The Solar Kite: a New Tethered Sail Concept – a High Level Introduction

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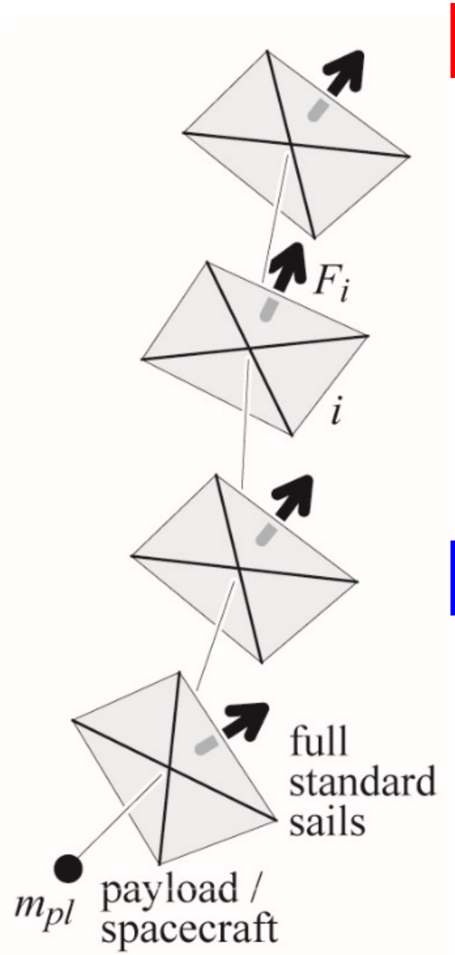
v2m

Tethered Solar Sails

Harvest thrust with individual surface units along a tension structure



Pros:

- **Modular/Extendible**
- **Virtually unlimited thrust performance**
- **System mass is proportional to total thrust**

- **The scaling penalties are linear (flexed component dimensions don't change)**
- **Thrust is limited only by cable/filament strength**

Cons:

- **May be sensitive to some environmental effects (e.g., gravity gradients)**
- **Line failure risk**

- **Conditions of operability to be examined**
- **Risk to be assessed**
- **Can be remedied**

Unique to Tethered Sails

- **Flexed member dimensions don’t need to increase when a design is scaled up.**

  → Thrust performance depends on the streamlined/minimalist design of flexed components (beams, booms, stiffeners)

- **How efficiently units can be stacked is a major practical bottleneck**

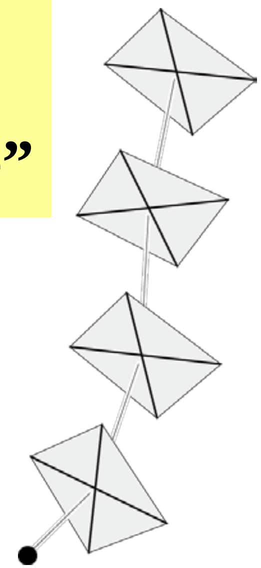
  → For the tow & the kite which feature many panels, even minute stowage inefficiencies may render a design less than attractive

Tethered Sail Concepts

Sail Liner

1982, Lukyanov

Full sails on a "rope"

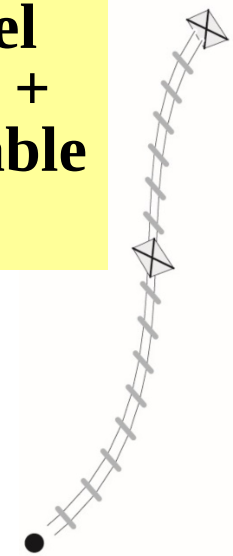


- **Linearly coupled "standard" sails: 100s of miles' length, 100s of tons of cargo**
- **Struct. scaling issues keep undermining the making of even a single sail for cargo purposes**

Space tow

2006, Greschik

Parallel panels + navigable units

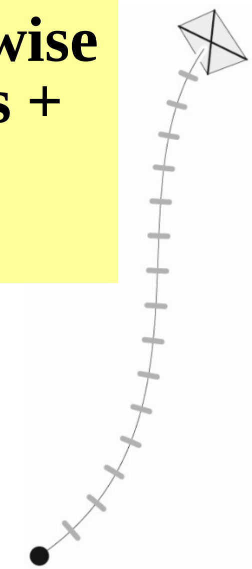


- **No struct. scaling issues, low-risk R&D, great thrust efficiency, great packaging**
- **Control/navigation conundrum, unless the number of navigable units is high**

Solar Kite

2023, Greschik

Crosswise saillets + lead sail

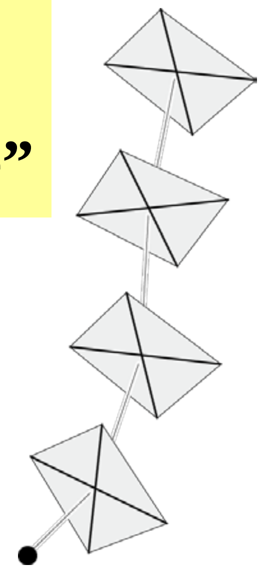


- **All of the space tow benefits + easily navigable**
- **No architectural issues known so far**

Some Sail Liner Issues

Sail Liner
1982, Lukyanov

Full sails on a “rope”



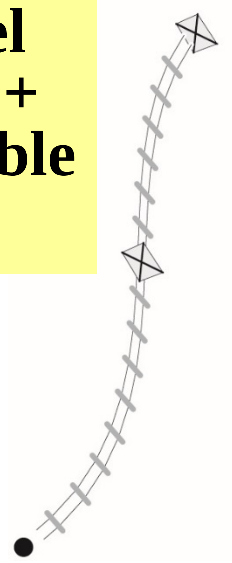
- **Linearly coupled “standard” sails: 100s of miles’ length, 100s of tons of cargo**
- **Struct. scaling issues keep undermining the making of even a single sail for cargo purposes**

