Abstract—The Thermal InfraRed Sensor (TIRS) instrument was launched into space on board Landsat 8 in February 2013. This instrument was added to Landsat 8 to measure water evaporation and transpiration as well as provide two thermal infrared bands to complement the optical suite. TIRS has a refractive telescope which focuses a light onto a focal plane cooled to 43K with a two-stage cryocooler. This paper will detail the mechanical aspects of TIRS including a description of its composite honeycomb box design, flexures, large deployable earth shield, and accommodations for the telescope, detector, and cryocooler. The design, build, test, and delivery of TIRS was accomplished in three years on an accelerated schedule at NASA Goddard Space Flight Center. The assembly and test flow are discussed including qualification of the structure in vibration and acoustic tests.

1. INTRODUCTION
The Thermal Infrared System (TIRS) instrument was launched on board the Landsat Data Continuity Mission (LDCM) in 2012. The purpose of TIRS is to provide imagery of the earth at two infrared wavelengths at a resolution of 100m to provide information that helps determine the type of crops being grown and evapotranspiration rate measurements for water management. The LDCM mission, renamed Landsat 8 after commissioning, is the latest in the US Geological Survey’s series of earth observation satellites that scan the earth and provide many important data products to government agencies around the world in the areas of land usage, climate change, and crop management, among many others. Details of this mission are beyond the scope of this paper.

TIRS was designed, built, tested, and delivered to the spacecraft in February 2012 in only 27 months from the time it was added to the LDCM mission in December 2009. Building an instrument of this complexity from scratch in such a short time presented many challenges to the mechanical team. This paper will detail how the mechanical design and development of TIRS contributed to the instrument's rapid development.

2. TIRS OVERVIEW AND MECHANICAL REQUIREMENTS
TIRS consists of an f/1.64 178 mm focal length telescope with four optical elements in an aluminum housing that is passively cooled to 185K [1]. This necessitated a large radiator and earth shield to keep the radiator in shadow continuously in-orbit. To fit in the rocket fairing and avoid interference with a neighboring instrument named OLI (Operational Land Imager), the sunshade had to be stowed during launch and deployed on-orbit. Figures 1 and 2 show TIRS and its large earth shield. Figure 3 shows TIRS on the LDCM observatory next to the OLI instrument.

Goddard was responsible for providing the telescope assembly, primary structure, radiator, and deployable earth shield. The cryocooler assembly was provided by Ball Aerospace. Integration and test of TIRS was accomplished at Goddard.

The fundamental mechanical requirement for TIRS was to hold, protect, and align its telescope and related supporting equipment, electronics, and harnesses onto the LDCM spacecraft and maintain alignment during operation. All the other mechanical requirements flowed from that starting point.

The focal plane assembly operates at 43K which necessitated a cryocooler assembly to extract heat from
the focal plane assembly. The cryocooler has its own large radiator which needs a view to deep space without sunlight impingement during on-orbit operation. In addition, the focal plane assembly requires a nearby electronics box to power and control the telescope and process its signals before passing the data downstream to the LDCM.

The telescope boresight had to be stable during on-orbit operation and co-aligned with the OLI boresight within several arc-seconds. This created a derived requirement for a very stable primary structure using near-zero thermal expansion materials. Later in the project, it was discovered that the cryocooler created jitter which reduced image quality, so an additional jitter threshold requirement was developed which led in turn to the need for a vibration isolation system between the cryocooler and the primary structure.

All these requirements led to the need for a primary structure that was stiff, lightweight, and with near zero thermal expansion coefficient (CTE) on-orbit. In addition, the primary structure was required to be attached to the spacecraft via flexures to reduce the influence of spacecraft temperatures, thermal expansion, and launch loads on the instrument. It had to fit on the top of the spacecraft and avoid OLI and its fields of view.

Many of the standard mechanical requirements required of spaceflight instruments also applied to TIRS including surviving launch loads of about 10 G’s and maintaining a first mode frequency above 50 Hz. TIRS had a mass allocation of 186 kg.
3. DESIGN FOR RAPID DEVELOPMENT

The schedule for TIRS was compressed due to a late decision to add TIRS to the LDCM observatory. Instead of a typical 3-4 year development time for an instrument of this complexity, the TIRS project was given a little more than 2 years. This necessitated designing and building the TIRS primary structure in parallel before the other subsystems and their interfaces were fully mature.

