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Passive compensation of gravity flexure in optical instruments

by Edward A. Hileman et al.

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Passive compensation of gravity flexure in optical instruments

E. Hileman, J. Elias, R. Joyce, R. Probst, M. Liang, E. Pearson
National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, Arizona, USA 85719

ABSTRACT

We present case studies on the application of passive compensation in two large astronomical instruments: the Gemini Near Infrared Spectrograph (GNIRS), including actual performance, and the NOAO Extremely Wide Field Infrared Mosaic (NEWFIRM) camera. Image motion due to gravity flexure is a problem in large astronomical instruments. We present solutions for two different cases using passive mechanical compensation of the optical train. For the Gemini Near Infrared Spectrograph (GNIRS), articulation of a single sensitive optic is used. Adjustable cantilevered weights, designed to respond to specific gravity components, are employed to drive tilt flexures connected to the collimator mirror. An additional requirement is that cryocooler vibration must not dynamically excite this mirror. Performance testing of the complete instrument shows that image motion has been satisfactorily compensated. Some image blur due to dynamic excitation by the cryocoolers was noted. A successful damping scheme has been developed experimentally. For the NOAO Extremely Wide Field Infrared Mosaic camera (NEWFIRM), the entire optical support structure is mechanically tuned to deflect and rotate precisely as a rigid body relative to the telescope focal plane. This causes the optical train to remain pointed at a fixed position in the focal plane, minimizing image motion on the science detector. This instrument is still in fabrication.

Keywords: flexure, compensation

1. INTRODUCTION

Modern astronomical instruments mounted on large aperture telescopes are of such a scale (typical dimensions > 1 m; weights > 1000 kg) that mechanical deflection within the instrument is inevitable as the telescope moves about the sky, yet they must also meet very stringent requirements on gravitationally induced image motion at the detector. For example, the GNIRS image motion from gravity-induced flexure is budgeted to not exceed 2.7 microns at the science detector during a one hour exposure (15 degree change in gravity vector). The NEWFIRM instrument is budgeted to not exceed 2.5 microns at the science detector during a 15 minute exposure (4 degree change in gravity vector).

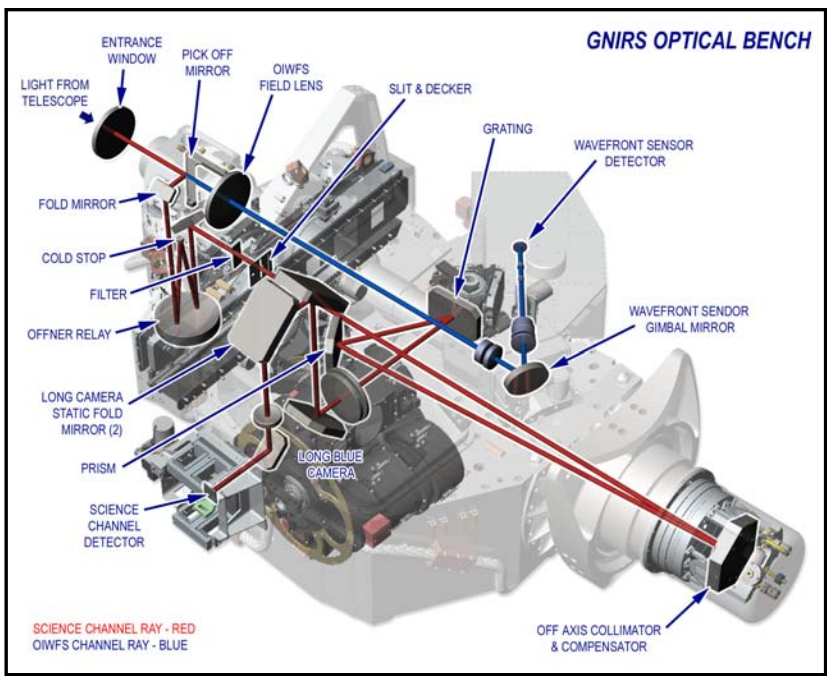

Figure 1. GNIRS Optical path through the OSS bench assembly. The collimator mirror has substantial leverage to reposition the image at the science detector.

Gravity flexure may be broken into two categories: (1) flexure occurring within the Optical Support Structure (OSS) itself, including mechanisms, causing optics to misalign with respect to one another, and (2) 'rigid body' motion of the entire OSS with respect to the instrument mounting location due to flexure of structure connecting the OSS to the mounting location. GNIRS employs a wave front sensor mounted to the OSS housing assembly that nullifies rigid body flexure of the OSS by commanding small pointing corrections of the telescope. Thus, we are primarily concerned with deflection within the OSS itself.

NEWFIRM, unlike GNIRS, does not have an onboard wave front sensing device mounted to the OSS. A separate telescope guider, attached to the truss connecting the OSS to the telescope mirror cell, is included on NEWFIRM. Gravity flexure of all structure between the guider and the OSS will therefore contribute toward image motion at the detector. These different instrument architectures led us to two distinct solutions of the flexure problem.

