State of the art concepts and verification strategies for passive de-orbiting systems using deployable booms and membranes

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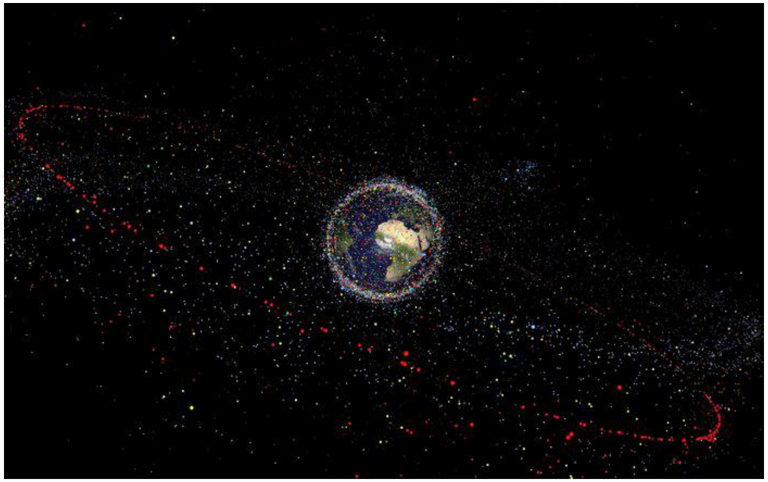
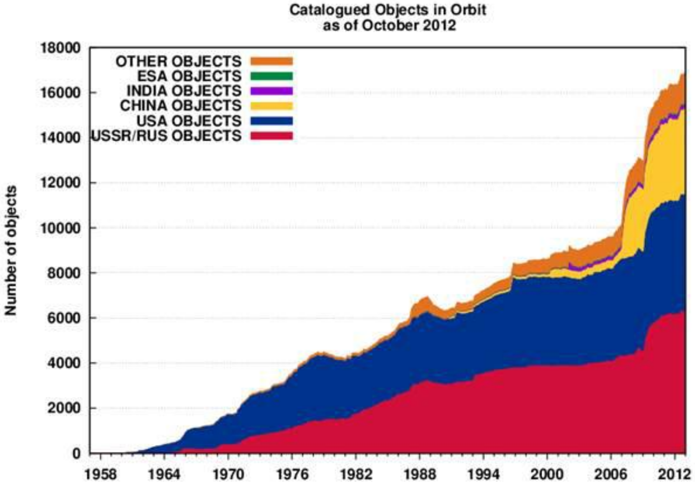
Content

- ➢Space Debris and Drag Augmentation Introduction
- ➢What can we learn from precursor projects?
    - Applications for Deployable Membranes
    - Membrane Stowing
    - Membrane Design Aspects
    - Materials and Space Environment
    - Deployable Booms
- ➢Gossamer Structures Verification Strategies

Space Debris and Drag Augmentation

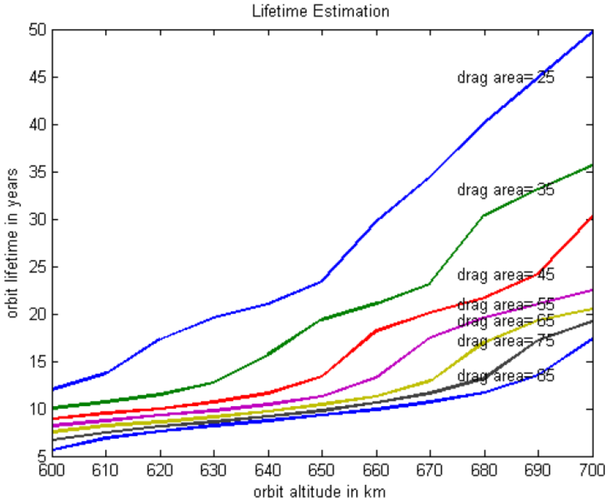




- Sharp increase due to Chinese anti-satellite missile test in 2007 and a collision of two satellites (Iridium33 and Kosmos2251) in 2009
- Envisat orbiting at 790km altitude brings a risk of a new collision
- Deorbiting strategies are required, (one) solution is drag augmentation

⇒ESA’s **Deployable Membrane** and **ADEO** Projects,
will be presented in the upcoming presentations

Space Debris and Drag Augmentation



Preliminary de-orbit analysis, 1000 kg satellite, forecast of the Sun activity, start 2014.

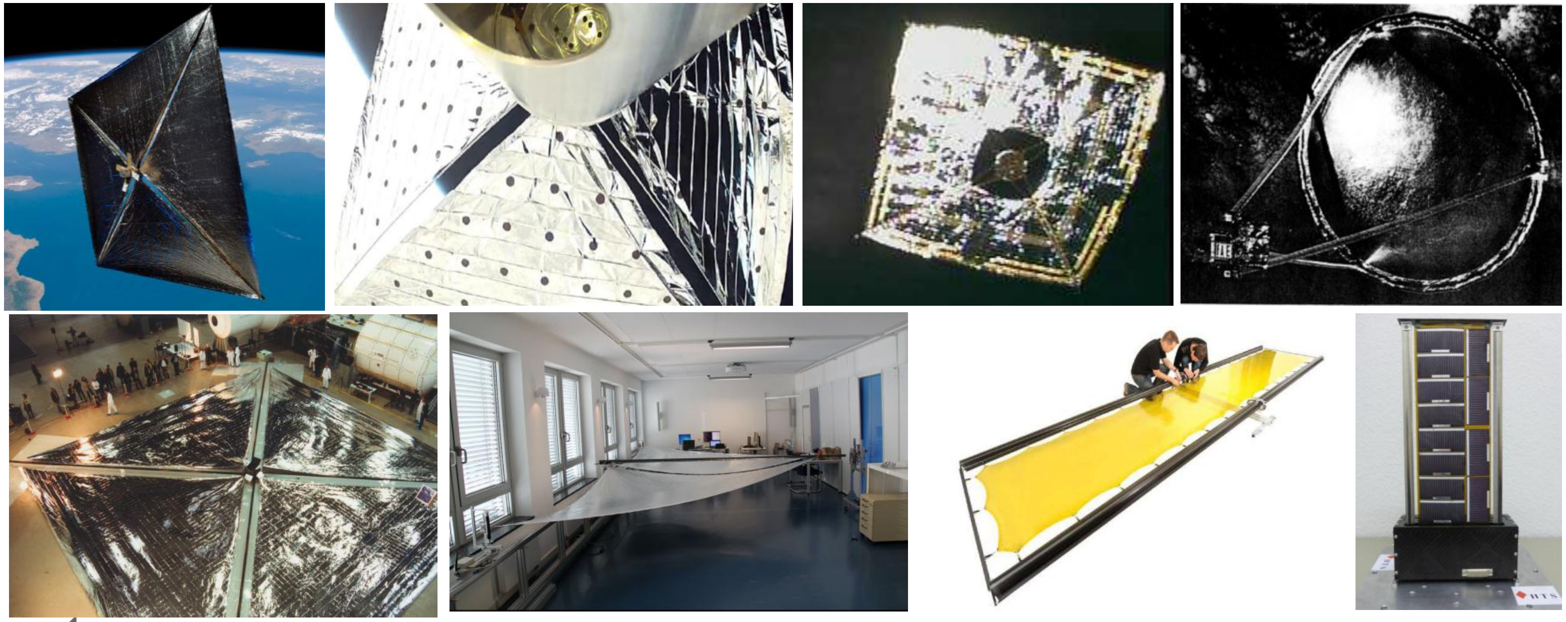
- Deorbiting strategies are required, (one) solution is drag augmentation

$$a_{\mathrm{D}} = \frac{1}{2}\rho v^2 \cdot \frac{C_{\mathrm{D}} A}{m}$$

- ➢ Heavy satellites require large drag area respectively sails
- ➢ Strongly depend on the orbit, especially the altitude. Atmospheric density decreases exponentially with the altitude.
- ➢ Strongly depend on sun activity due to its influence on the atmospheric density
- ➢ In high orbits where drag forces are comparable to other disturbances like solar radiation pressure the dynamic behavior of the satellite is important

Applications for Deployable Membranes

- In former projects and missions lightweight deployable membrane technology was developed for
    - ➢Drag Sails (mainly CubeSats)
    - ➢Solar Sailing
    - ➢Ultra lightweight solar photovoltaic generators
    - ➢Membrane Antenna
    - ➢Sun Shielding



