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Mounting large lenses in wide-field instruments for the converted MMT

R. G. Fata and D. G. Fabricant

Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

ABSTRACT

We describe the techniques that we have used to mount large optics in three wide-field instruments for the converted MMT: the wide-field corrector used to provide a 1° diameter field at the f/5 focus of the converted MMT, the Hectospec bench spectrograph fed by 300 optical fibers and the wide-field dual-beam Binospec spectrograph. These optics are primarily refractive elements with diameters between 0.2 and 0.8 m that must be mounted from their edges, although we also describe mounts for two large mirrors in the Hectospec bench spectrograph. Both the wide-field corrector and Binospec mounts must perform under varying gravity loads: the corrector is fixed to the converted MMT's primary mirror cell and is tilted from zenith to horizon while Binospec is mounted at the converted MMT's Cassegrain focus. Furthermore, the optics mounts for both instruments must fit within tight space constraints. The Hectospec spectrograph is mounted in the MMT's rotating building and experiences a constant gravity vector. In all cases, the mounts must perform over a wide temperature range, -20 to 20 °C, so the issue of differential thermal expansion between the mounts and optics must be carefully considered. As a result, the mounts we discuss include either RTV elastomeric or flexural elements.

Keywords: Optical and multi-object spectroscopy, optics mounts

1. INTRODUCTION

The conversion of the MMT to use a single 6.5 m primary mirror is underway, and is scheduled for completion by mid 1999. The converted MMT uses a large refractive corrector[1] to provide a fast (f/5) wide-field focus optimized for direct imaging and optical-fiber spectroscopy. Here, we describe the techniques used to mount the optics in this wide-field corrector and two of the wide-field spectrographs that we are developing for the f/5 focus: Hectospec[2,3] and Binospec.[4] These optics are primarily refractive elements ranging in size between 0.2 and 0.8 m. The wide-corrector mounts are discussed in Sect. 2 and those for the Hectospec and Binospec are described in Sect. 3 and Sect. 4, respectively.

2. WIDE-FIELD CORRECTOR CELL

A glass lens can be conveniently bonded to a metal support bezel with pads or a continuous ring of room temperature vulcanizing rubber (RTV). If the metal bezel is chosen to have a coefficient of thermal expansion (CTE) larger than the glass lens, and if the thickness of the RTV bond is chosen properly, this mount can be designed to eliminate thermally induced stress caused by the differential expansion of the metal and glass. This is possible because RTV has a CTE that is much higher than typical metals and glasses so that a thin layer of RTV is able to compensate for the thermally varying gap between the lens

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other author information:
DGF: E-mail: dfabricant@cfa.harvard.edu
RGF: E-mail: rfata@cfa.harvard.edu

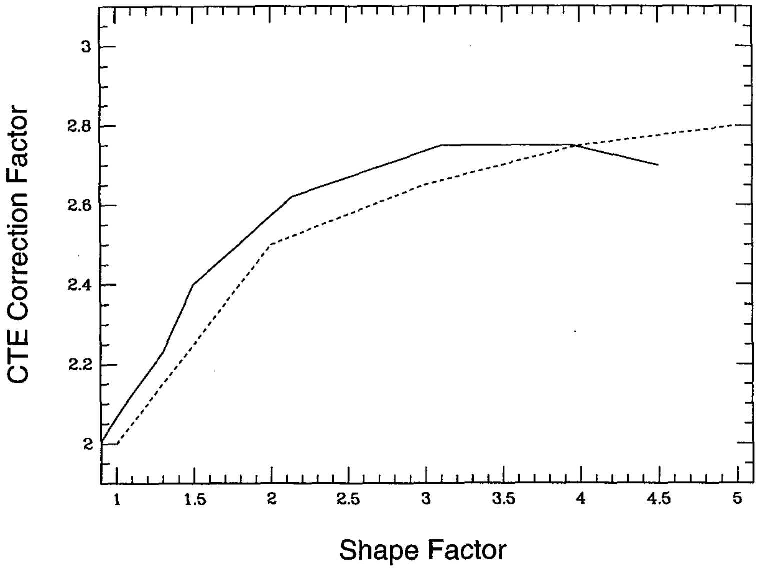

Figure 1. The dependence of the CTE of RTV on shape factor from Lobdell's measurements[5] (solid line) and Finney's calculations[6] (dashed line).

and bezel. This is an appealing approach that we have chosen to use for mounting the wide-field corrector lenses[1] and the Binospec[4] lenses, but its success relies on precise knowledge of the material CTEs.