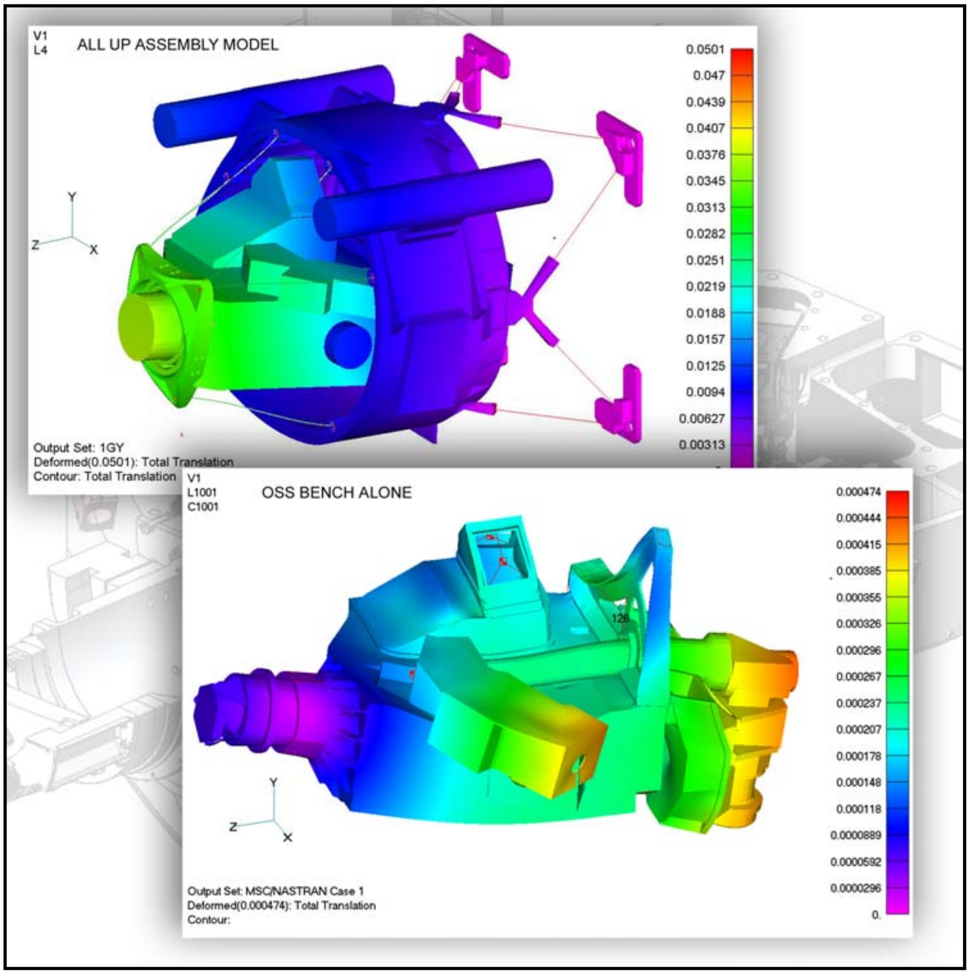

*Figure 2. Finite element models used for flexure analysis of GNIRS. Upper model addresses rigid body motion of the OSS optical bench with respect to the telescope interface due to flexure of the supporting structure. Shown here is deflected shape (inches) for 1G in the **y** direction. Portions of this model not displayed for clarity. The Onboard instrument wavefront sensor (OIWFS) mounted to the bench corrects for image motion due to this flexure. Lower model addresses flexure within the bench itself. Deflections of nodes at optic vertices are used to determine image motion at the detector. Shown here is the deflected shape (inches) for 1G in the minus **y** direction.*

2.0 GNIRS METHODOLOGY

2.1 Flexure control strategy for GNIRS

Within the GNIRS OSS housings, the optical beam path is complex and long, magnifying small mechanism and housing distortions (*figure 1*). Structural deflection of the OSS from changing gravity loads was analyzed utilizing Finite Element Analysis *(figure2).* Mechanical flexure was measured directly at room temperature for the three mechanisms carrying relevant optical elements, and these flexure values were also included in the model. Flexure induced image motion in excess of the specified maximum was indicated *(figure 3).* Compensation was therefore necessary.

Load Case	Motion on Detector (micron)	Motion direction (Global Coordinates)	
1 G in **X**	43	Z	Lateral to slit
	-16	Y	Parallel to slit
1 G in **Y**	48	Z	Lateral to slit
	17	Y	Parallel to slit
1 G in **Z**	0	Z	Lateral to slit
	0	Y	Parallel to slit

*Figure 3. Image motion on GNIRS detector when moving to gravity in **x** or **y** directions assuming alignment when gravity is in **z** direction. Slit tracked by wavefront sensor.*

Because of its location, the GNIRS collimator mirror has high sensitivity to affect image motion via tilt. It was decided to utilize this optic for compensation. Also, the modeling showed that corrections applied at the collimator would be very similar for different instrument configurations, allowing a passive compensator to be used. A totally passive system was desirable so as to avoid the complexity, risk, and integration effort associated with an active system.

2.1.1 GNIRS compensator

A passive compensation assembly, connecting between the back of the collimator mirror and the OSS, was designed, fabricated, tested and integrated into the instrument. At the time of its design, the magnitude and direction of compensation needed was only known approximately. Therefore, the goal with the compensator is to provide tilting correction in any direction and of adjustable magnitude given a gravity direction. This will allow compensation of gravity induced repeatable linear errors regardless of their magnitude (within limits) or direction. For example, if gravity is in the **y** direction, the mechanism shall be capable of corrective tilt about the collimator's **x** axis or the **y** axis or both. Both the sign and magnitude of the corrective tilt shall be adjustable.

2.1.2 Design configuration

Configuration of the GNIRS passive compensator is shown in *figure 4*. The collimator mirror is supported from the base housing by three tangentially stiff support brackets located at 120 degree intervals about the mirror perimeter. The brackets are designed to be radially compliant, so as to allow thermal mismatch and minimize mechanical distortion of the mirror. The bracket located on the –**x** face is stiff in the **z** (optical axis) direction. The other two brackets have flexures machined into them so as to be compliant in the **z** direction. Pushing or pulling these flexures along **z** tilts the collimator mirror about the **x** or the **y** axes. The brackets are stiff in the circumferential direction, which rigidly locates the mirror with respect to translation in the **x** or **y** direction. Arms equipped with flexural pivots and adjustable counterweights (termed the "Actuators") provide the necessary push/pull force on the flexures.

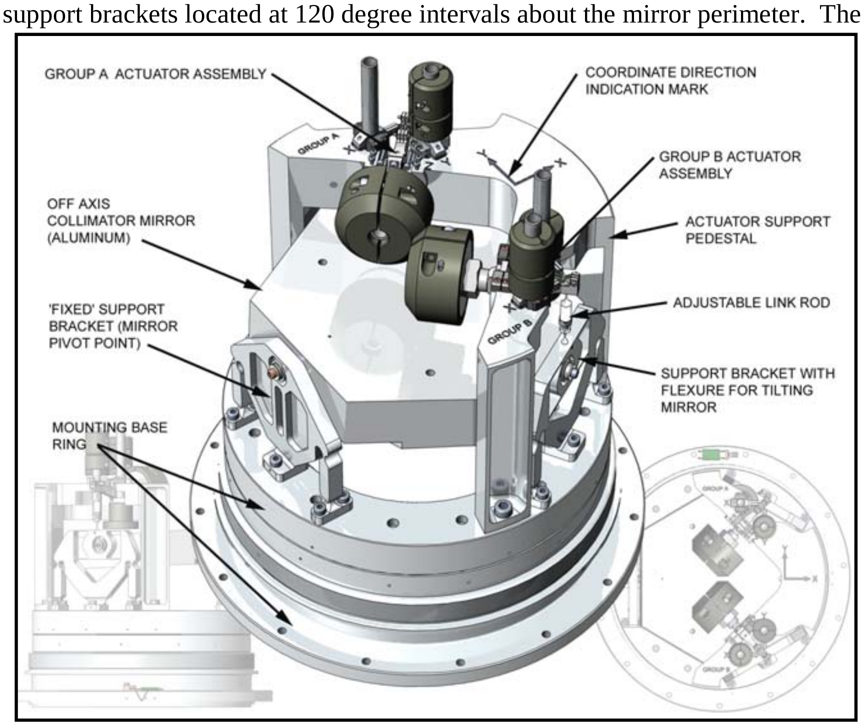

Figure 4. GNIRS collimator mirror compensator assembly.

The compensator utilizes two groups of three actuators; one group on the –**y** side of the **x** axis, the other, a mirror image, on the +**y** side of the **x** axis. Each group is comprised of an **x** direction actuator, **y** direction actuator and **z** direction actuator. That is, these are actuators that supply **z** direction force due to gravity loads in the **x**, **y**, or **z** directions respectively. The actuators are aligned orthogonal to one another. This ensures that a gravity component in one direction will have no effect on the other two actuators. Shown in *figure 5* is a single group of actuators. The "output" (**z** direction) forces of all three actuators are tied together at a common point, via 'cross' flexures, and actuate the support bracket through a post linking the actuator arms to the mirror support bracket.

2.1.3 Operation

Operation of the compensation mechanism can be illustrated by considering an example. Suppose for gravity in the **x** direction, we need the collimator mirror to tilt negative about the **x** axis. Because of the orthogonal layout, solely the **x** direction actuators will create an actuation force. Depending on **x** actuator counterweight adjustment, gravity will cause the **x** actuator of group 1 (-**y** side of **x** axis) to pull in the +**z** direction on the support bracket, lifting that side of the mirror. Likewise, the group 2 (+**y** side of **x** axis) **x** actuator can be adjusted to push an equal amount in the **–z** direction on its respective support bracket, thereby lowering that side of the mirror. The combined effect is to tilt the mirror about the **x** axis with a negative sense. By biasing the weights so that the pull force of group 1 is greater than the push force of group 2, one can also cause a simultaneous tilt about the **y**-axis in a negative sense. Extrapolating the above scenario, we can visualize how it is possible to achieve varied magnitude of + or – tilt about either or both axes for only a single gravity direction. A similar argument applies to the other two gravity directions as well. Simultaneous application of gravity components in all three dimensions cause mirror tilt which is the superposition of the individual component cases.