Transferable Design Aspects for Drag Sails

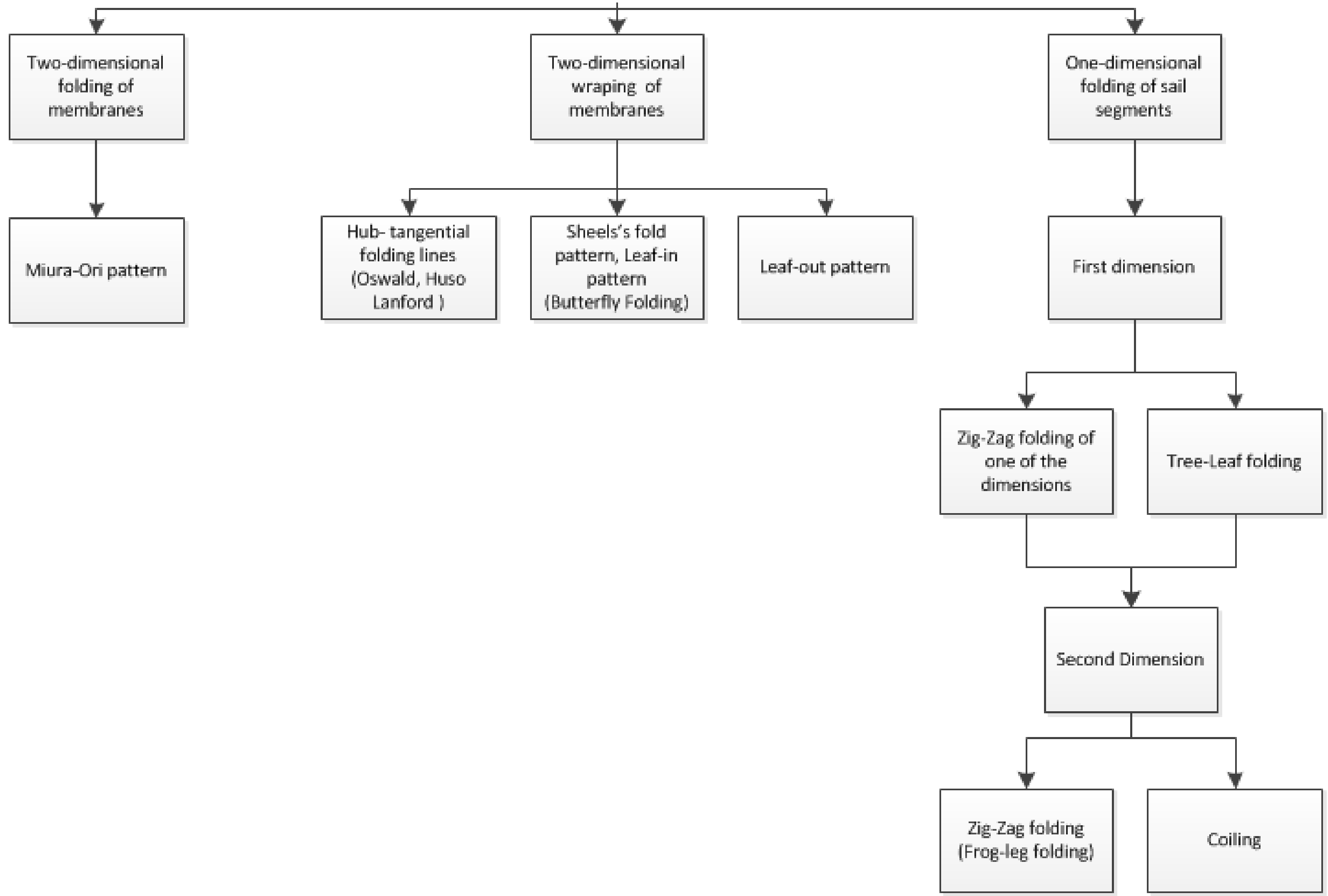
- Drag Sail Projects (mainly CubeSats)
  - Stowing and deployment strategies (scalability from CubeSats is difficult)
  - Materials
  - Membrane design

- Solar Sailing
  - Stowing and deployment strategies
  - Materials
  - Membrane design

- Ultra lightweight solar photovoltaic generators
  - Protective coatings

- Membrane Antenna
  - Load introduction, surface accuracy

Membrane Stowing



Two-dimensional folding of membranes

Miura-Ori pattern

Two-dimensional wraping of membranes

Hub- tangential folding lines (Oswald, Huso Lanford)

Sheels's fold pattern, Leaf-in pattern (Butterfly Folding)

Leaf-out pattern

One-dimensional folding of sail segments

First dimension

Zig-Zag folding of one of the dimensions

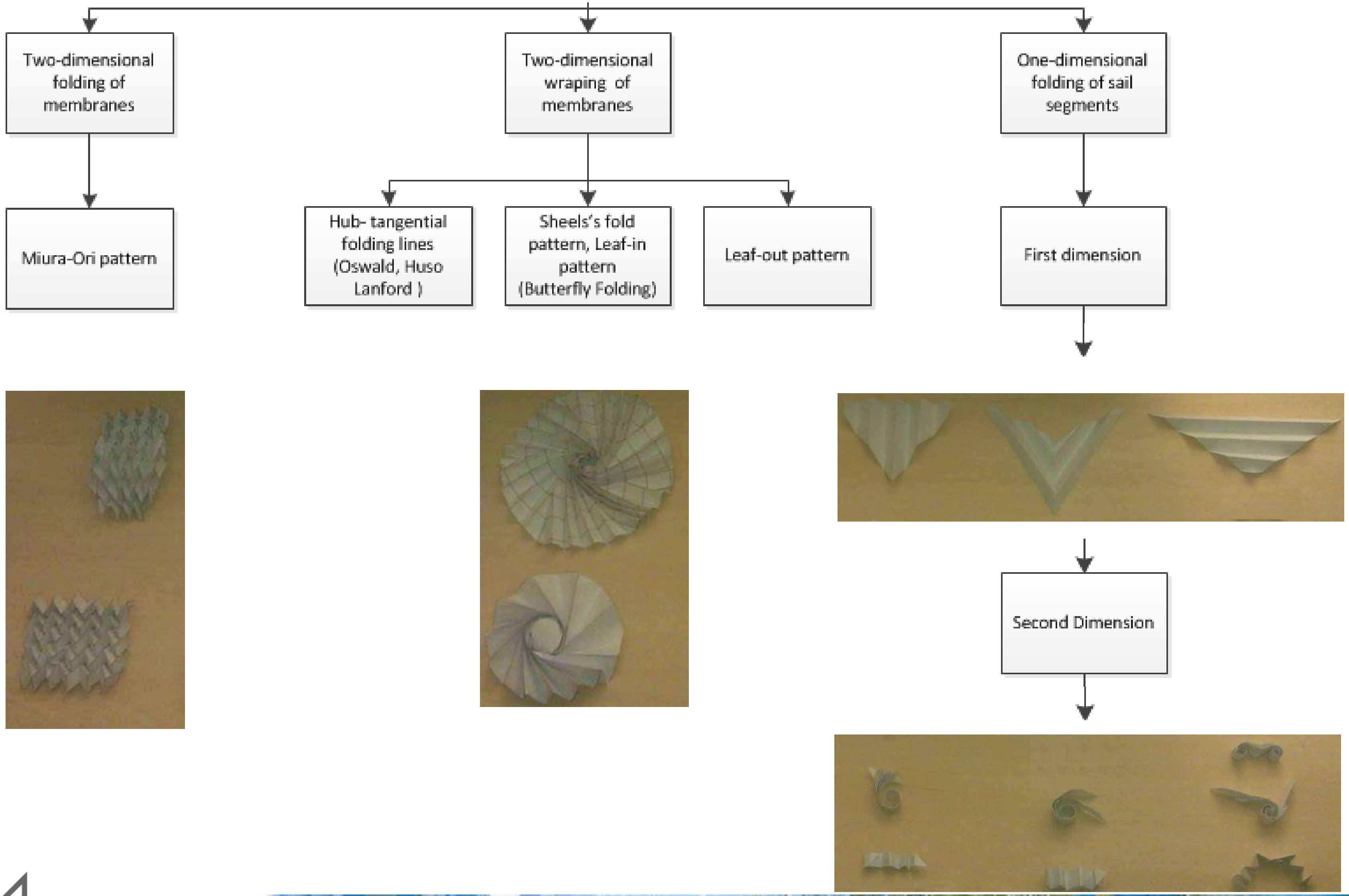
Tree-Leaf folding

Second Dimension

Zig-Zag folding (Frog-leg folding)

