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Design, fabrication & assembly of the high resolution mirror assembly for NASA's Advanced X-ray Astrophysics Facility

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ABSTRACT

The new and powerful NASA Advanced X-ray Astrophysics Facility (AXAF) has entered the design and development stage and is currently scheduled for launch in the mid-1990s. AXAF will be 100 times more powerful in detecting x-rays, will double the spectral wavelength coverage, and provide ten times the resolution over its highly successful predecessor, the Einstein Observatory. To achieve these goals, AXAF will be equipped with a high resolution mirror assembly (HRMA) consisting of a nested set of six Wolter Type I, x-ray telescopes with outer diameters varying from 0.68m to 1.2m, and parfocalized at a common 10.0m focal length. The mirror mounting, assembly alignment, and orbital thermal stability requirements are nearly an order of magnitude more stringent than those of the HRMA developed for the Einstein Observatory. This paper summarizes the key design features and assembly alignment approach planned to meet these very stringent requirements.

1. INTRODUCTION

AXAF will be a space-based national observatory designed to address fundamental questions in astronomy and physics through celestial observations at x-ray wavelengths. The importance of AXAF results from its high sensitivity to x-rays, exploiting the fact that x-rays are emitted as a result of fundamental processes associated with stellar objects. AXAF is the successor to the Einstein X-ray Observatory flown from 1978-1981 which made significant discoveries in astronomy. Like the Einstein, AXAF will have special mirrors capable of forming high quality images of astronomical objects in x-ray light. AXAF, however, will go far beyond the short-lived Einstein in capability. AXAF will have ten times the resolution, 100 times the imaging sensitivity, and 1,000 times the spectroscopic sensitivity.

In early 1989, AXAF entered the design and development stage, which in the initial years will emphasize the development of its special HRMA. Scheduled for launch in the mid-1990s, AXAF is being developed by a broad-based industry team led by TRW, Incorporated, and including Eastman Kodak Company, Ball Aerospace, and the Perkin-Elmer Corporation. The AXAF configuration appears in Figure 1; key AXAF characteristics are summarized in Table 1. TRW is the prime contractor, responsible for systems engineering and integration, and development of the spacecraft. Kodak is responsible for the development of the telescope including the HRMA. Ball Aerospace is responsible for the star tracking aspect camera and science instrument accommodation hardware. Perkin-Elmer will fabricate the HRMA optics. Boeing Aerospace Corporation will develop the telescope's graphite epoxy optical bench structure for Kodak. The AXAF program is managed by the MSFC for NASA's Office of Space Sciences and Applications with technical support from the Smithsonian Astrophysical Observatory at Harvard College.

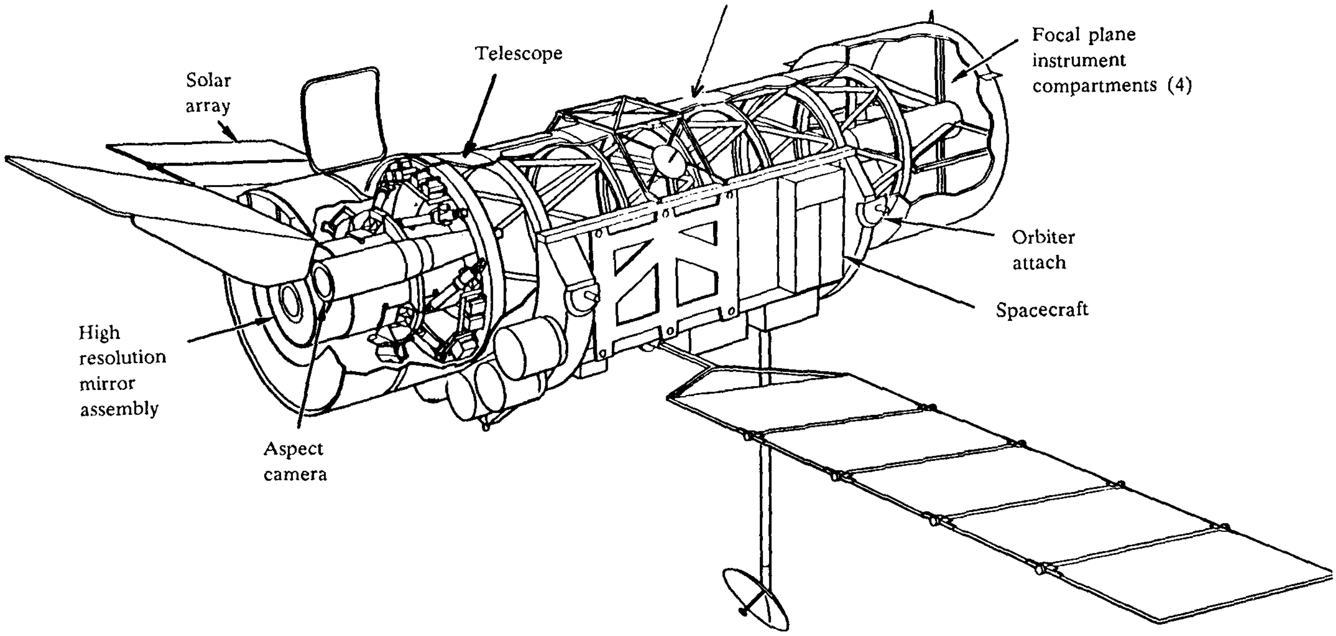


Figure 1. AXAF configuration.

