# Cryogenic Scan Mirror Mechanism for SIRTF/MIPS

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## Abstract

A Cryogenic Scan Mirror Mechanism (CSMM) has been developed for the Multi-band Imaging Photometer for SIRTF (MIPS) which is one of three scientific instruments in the focal plane of the Space Infrared Telescope Facility (SIRTF). The design of this scan mirror is based on a mirror mechanism which is currently in operation onboard the Infrared Space Observatory (ISO) Short Wave Spectrometer (SWS). The SWS team provided this design through the University of Arizona, to Ball Aerospace, where it was modified to satisfy the requirements for MIPS. A brassboard unit (figure 1), built to the new design, has been fabricated and tested. This unit is the predecessor to the flight unit and the subject of the testing. This paper summarizes the modifications made to the mechanism, the subsequent testing, and describes the flight design of the MIPS cryogenic scan mirror mechanism.


## Background

The design of the SIRTF MIPS instrument[1] incorporates a single axis scan mirror to direct the optical path. Because SIRTF is a far infrared observatory, it must operate at cryogenic temperatures. All instruments and mechanisms within the Multiple Instrument Chamber (MIC) will be launched and operated at about 1.5 Kelvin.

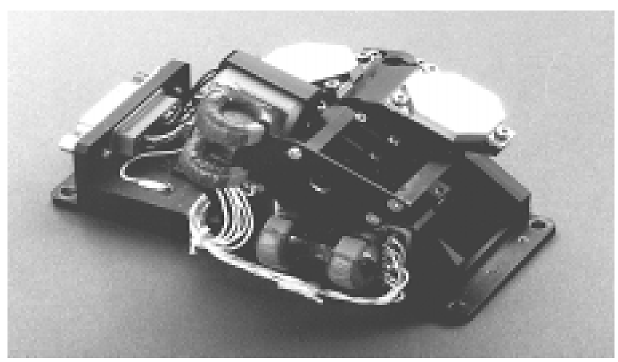

**Figure 1. CSMM Brassboard Unit**

The CSMM is the only moving part in the MIPS instrument and it serves three basic functions. First, it allows for mapping a region of sky by compensating for the SIRTF scan motion with a corresponding mirror motion. Second, it performs “beam switching” to move the MIPS instrument FOV between the desired celestial source and nearby “blank” sky. Third, it is used to move and hold the mirror in one of several specified positions to direct light into the appropriate optics for each MIPS observing mode.

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The CSMM is a limited angle rotation device (±7.5 degrees) which uses steel flexures to support the mirror while allowing it to rotate without wear or friction. A linear voice coil motor is offset from the center of rotation to provide the actuation force needed to rotate the mirror. Stable and accurate position sensing is obtained by means of redundant differential impedance coils. This scan mirror is not a fast steering mirror; the MIPS requirement for closed loop bandwidth is only about 10Hz.