Coiling

Membrane Stowing



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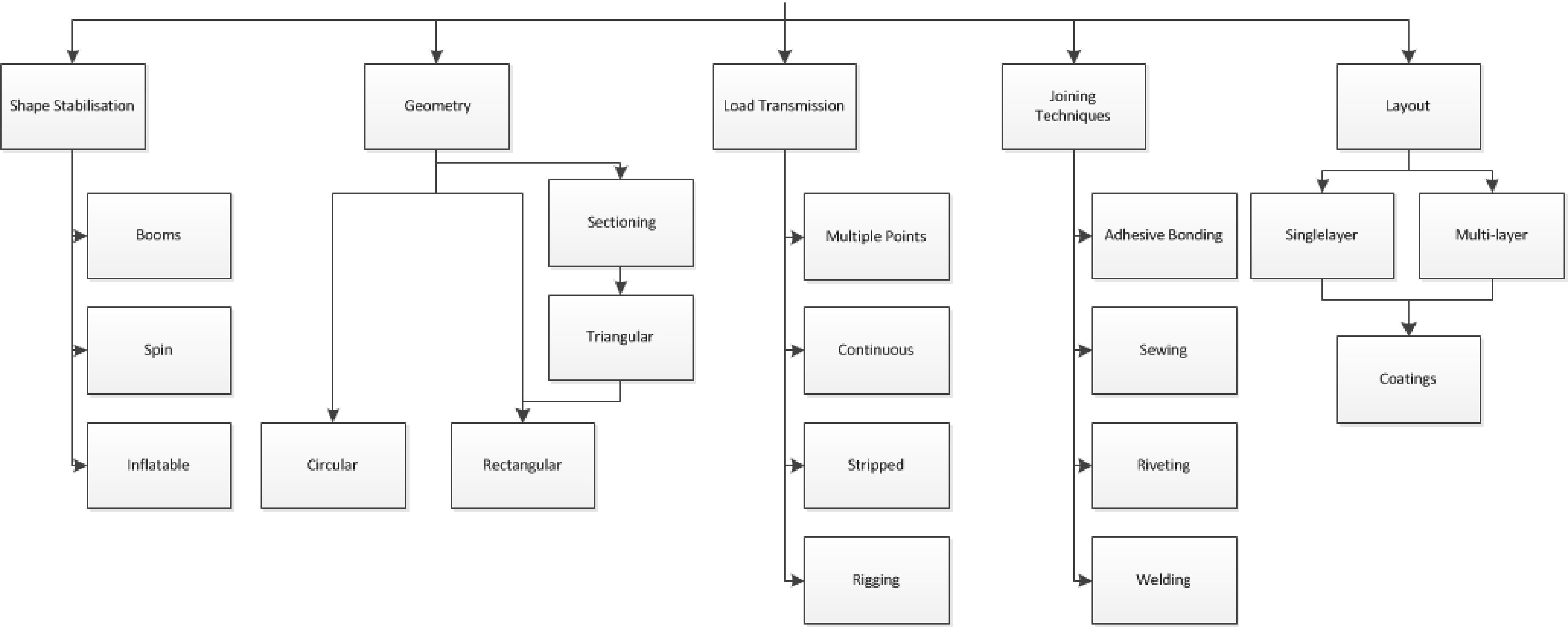
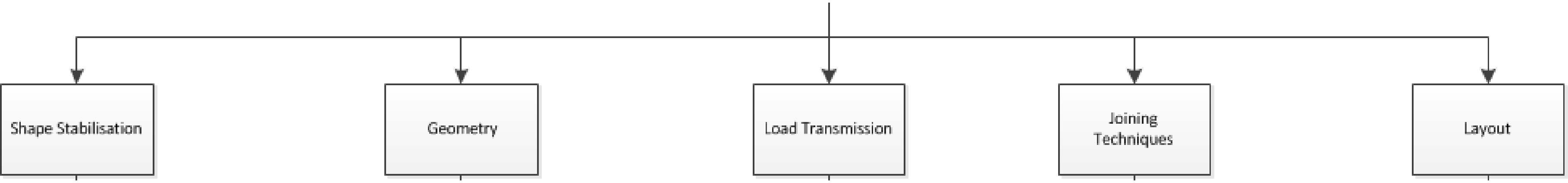
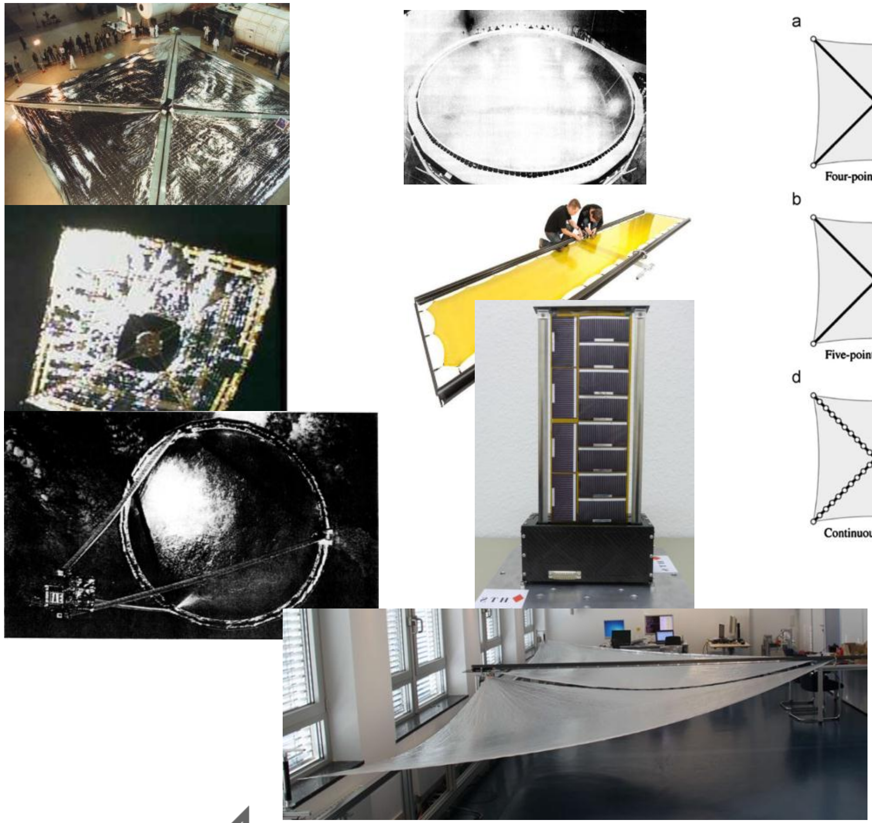
Second Dimension

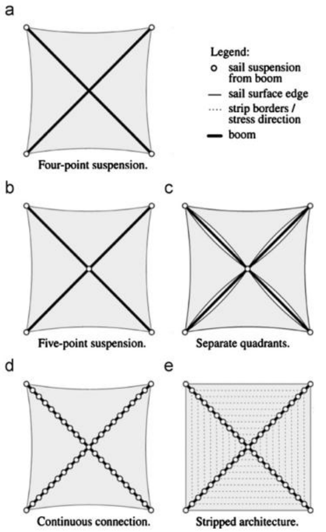
Membrane Design Aspects

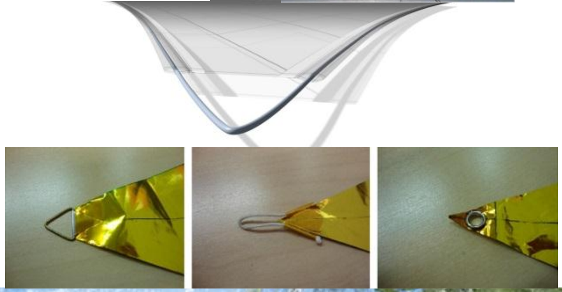

Shape Stabilisation
Booms
Spin
Inflatable
Geometry
Sectioning
Triangular
Circular
Rectangular
Load Transmission
Multiple Points
Continuous
Stripped
Rigging
Joining Techniques
Adhesive Bonding
Sewing
Riveting
Welding
Layout
Singlelayer
Multi-layer
Coatings

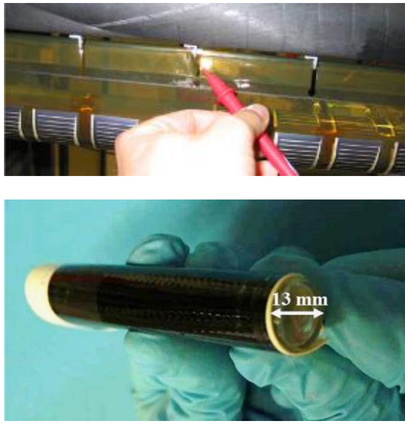
Membrane Design Aspects


- Shape Stabilisation
- Geometry
- Load Transmission
- Joining Techniques
- Layout









Materials

- Most projects considered coated polyimide films (Kapton or Upilex) due to good mechanical behavior and thermal resistance

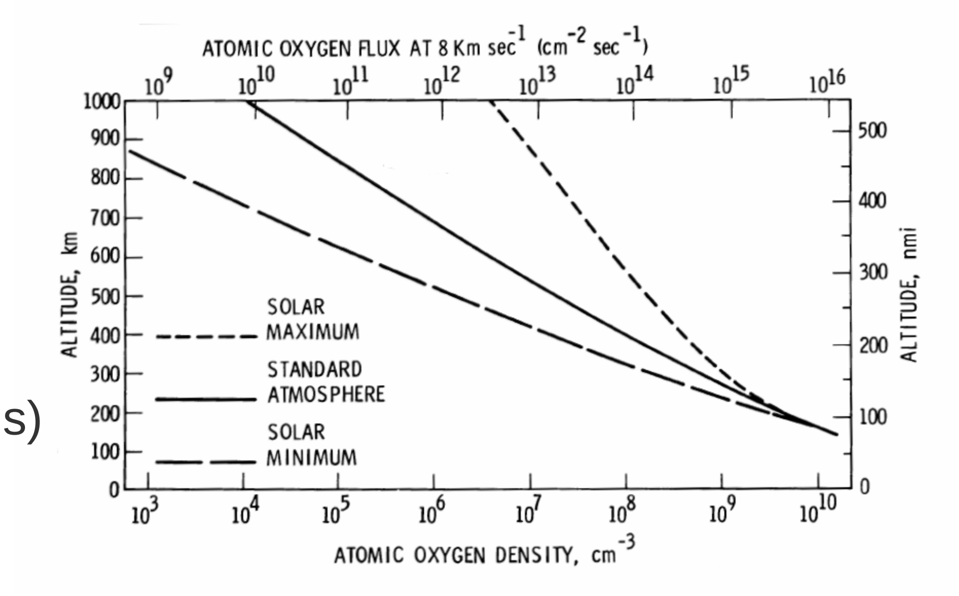
- Vacuum Deposited Aluminum (VDA) on polyimide is a standard product and was chosen in many former projects. Additional protective and thermo-optical coatings were considered especially for photovoltaics (SiO_2) and are used for various MLI materials.

  - Coatings are required as protection against space environment and for thermal design

  - Coatings need to be robust in order to stow the membranes

Space Environment in Low Earth Orbits (200 .. ~700 km)

- High concentration of Atomic Oxygen
    - ➢Generated by solar radiation of wavelength of about 243 nm,
    - ➢Impact energy of 5 eV
- High energetic EMR radiation
    - ➢Bond braking e.g. C-C, C-O (especially hazard to polyimide films)
- Flux of solar p+/e- is negligible small comparing to the AO flux.