Table 1. AXAF Characteristics

Weight	12,000 kg
Dimensions	Cylindrical, 14m long, 4m diameter
Power	2,500W, orbital average for entire observatory
Data Rate	32 kbps, 24 kbps science
Pointing Accuracy	30 arcsec (3σ)
Pointing Stability	0.5 arcsec per 10 sec period
Post Facto	0.5 arcsec (rms diameter) relative
Aspect Accuracy	1.0 arcsec (1σ radius) absolute
Instruments	2 gratings, 4 focal plane
HRMA Angular Resolution	0.5 arcsec
HRMA Optics	1.2m diameter, 10m focal length, 1 deg field of view
Spectral Range	0.1–10 keV
Orbit	600 km circular, 28.5 deg inclination
Lifetime	15 yr with on-orbit servicing

2. HRMA OPTICAL CONFIGURATION

The mirrors that form x-ray images are a special optical form known as Wolter Type I grazing incidence mirrors. X-rays incident between normal and a few degrees of grazing incidence are absorbed by the mirror. With grazing incidence angles of less than a few degrees, soft x-rays down to a few angstroms in wavelength are reflected and imaged by properly designed optics. Reflectance is further enhanced with heavy metal coatings of nickel or gold. As with conventional optical forms, geometrically perfect images are obtained with aspheric primary and secondary mirrors. The AXAF mirrors are thin-walled cylinders constructed of Zerodur material. The primary mirrors are parabolas; the secondary mirrors are hyperbolas. Because the grazing angle of incidence required is so shallow, the collecting area of Wolter type optics is quite small. Collecting area is increased by nesting concentric sets of mirrors. The AXAF HRMA (Figure 2) uses six sets of grazing incidence optics, parfocalized radially and axially at a 10m focal length. The largest parabola has an inner diameter of 1.2m; the smallest 0.68m. Each mirror is 83.8 cm long; the set of mirrors will weigh 1,500 kg. The AXAF HRMA has a geometrical collecting area of 1,700 sq cm; with structural and thermal components it will weight 2,250 kg. Table 2 summarizes the key optical parameters of the HRMA.