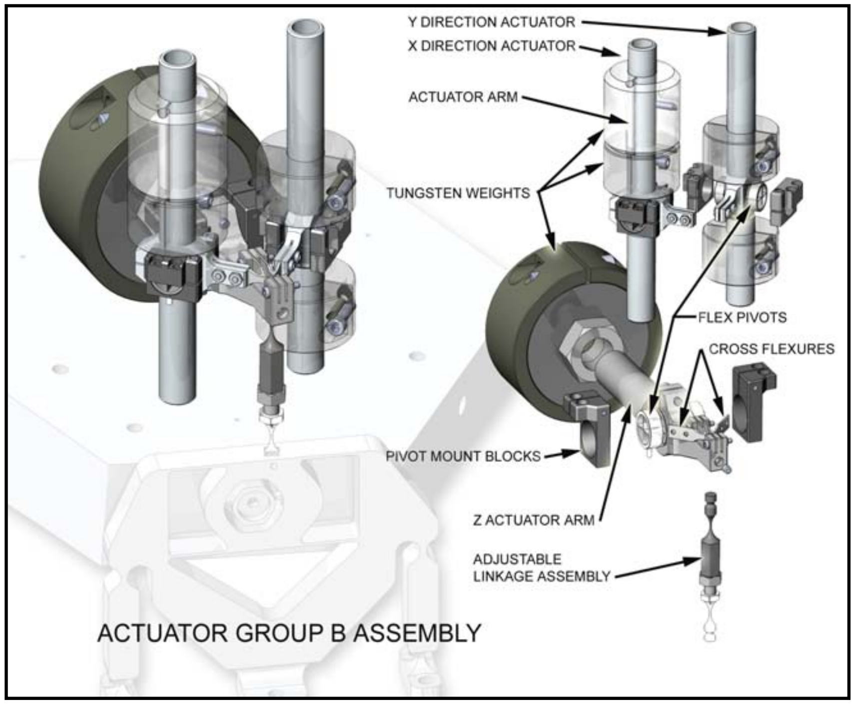

*Figure 5. Actuator group B assembly. A group is comprised of three actuators, each of which respond only to gravity components in the **x**, **y**, or **z** directions respectively. Each actuator is tied together by the cross flexures. Each will generate **z** direction push/pull forces on linkage assembly. The **x** and **y** direction actuator counter weights and arms are biased toward the +**z** side of their pivots.*

2.1.4 Design considerations and details

2.1.4.1 Counterweights

Based on preliminary structural analysis of the OSS, we designed for 3 arc-sec (15 micro-radian) of compensation tilt. To achieve this, the primary counterweights are about 0.37 pounds, and the larger **z** counterweight is 2.20 lbs. If necessary, the size of the weights may easily be modified. The counterweights are fabricated from machineable tungsten alloy (density = 17.0 g/cm^3) to maintain a necessarily compact space envelope behind the collimator. Counterweights are threaded onto the actuator arms providing easily quantifiable adjustment. Once adjusted, the counterweights are clamped to the arm threads with cap screws. Each weight is slotted through nearly its entire diameter to provide the necessary clamping flexibility.

The range of motion of the weights was about 0.5 inch for the Z weights and 1.5 inches for the **x** and **y** weights, in order to provide the range of adjustment indicated previously. The weight position adjustments could easily be made to 0.02 inches or better, providing more that the required resolution.

The **z** direction compensator counterweight is much larger than the other two counterweights in the group. In addition to supplying corrective tilt forces, it must also equalize the weight of the collimator mirror for **z** direction gravity force, since the support brackets are compliant in that direction. Employing larger weights on the shortest possible arm is also a goal because the resonant frequency of the system is minimized. [1]

Two counterweights are provided on each of the x and y actuator arms. This allows a continuous range of adjustment from plus to minus. The range of motion for these weights is not equally spaced because the locations at which the support brackets hold the mirror lie in a plane not coincident with mirror center of gravity. Bracket attachment holes in the sides of the mirror are biased toward the back face to reduce local distortion reaching the working side of the mirror. This causes the mirror to tilt slightly when no compensators are attached. For instance, when gravity is in the **x** direction, the mirror wants to tilt negative about the **y**-axis. Biasing of the **x** direction counterweights counteracts this tendency.

2.1.4.2 Support Brackets

In addition to the **z** direction flexure, support brackets incorporate flexures on their 'feet' to allow for thermal growth mismatch between the titanium bracket and the aluminum base to which it is bolted (*figure 6*). Machined into each support bracket is a semi-gimbaled flexure where a cap screw mounts the bracket to the sides of the collimator mirror. This gimbal flexure reduces reaction moments due to mirror tilt. Dimensionally small features of the bracket flexures and the substantial stress resulting within them from assembly and testing forces dictated the use of a high strength material. Titanium 4Al 2.5Sn was chosen for its high strength and good toughness at cryogenic temperatures. Wire EDM was used to cut out the bracket shape including the **z** flexure blades and part of the gimbal flexure. Milling procedures created the remaining features.

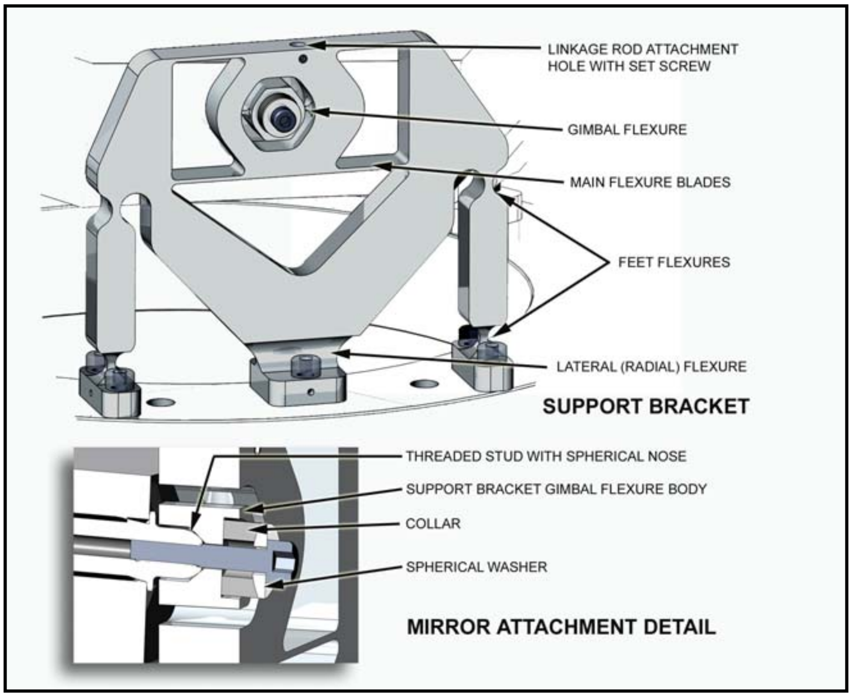

Figure 6. Compensator support bracket flexure with detail view of mirror attachment. Flexure allows tip-tilt of mirror but not decenter.