We use RTV560 (manufactured by GE Silicones) pads in the wide-field corrector to provide axial and radial support of the fused silica lenses in Invar bezels and the atmospheric dispersion compensation prism assemblies (made from bonded pairs of Ohara PBL6Y and S-FSL5Y prisms) in 4130 alloy steel bezels. The lens diameters range between 520 and 830 mm and the prism assembly diameters are 750 mm. The axial RTV pads provide uniform axial support that is sufficiently compliant to absorb minor irregularities in the lens cell. Radial RTV pads are subsequently added to provide additional axial and most of the radial support.[1] The radial RTV pads are sized to minimize thermal stress due to differential thermal expansion, but the the axial supports cannot introduce significant thermal stress.

Accurate CTE values for the glasses and fused silica are provided by the manufacturers. We describe below our measurements of the RTV CTE and the manufacture of custom Invar bezels to achieve a desired CTE. Our ray traces of the wide-field corrector using the deformed lens geometry predicted by finite element models for a 40 °C temperature change demonstrated that knowledge of the material CTEs to 10% accuracy is sufficient.

2.1. RTV Coefficient of Thermal Expansion

The geometry of the RTV pads is important because the physical properties of the RTV such as its CTE[5,6] and compression modulus[7] depend on the shape factor of the pad. The radial RTV560 pads have typical dimensions of 22 mm square and 1.8 mm thick. The shape factor[1] is defined as the ratio of the loaded area (one face, here 22×22 mm^2 = 484 mm^2) to the unloaded area ($4 \times 1.8 \times 22$ mm^2 = 158 mm^2) for a shape factor of 3. Figure 1 shows the measured dependence of the CTE on shape factor for a different GE RTV, RTV11. Finney[6] describes how to predict this behavior using finite element techniques and demonstrates that all rubber-like materials will behave similarly.

We made RTV560 CTE measurements of samples with a shape factor of 4, which we originally intended to use. Lobdell's curve[5] (Fig. 1) shows that the CTEs for a shape factor of 3 and 4 differ by only a small amount. We made three test samples with a 25 mm square by 1.6 mm thick RTV pads bonded between two thin Invar plates. The initial CTE test was performed by Harrop Industries using a dilatometer. The three samples were cooled to -40 °C and then warmed to 32 °C over a four hour period. The results show the strain to be nearly linear over the full temperature excursion with an average CTE of 626×10^{-6} per °C. Another CTE measurement was made by Advanced Materials Laboratory using a capacitance probe in a cryostat. One sample was cooled to -58 °C and warmed to 20 °C over an eleven hour period, yielding a CTE of 716×10^{-6} per °C. We also performed a measurement in house by cooling two of the samples down to -34 °C and measuring the thickness of the samples with a dial indicator. This test yielded CTE values of 658×10^{-6} per °C. The average of all three measurements is 667×10^{-6} per °C, with the most discrepant measurement differing by 7% from the mean.

We can predict the CTE of the unrestrained RTV560 if we divide our measurements by Lobdell's[5] correction factor of 2.75 for a shape factor of 4. We predict a CTE of 243×10^{-6} per °C for unrestrained RTV560, a factor of 1.23 higher than the manufacturer's specification of 198×10^{-6}. Lobdell measured the CTE for unrestrained RTV11 and found it to be 266×10^{-6} per °C, a factor of 1.06 higher than the specified 250×10^{-6}.