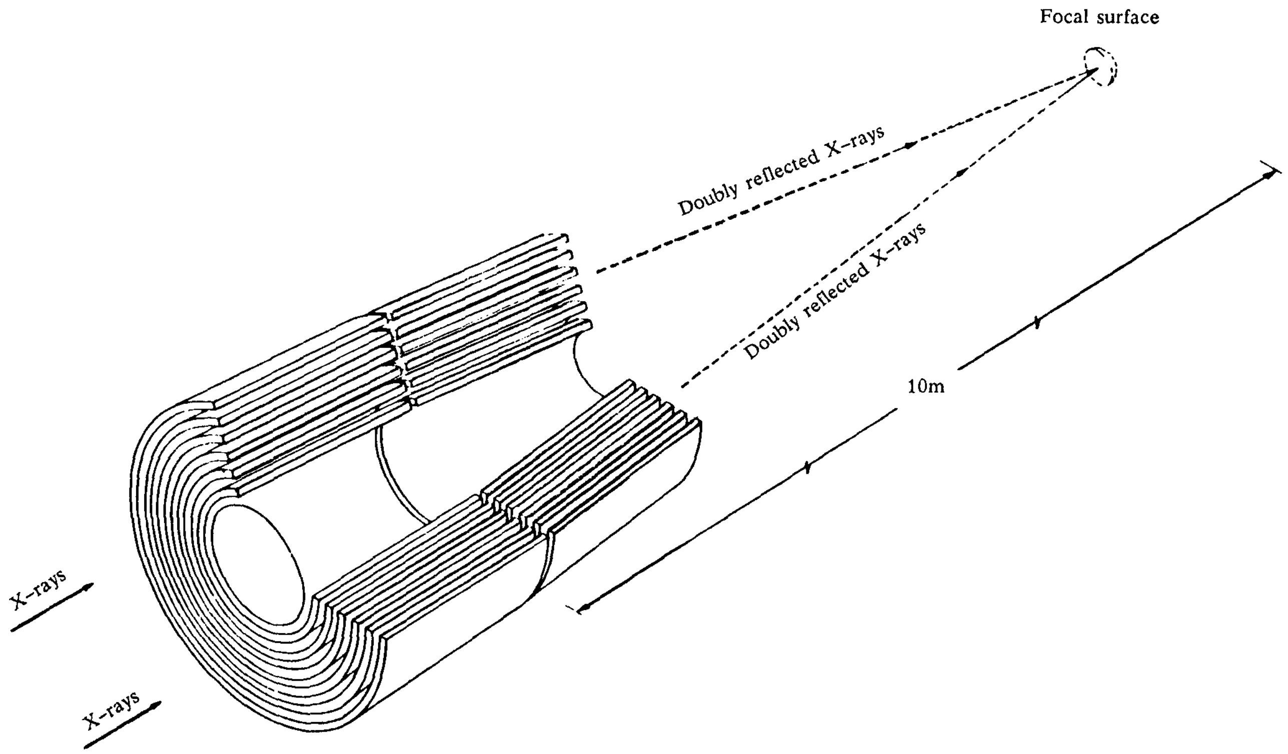


Figure 2. HRMA optical configuration comprises six sets of nested mirror pairs to maximize x-ray collection.

To meet the encircled energy requirements, the precisely polished mirrors must be mounted strain-free and assembled to tight alignment tolerances which must be maintained through launch and the orbital thermal environment. Table 3 is a summary of the assembly/alignment requirements for the HRMA. These alignment requirements correspond to 0.40 arcsec diameter blur circle budget allocation. A significant program challenge is to achieve the alignment accuracies devoid of gravity-induced biases.

Table 2. HRMA Key Optical Parameters

Focal Length	10m
Maximum Diameter	1.2m
Geometrical Collecting Area	1,700 sq cm
Field Of View (Diameter)	1.0 deg
Spectral Range (keV)	0.1 to 10.0
90% Encircled Energy Diameter (At 0.3 keV)	1.0 arcsec

Table 3. HRMA Assembly/Alignment Requirements

Mirror Pair Alignment:		
	Tilt (arcsec)	0.1
	Decenter (μm)	5.0
	Despace (mm)	5.0
Mirror Pair Parfocalization:		
	Axial (mm)	0.025
	Radial (mm)	0.0025

3. HRMA CONFIGURATION

Our HRMA structural configuration, shown in Figure 3, was specifically derived to meet performance requirements with minimum thermal sensitivity and assembly/alignment risk. The critical task of mounting the large, precisely polished mirrors is driven by the need to support the mirrors without strain, but with sufficient strength, alignment accuracy and stability to survive launch and perform in the orbital thermal environment. To minimize the potential for mirror over-constraint and distortion, each mirror is attached (bonded with epoxy adhesive) only at its midline to an ultrastable graphite epoxy (GREP) sleeve with a set of Invar tangential flexures. The mirror support sleeves are a zero CTE, pseudoisotropic, 6.1 mm thick layup of P75S/934 GREP material sealed against moisture absorption/desorption with a 0.05 mm thick aluminum foil barrier. The Invar tangential flexures (Figure 4) provide a low CTE attachment and support the mirrors with the required strength and stiffness while providing the radial compliance needed to accommodate temperature changes and long term material instability.

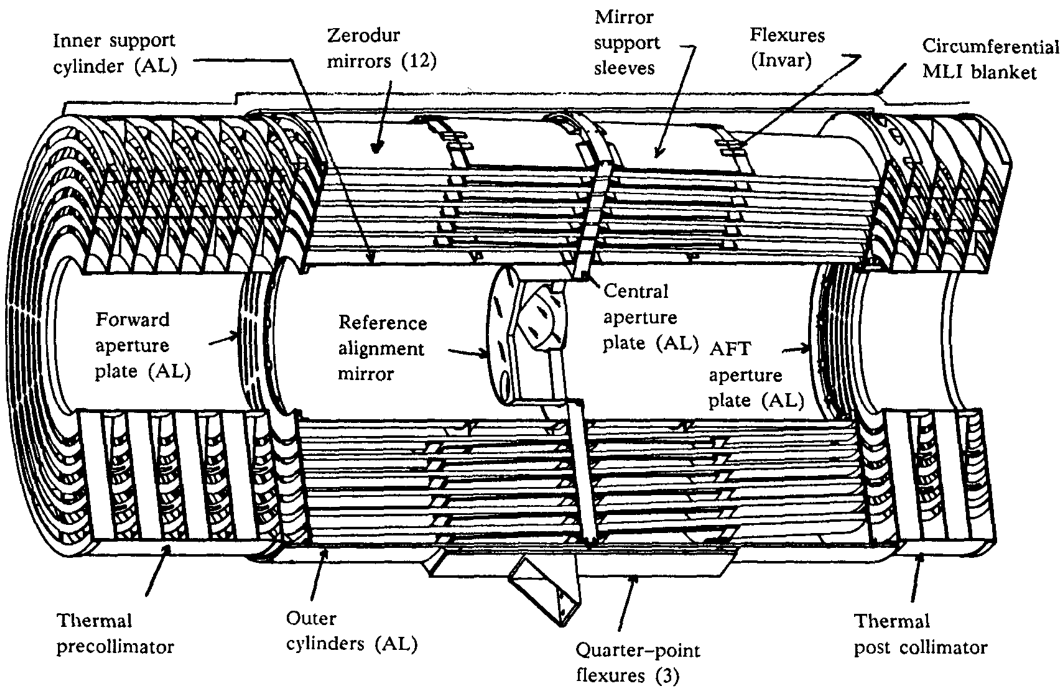


Figure 3. HRMA configuration meets performance requirements with minimum thermal sensitivity and assembly/alignment risk.