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[1] If d is the moment arm length between pivot and weight, and the mass of the weight m is varied with d such that the product of mgd (the moment) is constant, then the fundamental frequency ω of a simple cantilevered mass on an arm pivoting about a fixed point against a torsional spring will vary with d as the ratio:

$$\frac{\omega_1}{\omega_2} = \sqrt{\frac{d_2}{d_1}}$$

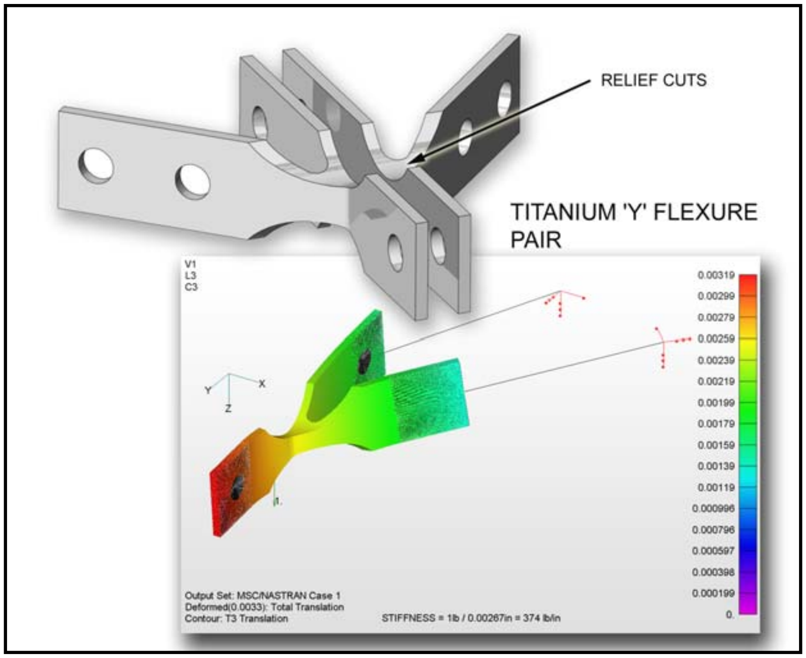

Figure 7. 'Cross' flexure detail with FEA used to determine spring rate (374 lb/in)

2.1.4.3 Actuators

Actuator arms are fabricated from aluminum 6061-T651 plate and incorporate stainless steel Lucas flex pivots at their rotation axes. Where the three actuation arms (**x,y,z**) intersect, a 'cross' flexure attaching one **x** or **y** arm to the **z** arm is employed (*figure 7*). It is designed to transfer shear force between arms while reducing moment reactions when the actuators displace.

Connecting the actuator arms to the support bracket is a titanium link rod. It is axially stiff to transfer actuator output force, but compliant in bending so as not to restrain small lateral offset of its ends during assembly, test and operation.

2.1.5 Design analysis

Lowering the resonant frequency of the collimator mirror assembly is a primary issue with regard to compensator design. Cryocooler impulse noise excitation is the main concern. Shown in *figure 8* is the finite element model developed to determine the natural frequency of the system. Beam elements, lumped mass elements, and spring elements are used in lieu of the actual actuator and bracket components to simplify the model and minimize run time. Spring rates are determined from separate models of the support bracket and the 'cross' flexure alone (*figures 7 and 9*). In its worst configuration (all weights at maximum travel away from the pivot), the fundamental natural frequency is about 80 Hz. Lacking quantified vibration input characterization (such as power spectral density), we made the engineering decision that the natural frequency was sufficiently high so that excitation would not be significant. As a backup measure, we considered the potential use of vibration dampening material to help attenuate response.

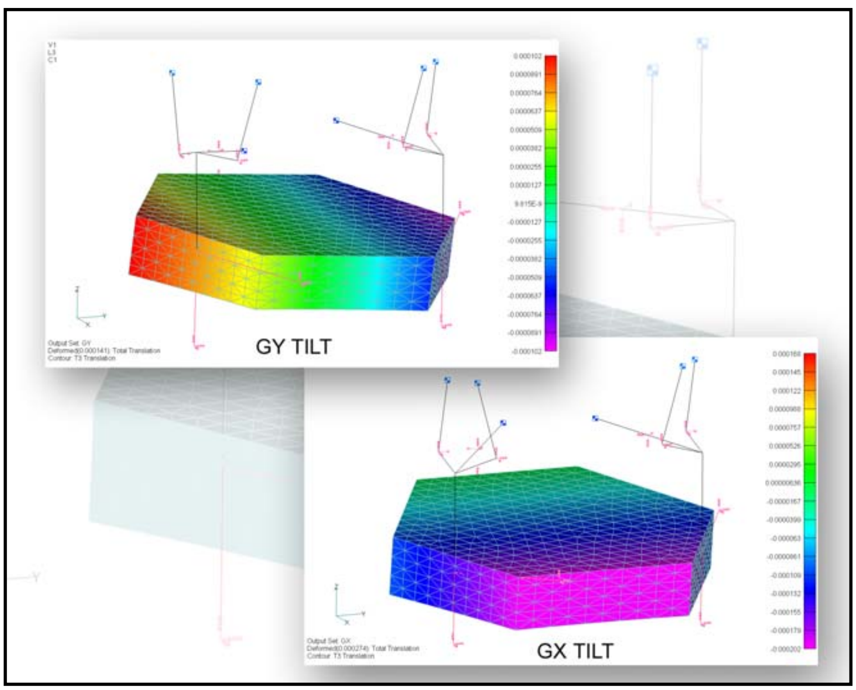

*Figure 8. Compensator FEA model showing response of the mirror to gravity in the **y** and **x** directions separately. Model also used to predict the fundamental frequency of 80 Hz. Note counterweight magnitude and position in the tuned final version is not as shown here.*

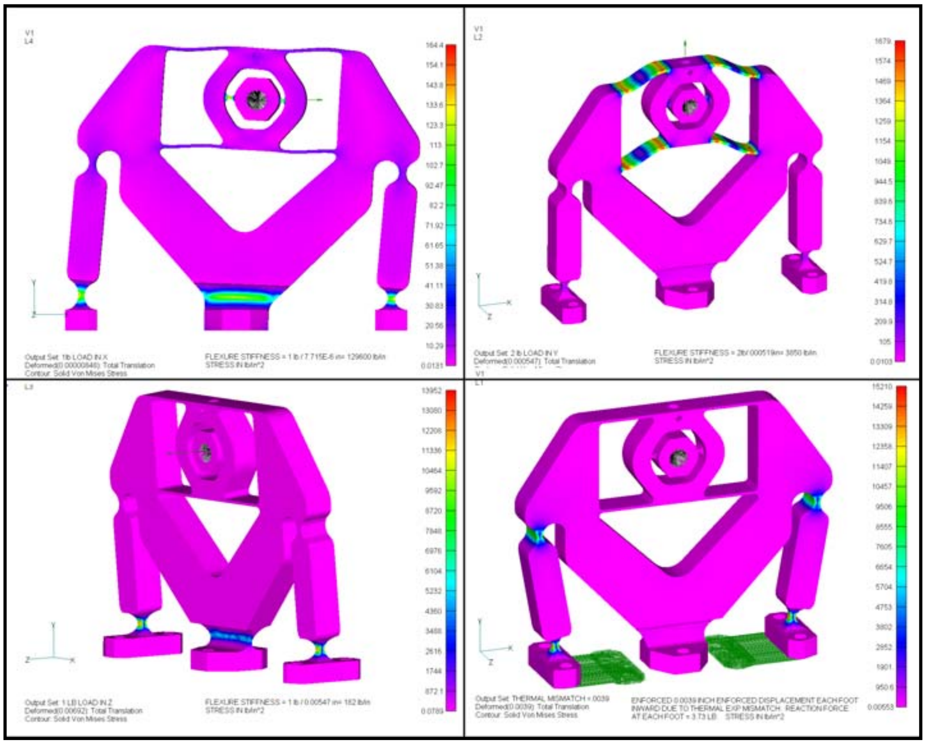

Figure 9. Stiffness analysis of collimator mirror support bracket. Stiffness results from upper left clockwise: Tangential to mirror = 129,600 lb/in, Optical axis direction = 3850 lb/in, Thermal mismatch = 3.73 lb reaction on each foot, Radial to mirror = 182 lb/in.

