Design of Highly Stable Optical Support Structure

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Introduction

As spaceborne optical systems increase in diameter to achieve improved resolution, the stability requirements imposed on structures approach values which were unthinkable only several years ago. To achieve the capabilities of these apertures optical path errors must not exceed a specific fraction of the wavelength of light, and this fraction, typically $\lambda/20$ rms in the focal plane, is independent of system size. Thus, from a percentage error basis, large optical support structures represent a far more formidable development task than do smaller systems. The Large Space Telescope (LST) sponsored by MSFC/NASA is a case in point. The Optical Telescope Assembly (OTA) is shown (Fig. 1) installed in the LST spacecraft. The vertex-to-vertex spacing of the primary and secondary mirror is 193 inches. To achieve satisfactory optical performance, this spacing must be maintained constant to a precision of $\pm 1\mu$ for observation periods up to 10 hours. During this time it may be necessary to alter the spacecraft attitude with respect to the sun, which would change the temperature levels and gradients within the structures. It is believed that by exploiting the use of graphite-epoxy in a novel manner, the stringent alignment requirements can be satisfied with a nominally passive structure.

Design Requirements

Although principally driven by optical alignment criteria, the LST optical structures must also satisfy other technical requirements. These include strength, weight, dynamic, and cost constraints. Only those which include on-orbit alignment criteria, however, are discussed in this article.

Thermal Loads

It will be shown that the thermal changes, which occur between factory and orbit, are not critical to system performance. But the thermal changes that can occur subsequent to arrival on station are of consequence. The thermal design envelope, shown in Fig. 2, was developed from analyses of various vehicle pointing attitudes and heater system control accuracies. The envelope represents the maximum anticipated change that might occur during a single target observation.

Alignment Requirements

The working depth of focus at the f/24 image plane is $\pm 432\mu$ at 0.63μ wavelength. By applying the simple lens formula

$$\frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2}$$

to the two mirrors successively, the following useful relationship is obtained relating defocus to changes in mirror radii and spacing.

$$\Delta f = \left\{ \begin{array}{l} \left[(2\ell_1 - R_1 + R_2)\frac{R_2}{2} + \left(\frac{R_1 R_2}{2} - R_2\ell_1\right)\right]\partial R_1 \\ \left[(2\ell_1 - R_1 + R_2)\left(\frac{R_1}{2} - \ell_1 - \frac{R_1 R_2}{2} - R_2\ell_1\right)\right]\partial R_2 \\ \left[(2\ell_1 - R_1 + R_2)(-R_2) - 2\left(\frac{R_1 R_2}{2} - R_2\ell_1\right)\right]\partial \ell_1 \end{array} \right\} \div (2\ell_1 - R_1 + R_2)^2$$

The change in radius of curvature, ∂R, is equal to

$$\partial R = R\alpha\Delta\overline{T} + \frac{R^2\alpha\Delta T'}{h}$$

where the former relates to a uniform temperature change $\Delta\overline{T}$ and the latter to a change in the gradient through the mirror thickness, ΔT. The effect of material in homogeneity, a difference in α between the front and back of the mirror would simply be

$$\partial R = \frac{R^2\Delta\alpha\Delta\overline{T}}{h}$$

The terms employed in these equations are defined in Fig. 3.

For the system parameters shown in Fig. 3,

$$\Delta f = 58\,\partial R_1 - 48\,\partial R_2 - 117\,\partial \ell_1.$$

A (-) sign indicates a movement of the focus toward the primary mirror, i.e., for a positive $\partial\ell$, or an increase in the primary-to-secondary spacing, the focus moved toward (-) the primary. The system defocus is the difference between the change in focal plane position, Δf, and the change in position of the mechanical focal plane, $\partial\ell_2$.

With the above equation the tolerance on despace, $\partial\ell_1$, is developed. Based on the system thermal analysis prepared by J. Bartas of Perkin-Elmer the maximum $\Delta\overline{T}$ and $\Delta T'$ for the primary and secondary mirrors are

	$\Delta\overline{T}$	$\Delta T'$
Primary	$\pm 1.8°$F	0.45°F (cold front)
Secondary	$\pm 1.8°$F	1°F (cold front)

The result in a focus change, Δf, of

	$\Delta\overline{T}$	$\Delta T'$
Primary	$\pm 1.7\mu$	-171μ
Secondary	$\pm 1.7\mu$	-32μ

which added on an RSS basis is 175μ. Allowing for a focus sensing and correction (initial alignment) error of 100μ and another 50μ for growth of $\ell_2 (7.5)\mu/F°$) and location

