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Alignment design for a cryogenic telescope

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Abstract

This paper describes the alignment approach for the infrared astronomical satellite (IRAS) optical subsystem from initial design to acceptance testing. The constraints imposed by the requirement of maintaining alignment at 300K and 2K, in a 1-g and 0-g gravitational field, during warm and cold vibration, and during various stages of assembly, are discussed. The paper concludes with the methodology of applying NASTRAN finite element analyses to the alignment design, followed by the verification of the accuracy of the design with the test results.

Introduction

The United States, the Netherlands and the United Kingdom are jointly sponsoring the infrared astronomical satellite (IRAS) program to conduct astronomical surveys in the 8 μm to 120 μm spectral region. The satellite, containing a cryogenically-cooled telescope and detectors, will be placed into a 900 km circular, polar orbit and will scan the sky with its orbital motion. The optics and detectors will be cooled with superfluid helium to approximately 2K with the satellite carrying a sufficient helium supply to operate for one year.

This paper describes the alignment approach which was applied to the optical subsystem (OSS) from the initial design through acceptance testing.[1] Maintaining alignment through various stages of assembly as well as adverse environmental conditions was a major challenge in the initial design. The paradox of cryogenically-cooled instruments lies in the fact that they must be manufactured and assembled in a warm environment in a 1-g gravity field, yet operate cold in a zero-g field. A further restriction on IRAS is that it had to remain in alignment after room temperature vibration while at Perkin-Elmer and, in addition, remain aligned under cold vibration during full system testing and launch. Designing for any one of these configurations is routine, but designing for all conditions poses a considerable challenge for the system designer. Testing to date indicates that this challenge has been met.

The 154 lb OSS consists of the mirrors and metering structure, four sets of baffles, and the interface ring to the superfluid helium dewar. The optical system is a Ritchey-Chretien two-mirror system with a 24-inch diameter primary mirror. The mirrors and metering structure are constructed entirely from optical grade beryllium, except for three titanium flexures which attach the primary mirror to the baseplate, the main structural member. Of the four aluminum baffle assemblies, three are flexure mounted to the beryllium baseplate and one is flexure mounted to the secondary mirror. Finally, the entire OSS is flexure mounted to an aluminum interface support ring which is hard mounted to the aluminum dewar. When launched, the OSS will contain 50 flexure assemblies with 86 flexure surfaces.

System alignment issues

System alignment must be considered in the earliest stages of design. A proper identification of alignment issues early in the program permitted us to develop a methodical, optimized design. The critical issues for IRAS (Table 1) were used to derive the specific design requirements and constraints discussed below.

The first alignment issue we considered was the constraint of maintaining alignment in a 1-g field while the optical axis is horizontal. This constraint was dictated by the cryogen test chamber which could only accommodate the OSS in a horizontal orientation.

The preferred orientation for testing a large optical system is with the optical axis vertical such that gravity affects the system symmetrically. The dominant aberration introduced by gravity in this orientation is defocus due to the change in curvature of

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Table 1. Critical IRAS Alignment Issues

Issues	Major Design Implications
Perform all testing in a 1-g gravity field with the optical axis horizontal.	● Maximize stiffness ● Mount elements at the center of gravity
Maintain optical alignment during various stages of partial assembly, as well as full assembly.	● Flexure mount the primary mirror ● Stiffen the baseplate
Maintain optical alignment through room temperature vibration testing as well as 2°K testing and launch.	● Pinned joints
Maintain image quality during room temperature testing and testing at 40°K.	● Flexure mount all dissimilar metals

the primary mirror and despace of the primary and secondary mirrors. The system can be stiffened and balanced to accommodate this aberration quite easily.