2.2. Custom Invar Cell Castings

The corrector cell includes three Invar structures to support the fused silica lenses. In order to maintain a stress-free, athermal mount with thin RTV pads that offer high shear stiffness, we require Invar with a CTE of $\sim2.7\times10^{-6}$ per °C. The largest of these structures is a ring 0.9 m in diameter, 0.4 m high and with a wall thickness of ~1 cm. We were therefore faced with the two challenges of obtaining a large quantity of Invar with the desired CTE and then processing this material into a cylindrical tubes with appropriate machining allowances. We considered three approaches to forming the tubes: (1) casting, (2) rolling flat stock and welding and (3) forging. Any of these processes might alter the Invar CTE, so monitoring the CTE throughout is important. We felt that rolling and welding would be least likely to result in a stable structure and the cost and risk of forging appeared to be high.

We located a foundry (D.W. Clark) that would make the Invar to our specifications and centrifugally cast the material into tubes. The centrifugal casting procedure is shown schematically in Fig. 2. Centrifugal casting produces high strength parts with few voids. Invar is an iron-nickel alloy and its CTE depends on the nickel content. Published data suggested that the desired CTE would be achieved with an nickel content of ~38%. To establish the precise mix, D.W. Clark centrifugally cast four test tubes with nickel contents between 36% and 39%. Test samples were machined from each of the four tubes and heat treated. As expected, the sample with a nominal 38% nickel content produced the desired CTE, so material from its parent tube was used as a reference standard for an emission spectrograph during the production of the final castings. Samples drawn from the molten production Invar were cooled and compared to the reference samples using the spectrograph and the nickel content was adjusted as necessary.

The final castings were heat treated and x-rayed to check for flaws. We machined samples from each casting to measure the CTE and the mechanical properties. Table 1 summarizes the material properties of the three castings. The final CTE, 3.2×10^{-6} per °C, is slightly higher than the target value, but this can be compensated for by slightly increasing the RTV pad thickness.

3. HECTOSPEC SPECTROGRAPH MOUNTS

The spectrograph optical elements are mounted on a 3.7 m by 1.8 m optical bench located in an insulated but unheated room adjacent to the observing chamber. To reduce thermal bowing, the optical bench is designed with an aluminum honeycomb core and Invar facesheets. The optics are mounted in a fixed orientation with their optical axes parallel to the bench surface. The expected temperature changes may

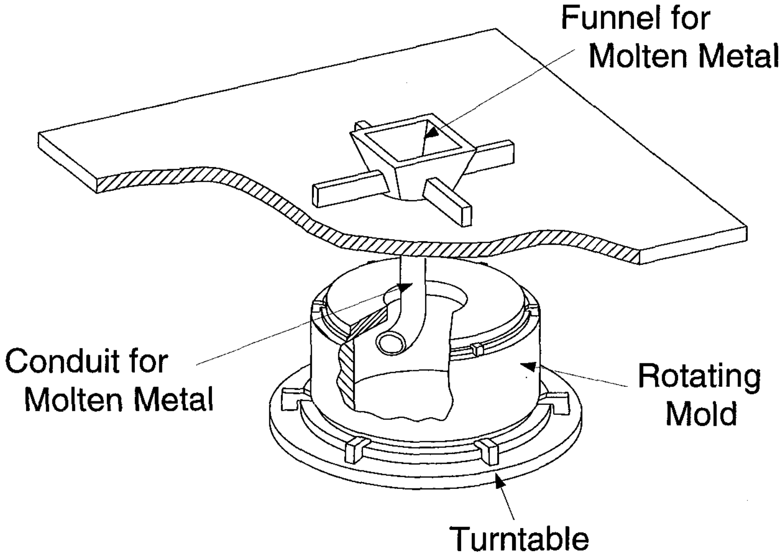

Figure 2. A schematic of the centrifugal casting process.

Table 1. Mechanical properties of the corrector cell castings

CTE	3.13–3.35$\times10^{-6}$ per °C
Tensile Strength	375-381 MPa
Yield Strength	228-241 MPa
Young's Modulus	114,000-130,000 MPa
Elongation to Failure	29-36%

be as large as 40 °C. A minimum fundamental frequency of 50 Hz for each of the mounts was set as a design goal. Since the spectrograph is not subject to varying gravitational loads, the major design challenges are to minimize thermal distortions and to maximize mount stiffness while controlling mass.