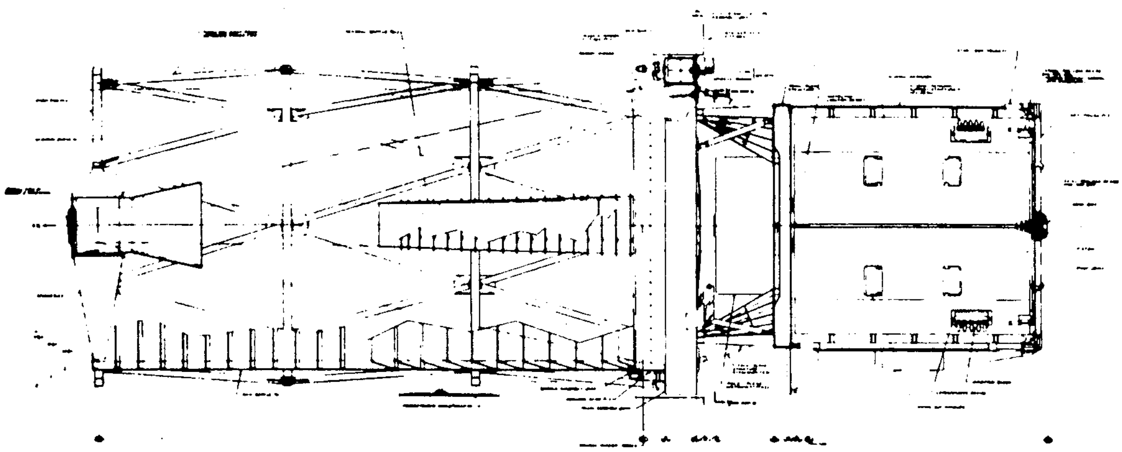


Fig. 1. 2.4 Meter OTA/SI Configuration.

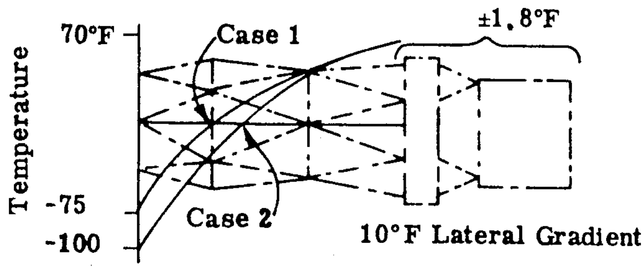


Fig. 2. Thermal Design Envelope.

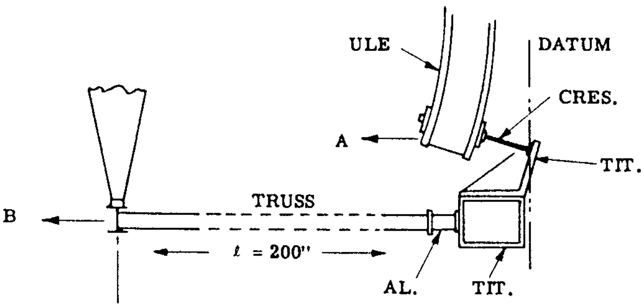


Fig. 4. Despace Paths.

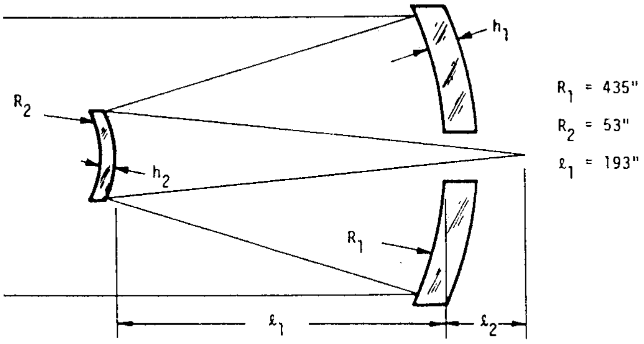


Fig. 3. Optical System Parameters.

uncertainty of the four Science Instruments, 107μ remain for the effect of a change in ℓ_1, as $\partial \ell_1$ equals approximately 1μ. Through reapportionment of tolerances and refinement of the manner in which they add, this despace requirement can be relaxed to 1 - 1/2μ. Regardless, over a 200 inch structural path length and over the temperature extremes presented in Fig. 2, attainment of this despace alignment is a formidable engineering challenge.

While the decenter and tilt tolerances were developed separately from ray tracing, the critical design driver actually was the despace.

