# Cryogenic Focus Mechanism for the Spitzer Space Telescope

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## Abstract

A new focus mechanism was developed, tested, and flown for the Spitzer Space Telescope ("Spitzer"), one of NASA's "Great Observatories". Figure 1 shows the Flight Focus Mechanism (FLT-FM), now in Spitzer. The mechanism uniquely provides robust support and precise focus adjustment for the Spitzer secondary mirror, from 300 K to a 5 K cryogenic environment.

This paper summaries the requirements, performance, description, and testing of the focus mechanism, including key component level tests of a geared-stepper motor and ball screw. Also, a secondary mirror mount is described that minimizes mirror distortion and supports high loads. Several design and test challenges were overcome and lessons learned from this successful development include:

- Titanium is useful as a flexure material to liquid helium temperatures.
- Adhesive bonds at cryo-temperatures should be well understood and / or tested.
- Geared-stepper motor and ball screw components were simply modified to work to < 5 K.

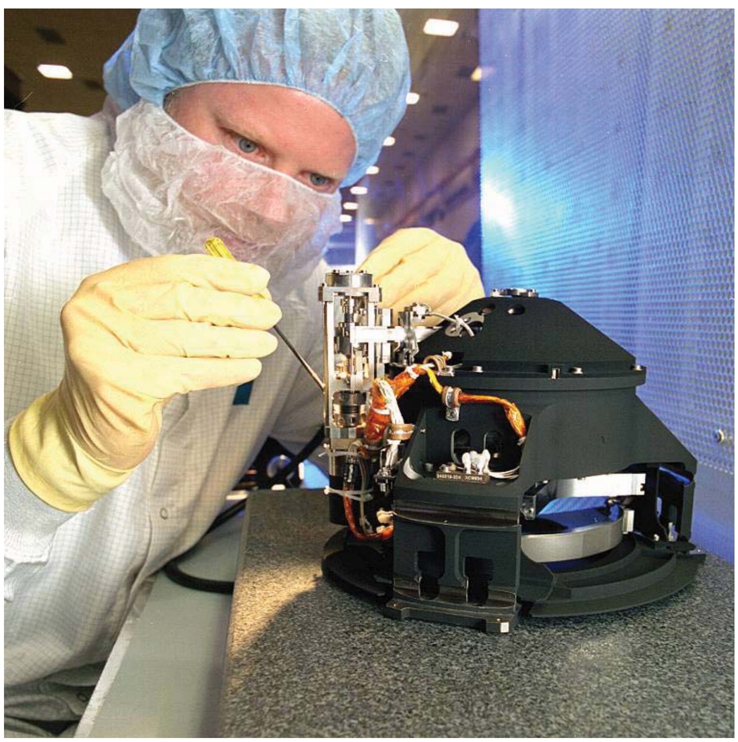

**Figure 1. Flight Focus Mechanism (FLT-FM)**

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## Introduction

The Spitzer observatory shown in Figure 2 includes the Cryogenic Telescope Assembly (CTA) that directs infrared signals to various instruments by means of a beryllium primary and secondary mirror. Ball Aerospace & Technologies Corporation (BATC) supplied the CTA as shown in Figure 3, with funding and oversight provided by NASA-JPL. Early in the program it was decided a focusing capability was desired, providing the cost and complexity to achieve it was reasonable and providing it could be developed on time. Fortunately these objectives were met, so the focus mechanism is included in the CTA as shown, mounted on a beryllium metering structure.

Spitzer was launched on August 25th, 2003 with the focus mechanism and other key telescope components at ambient temperature. The telescope components were later cooled in space to less than 5.5 K. This space-assisted cooling approach was beneficial in helping to preserve Spitzer's cryogen. Consequently, the observatory has surpassed its expected 2.5-year life and is approaching a 5 year life goal. Additional Spitzer facts are given on the next page, for reference.

