DEVELOPMENT OF THE SCENE SELECT MECHANISM FOR THE THERMAL INFRARED SENSOR INSTRUMENT

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ABSTRACT

This paper describes the design and development of the Scene Select Mechanism (SSM) for the Landsat Data Continuity Mission (LDCM) Thermal Infrared Sensor (TIRS) instrument, built by staff at NASA Goddard Space Flight Center (GSFC). The SSM is a single axis, direct drive mechanism which rotates a 207 mm scene mirror from the nadir science position to the 2 calibration positions twice per orbit. It provides pointing knowledge and stability to ~ 10 µradians. An overall technical description of the mechanism is provided, as well as an outline of how the design progressed from initial proposal through flight delivery. The paper concludes with significant technical and programmatic lessons learned.

1. Introduction

The LDCM satellite will launch into a low polar orbit in late 2012. LDCM will provide earth resources data continuity with the currently operational Landsat 5 and Landsat 7 missions. It will provide a high spatial resolution complement to the lower spatial resolution, higher temporal sampling Joint Polar Satellite System (JPSS) images. LDCM will be carrying TIRS, an actively cooled, nadir-looking, infrared imager. TIRS will require multi-scene calibration every orbit, so a flat scene mirror is used to switch the instrument FOV between nadir, space, and a black body calibration target. The Scene Select Mechanism will move and position the scene mirror.

2. Initial Instrument / Mechanism Design

There were two separate instrument architectures explored during the proposal phase, each requiring a very different type of SSM. Both architectures utilized a 108 mm aperture, actively-cooled, -88°C telescope and a -233°C focal plane array. The major mechanisms for each were very different. The initial concept did not utilize a scene mirror. To accomplish calibration, full-aperture, temperature-controlled blackbody plates were rotated in front of the instrument telescope. A carousel-type rocking mechanism was conceptualized to accomplish this. The carousel was analogous to a 3 position filter wheel; positions 1 and 3 contained blackbodies, and position 2 was clear. With position 2 selected, the blackbody plates were shrouded. The fixed shrouds were tightly controlled thermally and maintained the blackbodies at uniform temperature radiatively. However, thermal analysis showed that when the blackbodies were rotated out of the fixed shrouds and in front of the telescope, temperature gradients would immediately form, resulting in degraded calibration quality. The degree of active thermal control required to compensate for the induced gradients on the rotating blackbodies was prohibitive. A more traditional approach, with a scene mirror switching views of nadir, a uniformly cold deep space view, and a fixed blackbody at 47 °C, would provide improved calibration performance, resulting in better science data.

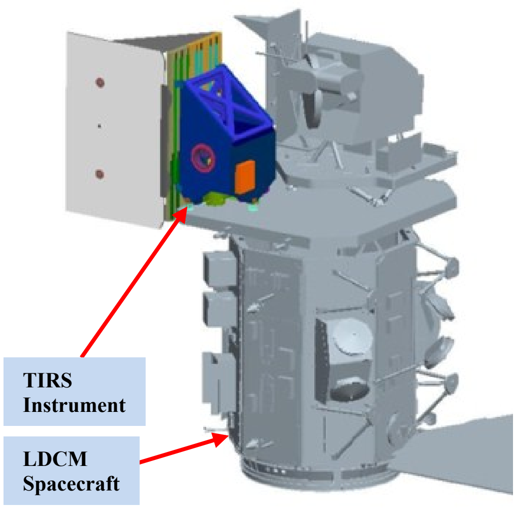

Figure 1. The TIRS instrument on the LDCM satellite

The scene mirror approach would require a mechanism with a higher degree of precision than the rotating blackbodies mechanism. The rotating blackbody mechanism would need coarse positioning as the blackbodies required a positional accuracy of a few milliradians. It was generally accepted that the scene mirror mechanism would require position knowledge