Design Approach

The structural path that controls primary-to-secondary mirror despace is illustrated in Fig. 4. From a common datum where the primary mirror attaches to the main telescope ring, the primary and secondary mirror components of despace are calculated. The primary mirror axial position reference is established by mount design on the back surface. The displacement of the primary mirror, ΔA, is

$$\Delta A = (\alpha_1 \ell_1 + \alpha_2 \ell_2 + \alpha_3 \ell_3 + \alpha_4 \ell_4)\Delta \overline{T}$$

$$\Delta A = 51 \times 10^{-6} \text{ in/F}^\circ (1.3\ /\text{F}^\circ)$$

Similarly

$$\Delta B = (\alpha_5 \ell_5 + \alpha_6 \ell_6 + \alpha_5 F_5)\Delta \overline{T} + \Delta \ell_T$$

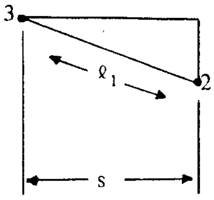
The term $\alpha_5 F_5 \Delta \overline{T}$ accounts for the quasi-Poisson effect in the truss caused by expansion of the ring. The length ℓ_6, actually a trim spacer, is intended to make ΔA equal to ΔB when the truss elongation, $\Delta \ell_T$, is zero. Thus from a despace aspect the system is insensitive to the anticipated ±1°C changes in the main ring temperature. Since α_1 through α_6 are in physical contact and since the ring and mirror are heater controlled to 21° ± 1°C, it is reasonable to expect that elements 1 through 6 will be isothermal.

ΔB is equal to $(70 \times 10^{-6} - 3.4\alpha_5)\Delta \overline{T} + \Delta \ell_T$, where F_5 is -3.4 and ℓ_6 is 1.6" of aluminum.

To calculate the factor F_5 an equation was developed relating the axial expansion of a truss bay (which can be summed over the total number of bays) to the ring and strut geometry.

Figure 5 illustrates the geometry of a single bay showing projection normal to axes 1 and 2.

Consider the projection on plane 2 (looking along axis 1)



$$\alpha = R\sin\theta \qquad s = [\ell^2 - a^2]^{1/2}$$

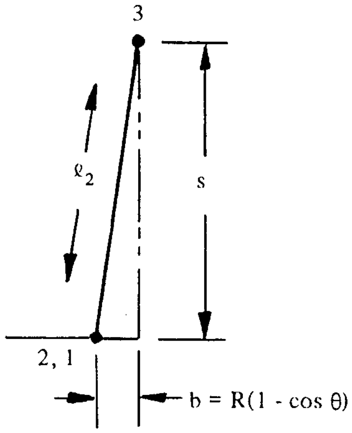
$$\partial s = 1/2[\ell^2 - a^2]^{-1/2}(-2a)\partial a$$

$$\therefore \Delta s = -\frac{a\Delta a}{s} \qquad a = R\sin\theta$$

$$\Delta a = R\sin\theta\,\alpha\Delta T$$

$$\boxed{\Delta s_1 = \frac{(R^2\sin^2\theta)\alpha\Delta T}{s}} \quad \text{(for each ring)}$$

Consider the projection on plane 1



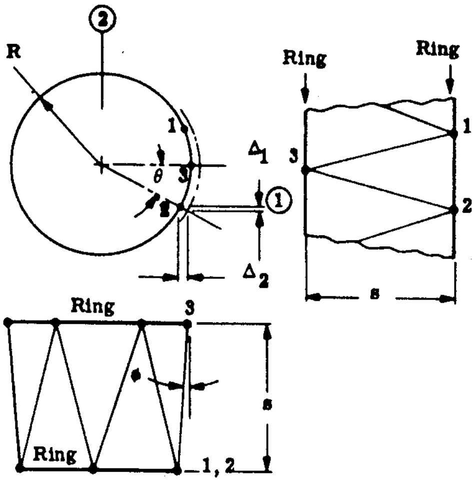
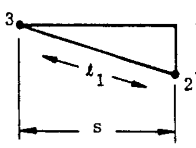


Fig. 5 Truss Bay Geometry

Consider the projection on plane 2 (looking along axis 1)



$$\alpha = R\sin\theta \qquad s = [\ell^2 - a^2]^{1/2}$$

$$\partial s = 1/2\,[\ell^2 - a^2]^{-1/2}\,(-2a)\,\partial a$$

$$\therefore \Delta s = -\frac{a\Delta a}{s} \qquad a = R\sin\theta$$

$$\Delta a = R\sin\theta\,\alpha\,\Delta T$$

$$\boxed{\Delta s_1 = \frac{(R^2\sin^2\theta)\,\alpha\Delta T}{s}} \quad \text{(for each ring)}$$

Fig. 5. Truss Bay Geometry.

For the lower ring in the diagram

$$\Delta S_2 = \frac{R^2\cos\theta\,\alpha_R(1 - \cos\theta)\Delta T_B}{s}$$

A similar expression can be derived for the top ring so the effect of both rings are added,

$$\boxed{\Delta S_2 = \frac{R^2\alpha_R\cos\theta(1 - \cos\theta)(T_T + T_B)}{s}}$$

and Δ is understood.

