

Thermal Performance Comparison and Lessons Learned for the Thermal Infrared Sensor Instruments 1 & 2

Veronica Otero¹

NASA Goddard Space Flight Center, Greenbelt, MD, 20771

and

David Neuberger²

Lentech Inc, 7500 Greenway Center Dr. Suite 505, Greenbelt, MD 20770-3558

The Thermal Infrared Sensor (TIRS-1) is one of two instruments on the Landsat-8 Mission, which launched in February of 2013 and remains operational. The TIRS-2 instrument was developed for the Landsat-9 Mission, which is scheduled to launch in September of 2021. The TIRS-2 instrument design was adjusted to account for requirements changes and to include key lessons learned from its predecessor. The overall thermal subsystem design of the TIRS Sensor Unit remained comparable from mission to mission, but there were some areas that needed modifications. The general design is comprised of five thermal zones which range in temperature from less than 43 Kelvin to 320 Kelvin. Most zones are proportional heater controlled. A two-stage cryocooler provided by Ball Aerospace is used to cool the cryogenic subsystem, and excess power dissipation is rejected via ammonia transport heat pipes to a dedicated cryocooler radiator with embedded ammonia heat pipes. The cryogenic subsystem includes a series of shells used to radiatively and conductively isolate the cold stage from the warmer surroundings. The Optical System (telescope) is passively cooled to 180-195 Kelvin using a dedicated radiator with embedded dual-bore ethane heat pipes. The warmer end of the instrument includes a Scene Select Mechanism, an on-board Black Body Calibrator with a dedicated radiator, and a Focal Plane Electronics Box, all of which are attached to the Sensor Unit primary structure. The TIRS-1 thermal subsystem design was successfully verified during an extended testing campaign and during more than 8 years of on-orbit operations. The TIRS-2 thermal subsystem design was successfully verified during months of ground testing prior to delivery in August of 2019 and at the Observatory level in the Spring of 2021. A detailed comparison of the thermal performance of the two instruments has been made with a focus on key lessons learned during each instrument development, and with the benefit of on-orbit data acquired for the TIRS-1 instrument.

Nomenclature

APG	=	Annealed Pyrolytic Graphite	MLI	=	Multi-Layer Insulation
CCE	=	CryoCooler Electronics	MMOD	=	Micrometeoroids and Orbital Debris
FCL	=	Flexible Conductive Link	NASA	=	National Aeronautics & Space Administration
FIS	=	FPA Isolation System	OLI	=	Operational Land Imager
FPA	=	Focal Plan Arrays	SSM	=	Scene Select Mechanism
FPE	=	Focal Plane Electronics	TCB	=	Thermal Control Board
FPW	=	Flexible Printed Wire	TIPCE	=	TIRS Instrument Performance & Cryo Evaluation
GSE	=	Ground Support Equipment	TIRS	=	Thermal InfraRed Sensor
GSFC	=	Goddard Space Flight Center	TMU	=	Thermo-Mechanical Unit
MCE	=	Mechanisms Control Electronics	TV/TB	=	Thermal Vacuum / Thermal Balance
MEB	=	Main Electronics Box	USGS	=	U.S. Geological Survey

¹ Thermal Engineer, GSFC-Code 545.0, Greenbelt, MD 20771

² Thermal Engineer, 7500 Greenway Center Dr. Suite 505, Greenbelt, MD 20770-3558

I. Introduction

The Landsat program, a joint NASA/USGS effort, is the longest continuously operated Earth satellite program since its first successful launch in 1972. Since then, there have been a total of eight satellite launches, including Landsat-6, which failed at launch. Today, the Landsat program continues to improve our understanding of Earth by providing essential data available to users around the world. Landsat-8 was launched in February 2013 and continues to successfully operate on-orbit. Landsat-9, which is currently in the midst of spacecraft integration at the vendor site in Gilbert, AZ, is scheduled to launch in September of 2021.

The Landsat-8 mission was initially baselined with only one instrument, the Operational Land Imager (OLI) instrument. The Thermal Infrared Sensor (TIRS) instrument was added late in development as a result of strong advocating on behalf of the science community. As a result of the late introduction of TIRS, the Goddard Space Flight Center (GSFC) development effort was constrained to 3 years and the instrument was designated Class C (in a Class B mission) to allow for a quicker delivery and higher risk posture. The short development time led to early long-lead procurements (as early as PDR), a compressed design phase, and an aggressive integration and test campaign in order to meet delivery.

The Landsat-9 mission was established as a full Class-B mission with the constraint to keep the design as similar to Landsat-8 as possible to minimize costs. The GSFC development effort made use of the existing TIRS design, documentation, and spare hardware where possible, building from past experience and maintaining a strong connection to the TIRS team. The TIRS-2 instrument therefore has a similar overall thermal control system design as that of TIRS-1, which allows for a unique opportunity to perform detailed thermal performance comparisons between the two instrument development efforts. This paper discusses the key thermal design differences between the two instruments, the thorough ground testing verification program (including challenges) for the main instrument subsystems, and a look at TIRS-1 on-orbit data to continue thermal performance trending.

II. Primary Design Changes From TIRS-1 to TIRS-2

The overall thermal control system design between the TIRS-1 and TIRS-2 instruments remained similar, but there were two primary drivers that lead to certain changes that were implemented on TIRS-2. The first driver was the result of modifications to higher-level requirements as follows: 1) TIRS instrument class level was raised from a class C to a class B, 2) new Landsat spacecraft safehold orientations were included, 3) micrometeoroid requirements were adjusted based on current GSFC studies, and 4) surface charging requirements were tightened based on historical data. The second driver originated from a desire to implement key lessons learned from the TIRS-1 program in order to increase thermal design margins suitable for a class B mission. All design changes were reviewed and approved by the Landsat program office early in the development flow, which allowed for adequate time for implementation.

The TIRS-1 instrument was categorized as class C due to its late inception into the Landsat-8 mission. However, the Landsat-9 mission primary objectives included a TIRS-2 instrument from conception, increasing the instrument reliability to that of a class B to be consistent with the overall 5-year mission life. This change drove the need for increased design redundancy, which required changes to the operational heater scheme. This scheme changed from a single Thermal Control Board (TCB) with a capability of 16 heater circuits to a fully redundant design with two Main Electronics Boxes (MEB) each with an independent TCB able to control 10 heater circuits. While the TIRS-2 design adds complexity in the harness design (i.e. quantity of harnessing doubles), it allows for full redundancy in the electronics.