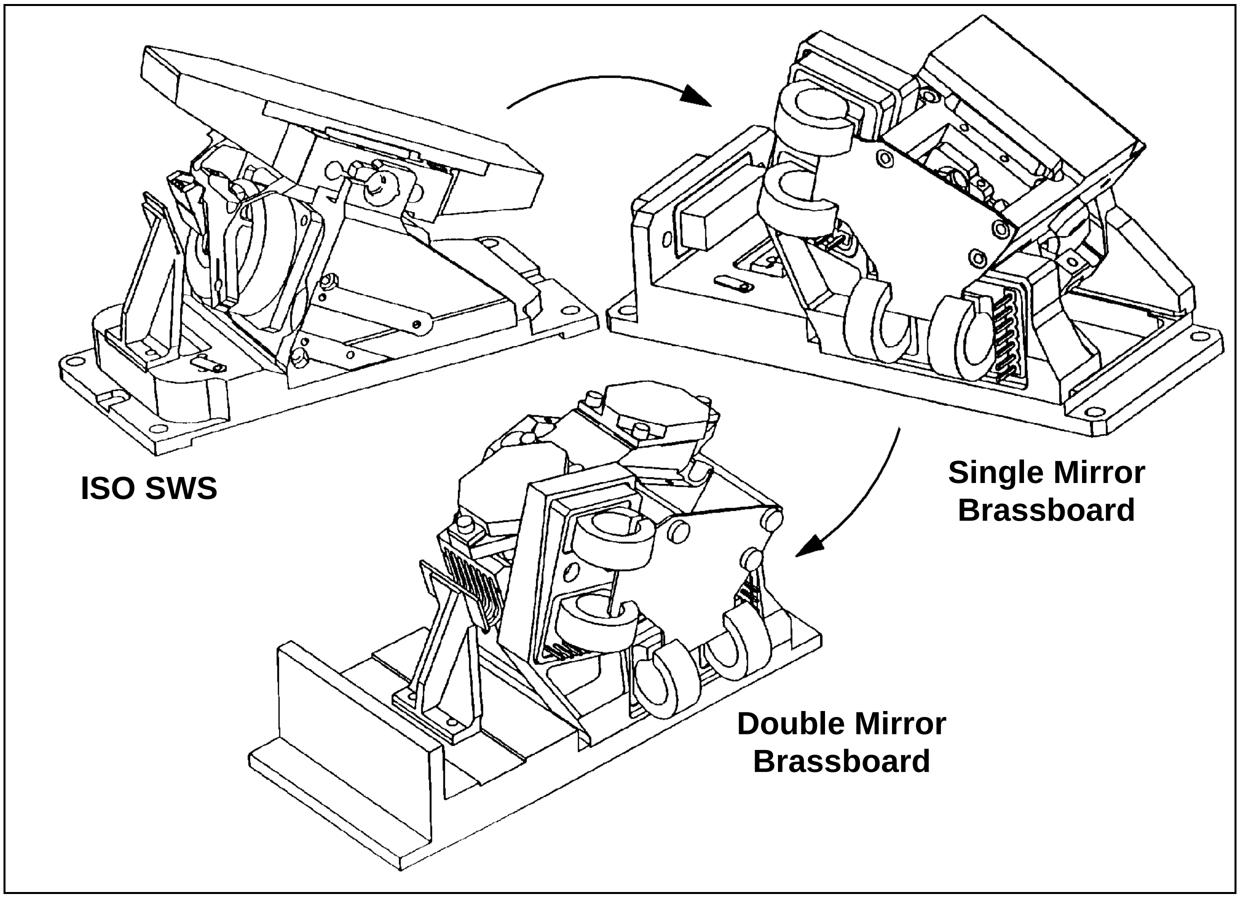



**Figure 2. Scan Mirror Evolution**

The scan mirror assembly consists of two main sub-assemblies. The fixed portion is made up of the base, frame, magnet and housings. The rotating portion is made up of the mirror carrier, the two mirrors and the coil assembly. Figure 2 shows the evolution of the scan mirror design. The original ISO SWS scan mirror[3,4] is shown in the upper left hand corner. This design was modified at Ball by incorporating a new position sensor in the first MIPS brassboard unit as shown in the upper right hand corner of Figure 2. This unit was later modified to support two mirror surfaces resulting in the brassboard unit shown in Figure 1 and the lower drawing in Figure 2. The brassboard design was further modified to produce the flight CSMM design shown at the end of the paper.

## Problem Statement

The purpose of this design effort was to adapt the ISO SWS scan mirror design to satisfy the requirements for MIPS. To this end, four separate tasks were identified.

1. Reduce power dissipation at cryogenic temperature.
2. Assess the reliability of the flexural elements in the CSMM.
3. Mechanical redesign to satisfy optical requirements.
4. Develop and verify a mathematical model of the mechanism.

Following the description of these tasks is a summary of the flight CSMM.

## Design Solution

### 1. Reduce power dissipation

The operational lifetime of the SIRTF instrument is closely related to the power dissipation in each instrument and, therefore, much emphasis is placed on minimizing the power dissipation in all of the cryogenic elements in the instruments. In addition, power dissipated in the CSMM could raise its temperature and result in excess background flux in the MIPS instrument. To reduce the power dissipation of the CSMM, the MIPS team modified the ISO design by substituting superconducting wire for the copper wire used in the voice coil actuator (Figure 3) and by redesigning the position sensor.

