Mass Efficiencies for Common Large-Scale Precision Space Structures

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This paper presents a mass-based trade study for large-scale deployable triangular trusses, where the longerons can be monocoque tubes, isogrid tubes, or coilable longeron trusses. Such structures are typically used to support heavy reflectors, solar panels, or other instruments, and are subject to thermal gradients that can vary a great deal based on orbital altitude, location in orbit, and self-shadowing. While multi layer insulation (MLI) blankets are commonly used to minimize the magnitude of these thermal disturbances, they subject the truss to a nonstructural mass penalty. This paper investigates the impact of these add-on thermal protection layers on selecting the lightest precision structure for a given loading scenario.

Nomenclature

A_b	=	Area of batten strut
A_d	=	Area of diagonal strut
A_l	=	Area of longeron strut
a	=	Length of truss bay
α	=	coefficient of thermal expansion
b	=	Length of truss batten
β_d	=	Scaling factor relating diagonal strut area to longeron area
β_b	=	Scaling factor relating batten area to longeron area
ΔT	=	Temperature gradient
δ	=	Thermal distortion
E	=	Modulus of elasticity
H	=	Height of truss
I	=	Moment of Inertia of truss
L	=	Total truss length
r	=	Radius of longeron
r_{coil}	=	Radius of coilable lattice longeron rod
r_{eff}	=	Radius based on total A_l of coilable longerons
R	=	Radius of truss
ρ	=	Volume density of graphite epoxy composite
ρ_{MLI}	=	Volume density of MLI blankets
t	=	Wall thickness of tube longeron
t_e	=	Wall thickness of isogrid longeron
t_{MLI}	=	MLI blanket thickness
f	=	Natural frequency
M	=	Total system mass

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I. Introduction

Increased science requirements for space-based instruments over the past few decades have amplified the need for large-scale support structures that are not only deployable, but also low in mass. Popular applications such as optical and RF reflectors and membrane antennae demand high-precision structural components to meet stringent flatness requirements. While thermal deformations are neglected for some types of satellites, designs for these precision structures must include such effects, which are proportional to material thermal properties and bulk temperature change. Since material properties are difficult to alter, thermal blankets (also known as multi layer insulation (MLI)) are often added to key structural components to minimize temperature variations. While this added insulation is effective, it imposes a non-structural mass penalty.

There are many spacecraft missions in the concept or development phase that will require structural hardware that is on the scale of up to hundreds of meters, with potentially larger structures in the future. Examples of these large structures, which are typically subjected to small bending, compressive, or torsional loads, include solar sails, sunshades, and large aperture reflectors. Such large assemblies will have to be as light as possible, thus requiring long, slender structural members. This architecture has generated some interest in hierarchical structures, that is, for example, a truss whose members are more complex than a simple rod, such as hollow tubes or even smaller trusses. It has been well documented that for trusses of equal weight, the one that is composed of tubular components is stronger than one whose elements are solid rods.[1] While thin-walled tubes offer a great deal of benefit, their walls can become too thin for them to resist even small compressive loading, particularly in the presence of local damage such as wrinkles introduced during the packaging and deployment phase. To resolve this limitation, isogrid tubes have been investigated. These structures have tows of graphite fibers that form a skeleton of a tube, where the effective wall thickness is much smaller than could be realistically manufactured and used in a structure[2,3]. Another popular lightweight boom structure is the coilable lattice strut, commercially known as an Astromast available from Astro Research Corporation[4]. The seminal paper in the field of large scale, light weight space structures is by Mikulus[3]. This paper calculates the structural masses for the thin-walled tubes, isogrid tubes, and tubular and solid rod columns as a function of applied load. The failure criteria used is based on the expected buckling modes for, in particular, long, lightly loaded structures. The influence of imperfections, such as thermal gradients, manufacturing, and lateral accelerations, is addressed as well. Based on these strength-driven mass calculations, one is able to determine the lightest geometric configuration for a particular loading scenario. Sometimes, the isogrid tube is the most efficient, other times the thin-walled tube is a better option.

