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

17th of March 2015

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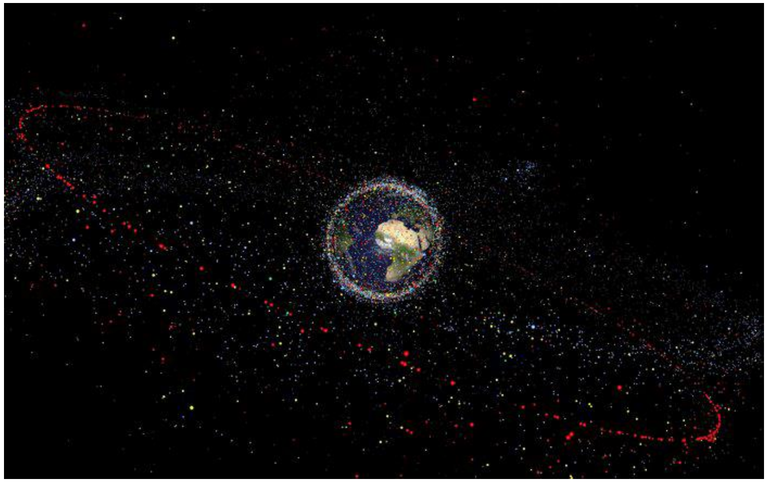
Content

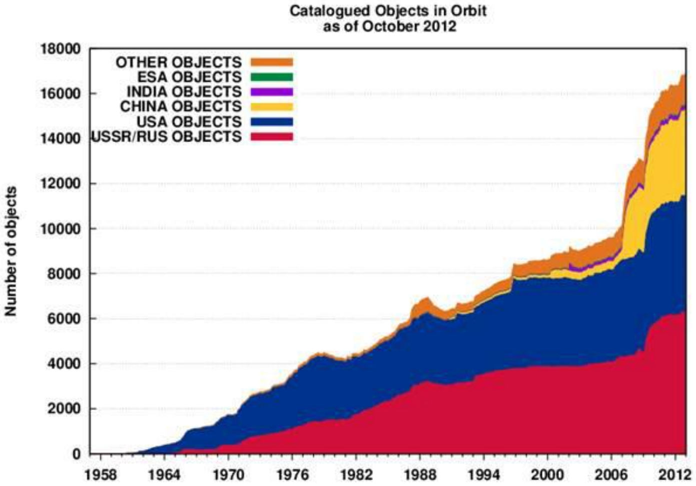
- ➢Space Debris and Drag Augmentation Introduction

- ➢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

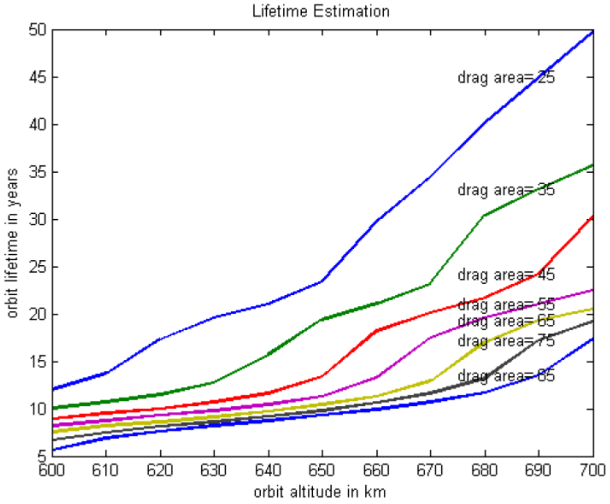




- Sharp increase due to Chinese anti-satellite missile test in 2007 and a collision of two satellites (Iridium33 and Kosmos2251) in 2009
- Envisat orbiting at 790km altitude brings a risk of a new collision
- Deorbiting strategies are required, (one) solution is drag augmentation

⇒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.