The Landsat Program Office flowed two primary requirements changes for Landsat-9 that impacted the Thermal Control System design on TIRS-2. The first set of requirement adjustments addressed Observatory surface charging concerns, leading to thermal blanket and coatings changes. The TIRS-2 Multi-Layer Insulation (MLI) blanket outer layer for external blankets was changed from Kapton to Stamet. All radiator white coatings were changed to Z93C55, an electrically-conductive white coating. Finally, radiator Silver Teflon taped surfaces were changed to an ITO coated version. The second set of requirement adjustments addressed Observatory micrometeoroid (MMOD) protection concerns, leading to additional shielding in strategic areas negotiated between the Landsat-9 Program Office and TIRS-2 systems engineering. After a detailed risk assessment, the agreement led to an adjustment in the TIRS-2 MLI blanket layout to include a layer of high-density Kevlar to protect exposed harnessing and electronics components.

As part of early planning for the Instrument Heritage review, which took place soon after confirmation of the mission, a summary of key lessons learned from TIRS-1 were collected and reviewed for implementation on TIRS-2. The primary thermal subsystem lessons which were implemented on TIRS-2 were as follows: 1) survival heater circuit design increased thermal zones to include SSM remote electronics and structure to meet new Landsat spacecraft safehold orientations, 2) increased number of spacecraft-read temperature telemetry to accommodate additional

survival heater zones, 3) moved damper survival heater to its own circuit to allow for possible circuit turn-off after deployment, 4) re-distributed radiator area from the Cryocooler subsystem, which had excess margin, to the Telescope subsystem which had less margin allowing for radiators to more evenly share the allocated volume on the +Y side of the instrument, and 5) removed decontamination heaters which were not as effective as nearby operational heaters in achieving temperature criteria during dryout and de-ice phases of the mission.

III. Ground Test Verification Process

The TIRS-2 Instrument completed a comprehensive testing campaign to verify design changes since TIRS-1 and confirm successful overall performance of the instrument after assembly. One of the benefits in the development of TIRS-2 was the availability of all TIRS-1 spare flight hardware. A selection of spare hardware was re-evaluated for possible use on TIRS-2 early in the development phase, including spare heat pipes, thermal doublers, and Flexible Conductive Links (thermal straps). TIRS-1 spare flight hardware was used to supplement TIRS-2 procurements as suitable.

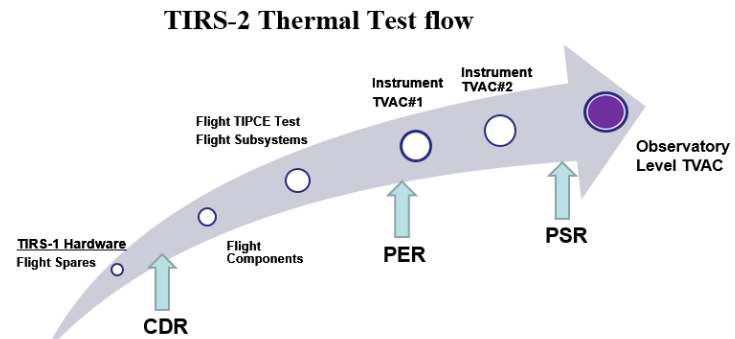


Figure 1. TIRS-2 Thermal Test Flow

TIRS-2 followed the Goddard protoflight qualification testing standards for a Class B mission (refer to **Figure 1** for test flow). Most components began the qualification campaign at lower levels, which resulted in about 18 component level thermal vacuum tests. In addition, several subsystem level tests were completed for areas with unique complexities requiring early risk mitigation, including the Scene Select Mechanism, Earthshield Cold Deployment, and a series of early science verification tests named TIPCE (TIRS Instrument Performance and Cryosubsystem Evaluation). The TIPCE testing campaign was a critical effort completed prior to full instrument assembly to properly verify placement of the Focal Plane Array relative to the telescope, measure the effect of stray light over full range of angles, and perform a series of science performance tests. Furthermore, the TIPCE testing configuration was developed to allow for early verification of the thermal subsystem cryogenic design. A total of three TIPCE tests were completed, including a series of thermal balance points at various temperature setpoints, which resulted in early confirmation of the thermal subsystem performance as compared against TIRS-1 testing.

A Radiator Thermal Vacuum / Thermal Balance (TV/TB) test was added into the overall test flow mainly to mitigate the risk that instrument level testing was configured in a vertical orientation with all instrument heat pipes in reflux mode. In order to attain more flight-like performance and one comparable to that of Observatory TV/TB testing, the radiator balance test minimized the influence of gravity on the heat pipes by configuring them horizontal to the gravity vector. The test was completed in March 2018 at Goddard Space Flight Center's Code 549 Chamber 239.

Two instrument level tests were completed at Goddard Space Flight Center's Code 549 Chamber 225 prior to delivery to the spacecraft vendor. The first test, which started in February 2019 and lasted for approximately 40 days, accomplished two cycles at protoflight levels, verification of end-to-end instrument performance at nominal and protoflight temperatures, and three thermal balance points. The second test was comparable in duration and was completed after dynamics/acoustics testing in May/June 2019. The primary objectives for the second test were to complete the remaining two cycles at protoflight levels and characterize any changes in performance since the first test. Both instrument level tests were configured with the instrument in a vertical orientation to accommodate science calibration equipment in the chamber; consequently, all heat pipes were in reflux mode. The TIRS-2 instrument has since been delivered, integrated onto the spacecraft, and participated in the Observatory testing campaign which included a thermal vacuum test completed in March 2021. During the extended instrument testing campaign, there were key lessons learned that were captured which will be discussed further, in particular for the radiator/heat pipe subsystems and cryogenic subsystem.

A. Lesson Learned – Telescope Radiator & Embedded Ethane Heat Pipes

The instrument optics uses a passive thermal control system consisting of a “telescope link” that connects the aft Optics barrel to a dedicated telescope radiator. The telescope link includes a flexible thermal strap made of high-purity aluminum foils and a high conductance bar made of aluminum with embedded APG (Annealed Pyrolytic Graphite).

The dedicated radiator is an aluminum honeycomb panel with two dual-bore ethane heat pipes, which were embedded at Goddard Space Flight Center. The size of the radiator was increased from TIRS-1 to TIRS-2 to allow for additional thermal margin.