- **<u>Complexity</u>**
  Each unit is a “full” sail – in terms of stowage & deployment, operation, navigation, etc.
- **<u>Unit size</u>**
  Not any easier to fabricate & handle than a “classic” non-tethered sail by itself
- **<u>Development path</u>**
  No advantage over classic sails

Some Space Tow Issues

Space tow
2006, Greschik

Parallel panels + navigable units



- **No struct. scaling issues, low-risk R&D, great thrust efficiency, great packaging**
- **Control/navigation conundrum, unless the number of <u>navigable</u> units is high**

- **<u>Dimensional sensitivity</u>**
  Longeron length errors can build up along the structure
- **<u>“Constrained” control</u>**
  Poor leverage: shear compliance renders direct shear control impossible
- **<u>“Hard to” navigate</u>**
  Poor leverage: the entire tow must be actively turned/re-oriented

The Kite Is Free of These Issues

- **<u>Dimensional sensitivity</u>**
  Longeron length errors can build up along the structure
- **<u>“Constrained” control</u>**
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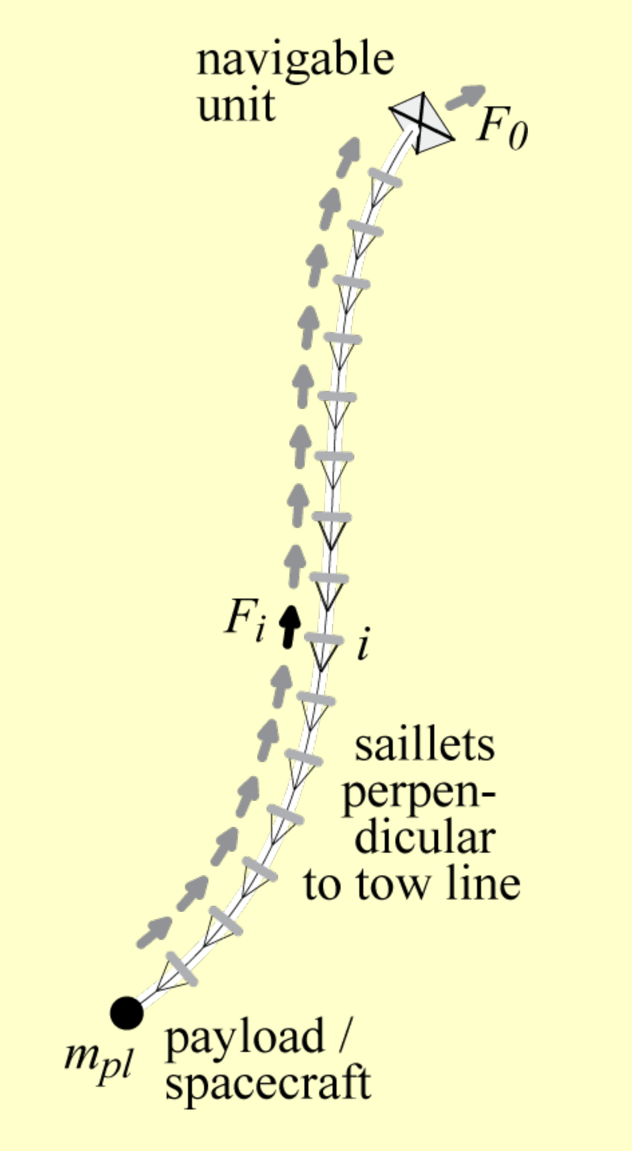
Cross-Aligned Panels Are Used

