Some Structural, Mission Performance, and Navigational Features of the Space Tow

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Presentation to Offer

- **A candid technical introduction to the space tow concept**
- **Insight into the intimate interaction of some associated structural & navigational issues**

The first journal publication on the space tow – Greschik, "*Solar Sail Scalability and a 'Truly Scalable' Architecture: the Space Tow*" – is yet to appear in the J. of Spacecraft and Rockets.

The Space Tow Promises

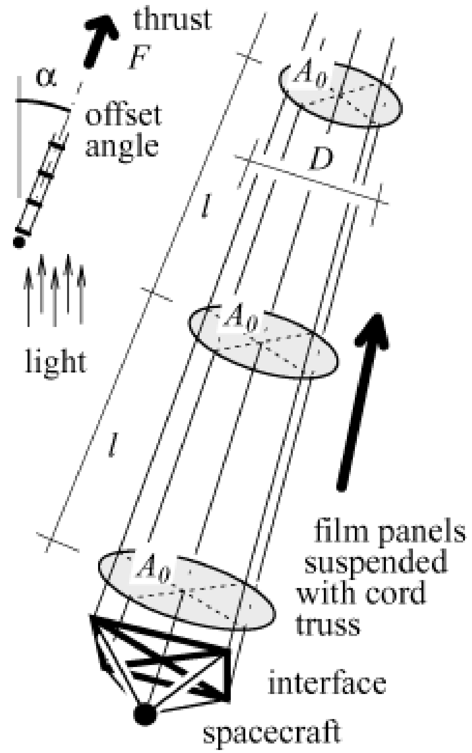
- **A solution to the most critical bottlenecks in solar sail engineering**
- **An easily practicable approach**

- **Near-optimal (net film) propulsion performance**
- **Scalability of performance & of technology**
- **Manageable dimensions**
- **Cost-efficient hardware development & testing**
- **Industrial perspectives (serial fabrication, off-the-shelf products)**
- **Structural & development modularity (challenges can be individually addressed)**

The Space Tow Is

A train of panels integrated with a tension truss column

- **Angular offset** from illumination
- **Tension** provides integrity
- **Design challenges** (deployment, panel, column, thermal) **mutually independent**
- **Tabletop** hardware development
- Stows in a **stack** and **self-deploys** once the top panel is lifted
- Intimate **coupling of structural and attitude dynamics** due to length and ethereal weight



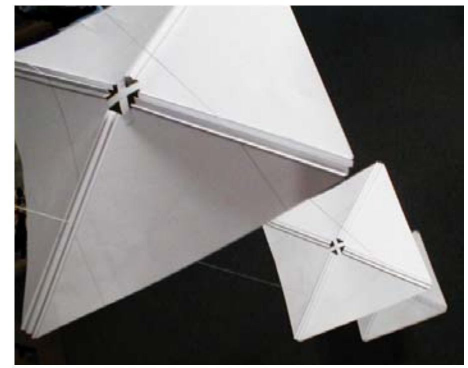
Greschik, Space Tow. ISSS'07, Herrsching, Germany, June. 27-29, 2007..

Latest Find in a Long Search

for practical architectures

Space Tow

performance + practicability



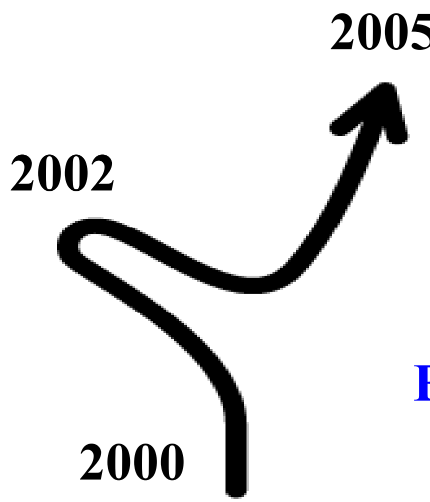
2006-07: support by NASA Marshall, Edward E. Montgomery

Cord Mat Sail

performance + feasibility

used by the *Encounter* & the *L'Garde-NASA Langley ST9* projects

Greschik, *et al.* *"The Cord Mat Sail – Concept Development And Design Example,"* *AIAA-2005-2049*.



Striped Concept

a limit state, not a design

Greschik & Mikulas, *"Design study of a square solar sail architecture,"* AIAA-2001-1259 and J. of S. & R., 39:5(653-661), 2002.