As seen in Figures 4 and 5, the TIRS primary structure consists of six composite honeycomb panels shaped like a box with its back panel longer than the others to provide interfaces for the large radiators and deployable earth shield.

The mechanical team made a key design decision to save time in the schedule. Laminas of M55J carbon fiber with 954-6 resin were procured very early and laminated into a near-zero CTE laminate of twelve .004" thick plies. These laminates were used to make about a dozen 36" x 60" x 2.00" honeycomb panels. The blank panels were fabricated over a year before the design had matured and sat on the shelf waiting for the other subsystems to mature sufficiently to proceed with cutting specific hole patterns and cutouts. All the inserts and fittings were to be installed "post-cured." The primary structure was going to be "match-bonded" together in a week-long campaign.

By cutting the panels to final shape as late in the schedule as possible, it allowed the telescope, cryocooler, and earth shield designs to fully mature in parallel without being very constrained by fixed interfaces. One example is that the cryocooler mounting hole pattern, which was controlled by the contractor Ball Aerospace, was not finalized until just a few days prior to its honeycomb panel being cut to shape well into Phase D of the project. That panel was bonded into the structure just a few weeks later.

One disadvantage of this approach from the management perspective was that there was very little hardware to look at to gauge progress by the mechanical team until very late. The outward appearance was merely a collection of fittings and inserts, and a stack of honeycomb panels. The benefit of the matched-bonding technique was apparent later, as will be discussed below.

4. PRIMARY STRUCTURE DESIGN

The TIRS primary structure consists of six composite honeycomb panels forming a box. Four of the six panels were permanently bonded together and the two front panels were removable for access to the interior. The telescope fits inside the box and is mounted to the top and bottom panels. The cryocooler mounts to the underside of the bottom panel. Three flexures attach TIRS to the spacecraft optical bench. One of the TIRS flexures was located on the front removable panel. A temporary adjustable jack stage was installed under TIRS to support it any time the front panel was removed.

Figure 4 – TIRS Primary Structure Front View.
When final interfaces were received and drawings released, the honeycomb panels were put on a large router and cut into shape. The cutting paths were imported directly from CAD (Computer Aided Design) models of the parts, saving a lot of programming time and eliminating errors.

Each panel had crenulations cut out around the perimeter for all the titanium edge fittings. Two cells of honeycomb core were removed from the facesheet perimeter, and the volume was filled with syntactic foam to provide a uniform bonding surface. Fittings were installed and match-bonded to the panels in a process that will be described later in this paper.

There were over 200 titanium fittings in more than a dozen varieties on the TIRS panels that provided the connections between panels to form the box shape. Keeping track of each fitting and its particular location required careful attention to the assembly drawings and the CAD model.

As seen in Figure 6, one style of fitting consisted of a tube insert which was bonded onto one panel and fit into a mating hole on the other panel. After assembly, the gap between the tube and the mating hole was filled with EY3010, and a washer, or shear ring, was inserted over the slightly protruding tube and bonded to the panel to take shear. This operation is shown in Figure 7.

Figure 5 – TIRS Primary Structure Back View.

Figure 6 – One style of titanium edge fittings with a male tube and edge clips.

Figure 7 – After the mating panel is installed, the gaps around the tube inserts are filled with epoxy.

Figure 8 – Edge fittings buttered with epoxy.
In some panel-to-panel joints, the titanium fittings were bonded directly to both panels. Figure 8 shows a row of fittings being prepared for bonding. Once the first fitting was buttered with epoxy, this was a time-sensitive operation that had to be accomplished in less than an hour.

For the two removable panels on the front of TIRS, another fitting style was used. One side of the interface had an insert with a protruding shear boss with a tapped hole, as seen in Figure 9. The other panel's insert had a tight-fitting counterbored hole to receive the shear boss. A screw through the two inserts took tensile loads and the shear boss took the shear loads.