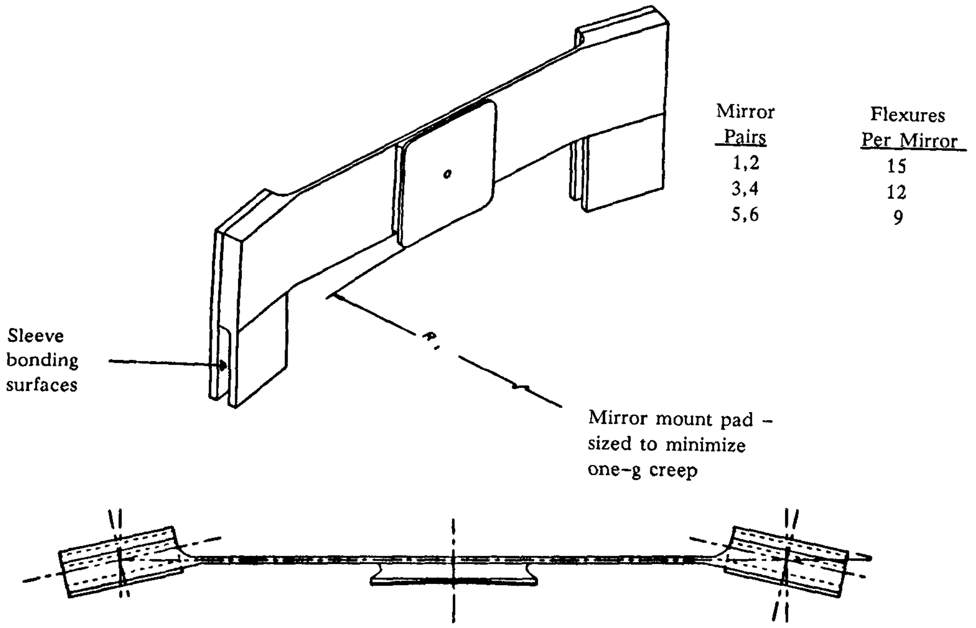


Figure 4. Tangential Invar flexures provide low CTE radially compliant, strain-free mirror mounting.

The mirror support sleeves are attached in cantilevered fashion with epoxy adhesive and precision fittings, to only the central aperture plate. The precise Invar/stainless steel fittings permit strain-free attachment, disassembly, and accurate reassembly of the mounted mirrors (Figure 5). The fittings are preattached mechanically with pins and bolts to the aperture plate. Oversized bolt holes in the fittings permit radial adjustment during assembly operations providing adhesive bondline gap control. Supporting the mirrors in this cantilevered fashion effectively isolates the mirrors from extraneous forward or aft aperture plate loads during assembly, ground handling and orbital operations.

The central aperture plate is high strength aluminum, selected because its high thermal conductivity minimizes aperture plate temperature gradients which can misalign the mirrors. The aluminum inner and outer cylinders support the aluminum forward and aft aperture plates and protect the mirrors. The forward and aft aperture plates are equipped with ghost image control baffles and multizone heater tapes to maintain the mirrors at the assembly room temperature of 20°C. Pre- and post-thermal collimators narrow the view factor to cold space and the 10°C telescope, and minimize heat loss. Heater tapes located on the quarter-point flanges and circumferential, multi-layer, insulation blankets on the inner and outer cylinders minimize diametrical thermal gradients. The HRMA interfaces structurally with the telescope through three quarter-point flexures located on 120-deg centers (Figure 6). This approach provides a long load path to the mirrors and mirror support sleeves isolating the mirrors from distortion and misalignment from external forces.

4. KEY FEATURES THAT FACILITATE ASSEMBLY ALIGNMENT

To meet the stringent assembly alignment requirements, our HRMA configuration was developed with close coordination with assembly alignment planning. The key features that facilitate HRMA assembly are indicated in Figure 7. Each mirror is supported only at the midline, minimizing potential mirror over-constraint during mounting. The mirror sleeves span only half the length of the mirror providing vital access to the critical mirror bond area. The mirror support sleeves attach only to the central aperture plate. This feature permits a modular approach to HRMA build up. We can separate the critical mirror bonding operation from the equally critical mirror alignment operation and we can optimize both. Individual mirror cells consisting of a mirror, flexures, and sleeve can be assembled, aligned, bonded, and verified off-line, prior to HRMA build up. The HRMA assembly operation can be tailored to optimize mirror cell integration and alignment.