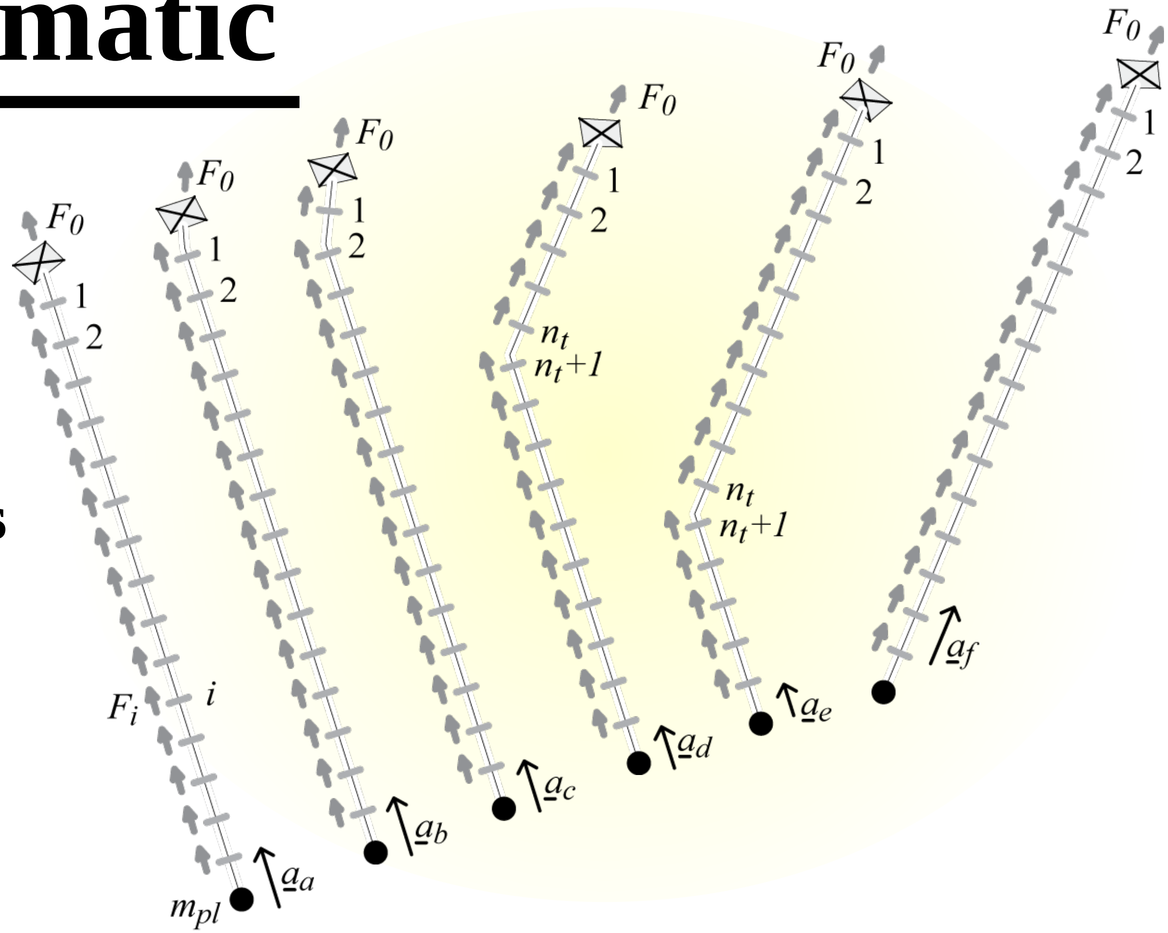


- **The saillets (panels) are linked by a tow line**
- **The panels are cross-aligned locally, by their individual suspension**
- **Lead sail controls operation**

- **Irregular system dynamics is expected to be tolerable**
- **Imperfections matter little**
- **Redundancy possible via extra tension structure**
- **Pullout & kickoff deployment both feasible**
- **Stows in a stack**

Turn Schematic

- **Lead sail starts turning, after steady state flight w/ accel. a_a**
- **Pulled off course, Panel 1 also turns**
- **Lead sail w/ 1st panel together continue exerting lateral pull**
- **The panels automatically & progressively re-align**
- **The thrust component in the original flight dir. diminish, while …**



- **… the thrust in the new direction keeps increasing**

Wave dynamic effects are to be examined, but are not expected to be detrimental.

Only a Few Points To Address

- **Panel alignment**
  … by suspension
- **Damage tolerance**
  … by tow line redundancy
- **Twist control**
  … by panel & suspension geometry
- **Lead sail & its control**
  … with little penalty

- **These points will be discussed in detail next**

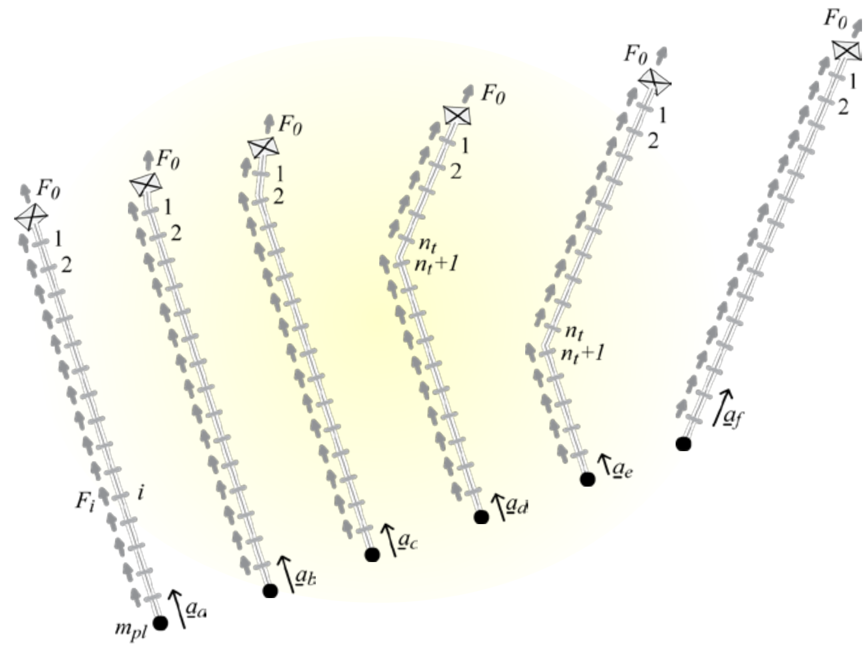
Can be resolved by architecture

Adding, Of Course …

- Panel alignment
- Damage tolerance
- Twist control
- Lead sail & control
- **Dynamics & navigation**
  … to be characterized & optimized: a quantitative problem, will one day be a story by itself
  - **Full 3D context makes the problem very complex, but …**
  - **Not a bottleneck because the architecture is robustly fault tolerant in terms of dynamics**

There Is a Twist To The Story

- Panel alignment
- Damage tolerance
- Twist control
- Lead sail & control
- Dynamics & navigation