![Figure 9 – Shear boss fittings with tapped holes secure the removable panels.](image)

Inserts were bonded to panels with Hysol 9309 epoxy using an injection process. First, the perimeter of the inserts was covered with aluminum tape to seal up the cavity. Small weep holes in the inserts allowed the epoxy to be injected with a syringe on one side until it began to run out of the weep hole on the other side. Weep holes can be seen in Figure 6. Bondline control was performed with stainless wire or glass beads in the epoxy to ensure a minimum bondline of .005".

![Figure 10 – Panel Coupon in a tensile testing machine.](image)

5. TITANIUM FITTING DESIGN AND ALLOWABLES

Several of the bonded titanium fittings were of unique shape and subject to eccentric loads. Strength allowables could not be reliably determined from finite element models and so coupons were made and pull-tested on an Instron tensile test machine at Goddard. No problems with bonding were encountered, and strength allowables were > 4000 pounds of force. This strength provided plenty of margin against expected loads.

6. PRIMARY STRUCTURE ASSEMBLY

Once the six panels were cut to shape and all the inserts were fabricated, it was time for assembly. The team decided it was not practical to bond the edge clips in exact position on each panel before assembly and expect that the panels would fit together. With several hundred inserts to be installed within about .005" of true position, we decided to let the inserts float and find their natural position prior to bonding. We devised the strategy of dry-fitting the panels together. This allowed us to determine the best assembly sequence and get a feel for how precisely the structure would come together as a cube with parallel surfaces.

The dry-fit procedure required many hands to accomplish but it went smoothly. It was done on a granite surface plate to ensure a good datum plane for the buildup. First, a drill template was clamped to the granite surface plate. This template had the hole patterns for the three support flexures. The flexures were pinned and screwed to the drill template so that they would be perfectly positioned for the buildup. The base panel was leveled parallel to the surface plate via three fine adjustment positioners. Edge clips and inserts were temporarily taped into position with aluminum tape and the panels were carefully mated together. When the last panel was installed, the structure became surprisingly rigid by all the interlocking inserts, even though they were just held in place by tape and friction.
A laser tracker was used to measure the parallelism and profile of the primary structure after the dry-fit. The box was within its tolerances of about .005” parallelism and perpendicularity. No adjustments needed to be made.

The structure was disassembled, and all the fittings and bonding sites were prepared. Each fitting location on the panel was lightly sanded and cleaned with acetone then alcohol. Fittings were also cleaned in acetone then alcohol to remove oils and other contaminants. The structure was reassembled again, and a laser tracker verified that everything was within tolerance.

Final bonding of one panel to another was a critical process that could not be undone without destroying the panels. First, the edge fittings were tack-bonded to the facesheets with epoxy around their perimeter. When cured, the epoxy provided enough holding force to keep the fittings in position, but not enough to make it impossible to remove the fittings in case of an assembly error.

It took about five days to complete the bonding of the primary box structure. The base panel was the starting point, as it would hold the telescope and cryocooler. It was leveled on the tooling plate and fittings were fully injection bonded. The next day, the back panel was installed to it using steel setup blocks to hold it in position while the epoxy cured overnight. Next, the top panel and then the side panels were installed and bonded over the following days.

After the four permanently bonded panels were assembled, the two removable panels were dry-fitted and bonded in a similar procedure. The sunshade panel, which was made offline, was dry-fitted to the primary structure. Small honeycomb panel outriggers with titanium fittings were bonded in place to hold the earth shield.

One final and tedious aspect of the primary structure was
to electrically ground each titanium fitting to a facesheet so that the fitting couldn't build up a static charge on-orbit. Grounding was accomplished by lightly abrading a small spot on each fitting and nearby on the panel and applying a stripe of Eccobond 56C silver paste epoxy to provide electrical contact to each spot. After the Eccobond cured, an ohmmeter verified that there was low resistance between insert and facesheet.

7. CR YOCOOLER ISSUES AND JITTER ISOLATION

One issue that emerged about the time the team was building the primary structure was the realization that there was going to be a problem with jitter from the cryocooler. Induced jitter from a hard mounted cryocooler would exceed the TIRS exported vibration requirement, and cause images to be blurred on the neighboring OLI instrument. The initial method for managing cryo-cooler induced jitter was “active cancellation” of the hard mounted system. Jitter analysis revealed that the active cancellation method would not work well enough, so the project decided to implement a soft mount vibration isolation system for the TIRS cryocooler. Unfortunately, a soft mounted system was not capable of surviving the launch environment due to its low frequency and modest strength. A launch lock was therefore deemed necessary for the cryocooler. The vibration isolation system and launch locks had to fit within the existing primary structure.