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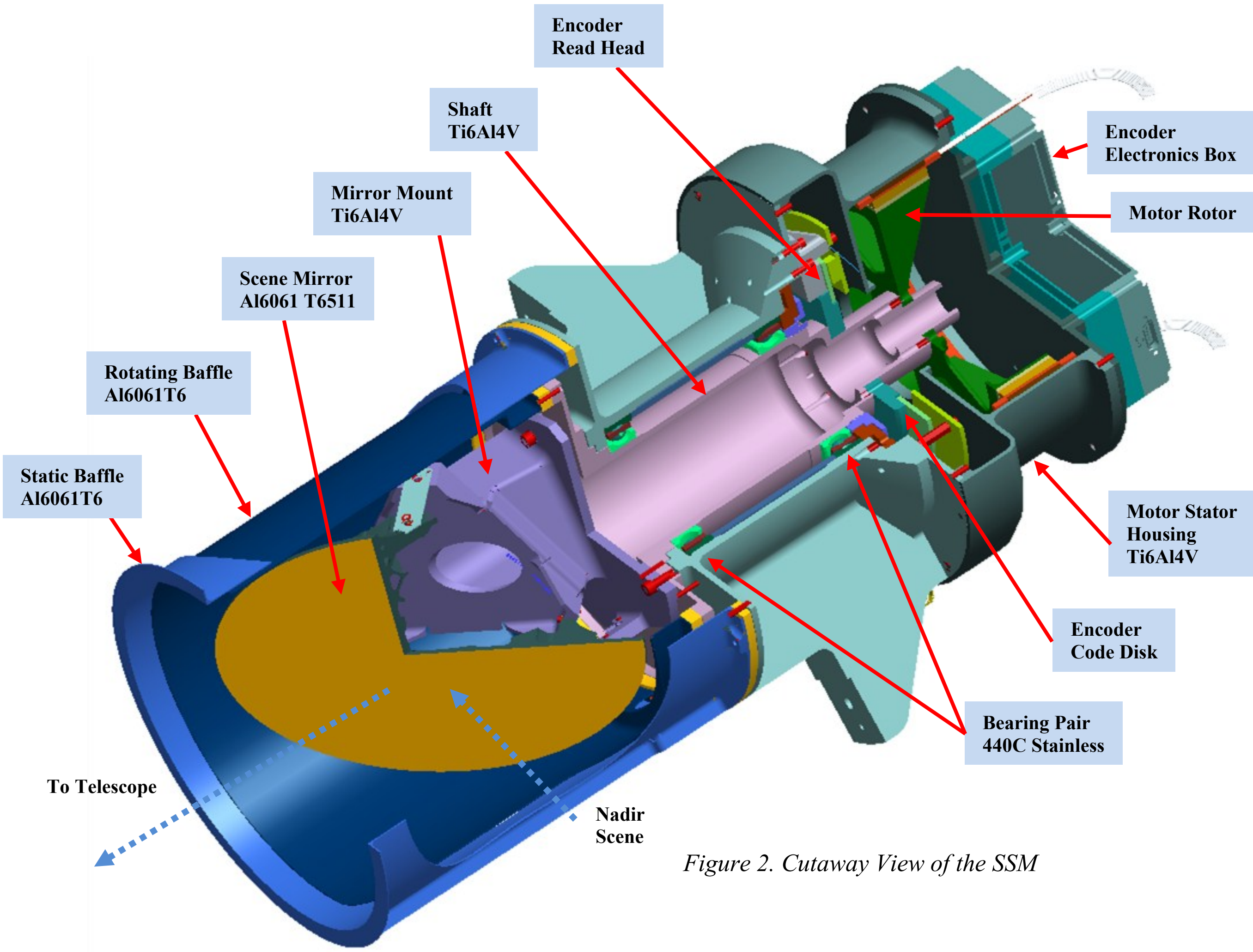

Figure 2. Cutaway View of the SSM

and stability of less than 20 microradians but was looser in repeatability. Just how tight the knowledge/stability requirement actually was would be argued throughout the initial design phase, and well past the System Requirements Review (SRR). In the absence of a hard requirement, and at risk of over-specification, the mechanisms team assumed the worst and forwarded a design that would be capable of microradian-level positioning to the instrument proposal team.

The design of the SSM is straightforward; it is a single axis rotational mechanism. The operational cadence was to hold the scene mirror stationary for ~40 minutes staring at nadir, rotate 120° to the space view aperture and stare for 30 seconds, rotate 120° to the internal blackbody and stare for 30 seconds and then rotate the mirror to the back to nadir. Then the entire process would start again. The mechanism would be operating all of the time, or have a 100% duty cycle. Since LDCM/TIRS was to be in a highly-inclined polar orbit, the general idea was to calibrate twice per orbit while over the poles.

