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Mechanical design of optical systems for space operation

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ABSTRACT

The age of large space optical systems began in the early 1960s. With very little precedent but driven by necessity, there emerged a series of new mechanical and structural technologies including dramatically lightweighted mirrors, ultra-stable low thermal expansion structures, large-scale testing thermal and vacuum environment testing, and robust alignment sensing and control systems. We will review in this monograph the growth of these and other technologies, beginning with a heritage that had its origins in amateur telescope making. We will also address a newer design technology, design-to-cost, which has become a dominant system discriminator in the past decade. This is not intended as a how-to technical paper. Instead it is intended to surface some of the questions and considerations that need to be answered in the development of any new systems concept, rather like a checklist, to ensure that low cost and a high probability of initial success are achieved.

1. TELESCOPE BUILDING IS NO LONGER AN AMATEUR AVOCATION

Until the advent of artificial satellites, the design and manufacture of large telescopes had been largely an amateur or at least non-commercial, albeit highly sophisticated, enterprise. The design of the 5-m Palomar telescope was actually developed in Springfield, Vermont by a group led by Russell Porter, an architect by training, and the chief engineer of the Jones and Lamson Corporation. This work was initiated in the late 1930s and completed after the war. Porter was also the founder of the renowned Stellafane Society, the oldest amateur telescope-making group in existence and which continues to meet every summer on Society Hill in Springfield. Attending some of the early 5-m telescope planning and design meetings was another non-professional telescope maker, Richard S. Perkin who with Charles Elmer founded the Perkin-Elmer Corporation. That corporation went on to design and build the Orbiting Astronomical Telescope, the OAO-C, in the early 1960s which was the pathfinder for larger and more powerful space-based astronomical systems.

What was different then from now? Those telescopes were largely financed by private funds, usually endowments from interested foundations. Without a high level of technical and financial oversight, their design often reflected a wider degree of experimentation than exists today. And sometimes these designs didn't perform as originally intended. Sometimes significant fabrication problems were encountered necessitating major redesigns. The Palomar primary mirror, for example, was originally to have been made from fused quartz produced in an electric furnace in Pittsfield, Massachusetts by General Electric. After nearly "browning out" the western part of that state an alternative material, Pyrex, made in gas fired furnaces by Corning in upstate New York, was substituted.

This anecdote is intended to provide a contrast to today's more structured technical culture, at least as far as space-based optical systems are concerned. Unlike a ground-based telescope where:

a) design flaws can be fixed and/or the system can be upgraded as new and desirable technologies become available; and

b) the means to transport the telescope to its operational site are always there, (i.e., roads),

space-based systems must rely on expensive, schedule driven launch vehicles and yet-to-be-proven manned repair missions. Space-based telescopes need to be "right" and they need to be on time. Pre-flight verification is a necessity as well as a very significant part of the cost of these systems which are between ten and fifty times the cost of their earth-based counterparts. The turn-key cost for an 8-m ground-based telescope is estimated to be about 100 million dollars, including the dome and mount structures. Space-based telescopes of that aperture have yet to be developed beyond the stage of speculative studies but costs are estimated in the 2 to 4 billion dollar category, exclusive of launch expenses. That's forty times as much as the ground-based version. And that kind of money doesn't come from foundations. It is Government money and with it of course must come insightful technical and programmatic management, both from the sponsoring organization as well as the performing one, i.e., the contractor.

The transition from the largely benign environment of ground-based telescope design to the unforgiving demands of space operation began about 30 years ago. To some extent it is still continuing both in the technical as well as in the programmatic sectors. Let us examine some of the principal factors that comprise this transition from the vantage point of a mechanical designer.

2. THE CHALLENGE OF SPACE OPTICS

Clearly, an objective of space-based operation is improved performance where limitations imposed by atmospheric distortion or "seeing" are absent. Free of these limitations, the theoretical resolving power of a telescope can be realized if the surface tolerances on the optics (mirrors) and the alignment between them is maintained to near-ideal conditions. This is often better than a fiftieth of a wave rms or about a tenth wave peak-to-peak. In mechanical engineering units this is about two millionths of an inch or less than a thousandth of the thickness of this page! The theoretical resolving power of a telescope, to first order, is directly proportional to the diameter of the aperture which in most cases is defined by the size of the primary mirror. But the tolerances on surface accuracy or alignment, being functions of the operating wavelength, remain constant or may even decrease. So as the quest for higher and higher performance continues and systems increase in size, the ingenuity and resourcefulness of the optical manufacturing teams and the mechanical designers become more and more challenged to achieve surface accuracies and element-to-element alignment tolerances that are no more forgiving than if they were for a 0.5-m system. And to do this without jeopardizing schedule or cost.