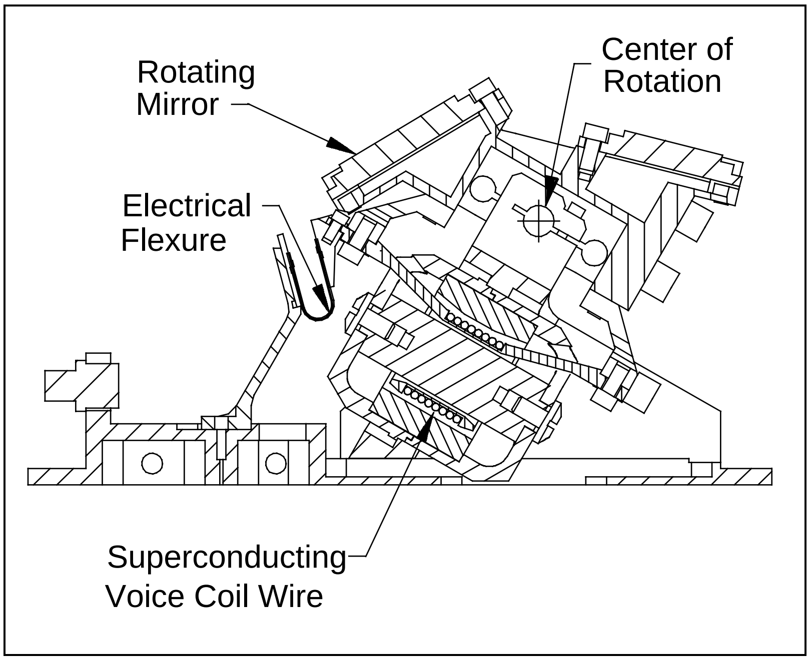



**Figure 3. Cross Section View of CSMM**

The ISO scan mirror uses standard copper wire in the voice coil actuator. This coil dissipates 0.65mW at the maximum deflection of 7 degrees. The MIPS design team investigated several alternatives for a lower power substitute for the copper actuator wire before settling on a superconducting wire manufactured by Supercon. This wire is made up of 54 filaments of a niobium titanium alloy which is supported in a copper matrix. The critical temperature for this wire is about 9.5 Kelvin.

The copper in the wire allows the mechanism to be operational at ambient temperature, although the resistance of the coil at this temperature is about 400Ω. Using this wire, power dissipation in the mechanism at maximum deflection when operated below the critical temperature is so small that it is practically unmeasureable. When making the voice coil actuator, two coils are wound on the coil former to provide redundancy in case one of the coils should fail in operation.

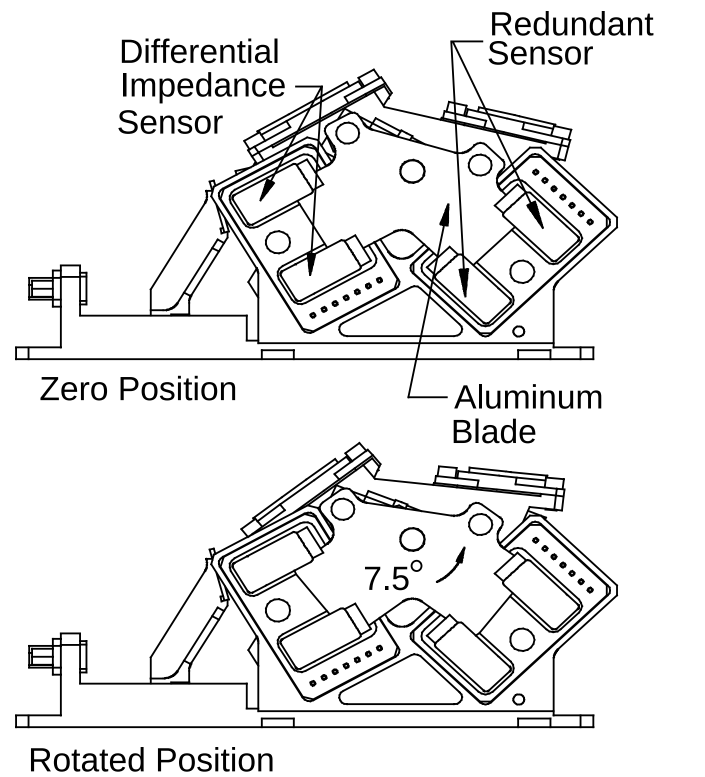



**Figure 4. CSMM Position Sensor**

The ISO SWS scan mirror uses a linear variable displacement transducer (LVDT) to provide position feedback information. The ISO LVDT power dissipation is about 350μW. The MIPS team replaced the LVDT with a new position sensor which is based on a sensor design developed at Ball for another application[2]. The new sensor, a differential impedance transducer, provides slightly reduced position accuracy when compared with the LVDT but with much lower power dissipation. The CSMM position sensor relies on a pair of transformers, each wound on a slotted torroid. Both transformer primaries are fed by a constant amplitude 10KHz sine wave. An aluminum vane, which is attached to the rotating scan mirror, moves in the slots cut in the torroid as shown in Figure 4. The vane is designed such that as the mirror rotates in one direction, the amount of aluminum in the slot for one transformer increases while it decreases for the second transformer. Eddy currents in the aluminum vane cause the coupling between the primary and secondary of the transformer to change relative to the amount of aluminum in the slot. Both of the transformer secondaries are fed to a differential amplifier in the electronics and then demodulated and filtered to produce a signal which is directly proportional to the scan mirror angle. The power dissipation of this position sensor is less than 100μW. Two sets of position sensors are included in the flight CSMM design for redundancy.