3. Flight Mechanism Technical Description

The SSM is a precision positioning mechanism, capable of 10 μradian performance. It can be driven in either direction for unlimited rotations. The rotating mirror is dynamically balanced over the spin axis, and does not require launch locking. The flight version of

Table 1. SSM Driving Requirements

Requirement	Value
Mass	15 kg
Power	6 W average
Knowledge	+/- 9.7 μradians over 34 minutes
Stability	+/- 9.7 μradians over 2.5 seconds
Duty Cycle	100%
Thermal Operational	0 / +20°C stable to +/-1°C
Thermal Survival	-50 / +40°C
Lifetime	3.25 years on orbit
Redundancy	A/B Side Block Redundancy
Operational Cadence	Stare nadir for 30-40 minutes Rotate 120°in <2 minutes to space view Stare for ~30 seconds, Rotate 120°in <2 minutes to blackbody view Stare for ~30 seconds Rotate to 120° in <2 minutes to nadir view

the SSM met the driving requirements defined in Tab. 1. The mechanism is shown in Fig. 2.

Structure

The SSM will operate at a nominal 7-10°C; the scene mirror it rotates will be near 0°C. To minimize heater power, low thermal conductivity titanium 6Al4V was chosen for the primary structural material. The 207mm x 149mm scene mirror is made of aluminum 6061-T6511 with a gold optical surface coating; the back is bare. The mirror is secured to a titanium mount with three aluminum 7075-T6 flexures to minimize thermal deflection of the mirror surface. The flexures are pinned to the mount then float bonded in place with Stycast 2850 epoxy to the mirror to reduce assembly-induced moment loading of the mirror. The mirror mount is bolted and liquid pinned to the shaft. The shaft is suspended in the bearing housing with a pair of angular contact ball bearings. The bearings are bonded in place to ensure stability at the μradian level. The bearings are mounted in the bearing housing, which serves as the main housing of the SSM and has three radial legs which serve as the mounting interface to the instrument. The encoder code disk and motor rotor are bolted and pinned to the shaft. The motor stator mount houses the stator, and attaches to the non-mirror end of the SSM. The motor stator mount is a separate part from the bearing housing so that it can be shipped to the motor vendor for stator build up independent of the rest of the SSM. Similarly, the mirror mount is a separate part from the shaft to allow concurrent, independent assembly. The motor mount, mirror mount, and rotor shaft are finished in Tiodize type II for corrosion protection. The bearing housing was not Tiodized; it was left bare since it is almost entirely covered with strip heaters and other thermal control components which require non-anodized surfaces to minimize thermal gradient “hot spotting”.

Baffles

A fixed aluminium baffle is fitted over the mirror end of the SSM, attached to the bearing housing. An aluminium rotating baffle, attached to the shaft, protects the back of the scene mirror and the mirror mount from the cold space view and hot blackbody view thermal loads, and reduces stray light getting into the telescope.

Actuator

The SSM is driven by a frameless brushless DC motor with redundant windings and damping coils. The 2-phase, 48 pole, moving magnet motor has an air gap of 0.4 mm, and a motor constant of 253 in-oz/amp.

Bearings

The SSM uses a pair of duplex back-to-back mounted, 70mm bore angular contact ball bearings with a 25 degree contact angle. The bearings are hard preloaded to 50 lbf. (222 N) and are bonded in place to ensure stability at the μradian level. The bearings use tri-cresyl phosphate (TCP) coated 440C balls in a phenolic cage, with 440C races. Pennzane lubricant is utilized; specifically an oil + grease slurry of (50% each by weight) Nye 2001 ultra-filtered synthetic oil and Nye Rheolube 2000 grease. The oil is also vacuum-impregnated into the retainer. Lubricant retention is provided by labyrinth seals sized for < 5% mass loss over the mechanism lifetime. Lubricant surface migration is prevented by the application of Nye-bar surface barrier coatings within the labyrinth seals.

Encoder

The SSM uses a 22 bit, pseudo-absolute optical encoder, which is an incremental unit that emulates an absolute encoder with a software counter and index pulses. The encoder has redundant read heads and drive electronics cards. The 125 mm code disk is fixed to the rotating shaft. The read heads are fixed to the bearing housing. The motor stator housing fits over the top the read heads, encapsulating them; an integral contamination shield protects the encoder from any potential particulates coming from the motor area. The encoder drive electronics are housed in a dedicated enclosure, which is mounted to the cover of the motor stator housing.

