Design and Requirements Creep in a Build-To-Print Mission

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Build-to-Print designs, or rebuilds of flight proven designs, are attractive to mission stakeholders, as they give the appearance of minimal engineering development cost, risk, and schedule. The reality is that seldom is a project an exact duplicate of a predecessor. Mission reclassification, improvements in hardware, and science objective changes can all serve as a source of requirements and design creep and have ramifications often not fully anticipated during initial proposals. The Thermal Infrared Sensor Instrument (TIRS) was a late addition to the LandSat-8 program to provide infrared imaging to measure evapotranspiration for water cycle management. To meet the launch requirements for LandSat-8, instrument design life requirements were relaxed, the sensor development expedited, and technology development was minimized. Consequently, TIRS was designed as a higher risk instrument, with less redundancy than an instrument critical to mission success. After the successful LandSat-8 launch in 2013 and instrument performance, a rebuild of the instrument for the next LandSat spacecraft was included in the baseline mission success criteria. This paper discusses the technical challenges encountered during the rebuild of the TIRS-2 (Thermal Infrared Sensor 2) instrument and the resultant impacts on the thermal system design.

Nomenclature

ETU	=	Engineering Test Unit
FPA	=	Focal Plane Assembly
FPW	=	Flexible Printed Wire
ITO	=	Indium Tin Oxide
L8	=	LandSat-8
L9	=	LandSat-9
OLI	=	Operational Land Imager
QWIP	=	Quantum-Well-Infrared-Detector
SSM	=	Scene Select Mechanism
TIRS-2	=	Thermal Infrared Sensor 2
TCS	=	Thermal Control System
TMU	=	Thermal Mechanical Unit (Cryo-Cooler)

I. Introduction

In the changing landscape of spacecraft and instruments, programs continue to see acceleration in schedule with reduction in budgets. Because of this, the appeal of Build-To-Print designs become more attractive to mission stakeholders. The conventional thinking holds that utilizing a successful design from a heritage flight instrument or spacecraft will realize significant time and budgetary savings, and are often "sold" as such during the bid and procurement process. The reality is that seldom is a mission a true duplicate of a predecessor, both in hardware and

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staffing. Risk reclassification, improvements in hardware, and science objective changes can all serve as a source of requirements and design creep and have ramifications often not fully anticipated during initial proposals. TIRS-2 is one such example of a rebuild of a successful flight instrument for a follow-on mission. This paper discusses the technical challenges encountered leading up to the TIRS-2 instrument CDR for the LandSat-9 program.