Also

$$\boxed{\Delta S_3 = \frac{\ell\Delta\ell}{s} = \ell^2\alpha_\ell T_L}$$

Summing ΔS_1, ΔS_2, ΔS_3.

T_T = Temp change of top ring
T_B = Temp change of bottom ring
T_L = Temp change of strut

$$\boxed{\Delta S = \frac{1}{s}\,[\ell^2\alpha_s T_s + R^2\alpha_R(\cos\ \ - 1)(T_T + T_B)]} \qquad (1)$$

From this equation, F_5 can be determined. In the case of a temperature rise in element 5 only T_L and T_T equal zero and

$$\Delta S = \frac{1}{s}\,R^2\alpha_R(\cos\theta - 1)\Delta T$$

For the LST truss

S = 67 inches $\alpha = 4.9 \times 10^{-6}$ in/in/F°
R = 55.5 inches θ = 22.5°

So $\Delta S = F_S = -3.5\ \alpha$ inches/F°

With the local effects in the main ring and mirror mount accounted for and negated, full attention is now directed toward the metering truss itself.

In elementary terms the elongation of the truss resulting from the change in axial gradient shown in Fig. 2 is

$$\Delta_t = \frac{1}{2}\alpha_E \ell_t \Delta T$$

or

$$\alpha_{t_{reqd}} \leqq 0.015 \times 10^{-6}\ \text{in/in/F}^\circ$$

for an elongation of 1μ. The fundamental problem facing the structural designer is twofold. One, the variability of α from a design nominal is on the order of ±0.05 ppm/F° for graphite-epoxy laminates and two, the expansivities at the various nominal temperatures along the truss length may be different.

To solve the variability problem, a means of adjusting the expansivity of the elements forming the structure is required. Ideally this adjustment should be performed in the post-cured condition so that process variables can be compensated. Further, the adjustment on tuning should not introduce additional process variables but should be a discrete operation. Finally, the tuning elements should not locally alter the thermal diffusivity of the member, otherwise transient behavior would be compromised. The concept described herein meets these requirements.

The concept, as applied to tubular members such as those forming a truss, is illustrated in Fig. 6. Here a single strut is constructed from a single graphite-epoxy system but with different laminate (i.e., layup) geometry in the left- and right-hand sections. On the left, for example, the laminate would be designed so that its expansivity, considering the process variables is $0 \pm 0.1 \times 10^{-6}$. To the right of the transition zone it would be $0^{+0.1}_{-0} \times 10^{-6}$. Obviously a net thermal expansion of zero could be achieved if the left- and right-hand sections could be proportional such that

$$\alpha_L \ell_L + \alpha_R \ell_R = 0$$

or some desired finite value. The difference in expansivities of the right- and left-hand sides is achieved by one of several methods. The wrap angle of the laminate may change at the

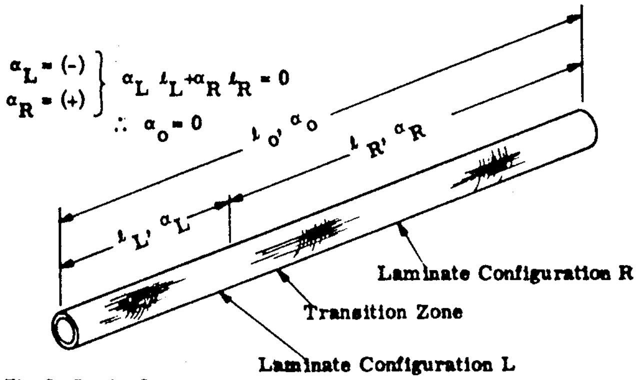


Fig. 6. Dual-α Strut.

transition zone as the number of layers in each section could be different. An angular difference of 5 degrees in a $[0°/\pm\theta/90°]_S$ laminate can alter the expansivity by 0.2×10^{-6} in/in/F°, for example. To achieve a specific expansivity the following procedure could be employed.

1. Construct a member as shown in Fig. 7 with different expansivities in the left- and right-hand sections. Note that the number is longer than actually desired in the finished piece.

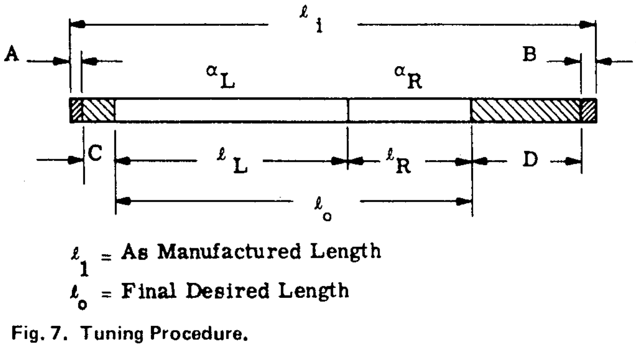


Fig. 7. Tuning Procedure.