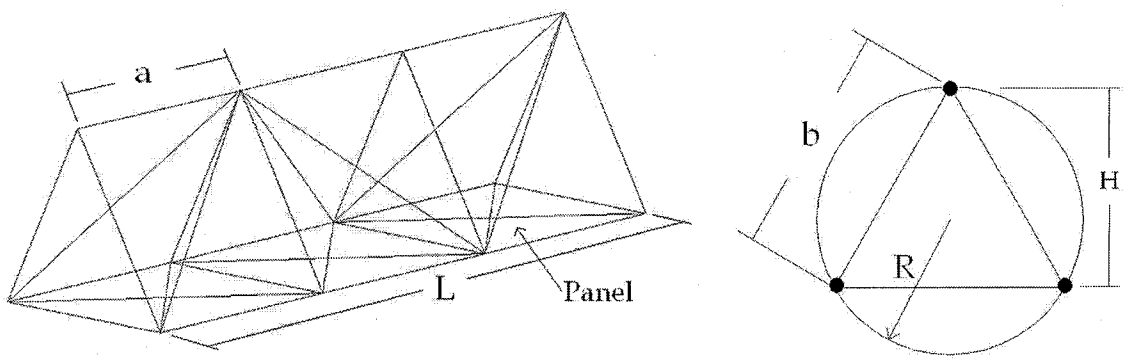
The current effort makes a similar type of comparison, however, the influence of thermal gradients and add-on MLI blanket mass is also considered in determining the lightest structure. The structure under consideration is a triangular truss, where the three longerons can be thin-walled tubes, isogrid tubes, or coilable lattice. It is assumed that the truss battens and diagonals will be insulated individually, as will the thin-walled tube and isogrid tube longerons. The solid rods that comprise the coilable lattice longerons will also be wrapped individually.

II. Description of Truss

This section will introduce the triangular truss configurations under consideration in this paper. The geometry and material properties will be presented, followed by basic equations that are used to analyze various types of mechanical behavior, such as thermal distortion and vibration characteristics.

A. Triangular Truss Definition

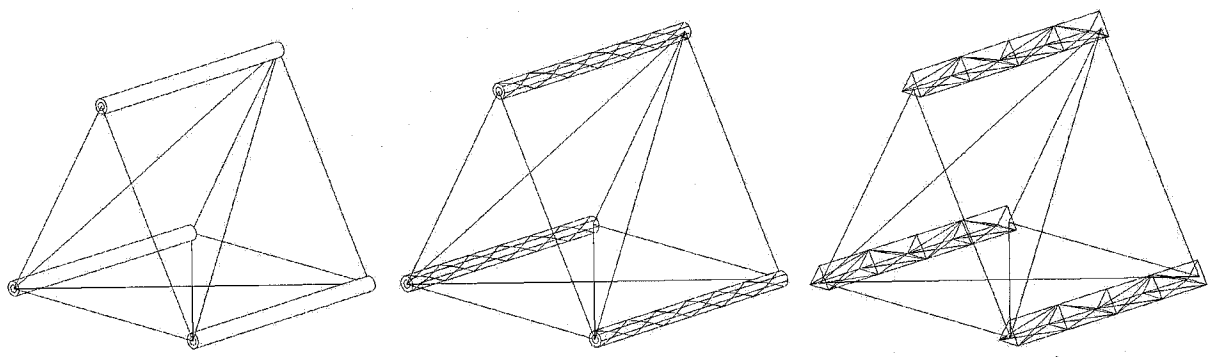
This paper considers the analysis of a single laced triangular truss with one double laced side. The double laced side is the one presumed to support a reflector panel, as seen on the bottom of the truss in Figure 1a. This truss, having a total length L, is depicted as having only three bays, however, the total truss is composed of n bays, each having length a. The reflector panel is assumed to be an L-band radar reflector that is 100 m long by 2 m wide and having an areal density of 15 kg/m^2. The mass of the reflector, as well as the spacecraft mass (taken to be 1000 kg) is assumed to be uniformly distributed for this preliminary investigation. The truss joints are assumed to behave in a pin-like manner. The cross section geometry of the triangular truss is shown in Figure 1b.