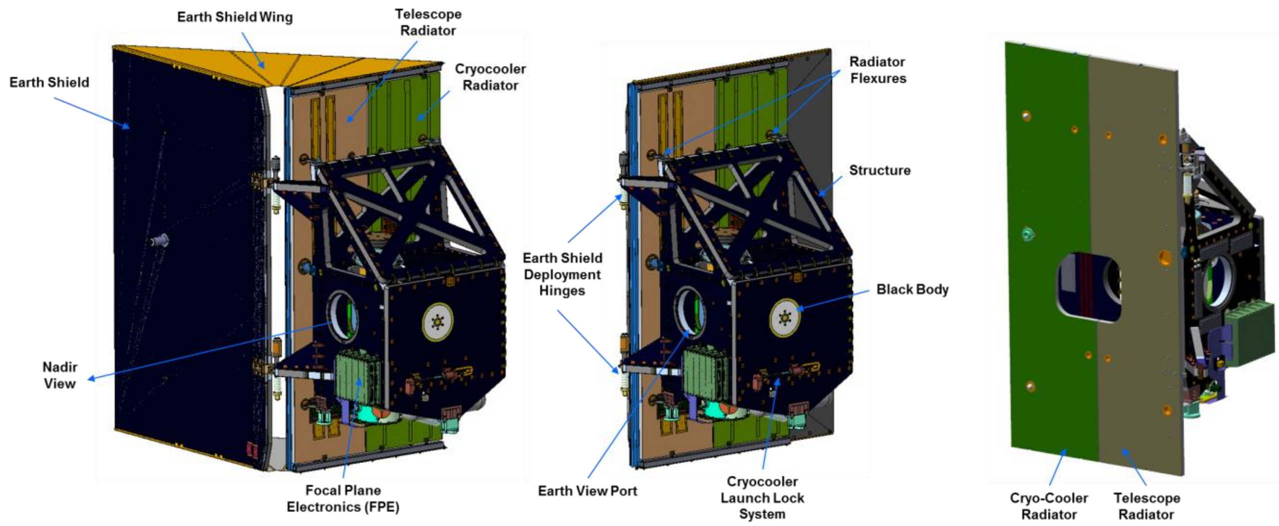

Figure 1. TIRS-2 Instrument. *TIRS-2 Instrument configuration, including sensor unit structure, radiators, and earthshield (shown in deployed configuration).*

II. TIRS History

The Thermal Infrared Sensor (TIRS) is one of the two instruments aboard the LandSat-8 (L8) mission. LandSat-8 was designed to operate in parallel with LandSat-7, to ensure continuity of access to LandSat science data. The original L8 instrument payload included only the Operational Land Imager (OLI). In 2009, the mission was updated to add infrared capabilities for evapotranspiration for water cycle management, and the TIRS instrument was added to the payload. The instrument delivery timeline was extremely strict, as LandSat-8 would launch with or without a TIRS payload. To meet this timeline, the instrument design life requirements were relaxed, the sensor development expedited, and technology development minimized. This placed the instrument in to a higher risk category, requiring less system redundancies. Despite these challenges, TIRS delivered in time to LandSat-8 (L8) and the spacecraft successfully launched in February 2013. TIRS continues to operate and provide valuable science data beyond its three year design life.

The LandSat program is currently building the LandSat-9 spacecraft, the last in this series of spacecraft. The success of L8 led to the selection of the OLI and TIRS instruments to be the payload for L9. The major difference with LandSat-9 would now have the TIRS instrument (now named TIRS-2) included in the baseline success criteria. This shift in baseline success criteria has affected the TIRS-1 “Build-To-Print” process in several important ways. These changes have produced technical challenges that had to be addressed during the early phases of the instrument program and will be discussed in the following sections.

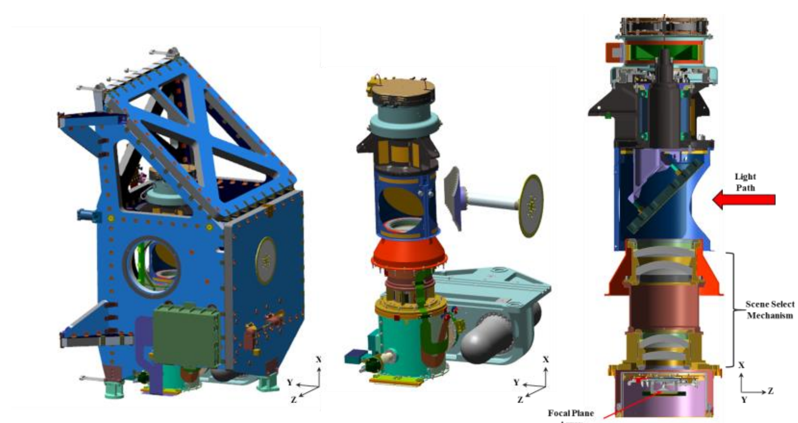

Figure 2. TIRS-2 Instrument. *TIRS-2 Instrument configuration, including sensor unit structure, radiators, and Earthshield (shown in deployed configuration).*

III. TIRS Instrument Design

The TIRS instrument sensor unit, shown in Figure 2, is a 2-band thermal imaging sensor with a four-element refractive telescope and three quantum-well-infrared-photodetectors (QWIP). The sensor unit is comprised of two discrete thermal zones: Warm End and Cold End. The Warm End encompasses the Scene Select Mechanism, the Scene Select Mirror and Baffles, and the internal Blackbody Calibrator. The Cold End encompasses the coldest components in the unit including the Telescope Stage/Assembly, the Warm Stage/FPA Shroud, and the Cold Stage/FPA.