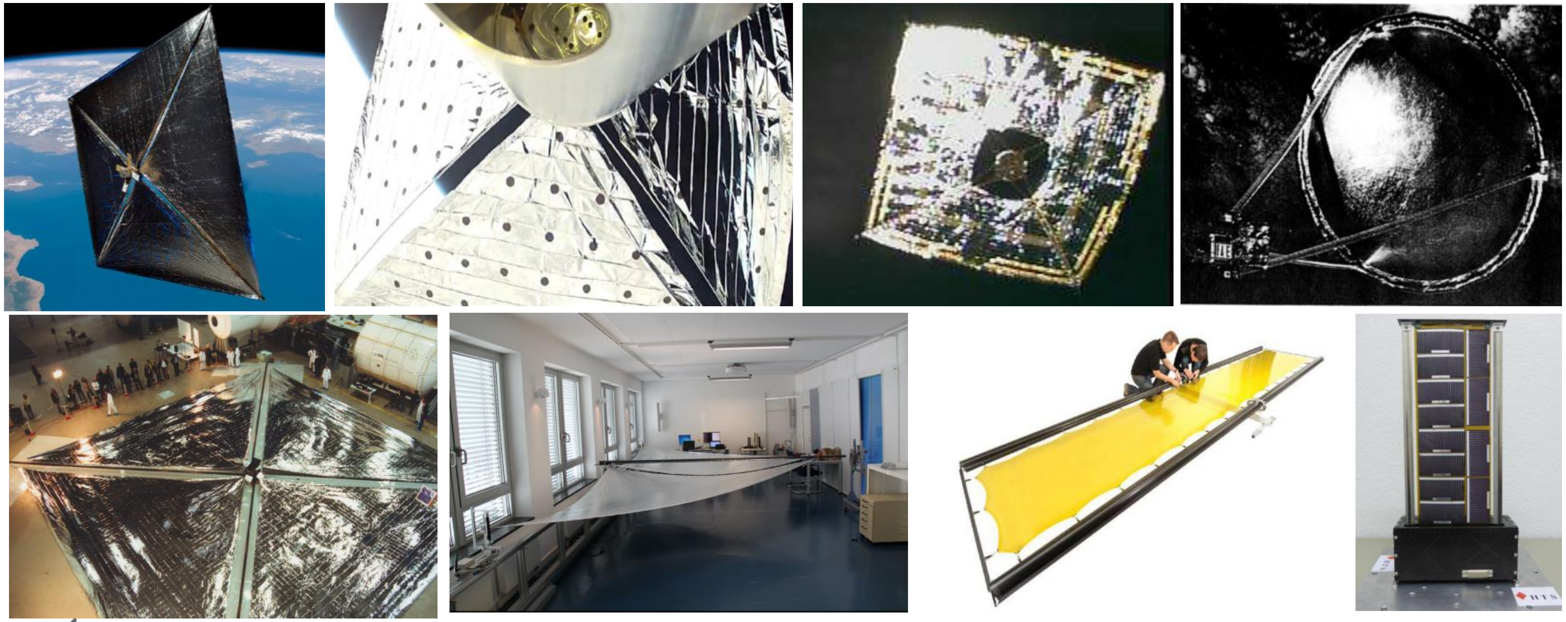
- Deorbiting strategies are required, (one) solution is drag augmentation