## 2. Flexural Elements

Functional Description

The CSMM has only two moving parts and both are flexural by design. In this way, all of the friction and debris problems associated with sliding surfaces are avoided. The two parts are the mechanical support flexures and the electrical contact flexures. This design was originally used in the ISO SWS mechanism, but further understanding of the operation was needed for the SIRTF program.

The mechanical flexures are used to support the rotating part of the mirror. For both MIPS and SWS, two 3/16 inch diameter Lucas Flex Pivots are used. The rotating mass is subject to three forms of loading. First is simple launch vibration. The flex pivot is rated at about ten times the estimated launch load so this requirement was satisfied by analysis. Second is life or fatigue. Again, analysis showed that the pivot should survive ten times longer than the required life. The CSMM was also life tested to verify that the pivots would survive. The third load case is impact loading due to the rotating mass hitting the end of travel stops. This is important because the steel used in the flex pivot has decreased impact strength at cryogenic temperatures. Analysis and testing have confirmed that impact loading is not an issue. Provided the rotating mass is well balanced, it will not hit the end of travel stops during launch.

The electrical flexures are used to electrically connect power to the voice coil. A simple service loop allows the mirror to rotate (see Figure 3) but this loop must survive the launch vibration as well as the millions of cycles expected over the mission. The SWS mechanism used 0.01 mm stainless steel for the electrical flexure. This material, however, did not satisfy the MIPS life requirements, so there was a need to increase the life of the flexure, while maintaining the flight heritage.

The solution was to change the material to Beryllium Copper which has much greater fatigue strength but otherwise has similar mechanical properties. This material is also easier to solder to and is a well understood spring material. Analysis showed infinite life for this material in this application.

Testing of Flexural Elements

An analysis of the MIPS instrument operation predicted that the CSMM will need to survive approximately 3 million cycles during its 2.6 year lifetime. 100,000 of these cycles are large scale deflection angle changes on the order of 7.5 degrees. The remaining 2.9 million cycles are small angle operations, $\pm$1 degree. A safety factor of 2x was applied to this lifetime estimate for the CSMM operational lifetime requirement.

In order to verify that the CSMM flex pivots and electrical flexures would survive over this lifetime a number of tests were performed:

1) Five pairs of flex pivots were cycled end to end (±7.5 degrees) 1 million times in the engineering brassboard CSMM at ambient temperature
2) A sixth pair of flex pivots was installed in the brassboard, cycled end to end (±7.5 degrees) 1 million times at ambient temperature plus 800,000 cycles at 77K plus 440,000 cycles at 4K.
3) This same set of flex pivots was then subjected to a two minute long 77K random vibration test which simulated the expected launch load on the mechanism (see vibration test description below).
4) Finally, this same set of flex pivots was cycled ±1 degree for 6 million cycles at room ambient temperature.

The same electrical flexures were used throughout tests 2, 3 and 4. Not a single flex pivot or electrical flexure failed or showed any signs of degradation during this testing.

As mentioned before, there was a concern that the rotating mirror would hit the stops during vibration. Analysis showed that this would not happen, but a simple cryogenic vibration test was performed on the brassboard CSMM to verify this analysis before proceeding with the design of the flight unit. The mechanism was vibrated at 77K instead of 1.5K because Liquid Nitrogen could then be used to cool the mechanism. Material properties of the structural elements are similar enough between these two temperatures.


**Figure 5. Cryogenic Vibration Test**

During launch, the SIRTF instruments will be held at cryogenic temperature. The purpose of the vibration test was to simulate the expected mechanism launch load and temperature. The test setup for the cryogenic vibration test is shown in Figure 5. In this test, an insulating box was used to cover the head of the vibration table. Liquid Nitrogen was used to cool a cold plate and also to purge the box.

Once temperature was reached, the vibration test was performed. The CSMM was vibrated for 2 minutes to the PSD level shown in Figure 6. During launch, the drive electronics will not be powered and therefore during this test the CSMM actuator drive current was disabled. The CSMM position sensor output was monitored and the maximum CSMM deflection angle measured during this vibration test was only 0.2 degrees.