The Cold End contains the Telescope Stage (190K), the Warm Stage FPA Shroud (105K), and the Cold Stage FPA. Cooling for the FPA and the Warm Stage FPA Shroud is achieved by a two-stage mechanical cryo-cooler, with the first stage cooling the shroud and the second stage providing a temperature of 43K for the QWIPs, while a dedicated radiator rejects the heat from the cryo-cooler. To minimize heat leaks in to the FPA, a multi-level isolation scheme is utilized including isolation inserts and isolation shells.

The telescope subassembly is passively cooled to below 190K by a second independent radiator. Telescope focus and stability requires active control of the telescope barrel to nominal operational temperature of 190K with a 2.5K gradient between barrel ends. This is achieved by proportionally controlled software heaters with programmable setpoints.

The Warm Stage of the optical assembly houses the components that require significantly warmer temperatures including the Scene Select Mechanism (SSM), the Scene Select Mirror, Blackbody Calibrator (BBCAL), and the Motor and Encoder Electronics. The Warm End is controlled to remain stable around room temperature, which is again achieved by proportionally controlled software heaters while the BBCal is controlled to provide calibration between 270K-320K. The scan profile of the Scene Select Mechanism rotates the Scene Select Mirror into one of three positions to view either: (1) deep space for cold calibration, (2) the internal warm BBCal, or (3) the nadir scene on the ground. The calibration points are designed so that all nominal calibration activities occur without impacting the spacecraft attitude.

IV. Instrument Risk Reclassification from Class C to Class B

As part of the new L9 requirements, TIRS-2 has been upgraded to a Class B instrument from a Class C with selective redundancy. With this risk reclassification, the instrument is required to carry full redundancy, including fully redundant heater services, sensors, and critical avionics. Only the Thermal Mechanical Unit (cryo-cooler) is not covered by the redundancy requirements. This reclassification resulted in multiple design and requirement changes. One of the largest changes to the design was accommodating fully redundant heater services, both operational and survival services. To meet this requirement, the instrument now carries a total of 20 active circuits, up from 16 for TIRS-1.

The increased circuitry for full redundancy had other cascade impacts to the TIRS-2 design. The increase in associated harnessing for the sensor unit resulted in the redesign of the Sensor Unit Disconnect Panel (SUDP). A box that was able to be located underneath the TIRS-1 sensor unit now requires external installation directly on the spacecraft deck, near the Focal Plane Electronics (FPE) unit. The likely location for a SUDP that satisfied the harnessing requirements encroaches on the FPE radiator field-of-view, and may impact the required FPE stability. This required characterization of the impact of FOV blockage on the FPE temperature and stability.

To meet the Class B requirements for TIRS-2, all heater circuits and sensors have to be fully redundant; this included adding redundant sensors in the cryo region and the FPA. In a cryogenic region, where milliwatts of a heat leak can be critical, more wires represent more paths for leaks in to or out of the assembly. TIRS-1 utilized Flexible Printed Wires (FPWs) instead of traditional harness bundles in the cryogenic region. These FPWs, shown in Figure 3, integrated easier in the constrained space of the isolation shells and the use of constantan (instead of copper) minimized the potential for leaks in to/out of the system. For TIRS-2, the additional sensors and wires necessitated the addition of a fifth FPA, which required a recharacterization of the total heat path for the FPA.

Another requirement change for a TIRS-2 was driven by more stringent surface charging requirements. This new requirement was responsible for a change of all blanket outer layers to Stamet from kapton and a change for +Y instrument radiators from AZ93 to Z93C55 conductive white paint. These increased charging requirements also baselined the addition of ITO to two small radiator surfaces on the instrument (BBCal radiator, FPE radiator). However, prior to PDR, the project received direction that this requirement would be relaxed and the ITO implementation would not occur. While these changes were not difficult to analytically fold in to the design, they all required detailed analysis to ensure no negative impacts to the thermal performance of the TCS.