$$a_D = \frac{1}{2}\rho v^2 \cdot \frac{C_D A}{m}$$

- ➢ 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

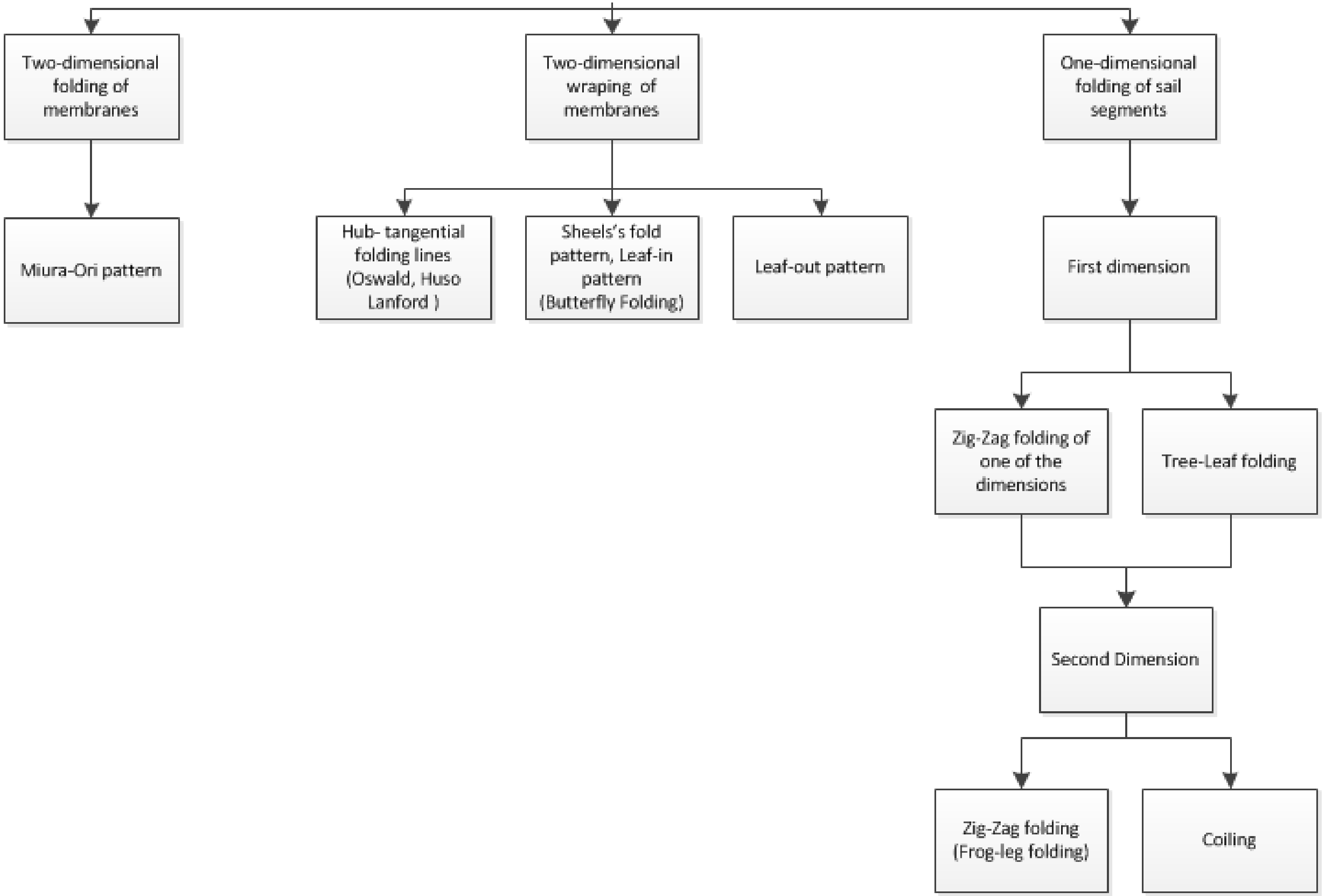
- Drag Sail Projects (mainly CubeSats)
  - Stowing and deployment strategies (scalability from CubeSats is difficult)
  - Materials
  - Membrane design

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

- Ultra lightweight solar photovoltaic generators
  - Protective coatings

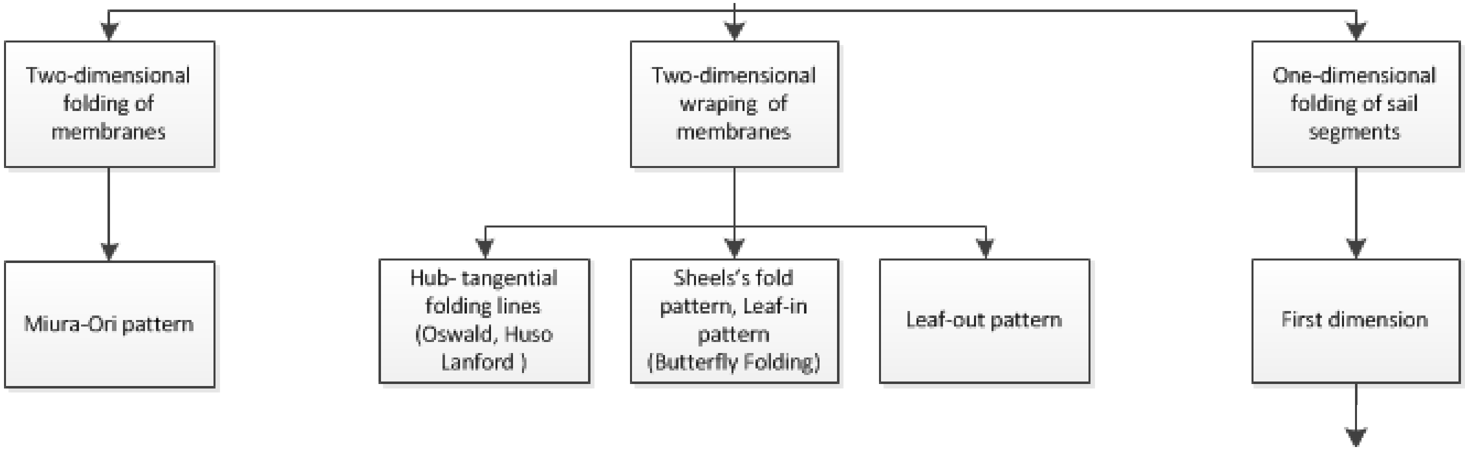
- Membrane Antenna
  - Load introduction, surface accuracy