2. After curing, remove a short section A and B from each end and measure the coefficient of expansion actually achieved. This is performed using a Fizeau interferometer.

3. The expansivity of the length ℓ_o is

$$\alpha_o = \frac{\ell_L \alpha_L + \ell_R \alpha_R}{\ell_o}$$

Since Since

$$\ell_L = \ell_o - \ell_R$$

$$\alpha_o = \frac{(\ell_o - \ell_R)\alpha_L + \ell_R \alpha_R}{\ell_o}$$

and for the case where $\alpha_o = 0$

$$\ell_o \alpha_L - \ell_R \alpha_L + \ell_R \alpha_R = 0$$

or or

$$\ell_R = \left(\frac{\alpha_L}{\alpha_L - \alpha_R}\right)\ell_o$$

where α_L and α_R have been determined by actual measurements.

4. The distance ℓ_R is measured off from the transition zone and the length D sawed off. The distance ℓ_o is measured back from this cut end and C removed.

5. The resultant strut will have the required length, ℓ_o, and the specific expansivity, α_o, desired. The tolerance on α_o is a function of the precision with which α_R and α_L are measured and the accuracy with which the center of the transition zone is located. This tolerance will be far less than the basic laminate tolerances to which the member is initially fabricated.

Final verification of the member is obtained by measuring α_o over the length ℓ_o with such a dilatometer.

The α measurement of the end coupons, A and B in Fig. 7 are made at the nominal operating temperature of the members for which they are intended. This solves the second problem, that of α variations with temperature. This form of construction and tuning is also applicable to the curved segments that comprise the truss rings. Struts may be tuned for zero expansivity when subjected to a uniform temperature change, $\Delta\overline{T}$, which results in a minimal error when a gradient is also present, or zero for a gradient, $\Delta T'$, which results in an error for a uniform change. Considering the struts of a truss bay to be arranged in pairs with alternating (+) and (–) mating ends shown in Fig. 8, the effective α is

$$\alpha_{eff} \cong \frac{1}{2}\left[\frac{\alpha_1\alpha_2}{\alpha_1 - \alpha_2} - \frac{\alpha_3\alpha_4}{\alpha_3 - \alpha_4}\right]$$

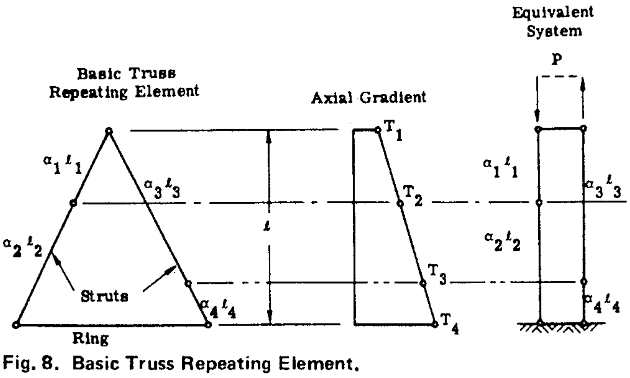


Fig. 8. Basic Truss Repeating Element.

The development of this expression is shown in the following analysis.

$$\Delta_1 = \alpha_1 \ell_1 \frac{T_2 + T_1}{2} + \alpha_2 \ell_2 \frac{T_4 + T_2}{2} - \frac{P\ell}{AE}$$

$$\Delta_2 = \alpha_3 \ell_3 \frac{T_3 + T_1}{2} + \alpha_4 \ell_1 \frac{T_4 + T_3}{2} + \frac{P\ell}{AE}$$

For compatibility, $\Delta_1 = \Delta_2$

$$\therefore \boxed{\Delta_1 = \alpha_1 \ell_1 \frac{T_2 + T_1}{4} + \alpha_2 \ell_2 \frac{T_4 + T_2}{4} + \alpha_3 \ell_3 \frac{T_3 + T_1}{4} + \alpha_4 \ell_4 \frac{T_4 + T_3}{4}}$$

For zero-α tuned dual-α struts

$$\alpha_1 \ell_1 = -\alpha_2 \ell_2$$

$$\alpha_3 \ell_3 = -\alpha_4 \ell_4$$

therefore

$$\Delta_1 = \alpha_1 \ell_1 \left(\frac{T_1 - T_4}{4}\right) + \alpha_3 \ell_3 \left(\frac{T_1 - T_4}{4}\right)$$