On TIRS-2 the telescope stage thermal design was verified via three primary sets of tests, including radiator balance, TIPCE, and instrument level testing. **Figure 2** details the end-to-end conductance path from the telescope to its dedicated radiator, and highlights where each interface was tested. In particular, the radiator/heat pipe assembly was verified in radiator balance and instrument level tests.

The Radiator Balance test objectives and results pertaining to the telescope radiator subsystem were as follows:

- Verification of radiator thermal performance: radiator was able to effectively reject max heat loads at operating temperatures
- Verification of end-to-end conductance along critical path: characterized the end-to-end temperature gradients for a series of flight-like and bounding configurations
- Verification of cold start at cold survival temperatures: heat pipes were able to carry full load after cold survival environment
- Completion of thermal balance points for thermal design verification and model correlation
- Completion of radiator panel bakeout & four cycles at protoflight temperature ranges

A re-assessment of the telescope radiator/heat pipe assembly during thermal model correlation after instrument thermal vacuum testing indicated a 7-9 K discrepancy in temperature gradients along the radiator panel between the two configurations, vertical and horizontal. There was a desire to investigate these phenomena further by implementing a stand-alone heat pipe test at various angles with respect to gravity, but this effort was not completed due to unavailability of spare flight hardware. However, with the information at hand from the Radiator Balance test and Instrument-level test we can deduct that even though the radiator performance remained acceptable in a vertical configuration due to available thermal margin, the heat pipe performance was impacted. **Table 1** shows the temperature gradients along the radiator panel, specifically at the heat pipe evaporator and top condenser locations. In

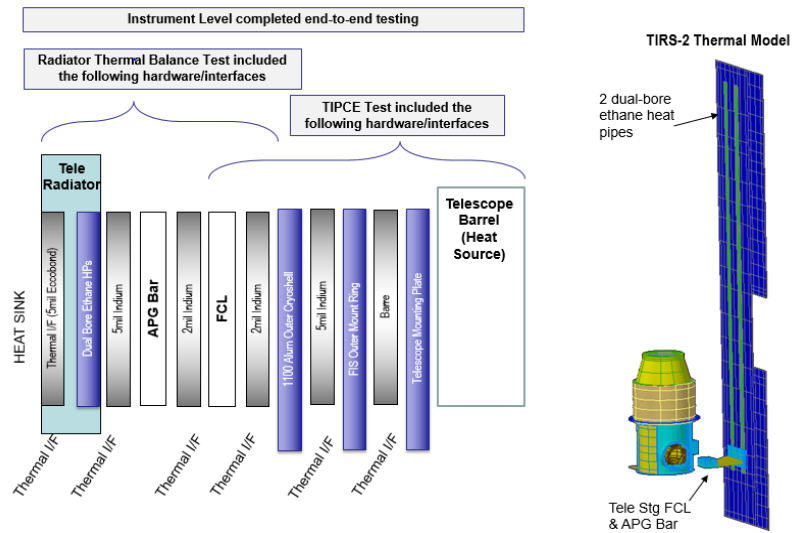


Figure 2. Telescope Stage End-to-End Thermal Verification. Conductance path from telescope outer cryoshell to dedicated radiator.

Table 1. Telescope Radiator Thermal Performance. TIRS-2 Telescope radiator temperature gradients for various test configurations.

	TIRS-2 Radiator Balance Test					TIRS-2 Instrument TV/TB Test				
	Hot Bal 2	Nom Bal 2	Cold Bal	Surv Bal	Surv Bal, post HP	iTvac-1, Cold Bal	iTvac-1, Hot Bal Clsd Loop	iTvac-2, Nom Bal	iTvac-2, HQ3	iTvac-2, Cold Surv
						2019-03-02 13:10 GMT	2019-02-24 10:00 GMT	2019-06-09 20:00	2019-06-06 08:00 GMT	2019-06-18 09:00 GMT
Sink Temp, K	90.05	90.2	89.6	91.69	90.15	90.31	91.5	89.2	91.9	89.7
Added Htr Heat Load, W	11.8	11.8	9.5	1.2	20	8.883	7.341	7.496	5.143	0
Q-meter Heat Load, W	18.83 / 12.69	18.9 / 12.74	16.08 / 10.62	6.07W / 2.8W	No Telemetry	17.484	15.877	15.616	13.973	No Telemetry
Ethane HP (outer edge, bot), K	159.7	159.5	152.8	132.1	141	165.3	168.1	168	170.3	146.4
Ethane HP (outer edge, top), K	158.4	158.2	151.4	130.9	139.5	SENSOR CAME OFF		159.4	164.9	144.4
delta T	1.3	1.3	1.4	1.2	1.5			8.6	5.4	2
Ethane HP (inner, bot), K	159.1	159	152.1	131.2	140.4	167.5	170.1	170.55	172.9	149
Ethane HP (inner, top), K	158.5	158.4	151.7	131	139.9	155.1	158.7	158.77	163.9	143.9
delta T	0.6	0.6	0.4	0.2	0.5	12.4	11.4	11.78	9	5.1

a horizontal configuration the gradient is approximately 0.3-1.4 K; in the vertical configuration the gradient is on the order of 7-10.4 K. The variation in temperature gradient is in part driven by a heat load into the systems (in the form of heater power), and in part driven by the heat pipe configuration.

The team performed a subsequent re-assessment of the telescope radiator/heat pipe assembly performance at the Observatory-level TV/TB test in the Spring of 2021. The instrumentation was consistent with that of tests at instrument level, so an “apples-to-apples” comparison is accomplished. As expected, the temperature gradients were in line with those of Radiator Thermal Balance test where the heat pipes were in a horizontal configuration, with gradients on the order of 0.3-1.4 K. This provided confirmation that the discrepancies seen between the two instrument tests were in fact driven by the test configuration, specifically the heat pipe orientation.

B. Lesson Learned - Cryocooler Radiator and Ammonia Heat Pipes

The TIRS-2 cryogenic subsystem is cooled to operating temperatures with the use of a two-stage stirling cryocooler. The efficiency of the cryocooler is such that for every Watt that is removed from the cold stage there is about 80 Watts of power dissipation at the Thermo-Mechanical Unit (TMU). This large amount of power dissipation requires a dedicated radiator that is connected to the cryocooler TMU via three long transport ammonia heat pipes. The heat dissipation from the TMU is rejected at the cryocooler compressor and displacer interfaces into a cryocooler mount made of aluminum with embedded high-conductance APG material. The heat then conducts to the three transport heat pipes that are connected on the condenser end to an APG doubler inside the cryocooler radiator, which then spreads heat to six embedded ammonia heat pipes to maximize efficiency of the radiator. Of the six spreader heat pipes, three are shorter with the evaporator at one end of the pipe, and three are longer with the evaporator in the middle of the pipe. The latter three heat pipes have presented the greatest challenge during ground testing and will be discussed further.