However, the required horizontal orientation led to other design considerations. As shown in Figure 1, the entire OSS is cantilevered off the interface support ring, which is located at the back end of the OSS. Gravity tends to affect alignment when in this orientation by:

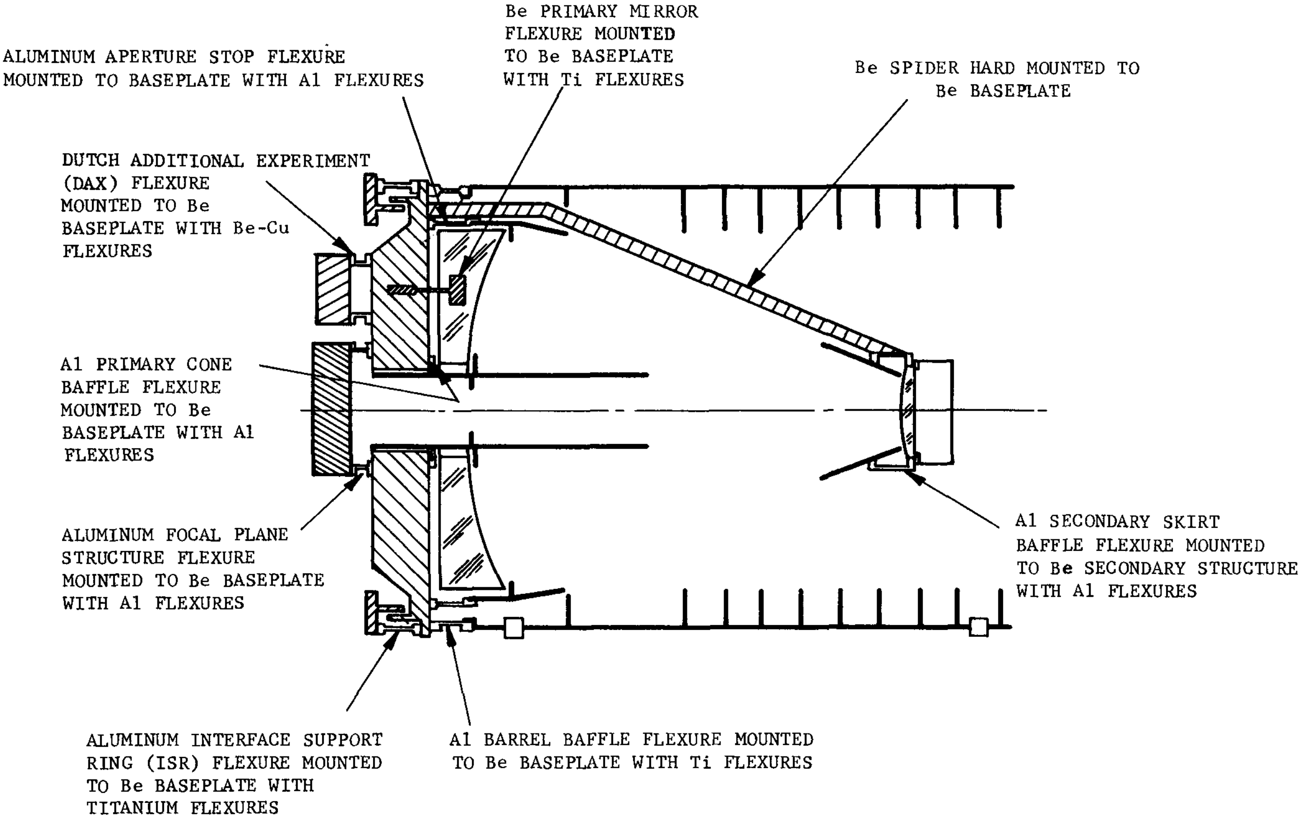


Figure 1. Critical load members on the baseplate

- Causing the primary mirror to sag asymmetrically, generating astigmatism.
- Causing the baseplate to distort, thus shifting the secondary mirror with respect to the primary mirror.
- Causing the secondary mirror to tilt and sag, developing coma and pointing errors.

These errors are asymmetric and highly dependent on the mechanical design and mount locations. This alignment issue led to a design requirement of maintaining the gravity-induced aberrations within tolerance margins by (1) selection of the rib patterns in the lightweighted primary mirror and baseplate, (2) location of the primary mirror mounts, (3) configuration of the primary mirror mounts, and (4) configuration of the secondary mirror support structure.

