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Case Studies in Inflatable Rigidizable Structural Concepts

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AIAA-99-1089

CASE STUDIES IN INFLATABLE RIGIDIZABLE STRUCTURAL CONCEPTS FOR SPACE POWER

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ABSTRACT

L'Garde has been involved in a number of conceptual and detailed designs of inflatable rigidizable solar arrays for space power. In order to facilitate future conceptual designs, several of these cases are discussed. Additionally, the relevant structural equations are derived in order to demonstrate parametrically the effects of critical tube design parameters such as radius and thickness. The future conceptual designer has several rigidization technologies available to choose from. These are summarized in light of the pivotal tube design parameters. Alternate beam types are discussed, as well as the effect of concentration ratio. It is observed that natural frequency and Euler buckling are often driving requirements. The advantages and disadvantages of practical material thickness limitations are shown in the case studies.

Approaches To Conceptual Design

In the attempt to choose the best material and optimize the design of an inflatable rigidizable solar array, the designer might try to look at the structural equations parametrically. He might also study past cases. Here we will do a little of both.

Parametrics are good for general insights, especially where strength is a strong function of one parameter, such as radius. It helps to point out the promise of new directions in structural design. There is, however, a danger of oversimplification and an unrealistic search for the "one optimum" design.

Case studies can be far more useful. Often, one requirement drives the design. Designing for it leaves extra margin in the other requirements. Minimum and maximum practical limits, such as for thickness and modulus, may determine choice of material at the outset. Good design practices, such as avoiding Euler buckling by increasing radius, might influence a design.

Sometimes, programmatics force a material and configuration to be selected before requirements can be well established. Some requirements remain "soft" and subjective. Natural frequency and risk are common examples. Other requirements are responsive enough to change to suit the design, especially if initially padded.

One must take care in assuming two designs being compared are "apples and apples." Usually, no two situations are truly alike. Also, before drawing conclusions from a case, be sure to understand all the groundrules of the case, especially verbal ones such as security, growth, technology development, and politics.

Tube Parametrics

The structural requirements of primary interest in the design and selection of an inflatable rigidizable solar array boom are as follows:

1. General Compressive Buckling
2. Beam Stiffness & Natural Frequency (fn)
3. Array Blanket Natural Frequency
4. Beam Bending Buckling

The design parameters available are:

1. Radius of tube (r)
2. Thickness (t)
3. Length (L)
4. Modulus of Elasticity (E)
5. Material Density (ρ)

General Compressive Buckling

General compressive buckling can be broken up into short cylinder compressive buckling, Euler (long column) buckling, and transitional buckling.

The short cylinder compressive buckling force "P_{sc}" is written here for an isotropic wall construction. This applies to composites, and to the so-called “core” type aluminum laminate, wherein the single layer of aluminum is dominant structurally:

"Core"

.002 POLYMERS
.003 ALUMINUM
.002 POLYMERS

$$P_{sc} = \text{buckle stress X area}$$
$$= \gamma_r \gamma_c\, 0.6\, Et/r \;\; X \;\; 2\pi rt \; = \; \gamma_r \gamma_c\, 1.2\pi\, Et^2$$

- 0.6 — effect of Poisson's Ratio "ν": $= 1/\sqrt{(3(1\text{-}\nu^2))}$ $= 0.6$ for $\nu = 0.3$ (most materials)
- γ_c — compressive correlation factor (thin walls)
- γ_r — rigidization correlation factor (packaging wrinkles)
- E — modulus of elasticity
- t — thickness (of isotropic wall)
- r — tube radius

Therefore, short cylinder compressive strength is proportional to t^2 and E. Rods are stronger than tubes as short cylinders.

Tests on packaged, and then rigidized inflatables show no degradation in short compressive buckle force with increased radius. This is advantageous to designs that crave large diameter, thin tubes.

Euler buckling load "P_E" is highly affected by the loading condition. The load generally comes from the tensioned array, which is usually connected to the tube in a pin-pin fashion. The pin-pin partially following load equation is therefore used:

$$P_E = \pi^3\, Etr^3 / L^2$$

Therefore, Euler buckling load is proportional to r^3, t, and E, for a given length. Large diameter cylinders are strongest in long column compression.