On TIRS-2, the cryocooler subsystem thermal design was verified via three primary sets of tests, including radiator balance, TIPCE, and instrument level testing. Furthermore, a series of ambient tests were performed prior to instrument TV/TB to confirm proper radiator heat pipe startup and functionality with the use of an IR Camera. This was also deemed necessary to gain a better understanding of system performance as a whole, including the addition of GSE heater power, and to mitigate the risk of possible challenges related to the heat pipe configuration during instrument TV/TB. **Figure 3** details the end-to-end conductance path from the cryocooler TMU to its dedicated radiator, and highlights where each interface was tested. In particular, the radiator/heat pipe assembly was verified in radiator balance and instrument level tests, as well as ambient IR camera tests.

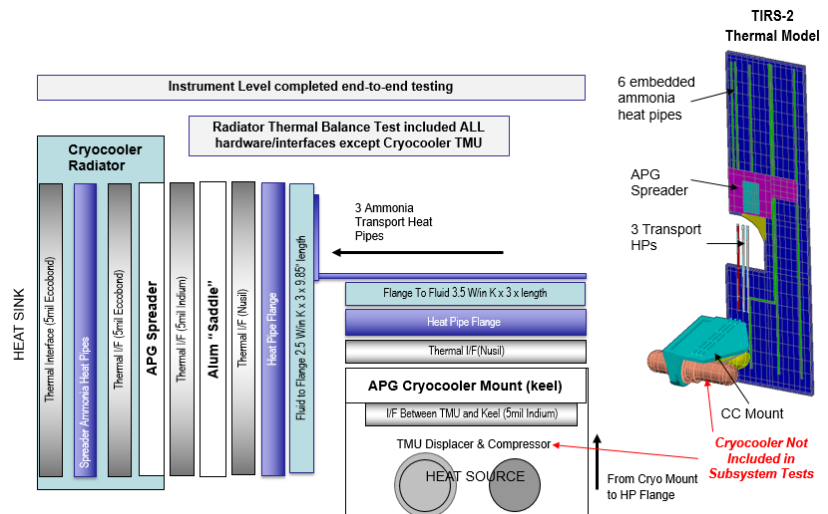


Figure 3. Cryocooler Subsystem Stage End-to-End Testing. Conductance path from cryocooler TMU to dedicated radiator.

The Radiator Balance test objectives and results pertaining to the cryocooler radiator subsystem were as follows:

- Verification of radiator thermal performance: radiator is able to effectively reject max heat loads, transport heat pipes meet transport requirements, but is difficult to confirm whether all ammonia spreader heat pipes are active (limited instrumentation during this test; additional telemetry for subsequent tests)
- Verification of conductance along critical path: characterized the end-to-end delta temperatures for a series of flight-like and bounding configurations
- Verification of cold start at cold survival temperatures: heat pipes were able to carry full load after cold survival environment
- Completion of thermal balance points for thermal design verification and thermal model correlation
- Completion of radiator panel bakeout & four cycles at protoflight temperature ranges

Prior to instrument level thermal vacuum testing a series of ambient tests were completed at various heat loads with the help of an IR camera. These tests were necessary in order to understand the impacts to flight hardware with the addition of a GSE heater used for startup and continuing operation of the long embedded heat pipes. The GSE heater is needed to heat the pool of liquid at the bottom of the heat pipes in order to begin circulating fluid along their full lengths prior to turning the cryocooler on. However, in an effort to reduce the additional heat into the system, it was important to determine the minimum GSE heater power required to keep heat pipes active in reflux mode to efficiently dissipate up to 140W of cryocooler TMU power dissipation. Refer to **Figure 4** for a visual of the test configuration and instrumentation. The test results indicated that a significant amount of heater power was necessary to get all three heat pipes started mainly because as one heat pipe started it took on the majority of the load thus requiring more heat into the system to reach startup on the remaining heat pipes. The test results also indicated that a minimum of about 20W was necessary to maintain these heat pipes active with sufficient evaporation in order to be able to reject about 140W of cryocooler TMU power while still maintaining temperatures at desired range of -30C to +10C (-5C nominal goal).

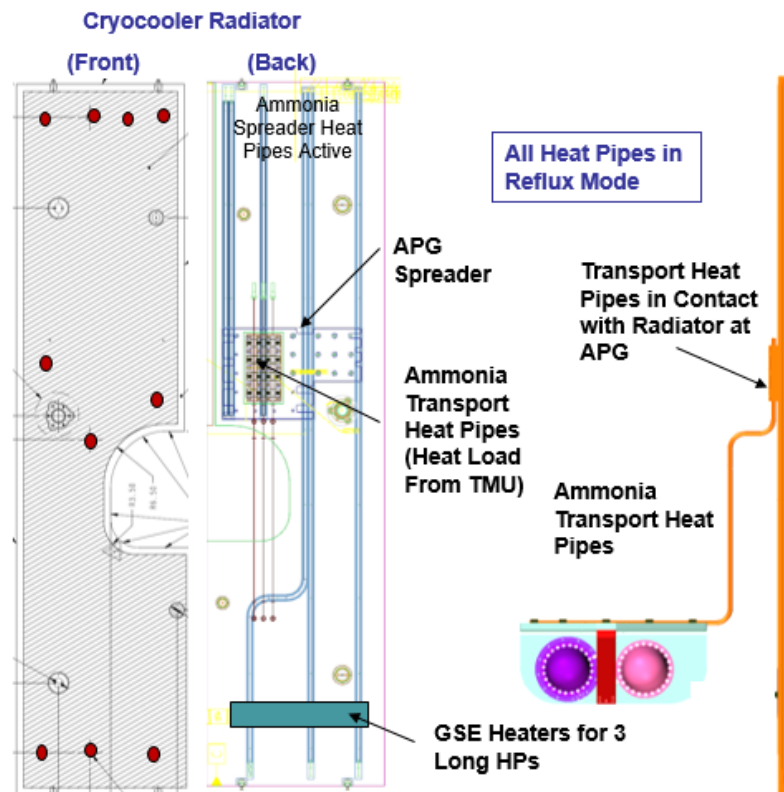


Figure 4. Cryocooler Radiator Instrument TV/TB Test Heat Pipe Orientation & Instrumentation. Figure on the left shows thermocouple locations; Figure in the middle shows embedded ammonia heat pipes; Figure on the right shows transport heat pipes.