What are the specific challenges confronting mechanical design? Following is a partial list, not arranged in any particular order of priority or importance; different people would probably have different views of that, based on their own experiences.

- Cost
- Weight
- Mirror Design and Mounting
- Mirror Manufacturing and Gravity Release
- Structural Alignment and Gravity Release
- Mirror Accuracy and Temperature Change
- Fear of Failure
- Alignment Accuracy and Temperature Change
- Launch Survival and Verification
- Dynamics and Controls Interaction
- Alignment Sensing and Control
- Producibility
- Integration, Assembly, and Test
- Verification, beyond what is Testable
- Structural Modeling, the Glue that Ties it Together
- Schedule Credibility
- Cost.

These topics will be discussed in a qualitative sense and for each, a checklist of factors that need to be considered will be presented and explained. It was not the intent to address detailed technical issues but to alert the reader to the right questions to ask in planning an attack on them.

To those of you new to the space optics field, there is another way of looking at the mechanical engineering challenge of space optics. It is to recognize that the success criteria for the structural system is almost invariably not an easily isolated and well defined event such as collapse of a wing under static test, as might be the case in the aircraft industry. It is a subtle loss of a fraction of a micrometer worth of alignment between elements often many meters apart. Some of the ways available to the designer to meet this criteria, in a deterministic and affordable manner, is the subject of this paper.

3. COST

No program will be funded if it isn't affordable and no contractor will win that program if his costs are not credibly low. In fact programs can and have been terminated for cost growth reasons. Historically, "cost" was not considered to be in the technical sphere and yet in today's environment it must be treated as a design parameter, just like weight budgets or wavefront error allocations. One must price to win and then ensure that the costs to design and produce the hardware are within that price. Very much like the automobile business! This of course had not been the case in the beginnings of space optics. Then, there was indeed a race with the Soviets to demonstrate who the technical leader of the world was and rocketry and space was a visible and spectacular area of competition. Risking simplification, the order of priority then was performance, then schedule, and then cost. Today that order is reversed. However, there remains a heritage, and it may be indigenous to the engineering and scientific professions, to do better than what is required. Surpassing the specifications is still today regarded as a demonstration of one's technical virtuosity. It is the unusual case where this doesn't add cost, either in design or in test. Today's mantra is to meet the specified requirements with the least cost and with the smallest technical and schedule risk. In most cases the requirements are difficult enough, don't try to do better.

How does one know that the least-cost approach to a particular design has been achieved? Simple: estimate its cost, analyze the results, and look for the drivers. Are there alternative solutions that can reduce them, what is the specific cost "delta" for these alternatives? This needs to be done during the concept definition and trade phase along with other candidate approaches. Presupposing the existence of a design concept, the cost estimate needs to reflect at least the following elements:

a) *A Program Plan.* What needs to get done and when needs to be defined in as much detail as practical. This is the programmatic equivalent of the system layout drawing; it establishes the direction that the individual operating groups will take. And by the way, just like a layout drawing, it's never really finished and may be changed or updated to reflect program maturation over the life of the program. Without a program plan, which clearly identifies the program deliverables and the paths, milestones and submilestones by which these deliverables will be implemented, the cost estimate would have no credibility.

b) *Requirements.* Now that one knows what needs to be accomplished and when, how well they need to be done has to be defined. In today's complex, technically interdependent high performance systems, the requirements for the various subsystems must be developed from a top-level systems approach. Piecing together various subsystems, sometimes developed by highly competent or "star" engineers but with the attitude of prima donnas, simply will not be successful. The technical management of a program and the role of the chief engineer and systems engineering are beyond the scope of this paper. It is a subject which merits it's own discussion. Suffice to say that to design to cost, which is what this section is all about, demands that the requirements for the design be in-place and expressed in the language of the specific discipline responsible for its implementation. A structural engineer doesn't usually relate to fractional encircled energy or the power spectral density (PSD) of an optical surface. Not to demean those who operate in this area, but the structural and mechanical designer needs to have these terms translated into linear units of deformation or misalignment between elements will occur.