3.0 GNIRS COMPENSATOR TESTING

3.1 Stand-alone testing

Following fabrication and assembly, the compensator unit including the off axis collimator mirror was tested as a stand-alone assembly using both optical and mechanical measurements. The first set of tests were done with the collimator in an expanding Zygo beam and a flat reflecting the collimated beam back onto itself; an autocollimating mode with the collimator itself in double pass. This set up orientation allowed testing of only the **y** direction actuators (gravity in the **y** direction). By symmetry one would expect the behavior of the **x** and **y** compensators to be the same.
Initial tests were performed with the pushrods connecting the compensation actuators not connected to the mirror support flexures. The intent was to see if the wavefront quality was degraded by the three support studs threaded into the mirror independent of any additional stresses that might have been introduced by compensating mechanism (*figure 6*). The wavefront quality was somewhat better than that measured with the mirror unmounted. Installation of the three support studs did not appear to introduce any distortion.

Next, with the **y** counterweights set to an initial configuration, the tilt on the Zygo was zeroed. The weights were then moved along the actuator arm a prescribed amount, and the resulting tilt measured from fringes on the interferogram. In this configuration, four tests were done: motion of the A and B primary weights individually, tandem motion of the weights both in phase and out of phase. Results of the **y** actuator test are summarized in *figure 10*.

Y Actuator test results

Group A	Group B	Tilt (μrad)	Predicted Tilt (μrad)	Predicted Axis Angle	Tilt Axis Angle
0.75" in	0.00	10.6	12.9	+30	~ +20
0.00	0.75" in	11.5	12.9	-30	~ -20
0.75" out	0.75" out	23	22	0	~ 0
0.75" in	0.75" out	10.6	13.6	90	~ 90

Z Actuator test results

Group A	Group B	A actuator motion (µinches)	B actuator motion (µinches)
0.5" in	0.0	-138	<10
0.0	0.5" in	<-5	-140
0.5" out	0.5" out	+135	+135
0.5" out	0.5" in	+140	-140

Figure 10. GNIRS collimator compensator pre-installation test results.

At least two items are worth noting. First, the individual weight motion produces a mirror tilt that is not exactly at the 30 degree angle of the flexure with respect to the horizontal, but slightly less. This might suggest some interaction with the other flexures. When the weights were moved in tandem, measured tilt angle about the **x** axis was as expected, suggesting the motion of the flexures was equal. When the weights were moved out of phase, however, the magnitude of the tilt about the **y** axis was significantly less than that predicted. While in this set up, we also varied the position of the **x** and **z** counterweights. No tilt change was noted on the interferogram as expected demonstrating independence of **x**, **y**, and **z** actuators.

Figure 11. Flexure testing of GNIRS at the NOAO flexure test facility in Tucson, Arizona.

The collimator assembly was then placed on a granite table with gravity oriented in the **z** direction. Because the Zygo cannot be used in this configuration, remaining tilt measurements were made with precision indicators. Test precision of 0.1 micron was possible, similar to that of the optical tilt measurement. The spring constant of the flexures was measured directly by pushing on A and B pushrod assemblies separately with a force gauge and measuring the motion of the flexure. A 5 lb. force yielded a deflection of 1100 micro-inches for both the A and B pushrod assemblies, equivalent to a spring constant of 4545 lb/inch, slightly more than measured prior to installation of the mirror. Next, the same series of z weight motions (individual, tandem in and out of phase) was tested. Results of the **z** actuator test are also summarized in *figure 10.* We note the results are consistent with equal spring constants for the two flexures and independent motion of the two flexures.

Dynamic response of the compensator assembly was also tested. The signal from an accelerometer placed on the back face of the collimator mirror was displayed on an oscilloscope. The mirror was gently tapped and the response observed. The lowest response frequency noted was around 90 Hz.

3.1.2 Testing after integration into the instrument

With the collimator mirror and compensator installed into the instrument and cooled to operating temperature (65K), flexure of the optical bench and mechanisms was determined. This was done using pinholes or other fiducials in the slit while placing the instrument in various gravity orientations on the NOAO Flexure Test Facility (*figure 11*).

Laboratory testing of the instrument revealed that the actual internal flexure was almost twice the model predictions. We were able to accommodate this by either moving weights from one side of the pivot to the other, or (in one case) by fabricating a weight with somewhat higher moment. Representative data after the initial iterations are shown in *figure 12*; the motion on the detector has been reduced by roughly a factor of 6. The larger flexure observed in the instrument beyond that predicted *(figure 3)* is almost certainly due to different flexure of the mechanisms at 65K in vacuum, compared with the measured performance at room temperature in air. The mechanisms are also almost certainly the source of the hysteresis seen in the figure, which effectively limits the compensator performance.

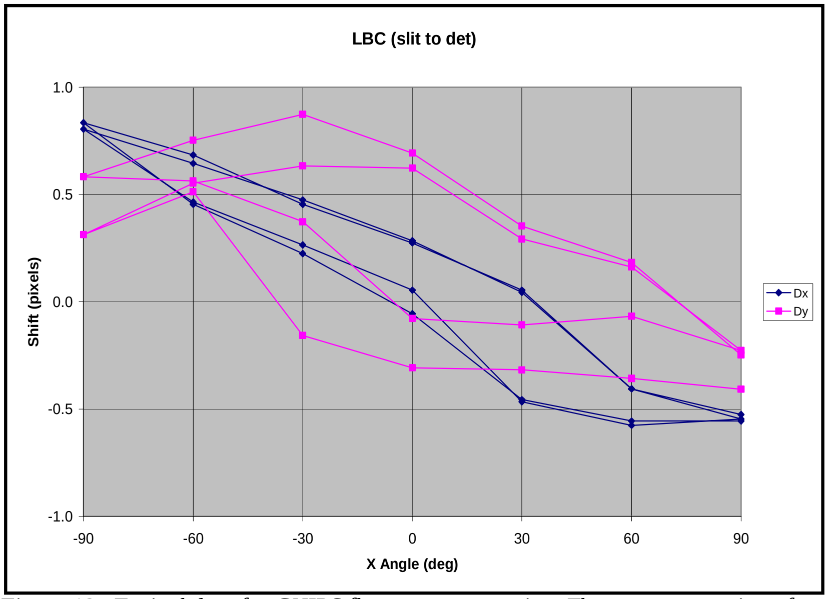

Figure 12. Typical data for GNIRS flexure compensation. The apparent motion of a pinhole at the spectrograph slit on the detector, in both X and Y, during rotation of the instrument about the Z axis. A motion of 1 pixel corresponds to uncorrected flexure of 27 microns, or about 9 micro-radians of tilt at the collimator. Note the effects of hysteresis, especially in the Y axis.