The spectrograph includes Zerodur camera and collimator mirrors, 0.63 and 0.58 m in diameter and with masses of 75 and 46 kg, respectively. Both mirrors have a diameter to central thickness ratio of 10:1 that was set by structural and manufacturing considerations. Two fused silica lenses are used to correct camera aberrations; these are 0.41 m in diameter and have masses of ~9 kg.

We considered a number of mounting techniques for the lenses and mirrors before settling on a three point support using tangent flexures. Our ray trace studies of the deformed optical surfaces predicted by finite element models show that the tangential support meets the spectrograph optical tolerances. This mount offers high stiffness, predictable performance and ease of assembly.

3.1. Hectospec Mirror Mounts

Each mirror mount (Fig. 3) consists of three components: (1) the tangential flexures, (2) a support structure and (3) an athermal interface to accommodate the CTE mismatch between the 400-series stainless steel support structures and the Invar optical bench. We chose titanium for the flexures instead of steel because

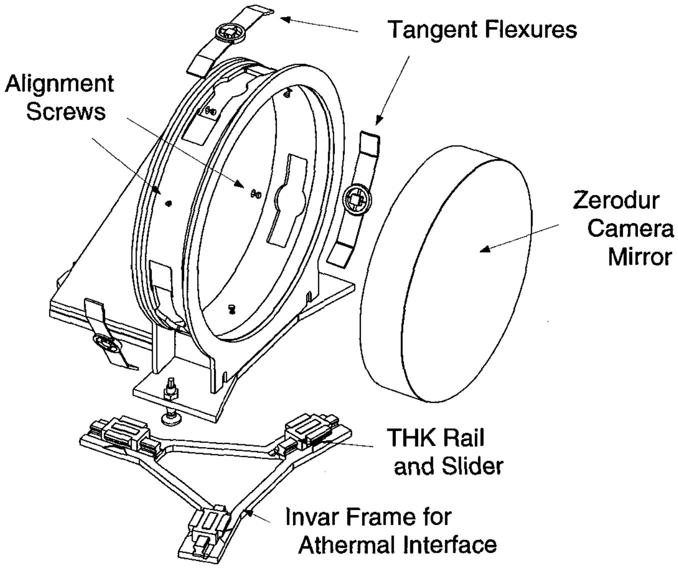

Figure 3. An exploded view of the Hectospec camera mirror mount.

titanium's lower Young's modulus results in thicker flexures which are easier to manufacture. The titanium provides a good CTE match to the 400-series stainless steel support. A flex pivot in the flexure minimizes radial moments which may occur during assembly or operation. A small Invar mounting block or nub that will be bonded to the Zerodur mirror is press fit into the flex pivot. An Invar nub is used to minimize the stress in the epoxy layer (Hysol EA9313) between the nub and the mirror due to the CTE mismatch. The support structure is bolted together from machined plate stock components 6 to 18 mm thick.

The flexures are designed to provide stiffness in the axial and tangential directions and to be compliant in the other four degrees of freedom. They must accommodate approximately 125 μm of (radial) differential thermal expansion between the 400-series stainless steel mount and the Zerodur mirror without introducing excessive stress. The flexures are 2.8 mm thick and 50 mm wide, providing a radial spring rate of 570 N mm^{-1}. The fundamental mode of the camera mirror and flexure system is a 200 Hz axial translation mode. The fundamental mode of the entire camera mount is a 57 Hz side-to-side rocking mode.

For assembly, the mount is rotated by 90° so that the mirror opening is facing up. The mirror is lowered into the mount until its back surface rests on three axial screws adjacent to the flexure locations. Three radial screws are also provided to align the mirror with respect to the support. Once the mirror is properly aligned with respect to the cell, the flexures are attached by bolting the ends of the flexure to the support structure and then injecting epoxy between the mirror and the Invar nub. Shims placed between the flexure and the support structure are used to achieve the desired bond thickness. After the epoxy cures, the axial and radial adjustment screws are removed. The collimator mirror mount is essentially identical to the camera mirror mount shown in Fig. 3. The mirror assemblies are aligned in the spectrograph by placing shims under the athermal interface or on top of the THK sliders.