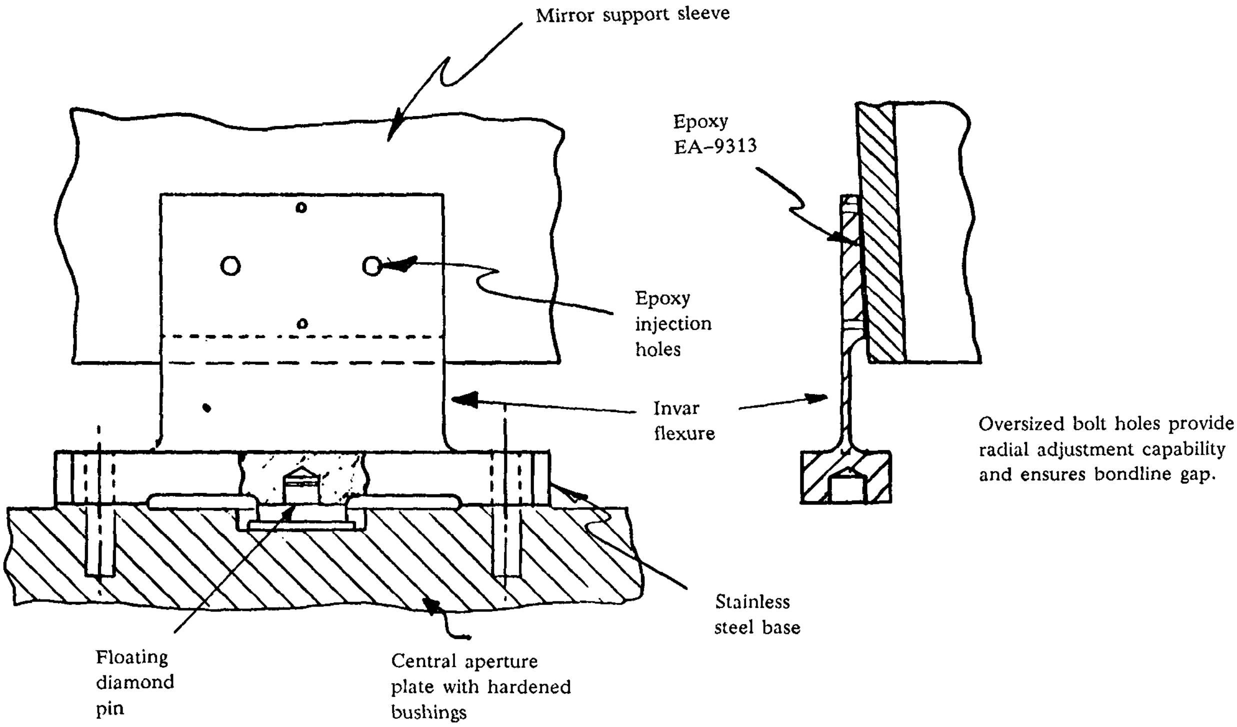


Figure 5. Mirror support sleeve fittings permit disassembly and accurate reassembly of mirror cells.

Attaching the mirror support sleeves only to the central aperture plate effectively decouples the mirrors and mirror cells from extraneous loads induced by the forward or aft aperture plates. This feature ensures that once critical mirror alignment is achieved, the HRMA buildup can proceed with little risk to alignment. The outer cylinders, forward and aft aperture plates, quarter-point flexures, precollimators and postcollimators can be added with little risk to critical mirror alignment. Mechanical fasteners are implemented to permit disassembly of the HRMA down to the mirror cell level. The precision fittings (bonded to the mirror support sleeve during HRMA alignment) and guide pins in the central aperture plate permit precise replacement of each mirror.

5. MIRROR CELL BUILDUP

HRMA assembly begins with the preassembly, verification and sequential installation of mirror cells (mirrors, flexures, and sleeve) beginning with the smallest parabola. Mirror cell buildup is driven by the need to bond the mirror strain-free, while maintaining bond integrity, product and personnel safety, and cleanliness. Mirror cell assembly, Figure 8, will occur in a class 100 environment with the mirrors, flexures and sleeve supported virtually strain-free. The mirror and sleeve will be supported in a vertical orientation on low-strain, multipoint supports. Dual axis tilt and translation stages and a rotary table permit accurate centering and alignment of the sleeve to the mirror. A uniform bondline gap (nominal thickness 0.15 mm) is ensured by the preassembly of cell components for fit checking and final flexure pad machining before bonding. Bond integrity is ensured through inspection of the bond area and strength testing of bonded glass/Invar test specimens. Strain-free mirror bonding will be verified through in-situ phase-sensing interferometry, accurate to 0.25 μinch.