- **Some photonic thrust characteristics**

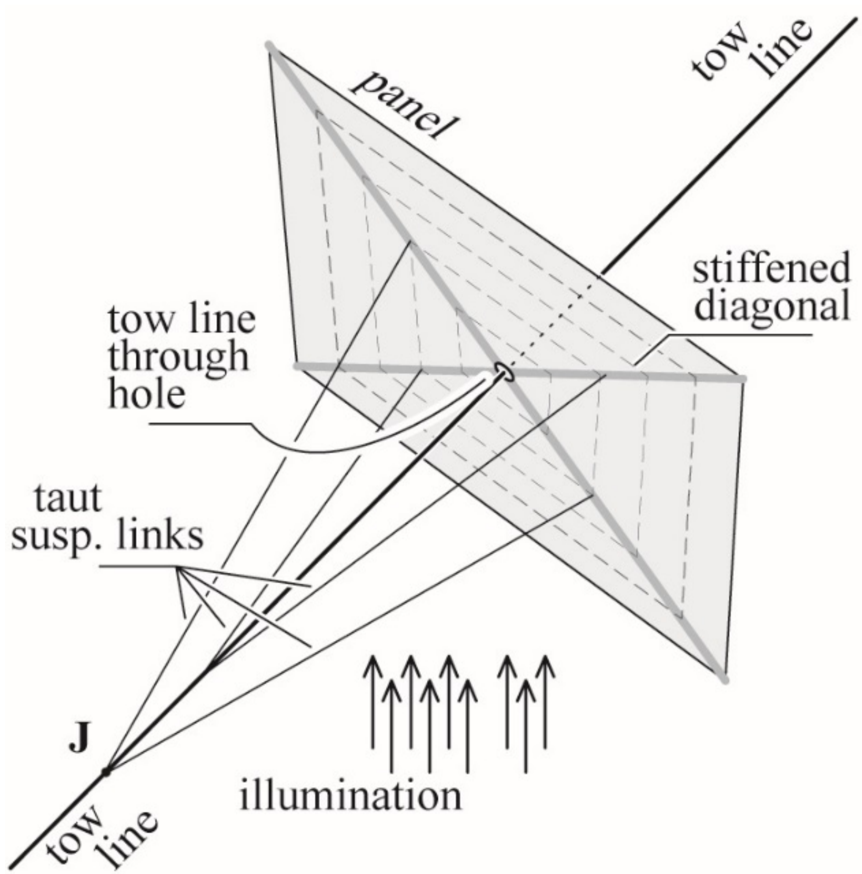
  … may impact on whether the turn schematic works as hoped

- **It is critical to assume the right reflectivity model**
- **Will be shown after the architectural review**

But First: the Architecture

- **Panel alignment**
  … by suspension
- **Damage tolerance**
  … by tow line redundancy
- **Twist control**
  … by panel & suspension geometry
- **Lead sail & control**
  … with little penalty

Panel Suspension Schematic

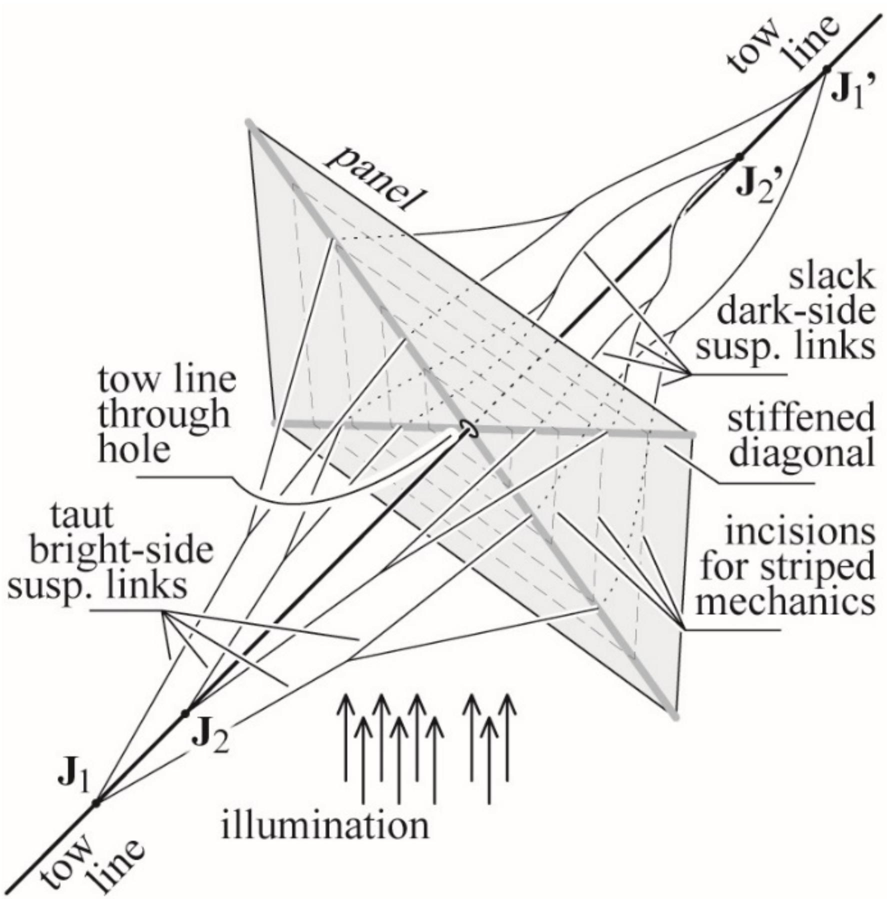


<u>Bare-bone configuration</u>

… to maintain the desired panel orientation

- **Suspension link set: the 4th one is redundant**
- **Tow line: *d*=5-10 µm fiber, carbon or other, readily available**
- **Links: *d*<1 µm fiber, to be identified**
- **Filaments laid between panels for storage**