3.2. Hectospec Lens Mounts

The lens mount (Fig. 4) consists of four types of components: (1) axial blade flexures with press-fit Invar nubs that are bonded to the lenses, (2) lens bezels, (3) a support structure and (4) an athermal interface to the bench. The flexures, bezel and support structure are machined from 400-series stainless steel. The axial

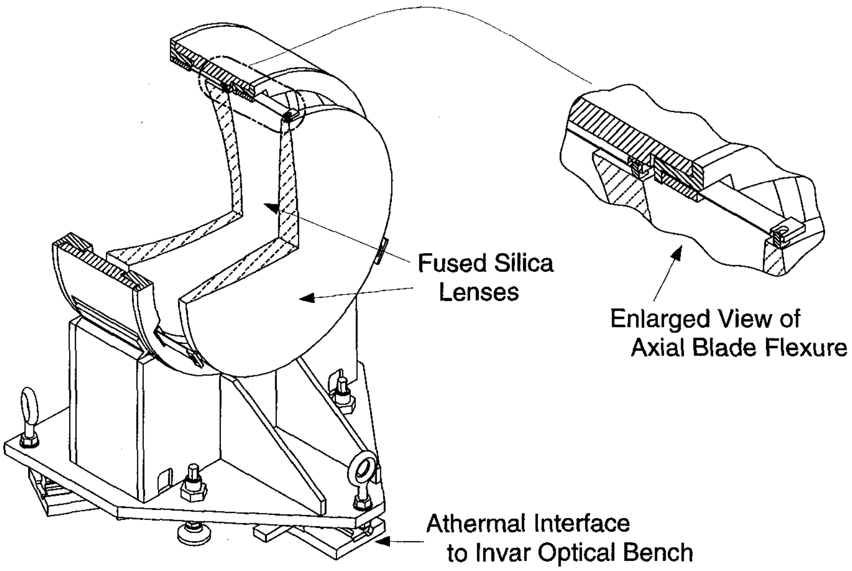

Figure 4. The Hectospec camera corrector lens mount.

blade flexures allow the lenses to be cantilevered in front of the bezel to avoid vignetting the optical beam from the collimator as it approaches the grating. Machined surfaces in the support structure maintain the lens bezels in proper alignment. An Invar nub is press-fit into the end of the flexures to minimize the thermal stresses in the epoxy (as in the mirror flexures). The support structure is bolted together from machined plate stock components 6 to 18 mm thick.

The axial blade flexures are 1 mm thick, 38 mm wide and 64 mm long. They have a radial spring rate of 32 N mm^{-1}. The fundamental mode of the lenses and flexures is a 140 Hz lateral translation mode. The fundamental mode of the complete lens mount is a 75 Hz front to back rocking mode.

An alignment fixture will be required to locate each lens with respect to its bezel during assembly. The flexures are first bolted to the bezel and then epoxy is injected between the Invar nub and the lens. Shims between the flexure and bezel are used to achieve the desired bond thickness. After the epoxy cures, and the alignment fixture is removed, the two lens-bezel assemblies are bolted to the support structure.

3.3. Athermal Interface Between Optical Mounts and Bench

An athermal interface (Fig. 5) compensates for the CTE mismatch between the 400-series stainless steel mounts and the Invar optical bench. The interface uses three THK linear slides between the base plate of the optical mounts and a Y-shaped Invar plate that is bolted to the bench. The THK slides are located so that each carries one-third of the mount's weight. The three THK slides are oriented with their rails pointing towards a point that will remain stationary as the temperature changes. This point is placed directly below the vertex of a mirror to elimate thermally induced focus shifts.