Transitional buckling arises because tubes are never perfectly straight or round, especially long thin ones. This creates moments that cause the tube to buckle at less than the short cylinder value, despite the fact that the tube is not long enough to meet the Euler criterion. This condition gets worse with higher L/r ratios. It is generally modeled as an interpolation between short cylinder buckling (the flat line in Fig. 1) and Euler buckling (nearly vertical curve in Fig 1).

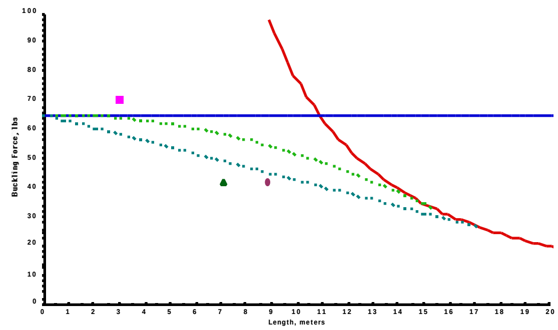

Figure 1. General Compressive Buckling
Buckling Force vs. Length for 5 inch Diameter Core Aluminum Laminate Tubes

Therefore, long booms (high L/r ratio) fail in transitional or Euler buckling. Prudent design avoids Euler buckling and attempts a straighter tube by increasing the diameter.

Beam Stiffness and Natural Frequency

Tests on section properties (bending stiffness) show high correlation with theory for both bending stiffness “k” and natural frequency “fn”:

$$k\ (\text{lb/in}) = 3\pi Etr^3 / L^3 \quad \text{(cantilever beam)}$$

$$f_n\ (\text{Hz}) = 1/2\pi \sqrt{\{3\pi Etr^3 / [L^3(m_t + .23m_b)]\}}$$

m_b = beam (distributed) mass
$m_b = 2\pi rtL\rho_b$
ρ_b = mass density of beam wall
m_t = tip mass

IF $m_t = 0$, $\quad f_n\ (\text{Hz}) = 0.41 \sqrt{(E/\rho_b)}\, r/L^2$

Therefore, stiffness is proportional to r^3, t, and E, for a given length, and natural frequency is proportional to r and $\sqrt{E}$, for a given length. Note that decreasing thickness to reduce mass would have no adverse effect on beam fn.

There is also a reduction in fn due to compression, but it is not usually a driver, as seen in Fig. 2.

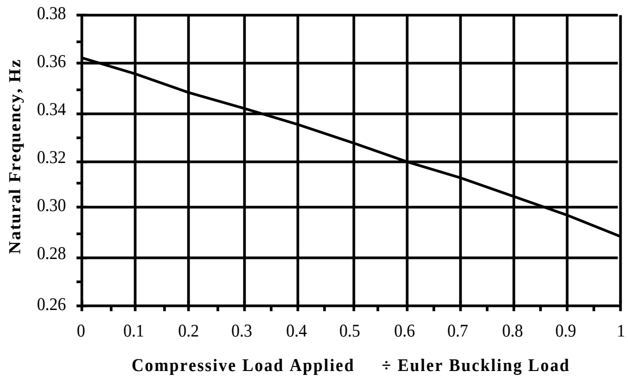

Figure 2. Effect of Compression on fn of Boeing/Teledesic Aluminum Laminate Tubes

Torsional stiffness is also a strong function of radius, but is usually not important in the design.

Array Support and Natural Frequency

Membranes have high damping, and this may in some cases quiet the system sufficiently to satisfy the attitude control system (ACS), but solar arrays have appreciable mass, so we generally want to tension the array to assure its component fn:

$$fn = a/2\pi \sqrt{(S/m)}$$

a = shape factor
S = boundary tension
m = array mass

Two different methods of tensioning an array are generally considered: catenary and simple.

Catenary support places the array in plane stress. Shallow catenaries produce unnecessarily high strut compression, and so are avoided.