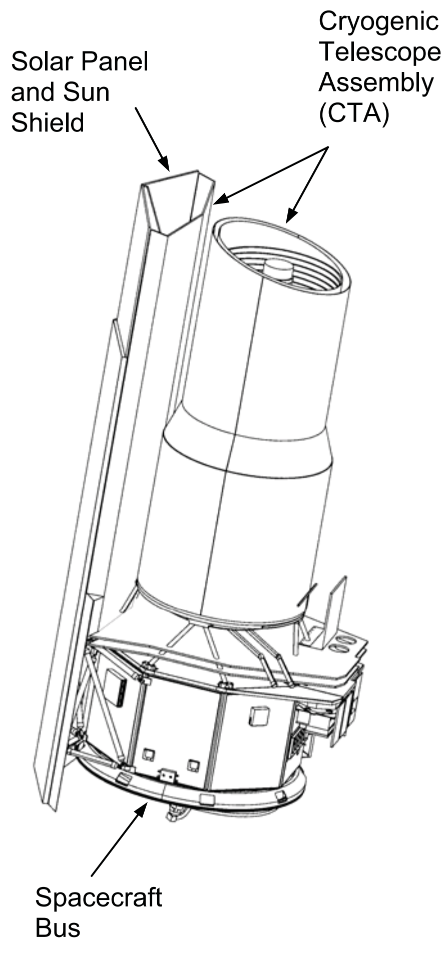



**Figure 2. The Spitzer Observatory**

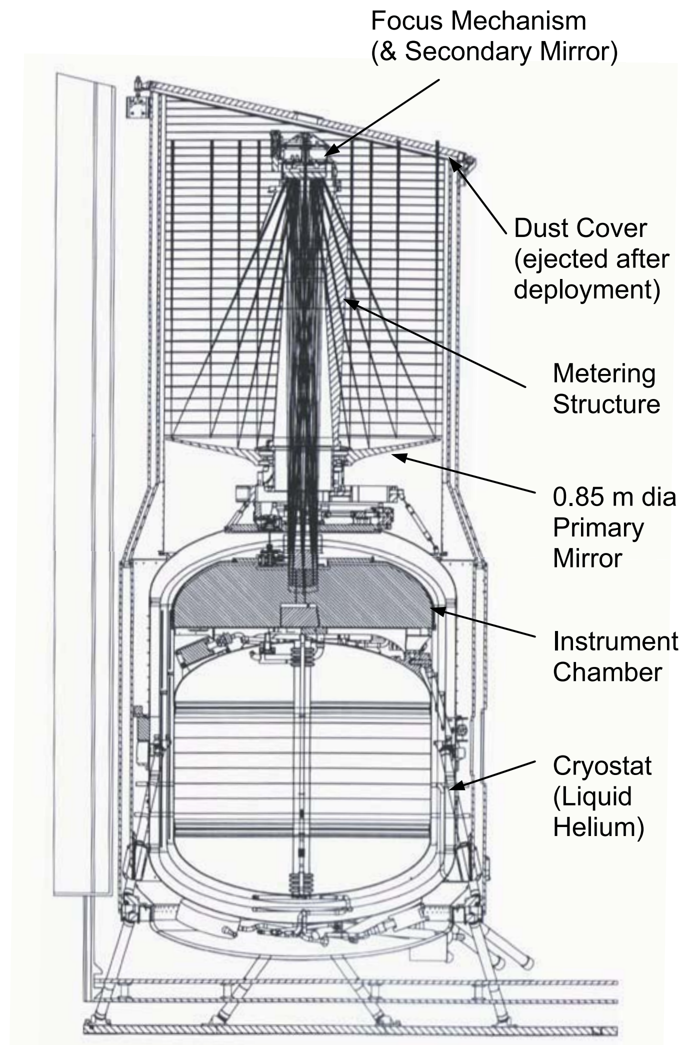



**Figure 3. Cryogenic Telescope Assembly (CTA)**

Spitzer “Fast Facts”

For reference, this page includes Spitzer “Fast Facts” from the California Institute of Technology web site http://www.spitzer.caltech.edu/about/fastfacts.shtml.

The Spitzer Space Telescope is a space-borne, cryogenically-cooled infrared observatory capable of studying objects ranging from our Solar System to the distant reaches of the Universe. Spitzer is the final element in NASA's, Great Observatories Program and an important scientific and technical cornerstone of the Astronomical Search for Origins Program.

| | |
|---|---|
| Launch Date: | 25 August 2003 |
| Launch Vehicle/Site: | Delta 7920H ELV / Cape Canaveral, Florida |
| Estimated Lifetime: | 2.5 years (minimum); 5+ years (goal) |
| Orbit: | Earth-trailing, Heliocentric |
| Wavelength Coverage: | 3 - 180 microns |
| Telescope: | 85-cm diameter (33.5 inches), f/12 lightweight Beryllium, cooled to less 5.5 K |
| Diffraction Limit: | 6.5 microns |
| Science Capabilities: | Imaging / Photometry, 3-180 microns<br>Spectroscopy, 5-40 microns<br>Spectrophotometry, 50-100 microns |
| Planetary Tracking: | 1 arcsec / sec |
| Cryogen / Volume: | Liquid Helium / 360 liters (95 Gallons) |
| Launch Mass: | 950 kg (2094 lb) [Observatory: 851.5 kg, Cover: 6.0 kg, Helium: 50.4 kg, Nitrogen Propellant: 15.6 kg] |

Major Innovations

- Choice of Orbit
- Warm-Launch Architecture
- New Generation of Large-Format Detector Arrays
- Lightweight, cryogenic optics

The Spitzer Team

- Jet Propulsion Laboratory
- Spitzer Science Center, California Institute of Technology
- Ball Aerospace and Technologies Corporation
- Lockheed Martin Space System Company
- Smithsonian Astrophysical Observatory
- NASA-Goddard Space Flight Center
- Cornell University
- University of Arizona

**Focus Mechanism Key Requirements and Performance**

The purpose of the focus mechanism is to maintain the Spitzer's secondary mirror position and, if desired, move it along the CTA optical axis for focus adjustment. As a single axis device, it must maintain mirror alignment with minimal de-center or tilt motion of the mirror due to launch, cool-down, or focus operation. This basic functionality is reflected in the key requirements and tested performance of the mechanism, as summarized in Table 1. And, since it must be controlled reliably and remotely, redundancy is required.

The performance results are for ambient and cryogenic temperatures, before and after exposure to launch vibration levels, and after life testing of a Focus Engineering Model (FM-EM) to 1X life. The FM-EM was built and tested to reduce risk and for life testing up to 4X life, prior to making the Flight Focus Mechanism (FLT-FM). The tests for the FLT-FM were more abbreviated, but performance was similar.

