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Design of infrared astronomical satellite (IRAS) primary mirror mounts

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Abstract

The design of an operational mount to rigidly secure the primary mirror to its baseplate without the introduction of figure error always proves to be a major task on diffraction limited optical systems. A summary of the design of the Infrared Astronomical Satellite (IRAS) primary mirror mount is given. The mirror was designed to be aligned and tested at room temperature and operated in a zero "g" field at temperatures of 2K. To minimize overstressing, a stiffness requirement of greater than 150 Hz was required for cold launch and room temperature vibration acceptance testing. Additional isolation was required to minimize strains, introduced via the mounting base, due to thermal and mechanical distortions.

Introduction

The Infrared Astronomical Satellite (IRAS) program has provided many interesting technical challenges. In addition to the complications normally found in space telescope designs, IRAS has combined the challenges of operating at 2K, packaging constraints requiring lightweighting, and operation in the visible as well as IR. This unusual collection of requirements and constraints has led us to re-examine many standard telescope design practices. Our paper describes the tradeoff which was made for mounting the primary mirror, and the application of NASTRAN finite element analysis to the tradeoff.

The optics for IRAS are contained in the Optical Subsystem (OSS), recently delivered by Perkin-Elmer for installation in a superfluid helium dewar. Figure 1 shows the OSS containing the mirrors, optical baffles, and metering structure. The optical design comprises a two-mirror Ritchie-Chretien form with a 24 inch diameter primary mirror. Optical grade beryllium was the material used in the construction of the two elements and the metering structure. The beryllium baseplate is the main structural element registering the primary mirror through titanium flexures to the secondary mirror through a beryllium support structure. Four sets of optical baffles are constructed from aluminum coated with Martin Optical Black, all flexure-mounted, three to the baseplate, and the fourth to the secondary mirror support structure. The entire optical assembly is flexure-mounted to an aluminum interface ring which hard mounts to the aluminum dewar.

Sponsored jointly by the United States, the Netherlands, and the United Kingdom, the satellite program will operate at 2K cooled with superfluid helium. At an altitude of 900 km circular orbit, the satellite will perform an all-sky astronomy survey from 8μm to 12μm.

The primary mirror and its operational mounting system have been successfully designed and tested to satisfy a varied, and often conflicting, set of harsh vibration and thermal environments. Maintenance of alignment throughout these conditions was a major factor in the design.

Optical design is established during telescope assembly and must be maintained through handling, environmental testing, and operation. Manufacturing and assembly is accomplished at room temperature in a one-g gravity field, thermal/vacuum testing is done at 40K and operation is at 2K at zero gravity. To design a system for one set of environmental configurations is routine, but designing for all conditions poses a considerable challenge for the design team.

Trade Considerations

Early analysis of manufacturing and environmental requirements showed significant cost and performance risk attached to the primary mirror mounting technique, indicating that several alternate configurations should be considered. Initial designs of IRAS used a simple hard mount for attaching the primary mirror to its baseplate, since a hard bolt-down attachment of beryllium to beryllium seemed like the simplest and most cost effective approach. Hub mounting a mushroom-shaped mirror near its center would allow for a localized rib-stiffening pattern in the mirror to minimize susceptibility to mount-induced strains. If the baseplate to which the mirror is mounted is stiff, it will not induce significant strain in the mirror.