Panel Suspension Schematic 2



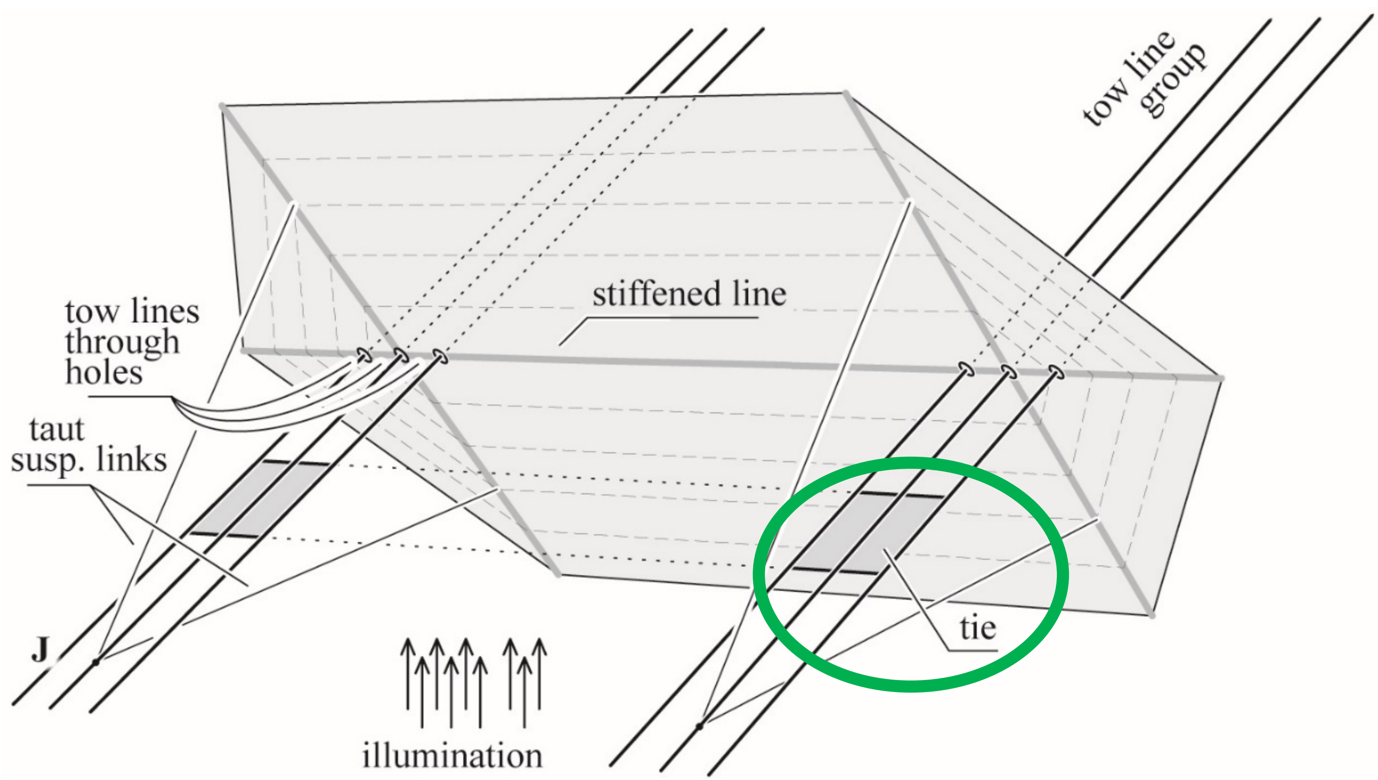
More features added

… to aid deployment, improve performace

- **Forked link improve stiffness**
- **Bright-side links taut, transmit thrust**
- **Dark-side links: slack in operation, assist pullout deployment (not needed for kickoff deployment)**
- **Slack dark-side links boost damping**
- **Incisions enforce ideal mechanics**

Redundancy & Twist Control

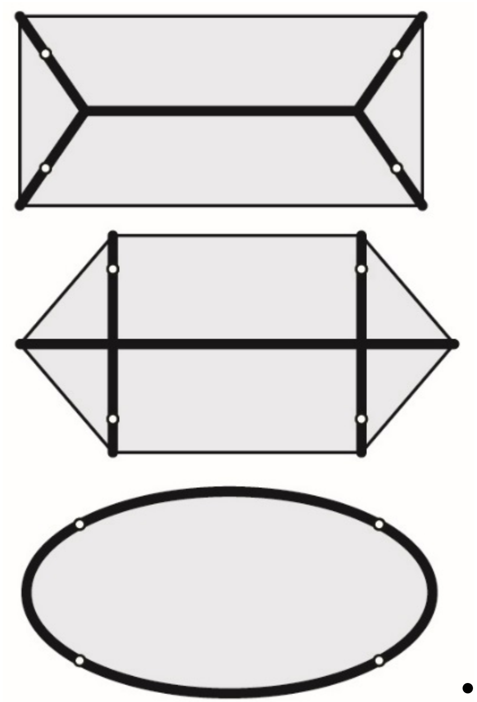
- **Multiple tow lines constitute a structural "ribbon"**



- **Twist resistance by geometric nonlinear effects**
- **Redundancy by periodically coupled multiple tow lines**