The second alignment issue arose from manufacturing considerations. The lightweighted beryllium baseplate is the main support structure for both the optical telescope metering structure and the baffles. During the manufacturing, assembly and test phases of the program, the alignment of the OSS had to be maintained; yet in each of these phases, the degree of assembly, and thus the loads on the baseplate, was different. The varying loads on the baseplate would induce distortions which could be transmitted to the primary and secondary mirrors. The obvious solution to this problem was to stiffen the baseplate such that its distortions were minimized. However, launch weight constraints hampered this approach. Analysis of the optical design showed that the primary mirror was most susceptible to induced distortions, so the decision was made to isolate the primary mirror from the baseplate as much as possible. Therefore, the manufacturing alignment issue resulted in stiffening the baseplate and the flexure mounting the primary mirror.

The third, and most troublesome, alignment issue was the environment. Again, weight considerations dictated that the OSS be short and compact, which led to an optical design which was relatively sensitive to alignment, even though its image requirements were not too severe. Once the system was aligned at room temperature, it had to maintain its alignment in the warm and cold states and through warm and cold vibration. To satisfy this requirement, all joints had to remain tight, both warm and cold.

Implementing the tight-joint philosophy was made difficult by the thermal environment. The main source of difficulty was large differential contractions occurring at the bimetallic joints. All bimetallic connections between the major components were made with flexures to accommodate differential contraction, and the flexures were pinned to the components.

Design analyses approach

Early planning for alignment included the development of a preliminary design from which a tolerance analysis and loads analysis were performed. The results of these analyses were used to evaluate the results of the three NASTRAN finite element analyses during which iterations of the design led to optimized configurations. Following the analyses, the remainder of the alignment program was relatively routine.

A key feature of the approach was to split the NASTRAN analysis into three independent analyses. The first analysis was to design the primary mirror and its flexures. Next the baseplate was designed. Finally, analysis of the secondary mirror support structure led to an optimum secondary mirror support structure design.

Constraints and loads

The origin of the design loads is illustrated in Figure 1. Seven assemblies are flexure mounted to the baseplate and one is hard mounted. All flexure attachments, except for the primary mirror, connect beryllium-to-aluminum components.

The resultant complexity of the load conditions is apparent in Table 2. The surface quality of the primary mirror was always measured with the mirror attached to its baseplate, the baseplate attached to the interface support ring, and the combination oriented such that the mirror was vertical. During the manufacturing phase, this arrangement satisfied the requirements of repeatability of the mount in that no mount-induced distortions were observed. For warm testing, the flexures experienced no bending except those induced by gravity. However, the first complication arose upon cold testing. The primary mirror interferograms were made at 40°K where differential contraction between aluminum and beryllium created substantial bending moments at the interface support ring flexures. During cold testing, a small amount of distortion was observed in the interferogram but, due to its localized nature, was attributed to inhomogeneity in the CTE of the beryllium rather than to mount-induced distortion.

Table 2. Load Conditions Affecting Alignment

Program Phase	Elements Involved	Environment	1-g Loads	Cryo-Induced Flexure Bending Moments
Manufacture	ISR (Interface Support Ring)	Warm	✓	
	Baseplate	Warm	✓	
	Primary	Warm	✓	
	ISR	Cold	✓	✓
	Baseplate		✓	
	Primary		✓	
Align	ISR		✓	
	Baseplate		✓	
	Primary	Warm	✓	
	Secondary		✓	
	Aperture stop		✓	
System Test	ISR		✓	
	Baseplate		✓	
	Primary		✓	
	Secondary		✓	
	Barrel baffle	Warm	✓	
	Primary cone baffle		✓	
	Secondary skirt baffle		✓	
	Aperture stop		✓	
	ISR		✓	✓
	Baseplate		✓	
	Primary	Cold	✓	
	Secondary		✓	
	Barrel baffle		✓	✓
	Primary cone baffle		✓	✓
	Secondary skirt baffle		✓	
	Aperture stop		✓	✓
On-Orbit Operation	ISR			✓
	Baseplate			
	Primary			
	Secondary			
	Barrel baffle	Cold		✓
	Primary cone baffle			✓
	Secondary skirt baffle			
	Focal plane			✓
	Aperture stop			✓
	Dutch Additional Experiment			✓

The next complication arose during alignment. The secondary structure and aperture stop assembly were attached to the baseplate before the secondary mirror was aligned to the primary mirror. The system had to allow for alignment in this configuration even though the assembly was only partially complete, thus experiencing only part of the gravity loads and none of the cryogen-induced flexure loads.