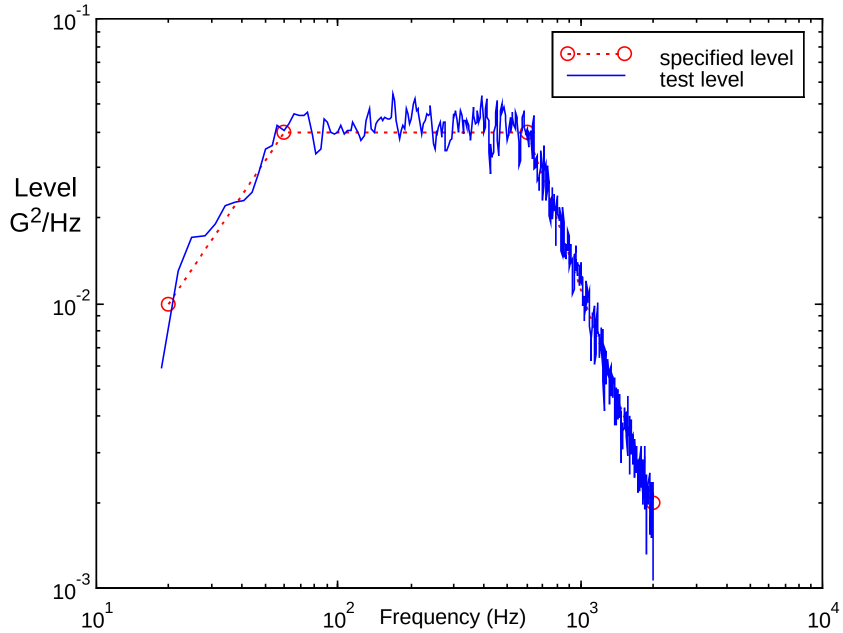



**Figure 6. CSMM Random Vibration Test Level**

At the conclusion of this test the flex pivots and the CSMM were visually inspected under a microscope and no signs of degradation were found.

## 3. Mechanical Redesign

The scan mirror used in the ISO SWS instrument was close to what was needed for the MIPS program, but several modifications were necessary to satisfy all the requirements. Mechanical redesign was needed to accommodate the new position sensor, but there were two changes that were needed to satisfy the optical requirements.

First of all, travel of the CSMM needed to be increased from ± 7.0° to ± 7.5°. To achieve this, material needed to be removed from the voice coil core without significantly modifying the properties of the motor. This modification proved to be fairly straight forward, but a detailed tolerance analysis was necessary to ensure that the operation of the mirror would not be degraded by variations in the machining or assembly of the unit. Intermediate dimension checks were used on sub-assemblies to monitor tolerance build-ups.

A magnetic analysis was also performed to verify that changes in the shape of the core and housing would not affect the magnetic flux of the motor.

The second change was to redesign the mirror to incorporate two mirror surfaces which could be individually removable. To do this, a new mirror carrier was designed to replace the old mirror. The new mirror carrier is based on the geometry of the ISO SWS mirror body with features added to attach the two mirrors. Raised pads enable the interface surface on the carrier to be diamond turned. The total mass and static balance was maintained so as to preserve as much of the previous design as possible.

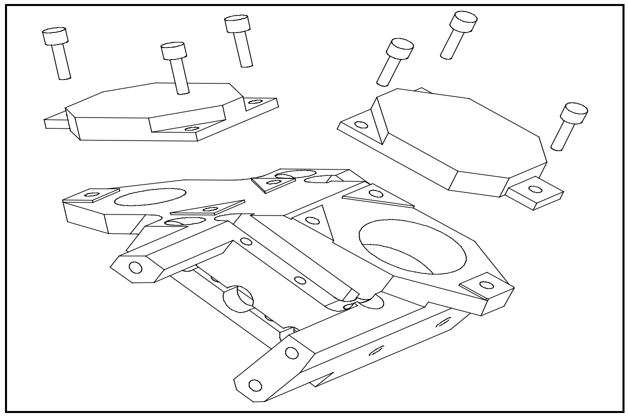


**Figure 7. Removable Mirror Config.**

The new mirror design was performed on I-Deas Master Series CAD Software. Using this tool, the parts could be modified so as to shift the center of mass of the rotating mirror assembly to line up with the center of rotation. Balance weights were incorporated to accommodate variations in machining.

