# Deployment Simulations of the Space Tow Solar Sail

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## Preface

The work presented in this thesis was initiated by Dr. Gunnar Tibert at the Department of Mechanics at the Royal Institute of Technology, KTH. It was carried out between September 2012 and May 2013 under the supervision of Dr. Gunnar Tibert.

I would like to thank Gunnar for continuously challenging the work as well as myself during the process. Your guidance and curiosity has followed and bettered this thesis at every step of the way.

Work such as this is not made in a vacuum, and I would like to thank the members of the Physics Chapter at KTH for their support, never ending questions as well as providing a sounding board whenever needed. Special thanks go to Johan Kvastad, Tomas Lycken and Clara Lynn. I also wish to thank the excellent help of the staff at the Department of Mechanics, especially Carolina Eneqvist and Pär Ekstrand.

Last, but not least, I would like to thank my family and friends for their encouragement. I would especially want to thank Fred Stenudd for reminding me of what's important.

Stockholm, May 2013
Patriq Banach

## Abstract

Solar sailing has been long in the coming, a notion almost a century old and only recently demonstrated to work. The idea of using ambient photons for space propulsion is an appealing one not only for the elegance of not having to carry heavy fuel, but also for the special physics of a continuously accelerating spacecraft.

One of the proposed architectures for a light, modular solar sail is the Space Tow, consisting of hundreds of $\mu$m thin sheets suspended in several km of carbon filament, at the same time stowable in mere meter-scale height.

This thesis investigates the deployment mechanics of the Space Tow for two passive deployment strategies, "drag along" and "leave behind" deployment. Simulations were made using a simple 3D model in ABAQUS/Explicit and compared to a 1D mechanical analysis.

Many of the problems with these deployment schemes were of acceleration-rate changes and the damping thereof. The last part of the thesis touches upon the involved energies and how these could be dissipated by dry friction, as well as how this would be described in an acceleration-rate proportional damping constant for use in future models.

The thesis concludes that the "drag along" scheme is sensitive to perturbations and that the "leave behind" scheme needs careful consideration of its parameters or risk that the undeployed stack accelerates to pass the deployed structure.

The thesis is composed of two parts, section I is a background presenting the subject and available literature. After that follows an article which at the time of writing is to be presented at the 3rd International Symposium on Solar Sailing, 2013.

## Svenska

Solsegel är inget nytt påhitt, de första beskrivningarna av solframdrivna rymdfarkoster är närmre ett sekel gamla, men det är inte förrän nyligen som de första solseglen visats fungera. Att använda fotoner för rymdfart är intressant inte bara för att det finns många fotoner tillgängligt i rymden, utan även för att undgå att skicka upp tungt bränsle med farkosten. Dessutom finns mycket intressant fysik att tillgå med ständigt accelererade farkoster som möjliggör uppdrag som inte vore rimliga med andra drivmedel.

En av de föreslagna lösningarna på ett lätt, modulärt solsegel är Space Tow, som består av hundratals $\mu$m-tjocka segel, fästa i flertal km långa kolfiberfilament som går att stuva i bara någon meter packhöjd.

Denna avhandling undersöker mekaniken för två passiva utfällningsstrategier för Space Tow, en "drag along"-metod, där ett pilotsegel drar ut de hoppackade seglen, och en "leave behind"-metod där de packade seglen skickas ut tillsammans för att sträckas ut allteftersom deras koppling till lasten sträcks ut. Undersökningen gjordes via simuleringar av en enkel 3D-modell i ABAQUS/Explict samt jämförelser med en analytisk 1D-modell.

Många av svårigheterna med dessa utfällningsstrategier är kopplade till accelerationsförändring och dämpning av fenomen likt ryckningar. Den sista delen av avhandlingen rör vid de inblandade kinetiska energierna och hur dessa skulle kunna dissiperas genom torr friktion. Därtill avhandlas hur detta skulle beskrivas som en accelerationsförändringsproportionell konstant för användning i framtida modeller.

Avhandlingen sluter sig till att "drag along"-metoden är känslig för störningar under utfällningen och att "leave behind"-metoden behöver nogrannt övervägda val av parametrar för att den utfällda strukturen inte skall passera den ännu ej utfällda.

Avhandlingen består av två delar, del I är en bakgrund och presentation av ämne och tillgänglig litteratur. Därefter följer en artikel som, då detta skrivs, skall presenteras på 3rd International Symposium on Solar Sailing, 2013.

# Contents

# I. Background

For the longest time, humanity has wishfully gazed upon the night skies, observing the multitudes of wondrous objects and possibilities that are hidden just beyond our reach. As humanity developed, our reach grew and for about half a century, humanity has started to explore space, not only by observing it, but actually travelling it.
Propulsion of any vessel usually requires an application of Newton's third law, be it from a reaction mass accelerated into a jet driving a solid rocket motor or a solar-electric ion drive [4, p. 1]. When using such modes of propulsion in space this fuel must be brought and expended into space, at great cost in mass and resources. An elegant form of propulsion that circumvents this need is the solar sail, a propulsion system that gains the momentum from an ambient source, photons, and thus provide continuous acceleration, limited only by the lifetime of the sail film. As the momentum of individual photons is vanishingly small, we would need to intercept a great many to get an appreciable effect, requiring a large reflecting sail surface, nearly perfectly reflecting as to be able to double the momentum gained per photon. If we add requirements on the acceleration of such a spacecraft, we would also need it to be extremely light for this momentum to accelerate it. So the picture of a solar sail would thus be a shining membrane of thin reflective film held stretched by some gossamer structure, accelerated by reflecting ambient light from the stars, slowly but continuously accelerated to accomplish any number of missions [4, p. 1–2].

## I.1 A brief history

The fundamental ideas of solar sailing are more than a century old, having been considered since James Clerk Maxwell demonstrated the theory of light pressure in 1873. But outside of writings of light pressure and solar sailing in fiction, the first writings seem to come from the Soviet in the 1920s, by Tsiolkovsky and Tsander, and the first American author, Carl Wiley wrote 1951 under the pseudonym Russell Sanders in *Astounding Science Fiction* sparking more detailed studies during the late 1950s and through the 1960s [4, p. 2–3].
The formulation by NASA of a practical mission for solar sailing during the 1970s, namely to rendezvous with the comet Halley in the mid-1980s, gave solar sailing a focus, making great progress with a spin-stabilised heliogyro using twelve 7.5 km long blades of film over a three-axis square solar sail configuration. The mission ultimately favored a solar-electric propulsion, but was dropped due to escalating costs and fast approaching deadline [4, p. 4–7].
During the 1990s, we saw development and flight testing of some key technologies. The Russian Space Regatta Consortium successfully deployed a spinning 20 m reflector in February 1993, demonstrating that such spin deployment can be controlled by passive means, although the principal use of the reflectors were to illuminate northern Russian cities to aid economic development [4, p. 7–8]. In May 1996 a 14 m diameter reflector was deployed in the Inflatable Antenna Experiment, demonstrating the promise of inflatable structures for robust and reliable deployment [ibid.].
More recent developments include advances in inflatable structures as well as tools for analysis and simulation [2, p. 191-261]. A team of L'Garde, Jet Propulsion laboratories, Ball Aerospace and NASA's Langley Research Center have designed, constructed and tested up to a $20\times20$ $m^2$ inflatably deployed square solar sail with successful results in a rough vacuum at ground level [2, p. 200–219], [3]. ATK-ABLE have conducted successful multicomponent tests for a $10\times10$ $m^2$ quadrant of the Square Scalable Solar Sail, $S^4$ [2, p. 219–230]. A flight ready small scale satellite propulsion sail, NanoSail-D was destroyed in launch due to rocket failure [1] to be followed by a successful low Earth orbit deployment and de-orbit demonstration by Nanosail-D2 [5] from a CubeSat.
JAXA launched a successful interplanetary solar sail demonstration with the Ikaros, with demonstrated success of photon propulsion, spinning square sail deployment, power generation

via flat solar cells as well as attitude control via LCD reflectivity, sending a 307 kg spacecraft past Venus [2,7].
A different take on the scalability issue, the Space Tow, was proposed by Greschik in 2007, with an eye to ease manufacturing, testing and payload scaling [6].