Several features were introduced to facilitate handling, reduce risk, and ease testing. The lifting points and shipping attachment points were independent of the flight attach points. This protected the precision flight interface from possible damage and wear from the numerous shipping and handling operations prior to installation in the instrument. A quartz optical cube was bonded to the motor housing to provide a boresight alignment reference. Mirror pointing and stability measurements were referenced to this fiducial. Three small mirrors were located 120° apart on the rotating mirror mount. Viewports through the static baffle ensured that these mirrors could be seen from outside of the SSM. These mirrors allowed an autocollimator to record the repeatability and stability performance of the SSM.

4. Design Trades

Several component combinations were traded before and during the refinement of stringent requirements.

Housed vs. Unhoused Components

The actuators and sensors could be procured framed (self-contained in a housing with internal bearings) or frameless. Framed units would require couplings to the SSM main shaft, and increase the size of the SSM. Also, it was felt that housed components would take longer to procure. Unhoused units would be used.

Direct drive vs. Gearing

Gearing would allow a smaller motor and potentially relax the precision of the position sensor if located on the motor output, but come with the cost of a proportionate increase in bearing rotations and input speed. It was felt that a direct drive actuator could be obtained faster as there were less components to specify and procure. Procurement time was factor in all of the trades, as TIRS was on a compressed schedule.

Stepper Motor vs. Brushless Direct Current (BDC) Motor

A stepper motor would preclude direct drive as the step sizes are too large, and gearing would be required. Stepper motors feature a useful detent torque which would prevent mirror backdriving. They also provide a secondary open-loop positioning mode via step counting. A stepper motor would likely provide adequate power-off detent torque to launch lock the mirror. Micro-stepping would not provide the required positioning performance without gearing. A BDC motor would have to operate at relatively low speed unless geared, and would not have the torque noise associated with stepper motors. Low-speed, zero cog flight motors were available so the BDC approach was taken.

Bearing Tribology: Dry vs. Wet

A pair of back-to-back angular contact bearings would be used for the SSM, and the lubrication type was traded. A dry lubricant would allow operation down to cryogenic temperatures, and would not increase drag torque due to viscous effects present in wet lubricants at lower temperatures. However dry lubricants have reduced operational life and require continuous humidity control once installed. Use of traditional oil/grease would limit operations to about -20°C and higher due to lubricant viscosity, and ease humidity requirements. It was also felt that wet lubricated bearings could be procured faster. An oil+grease lubricant approach was selected, with Bray 815Z/600 series selected for the proposal, with Silicon Nitride (SiN) balls and Cronidur 30 races with a 75mm bore. However, this changed after PDR.

Sensor: Optical Encoder vs. Resolvers

Initial communications with a flight optical encoder vendor indicated that 24 bit, absolute units (MIL-SPEC rated, but non-flight) were available on short notice and for low cost. 24 bit absolute units with recent flight heritage had been developed and could be modified for our application. The digital output was beneficial for the electronics development, and no rotary feedthrough was required. Inductively coupled resolver units would require a signal feedthrough which we wished to avoid. A 24 bit absolute optical encoder was selected.

Signal Pass-Through vs. No Signal Pass Through

The thermal system wanted to add decontamination and control heaters, as well as temperature sensors, to the back of the scene mirror. This would have required a rotary power/signal pass through, requiring brushes, roll rings, cable wraps, or a flex capsule. All but the roll ring would limit the rotation of the mirror, as well as add significant drag torque. No signal pass through was preferred. The mechanisms team pushed back on thermal, and the thermal hardware was not implemented. Thermally, the mirror could be passively controlled by heaters on the static baffle.