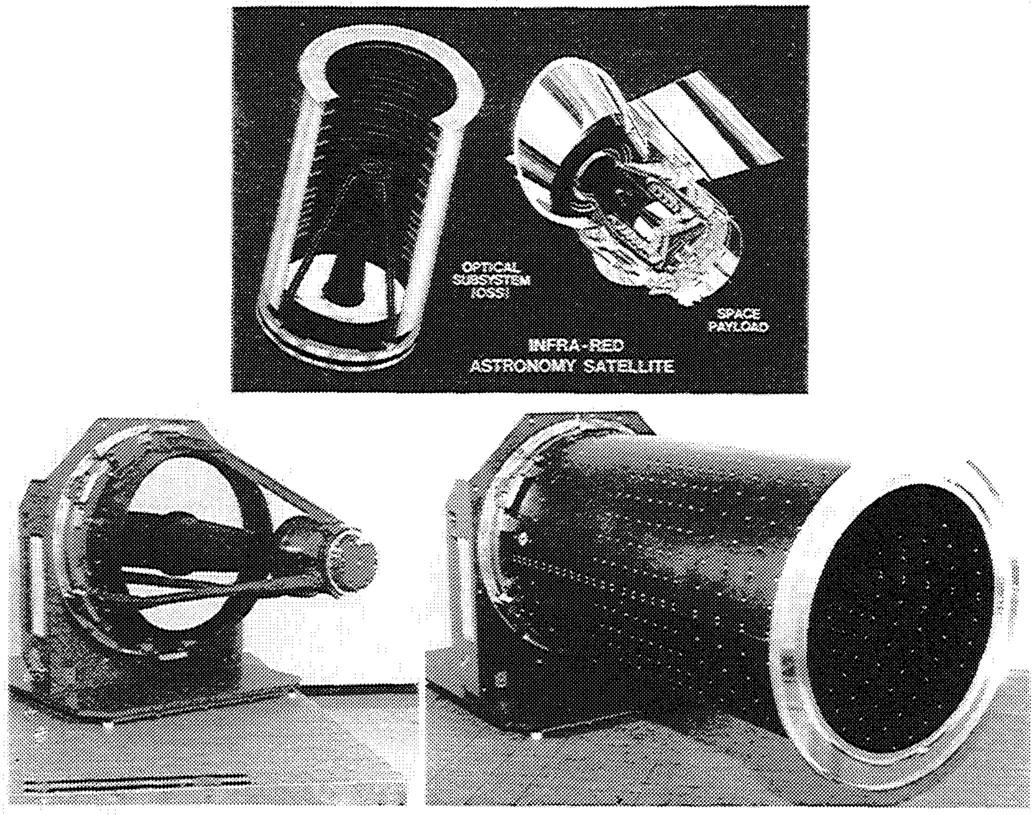

Figure 1. Optical subsystem

However, further analysis of the concept surfaced several problems. First, the launch vehicle weight and packaging constraints directed that the primary mirror and baseplate be lightweighted and packaged in a confined volume. This translates into a decrease in stiffness of the two components, making them more susceptible to strain. In addition, consideration of the machining tolerances of the mounting pads required to prevent inducing mirror surface errors at assembly indicated that precision machining would be required. These surfaces are sensitive to damage in a manufacturing environment where the mirror is required to assemble to its baseplate many times. This leads to a considerable performance risk, motivating the consideration of an alternative mount approach in a trade whose objective is to select a mirror mount technique that yields maximum performance with minimum cost, schedule and risk.

To effect a meaningful tradeoff, alternate approaches must be identified, conditions which effect performance parameters defined, and evaluation criteria established.

Table 1 summarizes the mounting trades. There are several approaches to mounting a mirror but experience with cryogenic applications induced us to consider only flexure mounting as an alternative to hard mounting. Because the stiff, brittle nature of beryllium makes it a poor flexure material, titanium was selected. The alloy of titanium 5AL 2.5 Sn ELI has a good coefficient of thermal expansion (CTE) match to beryllium. It has a high strength and remains ductile and compliant down to 2K.

Gravity and temperature were major drivers in the trade. This is best illustrated with reference to Figure 2, which is a schematic of the OSS. Attachment of the OSS to the IRAS dewar occurs with the entire subsystem cantilevered off the aluminum Interface Support Ring. In addition, the required orientation of the telescope is horizontal in order to fit into the test chamber during cold acceptance testing at Perkin-Elmer. These two constraints dictated that the telescope be designed for manufacturing, alignment and testing in a horizontal position, when in a one-g gravity field. This orientation induces asymmetric distortions in the system, the worst kind to design out.