If $T_1 \equiv 0$ so that T_4 represents the axial gradient

$$\Delta_1 = \alpha_1 \ell_1 \left(\frac{-T_4}{4}\right) + \alpha_3 \ell_3 \left(\frac{-T_4}{4}\right)$$

From $\alpha_1 \ell_1 = -\alpha_2 \ell_2$ where $\ell_2 = \ell - \ell_1$

$$\ell_1 = -\ell \left(\frac{\alpha_2}{\alpha_1 - \alpha_2}\right)$$

and

$$\alpha_3 = -\alpha \left(\frac{\alpha_4}{\alpha_3 - \alpha_4}\right)$$

so

$$\Delta_1 = \alpha_1 \ell \left(\frac{\alpha_2}{\alpha_1 - \alpha_2}\right)\left(\frac{T_4}{4}\right) - \alpha_3 \ell \left(\frac{\alpha_4}{\alpha_3 - \alpha_4}\right)\left(\frac{T_4}{4}\right)$$

After collecting terms,

$$\boxed{\Delta_1 = \frac{\alpha_1 \ell}{4}\left(\frac{\alpha_2}{\alpha_1 - \alpha_2}\right)\Delta T + \frac{\alpha_3 \ell}{4}\left(\frac{\alpha^4}{\alpha_3 - \alpha_4}\right)\Delta T \text{ where } \Delta T \equiv T_4}$$

The effective expansivity of strut pairs for several combinations of α_1, α_2, α_3, and α_4 is shown in Table 1.

Note the α_{eff} is on the order of 1/10th the basic laminate tolerance for these cases. On the other hand one may consider a single strut subjected to a temperature change shown in Fig. 9. The expansion of the strut caused by the $\Delta T'$ component of the temperature change is

$$\Delta \ell_o = \alpha_1 \ell_1 \frac{T_1 + T_3}{2} + \alpha_2 \ell_2 \frac{T_2 + T_3}{2}$$

which, after some manipulation, becomes

$$\Delta \ell_o = \left[\alpha_1 \frac{\ell^2}{\ell_o} + \alpha_2 \ell_2 \left(\frac{\ell_1}{\ell_o} + 1\right)\right] \frac{\Delta T'}{2}$$

and considering both components of ΔT

$$\Delta \ell_o = [\alpha_1 \ell_1 + \alpha_2 \ell_2]\Delta \overline{T} + \left[\alpha_1 \frac{{\ell_1}^2}{\ell_o} + \alpha_2 \ell_2 \left(\frac{\ell_1}{\ell_o} + 1\right)\right] \frac{\Delta T'}{2}$$

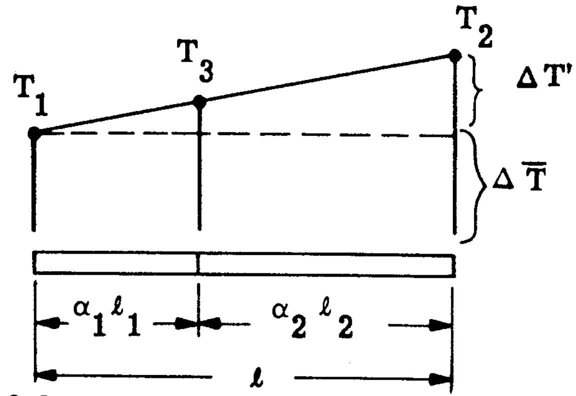


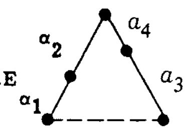
Fig. 9. Strut Temperature Change.

Thus, depending on the relative severity of the predicted $\Delta \overline{T}$ and $\Delta T'$, tuning may be biased to favor the more critical condition. If, for example, the strut in Fig. 9 is tuned so that $\ell_1 = [\alpha_2/(\alpha_2 - \alpha_1)]^{1/2}\ell_o$, i.e., $\Delta \ell_o$ is zero for a gradient $\Delta T'$ and that $\alpha_1 = -0.03$ and $\alpha_2 = +0.02$ ppm/F°, the effective expansivity in the presence of a uniform temperature

Table 1. Effective Expansivity

FOR AN AXIAL GRADIENT CONDITION:

$$\alpha_{o_{eff}} = \frac{1}{2}\left[\frac{\alpha_1 \alpha_2}{\alpha_1 - \alpha_2} - \frac{\alpha_3 \alpha_4}{\alpha_3 - \alpha_4}\right] \quad \text{WHERE}$$