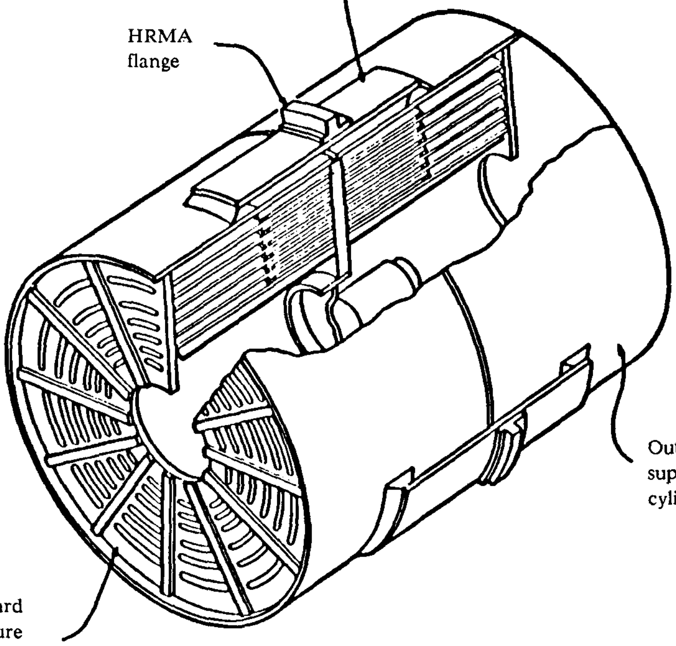
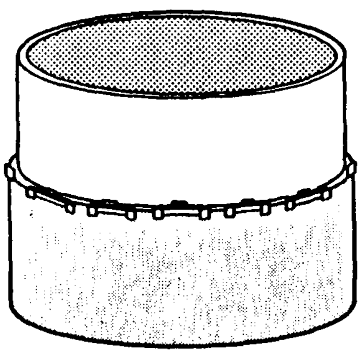
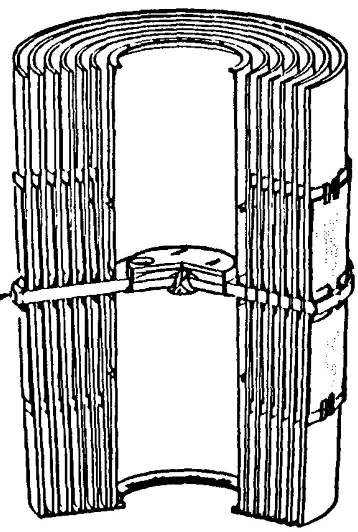


Figure 6. HRMA isometric view.



- Mirrors supported at midline with tangential Invar flexures
- Mirror support sleeves span only half the length of mirrors



- Mirror support sleeves attach only to central aperture plate

Figure 7. Key features that facilitate assembly.

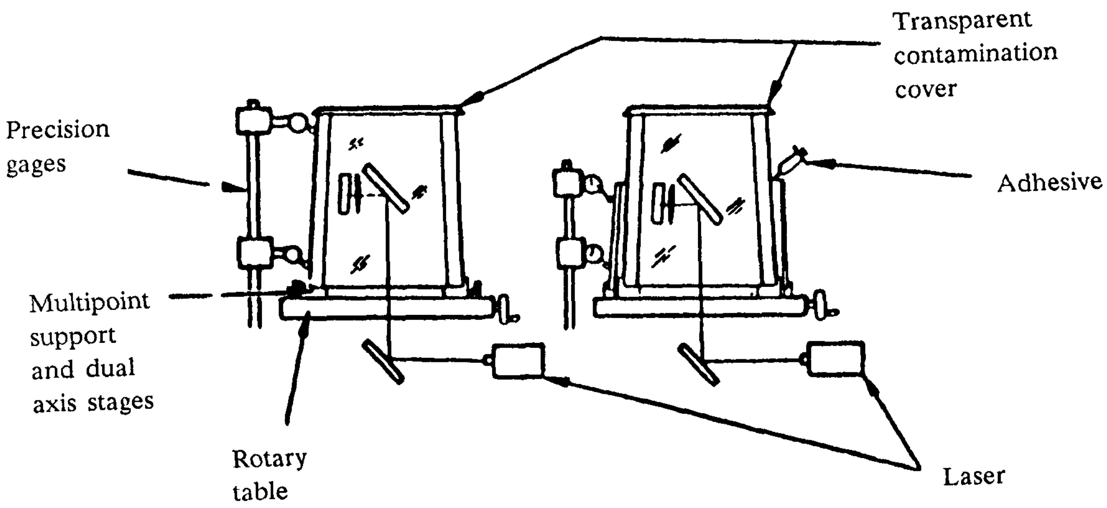


Figure 8. Mirror cell assembly and verification. Critical mirror bonding operation optimized for bond integrity, safety and cleanliness.