**Table 1. Focus Mechanism Key Requirements and Performance**

| Key Requirements | | Tested Performance (Meets all) |
|---|---|---|
| Range | ≥ ± 0.25 mm<br>≤ ± 0.50 mm | ≥ ± 0.25 mm (soft limits)<br>≤ ± 0.33 mm (hard stops) |
| Step size | ≤ 2.5 μm | ≤ 1.3 μm [a] |
| Repeatability | ≤ ± 1.25 μm<br>(unidirectional) | ≤ ± 0.81 μm [a]<br>(bi-directional) [b] |
| De-center over range [c] | ≤ ± 5.0 μm | ≤ ± 3.61 μm |
| Tilt over range [c] | ≤ ± 58 μrad | ≤ ± 41 μrad |
| Shift after launch [d] | ≤ ± 12.5 μm de-center<br>≤ ± 116 μrad tilt | ≤ ± 9.3 μm de-center<br>≤ ± 110 μrad tilt |
| Operating temperature | 300 to 2.5 K | Meets |
| Operating pressure | Ambient to $10^{-6}$ Torr | Meets |
| Launch acceleration | 70 G lateral<br>125 G axial | Meets |
| First mode frequency | > 150 Hz | 330 Hz |
| Clear aperture of SM | ∅ 120 mm min | ∅ 123.8 mm min |
| Mass (with mirror) | ≤ 4 kg | Meets |

Notes pertaining to Table 1:

a) Mean and standard deviation values for these are given in the assembly test section.
b) Repeatability was met bi-directionally, while only unidirectional was required.
c) De-center and tilt over range refer to mirror motion along and rotation about any axis normal to the optical axis, respectively, over the mechanism's full range.
d) Shift after launch refers to mirror motion due to temperature repeatability and launch vibration combined. The former is any difference in mirror position from ground alignment at 5 K and after cooling again on orbit. The latter is any permanent shift due to launch.

Aside from the requirements, a goal was set to limit the focus shift of the mirror after launch to ≤ 2.5 μm. This was a goal only since the mechanism can correct for focus after launch and it was anticipated performance might slightly exceed this. Performance for this was measured at ≤ 3.2 μm, which was just over the goal, as was expected might happen.

The FM-EM also demonstrated a viable flight mechanism could be made on time. The FM-EM design was started in November 1997, it was built, and cryo-testing was started by June 1998, as required. This success paved the way for the build of the FLT-FM.

## Focus Mechanism Description

Concept

An initial challenge was to select a concept that would efficiently constrain the mirror in all but one direction, yet provide for precise focus control. The concept in Figure 4 achieves this. The secondary mirror (SM) is held on a carrier and tube suspended on two diaphragm flexures, which are stiff in all but the focus direction. Focus is precisely controlled by a stepper motor acting though a lead screw, lever arm, and flexure system, as shown. Focus step size and position are simply determined by counting motor steps. Advantages of this concept are summarized as follows:

- Simplicity – *Minimizes cost*
- Effectiveness – *Meets requirements*
- Robustness – *Carries high launch loads*
- No free play in flexures – *Repeatable*
- Low actuation force – *Low screw loads*
- Symmetry of major supports – S*table over temperature*

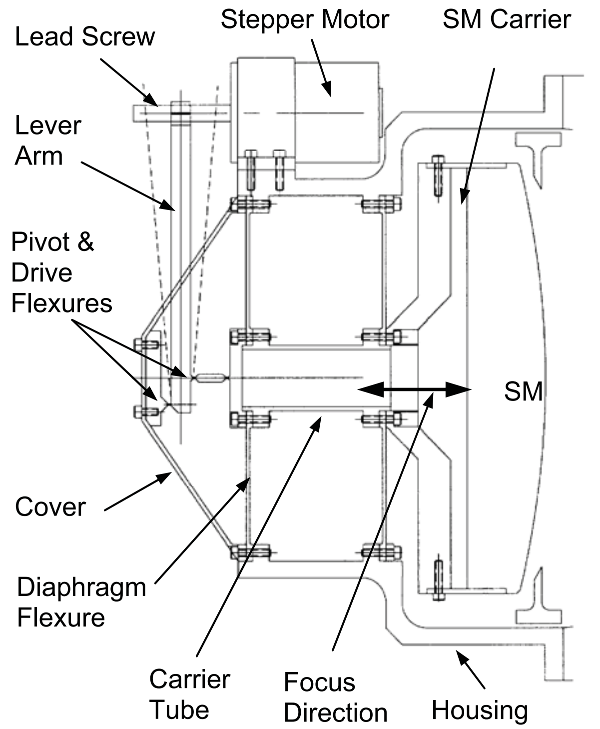



**Figure 4. Focus Mechanism Concept**

Focus Mechanism Engineering Model (FM-EM)

The FM-EM shown in Figure 5 was built and tested to mitigate risk early. Key challenges then were to find motor and lead screw components and a material suitable for flexures, for operation to 5 K.

A 2-phase stepper motor (Figures 8) was selected with a gearhead for further reduction to achieve the desired output step size. Motor detent torque and the overall mechanical reduction also prevent backdriving during launch. A ball screw (Figure 9) was selected to provide for a low friction, precision lead screw. Both these components were tested for operation near 5 K, as described in their testing sections.

Titanium was selected for all the flexures and major structure. Beyond its other desirable properties, it nearly matches the coefficient of thermal expansion (CTE) of the SM and metering tower (and flexures in the SM mount and main housing legs compensate for the small mismatch). The FM-EM used 6Al-4V, due to schedule. For flight, extra low interstitial titanium 6Al-4V (ELI) was chosen since it is generally tougher.

There was concern titanium may become too brittle at 5 K and not flex well over life. This was resolved by determining its plane strain fracture toughness ($K_{IC}$) was sufficient, as shown in the lesson learned below and with fatigue analysis. Cryo-life testing of the FM-EM to 4X life further alleviated this concern.

***Lesson learned #1:*** Titanium is useful as a flexure material at cryogenic temperatures. 6Al-4V (ELI) predicted $K_{IC}$ at 4 K is 54.9 MPa*$\sqrt{m}$ (50 ksi*$\sqrt{in}$) per the NASA/FLAGRO manual, JSC-22267A. This was more than sufficient to meet the focus mechanism requirements for flexure operations below 5 K. Additionally, 6Al-4V flexures were life tested in the FM-EM at 35 K to 4X life.