3.4. Performance of the Hectospec Mounts

The optical mounts are all made from stainless steel so that the optics will all decenter equally with respect to the bench as the temperature changes. The athermal mount ensures that the spacing between the optical elements is determined by the thermal expansion of the Invar bench. The stresses and deflections in the optical and structural components resulting from gravitational and thermal loads were calculated using

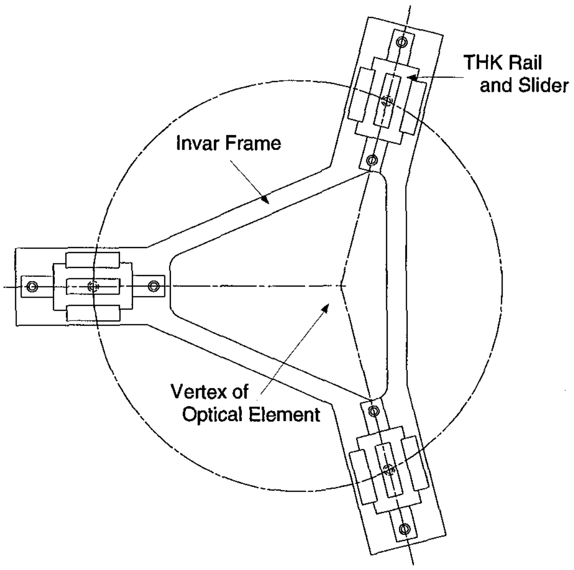

Figure 5. A conceptual drawing of the athermal interface between the stainless steel optics mounts and the Invar optical bench. The center of mass of the mount (with optics) falls at the center of the circle defined by the three sliders. The mount is bolted to the three sliders.

finite element techniques. The stress levels in the Zerodur mirrors and fused silica lenses are <1.5 MPa (220 psi) during normal operating conditions. A maximum stress of 5.3 MPa is developed at the bond between the optics and Invar nub with a 40 °C temperature change. This stress is well below the danger point to optics or epoxy. The maximum stress in the flexures, 64 MPa, is well below the yield stress for these materials. The stresses in the support structures and athermal interface are negligible.

The lens and mirror deformations due to gravity and to 40 °C temperature changes have been predicted by finite element studies and fitted with Zernike polynomials. The amplitude of the largest Zernike terms are shown in Tab. 2. The Zernike fits of the deformed surfaces have been ray traced, and the deformations have been shown to have a negligible effect on the image quality.

Table 2. Peak to peak deformation of the Hectospec optical surfaces

Element and Load	Peak to Peak Amplitude	Dominant Zernike Term
Corrector Lens 1–gravity	0.30 μm	astigmatism
Corrector Lens 1–40 °C	0.038 μm	trefoil
Camera Mirror–gravity	0.015 μm	astigmatism
Camera Mirror–40 °C	0.015 μm	spherical aberation

4. BINOSPEC SPECTROGRAPH LENS MOUNTS

Each Binospec beam contains seven lens groups and all but one are multiplets.[4] The multiplets are oil-coupled. The Binospec lenses have diameters between 165 and 356 mm diameter and masses between