Fortunately, a pattern of mounting holes was drilled in the design of the bottom panel just a few weeks before the panel was cut just in case such a launch lock was needed. Adding those extra holes turned out to be a very wise decision.

After the project decided to implement a soft mount vibration isolation system, the design shown in Figure 14 was purchased from Moog/CSA Engineering. It consisted of a metallic flexure and viscoelastic damping material. The frequency of the flexures was tuned such that the 6 rigid body modes of the cryocooler mount on the flexures were between 9 Hz and 30 Hz. This was sufficiently below the 42 Hz cryocooler drive frequency, and worked to reduce the OLI LOS (Line of Sight) error by a factor of 10 over the frequency range of 0 to 300 Hz.

![Figure 14 – The cryocooler on its "keel" was damped via the three red soft pads during operation.](image)

The launch lock system shown in Figure 15 consisted of a single ERM (Ejector Release Mechanism) attached to the front panel that preloaded a triangular linkage mechanism that in turn pulled the cryocooler up against hard stops under the bottom panel using tapered pins [2]. The ERM was purchased from TiNi Aerospace Inc. This release mechanism is activated by passing current through a shape memory alloy wire. When the ERM was activated after launch, the linkage rotated several degrees to release the cryocooler from its hard-stops and allow it to float on its dampers. The launch lock system was designed after the rest of TIRS was designed and nearly built, and so had to fit into whatever volume remained. It was therefore a more complex design than would have been the case if it had been part of the overall design from the beginning.

![Figure 15 – Cryocooler launch lock system utilized a linkage and a single ERM release mechanism.](image)

8. EARTH SHIELD INTERFACE AND DEPLOYMENT

The Earth Shield System deploys a 78” x 50.5” composite panel, from its stowed position to its deployed position of
90° from the TIRS radiators, as seen in Figure 16. The purpose of the earth shield was to block reflected light from the earth from getting into the telescope and to help keep the cavity around the telescope in a stable thermal environment. In addition to the shield, two thermal close-out blankets, or “Wings,” and a hinge-line blanket are employed to further shield the TIRS instrument’s radiators. The deployment mechanism is an ERM from TiNi Aerospace. Spring-loaded hinges on the earth shield rotated it and held it in position on-orbit.

Figure 16 – When the earth shield is deployed, the two radiators (green and beige panels) and the telescope are exposed and are shielded from stray light.

The earth shield deployment system was designed with the ability to easily remove and reinstall the large earth shield panel and two wings, as well as deploy and stow multiple times throughout the integration and testing of the TIRS sensor unit. The strongback, hinge components, and hinge-line blanket, are permanently installed on the structure and assure that the hinge-line configuration and alignment do not change between different earth Shield installations.

9. STRUCTURAL QUALIFICATION

After bonding the primary structure, the first task before qualification was to bake it out in vacuum to remove volatiles. Figure 17 shows TIRS loaded into the vacuum chamber at Goddard. The TIRS telescope lenses were susceptible to condensed volatile contamination and it was important to remove as much as possible prior to telescope installation. A QCM (Quartz Crystal Microbalance) was used to monitor the level of contaminants outgassing from the structure. After a few days the outgassing rate had dropped low enough to meet requirements.

![Figure 17 – TIRS structure in the vacuum chamber prior to bakeout](image)

After bake-out, mass mockups were installed onto the structure to simulate the telescope, cryocooler, and other subsystems. The large earth shield was installed. TIRS was moved into the vibration cell and many accelerometers were installed. Vibration testing took about a week, and consisted of a sine-burst of eight pulses of about 9 G's in each orthogonal axis. The sine burst test is a strength test which stresses the load path and verifies that the bonded joints are adequate. Before each sine burst, a signature sine sweep was performed to establish the resonant frequencies, and to provide a measure of correlation to the finite element analysis. After the sine burst another signature sine sweep was run to verify that resonant modes had not shifted, which would indicate a failure of some kind in the structure or bonded joints.