Experiments (e.g. MISSE) performed under real space conditions

➢ Large literature database of many degraded materials.

Preliminary material selection and characterization

Coating Examples

- VDA (standard polyimide film coating):
    - Unreactive to AO exposure
    - Limited shielding of the substrate from Ultra Violet radiation
    - VUV may ionize Al. atoms => charging
    - High α/ϵ ratio => High Temperatures

- SiO2:
    - Good AO resistivity (not 100%), thick coatings for long durations
    - Good shielding of the substrate form Ultra Violet radiation
    - High electrical resistance => Spacecraft charging
    - Decreases α/ϵ ratio => Lower Temperatures

- TiO2:
    - Good AO resistivity but less than SiO2, thin TiO2 coatings crack during AO exposure, thick coatings for long durations
    - Very Good shielding of the substrate from Ultra Violet radiation
    - Prevent ESD
    - Decreases α/ϵ ratio => Lower Temperatures

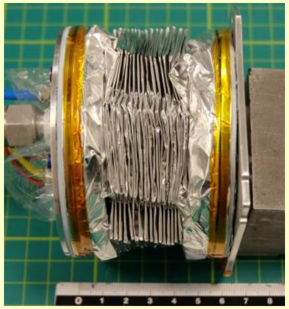
Deployable Boom Technologies

Strain Energy

- Flexible structures
- Stowage by elastic material deformation
- Deployment by stored strain energy

Inflatable

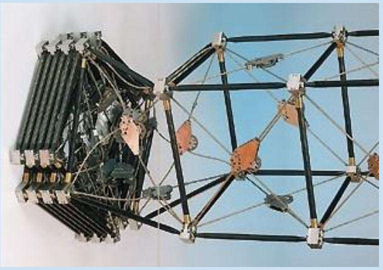
- Thin walled, highly deformable shells
- Stowage by shell folding
- Deployment by inflation gas
- Rigidization may be necessary



Courtesy of University of Surrey

Articulated

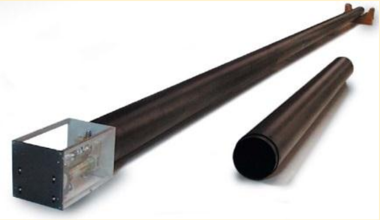
- Rigid structural members
- Stowage by use of hinges
- Deployment by additional mechanism



Courtesy of ATK/ABLE Engineering

Telescopic

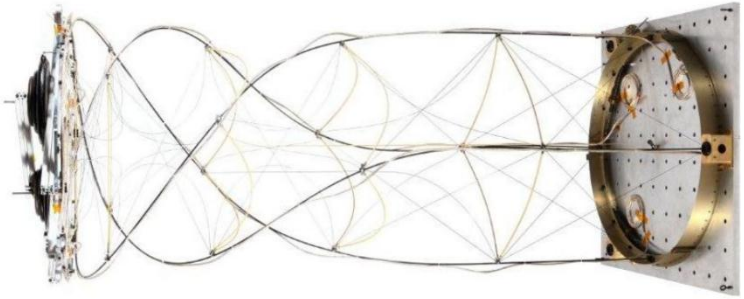
- Segmented rigid shell structure
- Stowage by use of telescopic segments
- Deployment by additional mechanism



Courtesy of Northrop Grumman

Strain Energy Deployment

- Thin-walled **shell booms** or **trusses with flexible members**
- Deformation of the structure within the **elastic region of the material**
- **Maximum elastic strain** limits shell/rod thickness
- Deployment by **stored strain energy**
- Deployment may require support and control by additional mechanism



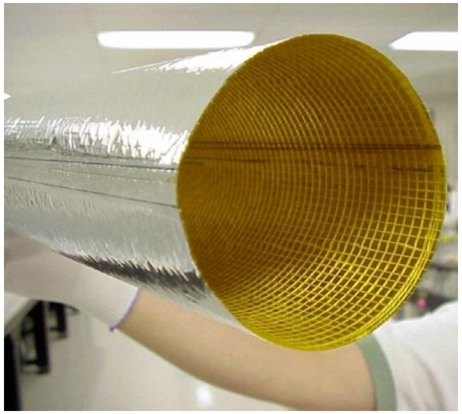
Four longeron deployable CoilABLE truss (Courtesy of ATK/ABLE Engineering)

Bi-stable CFRP-booms (Courtesy of RolaTube)

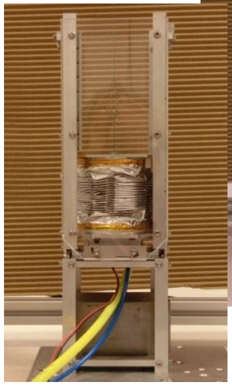
Deployed De-Orbit Sail drag sail using DLRS CFRP boom technology

Inflatable Structures

- **Tubular structures** made of **laminated foils** or thin walled **composites allowing plastic deformation** (thermoplastic or uncured resins)
- Stowage by **membrane-like folding** of the structure
- Gas-tight tubular structure allows **deployment by inflation**
- **Rigidization mechanism required** to maintain structural stability after venting of the inflation gas



Inflatable Sub-T_G boom sample for the Team Encounter Solar Sail (Courtesy of L'Garde)

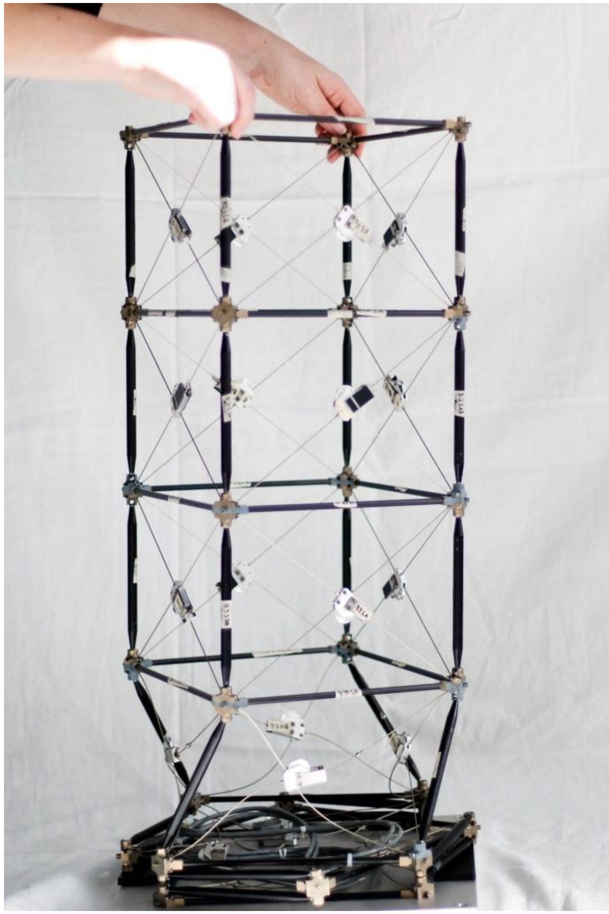


Inflatable Aluminum laminate boom of Inflatesail (Courtesy of University of Surrey)

Articulated Structures

- **Trusses or linkages** with **rigid structural members connected by hinges**
- **Deployment by springs** at the hinges or **additional mechanisms** like motor driven cable/pulley systems
- **Latches may be required** to lock hinges in deployed state

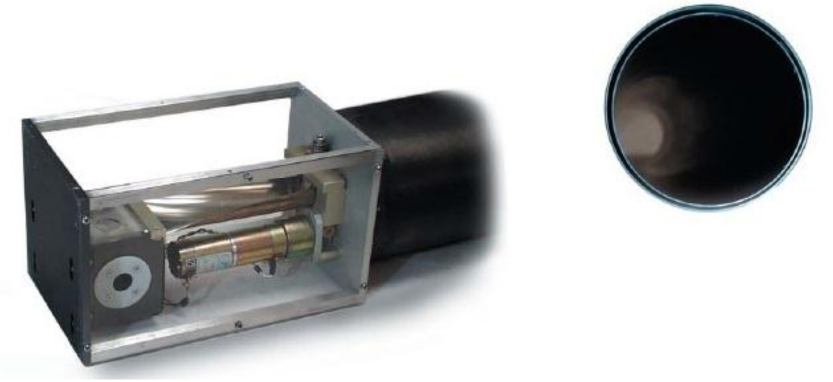
dragNET de-orbit system using pantograph type deployable booms for support of the sails (Courtesy of MMA Design)



ADAM truss developed by ATK/ABLE Engineering (O. Stohlman, “Repeatability of joint-dominated deployable masts”, PhD-Thesis, Caltech, 2011)

Telescopic Structures

- **Segmented, telescopic structure** made of **rigid elements** with mainly tubular cross-section
- **Linear deployment** driven by **additional mechanism**