## I.2 Why Solar sailing

Solar sailing is attractive not only as a fiction notion, but from a variety of viewpoints, economical, longevity of mission and mission physics to mention some. One of the attractive features of solar sails are their light weight, in part because very little fuel is needed to propel the craft, as well as the design requirements of a light craft. When no fuel is needed to propel the craft, the limitation of impulse force on the mission is dropped as well, as provided enough time, the accumulated photon thrust would provide all $\Delta v$ needed for any mission, effectively enabling long-distance planetary missions and missions with sample retrieval that would have a prohibitive fuel cost. However among the most interesting aspects is the sustained acceleration available through the solar sails, a continuous acceleration without affecting the craft enables access to non-keplerian orbits [4, p. 11–24] and equilibrium points outside of the Lagrange points, useful for example for the Geostorm warning system mission [5], and the Solar polar sail mission [4, p. 231–242].

### Mission applications

Macdonald and McInnes [3] categorised the key mission applications for Solar Sailing in an attempt to find an application to drive solar sail development . A critical review was presented of which of these missions would actually benefit from solar sailing, see Table 1.

**Table 1:** *Solar sail missions by benefit, reconstructed from [3].*

| Enable or Significantly enhance | Marginal benefit | No benefit |
|---|---|---|
| Non-inertial orbits, such as GeoSail or a Mercury sun-synchronous orbiter | Venus escape at end of sample return mission | Loiter at the gravitational lens |
| Highly non-keplerian orbits such as Geostorm and Polesitter | Mercury and high-energy small body sample return missions | Outer solar system rendezvous and centred trajectories |
| Kuiper-Belt fly-through | Outer solar system planet fly-by | Planetary escape at start of mission |
| Solar Polar Orbiter<br>Interstellar heliopause probe | Oort cloud | Mars missions |

### Challenges of solar sailing

The dimensioning challenge of solar sailing is the low amount of available photons, providing a pressure of at best 9 $N/km^2$ at Earth's distance from the Sun [4]. To be able to accelerate a space craft by sailing, not only must the sails have a large reflective surface, but must also have a small mass. Possibly, the payload must be light as well, to reach the required acceleration specifications. This requires some high-end materials for optimum efficiency. The design work requires computation-costly simulations, modelling beam and truss behaviour as well as large membranes with wrinkle-sized elements in static as well as dynamic processes, from

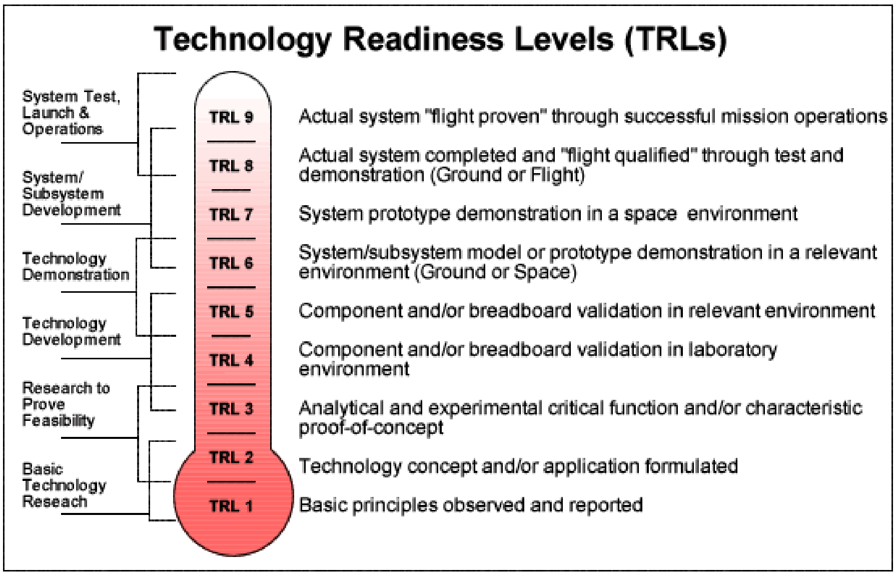


**Figure 1:** *NASA's technology readiness (TRL) definitions [11].*

deployment to maneuvering to fixed sailing. The often large sail surfaces provide challenges in manufacturing, multi-layer treatment of flimsy $100 \times 100$ m$^2$ sails as well as physical handling, packing and deployment. Making necessary scale tests and scalable designs as well as a compactly stowable, reliably deployable design. Not to mention testing all of these in a relevant environment, with vacuum and an effective gravity off-loading system. Preferably, this should be done cheap, in combination with existing technology and scalable enough to fit different missions. Fortunately, these challenges are not insurmountable and several designs have been developed and tested sufficiently for solar sailing at NASA to have achieved a near TRL6 [2, p. 214], [12] with applications for nanosatellites achieving successful launches [2, 5] corresponding to TRL9, Fig 1.

## I.3 Designs

Several designs have been proposed for solar sails, from large square sheets supported by long struts to spin-supported strips. Some common variants include

### Spar supported designs

This group uses one or more vast sail sheets kept under tension by spars, booms or equivalent constructions. An illustrative example is the three-axis stabilised square sail, Fig 2.

**Three-axis stabilised square sail** The three-axis stabilised square sail such as proposed for the Halley rendezvous mission consists of diagonal spars cantilevered from a central hub. As the planned sail area was $800 \times 800$ m$^2$, bending loads warranted supporting stays attached to a central boom attached normal to the hub [4, p. 76]. These stays would offload the spars and prevent buckling. The planned spars were to be lattice structures of titanium, to prevent undue thermal expansion, which allow for coiled storage of spars, stays and sail. One major disadvantage of the design was a large number of potential serial failures during deployment, as the complex load bearing structure would need to first deploy spars, then stays before deploying sail sheets, with all steps needing to be in place for the craft to manoeuvre properly.

Control of this craft could be accomplished by different methods. One such method would be displacing the hub and thus the centre-of-mass relative the sail, yielding an off-center rotation as the sail accelerates the craft. Another method could be physical displacement of the sail by reeling in one side whilst reeling out the other, much akin to conventional wind sailing. A third way would be to have small reflective vanes at the tips, angling these would create pitch, yaw and roll torque [4, p. 76–77]. Fig 2 .