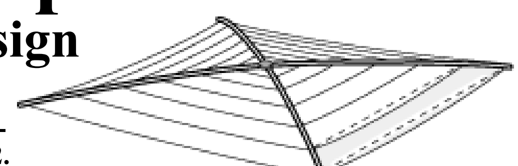


Illustration with Point Design

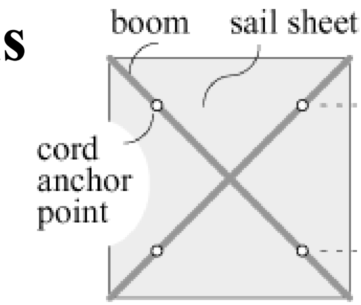
10000 m² sail with 50 kg payload
$\alpha = 30^o$ angular offset, $\eta = 0.8$ refl. efficiency

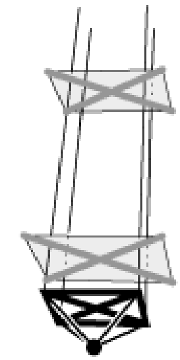
- 13.16 kg **gross structural mass,**
  $1.313\ g/m^2$ **sail surface specific mass**
- 63.16 kg **total system mass**
- $0.867\ mm/s^2$ **acceleration at** 1 AU
- 10.95 km **length**
- 4.43×10^8 kg-m² **system mass m. of inertia**
- $2.24^2 \times 0.25$ m **stowage envelope**

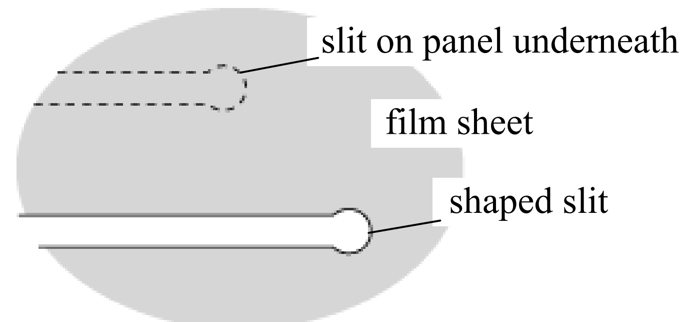
Sail Panels

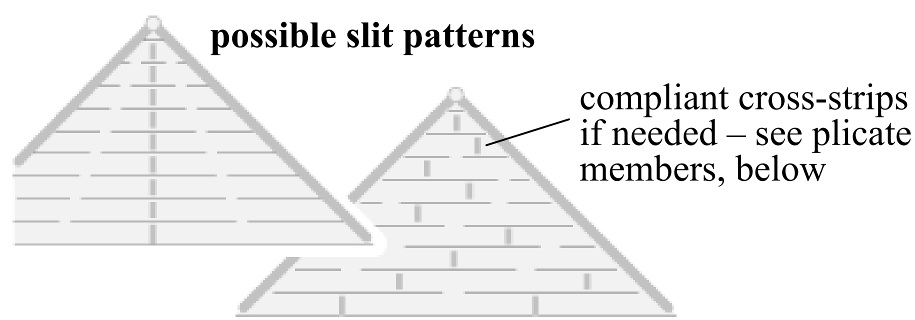
- Square panels + diagonal booms
- Strips between slits explicitly approximate the ideal limit of striped mechanics
- Shaped slits of finite width offset between adjacent panels
- Handling, fabrication w/ special tools (mandrel, etc.)

- Design for maximum size with reasonable tooling and handling









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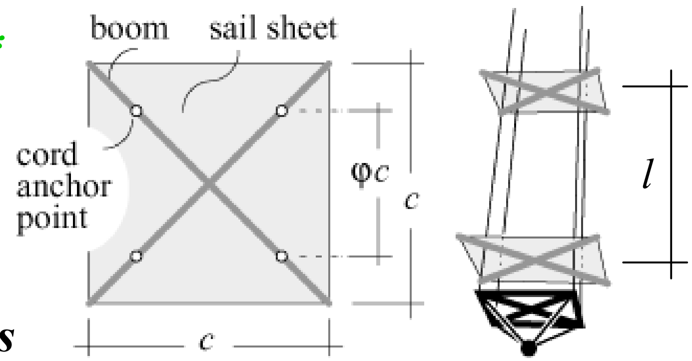
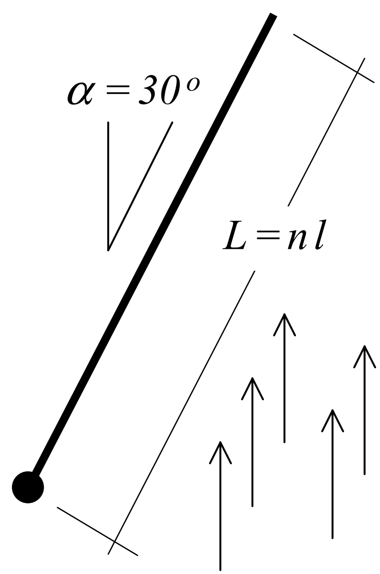
Sail Panels