Table 1. Primary Mirror Mount Trade Approach

Alternate Mounting Approaches:

1) Hard Mount
2) Flexure Mount

Mount Requirements:

1) Minimize repeatable errors in the primary mirror surface so they can be polished out.
2) Maintain non-repeatable errors in the primary mirror surface within tolerances.
3) Maintain temporary strains within the micro-yield strength.

Items Considered In The Trades:

1) Gravity Induced Strain.
2) Thermal Induced Strain.
3) Beryllium Material Properties.
4) Machining Tolerances.

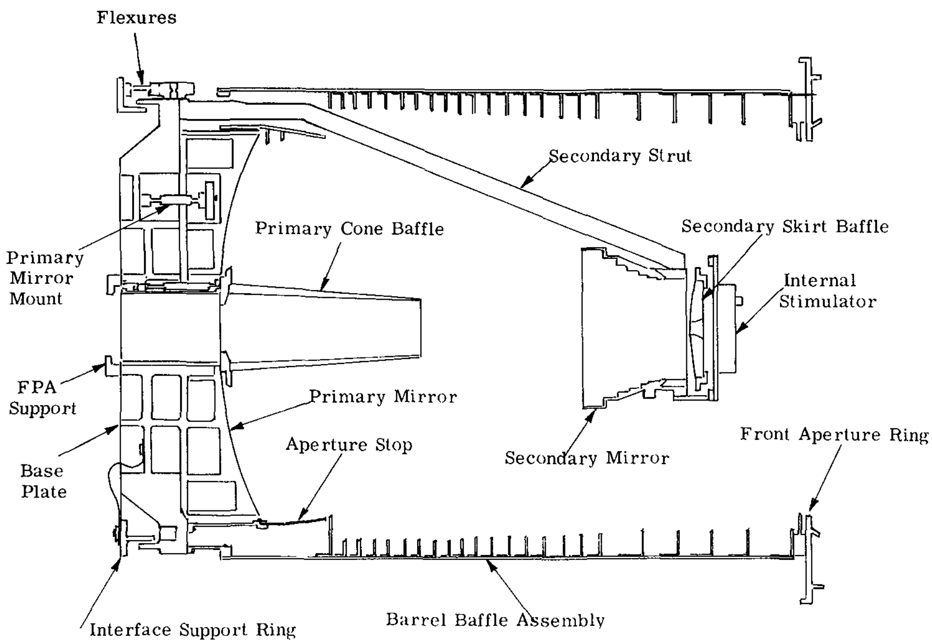

Figure 2. IRAS optical subsystem

Most distortions of the mirror are transmitted via the baseplate and are produced by the members it supports. Three forms of disturbances exist:

1) Their initial mounting
2) Gravity release effects
3) Thermal strains.

A list of baseplate-supported components, their weights, and materials is shown in Table 2.

Table 2. Baseplate Supported Masses

Assembly	Weight (Pounds)	Material
Primary Mirror	27.8	KBI-HP81 Beryllium
Secondary Structure	18.3	KBI-HP81 Beryllium
Barrel Baffle	29.3	6061-T6 Aluminum
Primary Cone Baffle	11.4	6061-T6 Aluminum
Focal Plane	30.8	Aluminum
Dutch Additional Experiment	17.5	Aluminum
Interface Support Ring	5.25	5083-H321 Aluminum

A second set of loads which induce distortions in the baseplate occurs when the telescope is cooled below room temperature. All the assemblies listed in Table 2 are flexure attached to the baseplate, with the exception of the secondary structure, which is hard mounted. When the telescope is cooled, the differential contraction of the materials will load the flexures, inducing bending moments on the baseplate. These loads are substantial and are sufficient to distort the baseplate. The relative effects on the primary mirror are the same as discussed for gravity effects. The mirror must remain distortion free both warm and cold.