$\alpha_1 = 0.05$, $\alpha_2 = -0.05$, $\alpha_3 = -0.05$

α_4	0	0.01	0.02	0.03	0.04	0.05
α_e =	-0.013	-0.008	-0.005	-0.003	-0.001	

$\alpha_1 = 0.05$, $\alpha_2 = -0.03$, $\alpha_3 = -0.05$

α_4 =	0	0.01	0.02	0.03	0.04	0.05
α_e =	-0.009	-0.005	-0.002	0	0.002	0.003

$\alpha_1 = 0.05$, $\alpha_2 = -0.03$, $\alpha_3 = -0.03$

α_4 =	0	0.01	0.02	0.03	0.04	0.05
α_e =	-0.005	-0.006	-0.003	-0.002	-0.0008	0

$\alpha_1 = 0.025$, $\alpha_2 = -0.025$, $\alpha_3 = -0.03$

α_4 =	0	0.01	0.02	0.03	0.04	0.05
α_e =	-0.006	-0.003	0	0.001	0.002	0.003

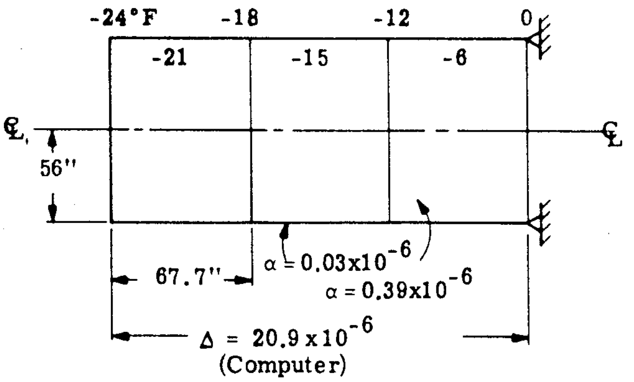
change, $\Delta\bar{T}$, is -0.011×10^{-6} in/in/F°. However, by alternating the (+) and (−) ends of the struts in the assembly the ratio ℓ_1/ℓ_2 of (+) and (−) segments will alternate with respect to $\Delta T'$ and the sign of $\alpha_{eff}(\Delta T)$ will change. Hence, in the complete truss assembly, cancellation will occur in a manner similar to that described in Fig. 8.

The sensitivity of the overall truss assembly of off-nominal (non-zero) values of α may be assessed by use of Eq. (1). This equation was also employed as a check on a finite element model of the truss which was then used to determine the deformations caused by more complex thermal conditions, such as axially varying side-to-side temperature gradients. At the time this paper was written work had not been completed on the final math model. In this model each strut is modelled with two discrete lengths with the transition node (mid-length grid point) randomly located and with separate material properties "cards" for each element of the model. The model used in the studies thus far employs 48 bar elements for the struts and 16 bar elements for each of the four rings. A total of 65 nodes with 390 degrees of freedom describes the deformations of the structure.

From the closed form solution, the change in length of each truss bay is given by

$$\Delta S = 74.75\,\alpha_S T_S - 3.53\,\alpha_R (T_B + T_T) \text{ inches}$$

The comparison between the results of the finite element model and the successive bay by bay use of the above exact equation is shown in Fig. 10. This excellent correspondence, limited only by round-off accuracy confirms the validity of the finite element model for more complex temperature profiles. Note that if α_R is $10.6\,\alpha_S$, ΔS is identical to zero when $T_S = T_B = T_T$ or the temperature change of the system is uniform. This form of temperature desensitization of structures has previously been used in telescope structures before the use of composites. In those instances the geometry of the structure was configured to satisfy α ratio constraints for titanium/aluminum combinations.



Solution:

$$\Delta s = 2.24264 \times 10^{-6}\ T_S - 1.375161 \times 10^{-6}\ (T_T + T_B)$$

Bay 1 $\Delta s = 3.0461 \times 10^{-6}$

Bay 2 $\Delta s = 7.615 \times 10^{-6}$

Bay 3 $\Delta s = 10.661 \times 10^{-6}$

$\Sigma\ \Delta s = 21.3 \times 10^{-6}$ by Formula

Fig. 10.

However, since this form of athermalization depends on the small difference of relatively large numbers (α in the case of metallic pairs) it is impractical except in those situations of precisely uniform soak conditions.

For the LST truss design under discussion here, the preceding equation can be used to examine the effect of laminate α tolerance on performance. Applying the temperature profile of Fig. 2, the axial deformation of the truss on a bay-by-bay basis is

Bay #1	$\Delta S_1 = -1570\,\alpha_S + 148\,\alpha_R$
Bay #2	$\Delta S_2 = -1121\,\alpha_S + 105\,\alpha_R$
Bay #3	$\Delta S_3 = -449\,\alpha_S + 42\,\alpha_R$

For a $\pm 0.05 \times 10^{-6}$ in/in/F° uncertainty or spread in the nominal strut (α_S) and ring (α_R) tolerances, the RSS despace error is 99×10^{-6} inches or 2.5μ. This is in excess of the 1 budget.