As a final confirmation of the cryocooler radiator/heat pipe assembly prior to delivery of the instrument, the system was assessed at instrument-level TV/TB. The startup process was written to mimic the IR camera ambient testing, and the three long heat pipes were successfully activated prior to cryocooler power ON. The cryocooler radiator was effective in rejecting the necessary heat load at various plateaus and the radiator gradients were as expected based on the reflux operation mode. Following the test, a goal temperature of -5C was selected for the cryocooler TMU interface based on a specific radiator size; the final radiator configuration with flight blanketing included was verified at observatory level TV/TB, which had all heat pipes in a horizontal configuration.

C. Lesson Learned - Cryogenic Subsystem (Cold & Warm Stages)

The cryogenic subsystem of the TIRS instrument consists of a Focal Plane Assembly (FPA) that is cooled by a two-stage cryocooler connected via a thermal heat strap. The warmer first stage of the cryocooler connects to a radiative shell which surrounds the colder second stage. The warm stage itself is surrounded by the passively cooled telescope stage. The telescope stage consists of an aluminum cylinder that surrounds the warm stage of the cryosubsystem. The cylinder is the connection to the telescope and keeps it below its operational limit as well as blocking the view of the warm stage from the much warmer structure. Refer to **Figure 5** for a visual of the design. The TIRS cryogenic subsystem thermal design uses solid cryogenic principles developed for and verified by other cryogenic instruments and fitted for TIRS. The two basic principles are as follows:

- 1) Maximize conduction between heat sink (cryocooler cold stage cryofinger) and source (Focal Plane Assembly). Design concepts include;
 - a. Use of pure aluminum heat straps with 1100 Aluminum end blocks.

- b. Use of Indium at all critical interfaces.
 - c. Use of Bellville washers to keep the preload at all interfaces.
 - d. Use of sapphire at detector to heat strap interface to allow for electrical resistance with minimal thermal resistance at operational temperature of 40 K.
- 2) Maximize isolation between the various thermal zones, including cold and warm stages, warm and telescope stages, and telescope and structure. Design concepts include;
 - a. Keep inter stage radiation as low as possible with VDA SLI and gold plating on all parts viewing the cold stage except black as needed for optics.
 - b. Use of recumbent cylinders to give the smallest “Area/Length” between the various thermal zones, including cold stage at 40K, warm stage at 100 K, telescope stage at 180 K, and structure at 265K. Material selected was G-10 due to the highest possible strength per conduction ratio at the expected operational temperatures.
 - c. Use of constantan FPW (Flexible Printed Wire) to thermally isolate power and signal wires to the FPA.
 - d. Use of gold plated radiation shields where possible.

In order to operate the FPA at 38K, it is critical to reduce the temperature difference between the detector and cryocooler cold finger. Using the equation $dT = Q / G$, the goal is to reduce Q of parasitic heat coming into the system and increase conduction G along the path to maximize cryocooler efficiency and increase design margins. In addition to lowering the temperature gradient between the coldfinger and detector, it is very important to keep the parasitic loading as low as possible. At 80 W of input power needed to remove 1 W of heat at the cold finger, keeping parasitics as low as possible is paramount.

The TIRS-1 thermal design of the cryogenic subsystem, including cold and warm stages, was verified via three primary set of tests, including CryoSubsystem (CSS) test, instrument level test, and observatory level test. The CSS test was focused on verification of the thermal design and was developed using flight spare or flight-like parts to represent the cryogenic thermal zones. The remainder of the test set up was built to represent the correct environment that the cryo portion radiates and conducts to, including the warmer stages such as the telescope stage and structure. The FPA was configured in a flight-like manner except the detectors (QWIPs) were replaced with a heat source. An increased number of temperature sensors were used in this test compared to allow for additional information used to correlate key interfaces in the thermal model. Care was taken to reduce parasitics while not compromising accuracy of temperatures through the use of low conducting small gauge lead wires and heat sinking leads to improve sensor accuracy. The thermal design verification was completed with the use of a detailed thermal model in parallel with the standard hand calculations at important paths and interfaces. The key measurements of heat flow are across the heat straps. Since all heat must flow through them to get to the sink, this is the vital choke point and all heat can be accounted for. Of course, the Q calculated can only be accurate if both the conductance and delta temperature measured across it are accurate. In other words, our Q meter using $Q = GdT$ is only as good as the G and the dT. Care was taken to have the vendor test their heat straps accurately and using the same temperature sensor locations as would be used in flight. The next step is to isolate the parasitics from the detector power. $Q_{total} = Q_{det} + Q_{parasitics}$. Since accurate power measurements of the detector simulator were made, this assumes all remaining Q were parasitics.

The TIRS-1 thermal team developed a thermal model and correlated it to several thermal balance points; refer to **Table 2** for a summary of results. The results were promising with Q parasitics = 270 to 450 mW while holding the gradient between cold tip and detector to less than 3K. The warm stage parasitics were estimated between 0.7 and 1.4 W. These results gave the team confidence and provided a few lessons learned, and allowed to build of the flight unit

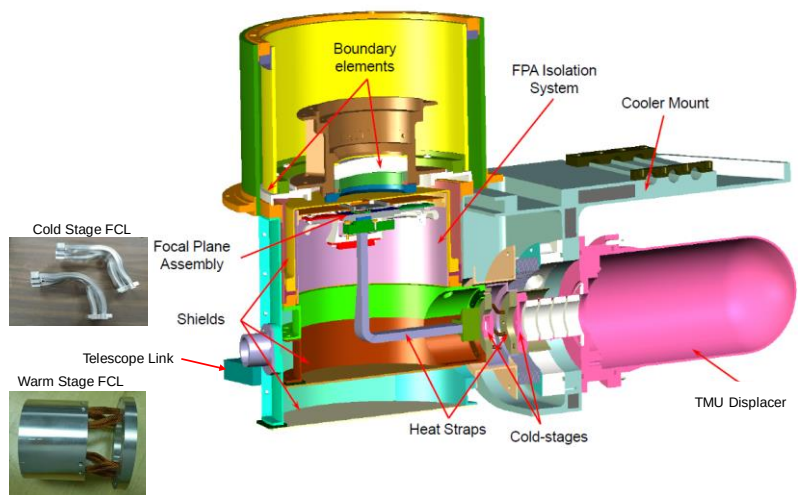


Figure 5. Cryogenic Subsystem Design

Cryogenic Subsystem is comprised of a cold stage (~38K) and warm stage (~95K), surrounded by a telescope stage (~180K).