Other development included: For modularity of the SM mount and carrier, the carrier mounting screws are accessible from the cover side. A SM and carrier mass simulator (shown in the photograph) was made for FM-EM testing. The drive flexure passes through the lever arm before attaching to it, to reduce its deflection. Ball screw nut flexures provide compliance to prevent binding at the screw, yet are stiff in the drive axis and prevent excessive rotational windup of the nut. And non-jamming hard stops on the screw provide for range limits.

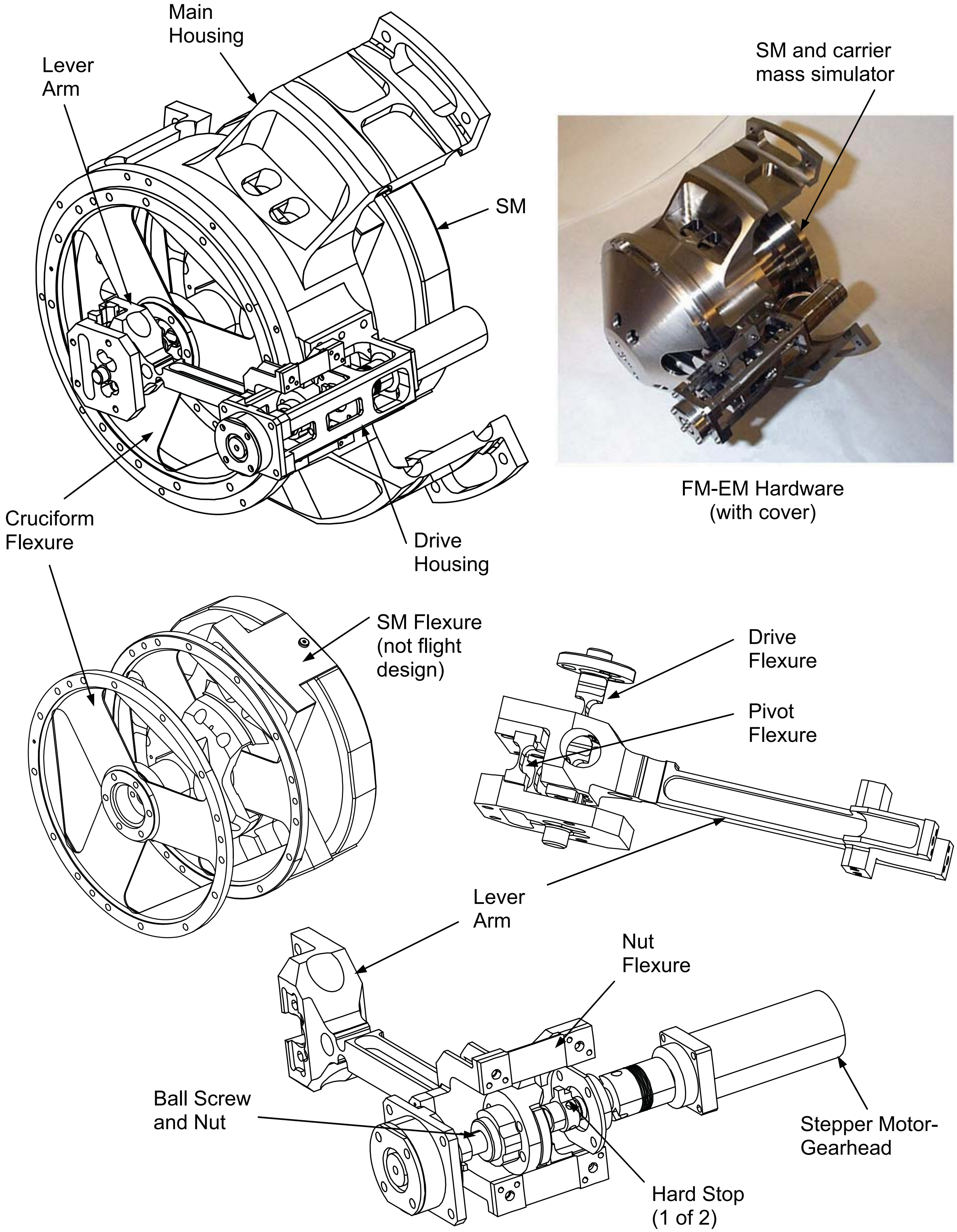



**Figure 5. Focus Mechanism Engineering Model (FM-EM)**

Flight Focus Mechanism (FLT-FM)

Figure 6 shows the Flight Focus Mechanism, which is much like the FM-EM except for some notable developments. Most notable is the addition of the flight secondary mirror and its mount, shown in the next section. Also, the motor is dual wound for redundancy.

The drive and pivot flexures were also significantly strengthened because the axial (focus) load requirement was changed from 70 G to 125 G and a “low risk fracture part” methodology was voluntarily imposed to enhance reliability. This methodology is defined in a JSC memo (June 1992), TA-92-013 and included designing the flexures to ≥ 10X their required fatigue life (including all vibe cycles).

Other developments included: The addition of the mirror mask and stray light baffle. A larger motor was provided for more torque margin. And Variable Impedance Transducer (VIT) sensors were added for “soft” limits.