Finally, during operation, the system had to remain aligned through cold launch, with all cryogen-induced flexure moments, and with no gravity loads.

NASTRAN finite element analyses

The primary mirror, baseplate, and secondary mirror structure configurations were optimized separately using NASTRAN finite element models. An optimized structure is defined as having minimum weight, natural frequency well above 100 hz, six-degree-of-freedom motion at all critical optical element mounting pads within tolerances, and stresses below microyield. The analyses were performed iteratively by (1) assuming a design, (2) performing the NASTRAN analyses, and (3) improving the design where problems were indicated. The following is a summary of these analyses.

Primary mirror NASTRAN analysis. The primary mirror and its flexure mount were optimized first to minimize susceptibility to mount-induced and g-released distortions. The objectives of the analysis were to determine the mirror lightweighting rib pattern and the radial and axial locations of the mount attachments.

The NASTRAN model consisted of 336 nodes and 252 plate elements representing the mirror's front face supported by 276 beam elements for the radial and circumferential ribs.

The final mirror design is shown in Figure 2. After the initial computer run, we recognized that the edge of the mirror suffered most from sagging. To counteract this, the support points were moved radially outboard at a 23.36 cm (9.2 inches) radius. In addition, the two intermediate circumferential ribs, which transfer lateral loads to the mount, were adjusted outboard. To minimize out-of-plane bending, the support points were located at a point that passes through the mirror center of gravity 4.42 cm (1.74 inches) from the back surface.

When the changes were incorporated into the NASTRAN program, it was rerun. The resulting gravity-induced deflections are shown in Figure 3. Note that these deflections are absolute values, and the rigid body translation caused by mount deflection must be subtracted. The net deflection is 6.43×10^{-6} cm (2.53×10^{-6} inches) peak-to-peak. The results of a 1-g deflection in the Z direction are shown in reference only.

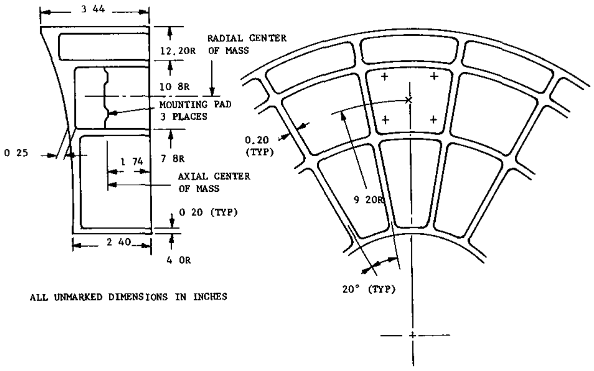
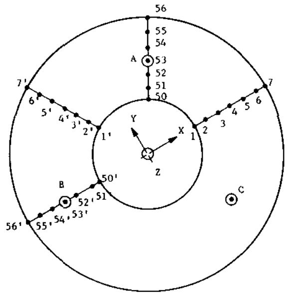


Figure 2. F/1.5 primary mirror



Gravity X Direction				Gravity Z Direction	
Node	Z	Node	Z	Node	Z
7	1 79	7'	-0 89	7	-19 09
6	1 66	6'	-0 83	6	-18 95
5	1 53	5'	-0 76	5	-18 82
4	1 23	4'	-0 62	4	-18 55
3	0 95	3'	-0 47	3	-18 30
2	0 59	2'	-0 30	2	-18 08
1	0 26	1'	-0 13	1	-17 90
50'	-0 36	50	0 18	50	-17 70
51'	-0 30	51	0 15	51	-17 17
52'	-0 20	52	0 10	52	-16 43
53'	0 02	54	-0 008	54	-15 67
55'	0 07	55	-0 04	55	-15 66
56'	0 10	56	-0 06	56	-15 59
Mount B	-0 10	A	0 05	Mount	-15 64

Figure 3. Gravity effects on flexural supports surface displacements (in micro-inches)

To isolate the effects of the mirror mounts, another computer run was made that assumed the mirror was supported on ideal mounts. The resultant mirror surface errors remained unchanged.