to proceed. For the TIRS-1 instrument test, all components, including the cryocooler, were flight. The team ran an Instrument Thermal Vacuum Test (iTVAC) and determined that parasitics were 420 to 840 mW using the thermal calculation, $Q = GdT$. The team had high confidence in the G value that was measured accurately at the heat strap vendor as a function of temperature. The sensor accuracy and the data system reading the telemetry was a little less certain, noting for example that with a heat strap $G = 3 \text{ W/K}$, an error of 0.1K results in an enormous 300 mW discrepancy, which is equivalent to about 2/3 of the detector power. The verification process then moved on to the Observatory TVAC test without having a critical GSE temperature sensor: a Cernox which had been placed on the warm end block of the cold stage heat strap to get an accurate dT across the heat strap. This sensor was not available for use at Observatory testing or for on-orbit flight operations, so the team had to rely on actual detector temperatures. The primary disadvantages were 1) the parasitics that are introduced at various points after the detector and 2) the G through the heat strap/indium/sapphire/indium/invar/epoxy/silicon/epoxy/detector stackup, which is much more variable and error-prone than just the tested heat strap. An alternate method was chosen which uses thermodynamics to determine parasitic heat loads. This method uses thermodynamics instead of heat transfer. At the vendor, the cryocooler was tested at many points representing various 1st and 2nd stage cold finger temperatures, heat loads at those cold fingers, and reject temperature of the cryocooler. These results were turned into a spreadsheet known as a “Performance Map” that calculates various possible states for the cryocooler. The user can input 3 variables and the Performance Map outputs the 4th; for example, if the user has motor power and cold finger temperatures, the tool will output a heat load; if the user has heat loads and cold finger temperatures, the tool will output motor power. Given the reduced telemetry in the flight build the team made use of the thermodynamic method to predict parasitic heat loads, which ranged from 170 to 280 mW. The final verification was via on-orbit data, and with the thermodynamic method the team estimated the parasitics to be 160 to 300 mW. Note that the thermal calculations using the torturous path and sensor inaccuracies resulted in a range of negative heat flow to 410 mW.

Table 2. Cryosubsystem Performance

	UNITS	T1 CSS	T1 ITVAC	T1 OTVAC	T1 FLIGHT	T2 TIPCE	T2 ITVAC
Thermal Method							
CS T*	K	37 – 42	38 – 39	38 - 39	38 – 39		36 – 42
CS dT**	mK	170-1180	287 - 432	N/A	1300-2000 ***		92 - 342
CS Q min	mW	270	420	N/A	-14***	300	257
CS Q max	mW	450	840	N/A	410***	300	389
WS T*	K	56-86	104 – 106	103-104	104-105		72 - 107
WS dT**	K	0.6-1.6	0.8 – 2.4	N/A	1.3 – 1.6		0.3 – 2.2
WS Q min	W	0.7	0.6	N/A	1	0.97	0.2
WS Q max	W	1.4	1.9	N/A	1.3	1.08	1.8
Thermo Method							
CS Qmin	mW	N/A	N/A	170	160	N/A	N/A
CS Qmax	mW	N/A	N/A	280	300	N/A	N/A
WS Q min	W	N/A	N/A	1.8	1.3	N/A	N/A
WS Q max	W	N/A	N/A	3.1	2.0	N/A	N/A

Thermal Method uses flight or test sensors; $Q = G \cdot dT$

Thermo Method uses thermodynamic performance mapping

* Temperature location: detector for cold stage; heat strap for warm stage

** dT across heat strap (warm end to cold end)

*** Using dT from detector to Cold Stage HS cold end - sensor inaccuracy

The TIRS-2 verification process was a mixture of built to print from TIRS-1 with changes described in detail above, but the cryogenic subsystem remained unchanged. Since the design was proven during the TIRS-1 verification process, the team did not need a full-blown independent CSS test, but wanted a way to verify workmanship and get a first look at the parasitics before the instrument TV/TB test. The TIPCE testing campaign, which was intended for early science verifications provided a great opportunity to gain some valuable thermal data. The team added a few more temperature sensors for added telemetry. Cooling was accomplished with the use of a cryo refrigerator attached to a cold finger simulator via a long copper bar, which was a similar configuration to the TIRS-1 CSS test. Test Results indicated the heat load into cold stage cold tip is within acceptable margins. Parasitics were measured at 300mW, which falls in line with CDR estimates of 296mW (Nominal) and 326mW (w/ 10% uncertainties). The warm stage parasitics were estimated at 1 to 1.1 W.

Subsequently, the team completed two instrument TB/TV tests, paying closer attention to sensor accuracy and data acquisition. However, the cryocooler performance map had some inaccuracies for the TIRS-2 build. Using only the thermal sensor calculations, the cold stage parasitics were measured between 260 and 390 mW with less than a 1.5K gradient between detector and cold finger. Furthermore, the warm stage showed a 0.2 to 1.8 W parasitic heat load. The team was able to continue trending the cryogenic subsystem performance during Observatory TV/TB testing, though the flyaway test Cernox sensor used to calculate cold stage parasitics was not available and FPA sensors were used instead. The team has now completed ground test verifications and with the data gathered is able to confidently say that the performance of the cryogenic subsystem is as expected. It is worth restating that it is critical to provide a way to measure parasitic loading into the cryogenic zones by use of proper sensors, mounting and sinking of leads, and proper data acquisition system for accuracy. Furthermore, with the use of a cryocooler, care must be taken during the performance mapping process to accurately characterize cold finger heat load vs cryocooler motor power.