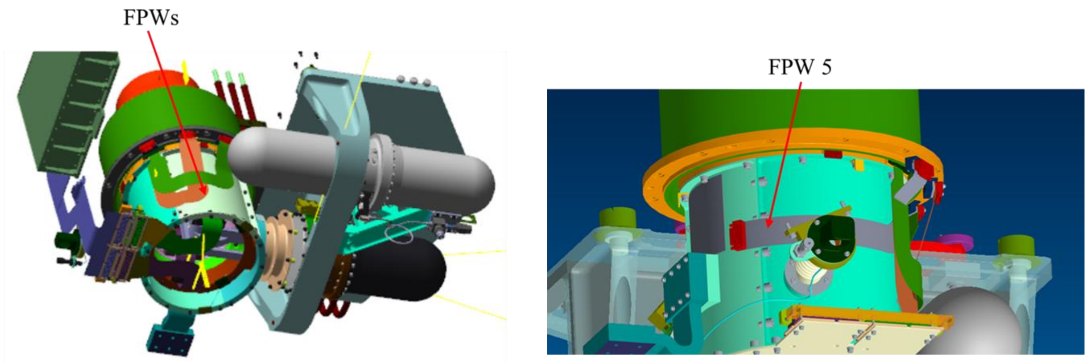

Figure 3. TIRS-1 and TIRS-2 FPW Layouts: *Flexible Printed Wires for TIRS FPA. FPW 5 added for TIRS-2.*

V. Accommodation of All Anticipated Spacecraft Modes

After TIRS-1 had completed its integration and testing program and was delivered to L8, a new credible failure mode for the spacecraft was identified by the vendor. This mode was more extreme than any other mode that TIRS-1 had been designed for. At this late date, it was impossible to implement any changes to the instrument in order to survive this new failure mode and TIRS-1 was exempted from any survivability requirements for this new mode. For LandSat-9, the program has moved in to the design phase with the direction to meet requirements for all L8 modes, including this new credible failure. This configuration places the instrument –X axis full to the Sun with the spacecraft in a 2 revolutions per orbit roll, resulting in TIRS-2 in complete shade with only minimal planet loading. Detailed review of the thermal and structural results for this configuration showed concern with minimum temperatures on the sensor unit structure and stresses around inserts. To mitigate structural concerns, the decision was made to implement a dedicated survival heater design for the main structural panels. However, the minimum required temperature for these panels requires the heaters to operate in a temperature regime that is very close to the operational temperature range for the telescope assembly. The instrument stability would be adversely impacted if these heaters activate during science operations; therefore, this heater service is to be enabled only in modes where the instrument is powered OFF.

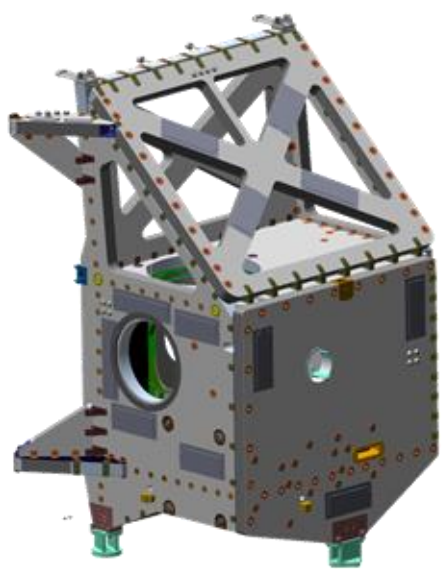

Figure 4. Structure Survival Heaters: *Survival heaters added to the TIRS-2 structure to maintain structure above limits during extreme failure modes. Note the many inserts along each panel perimeter.*

The design of the sensor unit structural panels also proved challenging to effectively implement these survival heaters. The panels are M55J composite, aluminum honeycomb core, and provide very poor lateral conduction. The structural concern with the panel temperatures applies only to insert locations. However, the panels are extensively populated with inserts along the perimeter of each panel, as seen in Figure 4. Effectively protecting the insert locations while minimizing large gradients to the largest extent possible resulted in an outside/in approach to heater placement: heaters are placed, wherever possible, along the perimeter of panels and the internal areas without inserts will receive what little heat is able to be conductive via the M55J facesheets (Figure 4). The implementation of the new structure survival heaters not only resulted in a design change, but also has testing implications. For TIRS-1, a panel/structure qualification only test now becomes a panel qualification plus a thermal design verification test for the new structure thermal control system. The test will have to be designed such that each individual heater service can be independently verified, including thermostat setpoints and effective temperature control and heater functionality. This increases the complexity of the planning for this portion of the instrument verification process.