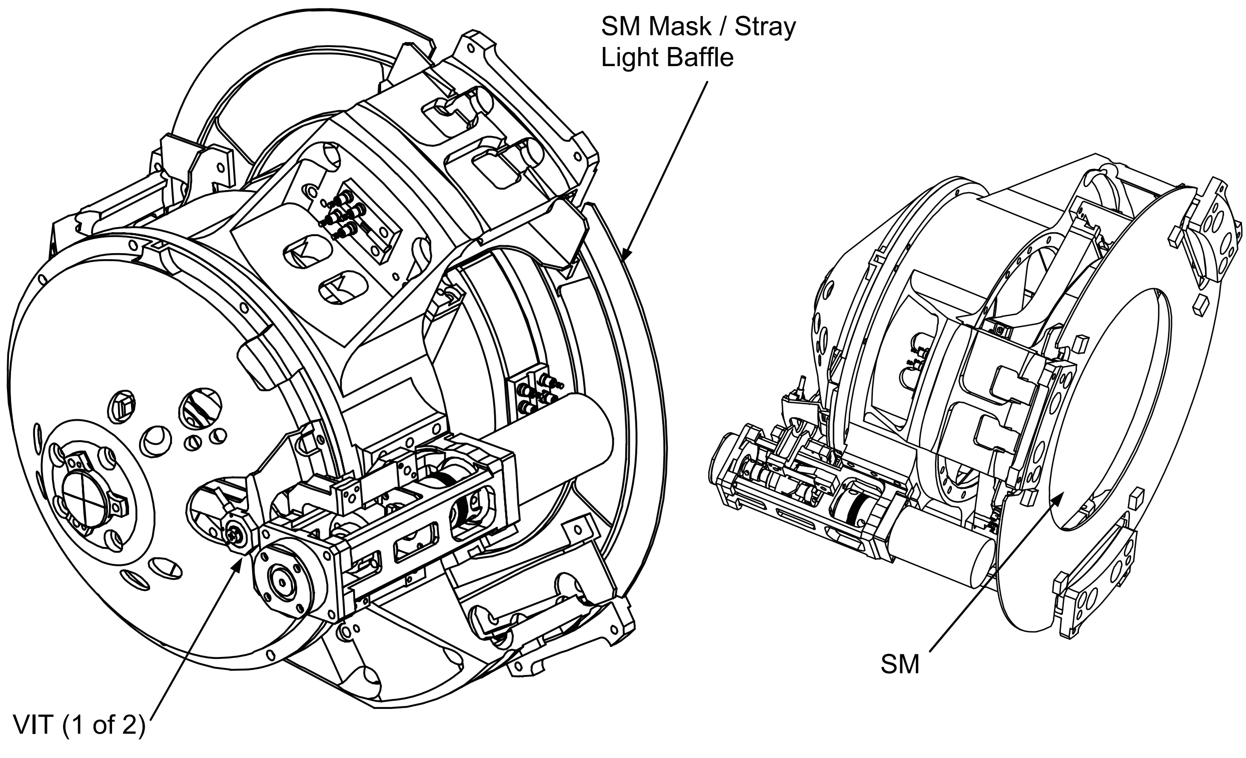



**Figure 6. Flight Focus Mechanism (FLT-FM)**

Secondary Mirror Mount

The secondary mirror mount approach is shown in Figure 7. The mirror is a convex hyperbolic front surface on a beryllium substrate. Beryllium spacers are bonded to the substrate and titanium bi-pod flexures are then conventionally attached. This approach helps to minimize mirror distortion and provides high load capacity. It also presented challenges due the bonds being used at cryogenic temperatures.

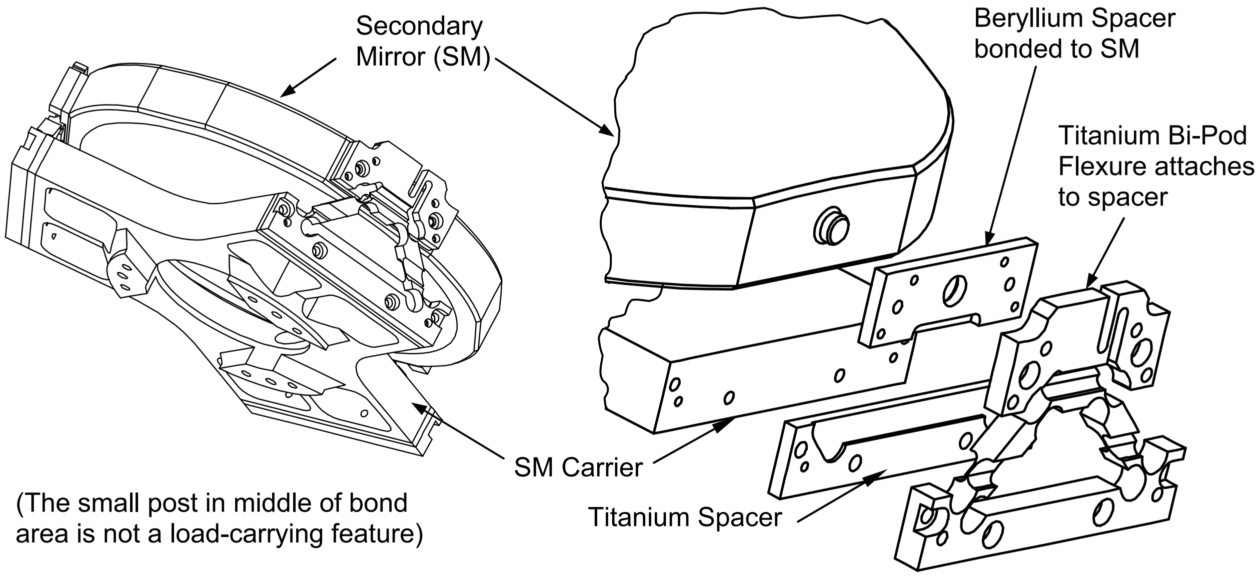



**Figure 7. Secondary Mirror Mount**

The beryllium spacers match the CTE of the mirror to minimize thermally induced strain in the bondline and to maintain mirror figure. The bondline also provides some isolation from flexure fastener preloads, which were light, to further minimize mirror distortion. Titanium spacers at the carrier interface were machined in thickness and wedge to achieve ideal flexure alignment and for optimal mirror figure at 5K.