IV. Trending of TIRS-1 On-Orbit Data

Trending the thermal performance of an instrument through on-orbit operations provides support in continuing to characterize design assumptions post-launch. Most engineering design teams are unable to continue trending post-launch or commissioning phase due to limited program budgets, but when there is the opportunity to assess the thermal control system design on orbit, the effort is beneficial not only to the program but also the thermal community at large. Ground testing provides insight into the beginning-of-life instrument thermal performance, but it does not address any end-of-life hardware degradation that may result from long-duration on-orbit exposure during the mission life. The end-of-life trending can only be assessed after years of on-orbit data is reviewed. The Landsat-9 program allowed the thermal team to continue the trending effort of thermal parameters, such as heater power and component temperatures. The Landsat-8 / TIRS-1 mission has been successfully operating on orbit for more than 8 years now, and this data-gathering effort was encouraged in part to aid in the Landsat-9 / TIRS-2 instrument development by means of capturing lessons learned. Furthermore, there were a few findings worth noting for the thermal community, which are described in detail below.

A. Data Trending – General Findings

The data collected during this study included information from February 2013 (launch) to January 2020. The team used a sampling period of 3 months and gathered data at noon for one orbit. This allowed the team to track the orbital variations as well as the performance changes over the life of the mission. The data gathered included temperature data for key components, as well as component power dissipations, voltages, currents, and heater power data. With the limited sampling rate, the data collected does not include all spacecraft slews and calibration phases of the mission; instead, the data focuses on general trends over the duration of the mission and certain events of interest. Overall the data assessed shows nominal operational heater control and stable temperatures for the instrument. For example, the Black Body Calibrator, which is critical for instrument calibration activities, indicates nominal operations, with less than a 1/3 K temperature change over time. Operational heaters, primary and secondary, show nominal heater control with no variation over time. The three cryogenic thermal zones were assessed over the life of the mission. These zones include telescope stage, warm stage, and cold stage as shown in **Figure 6**. The data shows the following three conclusions: 1) consistent temperatures over time, 2) constant temperature gradients between thermal zones, and 3) constant power consumption. Overall, the parasitics between stages is constant and data does not indicate an increase.

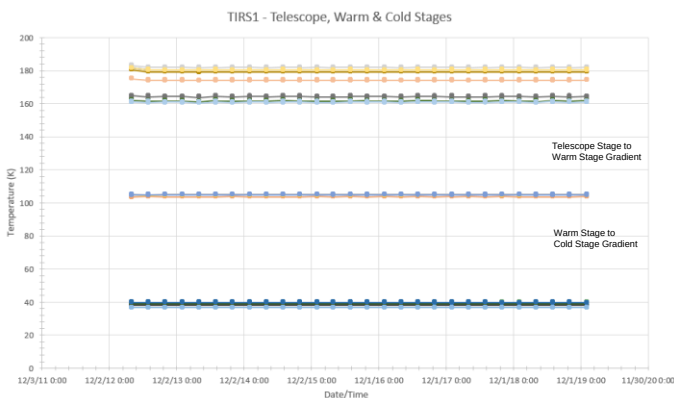


Figure 6. TIRS-1 On-Orbit Trending – Cryogenic Stage-to-Stage Temperature Gradients

B. Data Trending – Focal Plane Electronics

The Focal Plane Electronics temperatures have been stable throughout the mission, although data since January 2020 shows a small seasonal increase as shown in **Figure 7**. A closer look at the data indicates FPE temperatures

increasing with time as heater power authority is lost. The most likely culprit is reduced radiator performance due to degradation in Silver Teflon tape. It is common for the solar absorptance of Silver Teflon to increase over time, therefore increasing energy absorbed by the radiator. The FPE has a fixed operational heater design, and as heater power drops to zero the temperature of the electronics box increases. In spite of an FPE housing temperature increase during this time, the ASIC temperature was not affected and therefore the science data has been nominal.

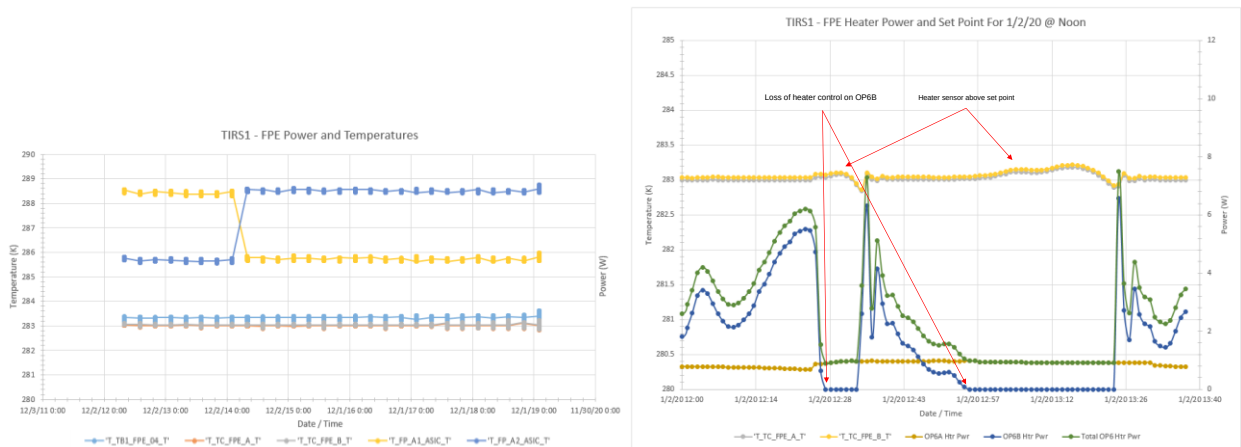


Figure 7. TIRS-1 On-Orbit Trending – FPE Loss of Heater Control Authority

Figure on left shows FPE temperature and heater power from launch to January 2020.

Figure on right shows a close-up of FPE temperature and heater power on January 2, 2020.

Nevertheless, the thermal team's recommendation was to adjust the heater setpoints for the remainder of the mission. Baseline configuration for the mission included two heaters enabled, primary heater in temperature control mode and secondary heater in flux mode to support the primary heater as needed. The solution was therefore to change the setpoints for the secondary heater from flux mode to temperature control mode, setting it 2K below the primary heater setpoint. This configuration allows the secondary heater to provide a safety net in case the primary heater is overburdened during cold seasons. If needed, the heater setpoints can be adjusted to increase thermal margin.

C. Data Trending – Cryocooler Subsystem

The cryocooler subsystem is a critical component for the TIRS instrument, and data trending for it has been particularly important over the life of the mission. The team assessed Cryocooler Electronics (CCE) and Thermo Mechanical Unit (TMU) power dissipation as well as temperature. The data showed a slight decrease in overall power dissipation from 62 W to 60W. Temperature data also indicated a slight decrease as shown in **Figure 8**. Overall this is encouraging news given other missions develop an increase in parasitics which over time can lead to higher power dissipation and warmer temperatures.