a) b)

Figure 1: Triangular truss definitions: a) 3D View of Truss, b) End View of Truss and Longerons

For the comparison study presented in this work, the three longerons in this truss are considered to have one of three geometry types: thin-walled tube, isogrid tube, or a coilable lattice strut. The repeating bay structures for the three types of longerons being considered are shown in Figure 2.



a) b) c)

Figure 2: a) Tubular Longeron Truss, b) Isogrid Tube Longeron Truss, c) Coilable Longeron Truss.

B. Truss Geometry and Material Properties

For the analysis of a triangular truss, a few formulae for the geometry and stiffness properties are required. The radius of the truss, defined in Figure 1b is[5]

$$R = \frac{b}{\sqrt{3}} \tag{1}$$

while the height H of the truss is given by

$$H = \frac{b\sqrt{3}}{2} \tag{2}$$

The moment of inertia about the centroid of the truss cross section is

$$I = b^2 \frac{A_l}{2} \tag{3}$$

where A_l is the cross sectional area of a single longeron. For a thin-walled tube longeron with radius r and wall thickness t, then the area is given as

$$A_l = 2\pi r t \tag{4}$$

For an isogrid longeron, the area is

$$A_l = 2\pi r t_e \tag{5}$$

where t_e is the equivalent thickness of the isogrid wall[3]. For the truss whose longerons are each a coilable lattice strut, the area calculation is a bit more complex. In this case, when the area of a longeron is calculated from a frequency or geometry requirement, as discussed later, the area is actually spread between the three rod longerons of the coilable lattice strut. Thus the radius of one of these rod longerons is

$$r_{coilable\ rod} = \sqrt{\frac{A_l}{3\pi}} \tag{6}$$

The geometry of the battens and diagonals is not investigated in detail, but rather, taken to be proportional to the area of the longerons[5], such that

$$A_d = \beta_d A_l \quad and \quad A_b = \beta_b A_l \tag{7}$$

In Eq. 7, A represents cross sectional area, β is a scaling factor, and the subscripts b, d, and l refer to batten, diagonal, and longeron struts, respectively. Equation 7 is valid for both the truss being considered (ie Figure 1a), as well as the coilable longeron trusses that comprise the longerons for the case of Figure 2c.

All members of the trusses under consideration are assumed to be made from a graphite epoxy composite material having quasi-isotropic in-plane material properties. To minimize thermal loading on the truss, MLI blankets can be added, which add a non-structural mass penalty. The required geometric and material properties for both the graphite epoxy and the MLI blankets are given in Table 1[5,6].

Table 1: Material Properties

Property	Value	Units
E	50	GPa
ρ	1522	kg/m^3
α	1E-06	m/m/C
δ	0.012	m
ρ_{MLI}	249	kg/m^3
L	100	m
f	0.1	Hz
β_b	0.5	-
β_d	0.25	-
t	5.08E-04	m
t_{iso}	4.16E-04	m
t_{MLI}	0.003	m
Mpanel	2000	kg
Mspacecraft	1000	kg

C. Mechanical Behavior Requirements for Truss

This section presents a few formulae which are used to design the truss to meet various geometric and structural response requirements. In the "Structural Analysis" section below, these formulae will form the basis for comparing the masses of the three longeron geometries presented in Figure 2, with and without MLI blanketing.

The first requirement for the truss is that its longeron members may not be too slender. That is, it is very difficult to manufacture an extremely long, thin rod or thin-walled tube that has negligible straightness imperfections. Thus, a limit on the slenderness ratio for all of the longerons to be considered is

$$\frac{a}{2r} \leq 100 \tag{8}$$

This requirement restricts the length to diameter ratio of a longeron member to be less than or equal to 100.