The tests also showed that the cryocoolers used to cool the instrument's internal structure were capable of exciting resonance in the compensator by enough to produce small but measurable tilts of the collimator (image blurring). These resonant frequencies lay between 100 and 200 Hz, and comprised motion in the actuator assemblies and in the mirror/mount assembly. The actuator assemblies were damped by slightly loosening the clamping screws of the largest (Z) weights, effectively decoupling the weights from the rest of the system. Additional damping was achieved by attaching a tightly wound coil of copper braid between the mirror support point and the bracket body in the triangular opening of the mirror support brackets (*Figure 6* - braid not shown in the figure). These two remedies reduced both the amplitude and damping time of the collimator system response to impulsive input from the cryocoolers by roughly an order of magnitude, though not they are not entirely eliminated.

4.0 NEWFIRM METHODOLOGY

4.1 Flexure control strategy for NEWFIRM

The NEWFIRM instrument features a relatively simple, single pass, straight through optical path with all optics clustered together in a fairly small space with the exception of lens 1, the field lens (*figure 13*). None of the optics articulate via mechanisms (except filters) eliminating mechanism flexure as a source of error. Compactness of the optical train allows design of the OSS to be quite stiff having internal gravity deflection well under that needed to maintain image motion specification. "Rigid body" deflection of the OSS with respect to the guider is therefore a primary concern with this instrument.

The NEWFIRM OSS is mounted to the telescope in a somewhat flexible manner. By design, rotation of the OSS by gravity loads cause the optic train therein to "look at" a constant point on the telescope focal plane regardless of instrument orientation. This action minimizes image motion at the detector.

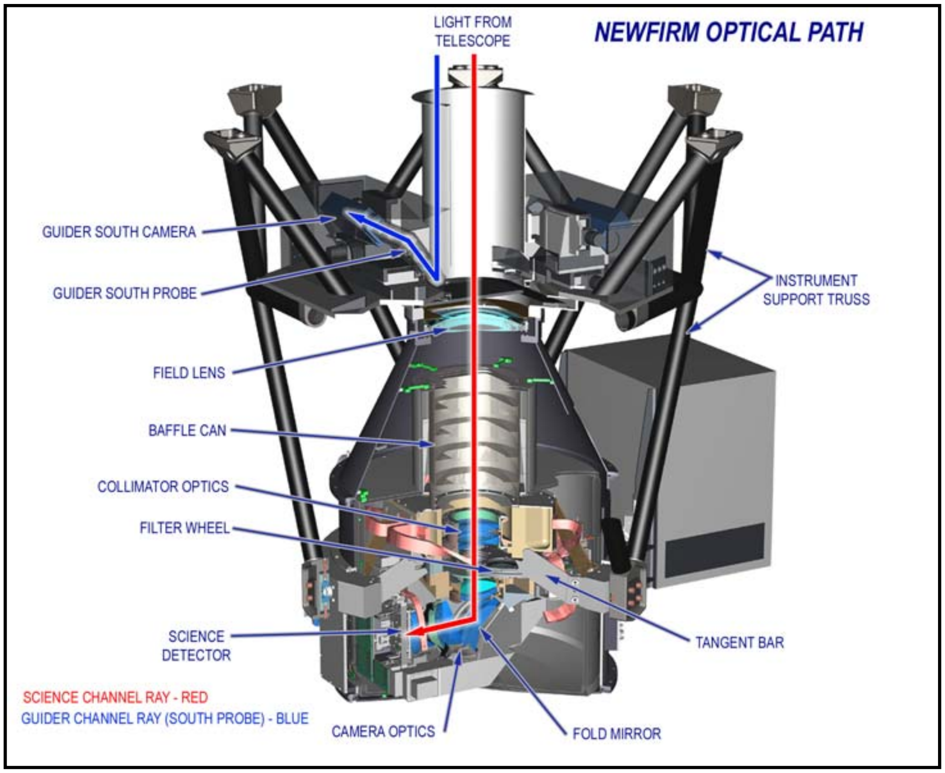

Figure 13. NEWFIRM optical path through guider, into dewar, and OSS housings. The tangent bars connecting OSS to truss provide some flexibility for rigid body rotation of the OSS.

4.1.1 NEWFIRM compensation

It is difficult to provide sufficient stiffness for an instrument the weight and size of NEWFIRM so as to maintain position of the OSS with respect to an external guider within tight tolerances needed to meet the tracking image motion requirement. Instead the NEWFIRM OSS incorporates a support structure that allows gravity forces to purposefully rotate the OSS in a controlled manner designed to compensate for the gravity-induced sag of the instrument.

4.1.2 Design configuration

The collimator and camera lenses, filter wheel, and detector assembly are contained in the OSS housings assembly. This comprises the 310 kg 'cold mass' of the instrument, to be maintained at 65K (detector at 30K). The OSS is held in place at its upper end by three 'tangent' bars spaced at 120 degree intervals which, in turn, connect to the inside face of the dewar girth ring. On the girth ring outer face directly opposite the tangent bar connections are attachments to the instrument support truss. The load path for the OSS is: from OSS, through tangent bars, through dewar girth ring, through instrument support truss, to telescope mirror cell. Refer to *figure 14.* Also connected to the support truss close to the telescope focus is the guider assembly.

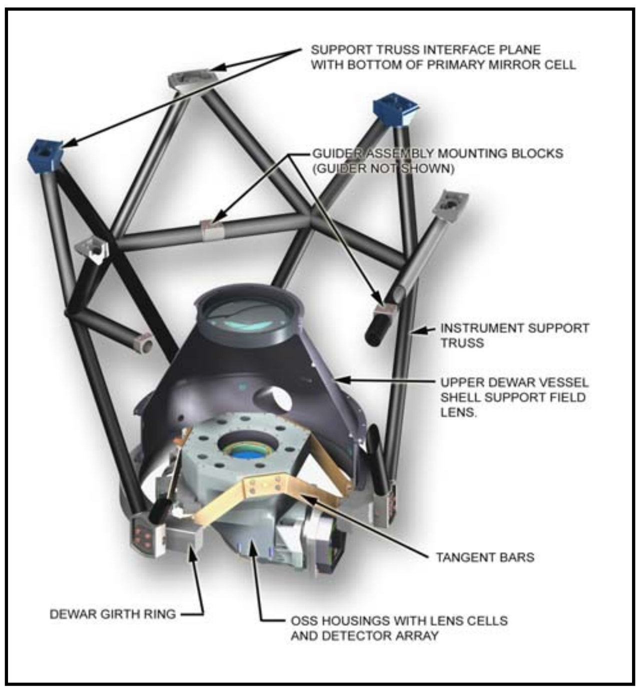

Figure 14. NEWFIRM instrument cutaway view showing the OSS support scheme and load path; OSS to tangent bars to girth ring to truss to telescope mirror cell.

4.1.3 Operation

Lateral gravity components deflect laterally the entire dewar and cold mass within. Similarly, the guider is also deflected to a lesser extent. If uncorrected, this action causes the optic train within the OSS to 'look at' a varying point on the telescope focal plane resulting in image motion on the detector. The tangent bars are designed to correct for the majority of this error by allowing the OSS to rotate by an amount necessary to nullify translation of the truss. Rotation occurs because the OSS center of gravity is below the connection centerline of the supporting tangent bars, creating a moment that flexes the tangent bars by a prescribed amount. The tangent bars maintain high stiffness against lateral translation of the OSS, yet allow the OSS to shrink when cold without significant stress or decenter.