The Cryocooler TMU heat flow path was also part of the trending effort and is shown in **Figure 9**. The sink temperature for this subsystem is the Cryocooler radiator. Care was taken to build a path with minimal thermal resistance by using a highly conductive APG material and heat pipes. For every interface care was taken to reduce resistances by using Indium or Nusil. The result of this careful design and assembly effort, as detailed in **Figure 3**, is an end-to-end temperature gradient of less than 8 K.

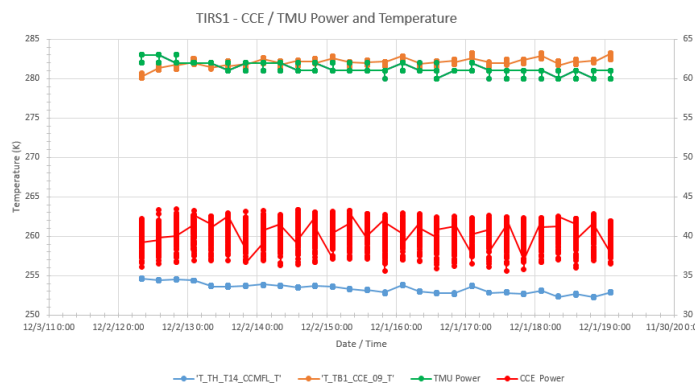


Figure 8. TIRS-1 On-Orbit Trending – CCE and TMU Temperatures and Power Dissipation

D. Data Trending – Focal Plane Array

Temperatures in the Focal Plane Array (FPA) and in the cryo subsystem remained stable from launch to 2018. In 2019 an event was observed where the detector temperature increased by 0.1K. The cryocooler control sensor maintained a constant temperature but the backup sensor dropped in temperature. Furthermore, the Cryocooler TMU power dissipation and reject temperature decreased slightly during this event. While the science data remained nominal, the team was surprised by this trend. The team ruled out the possibility that the Cryocooler Electronics (CCE) temperature affected the sensor reading since its change in temperature was negligible and there was a difference in temperature reading between the primary and backup cryocooler control sensors, with the backup one decreasing in temperature. The team believes the primary control sensor, although showing no change in temperature reading, actually decreased slightly, signaling the TMU to back off on cooling. The cryocooler TMU power therefore decreased, which resulted in the detector temperature increasing by 0.1K. The temperature sensors used on TIRS-1 were Silicon Diodes, but these changed to Cernox sensors for TIRS-2. Parasitics into the cold stage remained constant during this event; if they had increased the TMU power dissipation would have also increased. The team generated a variety of plots to better understand the event described, and one summary plot is included in **Figure 10**.

V. Conclusion

The Landsat program has continued a successful legacy of providing invaluable data to communities around the globe. The Landsat-8 satellite is currently on-orbit and successfully operating beyond its 5-year mission life. The Landsat-9 satellite is in development, and is scheduled to launch in September of 2021. It has been an honor serving as part of the thermal team on both missions; and it has allowed for a unique opportunity where lessons learned on the first program were strongly advocated for on the second program. The key lessons learned discussed here were gathered during instrument ground testing, as well as during on-orbit characterization efforts. The TIRS instrument comprehensive testing campaign, for both missions, shed light on a few interesting findings, including during telescope and cryocooler radiator heat pipe testing and cryogenic subsystem testing. Furthermore, post-launch trending of the TIRS-1 instrument thermal parameters were very useful in continuing to evaluate the thermal control system design and on-orbit degradation over the life of the mission. The key findings discussed here will hopefully provide insight for future programs, in particular cryogenic instruments.

Acknowledgments

We would like to acknowledge the tremendous efforts of the entire TIRS-2 thermal team and the support of the systems and management teams, all of whom worked exceedingly hard over the past four years to support a successful integration and testing campaign, and allow for an early and under-budget delivery of the instrument. Special thanks to Dennis Hewitt, Sharon Peabody, and Jordan Effron.

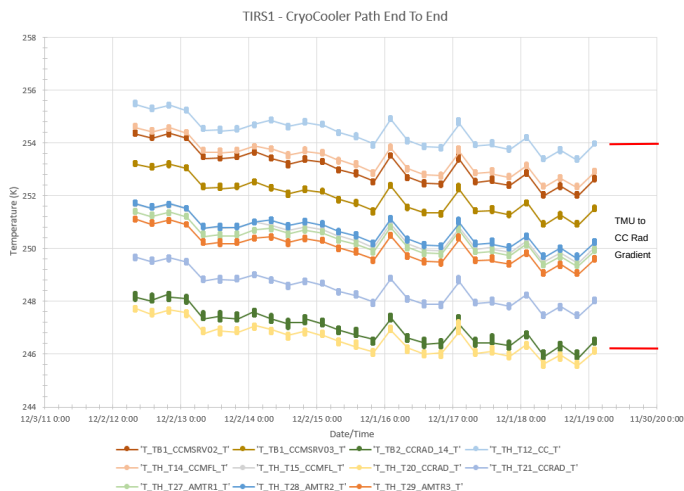


Figure 9. TIRS-1 On-Orbit Trending – Cryocooler Subsystem End-to-End Temperature Gradient

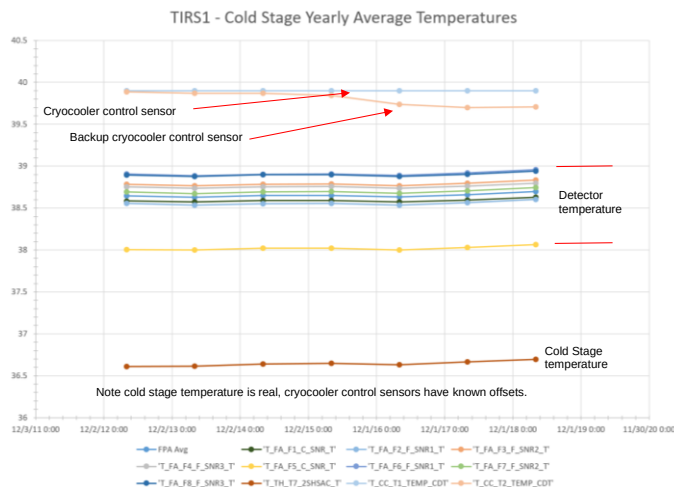


Figure 10. TIRS-1 On-Orbit Trending – FPA Detector Temperature Increase