Magnetic Analysis

The CSMM is powered by a linear voice coil motor but instead of a linear travel, the coil is mounted on a pivoting carrier which is supported by two flexures. The philosophy of the motor design was to make the stationary parts heavier in order to make the rotating parts lighter. This reduces the moving mass and therefore allows the system to respond faster. Also, the power required by the electronics to position the motor is reduced. The magnet is made of Samarium Cobalt and the core and housing are made of a high permeability steel. The design is such that minor changes in the core and housing do not change the properties of the motor. This also makes the motor very stable over a broad temperature range which is desirable for a cryogenic mechanism.

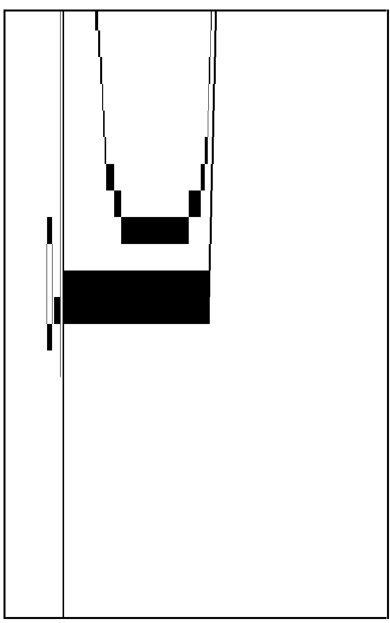


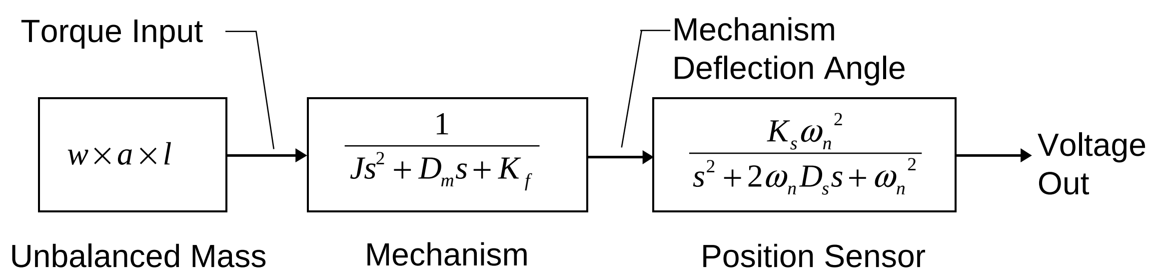
**Figure 8. Magnetic Diagram**

The original configuration of the CSMM brassboard model fit fairly well into the MIPS flight envelope but some mechanical redesign was needed to satisfy the optical and packaging requirements. This redesign required that the motor housing be modified and there was concern that the redesign would change the properties of the motor.

In the magnetic analysis of the motor system, it was found that certain thicknesses in the motor housing were critical to the flux path. The outer corner of the motor was chamfered in order to package the CSMM in the specified volume. To maintain the flux path, the inner radius was increased. Magnetic analysis of the two configurations were compared and found to have similar flux paths.

## 4. Mathematical Model

A model was developed for the CSMM in order to predict the reaction of the CSMM when deliberately unbalanced and subjected to a vibration sine sweep. The complete model for the unbalanced mechanism is shown in Figure 9. In the model, the unbalanced mass produces a torque input to the CSMM. The model for the mechanism is a simple, damped spring mass system. The position sensor is modeled as a second order low-pass filter.




Where:

- $w$ = weight of unbalancing mass (oz)
- $a$ = acceleration due to vibration (g)
- $l$ = moment arm length (inches)
- $J$ = moment of inertia of mechanism (oz-in-sec$^2$)
- $D_m$ = mechanism damping (oz-in-sec/radian)
- $K_f$ = spring constant of both flex pivots (oz-in/radian)
- $K_s$ = position sensor gain (volts/radian)
- $\omega_n$ = position sensor cutoff frequency (radians/sec)
- $D_s$ = position sensor damping (dimensionless)

**Figure 9. CSMM Mathematical Model**

When a force (torque) is applied to the mechanism, it rotates and eddy currents are induced in the aluminum coil former. These eddy currents induce a magnetic field which produces a force in opposition to the applied force. Thus, the eddy currents provide a damping force for the mechanism. This damping will help stabilize the mechanism during launch.

Test data from the original ISO SWS mechanism showed that the mechanical damping of the mechanism ($D_m$) actually increased at cryogenic temperatures by a factor of 2.86 over the room temperature. This increased damping is due to the increase in the eddy currents flowing in the aluminum coil former caused by a reduction in the electrical resistance in the aluminum at the cryogenic temperature.