6. HRMA ASSEMBLY AND ALIGNMENT

The HRMA will be assembled and aligned in an existing 13m tall, vibration–isolated tower, which is surrounded with a passive thermal enclosure. The tower, located at Kodak's Optical Facility in Rochester, NY, can support a test unit weight of 4,500 kg. The tower will be modified with additional structural members to accommodate HRMA buildup and upgraded to class 100 cleanliness level in the vicinity of the HRMA. The assembly/ test configuration (Figure 9) will use a 1.3m–diameter autocollimating test flat and double–pass testing to evaluate HRMA alignment. To minimize gravity effects, the HRMA will be supported in a vertical orientation to gravity (parabolas on the bottom) with the central aperture plate supported 3.3m above the floor. Two stationary folding flats and a small (30 cm) movable flat provide a parfocal test configuration with rapid change over from the 20m–paraboloid focus to the 10m focus of the HRMA. The alignment sensors include full aperture, focal plane interferometry and a subaperture quadrant detector to level the test setup to gravity, align the mirrors, and parfocalize the ensemble of six HRMA images. During assembly and test operations, personnel are supported from work platforms cantilevered from the tower enclosure or anchored to the floor, to avoid perturbing HRMA alignment or sensor test data.

7. MIRROR CELL INSTALLATION AND ALIGNMENT

Figure 10 illustrates the principal equipment configuration for critical mirror cell (p–cell and h–cell) installation. During mirror cell installation and bonding, the mirrors, flexures, and sleeves must be held nearly strain-free (within test budgets). Inspected and verified mirror cells will be handled with mirror cell handling fixtures that minimize cell distortion by supporting the mirror at its Invar mounting pads with flexure rods, spring loaded in the mirror axial direction. The spring loaded rods ensure a uniform support around the periphery of the mirror but will be stiff enough to make small tilt (<30 arcsec) adjustments required to align the mirrors.

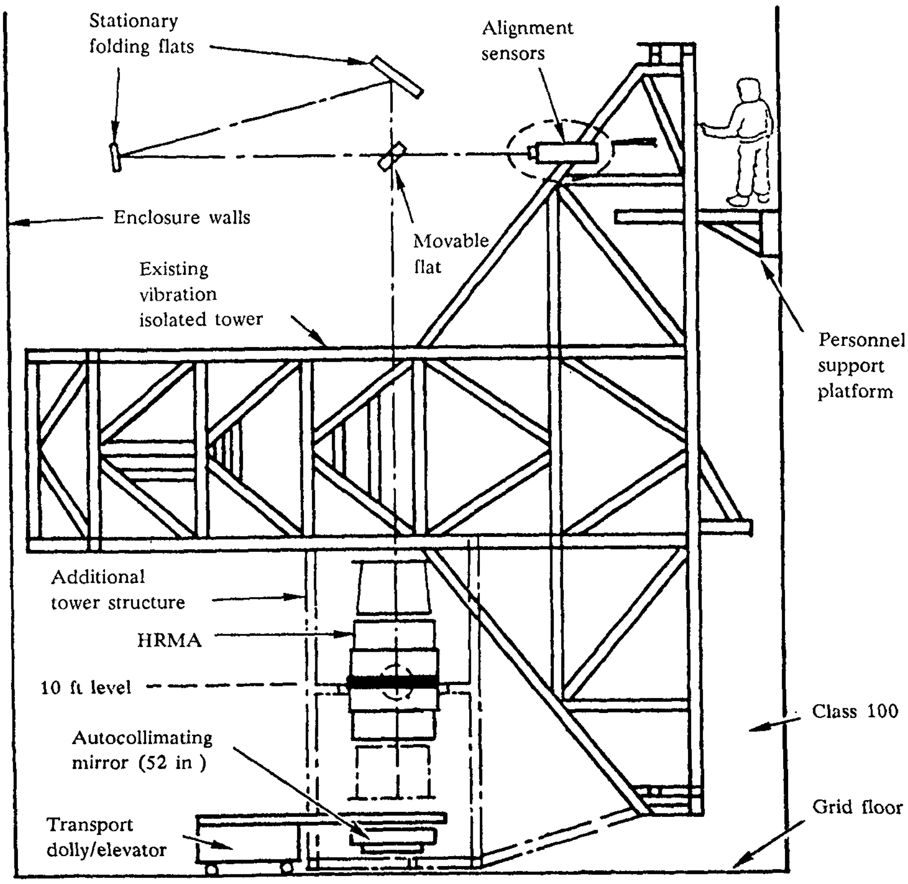


Figure 9. HRMA assembly and alignment configuration. Parfocal test configuration permits rapid change over from paraboloid to HRMA foci with a common test station.