After vibe, TIRS was put onto its turnover dolly and rolled into the Goddard Acoustic Test Facility. It was subjected to Atlas V protoflight acoustic levels for 120 seconds. Afterwards, the earth shield successfully deployed using the flight actuator system, which qualified that system for flight.

10. INTEGRATION AND TEST

After qualifying the structure, it was delivered to the
Integration and Test team to begin the work of installing the telescope, cryocooler, and other subsystems. Installation of the telescope was a delicate but not too difficult task. The telescope's equatorial flange sat on a Titanium ring bonded to the top panel of TIRS. The plane of the ring had been bonded to the panel within .0005" of parallel, and the equatorial flange was machined to similar tolerances, so the interface was a simple flat-on-flat. The clocking of the telescope relative to the TIRS coordinate system was important, so oversized clearance holes were used to provide a little adjustability. To ensure the telescope did not shift from launch loads, it was to be pinned into place. Two pins on the titanium ring fit into wide slots on the telescope's equatorial flange. After alignment was completed and verified, the slot with the pins was filled in with epoxy, thus locking the telescope into the desired position.

The remaining subsystems, including the earth shield were installed over the next several months and electrical checkouts were performed. Then TIRS went through a random vibration test to expose any workmanship issues with the electronics and harnessing. Next was an acoustic test, then an EMI/EMC (Electromagnetic Interference / Electromagnetic Compatibility) test, and finally a thermal-vacuum test. After each test, TIRS was functionally tested to verify it was still in good working order.

TIRS shipped to Orbital Science's facility in Gilbert, Arizona in February 2012 for integration onto the LDCM satellite.

11. TIRS INTEGRATION ONTO LDCM SPACECRAFT

Prior to TIRS installation on LDCM, the same drill template that TIRS was built on was used to drill the flexure mounting holes on the LDCM optical bench. That helped to make the installation of TIRS relatively undramatic. The hole patterns on the three flexures on TIRS interfaced perfectly to three pads on the LDCM Optical Bench. Tethered tapered guide pins were used during the installation to help position the TIRS sensor unit flexures. Also, the TIRS lift sling had an adjustable ballast mass to level the flexure interface plane.

Figure 18 shows TIRS on LDCM. Installation occurred when the OLI was already installed to the LDCM bench, and the TIRS -Z side was close to the OLI while lowering the sensor unit. Additionally, delicate hardware was close to the lift areas surrounding the OLI and TIRS, so it was critical to exercise caution during the TIRS installation process.

The earth shield was installed separately because it extended below the plane of the LDCM bench and reduced access to the mounting flexures. A crane operation was performed to install the earth shield in the deployed position, and staging of personnel on man lifts was needed to stow and preload the earth shield.

Electrical and thermal interfaces were then installed and verified, including thermal blankets and electrical grounds.

The full spacecraft integration and test phase took about another year. Launch occurred on February 11, 2013 on an Atlas 401 rocket. The TIRS launch locks and the earth shield were successfully deployed. The cryocooler isolation system worked as planned, and TIRS continues to produce infrared images that meet or exceed its requirements.

12. SUMMARY

TIRS development and delivery took 27 months and caught up to the other instrument and spacecraft by developing its subsystems in parallel. The method of building the primary structure as late as possible in the flow was very helpful for the project to maintain its accelerated schedule. The technique of "match-bonding" composite honeycomb panels together in a one-week process contributed to the success of TIRS. Using post-cured inserts and adding additional mounting holes to panels before all the interfaces had been established.
provided additional flexibility when the cryocooler vibration isolation and launch lock assemblies were added after the structure was bonded together.

REFERENCES


BIOGRAPHY

David Robinson is currently the Lead Mechanical Systems engineer of the Astro-H and GEDI projects at the NASA Goddard Space Flight Center. He started his career with NASA Glenn Research Center in 1990 working on the International Space Station and several microgravity fluids space experiments for the space shuttle and the Russian Mir space station. While at Goddard, he has worked on JWST, Swift, Solar Dynamics Observatory, the TIRS instrument on LDCM, the International X-ray Observatory and many proposals along the way. He received a B.S in Aerospace Engineering from the University of Virginia, an M.S. in Mechanical engineering at Cleveland State University, and an M.S. in Space Studies at the International Space University in Strasbourg, France.

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