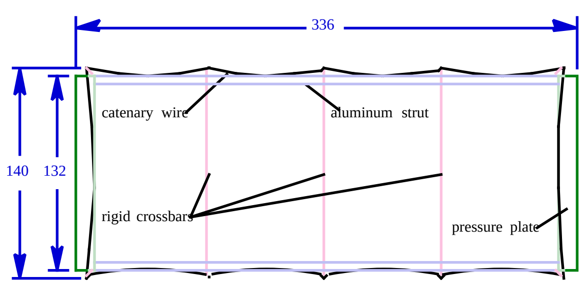

Figure 3. Boeing/Teledesic Solar Array Catenaries

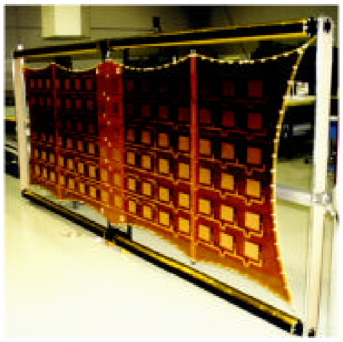

Figure 4. Synthetic Aperture Radar Catenaries

In simple support, the array is simply pulled at its corners. Stress varies over the array, and may cause wrinkling.

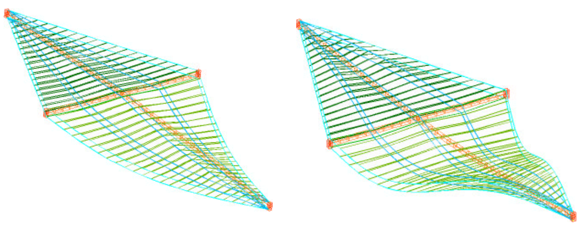

Figure 5. Simply Supported NGST Sunshield Mode #1, 0.22 Hz; Mode #25, 0.43 Hz

Therefore, the need to assure *array* fn places the struts in long column compression. The best way for the strut to resist buckling is to increase diameter. This is also what's necessary to assure *strut* fn.

Bending Buckling

Tube bending buckling failure stress is as follows:

$$\gamma_r \gamma_b \, 0.6\, Et/r$$

γ_r = rigidization correlation factor (due to packaging wrinkles)
γ_b = bending correlation factor (due to thin walls (high r/t))

The applied stress is:

$$Mr / I_z$$

$I_z = \pi t r^3$ = Section Moment of Inertia
M = maximum moment along beam

One potential source of applied moment "M" in the above equation is the rotational moment due to fast array slewing and/or ACS torques (applied angular acceleration):

$\sum M$ = mass moment of inertia X angular acceleration
mass moment of inertia r,t,L^2

Another source of applied moment "M" is the cantilevered g-load from translational maneuvers. This is usually the dominant source due to fixed thruster sizes:

$$\sum M = \text{mass X g-load X length}$$
$$\text{mass} = 2\pi r t L \rho \quad (\rho = \text{density})$$

Aerodynamic drag and solar pressure are usually not significant factors.

If we set the applied stress due to g-load equal to the failure stress:

$$\text{g-load } 2\pi r^2 t L^2 \rho / \pi t r^3 = \gamma_r \gamma_b\, 0.6\pi\, Et/r$$
$$\text{g-load @ failure} = \gamma_r \gamma_b\, 0.6\, Et \,/\, (2\pi L^2 \rho)$$

Therefore, bending strength is proportional to t, E, and $1/\rho$, for a given length. So, to resist high g-loading, we must increase thickness and use a higher modulus and/or less dense material.

Aluminum laminate maximum thickness is limited to ~ 4 mils due to packaging. However, the so-called "clad" lamination, a sandwich wall construction, approximately doubles the strength without increasing total thickness or mass:

"Clad"

.0015 ALUMINUM
.003 POLYMERS
.0015 ALUMINUM

Composites are not limited in maximum thickness.

Aluminum is approximately twice as dense as composites, but the parasitic mass of composite rigidization equipment may obviate this difference._

Parametric Guidelines

Increased radius usually serves to kill two birds with one stone:

1) Increases fn and stiffness
2) Prevents long column buckling

Fortunately, tests show no loss of short cylinder or bending strength with radius

Euler buckling, boom fn, and bending strength are all strong functions of length ($1/L^2$). Long booms are unavoidable for larger arrays, but aspect ratio should be minimized wherever possible.

A simple design rule might now read as follows:

If the boom is long (high L/r), use a large radius.

If a large radius is used, use thin material for low mass (high W/kg), and high natural frequency.