Vertical assembly clearly minimizes gravity distortion of the mirrors, but to preclude one–g biases the central aperture plate must be mounted strain–free and counterweighted as mirrors are added. The central aperture plate will be flexure mounted to the tower support ring and counterweights applied to the central aperture plate through the inner support cylinders. As P–cells (parabola/flexures/sleeve) are installed on the bottom of the central aperture plate (CAP), the weight of the previously installed P–cells and the CAP is counterbalanced by upward loads applied through the upper inner cylinder. As H–cells are installed on the gravity top of the CAP, the CAP is load–compensated by applying an upward force on the lower inner cylinder. NASTRAN analysis has shown that the load compensation force must be accurate to ± 14 kg to meet the axial parfocalization test error allocation. The moment induced in the CAP must be less than 60.0 g–m at the inner cylinder (61 cm diameter) to meet the radial parfocalization test error allocation.

Mirror cells, supported strain–free by mirror cell handling fixtures will be attached to the alignment platform for precise final alignment. The alignment platforms will be controlled by six linear actuators arranged in a triple bipod configuration, providing six–degree–of–freedom control of the mirrors. P–cells will be raised by elevator and attached to the alignment platform. H–cells will be lowered into place with an overhead crane and hydraset and attached to the alignment platform for precise final positioning.

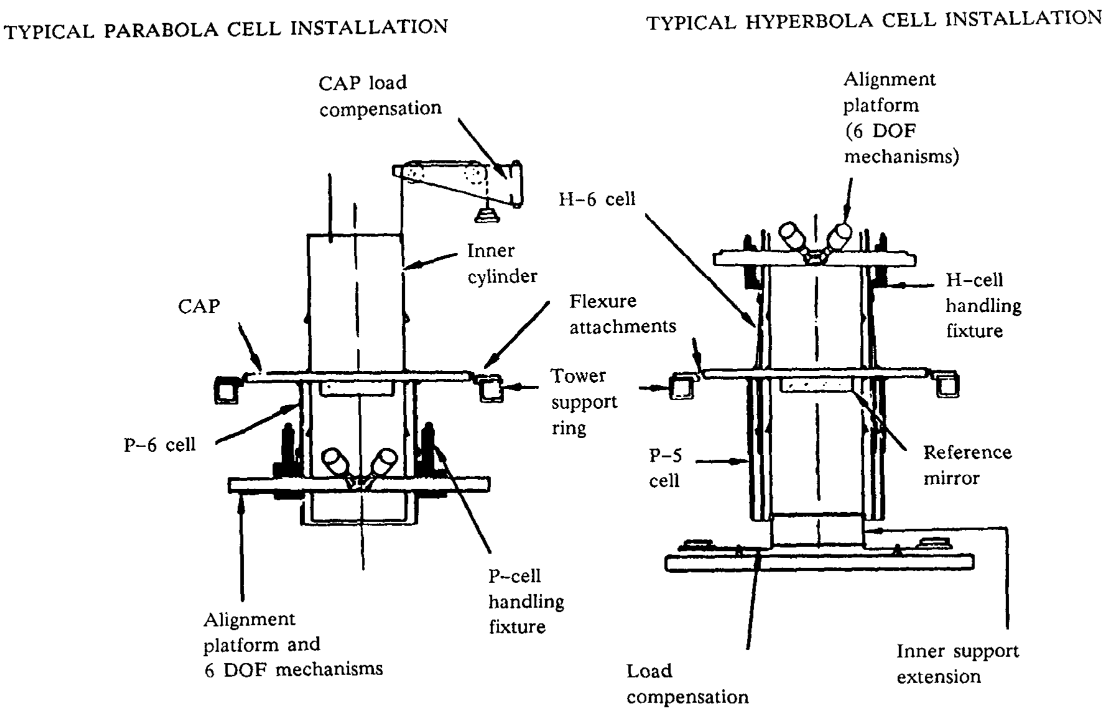


Figure 10. Mirror cell installation and alignment. One-g biases minimized by vertical assembly, CAP load compensation, and strain-free mirror cell attachment.

The mirror support sleeves are attached to the CAP with precision fittings which permit strain-free attachment of the mirror cells and precise reassembly/alignment. The fittings have a hardened, stainless steel base which attaches with bolts and a floating pin to the CAP, and a short Invar flexure which is bonded to the mirror support sleeve. The fittings are initially, loosely fastened to the CAP. After the mirror is aligned, the required bondline gap is achieved by adjusting the fittings radially (using the oversized holes in the fittings) and torquing down the fittings. The sleeve is then bonded to the flexure and a quick setting adhesive (STYCAST) is injected into the space between a floating diamond pin and a retaining slot in the CAP. If the mirror cells must be demated, the fittings remain bonded to the sleeve. Precise reassembly is achieved using the guide pins and the flat mating surfaces of the stainless steel fittings and bushing inserts in the CAP.

The completed HRMA verification program includes vibration stability testing and horizontal alignment baseline testing at Kodak, and horizontal x-ray imaging performance and effective collecting area testing at the Marshall Space Flight Center's X-ray Calibration Facility in Huntsville, Al.