VI. Additional Analyses

Not all investigations in to potential design changes result in actual modifications to the hardware design. Between PDR and CDR, an investigation in to the feasibility and impact of changing the TMU mounting keel from an Aluminum/APG assembly to an all-aluminum unit was performed. This trade could yield financial and fabrication savings to the project over the composite keel and would avoid manufacturing difficulties encountered during the annealing process. These options had to be balanced against the impact to the thermal TCS and requirements for the cryo subsystem. The TMU subsystem relies on a complicated thermal path between the source (the TMU compressor and displacer) and the radiator sink. In addition to multiple interfaces, minimizing the temperature delta across the keel (the main mounting interface for the TMU) becomes an integral part of the thermal path. Availability of a TIRS-1 ETU aluminum/APG keel and an aluminum ETU allowed for an in-house thermal test to be performed whereby the end-to-end conductance could be compared between the two designs. Results from the testing showed that an all-aluminum keel was unable to meet the spatial gradient requirements for the compressor and displacer interfaces and the APG keel design was not changed. Although resources were spent evaluating a design change that was not implemented, valuable data was obtained from the test and lessons learned during the testing will be incorporated for instrument level testing.

Analytical assessment of the new –X to Sun failure configuration identified some areas of temperature concern on the instrument earthshield. During detailed working group meetings, temperatures of the earthshield pre-deployment were revisited and shown to be at temperatures markedly below the temperature at which deployment tests on TIRS-1 were conducted (160K vs. 190K for TIRS-1 deployment). Addressing this concern encompassed thermal and structural analytical support, review of TIRS-1 deployment testing processes and a detailed evaluation of earthshield limits. As a result of this work, the TIRS-2 deployment test will now be performed at a colder temperature (160K), requiring re-evaluation of the test procedure, as this deployment temperature is near to the cold survival temperatures. Additionally, new limits/requirements for the earthshield were derived based on this data for pre- and post-deployment. Options for additional changes to the deployment test which would yield additional thermal data for the earthshield are also being considered.

VII. New Hardware Design

The TIRS-2 program has also encountered design and requirements creep due to changes in components as a result of flight experience. With the knowledge of the on-orbit performance of TIRS-1, a new SSM encoder electronics unit was procured for TIRS-2, which has a higher unit power dissipation. The encoder electronics is mounted on the top of a titanium motor housing and is within the blanketed top section of the instrument. As such, it has a poor thermal path to reject its heat: conduction to a low conductivity titanium housing or radiation to a relatively warm sink (~263-273K). Additionally, the electronics chassis temperature is extremely sensitive to internal component dissipations and the mounting interface. Further complicating the encoder electronics accommodation is the requirement to maintain positive operational heater control on the bearing housing and maintain bearing gradient requirements, both of which are located below the motor housing. If too much heat conducts in to the SSM from the encoder electronics, the ability to maintain positive operational heater control is compromised. If the encoder electronics starts to run cooler than the SSM, it is possible that the electronics could begin to cool the SSM and increase the operational power draw. The required interface must balance both the encoder electronics requirements and heater control authority for the SSM.