However, if g-loads are high, we may need thicker material, increasing mass. One way around this would be to reduce the requirement. For example, if g-loads are due to infrequent or singular maneuvers, consider pressurizing the tube temporarily during the loading to prevent buckling. Pressure can resist almost any realistic g-load.

Most designs to date have been driven by natural frequency and long column compression (straightness), not bending, as we will see in the case studies.

Another important point is that inflatable rigidizable designs must be strength / mass or cost competitive with space-proven mechanical systems to survive past technology development. This rule should be evaluated in any case study.

Configuration Options to Choose From in Design

The rigidization technologies include:

1) Aluminum laminate, core & clad
Rigidizable composite matrix:
2) Sub-Tg
3) Hydrogel
4) UV cured
5) Thermoset

The possible beam types include:

1) Tube
2) Bundled Tubes
3) Truss

The following configurations are characterized by varying stages of concentration ratio:

1) Fixed (non-articulated) cell blankets; flat and spherical
2) Flat gimbaled
3) Concentrators - refractive and reflective

No rigid panel solar arrays are considered in this paper. They are generally heavier than stringer-membrane systems.

Cell type and coverglass thickness (radiation environment) are not considered here either, They are crucial trades which must be interleaved with the structural trades, but this paper is strictly concerned with the surrounding structure.

Controlled deployment methods and packaging efficiency generally apply to all rigidization types, so were not considered here either.

Rigidization Options

Figure 6. Rigidization Technologies Used by L'Garde

Aluminum Laminate

This technology uses a thin aluminum laminate which is packaged, deployed by inflation, then overpressurized to remove packaging wrinkles. It is then evacuated, leaving a smooth, stiff shell structure. Both core and the stronger clad types are in use.

Aluminum modulus is ~8,000,000 psi, even when very thin (1.2 mils). Maximum thickness is limited to ~4 mils due to packaging.

This technology requires higher pressure to rigidize than composites, but this seldom makes a big mass difference.

Composites

The rest of the rigidization technologies consist of a rigidizable matrix for a composite. A variety of high modulus fabrics are available to all the technologies.

Composite modulus is driven by the reinforcement fibers, which are far stiffer than the matrix. Fiber modulus is limited by packaging (breaking fibers in folds) to ~60-75 Mpsi. With enough development, any rigidization method could eventually approach the law of mixtures composite E, although the higher Tg matrix materials are generally stiffer. Most composites use a 50/50 fiber/matrix ratio, so the maximum composite modulus we might eventually expect would be ~30 Mpsi. 10,000,000 psi is the near-term goal for most, very close to aluminum.

Composite mass can be lowered using optimal weaves, but multiple plies are generally necessary to get high composite modulus. The minimum ply thickness available is ~3 mils, so the minimum composite thickness is ~10 mils. The use of composites would result in mass penalties in many of the case studies to be discussed.

Composite rigidization methods differ in mass basically due to the rigidization equipment. Sub-Tg is lightest because it uses existing MLI and requires no bladders. Thermoset is heaviest due to the need for resistive heaters.

Sub-Tg Rigidization

"Tg" refers to the glass transition temperature of a material. Cooled sufficiently below this temperature, the matrix becomes hard, rigidizing the composite. Materials can be synthesized with a variety of Tg's to suit mission needs. A 0°C and a room temperature material are seen in Figure 6.

Sub-Tg materials are pliable before deployment due to the relatively warm spacecraft. After deployment, the multi layer insulation (MLI) used to equalize long boom temperatures will also cool this material to rigidization temperatures, where it remains.

Thermoset

This matrix cures by heat. It requires high power to rigidize.

UV Cured

This material's cure is triggered by ultraviolet radiation (UV), either from the sun, or from lamps. It requires an order of magnitude less power than thermosets to rigidize.

Hydrogel

This matrix is water based. Once deployed, the water is allowed to evaporate to the vacuum of space, leaving a rigid composite. The initial outgassing of H_2O can be an issue for certain applications.

Alternative Beam Types

Bundled Tubes

Bundled tubes were developed to help overcome the maximum thickness limitation of aluminum laminate. It is a stage between a single tube and a truss. The tubes are bonded to each other, so the truss radius is not large, but it does not suffer from the parasitic mass problems of a truss. The bundle could be used individually, or as a longeron in a larger truss. This is a recent development, so it was not considered in the case studies, but it is now available for future use.