The data generated from the NASTRAN model produced gross, absolute surface displacements. A portion of this error represents overall mirror decentration, defocus and tilt. To evaluate this effect, the NASTRAN-generated deflections were entered into a Perkin-Elmer curve-fitting program, whose results not only removed decentration, defocus and tilt, but also calculated the residual rms error.

The final design iteration produced a mirror having the following performance characteristics:

● Decentration	: < 39 µm
● Tip	: 13 arc-sec
● Residual Surface Error	: 0.020λ rms (λ = 0.6328 µm)

The budget for the 1-g residual surface error is λ/10 rms at λ = 0.63 µm.

Baseplate NASTRAN analysis. The baseplate configuration was optimized against the load conditions of Table 2; 33 load-bearing support points on its surface were considered. In order to minimize the strains induced by the supported masses, two fundamental philosophies were established: minimize load paths and maintain symmetry of loading. Figure 4 shows the rear of the baseplate mounted in a support fixture. Where latitude existed, masses were placed as close to the support points (OSS mounts) as possible. Note the location of the secondary struts, primary cone baffle, and primary mirror mounts. The mounting arrangement and location of the Dutch Additional Experiment (DAX) and focal plane assembly were customer-directed.

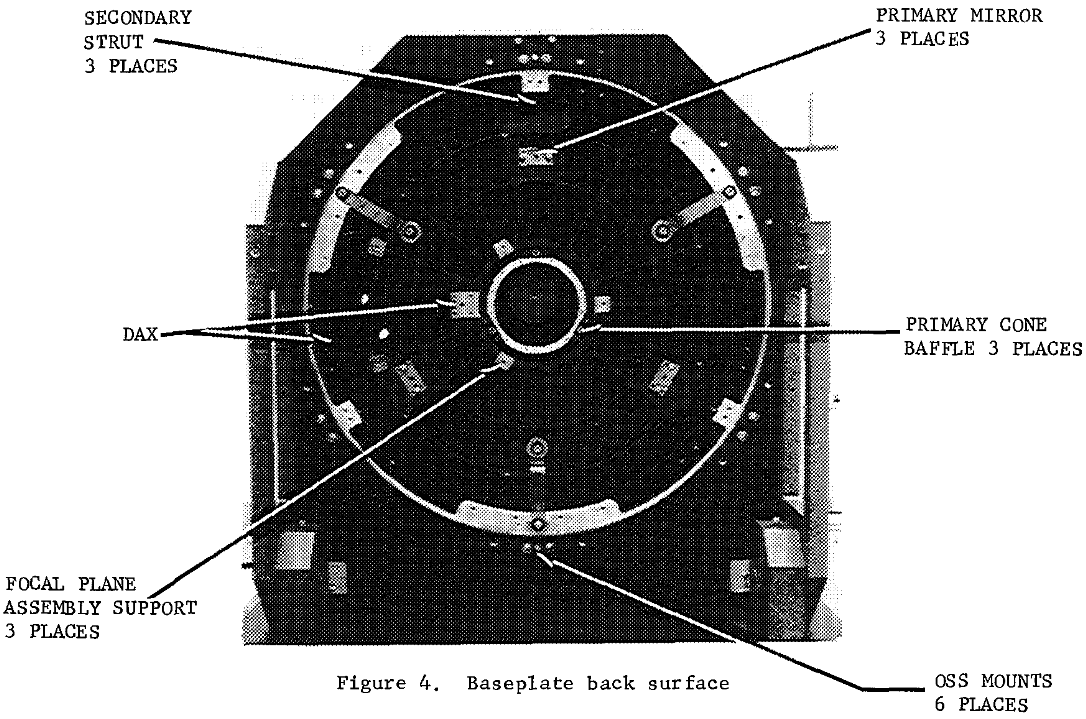


Figure 4. Baseplate back surface

A gravity-loading matrix was established for three orthogonal axes for every mass support point. The support reactions for the primary mirror and secondary mirror support strut were determined from individual NASTRAN analyses; all other loads were obtained by hand calculations.