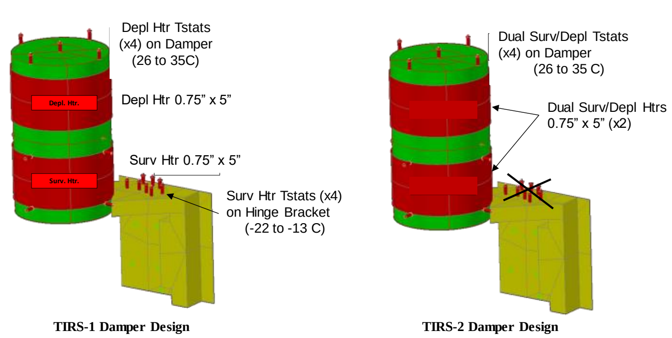

Figure 5. Damper Design Change. *TIRS-2 damper design modified to a single heater design from a dual heater design (survival and deployment) after selection of new damper unit.*

Between instrument PDR and CDR, the instrument earthshield damper changed from a 270° range to a 90° range damper after determination that the 270° damper had an unacceptable dead band. This new damper requires significantly warmer operational and survival temperatures compared to the previous design, with new operational limits in the range of 273K – 308K (compared to 238K – 323K). These new limits must be maintained, even post-deployment of the earthshield. The TIRS-1 design utilized two separate heater services for the damper, one survival service to maintain survival temperatures, and one deployment service, to maintain minimum deployment temperatures.

TIRS-2 combined these two circuits in to a single circuit that is enabled at all times post-launch and was able to optimize thermostat and heater placement on the hardware, as shown in Figure 5. The location of the damper will result in the heater drawing power in all instrument configurations, and was analytically shown to be a minimal power draw (< ~2W).

VIII. Assumptions About Hardware Performance

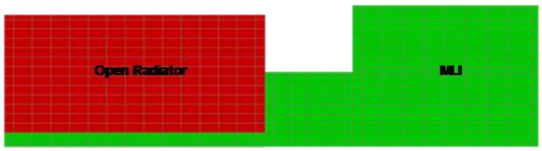

Figure 6. Cryo-Cooler Radiator Blanketing. *Uncertainty in cryo-cooler performance results in large portion of cc radiator blanketed off. Radiator maintains capability to accommodate increases in cryo-cooler power*

In any rebuild of a previous design, it is a reasonable assumption that any procured hardware will perform at least as well, if not better, than the original, especially when vendors do not change. However, this assumption may not always hold true, particularly for less common thermal hardware. TIRS-1 and TIRS-2 both utilize a mechanical cryo-cooler to provide cooling to the instrument FPA. The compressed schedule and time required for the development and test of the cryo-cooler for TIRS-1 did not allow for the unit to be delivered prior to radiator area assignments. As such, the thermal design for the cryo-cooler radiator utilized allocated power dissipations and the radiators were sized accordingly. After the unit was completed, the performance of the TMU was significantly better than expected, resulting in a reduced power dissipation. Consequently, the TIRS-1 flight cryo-cooler radiator was oversized and required significant blanketing for flight (~50%). Each build of a mechanical cryo-cooler is unique, and the performance and efficiency of the unit cannot be validated until testing is completed. As with TIRS-1, TIRS-2 is proceeding with a baseline power assumption for the TMU and sizing the TIRS-2 radiator for that assumption. Because the cryo-cooler operation is fairly well known, there is no anticipated change in the TMU power dissipation. Any changes would likely result from heatloads in the cryo-subsystem. As with the TIRS-1 design, this TMU power dissipation results in significant area blanketing for the cryo-cooler radiator, as shown in Figure 6. However, to gain confidence in the design, a new analysis was required to characterize the cryo-cooler radiator rejection capabilities based on the desired interface temperatures and available radiator area. This analysis demonstrated that the TIRS-2 cryo-cooler radiator maintains healthy margin should the TMU power dissipation increase significantly.

The TIRS instruments utilize ethane heatpipes to efficiently reject the telescope heat and maintain its temperature. These pipes are not nearly as common as ammonia pipes, are not used on many missions, and as such are considered unique builds. Additionally, heatpipes are often long lead-time items and are needed for integration efforts earlier in the build process. If a problem with pipe performance occurs, it can be difficult to procure a new replacement unit that has been qualified under an even further compressed schedule. This reliance on hardware performance can, in unexpected circumstances, become a project risk. To mitigate this project risk, the TIRS-2 program began with a complete set of flight spare ethane pipes from TIRS-1 and procured a set of TIRS-2 flight pipes. The TIRS-1 ethane pipes are undergoing a requalification program to enable their use on the flight instrument should they be needed.