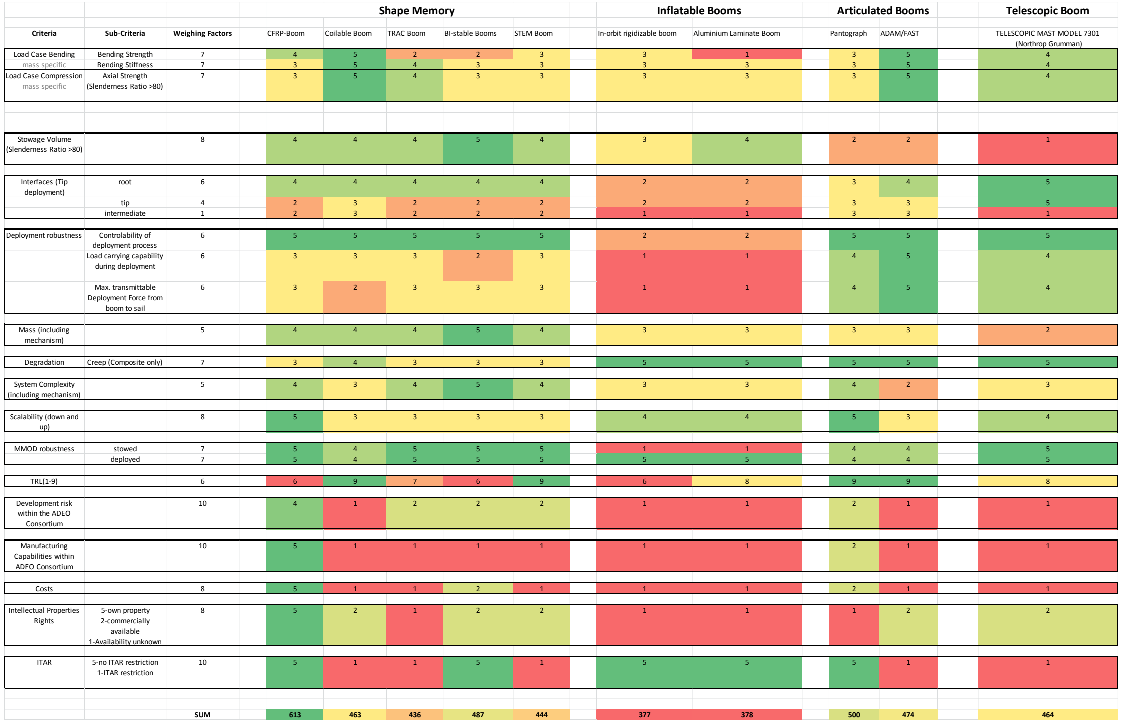
Telescopic composite mast deployed by an internal metal STEM boom
(Courtesy of Northrop Grumman)

Boom Evaluation Criteria

- **Boom evaluation criteria for de-orbiting applications:**
    - Stowage Volume, Mass (including deployment mechanisms), Structural performance (stiffness, strength), Scalability, Long term stowage capability, Complexity, MMOD resistance, Thermal characteristics, Material degradation

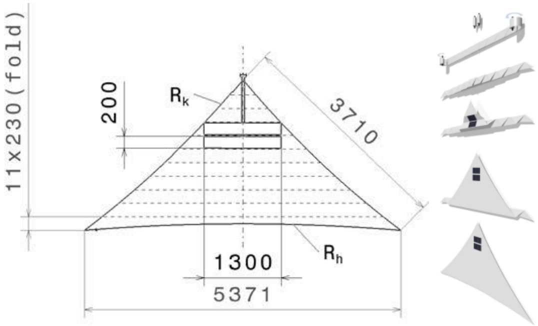
- **Evaluation of entire boom categories is necessarily defective** as properties among representatives of the same category may vary strongly.

➢ Therefore, **individual evaluation of boom concepts is necessary**.

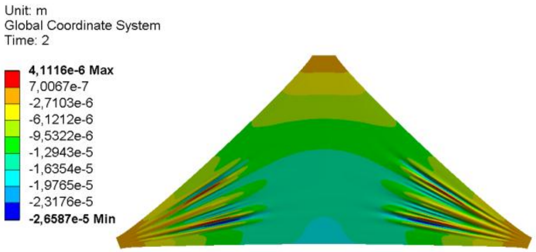


			Shape Memory					Inflatable Booms		Articulated Booms		Telescopic Boom
Criteria	**Sub-Criteria**	**Weighing Factors**	CFRP-Boom	Coilable Boom	TRAC Boom	BI-stable Booms	STEM Boom	In-orbit rigidizable boom	Aluminium Laminate Boom	Pantograph	ADAM/FAST	TELESCOPIC MAST MODEL 7301 (Northrop Grumman)
Load Case Bending	Bending Strength	7	4	5	2	2	3	3	1	3	5	4
mass specific	Bending Stiffness	7	3	5	4	3	3	3	3	3	5	4
Load Case Compression mass specific	Axial Strength (Slenderness Ratio >80)	7	3	5	4	3	3	3	3	3	5	4
Stowage Volume (Slenderness Ratio >80)		8	4	4	4	5	4	3	4	2	2	1
Interfaces (Tip deployment)	root	6	4	4	4	4	4	2	2	3	4	5
	tip	4	2	3	2	2	2	2	2	3	3	5
	intermediate	1	2	3	2	2	2	1	1	3	3	1
Deployment robustness	Controlability of deployment process	6	5	5	5	5	5	2	2	5	5	5
	Load carrying capability during deployment	6	3	3	3	2	3	1	1	4	5	4
	Max. transmittable Deployment Force from boom to sail	6	3	2	3	3	3	1	1	4	5	4
Mass (including mechanism)		5	4	4	4	5	4	3	3	3	3	2
Degradation	Creep (Composite only)	7	3	4	3	3	3	5	5	5	5	5
System Complexity (including mechanism)		5	4	3	4	5	4	3	3	4	2	3
Scalability (down and up)		8	5	3	3	3	3	4	4	5	3	4
MMOD robustness	stowed	7	5	4	5	5	5	1	1	4	4	5
	deployed	7	5	4	5	5	5	5	5	4	4	5
TRL(1-9)		6	6	9	7	6	9	6	8	9	9	8
Development risk within the ADEO Consortium		10	4	1	2	2	2	1	1	2	1	1
Manufacturing Capabilities within ADEO Consortium		10	5	1	1	1	1	1	1	2	1	1
Costs		8	5	1	1	2	1	1	1	2	1	1
Intellectual Properties Rights	5-own property 2-commercially available 1-Availability unknown	8	5	2	1	2	2	1	1	1	2	2
ITAR	5-no ITAR restriction 1-ITAR restriction	10	5	1	1	5	1	5	5	5	1	1
		SUM	**613**	**463**	**436**	**487**	**444**	**377**	**378**	**500**	**474**	**464**


Deployment Test

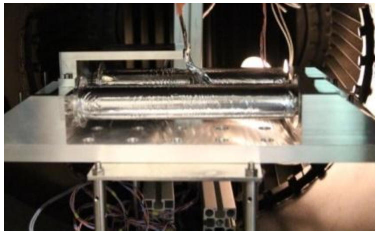


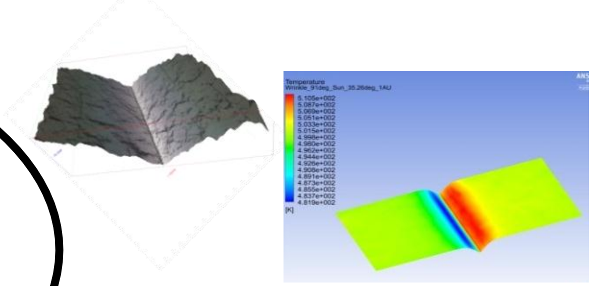
Design

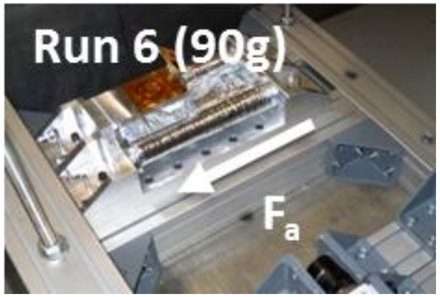


Structural Analysis

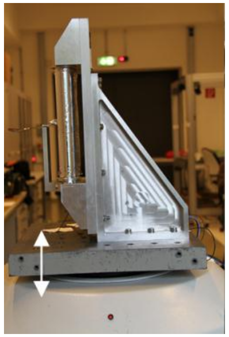
DLR's Development of Deployable Membrane Spacecraft Structures


Fast Decompression

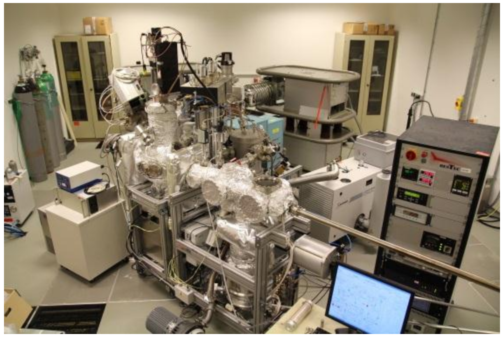

Thermal Analysis



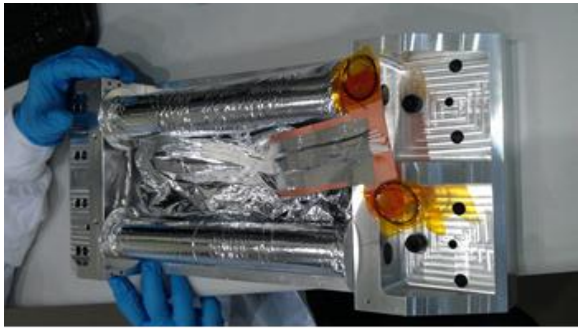
Centrifuge Test


Shaker Tests

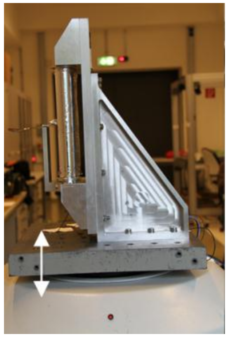

Manufacturing

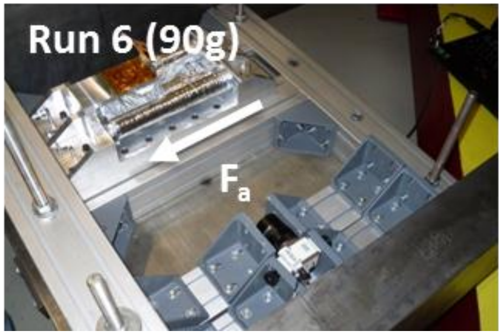

Degradation (e^-, p^+, EMR)