Next, the truss should have some minimum natural frequency to minimize vibrational disturbances while in orbit. The first natural frequency of flexural vibration for a free-free beam with total mass M, length L, modulus of elasticity E and moment of inertia given by Eq. 3 is[7]

$$f = \frac{22.4}{2\pi}\sqrt{\frac{EI}{ML^3}} \tag{9}$$

Lastly, the truss must meet a specification on how much it can warp in the presence of a thermal gradient. Thus, for a truss subjected to a temperature gradient between its top and bottom surfaces, ΔT, the thermal distortion depicted in Figure 3 is calculate as[5]

$$\delta = \frac{2\alpha\,\Delta T\,L^2}{8b\sqrt{3}} \tag{10}$$

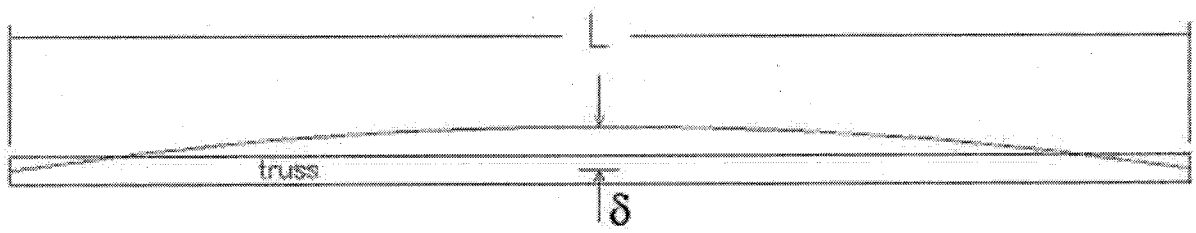


Figure 3: Thermal Distortion Resulting from Temperature Gradient.

D. Mass Calculations

In the structural analysis section below, the various truss configurations will be designed to meet certain requirements on structural behavior. Specifically, the truss depth and longeron radius are designed to meet these specifications. Once the designs have been made, the add-on mass of MLI blankets can be calculated to give the total truss mass. The required mass formulae are given in this section.

For the triangular trusses shown in Figures 2a and b with a large number of bays n, the total mass of the truss is[5]

$$M_{truss} = LA_l\rho\left(3 + 4\sqrt{2}\beta_d + 3\beta_b\right) \tag{11}$$

For the triangular trusses shown in Figures 2a and b with a large number of bays n, the total mass of the truss is

$$M_{MLI} = 2\pi L\,\rho_{MLI}t_{MLI}\left(3\left(r + \frac{t_{MLI}}{2}\right) + 4\sqrt{2}\left(\beta_d r + \frac{t_{MLI}}{2}\right) + 3\left(\beta_b r + \frac{t_{MLI}}{2}\right)\right) \tag{12}$$

where r is the radius of the longeron and t_{MLI} is the thickness of the MLI blanket. For the truss having coilable longerons struts, the truss mass is

$$M_{truss} = LA_l\rho\left(3 + 8\sqrt{2}\beta_d + 6\beta_b\right) \tag{13}$$

while the MLI mass is

$$M_{MLI} = 2\pi L\,\rho_{MLI}t_{MLI} \times$$
$$\left(9\left(r_{coil} + \frac{t_{MLI}}{2}\right) + 12\sqrt{2}\left(\beta_d r_{coil} + \frac{t_{MLI}}{2}\right) + 9\left(\beta_b r_{coil} + \frac{t_{MLI}}{2}\right) + 3\left(\beta_b r_{eff} + \frac{t_{MLI}}{2}\right) + 4\sqrt{2}\left(\beta_d r_{eff} + \frac{t_{MLI}}{2}\right)\right) \tag{14}$$

where r_{coil} is the radius of a single rod of the coilable longeron strut calculated from 1/3 of the required A_l to meet a specification, and r_{eff} is the effective radius calculated from the full A_l.