c) *Confidence in the design approach.* Is it readily analyzable and does it have a high probability of initial success? How dependent is the analysis on assumptions and idealizations, or what I sometimes refer to as the dilemma of "interlocking ifs." If the moments applied to a mirror are..., or if the CTE homogeneity of the material is..., or if the hysteresis in a joint was..., well that's what I mean by interlocking ifs. The assembled hardware has no way of knowing what assumptions the designer made. Discovering design faults is expensive, especially if they are discovered late in the development stage. Design the system to be verifiable, either by end-item test or by analysis augmented with subsystem or developmental test data. The verification process must be treated as an inherent element of the design process. It must be reflected in the program plan and usually expanded via an MIT or detailed Manufacturing, Integration, and Test plan which defines every step of the assembly and test process, including the facilities that are needed, and should dovetail with the system verification plan which defines how each element of the requirements specification and error budgets will be verified.

d) *A detailed drawing count or estimate.* It sounds trite but every part that comprises the design needs to be drawn, all drawings need to be engineered, all parts need to be made, bagged, tagged, inspected, and assembled. And all of those operations take time and time of course, multiplied by rates, is cost. Drawing counts and design labor estimates need to be made in concert between the program office and the various operating departments, neither alone is adequate. Don't omit any of the special test equipment or other factory equipment needed to verify the hardware. It needs to be designed with the same care and professionalism as the flight equipment itself.

e) *Real hardware fabrication estimates.* No substitute for cost quotes from vendors either, although in most instances (at least for one-off systems) the actual structural fabrication costs are small compared with the engineering and test labor that was needed to design and specify them.

f) *Historical precedence or heritage.* Lastly, innovation for its own sake needs to be minimized or better yet, avoided. Wherever possible, design trades should be confined to configuration variations and material selection. The latter is based on proven materials in similar applications. The development of new materials or the incorporation of non-traditional materials is best left for a pre-flight hardware development program which is independent of flight hardware schedule constraints.

g) *Sufficiency.* Know when you are done, know when the design is good enough, declare completion and move on to the next piece of work. It isn't required to do better than the specifications require, albeit one needs to provide for some margin. In only rare circumstances does doing better not add cost and as proclaimed earlier, cost is indeed a design parameter in today's competitive climate. That of course demands a clear definition of the requirements as stated at the outset plus sufficient judgment, insight, analysis, and possibly test data to confirm that the requirements have indeed been satisfied.

h) *Clearly defined work definitions.* "I thought you meant this, and now you're telling me that the customer wants a stand-alone flight safety analysis report. Where'n the heck do I have a charge number for that?" Not an uncommon complaint. A clearly defined and documented and agreed to statement of work between the program office and the customer and between the program office and the various operating groups supporting the project is absolutely essential. No further comments are necessary.

There is, of course, far more to the area of design-to-cost than what is briefly mentioned here. That, however, is a subject unto itself.

4. WEIGHT AND MIRROR MECHANICAL DESIGN

Progress in lightweighting has possibly been more dramatic in the field of space optics than in any other discipline. Whereas the aircraft industry provided the heritage for lightweight spacecraft structures, there was no such parallel for large space optics systems. Weight was often considered an asset for ground-based telescopes insofar as it provided rigidity and thermal stability. Some lightweighting was employed for mirrors, however, to reduce their thermal time constant in an effort to prevent localized seeing errors.

Mirrors in particular, over the last 35 years, have progressed from solid fused silica disks whose diameter-to-thickness ratio was 6, to early sandwich designs that achieved weight reductions on the order of 70%, to a variety of design approaches in both glass and metals that are no more than 10 to 12% of their equivalent-size 1960 predecessors in the 1-m class. And they perform as well or better. Where did the 6:1 ratio come from? Ritchey, of Ritchey-Chretièn fame, observed in 1903 that when the aspect ratio of a mirror was 6:1 there was no sensible difference in its figure when measured on edge to when it was measured with gravity normal to its surface. He described these conclusions, based on 12-inch mirrors, in his logbook at the Harvard Observatory. For constant self-weight deflection, the ratio of diameter squared to thickness is the relevant metric so that as the size doubles, the thickness needs to be increased by four. The 6:1 rule, despite not being rigorously correct, persisted into the 1970s and for some commercial telescopes, is still adhered to.