A final thermal consideration is cool-down gradients. The OSS will be conductively cooled through the Interface Support Ring, then from the ring through three copper straps to the baseplate and three to the primary mirror.

The complexity of the load conditions is apparent. The net effect of these gravity induced loads will be to distort the baseplate. If the primary mirror is hard mounted, these distortions will be transmitted to the mirror surface, and if these errors are polished out, they will reappear in the zero-g operational environment. Therefore, mirror and baseplate stiffness must be maximized to maintain the surface errors induced into the primary mirror within tolerances. However, if flexures are used, the amount of distortion transmitted from the baseplate to the mirror will be minimized, allowing for a reduction in the stiffness of the two components.

Beryllium's material properties played an important part in the trades. The hexagonal cell structure of elemental beryllium has a Coefficient of Thermal Expansion which is 38% higher in the plane of the hexagonal face than perpendicular to it. Optical grade beryllium is produced by randomizing the crystallographic direction to produce an average CTE which is constant in all directions. However, small residual anisotropy and inhomogeneities in CTE remain even in optical grade beryllium. For optical applications where surface errors measured in fractions of a micrometer are important, these residual effects cannot be ignored.

Data from a previous Perkin-Elmer program showed a variation in the integrated contraction of beryllium to be 7×10^{-5} m/m for optical grade I-70A beryllium from 300 to 2K. For IRAS, HP-81 inhomogeneity was specified to be no greater than 7.6×10^{-5} m/m. The latter value was used for this study as a conservative approach. The IRAS beryllium pressing was cylindrical in shape. As a result of the manufacturing process of the pressing, CTE anisotropies exist between axes radial to the cylindrical axis and parallel to the axis. In addition, we expect a radial inhomogeneity in CTE to exist. The three fixed mounting pads on the mirror and the baseplate are machined to required tolerances when warm. CTE anisotropy or inhomogeneity can perturb the relative orientation of the mounting pads when cooled. The tradeoff of mounting techniques is obvious. Distortion of the mounting pads can induce surface errors in the primary mirror.

The machine tolerances associated with the mounting pads on the baseplate and on the primary mirror are involved with the primary mirror surface figure. Ideally any three mounting pads should be coplanar, but in practice they are neither coplanar nor parallel. Figure 3 illustrates the three possible pad mismatches which were investigated, along with their effects on mirror shape when mounting bolts bring the pads into contact.

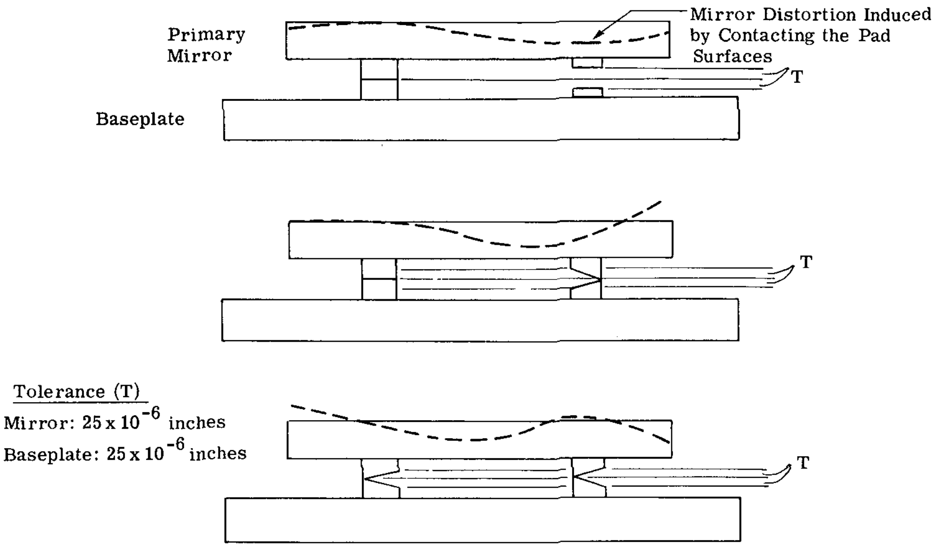

Figure 3. Coplanarity error effects

Analysis

First, hand calculations and past experience were used to produce relatively detailed lightweighting designs for both primary mirror mount configurations. Second, a NASTRAN finite element computer model of the mirror was generated and used iteratively to evaluate the designs and to optimize them individually.