The model was used to predict the vibration test results using the following parameters:

$w$ = 0.028 oz
$a$ = 0.7g peak
$l$ = 0.76 inches
$J$ = 3.4 oz-in-sec$^2$
$D_m$ = 0.1797 oz-in-sec/radian (@300K)
$D_m$ = 0.1797 * 2.86 = 0.5139 oz-in-sec/radian (@77K)
$K_f$ = 11.29 oz-in/radian
$K_s$ = 88.54 volts/radian
$\omega_n$ = 2*pi*200 radians/sec (200Hz bandwidth)
$D_S$ = 0.707

The moment arm of the unbalance weight ($l$) and the moment of inertia ($J$) of the mechanism were measured using the I-DEAS mechanical model. The damping at 300K and the spring force of the flex pivots was taken from data provided for the original ISO SWS mechanism. The position sensor is designed for a bandwidth of 200Hz.

Using these parameter values, a Matlab model was used to determine the response of the deliberately unbalanced mechanism vs. frequency for both the 300K and 77K temperature. The results of this model are shown in Figure 10. The voltage output of the model was multiplied by a gain of 1.5 volts/degree to produce the plot shown in this Figure.

As Figure 10 shows, the model predicts a slight resonant peak at about 7Hz at 300K. The 77K data in Figure 10 shows that the increased damping has eliminated the resonant peak.

Also note in Figure 10 that the response of the mechanism is quite small beyond 100Hz and therefore the position sensor bandwidth of 200Hz does not affect the modeled or measured data.

CSMM Mathematical Model Verification test

The brassboard CSMM was artificially unbalanced using a simple washer which was attached to the side of the scan mirror with a screw. This configuration was then subjected to a sine sweep from 4Hz to 200Hz both at 300K and 77K (using the same cryogenic vibration test setup as was used in the random vibration test shown in Figure 5). The test results are shown in Figure 10 along with the predicted results. Figure 10 shows that the model agrees quite well with the actual values. Again, the voltage output of the position sensor was multiplied by the transfer gain of 1.5 volts/degree to produce this plot. Testing at these low frequencies and low temperatures is difficult. However, the test data does show that the model accurately predicts the response of the CSMM to the unbalanced vibration input at both 300K and 77K.