High load capacity was achieved with epoxy bonds to beryllium (> three times better vs. titanium). Beyond strength, a specific epoxy was also chosen for its desirable CTE and modulus of elasticity vs. other adhesives, based on tests at room temperature to 5 K.

A challenge arose when finite element analysis (FEA) predicted high stress in the bond due to the epoxy shrinkage when cycled to 5 K. The high stress occurred around the exposed periphery of the bond, essentially independent of bond area. This raised concern micro-cracking could occur around the periphery and cumulatively degrade bond strength over multiple 5 K cycles. However, we realized the analysis could be too pessimistic in predicting the adhesive stresses, due to assumed linearity and stress infinity conditions at the bond edges often inherent in such FEA [1]. And BATC had successful use of adhesives to 5 K, which further suggested the FEA did not provide for sufficient understanding of this issue.

Testing was done to address this concern. Beryllium coupons were bonded and cycled ten times from room temperature to 4 K. They were then shear and leverage strength tested at room temperature to determine if any degradation resulted. There was essentially no difference in results between cycled and un-cycled samples. In fact, all the cycled sample actually showed slightly higher strengths (a pleasant surprise).

***<u>Lesson learned #2</u>*****:** Adhesive bonds at cryo-temperatures should be well understood and / or tested. For the secondary mirror mount, FEA showed high stresses that suggested the bond joint strength could cumulatively degrade by thermal cycling to 5 K. To better understand if this was an issue or not, tests were done as described above. These tests showed no degradation in bond strength after thermal cycling to 5 K and provided the understanding we needed to proceed.

## Stepper Motor Component Testing

A stepper motor-gearhead assembly was tested early, as a component, because it was considered a significant risk item to work at 5 K. We had one in house from a vendor that does a good job of matching the CTE of materials in their units and that would have a good chance of working. The following briefly summarizes the test of this motor.

<u>Test Description</u>
Measure power-off backdriving torque and operating output torques at room and cryogenic temperatures.

<u>Motor Modifications</u>
The stepper motor-gearhead is shown in Figure 8. This unit was disassembled and all its key bearing and gear surfaces were dry lubricated with a BATC proprietary process. The unit also had non-metallic parts that were replaced with metallic ones, as supplied by the vendor in another version of this unit. It was baked out to remove moisture and dry purged for testing.

**Figure 8. Stepper Motor-Gearhead**

<u>Test Set-Up</u>
See Figure 10 on the next page for the set-up description (also used for ball screw component testing).

<u>Success Criteria</u>
- Operate near 5 K.
- Show no big increase in backdriving torque (exhibit no to low binding).
- Show starting (pull in) torque ≥ 353 mN*m (50 oz*in).

<u>Results</u>
The unit met all the success criteria, as shown by the results in Table 2. Stall (pull out) torque and winding resistance were also measured for reference.

**Table 2. Stepper Motor Component Test Results**

| Temperature of Unit | Operated? | Backdriving Torque (mN*m) | Starting (pull in) Torque (mN*m) | Stall (pull out) Torque (mN*m) |
|---|---|---|---|---|
| Room (pre-test) | Yes | 212 - 233 | 466 - 480 | 508 - 530 |
| 7-14 K | Yes | 247 - 268 | 395 - 565 | 424 - 706 |
| Room (post-test) | Yes | 212 - 247 | 438 - 480 | 480 - 530 |

(Tests were done at less than peak power, CW / CCW, and at multiple step rates)

An approximately 100:1 Relative Resistivity Ratio (RRR) was measured at 5 K, the RRR being the ratio of winding resistance at room temperature vs. 5 K. This lower winding resistance at cryogenic temperatures was not an issue since the motor was current limited by its drive electronics.

The flight motor was similarly tested to higher acceptance torque values, since it is larger.

***<u>Lesson learned #3(a)</u>*****:** The stepper motor-gearhead needed only simple modification to work near 5 K. The modification was primarily dry lubrication, using a BATC proprietary process.

## Ball Screw Component Testing

Ball screw testing was performed early because there was concern its running friction torque might change appreciably when rotating at 5 K. The following briefly summarizes the testing of the ball screw.

Figure 9. Ball Screw

Test Description

Measure starting and running torque at room temperature and near 5 K. Two ball screws were tested, a smaller, preloaded, carbon steel unit, shown in Figure 9, and a larger un-preloaded 440C version.

Ball Screw Modifications

The ball screws were disassembled and dry lubricated with a BATC proprietary process. Some internal plastic parts were changed to metal parts, for flight but not for this testing. The units were baked out to remove moisture and dry purged for testing.

Success Criteria

Max torque of 35.3 mN*m (5 oz-in), but a goal of 17.6 mN*m (2.5 oz-in) is preferred.

Results

The test was a success, as shown in Table 3. The larger, un-preloaded screw met the torque limit and was near to the preferred goal. The preloaded units torque was shown to be undesirable. So, a smaller un-preloaded screw was chosen for the FM-EM, which ultimately met the preferred goal.

**Table 3. Ball Screw Component Test Results**

| Temperature at test | Smaller, preloaded screw max torque* (mN*m) | Larger, un-preloaded screw max torque (mN*m) |
|---|---|---|
| Room (pre-test) | 21.2 - 35.3 | 8.8 |
| At 4.8 – 5.2 K | 35.3 - 67.1 | 22.0 |
| Room (post-test) | 21.2 - 28.2 | 11.3 |

* 6 balls missing (2 per track), lost in lubrication process

Test Set-Up (used for ball screw and motor)

The items were tested in a dewar with liquid helium, per Figure 10. They were held with a low thermal conductance outer tube and turned with or by another tube. A torque watch was used for ball screw testing, while the dynamometer shown was used for the motor testing.