Geometry	$c = 2.236\ m$	*edge*
	$\varphi = 0.85$	*anchor location**
	$A = 5\ m^2$	*surface area*
	$l = 5.477\ m$	*spacing***
Material	$0.9\ \mu m$ *Mylar*	*film****
	$E = 5\ GPa$	*Young's modulus*
	$\nu = 0.38$	*Poisson's ratio*
	$\rho = 1390\ kg/m^3$	*density*
	$\alpha_T = 17\ ppm$	*coeff. of thermal exp.*
…then	$m_{ps} = 6.282\ g$	*panel sheet mass*
	$\rho_s = 1.25\ g/m^2$	*sheet surface density*
	$n = 2000$	*panels*
	$L = 10\,954\ m$	*tow length*





* For maximum footprint
** For full illumination (no shading)
*** Commercially available

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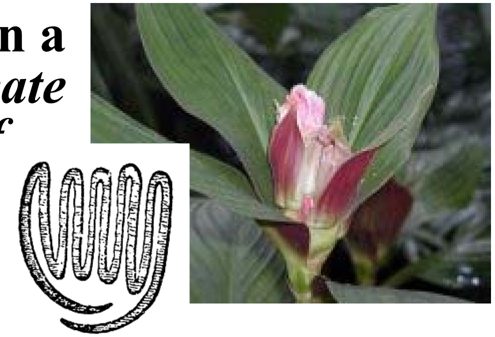
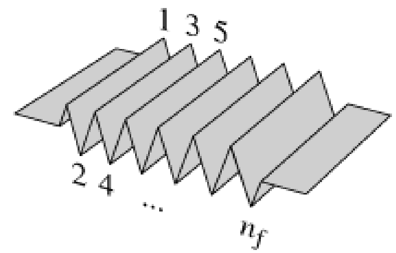
Panel Reinforcement

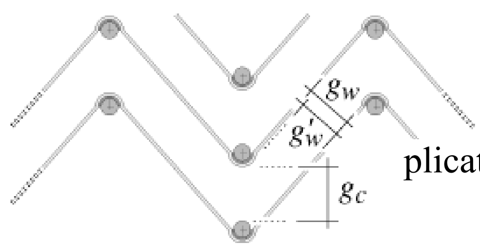
With plicate members formed by local film corrugation

as in a plicate leaf





- **Local film thickness for handling**
- **Composite filaments nest in folds**
- **Members nest in stowage**
- **Applicable to cross-strip reinforcement, too**



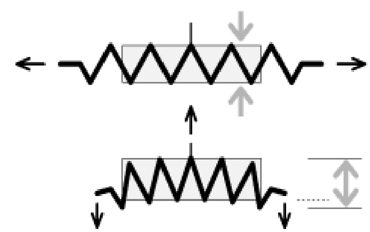
plicate members in stowage

- **Design for cross-stretch compliance & out-of-plane flexural stiffness EI_b**

the more folds, the better ☺

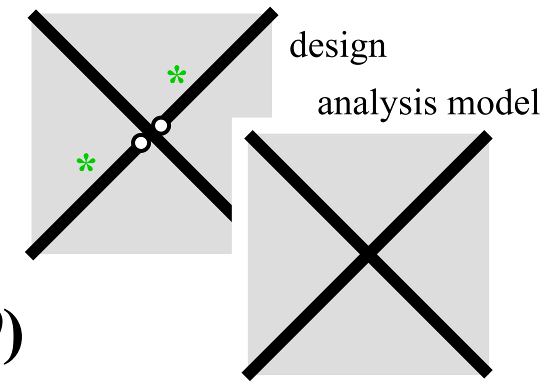
EI_b reduced by some geom. nonlinear (cross-stretch & Brazier) effects…

