuring it will have as little impact as possible. Design solutions might be identified to be necessary to implement, however the optimum time period for this implementation needs to be considered with the overall schedule. Schedule and resource savings should be considered in determining the best time period for implementation.

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