Structural Footnotes

- **Multiple skeletal options exist for the panels:**

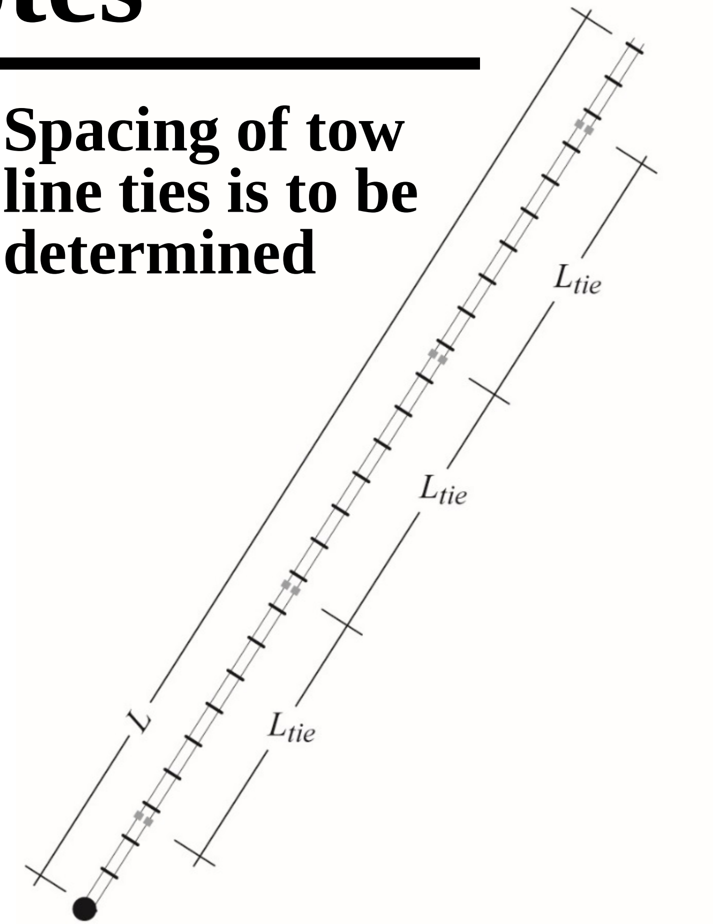


… etc.

Dimensions tailored to:
- **Allow "no-mass" stiffeners**
- **Facilitate handling + fabrication**

? 5x10 cm, 30x70 cm, 1x3 m, …

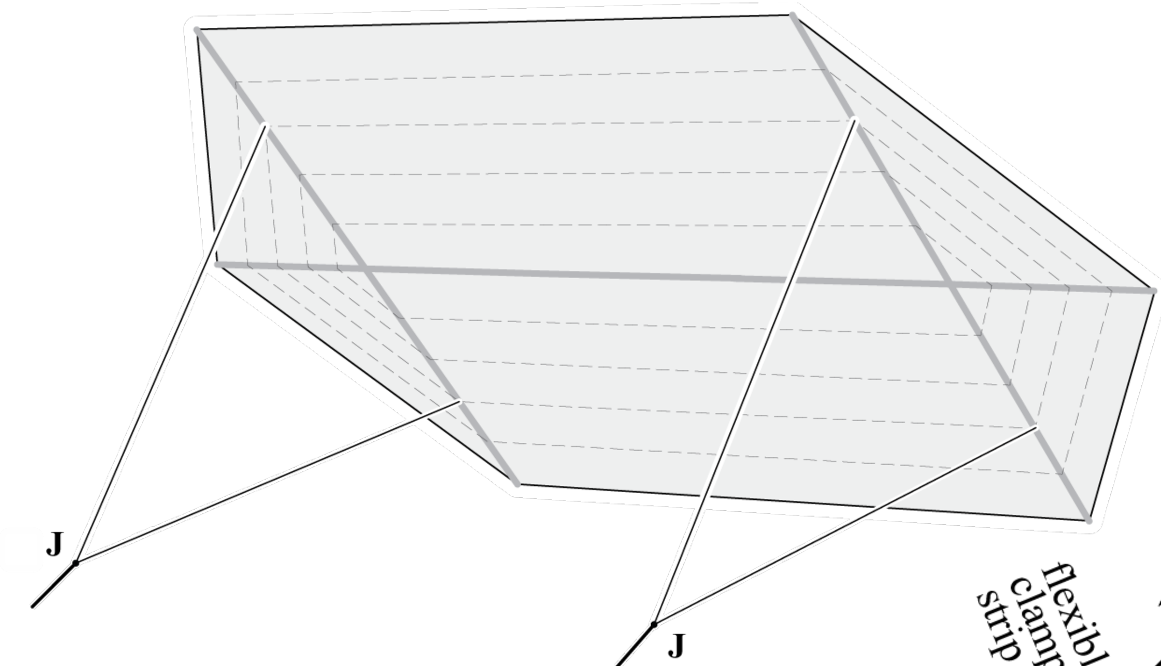
- **Spacing of tow line ties is to be determined**



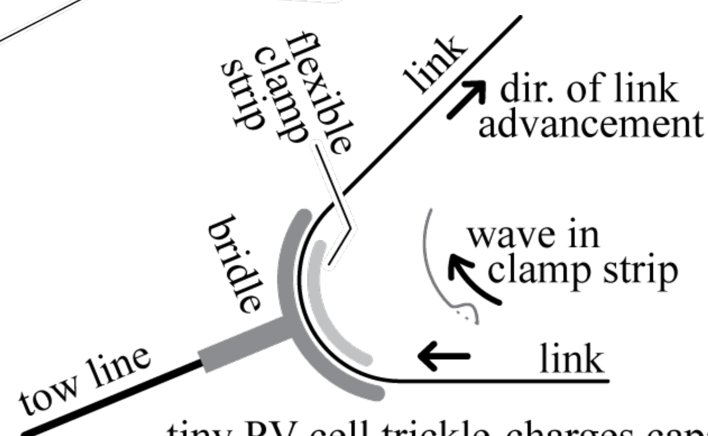
- **To Allow graceful performance degradation**
- **Defined w/ statistical estimates**