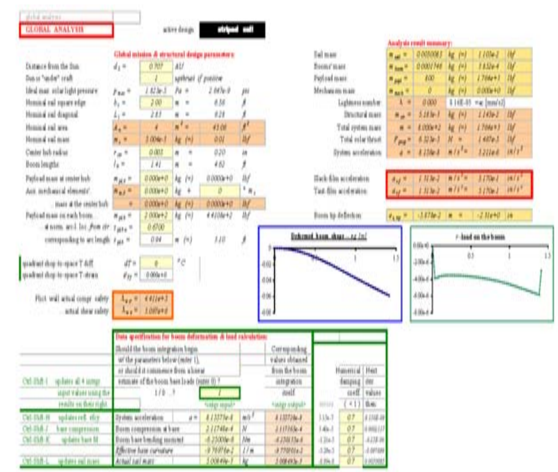
…& increased by geom. nonlinear cross-lateral flexure effect



Boom Analysis

- **Design: 1 full-diagonal member +**
  2 half-diagonal booms *
- **Analysis: all clamped at center** **
- **Safety in loads:** $FS_{lds}=2.6$
  (frontal illumination, $.707\ AU$, $\eta=0.9$**)**
  + infinite payload mass used
- **Geom. nonlinear modeling of…**
  - ✓ ***boom compression-flexure coupling*** ***
  - ✓ ***film slope-pressure coupling***
  - ✓ ***boom-, & film response coupling***
  - ✓ ***thermal effects***
  - ✓ ***plicate cross section def. effects***
- **Plicate wall strength satisfactory**
- **Thermal stress relief required** *,#



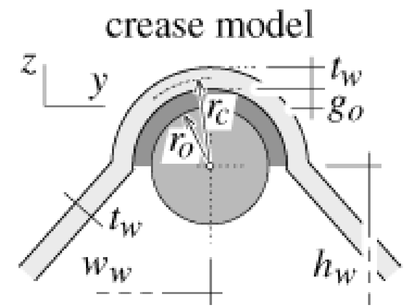


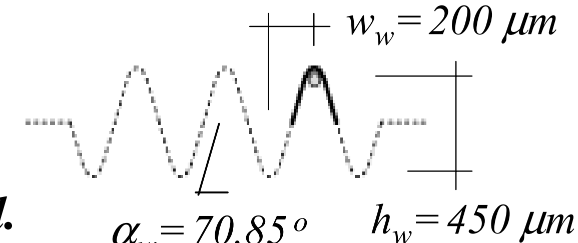
Graphic-interactive
finite diff. software
MS Excel

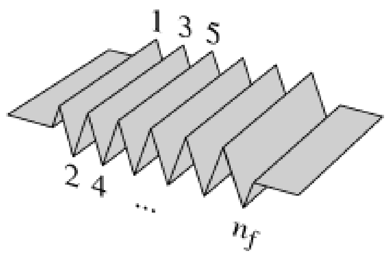
* Pin base support is compression-compliant
** Non-conservative base stiffness
*** Implicit boom strength (stability) control
\# Thermal loads alone can very severely load the structure

Boom Specs & Performance

Geometry	$d_o = 25.4\ \mu m$	*filament diameter*
	$g_o = 6\ \mu m$	*adhesive-filled gap*
	$t_w = 6.35\ \mu m$	*wall thickness*
	$n_f = 7$	*number of folds*
Wall	*Mylar*	*→ film sheet mat.*
Filament	*carbon fiber*	*Thornel K-1100 2k* *
	$E = 560$ GPa	*composite Young's mod.*
	$\rho = 1800\ kg/m^3$	*composite density*
	$\alpha_T = -1.5$ ppm	*coeff. of thermal exp.*
Adhesive	$\rho_a = 1600\ kg/m^3$	*density (in gap)* **
…boom	$w = 1.4$ mm	*width*
	$EI_b = 91\ N mm^2$	*flexural stiffness*
	$e_{tip} = 13$ cm	*tip deflection* #
	$\rho_{sL} = 43.4$ mg/m	*linear density*



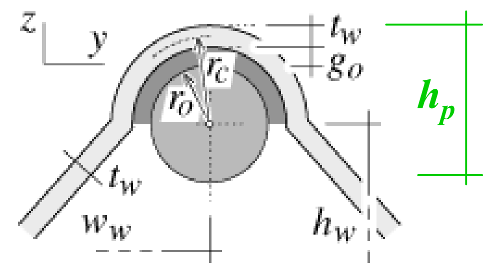


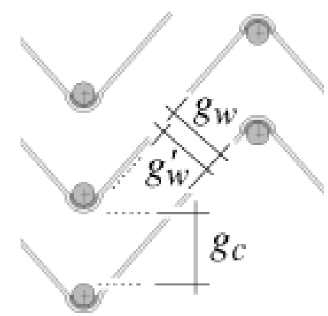


* For maximum stiffness
** No stiffness
\# 8.5% of boom length (of half diagonal)