Mirror Substrate Metal vs. Glass

The edge of the scene mirror was located within 15mm of the cold telescope. The mirror would be radiatively cooled by this close proximity to the cold lens. . We wanted the mechanism to be warm; this meant that a standing thermal gradient would be present in the mirror (and across the entire mechanism). Low expansion glasses such as Corning Ultra-Low Expansion (ULE) or Schott Zerodur would provide better optical surface flatness, and the low CTE would result in better thermal stability of the figure. However the low thermal conductivity would mean a steeper gradient would be held. Glass would require a more complicated mounting scheme, likely requiring bonded metallic inserts. A metallic mirror (aluminum or beryllium) would not have the flatness or stability of glass, but would be simpler to mount, as mounting features could be machined into the mirror back. The much higher thermal conductivity would result in a smaller standing gradient. Beryllium, vastly superior to aluminum in all respects, was removed from the trade on the basis of procurement time alone. The optical requirements were loose enough to allow aluminum to be used. Additionally an aluminum mirror could be completely fabricated, polished, and coated in-house allowing control of every process step, resulting in the fastest development time.

Figure 3. The back of the Scene Mirror before polishing

Aluminum 6061-T6511 (extruded and stress relieved) was chosen, with RSP-77 Aluminum (Rapid Solidification Process) as a parallel-path material. The open-back lightweighting pattern used on the mirror is shown in Fig. 3.

5. Proposal award through System Requirements Review (SRR)

With the good news that the proposal was awarded and SRR was fast approaching, the mechanisms team grew in size with the addition of computer-aided design (CAD) experts, and supporting mechanical and electrical design engineers. An increasingly detailed listing of requirements was prepared both for the instrument systems engineer and to go into the specification documents the mechanisms team was preparing for the motor, bearing, and encoder procurements, which were initiated during this phase. The motors and encoders were to be delivered fully qualified from the vendors. Conceptual CAD models were improved and our mass allocation was increased to 15 kg to allow for predicted mass growth. A development plan was generated to minimize risk wherein 4 identical SSM units would be built, even though only one would fly: A flight unit, a flight spare unit, and 2 engineering test units (ETU). The ETUs would be subjected to higher qualification environmental test levels than the flight units, thus "qualifying" the design for flight. One of the ETUs would be used for a 2X life test. The second ETU was to be used for developmental testing of the ETU and flight control electronics, which was happening early and needed a dedicated SSM to remain independent of the flight unit schedule. The ETU testing would be followed immediately by flight unit testing, reducing development time to meet the instrument schedule. This meant that there was no time to implement design changes to correct problems which may occur during the ETU qualification testing. Commercial equivalent bearings and a 24 bit absolute encoder were procured for use on a breadboard unit. This unit would be used to demonstrate the control algorithm, and verify that the predicted level of positioning performance could be achieved without waiting for the flight hardware.

6. SRR Through Preliminary Design Review (PDR)

Some critical electrical components, including field programmable gate arrays (FPGA), were procured by the instrument electrical systems team early to ensure availability later.

The encoder vendor was very experienced with bonded bearings, so they were to perform the bonding. As such, they would require that the bearing housing, shaft, bearings, and associated hardware be delivered to them well before instrument CDR. This was referred to as the "spindle assembly". Indications from the encoder vendor that a critical electrical ASIC component had not passed previous screenings, were disconcerting. The design was based on a potentially unflyable component, and the ASIC part would not be available for screening until after PDR. The sudden increased risk and the resulting schedule threat prompted the instrument to fund a parallel path effort that did not utilize an optical encoder, exploring alternate architectures for nadir precision positioning that still met the instrument schedule. After several months of effort, the parallel path team was unable to produce a viable alternate architecture; their results converged to the baseline design.

7. PDR Through Critical Design Review (CDR)

The encoder vendor received the critical ASICs, and screened them. Unfortunately, they failed, leaving two options: replacement of the single ASIC part with discreet components, requiring significant additional design work, or changing the encoder architecture. The alternate architecture was a flight heritage incremental encoder with a software counter, providing identical absolute output as the original absolute encoder. This was required as we were not going to change the SSM control electronics to accept incremental output. We needed the encoder electrical and mechanical interfaces to remain the same to minimize the schedule impact. This approach was known as the "pseudo-absolute" encoder and it is what was chosen, since the encoder electrical design could be copied from a previous program with minor modifications and the code disk was identical. Due to this occurrence, decreased confidence in the encoder vendor delivery prompted another parallel path effort to develop a SSM which used an encoder from an alternate vendor which had not previously built spaceflight units, but was very enthusiastic to develop a flight qualified design.