4.1.4 Design considerations and details

4.1.4.1 Tangent bars

The tangent bars control rotation of the OSS by bending stiffness about their strong axis. Geometry of the bar cross section is adjusted to structurally tune this stiffness in accordance with the OSS rotation needed for correction. The tangent bars are offset in the z direction to provide clearance for the filter wheel assembly.

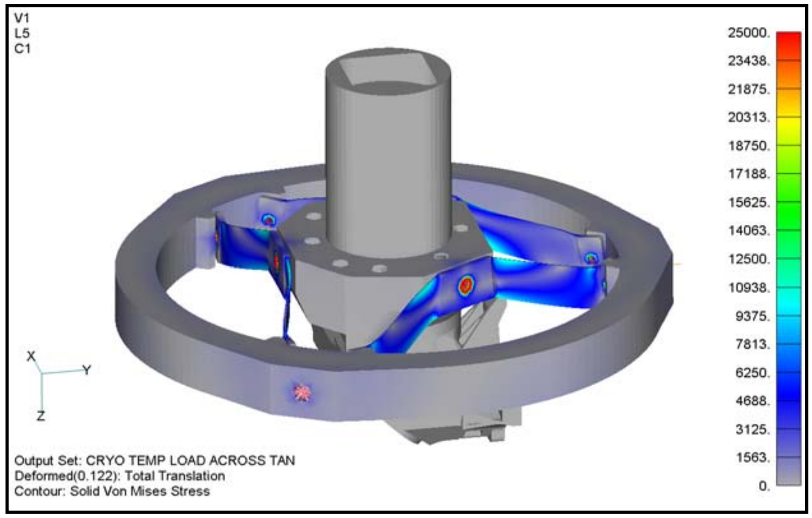

*Figure 15. Thermally induced stress and displacement of NEWFIRM tangent bars following cool down from 293K to 60K. Displacement scale factor is 50x. Maximum induced bending stress is 20 ksi (138 Mpa). Displacement of the OSS in **z** at the tangent bar connection location is 0.029 inch. Reaction force at ends of tangent bars is 2000 lb.*

Because the tangent bars connect directly between the cold OSS (65K) and the warm dewar girth ring (ambient), thermal conduction through the bars is a concern. Titanium 6Al 4V is chosen for the tangent bars for a combination of reasons; low thermal conductivity, low thermal expansion, predictable stiffness performance (Young's modulus well determined), and high strength. Mechanical connection of the bars to both the dewar wall and the OSS utilizes a split tapered cone insert locating into a conical hole in the bar and against the shank of a shoulder bolt aligned and threaded into the mating part. A G10 washer separates the two pieces. Heat loss through the 3 tangent bars including connections from OSS to girth ring are estimated at 14 watts, well within the cooling load budget.

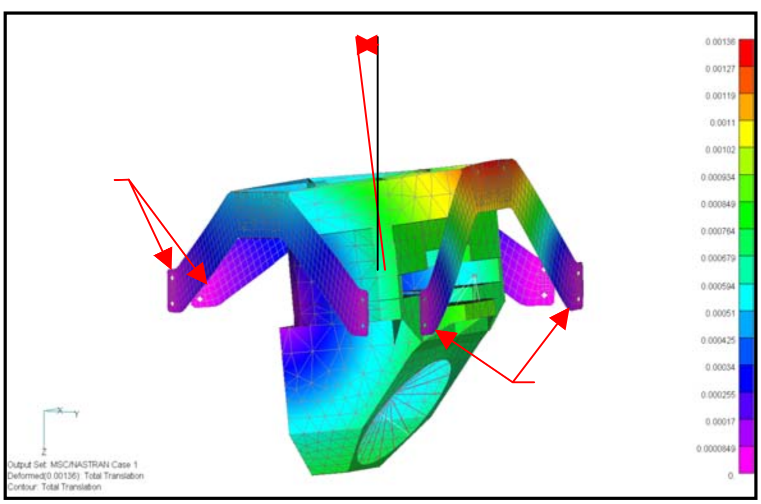

Figure 16. Temperature variation across the girth ring diameter results in rotation of the OSS due to thermal expansion of the tangent bars and their offset geometry.

Thermal contraction of the bars axially creates in plane bending loads on the bars and reaction forces on the girth ring. Bending loads arise from the offset shape of the bar. Shown in *figure 15* are the FEA results for thermally induced stress and displacement of the bars. Reaction force on the girth ring is 8.9 kN which is acceptable for both the girth ring and the connection. Small non-uniform variation of temperature in the bars with time will induce OSS pointing errors and consequent image motion at the detector. Presented in *figure 16* is a scenario where tangent bar ends at the dewar become 10K different across the girth ring diameter. The resulting OSS rotation causes image drift on the detector of approximately 25 microns. When compared to the budgeted amount from this source (1.25micron/0.25 hour, one half the total acceptable drift), this result suggests spatial temperature variation across the dewar diameter not exceed about 1K/hour. Given the temperature stability of the telescope enclosure environment, this is limit is reasonable.

4.1.4.2 Instrument support truss

The instrument support truss is a space frame designed to be stiff with low cost and weight *(figure 14).* At the dewar connection, it provides a lateral stiffness of 57.6 kN/mm and weighs 270 kg. Geometry of the truss causes dewar deflection to be translation only with no rotation. Connection with the dewar girth ring is designed to allow piston and tilt adjustment of the dewar with respect to the mounting face on the telescope mirror cell. Carbon steel mechanical tubing comprises most of the truss.

4.1.4.3 Dewar vessel

The 400mm diameter field lens of the NEWFIRM optical train serves also as the entrance window into the dewar vessel. It is supported and located by the upper dewar shell. It deflects laterally along with the dewar vessel and does not participate in the corrective rotation of the optics within the OSS. It therefore becomes decentered with respect to the optical path under the influence of lateral gravity loads. Because this optic is not very sensitive to decenter or tilt, this is an acceptable situation.

4.1.5 Design analysis

Shown in *figure 17* is the all up FEA model of the NEWFIRM instrument including the guider assembly. A similar preliminary model was used to establish and iterate location of the girth ring and cross section properties of the tangent bars. Deflected shape of the assembly is shown also in *figure 17*. Reduced deflection data are presented in *figure 18* in which is shown the movement envelope of the guider probes with respect to a point on the telescope focal plane to which the OSS optical train points. From this, we determine a maximum error of about 90 microns (1.5 pixels at the detector) between the guiding location and the 'look to' location on the focal plane when going from zenith to horizon pointing in any direction. For a 15 minute exposure interval (approximately 0.0625g) this corresponds to less than 0.10 pixel, which is the specified maximum. Without compensation, i.e. OSS rigid with respect to girth ring, a similar procedure results in a 15 minute image drift of 0.224 pixel.