IX. Improvements Of Previous Design

In a rebuild of a previous instrument, the project has the unique opportunity to improve the previous design, either based on flight performance or to improve on design compromises made during the previous program. TIRS-2 is no exception to this. The TIRS instruments rely on operational heater control authority for maintaining telescope stability during all conditions. While TIRS-1 was able to meet all science requirements while meeting all design requirements, analyses indicated that the operational heater margins on the forward telescope heater circuit was less than desired. The TIRS-2 rebuild presented the opportunity to reallocate radiator area from the over-sized cryo-cooler radiator to the telescope radiator, to gain additional margin. However, there was a constraint on the reallocation: the radiator heatpipes were not to be impacted (except for removing any pipes) and no changes could be made that would impact the design and locations of the mechanical flexures.

After detailed analyses prior to PDR, the TIRS-2 radiator design was modified to reallocate approximately 372in^2 from the cryo-cooler radiator to the telescope radiator, as shown in Figure 7. This yielded an increase in operational heater control margin and was implemented in to the cryo subsystem TCS design with minimal impact to the overall instrument design.

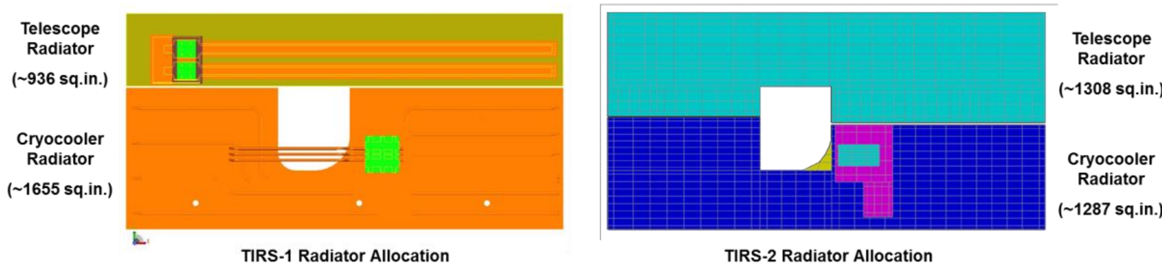

Figure 7. Radiator Reallocation. *Radiator areas reallocated from telescope to cryo-cooler radiator for improved operational heater control authority*

X. Conclusion

With a new instrument build, the expectations are that considerable expenditures will be incurred during the development phase; whereas the rebuild of a project often expects considerably less development costs. Despite these expectations, it is often unavoidable that there will be deviations to the rebuild plan, resulting in design and requirement changes. These deviations can improve the design based on flight performance of the original unit, accommodation of new hardware, or mission risk reclassification, among others.

The TIRS-2 program has seen a number of modifications to the original TIRS-1 instrument during the early phase of the project. Changes made will increase operational heater power margin, address requirements changes resulting from an upgrade from Class C to Class B, and accommodate redesigned or new hardware for the new mission. Increased redundancy requirements necessitated the addition of new heater circuits and sensors, which cascaded in to additional electronics, cards, and harnessing requirements.

All of these modifications, deviations, and investigations from a “build-to-print” TIRS-1 have required resource expenditures, some of which were likely unplanned. These modifications are difficult to quantify in terms of actual cost and/or schedule impacts, as the non-recurring engineering between the original build and current build are not tracked at this level of detail. Some of these modifications, such as the additional redundancy and its impacts, identified design changes from TIRS-1 and new requirements levied by the project were likely considered in the cost planning at the time of the TIRS-2 proposal. However, other design changes and trade studies, such as the structure survival heaters, damper changes, and radiator reallocation, were implemented as the design of TIRS-2 progressed and is optimized leading to PDR and CDR. These technical challenges have been successfully addressed by the TIRS-2 team and the instrument rebuild is proceeding with a sound and improved instrument design, as evidenced by the successful completion of instrument CDR in early 2017, and is proceeding to integration and test.

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