For all three longeron configurations, the total system mass is

$$M = M_{panel} + M_{spacecraft} + M_{truss} + M_{MLI} \tag{15}$$

Clearly, the longeron geometry must be determined prior to calculating the MLI mass. However, it is the total system mass, M_{total} that must be used to meet the frequency requirement, Eq. 8. That is, MLI mass will increase the total system mass, which will in turn change the natural frequency, which will alter the longeron geometry, which will change the MLI mass. Thus, an iterative procedure must be used to find a converged total system mass.

III. Structural Analysis

This section presents an analysis method using the formulae above to investigate the design of a triangular truss with the three longeron types shown in Figure 2.

A. Frequency and Slenderness Constraints

With Eq. 8 and the slenderness requirement for a bare truss (no MLI), Figure 4 was developed to show the relationship between bay length (assumed equal to batten length, ie $a=b$) and required longeron diameter for for the three longeron types under consideration.

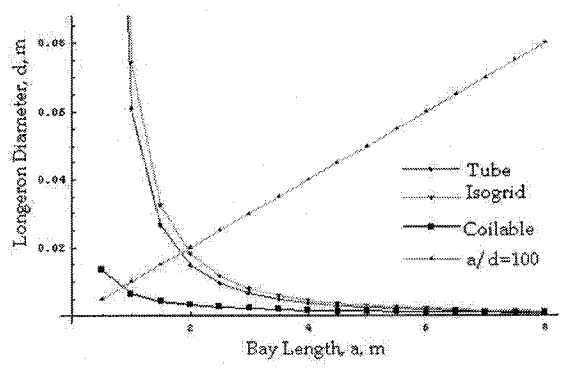


Figure 4: Longeron Diameter Versus Bay/Batten Length for Three Longeron Configurations.

From this plot, the design is controlled by the frequency requirement for the tube and isogrid longerons for bay lengths less than about 2 m. Over this length, the slenderness ration restriction dominates the design. Since the coilable lattice longerons "share" the calculated A_l between three rods, their diameter is obviously much smaller and therefore its design is dictated by the slenderness ratio except at very small bay lengths. Based on these diameters, one can use Eqs. 11-15 to calculate the total mass of the truss when covered in MLI blankets. An iterative procedure must be used because the added mass of the MLI alters the natural frequency of the structure. Figure 5 shows the converged total truss mass as a function of bay length with 15 layers of MLI insulation having a thickness of 0.003 m.

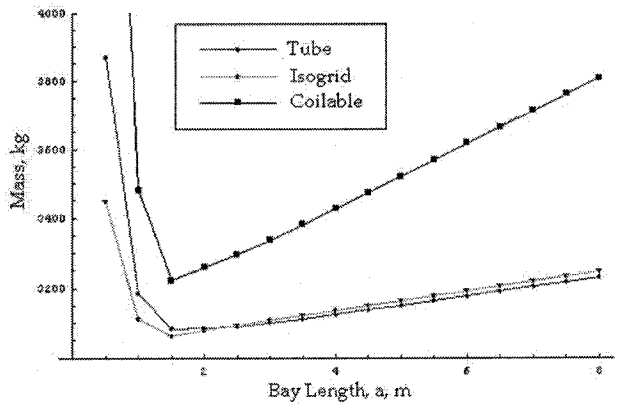


Figure 5: Total Truss Mass Based on Frequency and Slenderness Requirements.

Clearly, the coilable lattice longerons are the heaviest as they have much many more structural members to be covered with MLI blankets. The thin-walled tube and isogrid longerons have very similar masses. It should be noted that the panel and spacecraft mass in these figures is 3000 kg, therefore the structure and MLI make up only a small part of the total system mass.

B. Thermal Requirements

In Section A, the driving requirements were frequency and slenderness ratio. While MLI mass was considered, its effect on the thermal gradient and therefore truss geometry and total mass has not been investigated. For an L-band radar reflector, truss flatness requirements dictate that the thermal distortion be less than 1.2 cm. In this case, the required batten length b is calculated from Eq. 10 as a function of the thermal gradient, as shown in Figure 6.