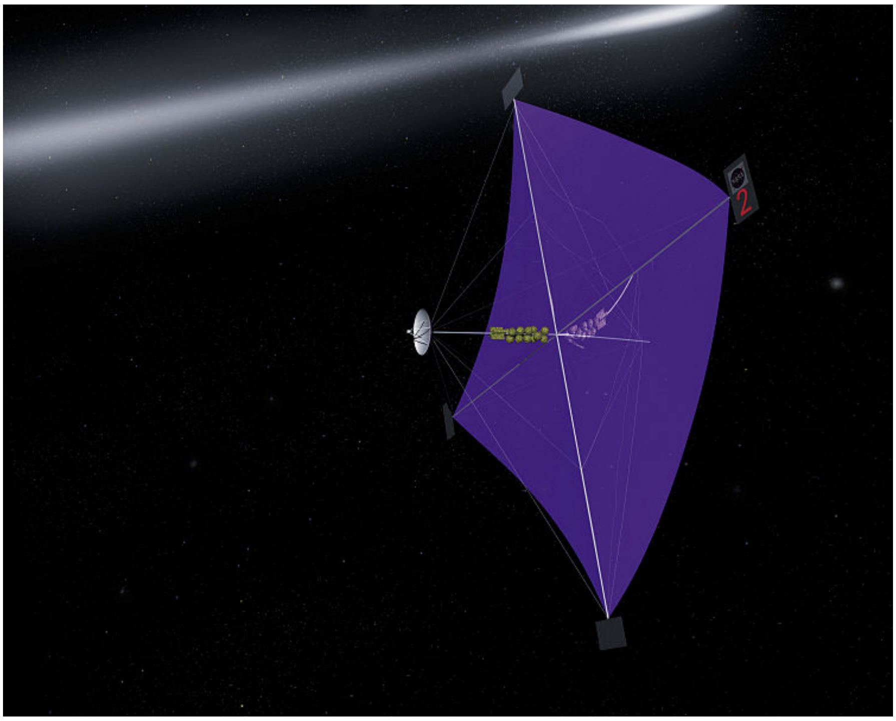


**Figure 2:** *An artist's concept of a three-axis stabilized spar supported space sail, [13]*

**Deployable spar-supported sail** Much work has been done to improve on the previous design resulting in successful deployment tests as well as an orbital technology demonstration [2, p. 200–230], [3,5]. The design is a simplification of the above, with smaller sails and better construction, the flexing of the spars could be managed. One or more sheets are fastened at four or more points of a deployable boom. Variants include dividing the sail into quadrants, fastening the sail at several points along the booms, as well as incorporating stiffening strips into the sail sheet to make it billow less [14]. This class of spacecraft is engineered in several clever ways such as with inflatable booms [2, p. 201] or with coiled composite booms [2, p. 223–224] [1]. The control systems vary greatly as well, some use the vane system as mentioned above [2, p. 206], some use rotating booms to create a"windmill-shape" for roll control together with actuators moving a ballast for other degrees of freedom [2, p. 221]. Fig 3 .

**Cord mat and striped sails** To gain as much thrust as possible from the sail it would ideally be flat, and need be prestressed taut. This would put load on the sail, demanding some load bearing qualities, usually adding weight to the sail. And despite this, we will still have some billowing which will affect the booms. To increase the stability and thus decrease the weight of the sails, the loading from the photon pressure could be better directed onto the structure. One way of reducing the axial load on the booms is to make sure the sail billowing transmits load parallel to the sail edge in a mechanically optimal way [14]. This could be realised by adding reinforced parts in the sail, either by glueing strips of sail material into overlapping sections or by glueing an additional layer on the sail itself. This would have the added benefit of creating a radial rip-stop of the sail as well as distributing loads.

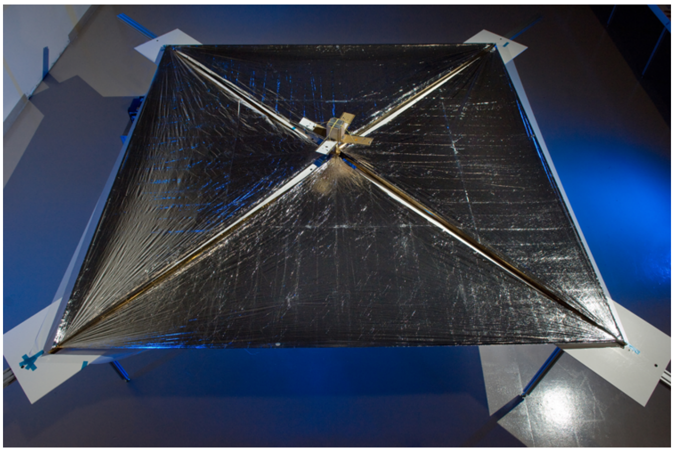

**Figure 3:** *A blue-tinged image of a fully unfurled solar sail. (NASA/MSFC/D. Higginbotham), [?]*

Another approach could be to set the sail on a matrix structure, such as a cord mat, effectively adding fibers in both edgewise and transverse directions. The mat itself would then be load bearing, rip-stop and load distribution as well as providing unambiguous load paths and relatively straight-forward inter-cord billowing kinematics [18] used in the Scalable Inflatably Deployed Solar Sail [2, p. 204] and Nanosail D [1].

As the booms are heavy and inefficient, Greschik [7, 8] has proposed stiffening the solar sail by locally corrugating the film sheet, optionally reinforcing some fold lines with cord, filament or strips. This would provide compliant film suspension as well as flexural stiffness comparable to a solid boom with an order of magnitude lower mass. These could substitute conventional booms in part or entirety for several sail designs to much improve on mass to acceleration efficiency [7, 8, 12].

**Spin-stabilised designs**

The spar supported designs above rely on rigid structures providing tension at the edges of the sail at the cost of added mass, a different approach could be to use rotation to provide tension and spin stabilisation.

**Heliogyro** The Heliogyro was invented in the late 1960s, a concept of several long blades of film held to a central rotating body, a design for the planned Halley rendezvous consisted of twelve blades, each 8 m wide by 7.5 km in length. The blades need be reinforced to provide torsional stiffness and centripetal loads, as well as redundant load paths, reducing the mass advantage of this design. The structure would be deployed by spinning the central hub, unrolling the blades, the partially unfurled blades provide added torque that aids the deployment. [4, p. 81–83]. Control of the Heliogyro would be accomplished by cyclically twisting the blades in pitch, allowing change of spin rate as well as creating a torque to alter the heliogyro spin axis. [4, p. 88–89]. Fig 4

**Spin stabilised disc sail** Disc designs are of course also feasible, although statically supported the strut lengths required to provide radial tension seem to favor the square designs [4, p. 72–75], even when considering a supporting hoop around the edge of the disc. A hoop, upon which the sail itself is fastened, serves to give radial tension to keep the sail from collapsing under the photon pressure. The billowing could be reduced by rotating the disc, leading to a flatter film profile which could lessen the requirements on radial tension from the hoop. The lesser radial

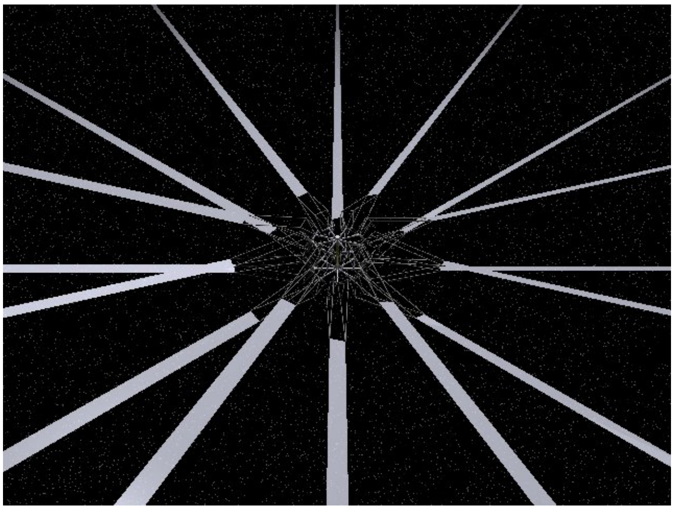

**Figure 4:** *Halley Rendezvous heliogyro solar sail. Spinning sail with long, thin blades [19]*

tension of the hoop translates to lower mass requirements and thus better efficiency. A craft like this could be controlled just as the spar supported versions, with an offset of the center-of-mass or with changes in reflectivity on the sail surface such as in the Ikaros [4, p. 72–74,89–91], [2].

**Ikaros - Spin stabilised square sail** The Ikaros is a square spin stabilised sail craft, augmenting the aforementioned design specifications of the deployable spar-supported designs with the tension reduction of the spin stabilisation. The Ikaros incorporates many clever solutions, one of which is the Reflectance Control Device (RCD) that via a thin LCD-panel on the sail film diffuses the incoming light to control the spin axis direction of the craft. The spin is controlled by a gas-liquid RCS system with 8 thrusters in radial directions for spin up/down and spin axis reorientation [2] The LCD panels and craft are powered by thin-film solar cells on the sail, which might also power an ion thruster in future missions [20].