The pertinent mirror characteristics used in the tradeoff are shown in Table 3. Note that these are not the final IRAS design characteristics as this trade was made early in the program before the design was frozen.

Table 3. Primary Mirror Design Characteristics

Outer Diameter:	24.0 inches
f number:	f/2.0
Circumferential Rings:	4 equally spaced
Radial Ribs:	Every 20°
Ring and Rib Thickness:	0.20 inches
Face Sheet Thickness:	0.25 inches minimum

Figure 4 illustrates the configurations for the mirrors and baseplates. Both mirrors were supported at three mounts, located 120° apart. In order to reduce the thermal effects, the hard mounts were located as close as possible to the center hub, at a 6.0 inch radius, via a plane passing through the mirror's back surface. The flexured mirror was supported close to its center of mass, at an 8.6 inch radius and 2.0 inches in from its back surface. All mounting pads were toleranced to be coplanar to $\pm 25 \times 10^{-6}$ inch.

The flexure assembly design used in the analysis is shown in Figure 5. Each of the three assemblies is comprised of a cruciform section and a blade section. A cruciform section attaches to the mirror with the axis of the cruciform in a radial orientation. This part of the flexure assembly accommodates mounting pad errors which cause bending moments about the radial axis. The blade sections of the flexure are oriented with the blade faces perpendicular to radial axes on the mirror. These sections accommodate mounting pad errors which produce radial translations and rotations about the tangential axis.

The flexures are designed to compensate for mounting pad machining errors, for mounting pad motions which are thermally or gravity induced, and for cool-down temperature gradients between the primary mirror and the baseplate. The compensation for mounting pad errors occurs in the assembly attached to the pad as already described. However, all three assemblies must be considered to describe compensation for temperature gradients and general mirror alignment.