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



Two-dimensional folding of membranes

Two-dimensional wraping of membranes

One-dimensional folding of sail segments

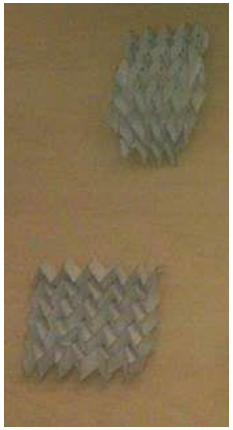
Miura-Ori pattern

Hub- tangential folding lines (Oswald, Huso Lanford)

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

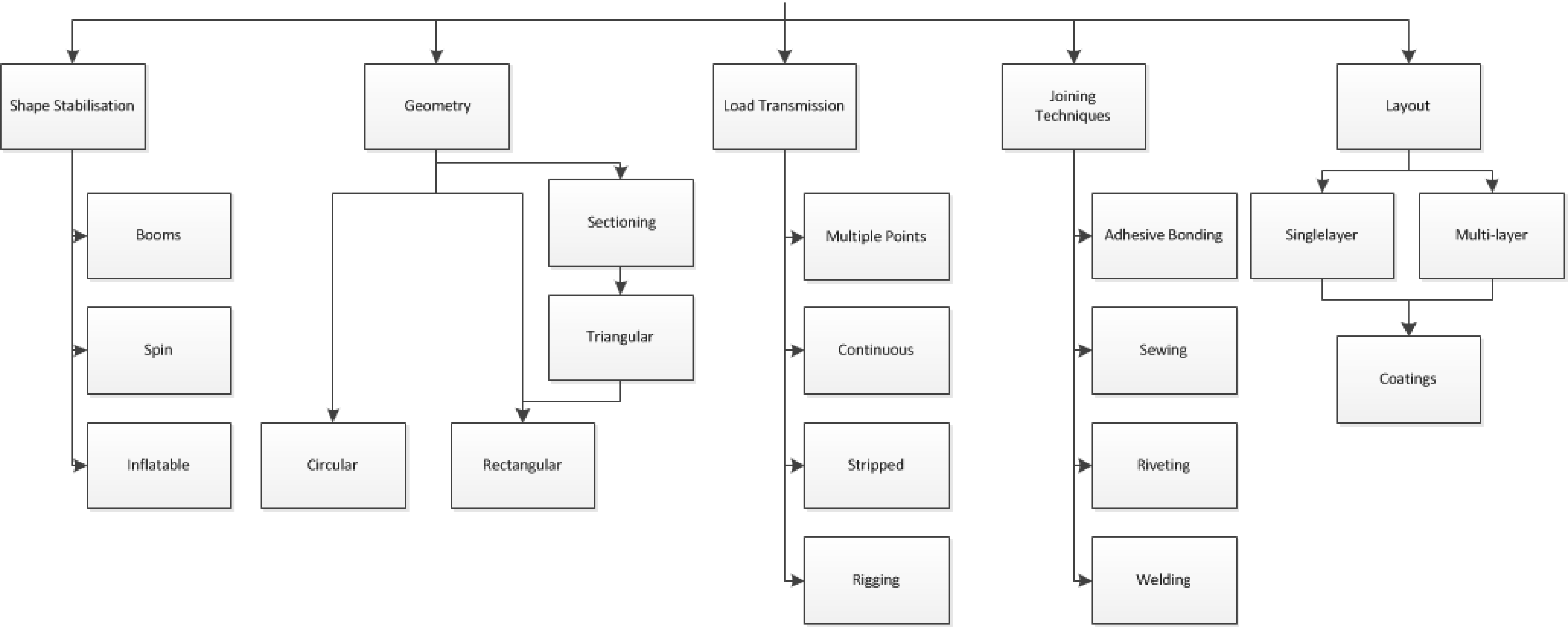