? L=20 km, L_{tie}=100 m, n_{panels}=10,000

The Lead Sail



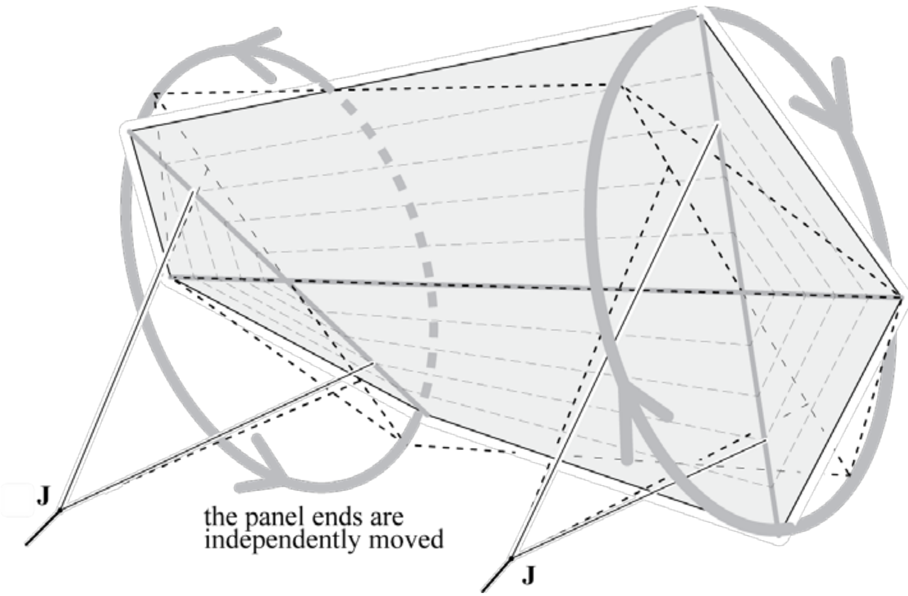
- **Suspension adjustment (panel alignment control) at junction J is possible**
- **Example schematic is shown, MEMS-type engineering may work**

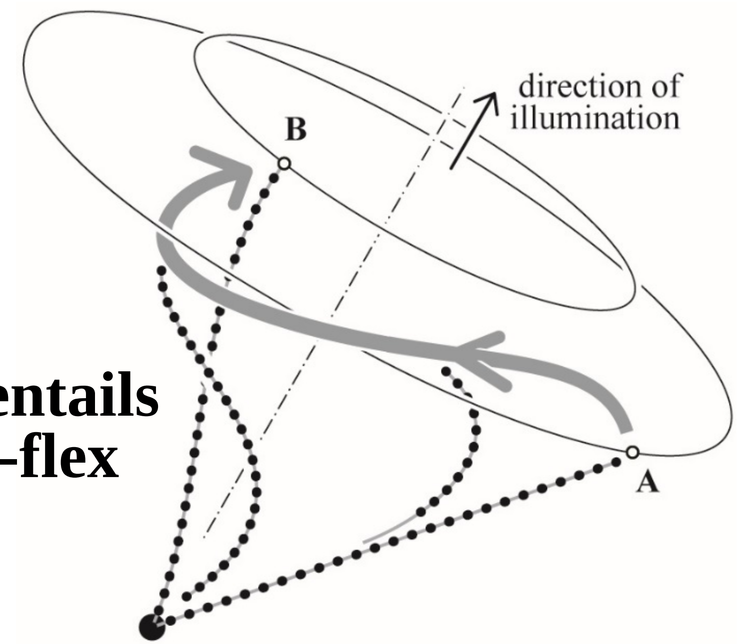


- tiny PV cell trickle-charges capacitor
- capacitor is discharged when RF signal is received, triggering wave in clamp strip
- signal also defines wave/trigger direction

The Lead Sail Can Tilt & Twist

… with the two panel ends actuated independent of one another





- **Maneuvering entails a 3D twist-and-flex choreography**

The Concept Has Been Defined

… it is time for a quantitative design study, in order to

- **Assess performance**
- **Reveal performance bottlenecks**
- **Gain initial insight into some "hands on" issues**

Numbers similar to space tow results are obtained, indicating absolutely outstanding performance.

Just Like the Space Tow

10000 m^2 **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-m^2 — **system mass m. of inertia**
- $2.24^2\times0.25$ m — **stowage envelope**

… 2000-panel point design in Greschik, *Some Struct., Mission Perfmc., and Navig. Features of the Space Tow*. ISSS 2007, Herrsching, Germany, June 27-29, 2007.

The Concept Has Been Defined

… it is time for a quantitative design study, in order to

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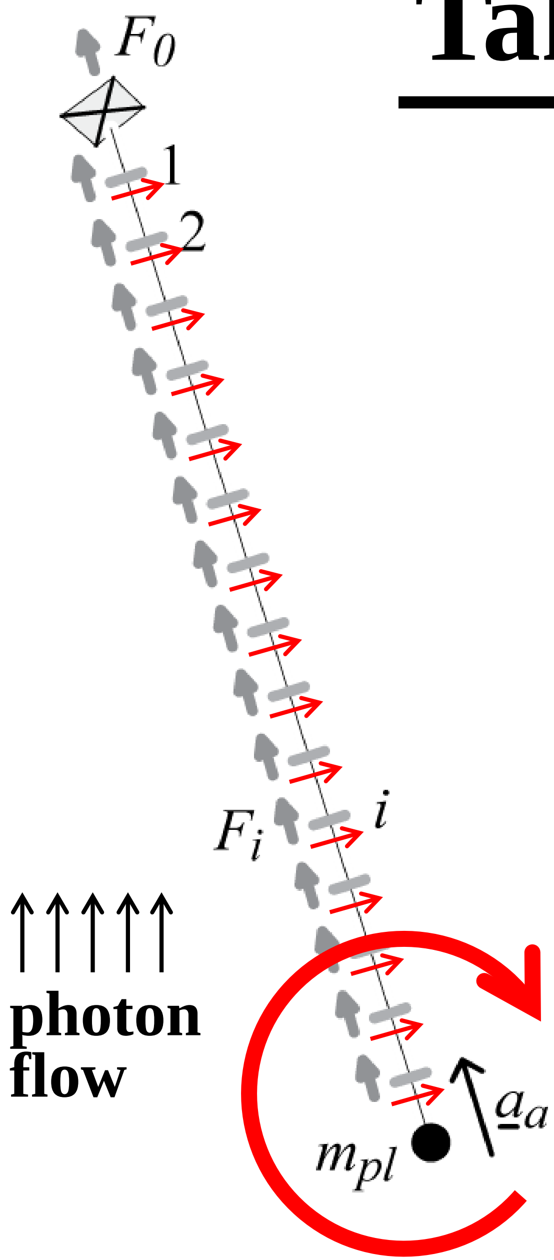
… IS IT, REALLY ?