**Tow sails, the Space Tow**

The common problems of the previously described designs are that they are quite difficult to scale, manufacture and test. With the first technology demonstrations flown, missions with unique performance specifications, perhaps even beyond nanosatellites, will arise for a variety of payloads, destinations and routes. The dimensions involved in the large sheet designs require large scale facilities to fabricate and test variations in designs and as payloads and/or acceleration increase, it is not trivial to scale film manufacturing or optical modeling. In an examination of the engineering and scaling challenges, Greschik proposed a modular architecture without large span compression or large film sail sheets, called the Space Tow [6]. The proposed design consists of several conveniently sized sail panels spaced along filament supporting resulting in a tow of several kilometers of length, but with each element small enough for convenient handling [6, 8].

**Scalability of the Space Tow** Scalability as a concept can be used in many different ways, one could view it as the repeatability of an engineering design over different dimensions, with the specifications formulated by scaling laws such as formulations of similitude, or as the application of an architecture to dimensions larger than first realized, without unacceptable performance loss or risk. The latter description touches not only the physics of the architecture, but also the engineering design process, from simulations to manufacture, testing and deployment.

From Greschik's analysis [6] we gain a few favorable qualities for scaling architectures, qualities that define the Space Tow. One major issue is that larger sail sheets need longer and stronger supports, either as spars or hoops, which scale nonlinearly with the dimensions of the sheet. To eliminate undue mass increase with sheet size, film sheets should be kept small, although numerous and ordered in a linear fashion to achieve a sufficient amount of sail thrust. An added benefit of this would mean that most fabrication and quality control problems would be eliminated as each sheet could be easily handled, modeled and tested. To allow construction of various sail sheet sizes, a modular structure with each module functioning as an independent sail, interconnected to exert thrust together. With smaller sail sheet elements, adaptable in size and shape after engineering, mission and/or design requirements, fabrication and stowage could be made on table top without any wrinkling. A trade-off is that the usually complex multi-scale physics of solar sailing is further complicated by adding an extra dimension several orders of magnitude larger than the structure. Typical design scales for the Space Tow correspond to $\mu$m scale sails, mm scale supporting panel rims, m scale cords in between panels and km scale for the overall structure [10], which require special consideration during design as few tools are apt at handling all of these scales simultaneously. Also, this means that the stowed configuration is small, on the order of m. Navigation of the Space Tow could rely on momentum inferred by relative positioning of payload and tow, controlled by offsetting the payload, or a pilot sail, aided by non-planar panel geometry coupled with a nonparallel alignment of the longerons at the truss base to passively stabilize spin and attitude [6,8,9]. The modular design and ease of fabrication of the Space Tow lends itself to adaptation for many different missions and payloads at relatively low investment cost, making solar sailing a more versatile and perhaps viable option for future missions.

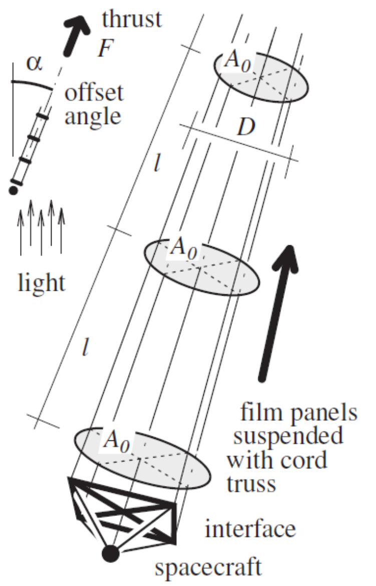


**Figure 5:** *Schematic of Space Tow, reproduced from [8]*

**Deployment** The Space Tow is designed as an ethereal structure, spanning several km of length with minimal materials in between and eminently stowable in a stack of a few meters height. To get from the stowed state to the full length there are several proposed deployment schemes [9, 11, 12]. From a pilot rocket propelled deployment, dragging the sails after it, deploying them one by one, to inertial deployment using the solar thrust from the sails to stretch the Tow. The latter can be achieved with outgassing otherwise applying an inertial "kick" sending payload, sail stack or a pilot sail away to deploy the sails one by one. A deployed pilot sail would be illuminated and slowly thrust out to stretch its tethers to the next panel, lifting it from the stowed stack, dragging along the Space Tow, subsequently aided by the following panels, called "drag along" deployment. With the stack separated from payload, the last sail panel would be illuminated, pushing the stack in front of it, and leaving behind sails as the tethers stretch, accelerating the payload incrementally as sails deploy, called "leave behind" deployment [11,12].

Tibert and Lennon [11] have made some simple analysis of the deployment of the Space Tow, taking into accord the partial illumination of circular disc sail sheets, shadowing each other. Their model considered a one-dimensional deployment of two rigid masses connected by a slack-taut elastic cord without damping and shows that during stretching the cords will stretch and then elastically contract again much like a bungee cord. They also propose some solutions

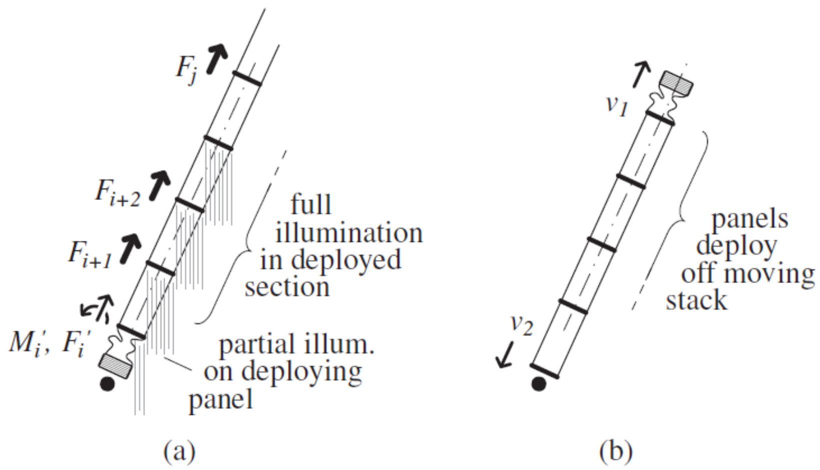


**Figure 6:** *Drag along (a) and leave behind (b) deployment strategies for the Space Tow. The black circle corresponds to the payload, the gray square the deploying sail stack. Reproduced from [8]*

including to introduce damping into the model. The current work explores the behaviour of a simple model of the Space Tow, in part by 3D simulations in commercial FEM software and explores the work to be cancelled in a 1D deployment of the leave behind and drag along deployment schemes as expressed in different expressions of friction.

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# Deployment Simulations of the Space Tow Solar Sail

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**Abstract**

*The Space Tow is a modular solar sail design, uniting versatility of size with ease of manufacturing in an easily stowable package. All stowed structures must be deployed to their mission configuration, which is challenging for such a light and flexible design. The present study explores the "leave behind" and "drag along" deployment strategies in simulation and mathematical analysis. The conclusions are that the "drag along scheme" is sensitive to perturbations and that the "leave behind" scheme needs careful consideration of its parameters or risk that the undeployed stack is overrun by the deployed structure. The present study also discusses the energy dissipation needed for a robust deployment and proposes both a frictional and acceleration-rate proportional damping such as occurs in deformations in an accelerating frame.*

## List of Symbols

| | |
|---|---|
| $E_k$ | Kinetic Energy |
| $m_s$ | Mass of sail panel |
| $F_s$ | Solar pressure force on panel |
| $M_i$ | Deployed mass |
| $v_{m,i}$ | Velocity of deploying stack |
| $v_0$ | Deployment speed |
| $U_f$ | Frictional work |
| $F_f$ | Force of friction |
| $F_n$ | Normal force |
| $\mu_f$ | Friction coefficient |
| $d_b$ | Braking distance |
| $l_0$ | Length of truss cord |
| $c_j$ | Jerk damping coefficient |
| $x_M$ | Position of payload |
| $x_m$ | Position of deploying stack |

## II. Introduction

Solar sailing for space missions is just around the corner, with the first demonstrations of flight-worthy solar sails successfully launched[A] [1,2].