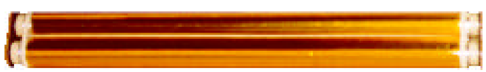

Figure 7. Aluminum Laminate Bundled Tubes
1.7X better bending buckling than equivalent mass tube
2.5X higher short compressive strength

Trusses

Trusses are much stronger and stiffer due to their high moment of inertia. They are generally limited to larger systems due to complexity and the parasitic mass of the cross members, joints, and diagonals.

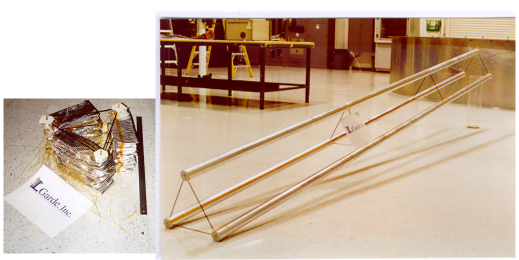

Figure 8. Solar Sail Aluminum Laminate Truss
114 g/m; EI = 10,333 Nt m^2

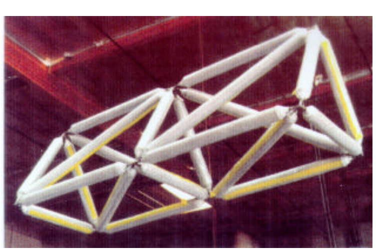

Figure 9. IRSS Hydrogel Truss
Mass < 2 Kg
Compressive Load Capability = 290 lb; Damping = 15.5%

Tapered Tubes (Conical Masts)

Tapering a tube can reduce mass by as much as 40%, with the same strength. This cannot be done with aluminum laminate due to the varying rigidization stress over the tube length. Tapering has not received much attention to date.

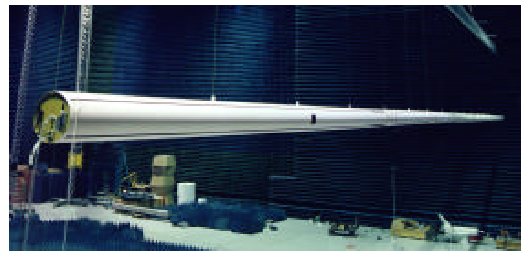

Figure 10. Tapered 100 ft. Boom

Concentration Ratio

The case studies will demonstrate that mass efficiency (watt/Kg) is a strong function of concentration ratio.

Fixed Arrays

In a manner of speaking, the off-normal angles that a fixed (non-articulated) array sees effectively gives it a concentration ratio < 1.0.

Fixed arrays are usually proposed to augment body-mounted cells on smallsats.

Flat and spherical arrays are possible. If the satellite is NADIR staring, L'Garde's trades show the flat system is more mass efficient.

Flat & Gimbaled

These arrays are defined as having a concentration ratio = 1. Most cases use this type of array.

Concentrator

Concentrator membranes are lighter and less expensive than the solar cells. This results in high w/kg and low $$/watt. The lower mass is also better for natural frequency, allowing lower strut compressive forces. However, the complexity of a concentrator design is usually only justified on larger systems.

For deep space missions, concentration eliminates LILT (Low Intensity, Low Temperature) solar cell performance concerns.

Thermal limits for the photovoltaics limit the concentration ratio. CR = 10-15 is the usual range considered.

There are refractive (fresnel) and reflective (troughs and dishes) concentrators. A fresnel membrane's minimum thickness is ~10X thicker than metallized reflector membranes. Fresnels also have transmissive losses and the potential for yellowing. "Potato chip" buckling modes are a concern with large flat apertures such as fresnel discs. The out of plane geometry of a lenticular reflecting dish, such as Power Antenna, or a reflective trough provides great aperture stiffness.