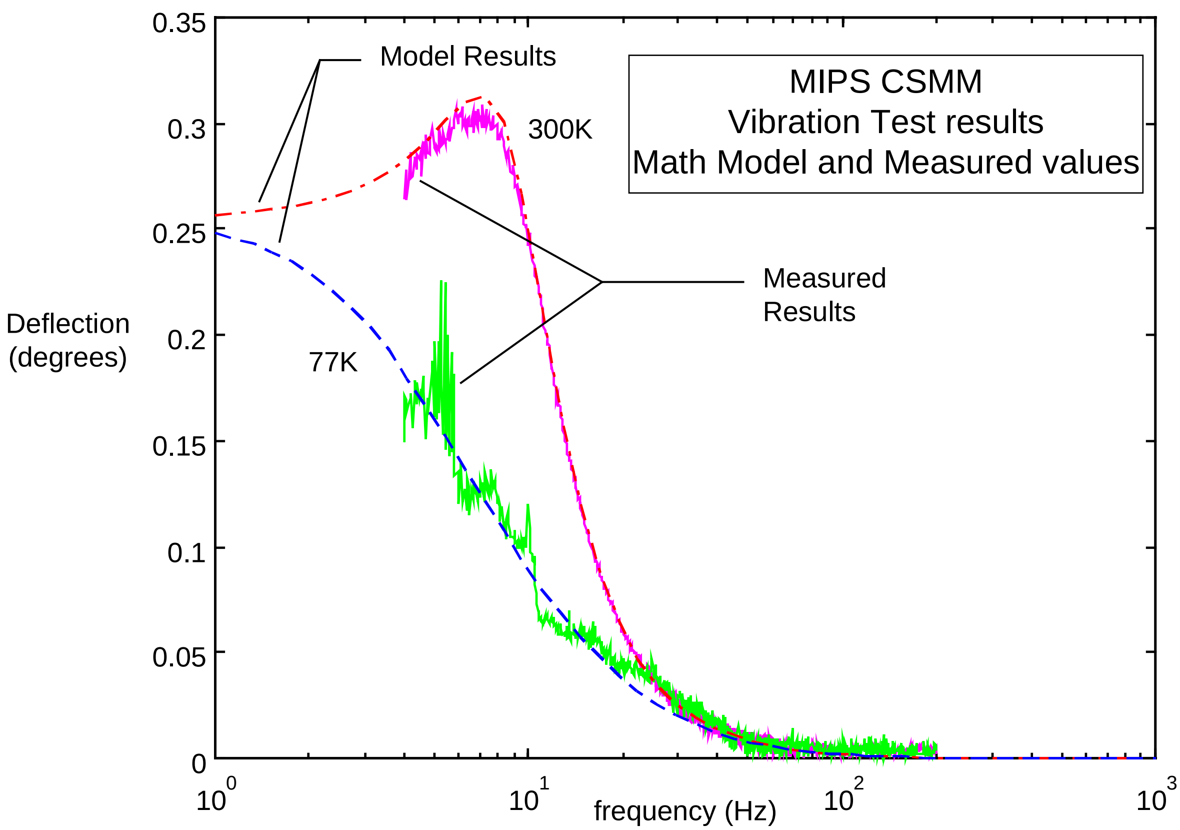



**Figure 10. 300K & 77K Vibration Test Data and Model Results**

## Description of the Flight CSMM

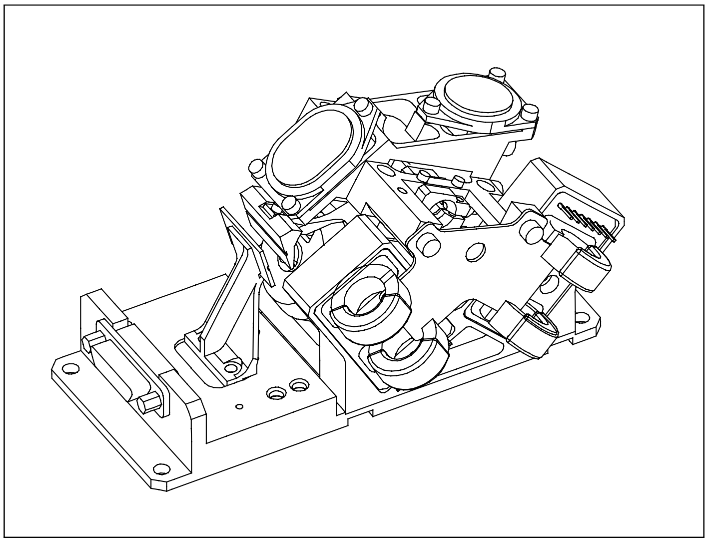


**Figure 11. CSMM Flight Configuration**

Summary of properties
Flight CSMM

- Single Axis Rotation
- Operating Temp. <2K to 300K
- Scan Angle: +/- 7.5°
- Weight: 362 grams
- Size: 63 x 61 x 120mm
- Power Dissipation:
  <0.5mW at 2°K
- 1° Step & Settle < 0.2 sec
- Precision: < 2 arcsec RMS
- Removable mirror facets
- Redundant Actuator Windings
- Redundant Position Sensors
- Linear Voice Coil Actuation
- Position Sensor Mode:
  Differential Impedance
- Structure: 6061-T651
- Insulation: G-10 Fiberglass
- Connector Interface: MDM-25
- Precision Mirror Lyot Stop

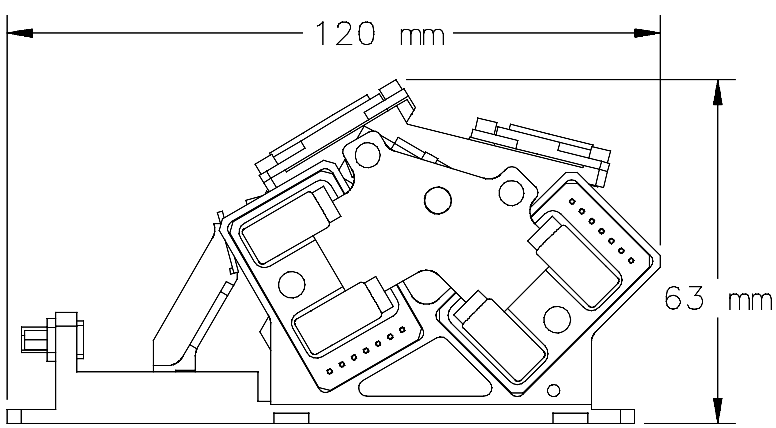



**Figure 12. Physical Dimensions**

## Conclusion

Ball Aerospace has constructed an engineering brassboard model of the CSMM to test the performance of the mechanism, motor, and position sensors at ambient and cryogenic temperatures.  The results of this testing show that the design meets all requirements of the MIPS instrument.  Preparation is now underway to construct, test and integrate the flight unit in anticipation of a SIRTF launch in 2001.

## Acknowledgments

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