### II.1 Why solar sailing?

Solar sailing uses the momentum of ambient photons to continuously accelerate a spacecraft, which is attractive not only as an elegant notion, but from a variety of viewpoints including allowing open ended missions and unique mission physics. Solar sails seem like an elegant solution to space propulsion, in no small part due to their light weight and compact size, as very little fuel is needed to propel the craft and the designs require a light craft for effective propulsion, enabling launch into orbit with a comparatively small foot-

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[A]"NASA Nanosail-D Home Page" `http://www.nasa.gov/mission_pages/smallsats/nanosaild.html` (accessed 2013-03-15) print in mass as well as size. When no fuel is needed to propel the craft, the limitation of impulse force on the mission is dropped as well, as provided enough time, the accumulated photon thrust would provide all $\Delta v$ needed for any mission, effectively enabling long-distance planetary missions and missions with sample retrieval that otherwise would have a prohibitive fuel cost. This would significantly enhance long-range missions such as an interstellar heliopause probe or a Kuiper belt fly-through [3]. Among the most interesting aspects is the sustained acceleration available through the solar sails, a continuous acceleration without affecting the craft enables access to highly non-keplerian or non-inertial orbits [4, p. 11–24], allowing for the Geostorm mission or a solar polesitter mission [3, 5].

## II.2 The Space Tow

One interesting design solving many scale and fabrication difficulties is Greschik's Space Tow, a scalable solar sailing system composed of a series of smaller sails connected together in a train, the main advantage of the Space Tow would be that it is easy to tailor total sail area by adjusting the number of small sails, Fig 7. The smaller dimension of the sails would also facilitate design, manufacture and testing [6–10].

Compactness, lightness and manufacturability are all attractive qualities for the Space-Tow concept, facilitating a launch in the foreseeable future. The thin sails and filament like cords give very little stiffness to use for deployment, and the sudden slack-taut transition induces dynamic shock that the lack of stiffness cannot alleviate. Tibert and Lennon recommend an inertial deployment system [11], proposed by Greschik [12], where the stack of sails and payload are separated by a "kick" that deploys the sails one by one from the payload and gradually accelerate the payload and craft to mission specifications. In Tibert and Lennon's investigation, one main cause for concern is the bungee effect at the slack-taut transition, with potential to collapse the whole structure. They propose that this could be resolved by frictional damping. But frictional damping is not the only damping present in such a structure, as due to the deformation of sail and filament, heat is dissipated in a way that could be conveniently described in the accelerated frame of the Space Tow, with said damping being acceleration-rate, or "jerk", proportional damping [9].

This study shows initial simulations of the deployment strategies in a commercial finite

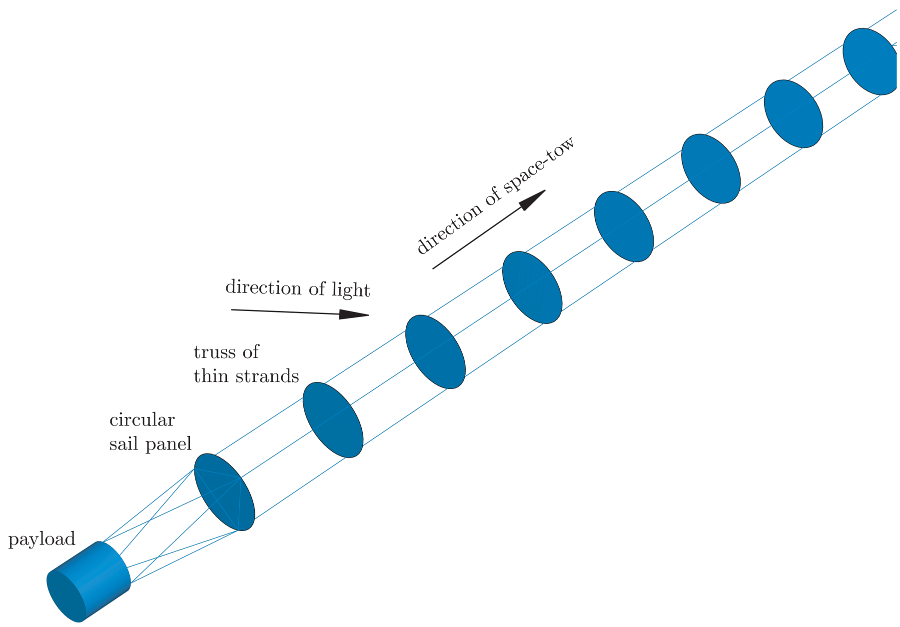



**Figure 7:** *Fully deployed Space Tow, reproduced from [11]*

element software as well as discusses the energies the frictional damping need to dissipate for the deployment of a Space Tow structure, and how this would relate to a model of jerk-based damping. The focus is to shed light on the behaviour and magnitude of the involved quantities.

## III. Modelling deployment

### III.1 Model setup

The model studied consists of a five panel version of a Space Tow with each panel consisting of a sail sheet and a reinforcing ring, the panels are interconnected by three longerons. The ring is modelled with a diameter of 4 m, consisting of carbon fibre with density $\rho$= 1800 kg/m$^3$, Young's modulus $E = 560$ GPa and Poisson's ratio $\nu$ = 0.35 [10]. The ring has a rectangular cross-section 1.65 mm by 0.60 mm with the wider direction in the ring plane and having a total mass of 22.4 $\cdot 10^{-3}$ kg. In this ring is a sheet of 0.90 µm Mylar with density 1390 kg/m$^3$ and Young's modulus 5 GPa, Poisson's ratio 0.38 resulting in a sail mass $m_s = 17.5 \cdot 10^{-3}$ kg, the ring is connected to the rest of the structure by three longerons of carbon fibre filament evenly spaced around the ring. Each filament is modeled with a circular cross section with a radius of 91 µm, corresponding to a 60-filament cable like the one proposed by Tibert & Lennon [10], the material parameters are the same as the ring. This gives a longeron mass of 0.33$\cdot 10^{-3}$ kg, or about 0.98$\cdot 10^{-3}$ kg per set of three longerons. This corresponds to a total mass of about 40.9 $\cdot 10^{-3}$ kg per bay of three longerons, a ring and sail sheet, the model's total mass adds up to about 0.21 kg. In a full scale Space Tow, this would correspond to a total tow mass of 32.51 kg plus the 50 kg payload.

The model was simulated in ABAQUS 6.11, with the 7 m longerons meshed as 16 truss elements of equal lengths. The rings were meshed as beam elements with an element length of 0.2 m, for a total of 63 elements, the sheets as triangular shell elements with a side length of 0.5 m, total 117 elements per sheet, Fig 8.

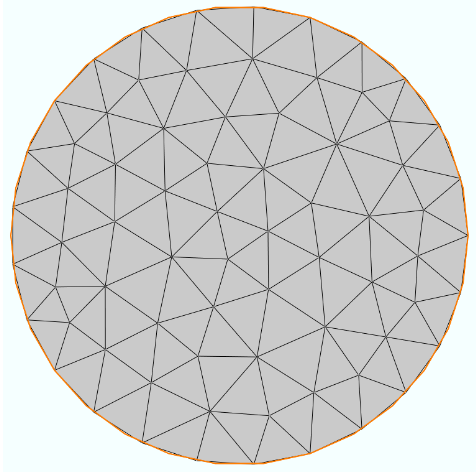


**Figure 8:** *The meshed sail sheet, 117 elements total*

The model was constructed with each of the rings having an attached sail sheet by tie constraint along the circumference of the ring, forcing all translational degrees of freedom to be equal on the nodes constrained [13, sect. 33.3.1]. The rings are each separated by 1 mm of "packing height", for a total model height of 5 mm from the plane of the boundary conditions. Each ring is fastened with a tie to three longeron ends, evenly spaced around the circumference of the ring. The longerons are each folded in four even lengths, in a slight zig-zag pattern. Each length ends 0.25 mm higher relative the panel plane so that the total height is the same as the 1 mm packing spacing between each panel. Fig 9. The deployment simulations are set up with the first set of longerons pinned at one end to a rigid boundary spaced as on the panels, the other to the first panel.