Further refinement of the higher level requirements showed that 22 bit position performance was acceptable; and the encoder specification was revised from 24 bits, but this had little effect on schedule. The bearings were changed from using electrically insulating SiN balls to TCP coated, electrically conductive 440C. This was done to increase electrical conduction across the bearings to aid in dissipating static charge that would build up on the rotating mirror, and 440C met the other bearing requirements. It was also noted that the 75mm bore could be reduced, saving mass. A 70mm bore size was implemented. The bearing lubricant was changed to Pennzane with a lead napthanate filler. The bearing vendor indicated difficulty in obtaining lead napthanate due to new hazardous material regulations. After consultations with the GSFC Materials Engineering Branch, the high pressure additive was dropped.

A prototype bearing housing and shaft made from aluminum and a set of extra breadboard (commercial grade) bearings were sent to the encoder vendor so they could practice the bearing installation, and to refine the flight assembly procedure. The vendor accomplished this task successfully, with GSFC engineers on-site to observe. This would prove crucial during the eventual flight build.

The flight bearing housings and shafts were fabricated early (before CDR) in order to not delay the encoder schedule. Unfortunately the parts came in several weeks late and upon arrival, had several threaded holes for installation of helical inserts that were too large. The error was traced to incorrect machining rates at the fabricator, which was inexperienced with titanium. Helical inserts would thread into the parts but were loose. The helical inserts were installed at Goddard, and the parts shipped to the encoder vendor for bearing installation as there was no time to remake the parts. At the encoder vendor, the helical inserts were found to be spinning out during assembly fit checks. Due to property liability, the vendor refused to attempt repairs to the hardware and a GSFC technician was sent to the vendor site to effect repairs. Unfortunately the repairs could not be accomplished locally and the parts were sent back to GSFC for re-work. At GSFC a procedure for carefully placing the helical inserts at the proper depth and threading the bolts into them was developed and verified, and the parts returned to vendor. This cost one month of delivery slip, much of it wasted in shipping and the 1-2 days at each end of each shipment devoted to inventory accountability and mission assurance procedures. This delay, combined with other delays in obtaining encoder electrical parts, as well as read head lens coating issues were threatening to push the encoder delivery back by several months during this phase.

In order to bring the date back in the delivery order of the encoders was reversed; the 2 flight units would be delivered first, and the ETU units would be delivered second. Fight unit environmental testing to be done at the vendor was removed, also to save time but at increased risk.

The breadboard SSM, made from commercial components (including the 24 bit absolute encoder) was completed and demonstrated positioning performance that met requirements with a breadboard controller. This verified the controls approach and aided the flight control electronics development.

Finally, the stator of the motor was integrated directly to the motor housing to reduce weight and simplify assembly/alignment. This allowed motor installation by tolerance only and avoided lengthy alignment procedures. However, the motor stator housings had to be provided to the motor vendor as Government Furnished Equipment (GFE) for assembly; fabrication of the parts was accelerated so that they would not delay the motor delivery.

8. CDR Through Pre-Environmental Review (PER)

The motor vendor ran into some wire out-of-date issues which required further analysis and some replacements, which delayed delivery of the first motor by about one month. Since the encoder was driving the mechanisms schedule, this slip was acceptable. However, the vendor rallied and delivered the remaining motors early, ending the procurement several weeks early overall. However, the flight bearings were received, several weeks late.
The flight bearings were shipped to the encoder vendor and build-up of the spindle assembly was started. While the breadboard bearings used had the preload direction marked correctly the flight bearings were marked opposite by the vendor! This was not detected until the bearings were being fit checked prior to bonding. Fortunately, since we were present during the previous breadboard build, we noticed something suspicious. Although the procedures were correct and the marking on the bearings showed that they were being installed correctly the physical configuration of the bearings, obviously going in face-to-face, raised a concern which led to the temporary stoppage of the build and contacting the vendor to investigate. Ultimately we modified the procedure and proceeded with the build, mounting the bearings back-to-back, opposite of the reversed markings. The bearing vendor later confirmed the error in the marking, and the flight unit 2 spindle was assembled correctly.

The flight unit 1 encoder was built up on the flight spindle assembly 1, functionally tested by the encoder vendor, and delivered, only one month later than the original plan, due to all of the descoping and shuffling of units. The SSM was quickly integrated and interface testing with the ETU control electronics, which were also delayed, commenced. At the encoder vendor, build-up of the second encoder onto flight spindle 2 commenced, and parts were kitted in preparation for the timely build of the remaining 2 ETU encoders.