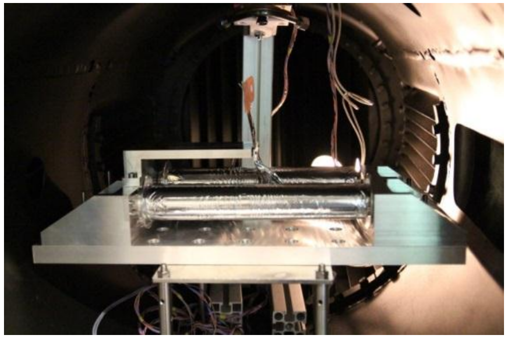
Membrane Verification on the example of DLR's Gossamer-1project



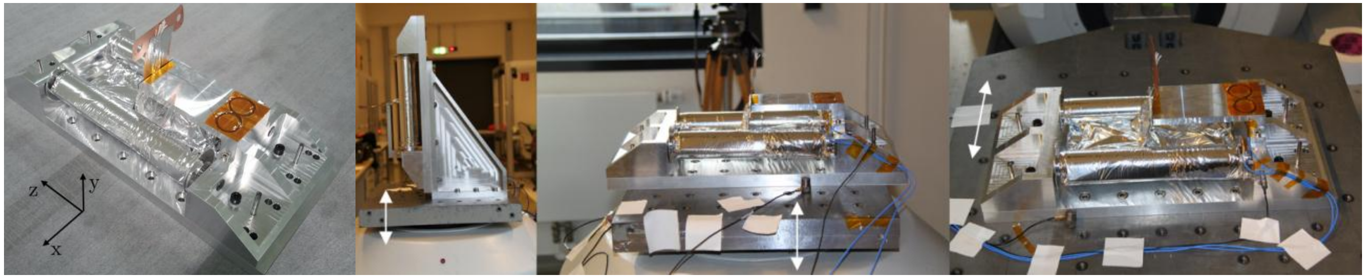
- Shaker
- Centrifuge
- Fast Decompression
- Deployment







Verification – Shaker



- Sine

Axis	Frequency	Level
X, Y	2 - 6 Hz 6 - 100 Hz	23 mm (0 to peak) 2.5 g
Z	2 - 6 Hz 6 - 100 Hz	23 mm (0 to peak) 3.5 g
sweep rate	2 octaves per minute (one upsweep)	

- Random

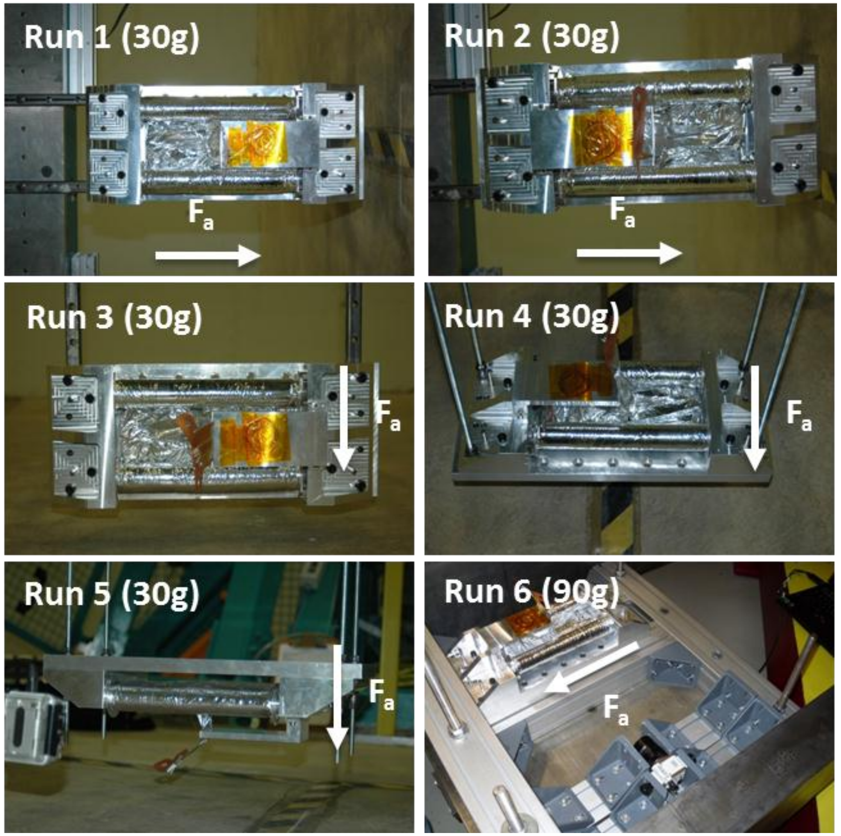
Axis	Peak Frequency	Peak Level	Overall level [g_{rms}]
X	100 Hz 120 Hz	7 g²/Hz 7 g²/Hz	19.89
Y	100 Hz 130 Hz	10 g²/Hz 10 g²/Hz	23.89
Z	190 Hz 215 Hz	7 g²/Hz 7 g²/Hz	28.53
duration		2 min per axis	

Verification - Centrifuge

- All axes tested with 30g
- It is difficult to test vibration and static loads at the same time in a laboratory environment

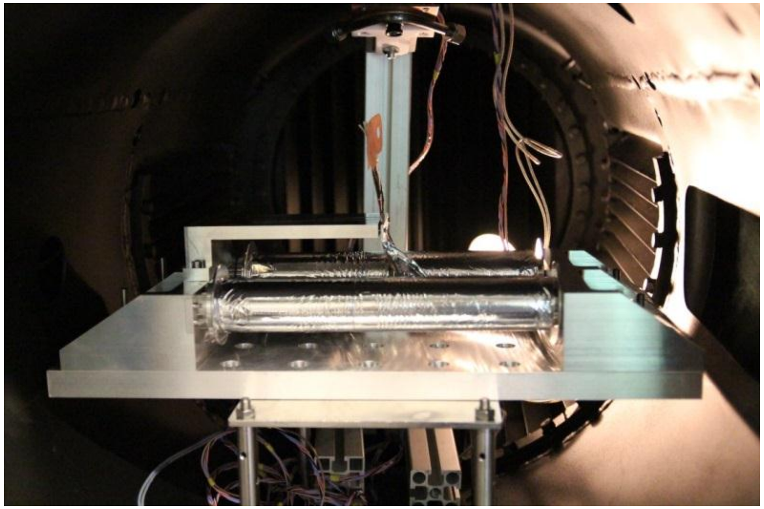
=>Centrifuge testing with very high g-levels

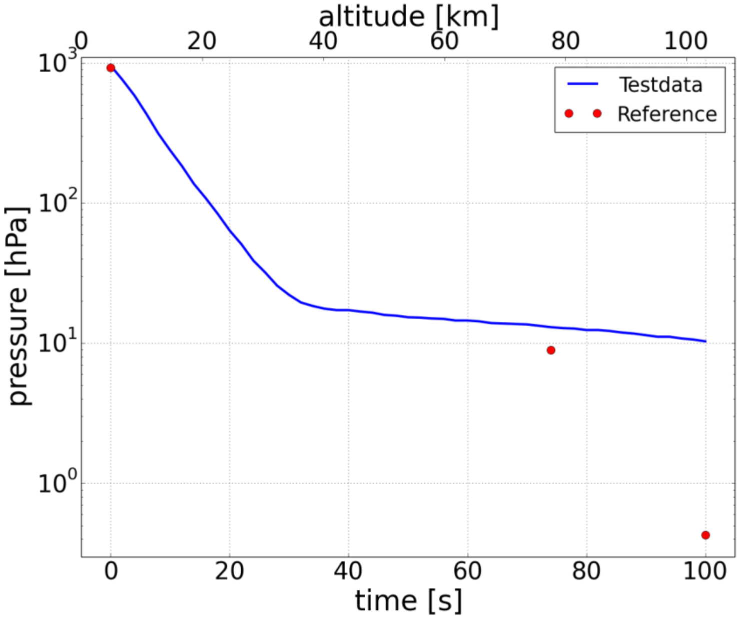
- 2σ standard deviation of the maximum vibration accelerations were covered (83.29g)



Verification - Fast Decompression

- Venting 99% of the air within the first 75 seconds
- Test was consistent to our reference launch of a Steel2.1 rocket, providing time-altitude correlations
- Employing atmosphere model NRLMSISE-00 and ideal gas law the pressure was calculated