Conceptual Design Cases

Six study cases are now presented. They cover a wide range of applications and missions, as listed below:

1) ITSAT (Inflatable Torus Solar Array Technology)
(200w-1000w; Low Earth Orbit (LEO); microsat)

2) Boeing/Teledesic
(~4 kw; LEO; commercial)

3) Champollion
(~13kw; deep space; solar electric propulsion (SEP))

4) Space Solar Power
(Megawatt; ~Geosynchronous (GEO); utility)

5) FlatSat
(<250w; LEO; nanosat)

6) Mars Sample Return
(~8kw; Mars surface; in situ propellant production (ISPP))

ITSAT (200w-1000w; LEO; Microsat)

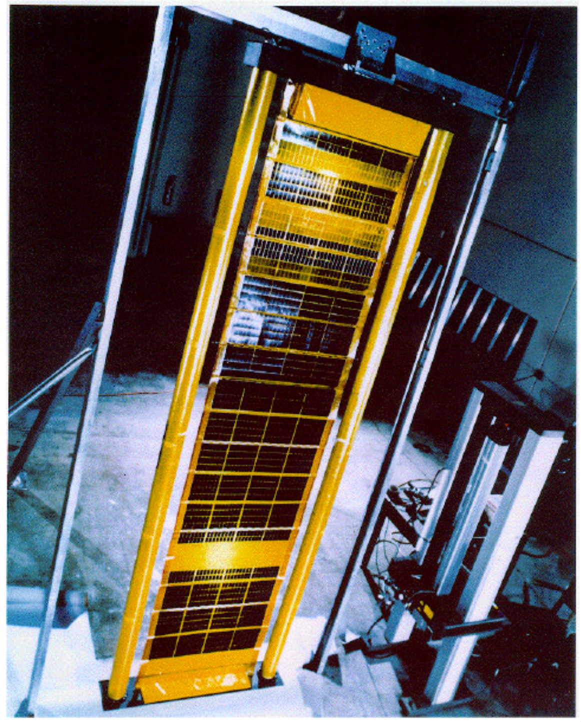

Figure 11. ITSAT in Space Simulation Chamber

Requirements:[1] fn ≥ 1Hz
max g = 0.03; safety factor (SF) = 2

Design: 274W; 13.8% efficient C-Si
29.2 X 128.2 in; flat gimbaled
3 mil thick aluminum core laminate

Performance: 93 W/Kg

In Phase 1, spherical and pillow shapes were also considered. Their projected W/Kg were 3 to 6 times lower.[2]

Natural frequency drove the radius. At 3 mils, the aluminum meets the max g requirement with the required margin. A minimum thickness composite (~10 mils) would be heavier and overdesigned.

The small size of this array does not justify the complexity and expense of a mechanical mast, but gimbaling was found to be worthwhile.

Boeing/Teledesic (~4 kw; LEO; Commercial)

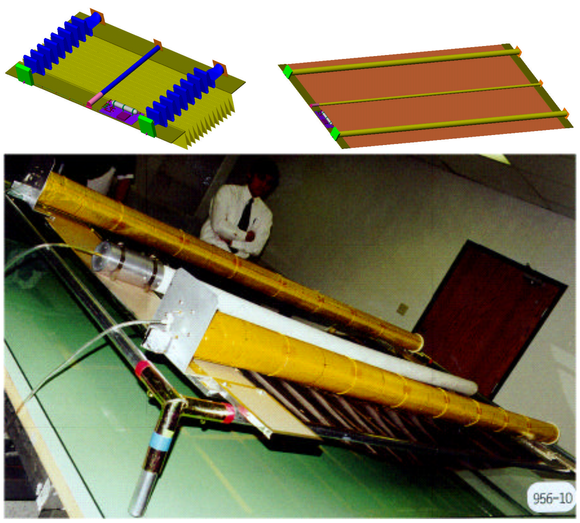

Figure 12. Deployment Demonstrator

Requirements: fn ≥ 0.3 Hz
blanket-tube offset = 29 in-lb
g-load ~ low
max aero cross sections specified
deployment speed specified

Design: (supplied) 4300W; 8% efficient C-Si
7.9m X 3.3m; flat gimbaled
3 mil thick core aluminum laminate tubes
combined compressive/bending SF = 2.7

Performance: 50 W/Kg (mostly due to heavy, low efficiency array blanket supplied by customer)

This was a commercial proposal, so cost, simplicity, and reliability were more important than mass. Otherwise, a concentrator might have been a good idea at this size. There were some non-structural requirements that affected the design, some of questionable importance or accuracy. Deployment speed and aero cross section are examples.