It was at this time that it was determined that the ETU encoders were not needed, and significant costs could be recovered if they were cancelled. Initial functional testing of the flight encoder was encouraging. The flight spare encoder was almost completed. The life test was being accomplished using a bearing cartridge approach instead of a full ETU SSM. Since the flight control electronics were late, they could no longer take advantage of a second ETU SSM. The encoder vendor was notified and told to stop work on the ETU encoder units, at points reasonable to their current assembly status. They would be delivered to GSFC with the shipment of the flight unit 2 encoder/spindle assembly, showing up as boxes of kitted parts, ready for future use if needed.

During initial SSM testing with the control electronics, a “glitch” was discovered in the encoder which resulted in a sudden position jump. Due to activity in the lab this error was at first dismissed as an accidental bump to the unit caused by a technician. The encoder was reset and resumed normal operation. One of the other issues was a step error in the control electronics which required program correction.

Eventually the "glitch" appeared again in further testing and was now occurring on both the primary and redundant sides. Initially some changes to harnessing were though to resolve the issue. Analysis of the events previously recorded led the team to believe that it was related to noise in the environment. After the issue appeared in two different test configurations the grounding schemes were examined and strengthened. While this reduced the frequency of the "glitch" occurrence, it was not known if it completely eliminated it as it was an intermittent, infrequent event, and was not something that could be induced. Only during environmental testing would we know whether the measures taken resolved the issue. An attempt was made to replicate the glitch at the encoder vendor using the completed flight unit 2 encoder. The glitch could not be replicated by the vendor; it may be present only in the flight unit 1 encoder, or was caused by something at GSFC.

Other last-minute changes stemmed from other systems. Optics informed us that they had discovered an error in their ray trace model, which indicated that the nadir opening in the static baffle had to be slightly enlarged to prevent vignetting. The static baffle already had been integrated, and was covered in strip heaters and thermal harness. It was removed from the SSM, the opening enlarged by hand using a Dremel tool and a template, and re-integrated prior to environmental testing without damage to any thermal components. Unfortunately thermal informed us that they had not included the G-10 isolators which sat between the static baffles and the bearing housing in the final flight analysis (these features had been included in previous thermal analysis). Since the thermal model worked without the isolators, it was faster to replace them with aluminium parts of equal shape, rather then re-running the thermal model with them and updating analysis documents.

9. PER Through Delivery

The SSM successfully passed the random vibration to $9.3g_{rms}$ and sinusoidal burst testing to 11.25g's at 15 Hz. It was subjected to 8 cycles of Thermal Vacuum (TVAC) testing and passed. The original test had 12 cycles, but this was reduced to save time. Fig. 4 shows the SSM in the TVAC chamber during testing.

The "glitch" showed up again during this testing. This confirmed that it still occurred (although infrequently) and that an effective mitigation be determined. A workaround solution to the "glitch" issue was developed. A software watchdog was implemented, capable of detecting when the "glitch" occurs and immediately switching the control method to compensate for it. While this does require a reset of the encoder to return to normal operation it does allow the accuracy to not be affected and for the SSM to operate successfully even if the glitch occurs. Testing confirmed this mode of operation can maintain functionality of the SSM.

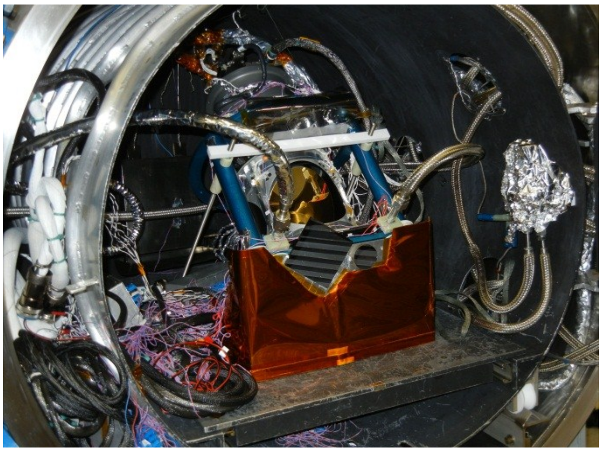

Figure 4. The SSM in the thermal vacuum chamber, tilted to allow direct horizontal measurement of the scene mirror position against in-chamber reference flats. The gold Scene Mirror is visible between the blue support frame posts.