If tuned struts are employed where the nominal strut uncertainty is ±0.005 ppm/F° and the ring tolerance remains ± 0.05, the RSS uncertainty is reduced to 0.33μ. The wider ring tolerance is retained because

(a) the system is less sensitive to ring α uncertainties

(b) the ring is more difficult to tune.

To accomplish uniform soak athermalization, as opposed to a zero-α approach

$$\alpha_R/\alpha_S = \frac{74.75}{2 \times 3.53} = 10.588$$

As a consequence of the assumption that the axial gradient in the strut is linear,

Bay #1	$\alpha_R/\alpha_S = 10.588$
Bay #2	$\alpha_R/\alpha_S = 10.588$
Bay #3	$\alpha_R/\alpha_S = 10.588$

If, in this instance, $\alpha_S = 0.05 \times 10^{-6}$ and therefore $\alpha_R = 10.588 \times 0.05 \times 10^{-6} = 0.5294 \times 10^{-6}$, the change in length of each bay is obviously zero.

However, by applying a ±0.05 ppm/F° tolerance on α_R and α_S, a 2.1μ error in the first bay alone is possible. If the temperature change over a bay is not linear then the near match between uniform soak and gradient athermalization is defeated. For example, if the temperature change is as indicated in Fig. 11, $\Delta S_1 = 1420\,\alpha_S - 148\,\alpha_R$ the gradient ather-

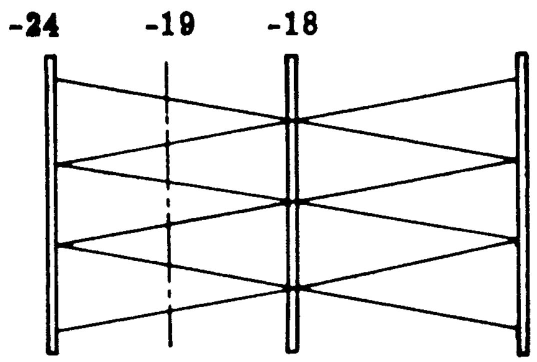


Fig. 11. Truss Temperature Change.

malization ratio would be 9.59. The associated despace error for this single bay is 0.2μ. Further, with ±1°C (1.8°F) uncertainties in the forward bay temperatures, the despace variability becomes approximately 0.4μ, for just a single bay. Based on the α tolerances previously discussed, individual piece part acceptance measurements are required. Tuning to zero or near zero α is a logical extension as it negates the effect of temperature uncertainties associated with athermalized structures.

The results of this approach are illustrated in Fig. 12, where the finite element model of the truss is subjected to simultaneous axial and lateral temperature gradients of 24° and 10°F, respectively. It must also be noted that careful attention is given the strut-to-ring joints to prevent a build-up of the graphite-epoxy thickness in the short transverse direction, where α is on the order of 25 x 10^{-6} in/in/F°. If this is not done, and assuming a total flange thickness of 0.18 inch per joint, an additional despace error of 3.6 could result. The joint design envisioned for the truss consists of a chopped fiber :(HiMAT) laminate whose expansivity is approximately 0.2 x 10^{-6} in/in/F°. The total length of these sockets is 8 inches over the entire truss, resulting in an additional despace error if only 0.5μ. This can be offset by setting the strut α values slightly negative. The truss design described in this paper weighs 242 pounds including the spider and has a first lateral mode of 26 cps, when supporting a total secondary mirror and mount of 70 pounds.

Condition	Despace	Decenter	Tilt
-1°F X-Tit. Ring	0.02μ	~0	~0
24°F Axial Gradient Change	0.37μ		
10°F Lateral Gradient	-0.11μ	0.3μ	0.01 sec

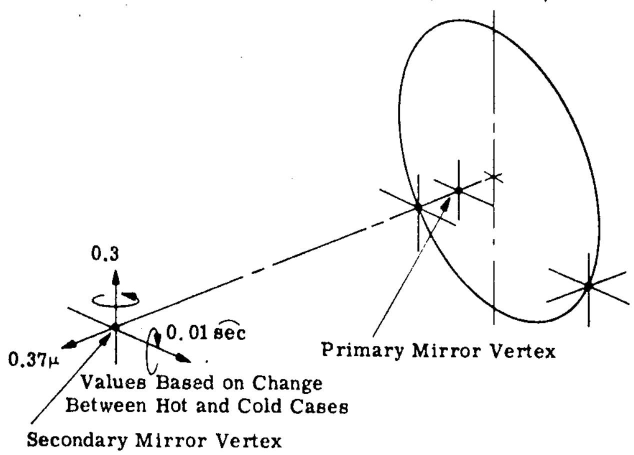


Fig. 12. Tuning to Near Zero.