Natural frequency drove the radius. This radius also provided ample Euler compressive strength. At 3 mils, the aluminum met the max moment requirement with margin. A minimum thickness composite (~10 mils) would be heavier and overdesigned.

The aluminum laminate's high relative state of development was also a factor.

In the end, a mechanical system won due to the perceived development risk of inflatables.

Champollion (~13 kw; Deep Space; SEP)

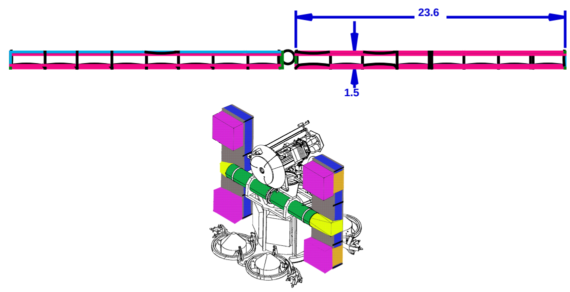

Figure 13. Early Champollion Concept

Natural frequency is especially important for solar electric propulsion missions. The SEP mission has thrusters firing for months at a time. Any off-pointing of the thruster due to vibration translates into lost propulsive performance.

Requirements: fn ≥ 0.1 Hz
max packaged width = 1.5m
max g = 0.001 (derived by L'Garde from assumed thrusters & mass)
growth to larger designs (max g = .01 to .03; SF = 4)

Design: 13kW; 17.5% efficient C-Si
1.5m X 23.6m; flat gimbaled
3 mil thick aluminum laminate tubes
combined compressive/bending SF = 2.4

Performance: 115 W/Kg (at 0.001g - no growth)

Only a no-growth design was done by L'Garde:

Natural frequency drove the radius. Using 0.001g, a 3 mil "core" aluminum is sufficient. A minimum thickness composite (~10 mils) would be heavier and overdesigned.

For a deep space mission, cold rigidization seemed a natural, but was rejected due to perceived risk.

The packaged width requirement caused a large, detrimental aspect ratio. The packaged width allowable was later doubled, cutting the length in half. This quadruples the g-load capacity and fn.

Selected Design: A single thermoset tube was baselined to provide growth and technological diversity. The large array provides ample power for rigidization.

A concentrator seems a good idea for a deep space mission, and as yet may be considered.

Space Solar Power (1.5 Megawatt; ~GEO; Utility)

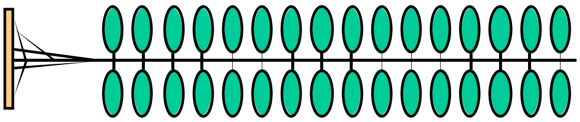

Figure 14. "Power Tower" Space Solar Power Station Configuration

Requirements: max practical fn
low g-loading (gravity gradient stabilized)

Design: 1.5MW; 17.5% efficient C-Si
200m X 40m fresnel concentrator (10X)
toroidal truss with composite longerons
ellipse tensioning places no moment on truss

Performance: 688 W/Kg
fn ≥ 0.01Hz

This utility application places a high value on $$/watt and W/Kg. Non-concentrator designs were extremely heavy. A parabolic reflecting trough has also been proposed.

A flexible body control system is assumed for such a large structure. Still, even a minimum membrane stress for fn causes compressive toroidal forces that dominate the design. Aluminum laminate is impractical at this scale, as is a single tube torus.

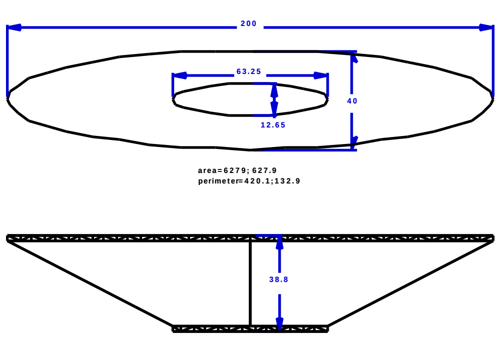

Figure 15. Elliptical Fresnel Concentrator (CR = 10)