A resultant stress distribution and the six degrees of displacement were determined for each of the mass support points. Final relative displacements of the optical elements were determined from a combination of individual members and baseplate displacements.

Two iterations were performed to optimize baseplate configuration, weight and stiffness. In order to minimize cost, the initial design had the lightweighted pockets only on one side of the baseplate and a circumferential lip which interfaced with the OSS mounts. This configuration produced excessive stresses in the lip and too great a flexibility. The evolved redesign placed the web on the section's neutral axis, requiring pockets on both surfaces and removal of the lip. The OSS mounts were reconfigured to tie directly into the baseplate's outer ring. Local interface mounting areas were also reinforced.

An early attempt to limit the number of OSS mounts to three (to eliminate possible overconstraint) proved fruitless since the frequency requirement could not be met. Six mounts were required; by controlling the coplanarity of their interfacing plane, the induced stresses were minimized.

Secondary mirror support structure NASTRAN analysis[2]. The analysis of the secondary mirror support structure was performed to determine the configuration of the struts to minimize obscuration while providing a high, natural frequency and minimum misalignment in a gravity field. The minimum allowable natural frequency was 160 hz in order to decouple the secondary structure from the system structural resonances. The tolerances for gravity release were primary/secondary mirror decenter of 27.8 μm, despace 7 μm, and tilt 33.4 arc-sec.

The resulting strut configuration is shown in Figure 5. The 1-g deflection of the secondary mirror was decenter of 7.47 μm, despace of 0.5 μm, and tilt of 6.3 arc-sec. These values are well within the tolerance allocation, implying that the strut configuration could be optimized further. However, the minimum natural frequency was 179 hz compared to a design requirement of 160 hz. This correspondence was considered close enough so that no further optimization was warranted.

The NASTRAN model consists of three bar-element structures fixed at one end and joined at the other by a rigid equilateral triangle, which represents the secondary mirror. Figure 6 is a computer-generated perspective projection plot of the three-legged structure. Each leg of the structure is represented by a series of bar elements whose grid points are shown and numbered. Note that the rigid triangle is formed by grid points 18, 36 and 54. Its centroid supports the concentrated 3.18 Kg (7 pound) mass. Grid points 1, 19 and 37 are rigidly attached to "ground". The X-axis in Figure 6 represents the optical axis; the Y-axis is negative gravity.

This model was exercised to determine fundamental frequencies, six-dimensional displacements of each grid point, support reactions, and maximum principal stresses.

One-g inertia loads, consisting of the structure self-weight and a 3.18 Kg (7 lb) end load, were applied in each of the three orthogonal axes. The resultant stresses and the performance at the secondary mirror were then determined. An eigenvalue analysis, which generated mode shapes and fundamental frequencies, was also performed.