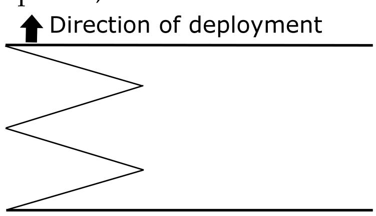



**Figure 9:** *Schematic over the stowed longeron geometry, detail depicts only one of three stowed longerons*

## III.2 Leave behind deployment

The leave behind deployment simulation models a stack of panels separated from the payload with an initial kick, where individual sail panels separate from the stack as their longerons unfold and are stretched taut [12]. When the longerons of a sail bay, here defined as panel with longerons, are stretched a solar force is applied to the film sheet. An initial velocity $v_0 = 0.03$ m/s is applied along the axis of deployment to all films, rings and longerons except the set fastened to the boundary points. The model then sequentially adds a uniform pressure of $1.01 \cdot 10^{-4}$ Pa normal to the film on the side facing the rigid boundary, the pressure is added instantaneously when the preceding set of longerons are fully unfolded, Fig 10.

## III.3 Drag along deployment

The drag along deployment simulation models a stack of panels where only the furthermost panel is separated from the payload, by initial kick, when its longerons become stretched, it lifts the next panel from the stack and so on. As the tow deploys the increasing solar pressure accelerates the deployment [12]. An initial velocity of $v_0 = 0.3$ m/s is applied only to the outermost ring and film. The model then adds a uniform pressure $1.01 \cdot 10^{-4}$ Pa normal to the film on the side facing the stack and/or rigid boundary, the pressure is added instantaneously when the preceding set of longerons are fully unfolded, Fig 11

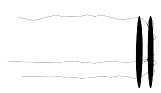
## III.4 Discussion

The initial velocity of the outermost panel in the drag along setup produces an accordion effect where the kinetic energy of the outermost panel is transferred almost entirely to the next panel when the longerons become taut. This effect propagates throughout the structure causing chaotic perturbations of the panel orientation relative to the axis of motion, when the perpendicular solar pressure drives the panel forward, these perturbations are exaggerated further with uncontrolled deployment as a result, Figs. 11(d)–(j).

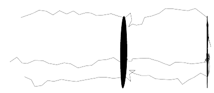
One could consider damping the bungee-effect from the initial kick and acceleration, alleviating such a problem, but if perturbations arise from other sources, the same situation applies. Control would then need to be applied on each panel, costing mass, or with high precision, possibly over long time spans, to counter not only chaotic perturbations but possible skew and translational accelerations. The constant acceleration will also yield increasingly larger shocks on the panel lifted from the stack, ending in a dimensioning shock on the payload itself.

In the leave-behind deployment, the mass of the stack provides inertia during deployment, making it more resistant to small perturbations, something Grechik, Mikulas & Freeland presented in 1999 [12], Figs. 10(d)–(h). Intuition indicates that if a few panels are perturbed, they are connected to the mass-bearing portion of the Tow, which not only provides a slight restoring effect due to longeron stretching against the inertia of the payload, but also gives access to centralised control systems as in [8,9]. One can see that the bungee effect is mitigated by this effect in Fig. 10. In contrast to the drag along system, the payload is accelerated in a stepped fashion, and damping will be needed as each panel decelerates to the speed of the payload and deployed tow. The panels will accelerate over the deployment so that the last panel will have the largest kinetic energy and thus be dimensioning for the shock. In the leave behind setup, the initial stack velocity is limited by the overall deployment time span of the Space Tow but also lower bound by the acceleration of the payload, the initial panel velocity must be large enough not to be overtaken by the payload, this is covered in more detail in a later section.

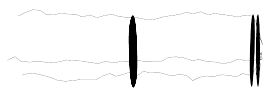
A consideration of the effect of the boundary conditions should be made, for the drag along deployment, the force of the omitted panels is not accounted for, such that the panels deploy as if the structure were made of only 5 panels. Couple this with the pinned boundary of the payload, the simulation is expected to show a reasonable sequence for the deploy-



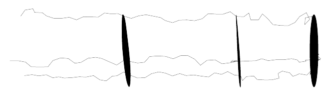
(a) Stack deployed by initial kick, first panel illuminated and deployed.



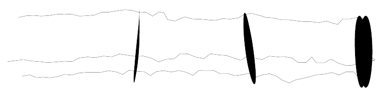
(b)



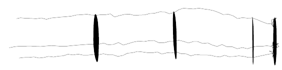
(c) Second panel illuminated



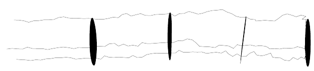
(d) Note the slight perturbation on the first panel (on the far left)



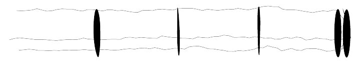
(e) Third Panel illuminated. Perturbation spreads



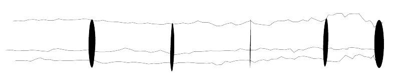
(f) Perturbations are slowly ebbing out



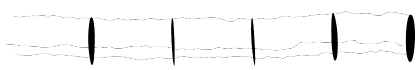
(g)



(h) Fourth panel illuminated

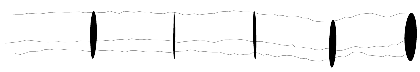


(i)



(j) All five panels are fully deployed and illuminated. Structure is settling

(k)

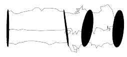


(l)

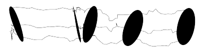
**Figure 10:** *Figures from Space Tow "leave behind" deployment simulation.*

(a) First panel deployed by initial kick and illuminated

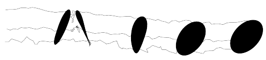
(b) Second panel deployed and illuminated, most of the initial kick is transferred to the second panel



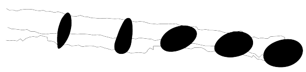
(c) Third panel deployed, most of the initial kick is transferred to the third panel



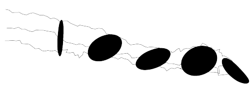
(d) Fourth panel deployed, most of the initial kick is transferred to the fourth panel. Perturbations from uneven longeron stretching start skewing illuminated panels



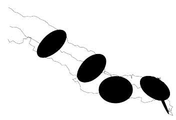
(e) Fifth panel deployed, most of the initial kick is transferred to the fifth panel.



(f) All panels illuminated and deployed. Panels 3,4,5 are skewed so that the normal pressure produces a moment



(g) The moment is starting to turn the deployed structure



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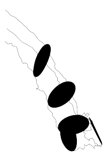

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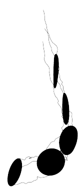

(j)

**Figure 11:** *Figures from Space Tow "drag along" deployment simulation.*

ment of the first panels until the longerons that connect to the clamped boundary are stretched. When the structure is deployed it will represent a slightly milder (low-energy) acceleration of the payload although without the effects of non-simultaneous stretching of the longerons; in reality the payload will be expected to be pulled by one of the longerons before the others due to the perturbed deployment.

In the simulations of the leave behind deployment, no acceleration of the deploying stack occurs, as well as no acceleration of the clamped boundary, the numerical calculations shown in a later section indicate that the effect of these are of the same order of magnitude, and four orders lower than the velocities in the finite element simulation. As the perturbations are smaller, the effects of uneven payload acceleration are expected to be negligible.

## IV. Deployment function

To better understand the underlying principles of the differences of the deployment process, one could examine the mechanics of a simple case. Here is considered a one-dimensional Space Tow accelerated by increasing photon pressure modelling shading effects of the stowed panel stack. Fig 12. The model considers a force linearly proportional to the distance between a deploying panel and the one behind, such as might be expected from a square sail illuminated perfectly from one of its sides. A circular panel will be illuminated in a much less linear fashion, as Tibert & Lennon proposed [11].