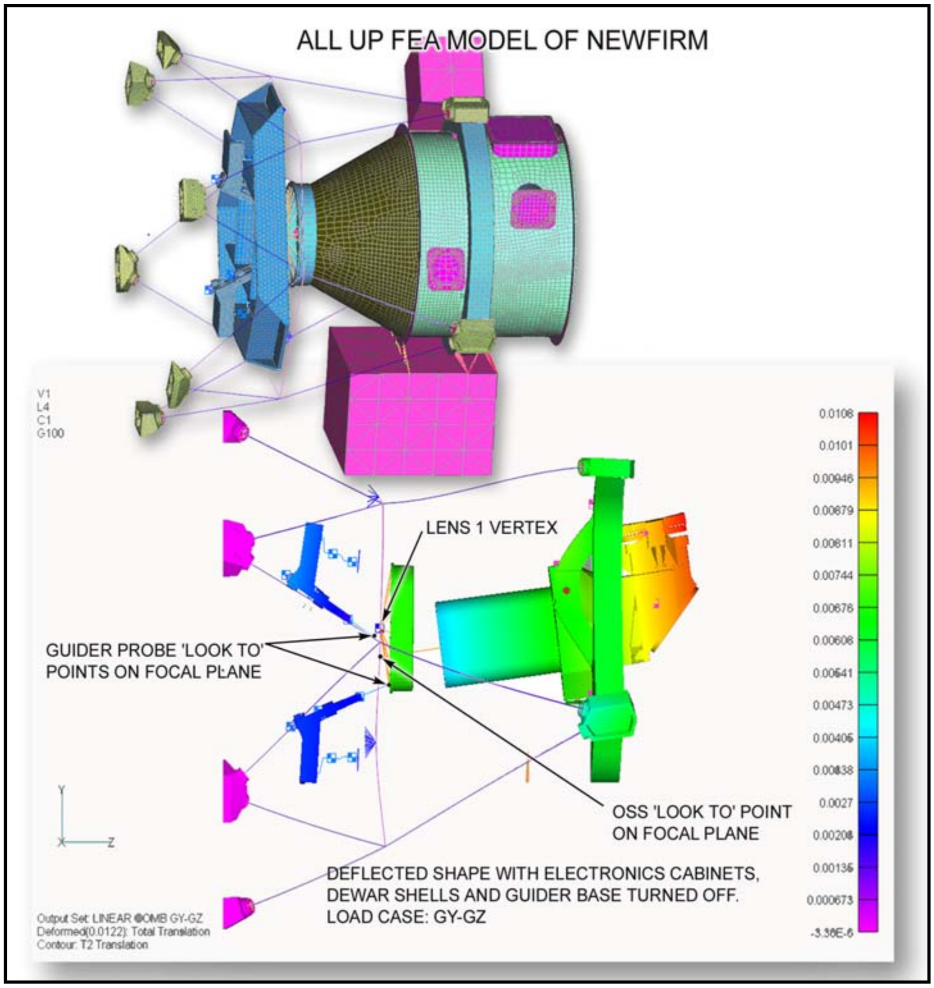

Figure 17. FEA of NEWFIRM for load case GY. Rotation of the OSS housings cause the 'look to' point on the focal plane to track those of the guider probes as lateral gravity component is applied. This reduces image drift on the detector array. Units shown are inches.

4.1.6 NEWFIRM compensation testing

Flexure testing of the instrument is planned for the fall of 2004. At the time of this writing, no testing information is available.

5.0 SUMMARY

We have described two distinct solutions to the problem of flexure-induced image motion in large astronomical instruments. Both use the general approach of passive mechanical compensation in response to varying gravity loads.

5.1 GNIRS passive compensation

GNIRS has a long, complex optical train with some elements mounted in moving mechanisms. An integral guiding capability corrects whole-body deflection. The challenge was to compensate for internal flexure. This is done by tilting a single sensitive optic, the collimator mirror, by means of articulating counterweighted arms acting through flexures. After tuning, image stability is within the demanding specification. A second challenge was to avoid excitation of this mirror, suspended on its articulating mechanisms, by cryocooler vibration. Some excitation was seen and a successful damping scheme was developed experimentally. GNIRS has been delivered to the Gemini South telescope and is in service now.

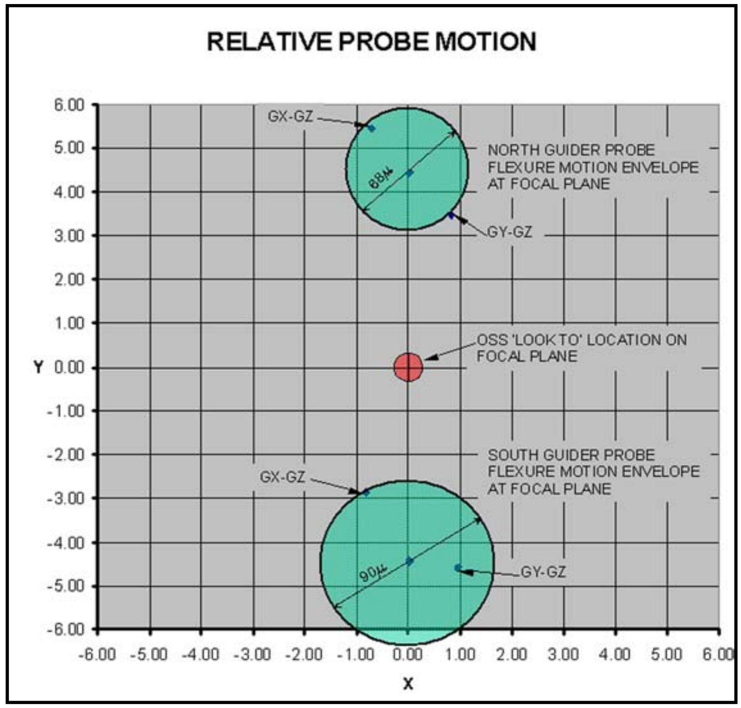

Figure 18. Relative guider probe motion at the telescope focal plane with respect to the OSS optical train 'look to' point for flexure from lateral gravity loads of 1G in any direction. Motion envelope graphics are scaled by 1000 for clarity. X and Y axes are in inch units. Note the diagram is not fixed with respect to the telescope but instead moves with the OSS optical train 'look to' point.

5.2 NEWFIRM passive compensation

In the case of NEWFIRM, the optical support structure is quite rigid. The challenge was to compensate for whole-body deflection of the OSS relative to the external guider and telescope focal plane. The solution is to tune the mechanical structure connecting the OSS to the telescope so that the OSS deflects and rotates in a controlled and predictable manner. This results in the science optical train and the guider (which has its own, lesser, deflection) remaining pointed to the same location in the telescope focal plane during an exposure. This approach is less amenable to post-fabrication tuning and there are likewise concerns about OSS vibration in response to cryocooler impulses. This instrument is currently in fabrication. We expect to begin laboratory flexure measurements in late 2004.

5.3 Limitations

The experience with GNIRS indicates the advantages and limitation of a passive compensator design. The primary advantage of passive compensation is the simplicity of operation. Once adjusted, the mechanism works without telescope interfaces, electronics or software, and should be virtually immune to failure.

There are three main limitations of the approach. The first is its inability to deal with non-linear flexure, such as hysteresis, which often is characteristic of mechanism deflection behavior. The second is a lack of capability to deal with configuration dependent flexure, when the optical train may be rearranged during operations. This is highly design dependent, and was fortunately not a factor with GNIRS or NEWFIRM. The final limitation is vulnerability to vibration, which is due to the relatively low frequency of internal resonance in the compensating mechanism. This was a problem that required experimental solution in GNIRS. Where there is an on-instrument source of vibration, such as cryocoolers, a more comprehensive approach to damping would doubtless give better results. This would require use of the cryocooler power spectral density (PSD) in optimizing the compensator design. These limitations suggest that correcting flexure by more than a factor of 10 would be very challenging for most instruments (though even active compensation without feedback would likely have difficulties at this level).