Presuming that the design and programmatic (cost/schedule) requirements have been defined, what are the "knobs" to turn for achieving a lightweight mirror and conversely what are the impediments to lightweighting. Some of these knobs are:

- Materials
- Configuration
- Substrate producibility
- Optical fabrication and test methods
- Mounting.

There is usually more than one design solution that will satisfy a specific set of requirements, a sample set of which is listed below:

- Diameter or geometry, f/no, prescription
- Fabrication and operational wavefront error allocations
- Type, i.e., passive, active, or correctable
- Thermal time constants
- Natural frequency
- Launch and operational dynamics loads
- Schedule, or lead time
- Weight
- Cost bogey, sometimes.

Producibility and cost tend to remain as key design and requirements factors. A brief discussion of some of the degrees of freedom, or knobs, that the mirror designer controls to achieve a lightweight design is presented below.

a) *Different materials are lightweighted differently.* Lightweighting may be achieved by selecting low density, high modulus materials like beryllium or by configuring the substrate to achieve high structural efficiency and thus not requiring much material in the first place. As with any structure, putting the right amount of material in the right places can lead to lightweight, efficient designs. However, not all materials used for mirrors are compatible with all lightweighting approaches. Today the designer has a variety of material options to select from (Corning's ULE and fused silica, Zerodur from Schott, fused quartz from Heraeus, beryllium both HIP'd and VHP'd, silicon carbide both CVD'd and reaction bonded and several others which are still developmental or otherwise not generally used in space applications such as borosilicate) but which generally are not lightweighted in the same way or to the same extent. ULE may be produced in a structurally efficient sandwich form by frit bonding thin faceplates onto a square or triangular grid core. Core depth to overall thickness ratios of 90 to 93% are achievable, which is near optimum from a stiffness to weight aspect. Zerodur on the other hand is usually lightweighted by machining recesses in the back to form a rib stiffened structure or is simply utilized as a thin meniscus, often in conjunction with shape control actuators. HIP'd beryllium can be produced as a sandwich by consolidating the powder over a sacrificial copper mandrel which is chemically removed through small holes in the back after the HIP'ing process is completed. Before selecting a final material/configuration it is important to confirm that the design is indeed producible. One must also be aware of materials and/or lightweighting processes that are developmental or have been accomplished in small sizes only. Early liaison with optical contractors and substrate manufacturers cannot be overemphasized.

b) *Is the material polishable?* Fully densified surfaces in the case of HIP'd beryllium and SiC mirrors and suitably small grain size are necessary to produce highly specular surfaces where microroughness needs to be limited to less than 5 or 10Å. The amorphous nature of glass, with no grain boundaries or other micro-structures, facilitates polishing. In certain instances, beryllium being most notable, electroless nickel plating several mils thick provides the hard, amorphous surface necessary for polishing. Unfortunately there is a mismatch in the coefficient of expansion of these two materials and especially with lightweight substrates, unexpected and certainly unwanted thermal bending occurred.

c) *Is the material available in the sizes needed?* This isn't much of an issue up to 1.5 meters but it is an important question for larger sizes. The size limit for HIP'd beryllium is 1.5 m, a facility issue. For frit bonded ULE, the limit is 2.5 m, also a facility limitation. Zerodur mirror blanks up to 8.2 m have been produced with thicknesses ranging from 0.2 to 1 m. Don't neglect the extra material needed at the edges to accommodate tool roll-off. On large mirrors the added weight can be significant as well.

d) *Optical fabrication and testing is another potential limit to lightweighting.* Two factors enter here: 1) the ability to grind and polish the mirror without causing the rib or grid structure to "print through" and 2) the ability to confidently support the mirror in a simulated zero-g environment. In the first instance this is largely dependent on faceplate thickness and rib spacing, (s^4t^3 to be specific) and other factors like tool size and pressure. This factor is typically between 250 and 1000 for glass and four times that for beryllium where the specific stiffness is greater by that amount. As the size increases and weight and stiffness decrease, the effect of gravity release needs to be accounted for with greater and greater accuracy. The Hubble Space Telescope (HST) 2.4-m primary mirror has 15 λ p-p of self-weight deflection when supported on three points at the rim. The error allocation for gravity release was only 0.004 λ rms, representing approximately a factor of 1000 on an rss basis. Essential to successfully predicting and/or supporting a mirror with an array of forces such that it approximates its weightless shape are highly accurate and verifiable finite element models. That in turn demands accurate knowledge of the mass distribution within the mirror.