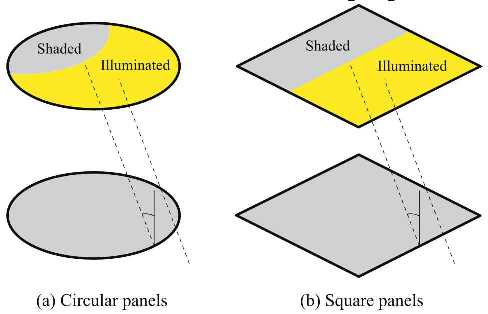


**Figure 12:** *Shading on circular and square Space Tow sail panels, image from [11]*

The one-dimensional equation $m\ddot{x} = F(x)$ is solved exactly for each deployment step and corresponding force function $F(x)$.

### IV.1 Leave behind deployment

Assuming that the payload starts in relative rest, and the stack is moving as an accelerated unit until the longerons are stretched. When longerons are fully stretched, the movement of the panel is damped so that it stops momentaneously and then starts to accelerate the payload. Due to the velocity of the panel stack, it continues to deploy and as the distance to the deployed panel increases, the stack accelerates again. Solving for an arbitrary step $i$, where $i$ panels have been deployed and are accelerating the payload and deployed bay masses. The deployed part has initial conditions as:

$$\begin{cases} \text{From start of deployment} & \text{step i} \\ t = \Sigma_0^i t_i & t = 0 \\ x_M = \Sigma_0^i x_{M,i} & x_M = 0 \\ v_M = v_{M,i} & v_M = v_{m,i} \\ \ddot{x}_M = iF_s/M_i & \ddot{x}_M = iF_s/M_i \\ M_i = m_{\text{payload}} + im_{\text{bay}} & \end{cases} \tag{1}$$

where $x_M$ corresponds to the position of the last deployed sail. Then the differential equation gives that

$$x_M = \frac{iF_s t^2}{2M_i} + v_{M,i} t \tag{2}$$

Simultaneously, the stack is deployed under acceleration with initial conditions such as:

$$\begin{cases} \text{step i} \\ t = 0 \\ x_m = 0 \\ v_m = v_{m,i} \\ F = F_s(x_m - x_M)/l_0 \\ \ddot{x}_m = F_s(x_m - x_M)/(m_i l_0) \\ m_i = N_{\text{panels}} m_{\text{bay}} - im_{\text{bay}} \end{cases} \tag{3}$$

Where $N_{\text{panels}}$ is the total number of panels. And the inhomogeneous nonlinear differential equation is solved with the boundary conditions as:

$$\begin{cases} t = 0 \\ x = 0 \\ v = \dot{x} = v_{m,i} \end{cases} \tag{4}$$

$$\begin{cases} t = t_{i+1} \\ x = l_0 + x_M \\ v = v_{i+1} \end{cases} \tag{5}$$

so that the end time of the $i$th deployment step is described by

$$t_{i+1} = \frac{1}{2\lambda_i} \ln\left(\frac{c \pm \sqrt{c^2 - b^2 + a^2}}{a + b}\right) \tag{6}$$

With the constants given as

$$a = \mp\left(\frac{v_{m,i} - v_{M,i}}{\lambda_i}\right)\left(\frac{im_i l_0}{M_i}\right)$$
$$b = \frac{1}{2}\left(\frac{v_{m,i} - v_{M,i}}{\lambda_i}\right)^2 + \frac{1}{2}\left(\frac{im_i l_0}{M_i}\right)^2$$
$$c = l_0^2\left(1 - \frac{im_i}{M_i}\right)^2 + \frac{1}{2}\left(\frac{v_{m,i} - v_{M,i}}{\lambda_i}\right)^2 - \frac{1}{2}\left(\frac{im_i l_0}{M_i}\right)^2$$
$$\lambda_i = \sqrt{\frac{F_s}{m_i l_0}}$$

For the data output, the lowest positive time of the sign-combinations was used. Finally, the stack velocity $v_{m,i+1} = v_m(t = t_{i+1})$

$$v_{m,i+1} = \frac{v_{m,i} - v_{M,i}}{2}(e^{\lambda_i t_{i+1}} + e^{-\lambda_i t_{i+1}}) - \frac{im_i l_0 \lambda_i}{2M_i}(e^{\lambda_i t_{i+1}} - e^{-\lambda_i t_{i+1}}) + \frac{iF_s t_{i+1}}{M_i} + v_{M,i} \tag{7}$$

where $v_{m,0} = v_0$ is the initial kick velocity. The payload velocity at time $t = t_{i+1}$ is described as

$$v_{M,i+1} = v_M(t_{i+1}) = \frac{iF_s t_{i+1}}{M_i} + v_{M,i} \tag{8}$$

where the initial payload velocity, as well as the payload end velocity at step 1 $v_{M,0} = v_{M,1} = 0$ as no longerons have yet stretched to transfer the force from the solar panels as well as assuming that the kinetic energy of the deployed panel is damped out. The subindex 0 corresponds to the initial deployment problem where the stack is accelerated as a whole from the payload and no longerons are stretched.

For deployment to continue, $\Delta v_{i+1} = v_{m,i+1} - v_{M,i+1} \geq 0$ , it can be shown that this will be the case as long as the relation of the previous step fullfills

$$v_{m,i} - v_{M,i} \geq \frac{im_i l_0 \lambda_i}{M_i} \tanh(\lambda_i t_{i+1}) \tag{9}$$

This indicates that as the number of deployed panels grow, the stack will have a slower relative velocity increase $v_{m,i+1} - v_{M,i+1}$. This is the problem of the payload being accelerated by more force than the deploying stack as mentioned earlier. The payload will quite simply start to catch up to the stack as more panels are deployed. The inequality is also dependent on the relative masses of payload and tow, as well as the force and distance affecting the panels, many of which will be set mission criteria and are thus not further discussed here.

A parameter study of the starting velocity of the simulated structure with full 796 panels and $N_{\text{panels}} F_s = 7.27$ N reveal that the starting velocity $v_0 \geq 2.111$ m/s, with equality resulting in the velocity difference between the deployed last panel and tow is $\Delta v_{796} \geq 6.910^{-5}$ m/s. With this velocity the structure is deployed in about 1 h 14 min with a final velocity of 2.3 m/s.

## IV.2 Drag along deployment

For the drag along mode of deployment, we separate only the outermost sail panel and let the solar thrust accelerate it until the longerons stretch enough to pull the next panel from the stack and so on. It is assumed that the payload and stack of undeployed sails starts in relative rest, and the deployed sails are moving as a unit accelerated by the sum of deployed sails until the longerons are stretched. When stretched, the next panel is instantaneously accelerated to the deployed sail velocity and continues to be accelerated

both by the deployed sails as well as the increasing partial illumination of itself.
For an arbitrary step $i$, where $i$ panels have been deployed and are accelerating the deploying bay and previously deployed bay masses. The deployed part has initial conditions as:

$$\begin{cases} \text{relative} \\ t = 0 \\ x = 0 \\ v = v_i \\ \ddot{x} == F_s(x + il_0)/(m_i l_0 \\ m_i = m_{\text{bay}}(1 + i) \end{cases} \tag{10}$$

The inhomogenous DE is formulated as

$$\ddot{x} = F_s \frac{x + il_0}{m_i l_0}; \quad x = x_h + x_p$$

For each step, the boundary conditions

$$\begin{cases} t = 0 \\ x = 0 \\ v = \dot{x} = v_i \end{cases} \quad \begin{cases} t = t_{i+1} \\ x = l_0 \\ v = v_{i+1} \end{cases} \tag{11}$$

This then solves so that

$$t_{i+1} = \frac{1}{\lambda_i} \ln \left( \frac{\zeta \pm \sqrt{\zeta^2 - \beta^2 + \alpha^2}}{\alpha + \beta} \right) \tag{12}$$

With

$$\alpha = \frac{v_i}{\lambda_i}$$
$$\beta = il_0$$
$$\zeta = l_0(1 + i)$$

and the end velocity given as

$$v_{i+1} = \frac{v_i}{2}(e^{\lambda_i t_{i+1}} + e^{-\lambda_i t_{i+1}}) + \frac{il_0\lambda_i}{2}(e^{\lambda_i t_{i+1}} - e^{-\lambda_i t_{i+1}}) \tag{13}$$

This would mean that the panels instantaneously accelerate from rest to tow speed without energy loss, which of course is impossible, but by handling each step individually, one could interject a transition stage between them where acceleration could be handled, then changing the step-initial velocity accordingly.