Performance & Stowage

1 panel	$m_{ps}=6.273$ g	*film sheet less booms*
	$m_{pb}=0.274$ g	*mass of four booms*
	$m_p\ =6.547$ g	*gross mass*
		4.4% over net film mass
	$F_p=27.4\ \mu N$	*panel thrust**
All panels	$m=13.094$ kg	*all panels' mass*
	$F=54.76$ mN	*total tow thrust**
Stowage	$h_p=38\ \mu m$	*panel net stowage depth*
	$g_c=87\ \mu m$	*gap: fill** + filaments*
		total → 0.125 mm / panel
	$H_s=25$ cm	*stowage stack height*





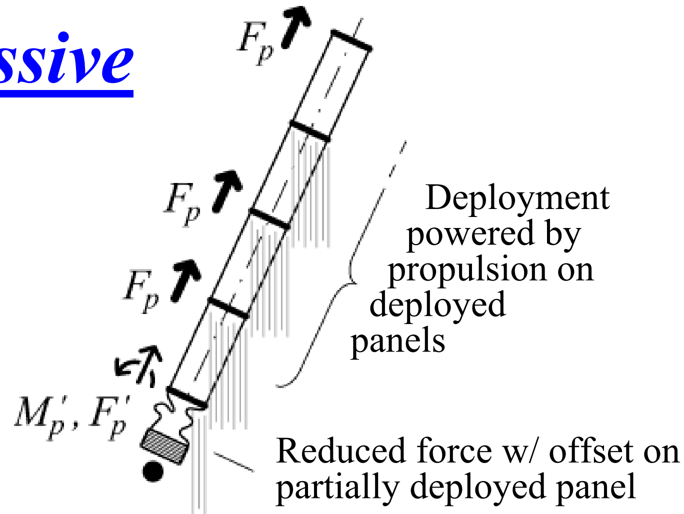
- **Filaments between stacked plicate booms laid in loose fold direction**
- **Gap fill** contributes to stack mass**

* $\alpha=30^o$, 1 AU, $\eta_{refl}=0.8$

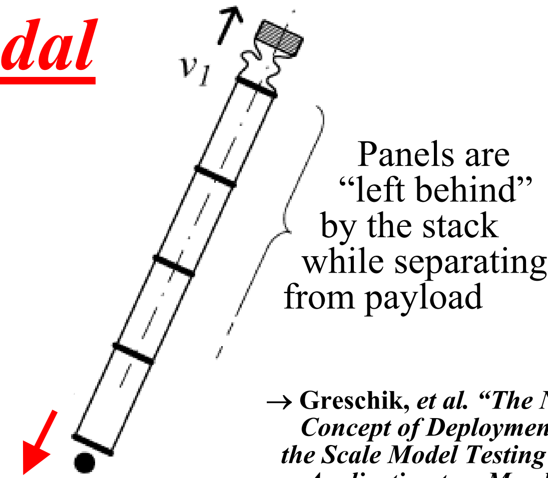
** To evaporate in space

Two Deployment Paradigms

Passive



Nodal



→ **Greschik, *et al.* *"The Nodal Concept of Deployment and the Scale Model Testing of its Application to a Membrane Antenna,"* *AIAA-1999-1523*.**

- **The first few panels pre-deploy…**
  - ✓ ***Mechanically* (e.g., w/ boom to lift them off the stack), or…**
  - ✓ ***With photon propulsion* (via sail lobes laterally deployed off the top panels, or with the help of a pilot sail)**