5. MIRROR SUPPORT SYSTEMS

Mirror support systems for rocket launched, orbiting systems need to satisfy two widely divergent criteria, namely strength and stiffness, to survive launch and be compatible with the vehicle dynamic environment on one hand, and support the mirror with the least number of constraints necessary to ensure alignment stability. The latter is of course a restatement of the familiar phrase "statically determinate." Mirror support is included as a topic because of its potential (sometimes justified) as a schedule or performance risk. Unfortunately the success of a mirror mount is often not demonstrated until late in the program during thermal vacuum test or even worse, during flight. Because mirror mount design has not yet, and may never, become a standardized technology, we have included here some reminders of things to consider when developing the concept.

There was no precedent in the beginning. In its infancy, mirror mount designs were often seat-of-the pants concepts, necessitated by a lack of real experience and the absence of advanced finite element modeling codes such as are available today which enable detailed analyses of the stresses at the "glass-to-metal" interface or of the effect on surface figure of secondary loads imparted to the mirror by friction or flexure stiffness to be calculated. A wide variety of support system designs flourished, at least on paper. Over the years different people and different organizations developed mount designs which solved the problem in many different ways. It shouldn't be surprising that there is no "universal" approach to mirror attachment and support. Different applications as well as different mirror constructions, not to mention different requirements, dictate different solutions. Spherical ball bushings imbedded in recesses so their lines of action pass through the midplane of the mirror have been used in some instances (the OAO-C for example). The HST used athermalized rods passing through the mirror which provided a compressive interface between the metal and the glass regardless of the axial load direction. Other applications employed Invar pads which were bonded onto the substrate. Flexures and tension-compression rods with spherical bearing ends have been used to couple the mirror to the support structure. Flexures of course take many forms and it seems to this writer that they've all been used at one time or another.

Regardless of which specific design approach one uses, experience has shown that there are certain characteristics common to all successful designs. They are described below. Not every one of the factors included below applies to every mirror application; however, collectively they serve as a design checklist. Please presume that each of them is preceded with the silent phrase, "The mirror mount design should be..."

- *Based on a Clear Definition of the Allowable Constraint Forces.* Idealized "statically determinate" support systems exist only in theory. In the "real world," one needs to contend with friction in pivots and joints, non-zero flexure stiffness in what one would like to be the "soft" directions, and other similar issues which can and will produce secondary or redundant loads. The effect that these loads will have on figure need to be determined and accounted for in configuring and proportioning the mount hardware. Thus a figure error/loads sensitivity analysis needs to be performed for the mirror design in question from which the allowable magnitude of these secondary loads is determined in conjunction with the error budget.

- *Free of Gimmickry.* How the mount design works ought to be explainable, at least to 1st order, without having to resort to complicated or extensive analysis of a series of interconnected "ifs." No amount of analysis can make an ill-conceived architecture successful.

- *Able to Interface With Uncomplicated Mating Glass Interfaces.* Avoid complicated machined glass configurations like holes with reentrant pockets for "blind" clamps, sometimes referred to as overgrown Molybolts. These pockets in general will exhibit extensive subsurface damage which if etched out (maybe) might destroy precision. Don't depend on tension across the seal-plane or frit-line of a sandwich mirror, because of potentially high stress concentrations.

- *Configured to Avoid High Stress Gradients in the Glass.* High stress gradients such as those caused by pins bearing on holes for example, even if compressive, will be accompanied by shear stresses which ultimately are resolvable into tension and that's what initiates spalling failures. Pins in holes or shoulder bolts in holes, while I'm on the topic, may become cocked and produce much higher direct bearing loads than one might expect. Glass doesn't yield like metals to redistribute these stresses, it just breaks. Gluing the pin in can ameliorate this problem but permanent bonds introduce other problems. Flat mounting pads also can present hard interfaces between glass and metal (which might have the potential for relative motion) and can result in "micro-cocking" which in turn produces higher direct bearing stresses than ordinarily expected, too. In these cases, half mil "mylar" shims have been used to provide a cushion. If extreme temperature ranges are to be encountered where plastic is unacceptable, try 3000 series aluminum foil or something like it which can flow. Low intensity compressive glass-to-metal interface loads are always preferred followed by low intensity shears.