***Lesson learned #3(b)*:** The ball screw needed only minor modification to work near 5 K. The modification was primarily dry lubrication, with a BATC proprietary process.

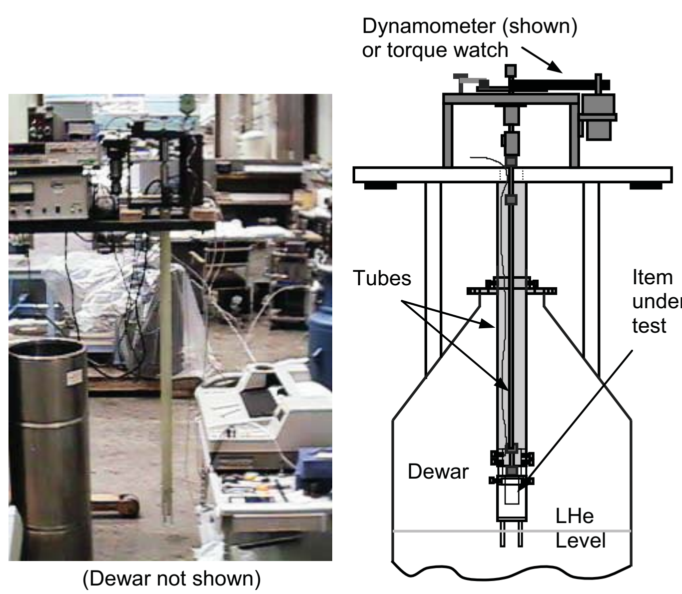



**Figure 10. Component Test Set-Up**

## Focus Mechanism Assembly Testing

The FM-EM and FLT-FM assemblies were tested as described in this section, to evaluate how well the focus mechanism met its requirements over ambient and cryogenic temperatures, before and after vibration testing, and after life testing of the FM-EM.

Challenges overcame included precisely measuring the “mirror” (simulator) motion in a cryogenic environment. Also, the flight mechanism survived a severe over-test condition, as described herein. And relevant items that contributed to successful testing are also noted.

<u>Test Description</u>
All the key requirements per Table 1 were evaluated, and are summarized as follows:

- Focus range, step size, and repeatability
- De-center and tilt over the focus range
- De-center, tilt, and focus shift after launch vibe
- Vibration testing and determination of mode frequencies
- Life testing to 1X life and for up to 4X life

FM-EM performance testing was done in vacuum at cryogenic temperatures and in ambient conditions, both before and after vibration testing, and after life testing.

FLT-FM performance testing was done at ambient conditions, but it was later cryo-tested at the telescope assembly level. The FM-EM and FLT-FM are similar, except for the notable differences shown in Table 4.

**Table 4. Differences between the FM-EM and FLT-FM**

| FM-EM | FLT-FM |
|---|---|
| SM mass simulator | Flight SM and mount |
| Smaller motor and single wound | Larger motor and dual wound |
| Flexures sized for 70 G in all axes | Flexures sized to 125 G in focus axis |
| Carbon steel ball screw | 440C induction hardened ball screw |
| No limit sensors | Limit sensors |

<u>Test Set-Up Description</u>
The FM-EM was tested in the dewar shown in Figure 11. The test measured mirror motion relative to the mechanism interface, using a mirror simulator. A brief description of the test set-up is as follows:

- The mechanism was mounted on a stable reference plate that was used for cryogenic or ambient testing and for vibration testing. It had position sensors on it that monitored the mirror simulator motion relative to the plate, hence, the mechanism interface.
- Legs (not shown) mounted the reference plate to the dewar and provided a conductive path to the dewar cold plate. The legs were removed so the plate could be used in vibration testing too.
- VITs (Variable Impedance Transducers) monitored the mirror simulator motion along the focus axis, in two axes of tilt, and in two lateral axes for decenter. The VITs were initially calibrated at room temperature and to 80 K, but not to lower temperatures.
- Anticipating the VIT calibration could change below 80 K, a secondary focus measurement technique was provided by using two laser interferometers on a stable base. One measured mirror simulator motion and the other measured the reference plate motion. The difference between these measurements represented the desired focus motion, relative to the plate.

- Likewise, another secondary measurement technique was provided for tilt of the mirror simulator in two axes (tip / tilt) using two quad-cell autocollimators, on a stable base. One measured mirror simulator tip/tilt motion and the other measured the reference plate tip/tilt motion. The difference between these measurements represented the desired tip / tilt motion, relative to the plate.
- The dewar has two stages, one for liquid nitrogen and one for liquid helium. It was modified to fit windows for the secondary measurement techniques.
- Thermocouples were used to monitor temperature at various locations.

Success Criteria
Meet the key performance requirements, as shown in Table 1, over ambient and cryogenic temperatures, before and after vibration testing, and over 1X life for the FM-EM, and as a goal for up to 4X life.

Results
The FM-EM met the above success criteria. Table 1 shows the FM-EM performance before and after launch vibration and over 1X life. Performance did not change appreciably for up to 4X life, meeting the goal to provide significant life margin.

Table 1 shows maximum values for step size and repeatability. The mean and standard deviation values for these over 1X life are provided in Table 5.

**Table 5. Mean and Standard Deviation for FM-EM Step Size and Repeatability**

| Parameter | Mean | Standard Deviation |
|---|---|---|
| Step size | 0.42 μm | 0.17 μm |
| Repeatability (bi-directional) | 0.0005 μm | 0.29 μm |

The FLT-FM performance was similar, based on abbreviated testing. A difficulty occurred during FLT-FM testing when it was erroneously vibration tested to 170 G in the lateral direction, due to a faulty control of the vibration table. This was far beyond the required 70 G.