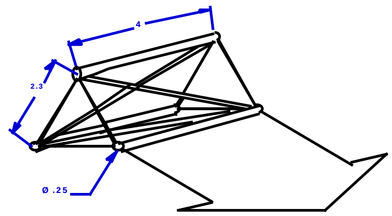

Figure 16. Toroidal Truss Segment

"FlatSat" NanoSpacecraft Concept (<250w; LEO; Low Inclination)

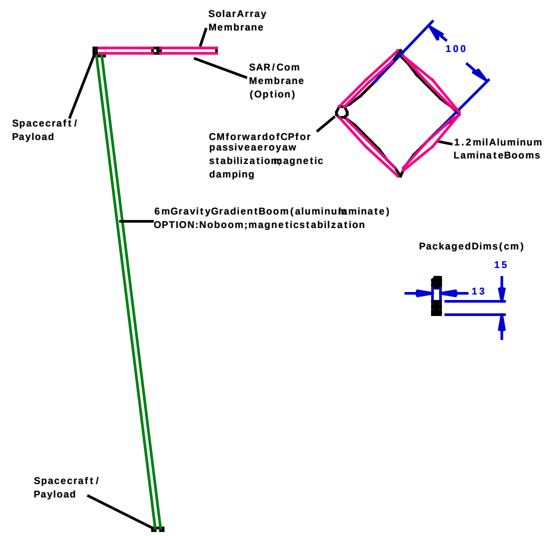

Figure 17. FlatSat Concept

Total tube mass = 250g:
Compressive capability = 10 lbf
Bending capability = 16.5 in-lb

Aperture = 1 m^2:
Cell mass = 395g (CIS); 630g (C-Si)
Power = 93w (CIS); 235w (C-Si)

NanoSat payload & spacecraft assumed: ~2 kg

As nanosats get smaller, body mounted cells become insufficient. They will need aperture that can be compactly packaged.

Many LEO microsats are NADIR-staring & passively stabilized.[4] It is best not to disturb the spacecraft with gimbal torques, so we use a fixed array.

Spherical arrays can handle any attitude, but NADIR staring gives a known attitude to work with. This makes flat arrays more attractive, especially for low inclination orbits.

Array tubes resist compression due to membrane tensioning. The length is not great, but the length/radius ratio actually puts this into the transitional region. The lightest solution is thin aluminum laminate.

The gravity gradient boom sees only very light torque. Stiffness (low deflection) and low mass are more important.

MARS Sample Return (~8kw; Mars Surface; ISPP)

Requirements: total area = 35 m^2 (30° latitude; dust tau = 0.5; 360° azimuth)
total mass < 121 kg
Mars g = 0.4
max winds 35 m/sec

Design: 8500W 1AU per wing; 17.5% efficient C-Si
6 arrays; each 1m X 5.8m; flat fixed
22 mil Hydrogel-Carbon tubes

Performance: total mass = 90 kg
safety factor > 2

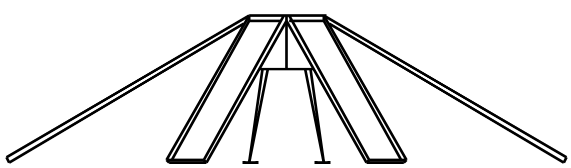

Figure 18. Mars Sample Return Lander

Gimbaled designs were also considered, but concentration is not practical due to the large proportion of diffuse light. Inflatable trusses are also a possibility.

Natural frequency was not an issue. Bending buckling drove the design, hence a thick composite was used. High temperatures prevent the use of Sub-Tg rigidization.

Arrays are deployed straight up, then lowered to position.

More recently, the power requirement dropped[3]. The new total area required is 12.4 m^2.

Conclusions

Case studies show that the real reasons designs get selected are far more complex and chaotic than simple parametrics would dictate.

One requirement does seem pop up again and again as a driver - natural frequency. The best way to achieve fn is large radius. This also obviates Euler buckling.

High power density (low mass) is also desirable, therefore thinner materials are preferable. This conflicts with bending buckling resistance, but g-loads can easily be lowered by using less thrust.

The maximum thickness of aluminum laminate is seen as a limitation, but its minimum thickness capability may actually give it an advantage over composites for a variety of applications.

Alternate beam designs, such as trusses, and concentrators offer great promise, but haven't seen much interest yet.

Inflatables are usually seen as applicable only to large systems, but they also have a potential niche with aperture-starved nanosats.

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