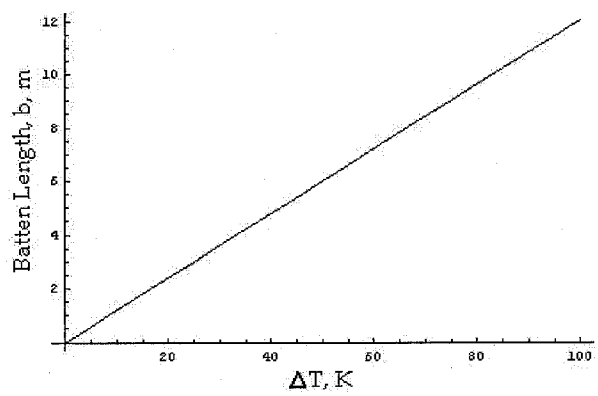


Figure 6: Batten Length versus Temperature Gradient.

For a known ΔT, one can calculate the required batten length, b. From the mass analysis above, the total system mass can be calculated. If one knows ΔT but does not have a specification for thermal distortion, δ, Eq. 10 can again be used to construct Figure 7.

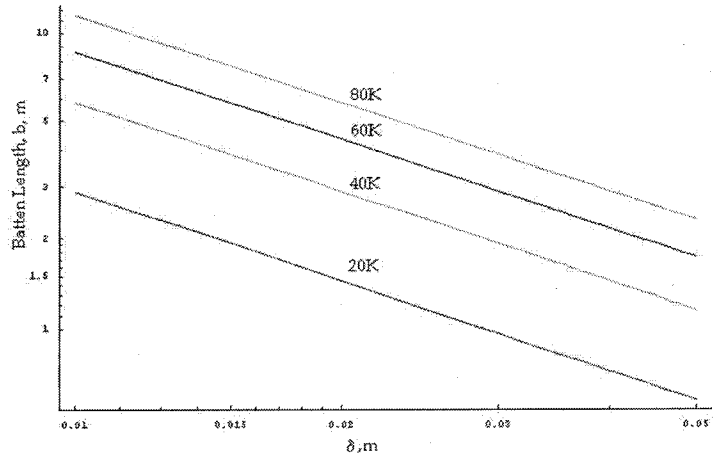


Figure 7: Log-Log Plot of Batten Length versus Thermal Distortion for Various Thermal Gradients

As the next step for this work, a relationship between the number of layers of MLI and the thermal gradient will be worked out. Currently, a bare truss is assumed to have a thermal gradient of 40 K, while one covered in 15 layers of MLI is assumed to have a thermal gradient of 20 K.

IV. Discussion

Using Figure 7, for a δ requirement of 0.012 m, batten lengths of about 6 m and 2.5 m would be required for thermal gradients of 40 K (bare truss) and 20 K (15 layers of MLI), respectively. This geometry results in total system masses of about 3100 kg and 3200 kg, respectively, for either thin-walled or isogrid tube longerons. For a coilable lattice longeron, the total MLI covered truss would weigh about 3400 kg. From this analysis, two important trends are noted. First, the coilable lattice longeron truss weighs the most, as it is primarily dominated by slenderness restrictions on its own rod longeron members. Second, the mass associated with the MLI is important for such large, lightweight structures. A careful analysis of this add-on MLI mass and its effect on the temperature gradient and total system mass should be performed in the early stages of mission planning.

V. Conclusion

The focus of this work was to determine which of three longeron configurations would provide the lightest truss that meets structural requirements on thermal distortion and vibration behavior, when the mass of MLI blankets is included. The analysis above showed that the coilable lattice longerons were the heaviest option, probably due to their large surface area that requires covering with MLI. The thin-walled and isogrid tubes were very similar in their total system masses. As mentioned previously, the next step to advance this analysis is to develop a thermal model that relates the temperature gradient as a function of the number of layers of MLI, which influences the tubes effective emissivity.

Acknowledgments

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