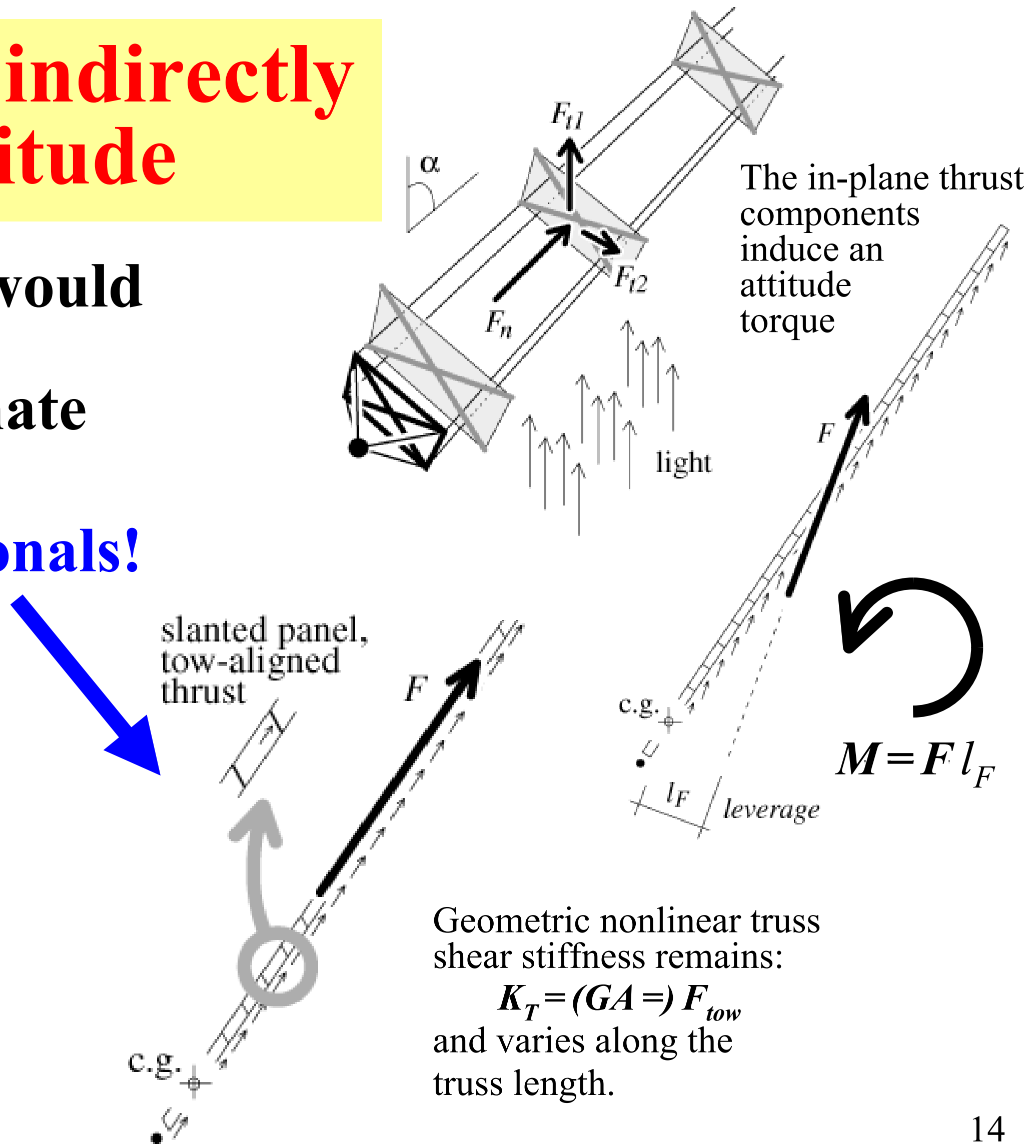
- **Instead of "kicking" the stack off the spacecraft, …**
  - ✓ ***Spacecraft may autonomously leave the stack* (with initial thrust impulse or sustained thrust)**

Filament Truss Column

Shear stiffness indirectly destabilizes attitude

- **Shear compliance would permit truss self-alignment to eliminate the torque…**
- **…so drop the diagonals!**
- **Joint locations marked on fibers with precision**

- **Design to control thermal & slew response**



Geometric nonlinear truss shear stiffness remains:

$$K_T = (GA =)\ F_{tow}$$

and varies along the truss length.

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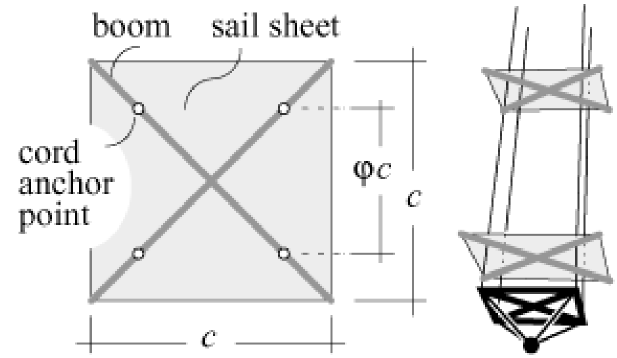
Truss Column Design