Verification – Laboratory deployment test

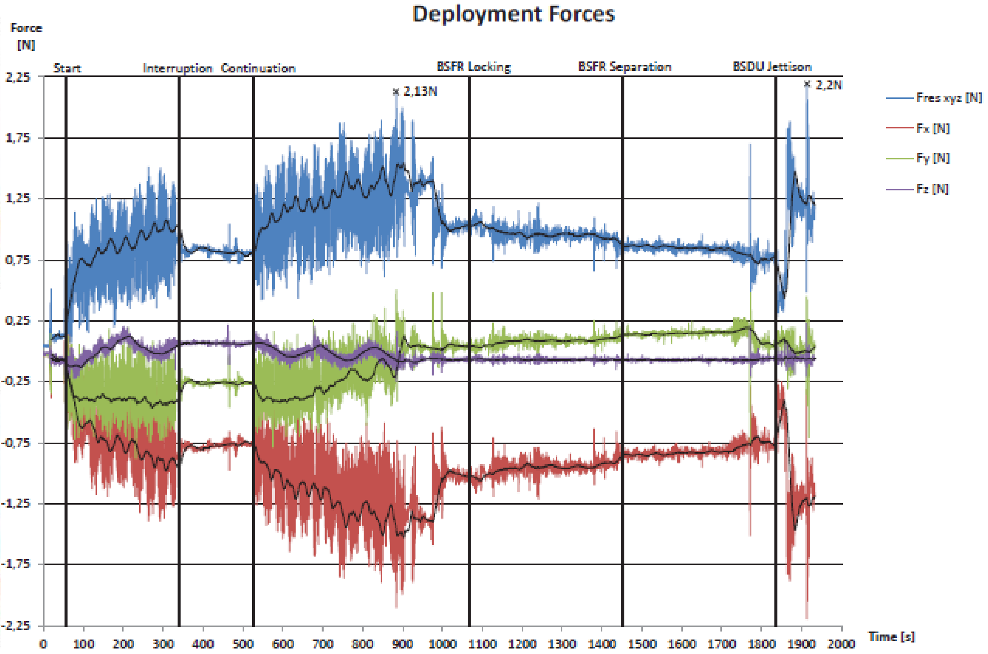
- Final laboratory deployment testing, including measurement of deployment forces

(a)

(b)

(c)

(d)



Verification – Further Aspects

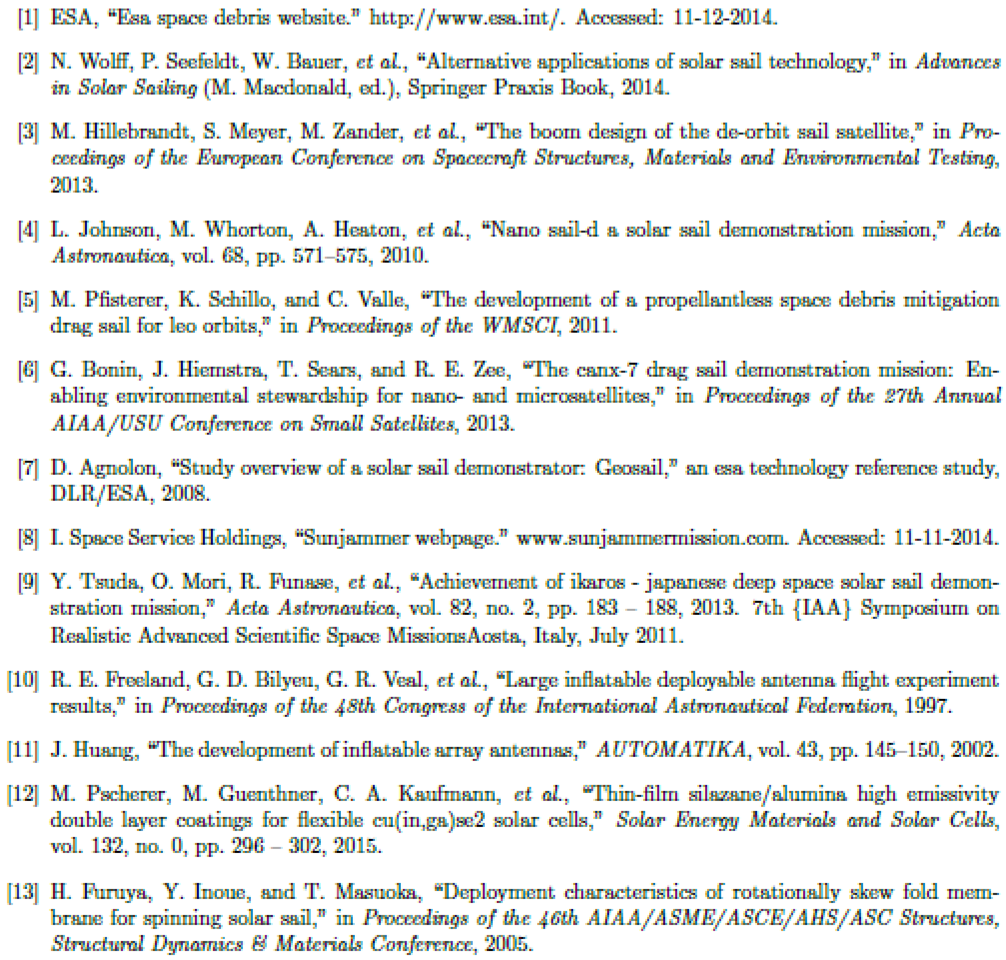
- Microscope investigations, package verification (e.g. coatings)
- Degradation experiments (e.g. VUV and ATOX)
- Boom characterization (e.g. Stiffness, creeping)
- …..

Summary

- State of the art review in the field of
  - Drag Sails, Solar Sails, Thin-film Photovoltaics, Membrane Antenna, Sun Shielding
  - Summary membrane stowing strategies
  - Summary membrane design aspects
  - Space Environment in LEO and impact on Materials
  - Exemplarily three different coatings were presented (Al, SiO2, TiO2)

- Membrane Verification
  - Qualification testing on the example of DLR’s Gossamer-1 Project
  - Shaker, Centrifuge, Fast Decompression and laboratory Deployment

Bibliography



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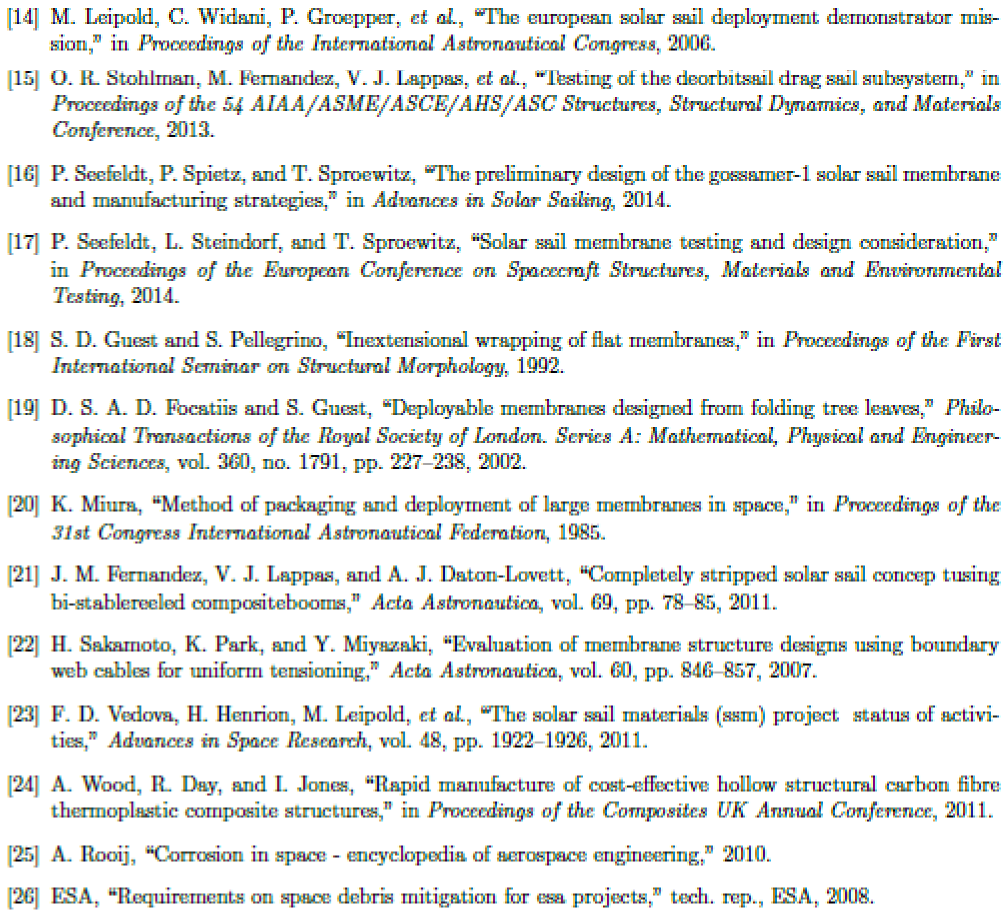