The effects of the 170 G over-test were carefully evaluated. Fortunately, due to the robustness and conservatism in the design, there were relatively few issues. However, the ball screw was loaded beyond its rating. So we loaded a spare flight ball screw to the same over-test level and well beyond. Based on inspections of the overloaded spare ball screw, we concluded the flight ball screw was still acceptable for use. This 170 G over-test also reduced the fatigue life of the flexures from 10X to 6X. But this was deemed acceptable, with customer approval.

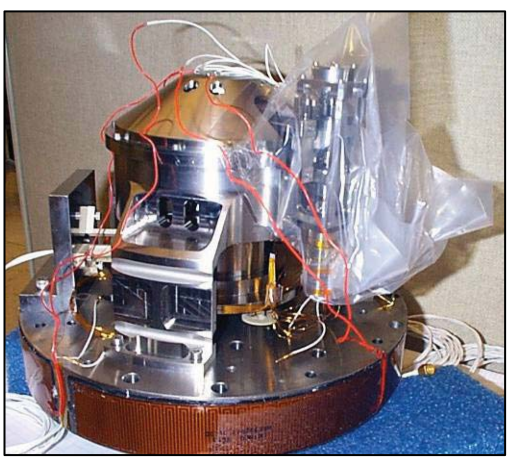
*Notable Items Contributing to Successful Testing*:

- The FM-EM was tested at 30 K to 49 K since the dewar had only one, liquid nitrogen shroud and due to parasitic radiation from the optical windows. This was accepted since the motor and ball screw components were tested near 5 K. Also, most material shrinkage occurs by these temperatures and the predicted toughness ($K_{IC}$) for titanium at 5 K was more than acceptable.

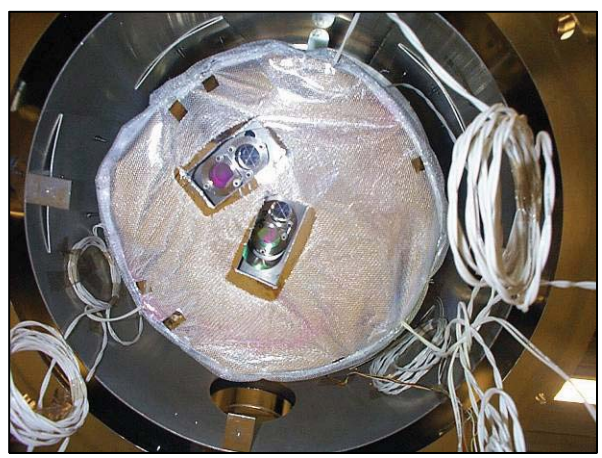
- Including secondary measurement techniques proved to be a prudent decision. As anticipated might happen, the VIT calibration changed below 80 K. Using interferometer and autocollimator data, it was found the slope of the calibration changed but the VITs retained good linearity. After accounting for this, the data between all the measurement methods agreed well. This also allowed for interpretation of VIT data measuring the lateral motions, which did not have the secondary measurements.

- Vibration testing without force limiting showed high magnification factors at resonant frequencies that would have resulted in over-testing the mechanisms capability, if vibrated to the required input levels on a standard shaker. As recommended by JPL, using force limiting [2] resolved this problem and it was successfully tested to its full levels. (Force limiting is now more routinely used at BATC)


**Dewar with Laser Interferometers**
(Quad-Cell Autocollimators not shown)



**FM-EM on Reference Plate**
(Without legs)



**FM-EM Shrouded in Dewar**
(Looking up at ref plate side)

**Figure 11. FM-EM Test Set-Up**

## Conclusion

The new focus mechanism was completed and shown to provide repeatable focus positioning to 5 K. Its design and test challenges were successfully overcome, on schedule. The mechanisms concept and implementation have been shown to be simple, effective, and very robust. It is currently in service in the Spitzer Space Telescope, one of NASA's "Great Observatories".

After launch on August 25$^{th}$, 2003, the new focus mechanism has performed as planned in flight. The observatory has surpassed its expected 2.5-year life and is now approaching a 5-year life goal. (The mechanism only needed operation twice during this time; once to verify its successful operation, and then to achieve the final focus position that is currently in use.)

Testing of the stepper motor and ball screw components significantly mitigated risk early in the program. The build and test of the mechanism engineering model further mitigated risk and allowed for verification of performance over and above the required life.

Lessons learned, resulting from this successful mechanism development, are summarized below.

<u>Lessons Learned Summary</u>

1. Titanium 6Al-4V (ELI) is useful as a flexure material to liquid helium temperatures since it has sufficient plane strain fracture toughness ($K_{IC}$) to < 5 K.
2. Adhesive bonds at cryo-temperatures should be well understood and / or tested. For the mirror mount, FEA did not provide sufficient understanding of the bond. Testing with coupons was required and showed the bond strength was acceptable after multiple cycles to 5 K.
3. The geared-stepper motor and ball screw components needed only slight modification to work at 5 K, which was primarily dry lubrication.

## Subsequent Developments

This mechanism has provided heritage for other programs at Ball Aerospace, as follows:

- The James Webb Space Telescope (JWST): Similar geared-motors are planned for use in the cryogenic nano-actuators used to position its primary mirror segments.
- Kepler (another space-borne telescope): A derivative of this mechanism is planned to move the primary mirror for focus adjustment.

## Acknowledgements

This device was developed with funding and oversight from JPL under contract 960669.

Thanks to Robert M. Warden (BATC) for developing the mechanism concept and to the BATC team and suppliers that supported this effort. And in memory of Mike Rice, an outstanding technician on the team.

## References

1. MIL-HDBK-17-3F, section 6.2.3.6.
2. T. D. Scharton. Force Limited Vibration Testing Monograph. NASA Reference Publication RP-1403 (May 1997).