Take a Close Look

… at the reflective thrust model!



- **In a 1st approximation model (ideal specular reflection), this configuration works great**
- **<u>But it is unstable if a surface-parallel thrust component is present</u>**
  - **A torque about the payload emerges, turning the system to align with the direction of illumination – the only stable orientation.**

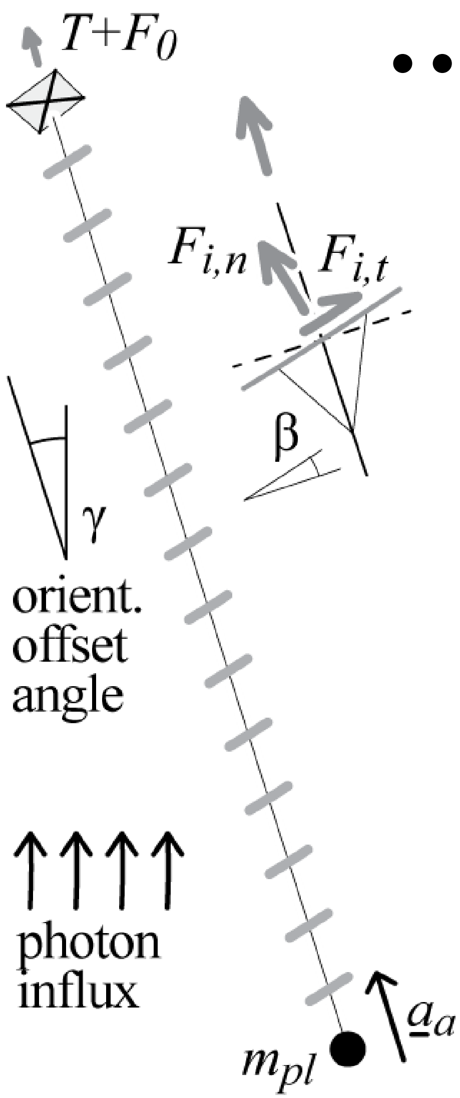
Greschik, *The Solar Kite: Yet Another…* Concept Review ISSS 2023, June 3-9, City Tech, CUNY, New York

An Initial Thrust Analysis

- **Was performed with the reflective thrust model established as preferred in an earlier study**

Greschik, *Direct Thrust Efficiency for the L'Garde Sail Surface with a Linear Reflectivity Model*. In Macdonald, ed., *Advances in Solar Sailing*, Springer Praxis Books, Astronautical Engineering, 2014, pp. 437-455.

The Equilibr. State Is Tunable



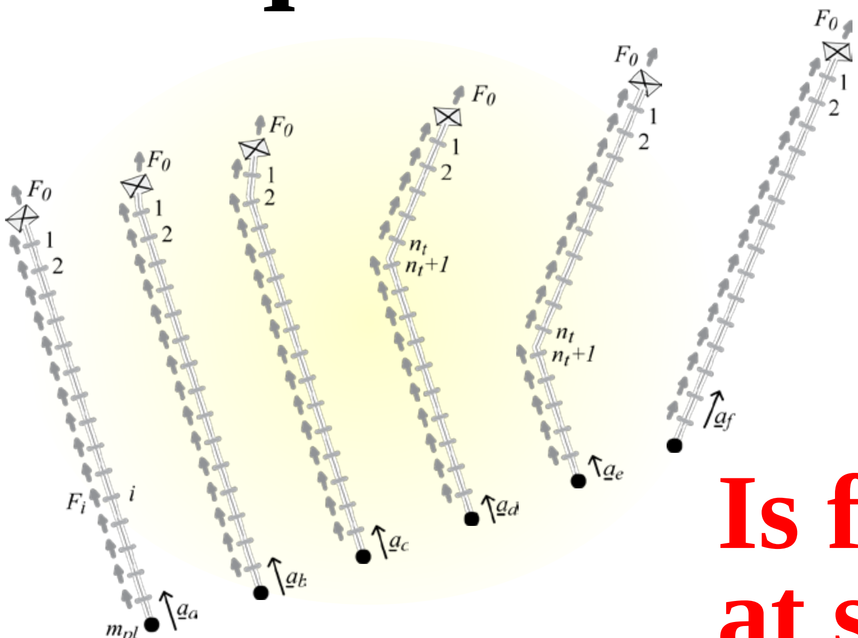
… via panel tilt β

- **The equilibrium states will be confined to a cone with cone angle γ**
- **With a symbolic closed form relationship between γ and β**

How effective will the envisioned navigation schematic be?

Two Subtle Effects Are At Bay

1. **Progressive auto-alignment to the lead sail**
2. **Restoring forces toward the equilibrium cone**



How to navigate best?

Is feasibility at stake?