Geometry	$\varphi c = 1.901$ m	*truss depth*
	$n_c = 16$	*fil. per longeron*
Filaments	$d_c = 6.4\ \mu m$	*diameter*
Material	*carbon fiber*	*Thornel T-650/35* *
	$E = 240$ GPa	*fiber Young's mod.*
	$R_u = 4.28$ GPa	*strength*
	$\rho = 1770\ kg/m^3$	*fiber density*
	$\alpha_T = -0.6$ ppm	*coeff. of th. exp.*
…then	$m_{tr} = 39.3$ g	*truss mass*
	$m_{tow} = 13.13$ kg	*total tow mass (truss + panels + interface)*
	$EI_{tr} = 439.3\ Nm^2$	*flexural stiffness*
	$dL = 0.488$ m	*tow elongation*
	$FS_{fail} = 200$	*safety against cord failure* **
	$r_{min,c} = 0.2$ mm	*min. radius of cord bending* ***

* For lowest CTE
** $FS_{fail} = 158$ for infinite payload mass
*** Limit cord corner radius in stowage to not break fiber

Dynamics: Vibration

- **Approximate assessment** via chain swing analogy

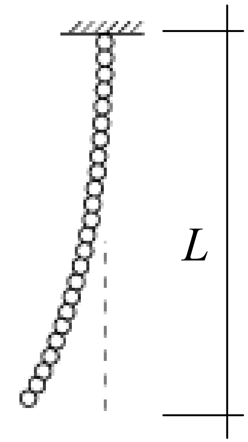
$$f_i = \lambda_i \, (g_{eq}/L)^{1/2}/(2\pi)$$

Mode	λ	f [1/s]	T [h]
1	1.2026	105.1×10^{-6}	2.64
2	2.7602	241.2×10^{-6}	1.15
3	4.3266	378.1×10^{-6}	0.73

Fixed support = massive payload
→ reduces frequency

No flexural stiffness
→ reduces frequency

Infinite shear stiffness
→ increases frequency



Equiv. acc. of grav.:

$$g_{eq} = F_{tow,max}/m_{tow} = 43.76\ mN / 13.13\ kg = 3.302\ mm/s^2$$

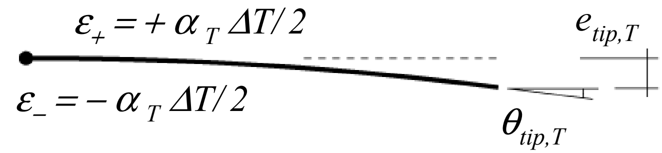
- **Geometric nonlinear model,** finite difference analysis

Mode	f [1/s]	T [h]
1	114.5×10^{-6}	2.43

Shear and flexure effects properly accounted for.

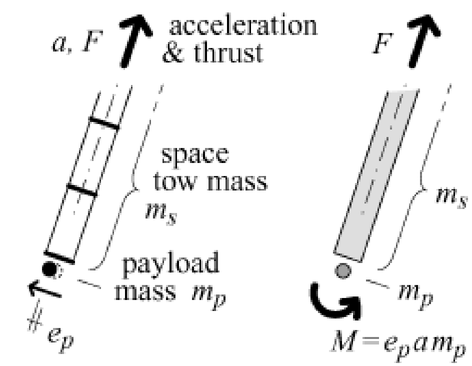
Thermal & Slew Loads

- **Gradient across truss:** $\Delta T = 50^o C$ *



$e_{tip,T50} = 944.7\ m$ — *tip deflection*
$\theta_{tip,T50} = 9.91^o$ — *tip rotation*

- **Steady state slew**
by $e_p = 0.5\ m$ payload offset



$M = 21.64\ Nmm$ — *attitude torque*
$Q = 2.785\ mN$ — *shear at payload*

$\beta = 4.89 \times 10^{-11}\ rad/s^2$ — *rotational acceleration*
$t_{30} = 57.50\ h$ — *steady-to-steady 30^o turn time*

$e_{tip,e0.5} = 1656\ m$ — *tip deflection*
$\theta_{tip,e0.5} = 11.85^o$ — *tip rotation*

* Reference number; not from thermal analysis

Nonlinear Model Is Necessary

- **Linear prediction for moderate loads (previous page):** *10°* **rotations**

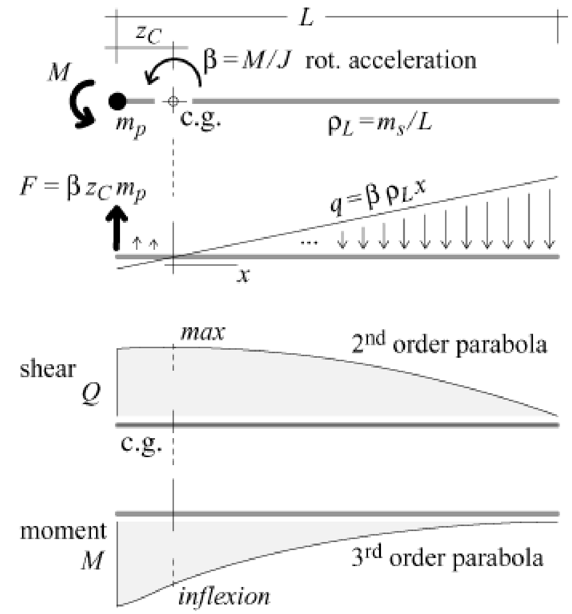
Impact on the cosine-squares:

$\alpha = 30^o \rightarrow 40^o$ $\cos^2\alpha = 0.75 \rightarrow 0.59$, -22%

$\alpha = 30^o \rightarrow 20^o$ $\cos^2\alpha = 0.75 \rightarrow 0.88$, +18%

- **Error margin: 20% for thrust alone, possibly with further nonlinear amplification**

Nonlinear approach is needed to model even the steady-state slew response



Linear results derived from the stiffness, shear, & moment functions defined on the stress-free shape.

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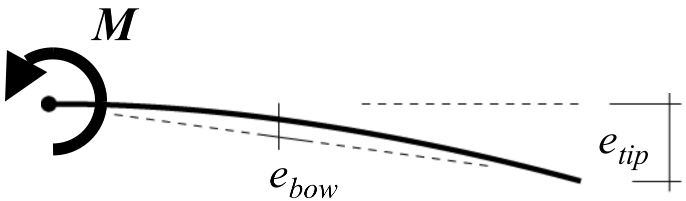
Absolutely necessary!

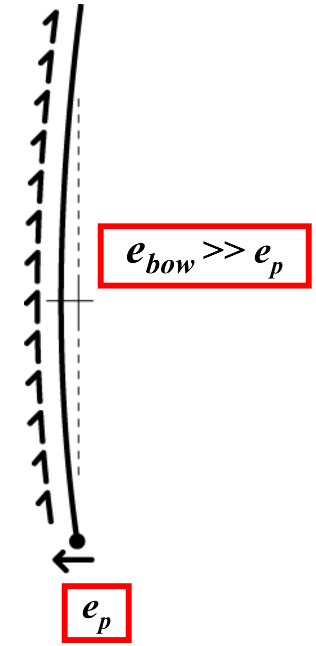
- **Another observation:**

$e_p = 0.5\ m \rightarrow e_{tip} = 1656\ m$

$e_{bow} = 278.5\ m$



- **Half a meter tip mass offset cannot effect this large bow – this response is impossible.**



Result is unrealistic if the mutual coupling of column deformations, flexibility, and thrust variation is ignored.

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The Structural Feature That…

…governs the space tow paradigm and, as seen, dominates design and analysis considerations is a uniquely intimate coupling of structural and navigational issues.

A truly "gossamer" structure with the outstanding advantage of an immediately practicable – modular, incremental, and cost-efficient – development path.

Along This Path

Work is progressing toward the following milestones:

- Nonlinear prediction of steady-state slew response
- Demonstration of full maneuver feasibility
- Stability: attitude and spin control strategies
- Improve tool for detailed, final panel design
- Trajectory design and mission applicability

↓

- Steps toward a comprehensive structural and mission design toolkit

Final Note

- **Despite its performance parameters, …**
- **…the space tow's most advantageous characteristic remains technological scalability – the scalability of design, fabrication, handling, testing, mission operation, and control issues.**

- **Designs even with small dimensions can be representative of full-size missions.**
- **An economy of development unheard of for more elaborate sails results.**

Extra Slides

Example with Extreme Length

100 000 m^2 space tow = ten *100×100 m* sails
$\alpha = 30^o$ offs., $\eta = 0.8$ refl. eff., *200 kg* payload

- 131.6 kg — **gross structural mass,**
  1.313 g/m^2 — **sail surface specific mass**
- 331.6 kg — **total system mass**
- 2.517 mm/s^2 — **accel. at** 1 AU
- 109.5 km — **length**
- $2.24^2 \times 2.5$ m — **stowage**
- 20 × — **fiber safety**

* *Steering / control with pilot sail at tail end of tow (away from the spacecraft) may be considered.*

Applicability & Limitations

No known mechanical issues inherently limit length or applicability.

However, viability in specific contexts is contingent upon the success of *low-risk and -cost work* to answer challenges such as…

- **Attitude control, navigation**
- **Truss / tow straightness vs. filament length precision**
- **E-magnetic & gravity gradient effects**
- **Deployment**
- **…etc.**