Leaf-out pattern

First dimension



Second Dimension

Membrane Design Aspects



Shape Stabilisation
Booms
Spin
Inflatable

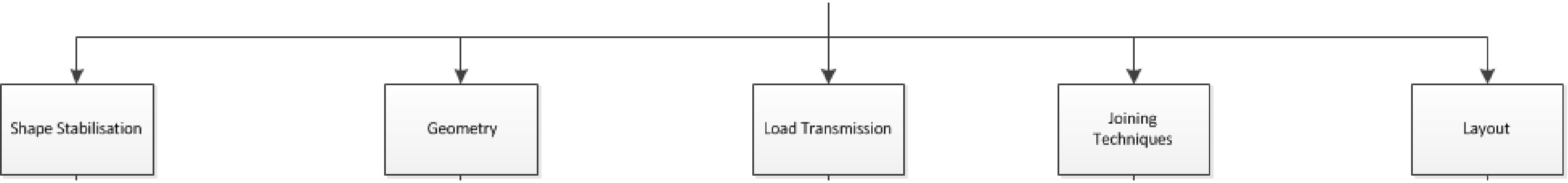
Geometry
Sectioning
Triangular
Circular
Rectangular

Load Transmission
Multiple Points
Continuous
Stripped
Rigging

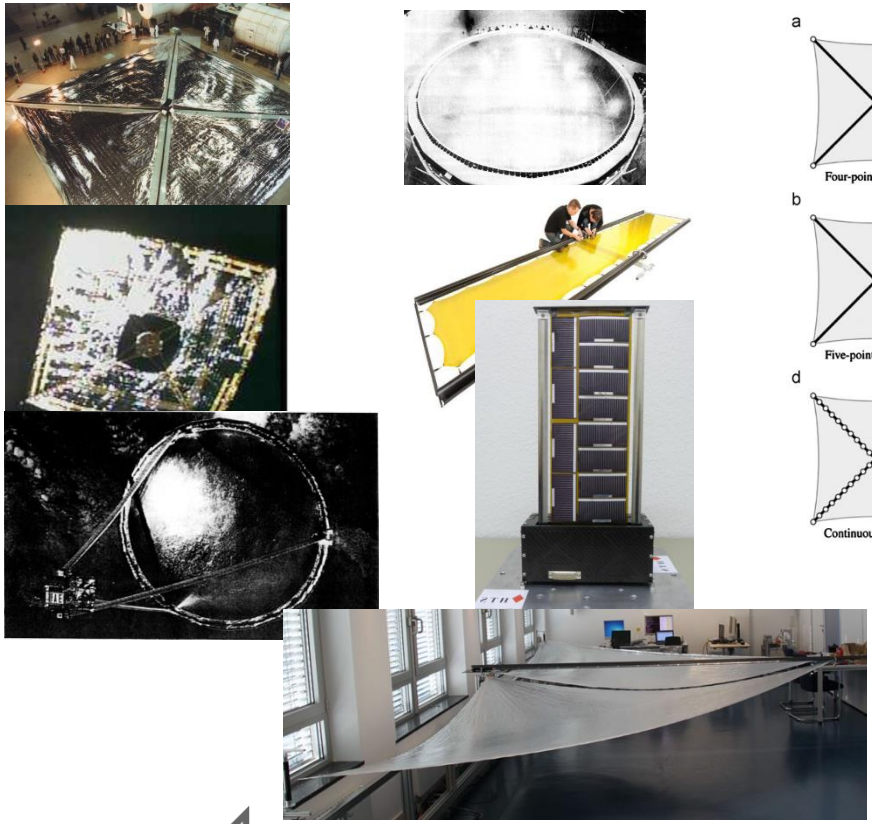
Joining Techniques
Adhesive Bonding
Sewing
Riveting
Welding