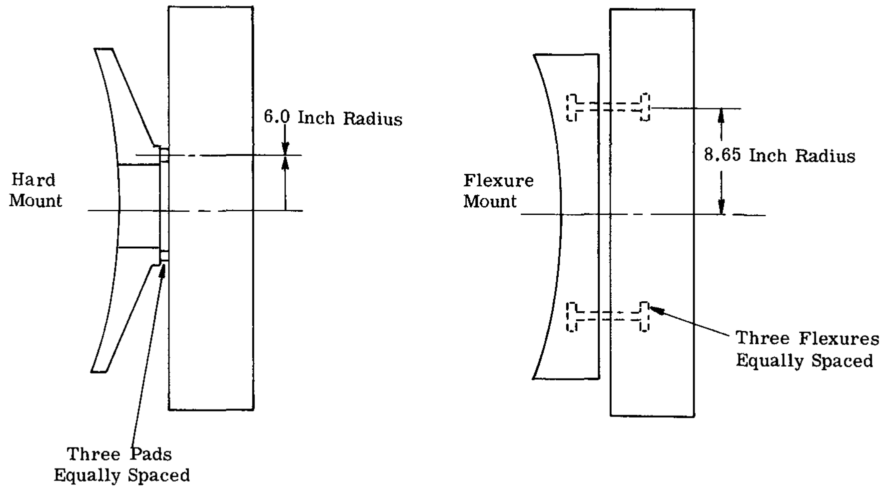

Figure 4. Mount options

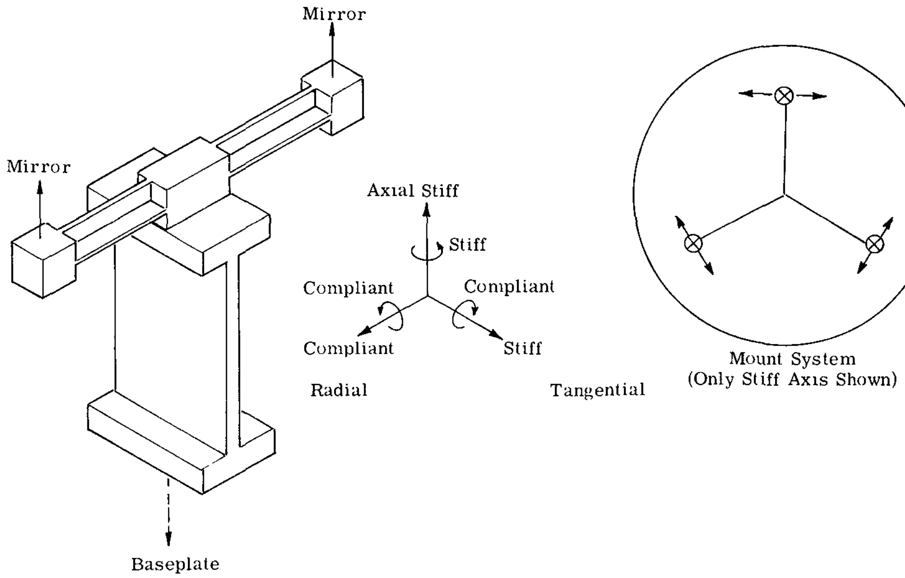

Figure 5. Primary flexure concept

The three assemblies are oriented 120° to each other. When attempting to translate the mirror with respect to the baseplate, consider a force in a radial direction through one of the flexures. The flexure in line with the force is compliant in that direction tending to flex. However, the other two flexures have a component of their stiff axes parallel to the force and therefore, are highly resistant to motion. Consideration of the vector sum of the stiffnesses of all the axes will show that the mirror is stiff to translation in any direction.

For cool down, both the primary mirror and baseplate are thermal strapped to the dewar for conductive cooling, but because the baseplate carries more thermal mass, its temperature is expected to lag behind the primary mirror temperature. Contraction of the primary mirror will occur faster than the baseplate, but since the displacement is linear, the net motion of the primary mirror mounting pads with respect to the baseplate mounting pads will be along radial lines. The flexures are compliant for radial displacements, thus compensating for the relative mount motions.

Two major tasks were performed: one which determined the distribution of forces and moments transmitted from the baseplate through the mirror mounts and into the mirror, and another which determined the effects of these disturbances on the mirror surface and the induced stresses within the blank. The NASTRAN finite element structural analysis computer program was utilized to perform both of these tasks.

For the hard-mounted mirror, the induced displacements and forces were assumed to be equally distributed between the mirror and baseplate, since each appears to have equal stiffness. However, for the flexured mirror study, the baseplate was assumed infinitely rigid.

In order to determine the load distribution for the latter configuration, a more detailed analysis was performed and a type of mount conceived and initially sized to meet strength, stiffness, and compliancy.

The mathematical model consisted of a rigid equilateral triangular plate representing the mirror. Six NASTRAN spring elements were connected at each vertex to ground (the baseplate). The springs defined the stiffness matrix of each mount. Unit ground displacements and angular rotations were individually applied in orthogonal directions. Resultant induced mirror forces and displacements were determined.

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

A sensitivity analysis was performed on the primary mirror to determine its stess distribution and surface error distortions due to forces and moments introduced via the mounts. By applying displacements to the mount force distribution model, to determine the resultant input forces for the mirror computer model, the resultant effects on the mirror can finally be determined.

Table 4 is a summary of mount performance for both the hard and flexure mounting concept. The range of values shown for the initial mount of the hard mirror is determined by the various mounting schemes.