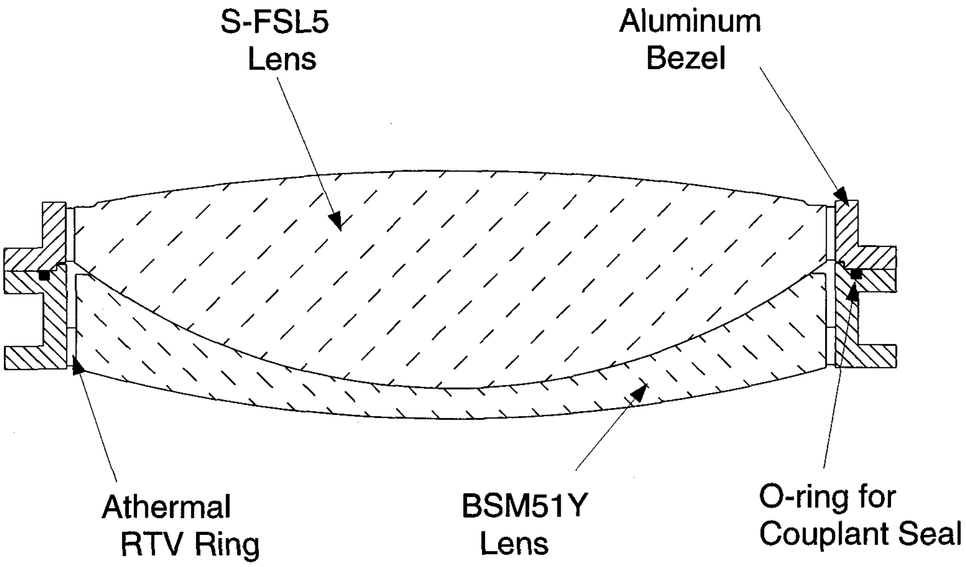

Figure 6. The mounting concept for the Binospec lenses

2 to 16 kg. Binospec is a Cassegrain instrument and its optics will experience varying gravity loads. In addition, the optics will encounter temperatures between -20 and 20 °C. The lenses are made from a variety of optical glasses, CaF_2 and NaCl.

Each lens (except for the single NaCl element) will be mounted to an aluminum bezel with a continuous ring of RTV560 (Fig. 6). The bezels are bolted together to create the multiple lens groups. The geometry of the RTV layer is chosen to athermalize the lens–bezel system and to provide adequate axial stiffness. The mount axial stiffnesses are matched to minimize the relative gravitational displacements of the lenses. The oil couplant is sealed between the lens surfaces by the RTV layer and an o-ring seal compressed between each bezel. A separate fluid reservoir is used between each pair of lens surfaces to allow easier assembly and maintenance.

A separate support and alignment fixture is required to bond each lens into its bezel (Fig. 7). Each lens must be accurately supported while the RTV bond cures to avoid locking in deformations. We find that a minimum of six points are required for proper axial support of most Binospec lenses under a 1 g load. To minimize assembly errors, we adopt the axial support concept from the wide-field corrector: discrete RTV pads.

The axial alignment fixture will be based on a stiff circular ring supported on three load spreaders so three support points are spread to six. The ring is machined flat to provide a planar surface to which the axial RTV pads are attached. If the RTV pads are coplanar to ±25 μm, the axial deformations of the lens are negligible. Since the oil gap between elements is small, a much looser tolerance is not practical. The lens is centered on the fixture and lowered onto the RTV pads. A similar fixture was used by Raytheon Optical Systems to support the MMT wide-field corrector lenses during optical acceptance tests. The lens bezel is placed on the fixture and aligned to the lens with axial and radial adjustment screws. The lens is then bonded to the bezel. Once the RTV cures, the lens-bezel assembly is removed from the alignment fixture.

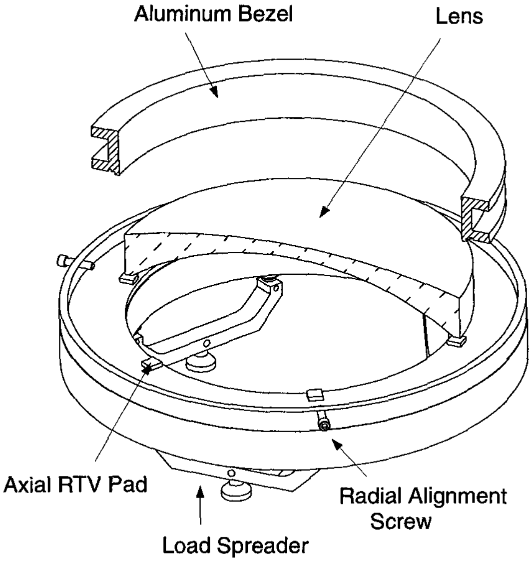

Figure 7. A Binospec lens supported on an axial support fixture. The axial RTV pads have been enlarged for clarity.

The current lens–bezel design achieves a ±10% match in axial stiffness. The fundamental mode for each mount is a 100 Hz axial translation of the lens. The NaCl element cannot be properly athermalized with this approach and it will be mounted with tangent flexures.

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