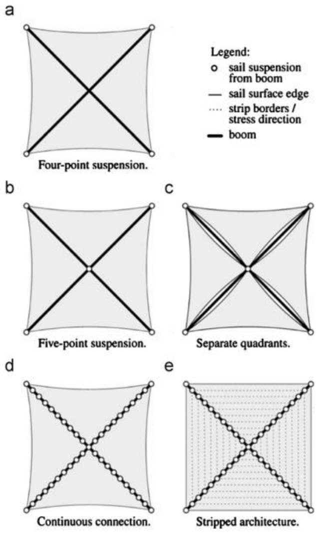
Layout
Singlelayer
Multi-layer
Coatings

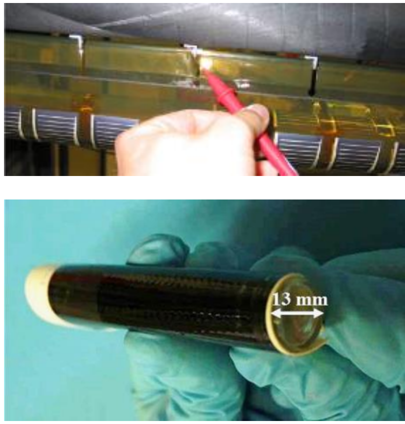
Membrane Design Aspects



- 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

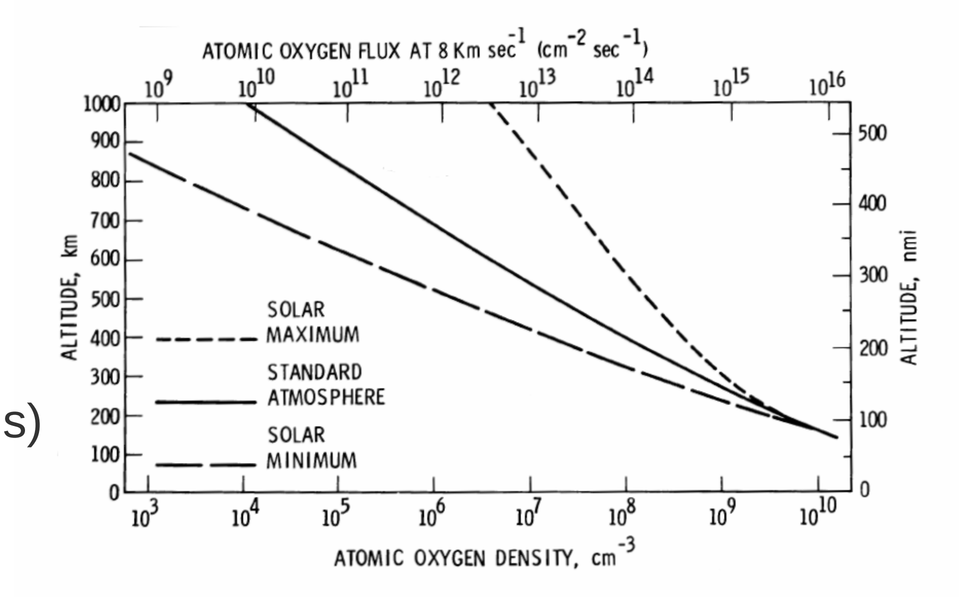
- Vacuum Deposited Aluminum (VDA) on polyimide is a standard product and was chosen in many former projects. Additional protective and thermo-optical coatings were considered especially for photovoltaics (SiO_2) and are used for various MLI materials.

    - 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

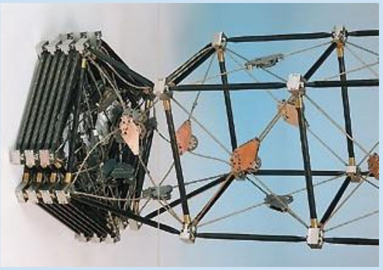
Inflatable

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

Courtesy of University of Surrey

Articulated

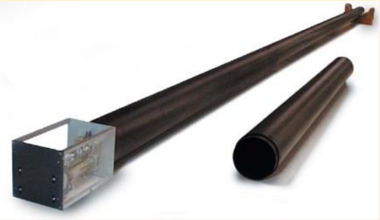
- Rigid structural members
- Stowage by use of hinges
- Deployment by additional mechanism



Courtesy of ATK/ABLE Engineering

Telescopic

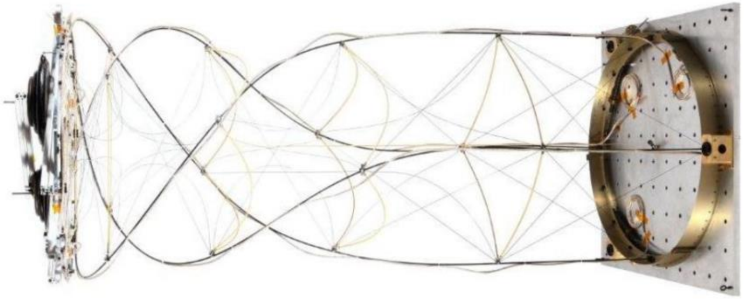
- Segmented rigid shell structure
- Stowage by use of telescopic segments
- Deployment by additional mechanism