Environmental testing was completed and the flight SSM successfully qualified, with workarounds in place to detect the intermittent glitch. Due to the high accuracy of the SSM control mechanism, some difficulties were a result of limitations of the testing equipment itself. Reliance on statistical analysis accuracy was assessed and compared to the instrument reported numbers to verify satisfaction of the requirements.

The encoder vendor delivered the unit 2 encoder/spindle assembly. The SSM flight spare was partially assembled, and the life test had reached twice the mechanism lifetime at the time of this writing.

The SSM was successfully delivered to the TIRS instrument. The installation of the mechanism into the instrument is shown in Fig. 5.

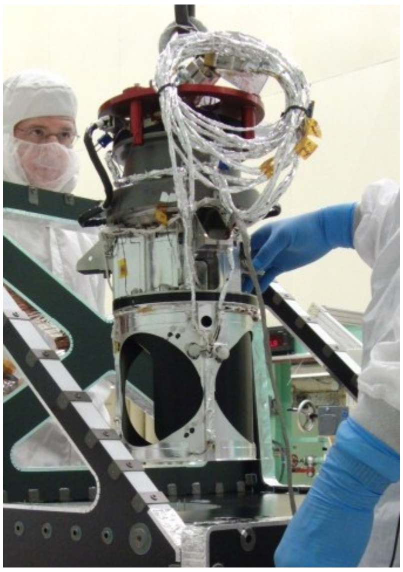

Figure 5. The SSM is lowered into the TIRS instrument

10. Conclusions

As with any mechanisms development, many important lessons were learned:

Procure critical components such as FPGAs and bearings before SRR, even though the design is not completed. It freezes those parts of the design and will pay off later.

Double check even the most esoteric of assumed truths, and understand what you are doing. Our bearings arrived with the preload direction markings reversed. The flight SSM would have had to be scrapped if we had blindly followed the procedure and unknowingly bonded the bearings in face to face. We likely would not have discovered the error until after the second SSM was built.

Concurrent mechanical design and thermal analysis in an aggressive schedule environment can lead to an underestimation of bulk temperatures and gradients in a mechanism operating near room temperature at one end radiatively coupled to a cryogenic source at the opposing (mirror) end. As the thermal analysis matured, unexpected shaft axial gradients and bearing radial gradients developed which required a significant analysis effort and highly specialized analysis tools to understand the resulting preloads for ambient testing and on-orbit operations. Assuming a worst case thermal environment early on would have led the design team to consider implementing a diaphragm bearing mount.

In a 10 μradian class pointing device, reduce the uncertainty in positional control by eliminating grease in the bearing contact area. While we did not investigate the impact of the 50% oil/grease slurry on positional accuracy, we uncovered some evidence of stochastic error which may have been introduced by the grease thickener. It is preferred to introduce only oil in the rolling contact and bound the area with a grease or grease slurry dam.

Functional prototypes are invaluable for risk reduction. We could not have delivered the mechanism on schedule if the electronics did not have the prototype breadboard SSM to verify performance early in the program. It also enabled the mechanisms team to demonstrate progress to program management prior to CDR. Additionally the practice prototypes used by the encoder vendor to verify the bearing bonding procedures were crucial in catching the mis-marked flight bearings prior to installation.

Ensure proper, flight like grounding and shielding of all harnessing (including GSE test harnesses) to prevent unpredictable effects. Also, review electrical designs for noise sensitivity to reduce potential grounding and shielding effects.

Back and forth shipping of hardware between ISO9001 compliant vendors and NASA takes a significant amount of time due to property transfer, inventory, and mission assurance paperwork, and should be avoided in a schedule constrained effort.. This was not taken into account and cost almost a month in delays, given all of the unplanned shipping that resulted from the helical insert issue alone.

The encoder delivery slipped significantly due to many factors. Only tight oversight and a major descope of the task which removed vendor environmental testing brought the delivery back in.

Relatively straightforward mechanisms such as the SSM are well understood and can be developed predictably in a Protoflight fashion by an *experienced* mechanisms team. In the end this approach is what occurred, after all of the cumulative delays impacted the original ETU/Flight development plan.

11. Acknowledgments

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