It is clear that this form of deployment accelerates with number of panels, with a quick decrease of deployment time per step. For the same structure and parameters as in the "leave behind" analysis, the structure deploys in about 40 min with an end velocity $v_{796} = 4.4$ m/s
If we change the initial velocity to a gentler $v_0 = 0.03$ m/s, the structure reaches full deployment in about 43 minutes, with the end velocity 10 mm/s lower than the case above.

## V. Damping the jerk

One pervasive problem of both these deployment schemes is that they will cause panels to spring back, due to tensional elasticity coupled with lack of compressive stiffness in the longerons. To avoid this, the kinetic energy of the deploying panel needs to be dissipated somehow, either via dry friction sliding along the longerons, or dissipation due to flexural waves in longerons or sail sheet, or some other mechanism.

### V.1 Simulated damping in the longerons

A few simulations were done with ABAQUS's mass-damping on the longerons, which translates to velocity-proportional damping. The observed effect was that of the longerons lagging behind the deploying structure, in a very unnatural way, clearly illustrating Greschik's point that for continuously accelerated structures, such as solar sails, an acceleration-rate ("jerk") proportional damping would be a better description for models of such structures [9].

### V.2 Damping with dry friction

Exploring the energies needed to be removed in a classic dry friction example, a sliding length on the longerons, ended by either a knot or thickening of the longeron. Allowing a clamped panel fastening to slide a short distance along the longeron whilst affected by frictional force.

### V.3 Classic approach

At some time the longeron will have stretched to its maximum length and the panel will have reached $l_0$ under continuous acceleration from the Sun, the panel will then have accelerated so that the kinetic energy is

$$E_k = \frac{m_s v_i^2}{2}$$

When the filament is stretched, the panel starts to glide until stopped by a frictional force. We assume that the solar panel is fastened onto the cable with a shoe of the same carbon material, resulting in a frictional force $F_f = \mu_f F_n$ from the normal force $F_n$ of the clamp acting on the longeron. Classically, to make this damping halt the panel, it would have to do work

$$E_k \leq U_f = \int_0^{d_b} F_f \, dx$$

which for the equality yields

$$F_n = \frac{E_k}{d_b \mu_f} \quad (14)$$

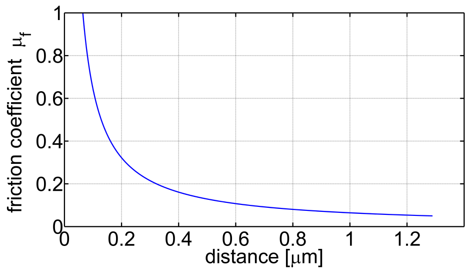


**Figure 13:** *Relation of friction coefficient and braking distance for a normal force $Fn = 5$ GN and $E_k = 322$ J of a fully "drag along"-deployed Space Tow at 4.4 m/s*

The work is done over a period $\Delta t = t_b - t_0$, $t_b$ being the braking time, and is one-dimensionally described as

$$\dot{x} = \int_{t_0}^{t_b} \frac{F_s - F_f}{m_s} \, dt = \{t_0 = 0\} = (F_s - F_f)\frac{t_b}{m_s} + v_i \quad (15)$$

as $\dot{x}(t = 0) = v_i$. This can be solved by integrating once again and applying our boundary conditions for the position.

$$u|_{t=t_b} = d_b = (F_s - F_f)\frac{t_b^2}{m_s} + v_i t_b \quad (16)$$

as $u(t = 0) = 0$. Solving for $t_b > t_0$ yields

$$t_b = \frac{-v_i m_s + \sqrt{v_i^2 m_s^2 + 2 m_s d_b (F_s - F_f)}}{F_s - F_f} \quad (17)$$

For the example in Fig 13, $t_b = 45\,\mu$s. When the work is done, the kinetic energy has been lowered so that the panel has come to the same velocity as the deployed structure. It then adds its solar force $F_s$ to the thrust upon the deployed structure, this remaining force will play a role in the the "jerk"-proportional damping in the next section.

### V.4 Jerk-proportional approach

Greschik [9] proposes that jerk damping, can be physically rationalised by energy dissipated in movements of the sail sheet, cords or other components changing shape or just increasing and decreasing their deformations. Greschik also shows that the mechanical energy removed from the system is described as

$$E_c = \pm \int_{\ddot{x}_0}^{\ddot{x}_1} c_j(\ddot{x}) \, d\ddot{x} = \int_{t_0}^{t_b} c_j(\ddot{x}) |\dddot{x}| \, dt; \quad (18)$$

where $\ddot{x}(t)$ monotonous in $[t_0, t_b]$, $c_j$ is a proportional damping coefficient.
For a constant $c_j(\ddot{x})$ we write

$$\Delta E_c = c_j |\Delta \ddot{x}| \; ; \quad F_c = -c_j |\Delta \ddot{x}| / \Delta x \quad (19)$$

and

$$\Delta v_c = F_c \Delta t / m = -\frac{c_j |\Delta \ddot{x}|}{m_s \Delta x} \Delta t \quad (20)$$

which can be restructured to

$$c_j = -\frac{\Delta v_c m_s \Delta x}{|\Delta \ddot{x}| \Delta t} \quad (21)$$

with all else being equal to the situation in the classical solution and the model in the simulations,

$$\begin{cases} \Delta \ddot{x} = -F_f / m_s \\ \Delta x = d_b \\ \Delta t = t_b - t_0 = t_b \\ \Delta v_c = v_i - 0 = v_i \end{cases} \quad (22)$$

which yields

$$c_j = -\frac{v_i m_s d_b}{t_b F_f / m_s} \quad (23)$$

For the last longeron set in the "drag along" deployment system, this would correspond to $E_k = m_s v_{796}^2/2 \approx 322.31$ J and the jerk damping $\Delta E_c = c_j|\Delta\ddot{x}| = -322.31$ J.

## VI. Summary

The present work has explored two different strategies for deployment of a Space Tow solar sail structure, the leave behind and drag along strategies. Simulations as well as mathematical analysis illuminate obstacles with both of these strategies.

The simulated model presented here shows the first five panels deploying in a Space Tow design. The simulations illustrate a bungee effect from the slack-taut dynamics of the longerons in both strategies, and also illustrate the "drag along" strategy's weakness to perturbations. The mathematical analysis shows the "leave behind" strategy's complex criteria for successful deployment as well as the dimensioning energies to be damped out in the respective strategies.

The "drag along" deployment, due to perturbations quickly multiplying, would demand much of a control system to deploy with only an initial kick, introducing cost in control mechanisms and mass. A more practical solution would then be to drag deploy the tow not by a pilot sail but by a controlled rocket or other steered craft. As each panel is lifted from the stack a sharp increase in acceleration would demand sturdier materials or necessitate damping of each sail bay.

The "leave behind" approach, due to the increasing and larger acceleration of the payload, demand a high enough initial speed for the Space Tow to be fully deployed. This initial speed is dependent of several different factors that limit design specifications.

The work also discusses how these energies could be damped. The model presented proposes a frictional damping that could work over a wide range of tolerances, as the proposed friction stretch needs little special preparation and as the masses and velocities are low, the frictional stretch could be kept short on each sail bay, magnitude of $10^{-7}$ m, keeping the stowed dimensions small.
The energy loss has also been compared to a coefficient for acceleration-rate proportional damping, which could be a property of interest for material selection of both sail and truss.

Control and navigation are important issues that will very much be affected by the choice of damping, but were outside the scope of this study.

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