Deterministic. Particularly in a "micro" sense. How accurately is the load distribution at the mount/glass interface known? Is the finite element simulation of that interface of sufficient fidelity. If a design can't be analyzed with a moderate degree of confidence and without too many "ifs" in series, a search for an alternative ought to be initiated, pronto. Areas with direct bearing loads need to be especially scrutinized particularly where misalignments or fabrication tolerances might cause cocking and so on. Do modeling idealizations possibly mask potential problem areas? Sensitivity analyses to test these idealizations, sometimes referred to as the "Principle of Overlapping Assumptions," need to be performed. Knowledge of the interface loads distribution is necessary to know where the lines of action of forces are and that in turn is necessary to evaluate the effect of constraint loads on the mirror.

Based on Actual Material Properties, Not Handbook Values. Athermalized mount designs need to be based on CTE properties from actual lot data. The design needs to be tailorable to accommodate these properties variations, especially if Invar is employed. It's even more important if graphite epoxy is employed. The latter needs to be "mellowed in" by thermal cycling until the measured CTE stabilizes.

Able to Survive Large Temperature Changes Without Damage. In the majority of cases, the operating temperature range of a mirror system is relatively small. However, that temperature may be hundreds of degrees away from the temperature that the mirror and mount was assembled at. Or large temperature excursions might occur during transportation or during a non-operating mode on orbit. Not only does the CTE of a material change with temperature, this change in CTE with temperature is different for different materials. Therefore, a specific CTE difference between two different materials in an assembly at one temperature, say the operating temperature, may be vastly different at another temperature. More to the point, the dimensional changes of different parts of an (athermalized) mirror mount system, $\Delta L/L$, over one temperature interval may be quite different than over another. This could lead to inordinately large incompatibilities between the parts and in certain cases, break the mirror. Check the $\Delta L/L$ curves for when large temperature ranges will be encountered. Watch out also for epoxies and other organics in confined volumes since large hydrostatic loads can be developed. Provide relief slots or whatever.

Tolerant of Non-Isothermal Conditions Especially if Athermalized. In addition to the non-linear $\Delta L/L$ considerations just mentioned, the mount system may not be isothermal or may not have the temperature distribution planned for by the designer. Why is it that we always tend to beat up on the thermal guys? Athermalized designs in general depend on isothermal conditions. In some cases athermalization can accommodate linear gradients but we'll ignore those for now. The effect of off-nominal temperature distributions may be important in some configurations and in those instances needs to be evaluated. Either the athermalization might not behave as expected and a few errant micrometers of displacement might sneak in or worse, thermal stresses might break the glass.

- *Verifiable Before Assembly to the Flight Glass.* This applies to all mount assemblies but is most germane to those configurations where the possibility exists for interferences or high local shear or direct bearing loads to occur. If the mount is designed to be athermalized by the subtractive effect of two relatively high (compared to the glass) expansion materials and if there's a (credible) possibility that the $\Delta L/L$ or the temperature issues identified above might be a problem, verify the assembly in a test piece whose possible loss can be afforded before committing to the "real thing."

- *Insensitive to Machining and Assembly Tolerances.* All parts in the real world only approximate the dimensions that the designer wishes they might have. The smaller the part, in general, the larger these tolerances are as a percentage of the nominal dimension and therefore, the more sensitive that assembly might be to these variances. Worst case tolerance buildups need to be considered in evaluating the interface loads. Where applicable, the parts should be able to be adjusted by shims or machining or whatever to compensate for tolerance buildup.

- *Disassemblable, Just In Case.* Bonding is in many instances a convenient and uncomplicated way to join the mirror to its mount. But it doesn't come apart too easily if recoating or refiguring or, heaven forbid, redesign of the mount is required.

- *Not Dependent on Bond-line Flexibility.* Don't rely on the "...3-mil bondline .... giving a little in compression" to accommodate the relative expansion between Invar and quartz. Even over a relatively small 15°C temperature change, it doesn't! Bondlines for certain adhesives can be made deterministically flexible in shear by dicing the surface into a multitude of discrete pads whose dimensions (thickness and size) are selected on the basis of structural mechanics.

- *Manufacturable and Assemblable.* Don't expect that manufacturing engineering necessarily understands all of the subtleties of the design that you as the designer (hopefully) had in mind, especially when developing a new concept. The design of any assembly tooling or fixtures needs to be an inherent element of the mount design process.