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



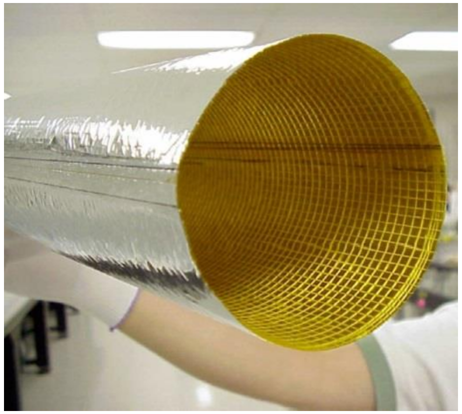
Four longeron deployable CoilABLE truss (Courtesy of ATK/ABLE Engineering)

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**

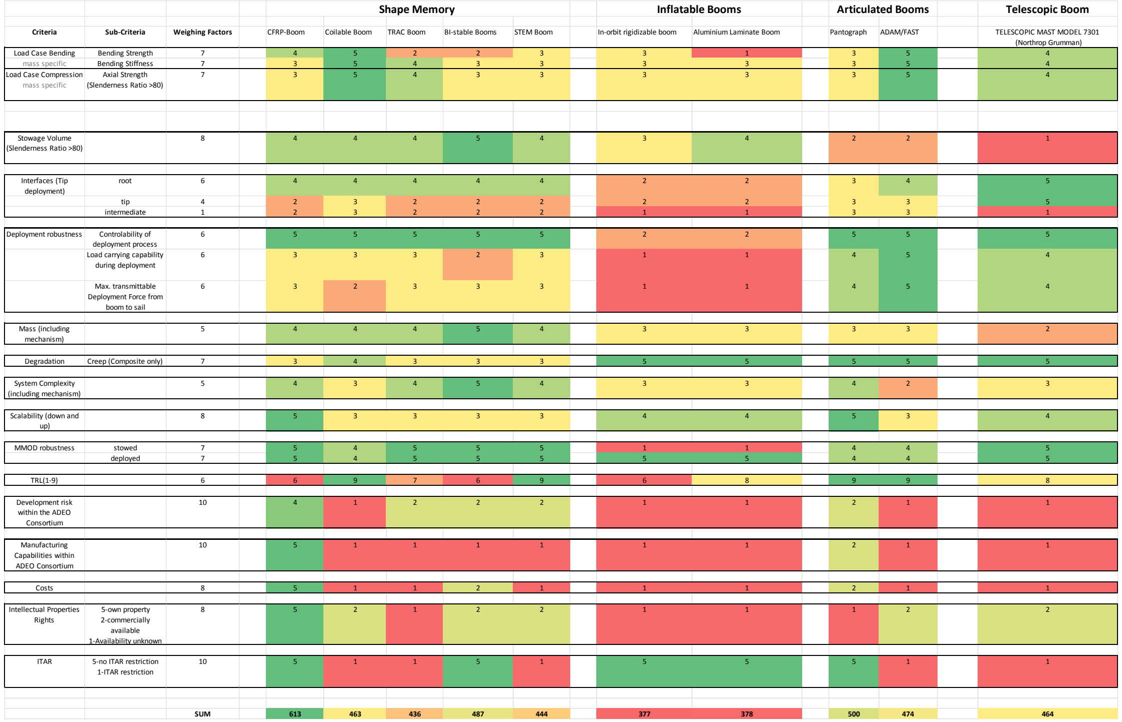
Telescopic composite mast deployed by an internal metal STEM boom
(Courtesy of Northrop Grumman)

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

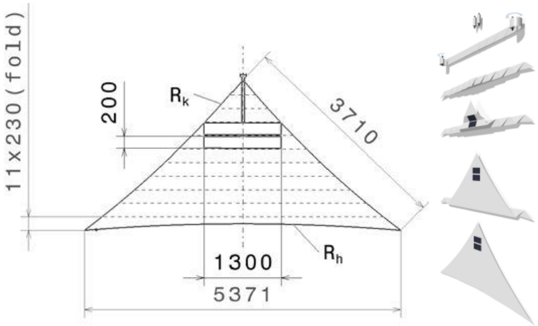
- **Evaluation of entire boom categories is necessarily defective** as properties among representatives of the same category may vary strongly.