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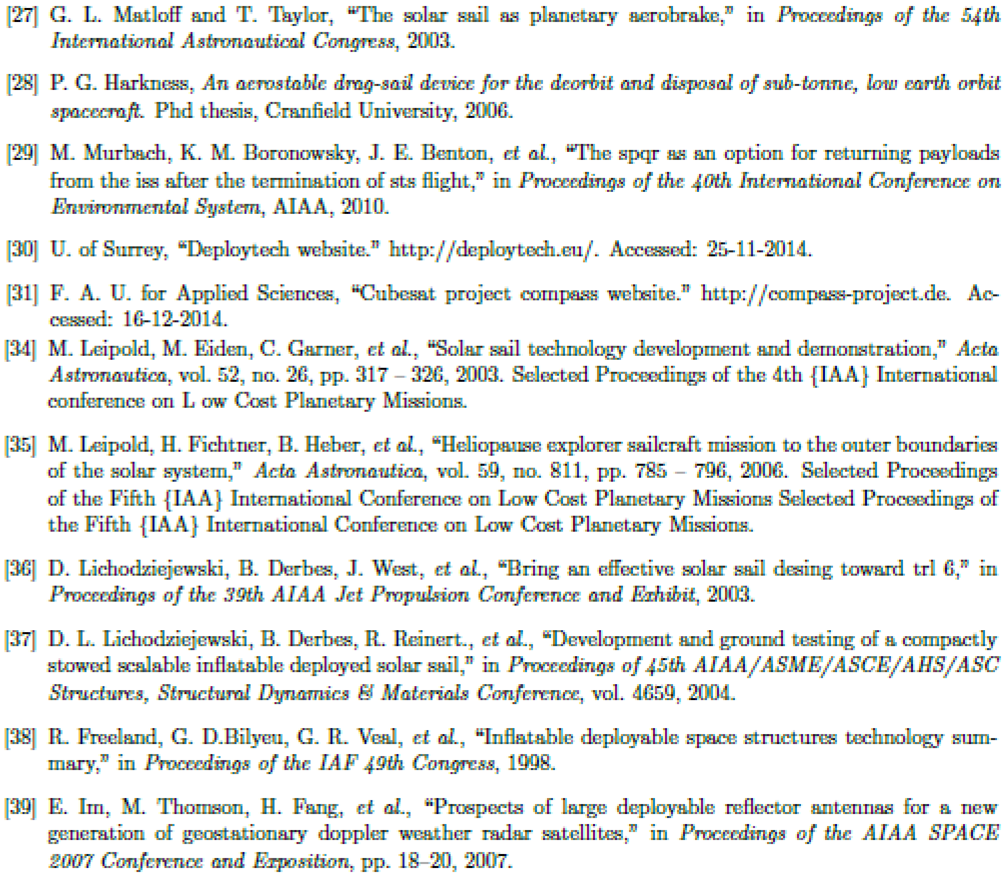

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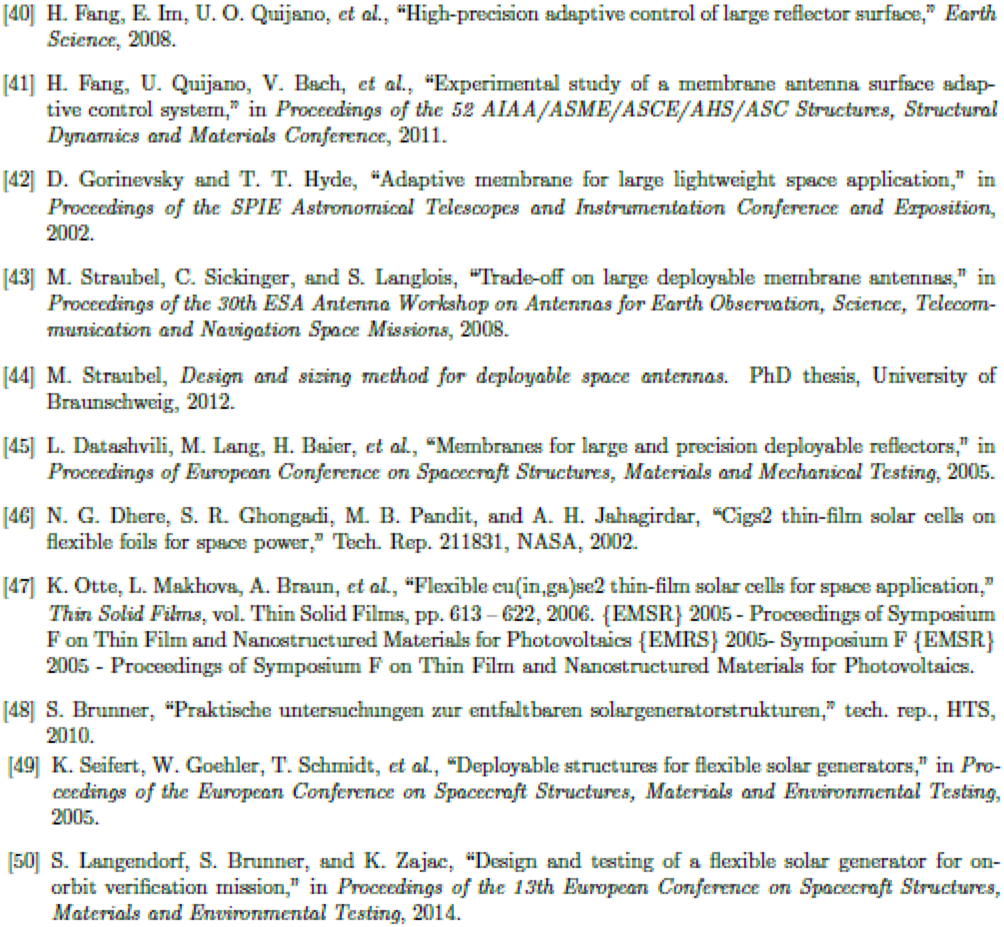

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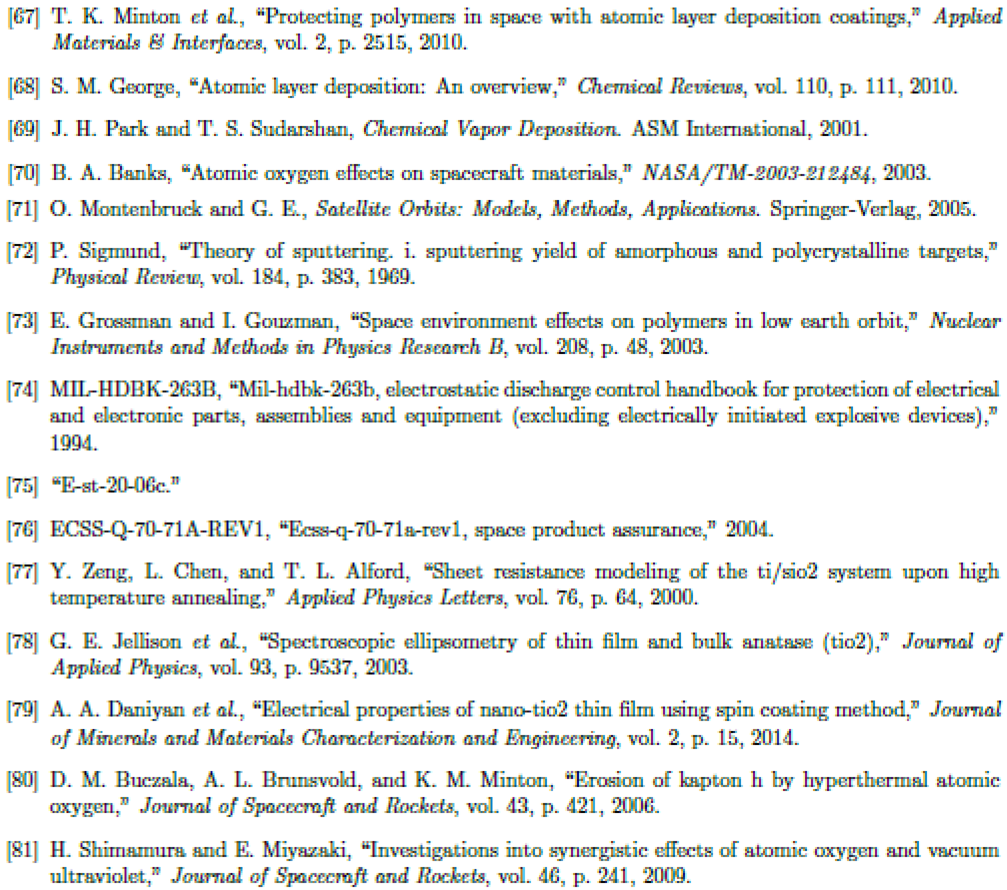

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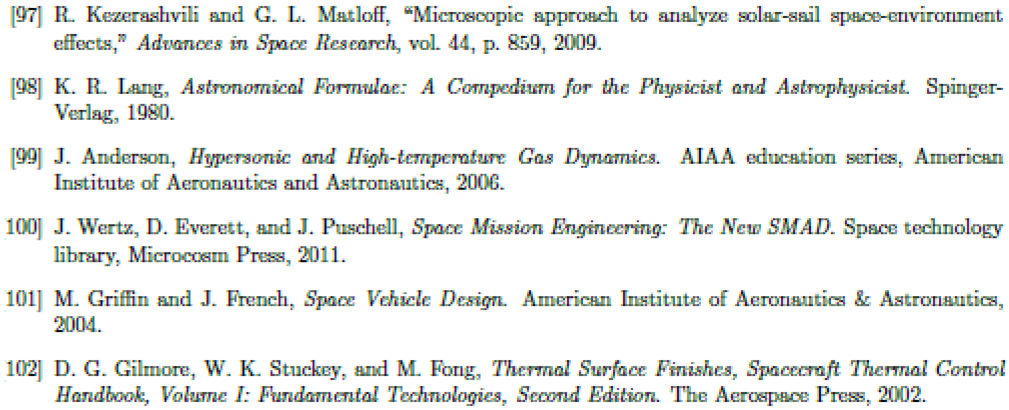

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