- *Able to Accommodate Small Clearances or Able to Accommodate Small Interferences as an Alternative.* Unless it's an all-bonded design, there is the possibility that some clearances will exist at the glass-to-metal interface, and at other places too if cylindrical or spherical pivots are used. In fact, some designs deliberately provide for clearance to avoid the interference nightmares that I've been writing about. There's three things at least that one needs to consider relative to clearance in a design.

    1. Is it small enough so that excessive shocks will not be developed? Is the clearance sufficiently small that a "free-fall" at 5 g's for example doesn't introduce excessive shock. The velocity at impact resulting from a 1 mil "drop" in a 5 g acceleration field is about 2 inches per second, a lot slower than most of us would put down a coffee cup.

2. Are the parts protected from impact shock during launch (regardless of the gap size) by some absorbant material, such as the aluminum shims mentioned earlier?

3. Does the design provide for a preload to ensure that the mirror is constrained against a registration surface subsequent to launch? Will the preload spring overcome friction or anything else that might "hang" the mirror up and prevent it from being nudged towards the registration surface.

- *Based on Some Demonstrated Heritage, If at all Possible.* Always a nice attribute! Sometimes though a precedent can't be found. Which brings us to the final element in this checklist...

- *Verified by Test, Before Committing to Flight Hardware.* It is often not practical to test a complete mirror/mount assembly in a simulated operational environment where the success criteria is typically a figure error change of 0.01 waves rms or so. To a large extent we depend on accurate finite element modeling for that. But the results of the model need to have some "anchor point" into reality and that can be obtained from subscale tests of a mount and a mirror test piece which represents only the region where the mount is located. Cryogenic systems such as SIRTF are possibly more dependent on engineering development tests in as much as the expansion properties of materials over the 500°F range from room temperature to a 2K operating temperature are far from constant or even linear.

6. OTHER CONSIDERATIONS

6.1. Drawings

One of my pet peeves, especially today, is that the mechanical architecture of a system is often left unexplored until too late in the design process. Insufficient priority in the initial architectural trades can result in structures which are sometimes awkward, difficult to align and integrate, and overly complicated which of course means risk and cost. There are three drawings of extreme importance to the mechanical engineering of any space optical system and they need to be developed right up front. They are the:

a) optical drawing
b) functional layout
c) mechanical or physical layout.

A brief description of each of these drawings is in order.

The optical layout needs to be a large scale, dimensioned, and accurate drawing depicting all of the optical surfaces, ray bundles (in the case of scanning systems the swept volume of the scanned bundles needs to be included) and baffling. It needs to be done in at least two views, unless the system is perfectly axisymmetric. The clear aperture of all elements should be readily discernable. It does not necessarily need to include folds should the system require them for packaging or space allocation reasons. These can be depicted on the functional layout.

The functional layout is a very important drawing. It defines the location and volumes of all equipment that must be positioned in a specific way to the optical surfaces. This includes the thickness of the substrates, focal plane devices and radiators, alignment sensing instrumentation, calibration sources, and so on. If the system needs to be folded, this is the place to show that. The interfaces with adjoining equipment need to be explicitly defined. Where alignment adjustments will be made should be identified. If there are specific access requirements or installation and removal paths that are required, they need to be shown. The HST science instrument replacement paths are an example of one such requirement. This drawing ideally should depict the system as if the structure was "invisible." Secondly, those components that don't have any specific location requirement with respect to the optics are not shown. Electronics boxes are one such example.

The mechanical layout builds on this drawing by adding the structure and everything else. It needs to be consistent with interface envelopes and other space allocation requirements. It is at this time that any potential problems insofar as insufficient volume or excessively contorted load paths would be identified and presumably it would be early enough in the program to resolve any difficulties. This drawing provides the first real-world visualization of the system and as stated earlier, establishes the direction that the opto-mechanical aspects of the program will follow. The importance of this drawing, often the culmination of significant concept trades, to the overall success of the project cannot be overemphasized.