Table 4. Summary of Mirror Mount Performance

Error Source	Hard Mount Primary Surface Error (μm p-p)	Flexure Mount Primary Surface Errors (μm p-p)
Initial Mount	1.0 - 2.7	<0.001
Gravity Release	0.83 Mounter in System 0.23 Mirror Self Wt Only	0.14 mounted
Anisotropy	8.23	0.12
Inhomogeneity	9.85	0.001
Thermal Strains Transmitted Through the Baseplate		
(a) OSS Mount	0.64	(3×10^{-5})
(b) Primary Cone Baffle	0.01	(4×10^{-8})
(c) DAX	0.01 Assumed	(4×10^{-8}) Assumed
(d) FPOA	0.01 Assumed	(4×10^{-8}) Assumed
Total (Errors RMS)	13.16	0.18

Discussion of results

To evaluate the results of the analyses, a tolerance allocation for wavefront error was made as illustrated in Figure 6. The IRAS image quality requirement was to provide diffraction-limited performance at a wavelength of 8μm, which is interpreted as an rms wavefront error of 0.63λ at the metrology wavelength of $\lambda = 0.6328$μm. Allocation of this error to the various contributers resulted in a 0.372 λrms wavefront error which was approximated as a 0.47 μm peak-to-peak surface error.

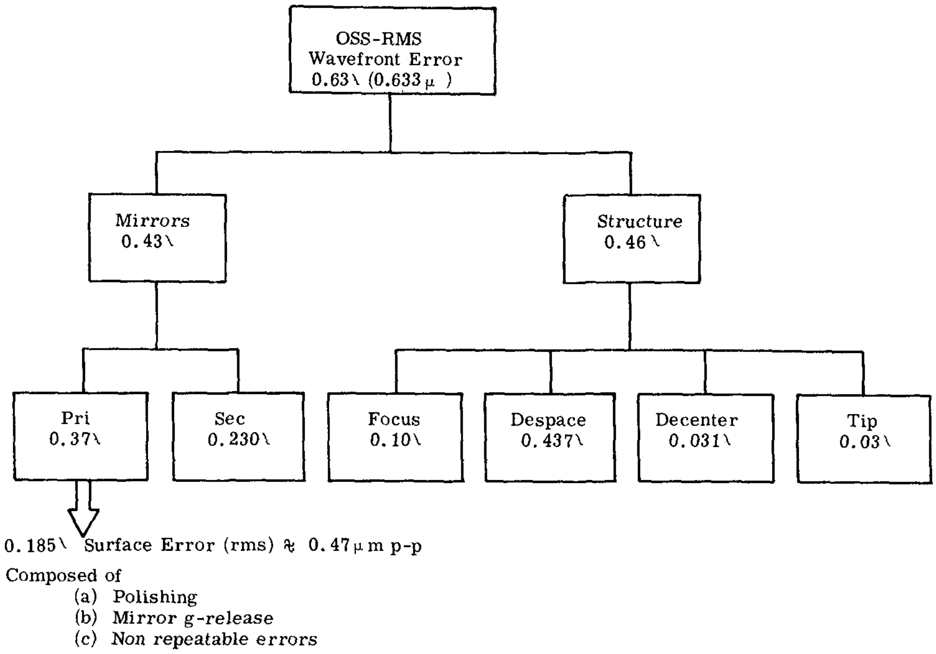

Figure 6. Image quality tolerance budget

Comparison of the allowed p-p surface error with the calculated values of Table 4 shows that the flexure mount approach yields results within budget by a factor of 2.6 while the hard mount approach produces deformations which are a factor of 28 over budget. At first glance the hard mount approach might be dismissed as totally unacceptable. However, at least four possibilities exist to improve the hard mount performance. 1) Polish out repeatable mount related errors, 2) Budget more tolerance to non-repeatable errors, 3) Lap the mount pads to tighter tolerances, and 4) Stiffen the baseplate to minimize induced errors.