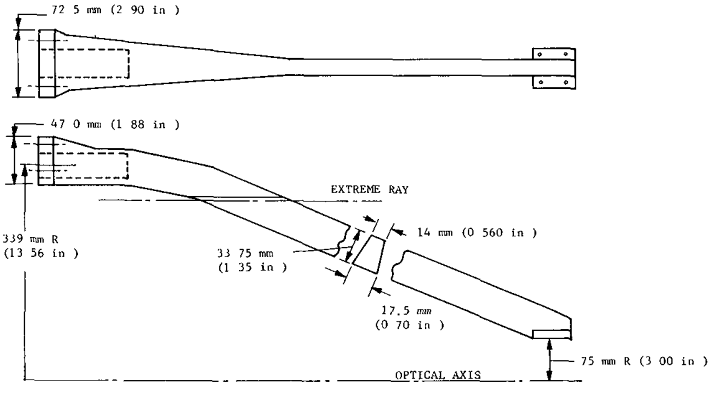


Figure 5. Secondary strut

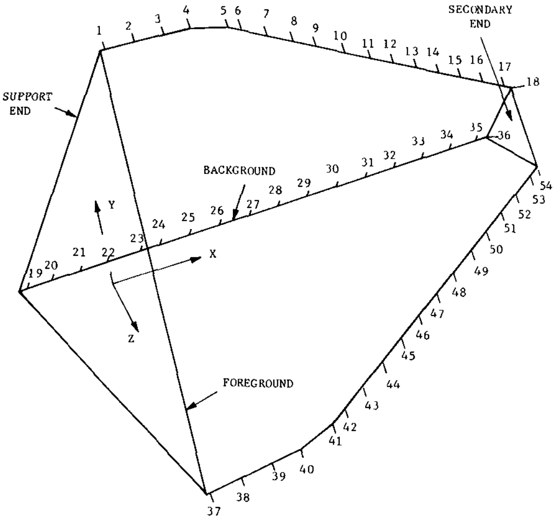


Figure 6. Grid point layout - perspective

Test results

The optical subsystem has been acceptance tested and delivered for integration in the dewar. Alignment was measured before and after vibration in three orthogonal axes, while cooled at 40°K, and again after cryogenic testing. In addition, the primary mirror surface figure was measured in both the warm and cold conditions. The results are shown in Table 3.

The first test of the adequacy of the design occurred during the survey of the performance of the primary mirror at cryogenic temperature. This survey was made early in the mirror manufacturing cycle to determine whether the inhomogeneities in coefficient of thermal expansion of the beryllium material were large enough to distort the mirror surface beyond tolerances when cold. The mirror was flexure mounted to the baseplate, the baseplate was flexure mounted to the aluminum interface support ring, and the support ring was hard mounted to a cold plate, thus simulating the thermal/mechanical interface in the IRAS dewar. The 0.1λ rms wavefront distortion, which occurred when the mirror was cooled to 30°K, was attributed to localized CTE inhomogeneities rather than mount-induced strains, indicating that the alignment designs were adquate. The unpredicted change in focus when in the cold condition was attributed to uncertainty in the integrated expansion coefficient at 30°K. The permanent shift in focus when the mirror was warmed to room temperature may be a stress relief (amounting to 0.01%) or may be measurement uncertainty.

Table 3. Measured Alignment Performance

Test Item	Test Conditions	Changes in Wavefront Quality	Change in Focus
Primary mirror	Warm to cold	0.1λ rms	1.28 mm (1.08 mm predicted)
Primary mirror	Before and after cold test	No change	0.119 mm
Optical subsystem	Before and after warm vibration	0.04λ rms on-axis 0.53λ rms off-axis	0.28 mm ±0.2 mm
Optical subsystem	Before and during cold test	0.5λ rms (on-axis)	8.5 mm
Optical subsystem	Before and after cold test	0.03λ rms	0.61 mm

$\lambda = 0.6328\mu m$

The second test of the alignment design occurred during warm vibration of the assembled optical subsystem. Changes in wavefront quality and focus were observed. These changes were only slightly greater than the measurement accuracies and are attributed to "settling in" of the numerous joints.

The largest change in alignment occurred when the optical subsystem was cooled to 40°K, where the predominant distortion was 0.7λ rms of coma. The exact cause of this distortion was not determined, but it most likely was due to decenter and tilt of the secondary mirror with respect to the primary mirror. The return of the wavefront quality to essentially its ambient value after the cold test implies that stress relief was not the cause of the distortion.

The shift in focus of 8.5 mm warm-to-cold was greater than originally predicted. However, a review of the original prediction model indicated that it was too simplistic and did not utilize the most probable values of integrated expansion. The focus was measured at a temperature of ≈ 40°K; an additional 0.1 mm focal shift is anticipated when the optical subsystem is cooled to 2°K. To compensate for this focal shift, the focal plane will be aligned to the optical subsystem such that it is in focus when cold.

Conclusions

The IRAS optical subsystem was designed to operate in an adverse environment. Conservative design practices were used because of the variety of environments to which it will be exposed and because of uncertainties in material properties at 2°K. Measured alignment performance after environmental testing was degraded somewhat from predictions, but the degradations are within acceptable limits for the IRAS mission.

Acknowledgments

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