6.2. Modeling and Analysis

In the beginning there was Roark, Timoshenko, the moment distribution method, free-body diagrams, and Friden calculators. Accurate analysis of a point design was difficult enough, not to mention analysis and trades between competing design concepts. Optical performance criteria, as they flowed down to a mirror for example, were often specified as a "single valued" number, the rms wavefront. The emergence of finite element codes and their application to optical structures began in the late 1960s, with simple branched beam models whose principal use was in estimating dynamic characteristics. Today we have at our disposal sophisticated finite element codes which may be invoked both during the design phase for architectural and concept trades and later for performance predictions of the detailed and matured final design. Today we have the ability to model with unprecedented accuracy the behavior of mirrors under thermal, gravity, and mount constraint force loadings. The CTE distribution in the substrate can be modeled with measured data supplied by the manufacturer to determine precisely what the surface errors will be as a function of temperature change. We can use the resulting displacement data in optical performance codes to determine the specific nature of the image defects, whether they be in the geometric or diffractive regime.

So why do anomalies still occur? What happens when test and analysis don't agree or more acutely, when orbital performance is significantly different from what had been predicted? Unfortunately, no amount of analysis can make a poorly conceived design perform any better than it is intrinsically capable of. Secondly, the mere existence of a detailed finite element model does not necessarily pre-ordain the behavior of the structural systems. When these anomalies occur, costs increase due to program delays, "tiger team" investigations, diminished incentive fees, and the like. In concluding these remarks, I would like to offer a few cogent observations regarding the role of modeling and how to maximize agreement between prediction and test.

a) *Carefully review the design.* Does the as-built system look like what the analyst and the designer anticipated? If it doesn't, it's unlikely to provide accurate results. Some things to look for are:

  - Has the FEM been updated to reflect the geometry and supported loads of the as-built hardware or is it a relic from the CDR?

  - How are cable bundles accounted for? They may have a significant effect on the performance of low expansion structures.

  - Is the modeled weight the same as the actual weight? What about the CG?

b) *Carefully review the models.* Are the structural models behaving as expected? Over the years, we have become more and more confident about our FEMs and have begun to accept their results as being absolutely accurate. In many instances this confidence is justified but not in the world of large optical structures, at least not yet, where success or failure is measured in micrometers or even less of deformation. Some questions to ask yourself are:

  - Is there anything in the loadpath that might lead to anomalous performance? In composite structures, for example, are there any regions where the high expansion, through-the-thickness direction of the laminate is not accounted for. Three millimeter thick shear webs, if not specifically accounted for in the design of the HST metering truss, would have produced 3 μm of despace, twice the allowable for that 5-m long structure.

  - Have lower level assembly tests been performed and compared with predictions before subsystems are combined, often masking anomalies that might have been discovered earlier?

  - Joints are often a major source of inaccuracy, especially with composite structures because of complex geometries coupled with non-orthotropic material properties. Test joints at an engineering development test level and develop an accurate FEM representation of it.

  - How well are material properties in the models represented? This is especially true of composites where not only must part-to-part CTE variations be expected and accounted for, repeated thermal cycling can alter the CTE of certain laminate designs. In critical applications, measure the individual parts before assembly and account for it in the models. This applies to composites, mirror substrates, and certain metals, notably Invar.

- The CTE of most engineering materials change with temperature. This needs to be accounted for in the models. In the case of systems where the operating temperature range is far from assembly temperature, the effect of the different $\Delta L/L$ characteristics of the different materials comprising the structure need to be accounted for. Simply using the RT or even average CTE over the range may be insufficient to avoid unanticipated interferences at operating temperature. This is especially important in the area of mirror mounts for cryogenic systems.

c) *Carefully review the test.* Particularly in thermal/vacuum testing, the impressed temperatures may not be what had been used for the pre-test analysis. Ensure that sufficient instrumentation exists to determine the actual temperature distributions.

   - Are the test conditions identical to those used for analysis? Is the system at equilibrium? Is it outgassed in the case of composites?

   - Have the test fixtures been included in the thermal and structural models, i.e., does the model represent the test?

A more complete description of these and additional subtle issues associated with optical structures and the factors that set them apart from more conventional applications is contained in "Athermalization of Optical Structures" by Krim, dated 1/23/92, and published as Short Course Notes by the SPIE.

It is hoped that what is presented here will be a valuable adjunct to the other more technically focused papers contained in this compendium. As stated at the outset, this was not intended as a design manual or even as a summary definition of the state-of-the-art in designing for optical systems for space operation. Rather it is offered as a guide or checklist to help round out the total perspective of design in today's cost-driven environment and to that end, I hope that I have been successful.