Polishing out repeatable errors, although feasible, is a high risk approach since the degree of repeatability of the errors does not readily lend itself to analysis. Lapping the mounting pads to tighter tolerances increases program cost, and stiffening the baseplate generates a weight and/or packaging penalty.

A typical effect of reallocation of tolerances is shown in Figure 7. The primary mirror surface budget must be divided between polishing accuracy and non-repeatable errors. The p-p polishing tolerance is inversely relatable to cost, so that maximization of allowed mirror surface error yields the lowest cost. Because the non-repeatable errors of the flexure mount approach are low, most of the budget is allocated to mirror surface error. For the hard mount approach, an estimate of performance enhancement by polishing out repeatable errors, stiffening the baseplate, and lapping the pads leads to an estimate of non-repeatable peak-to-peak mirror surface error of 0.375μm. The amount of tolerance remaining for polishing is almost a factor of two less than for the flexure mount approach. Yet the effort required to achieve the 0.375μm value and the required surface polishing tolerance both lead to increased cost. Clearly, this is not a cost effective trade.

A final consideration in the trades was the stress distribution produced under the expected loads. For both configurations, cooling down produced the greatest stresses in the mirror — 3370 psi for the hard mount approach and 385 psi for the flexure mount. Using a microyield strength value for beryllium at cryogenic temperatures of 3500 psi as a design criterion, it is apparent that the flexure mount approach yields a much higher safety margin than the hard mount approach.

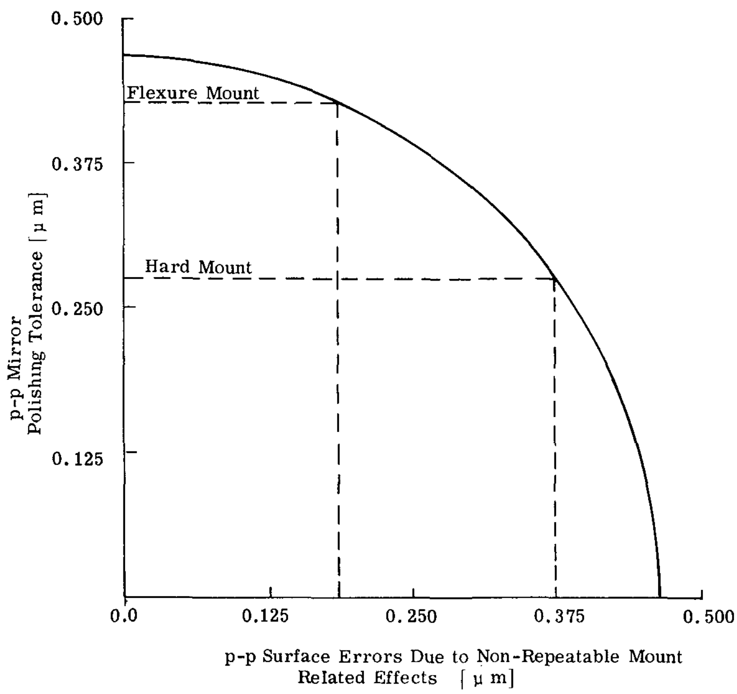

Figure 7. Primary mirror error budget trades

Conclusion

As a result of the trade, a flexure mount approach was selected over the hard mounting. The conditions which drove the selection were the packaging constraint which necessitated lightweighting with the accompanying decrease in stiffness, and cryogenic operation which produced distorting loads due to dissimilar metal attachments. Even though the hardmount approach that was analyzed could be modified so that it would satisfy IRAS requirements, the resultant increase in cost and risk was not deemed acceptable.

Acknowledgements

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1. "OSS Primary Mirror Mounting Trades Summary" Perkin-Elmer Report 13509, The Perkin-Elmer Corporation, Danbury, CT, February 1978.