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

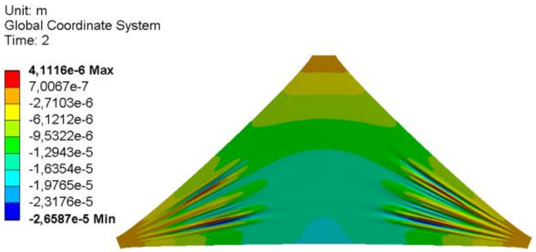


			Shape Memory					Inflatable Booms		Articulated Booms		Telescopic Boom
Criteria	**Sub-Criteria**	**Weighing Factors**	CFRP-Boom	Coilable Boom	TRAC Boom	BI-stable Booms	STEM Boom	In-orbit rigidizable boom	Aluminium Laminate Boom	Pantograph	ADAM/FAST	TELESCOPIC MAST MODEL 7301 (Northrop Grumman)
Load Case 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**

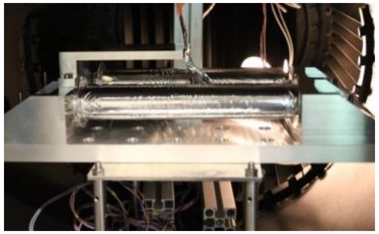
Deployment Test



Design

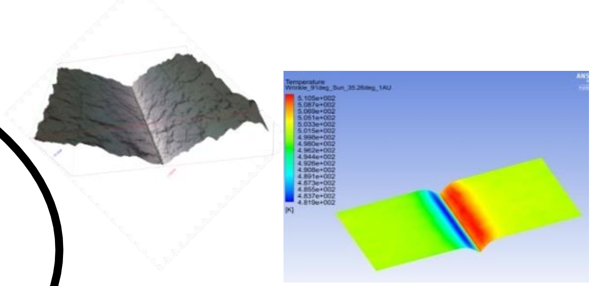


Structural Analysis

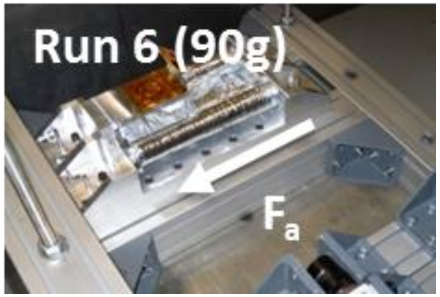


Fast Decompression

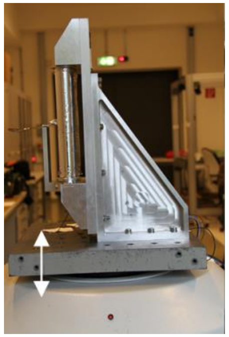
DLR's Development of Deployable Membrane Spacecraft Structures



Thermal Analysis



Centrifuge Test

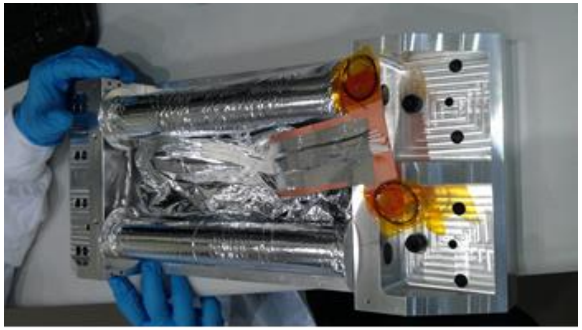


Shaker Tests

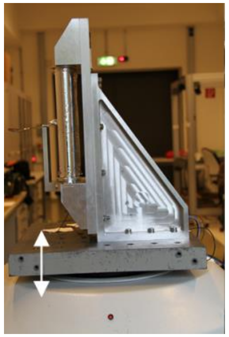
Manufacturing

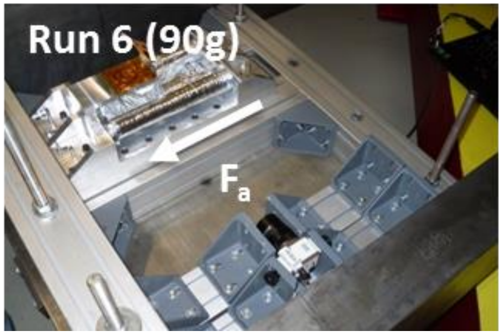
Degradation (e^-, p^+, EMR)

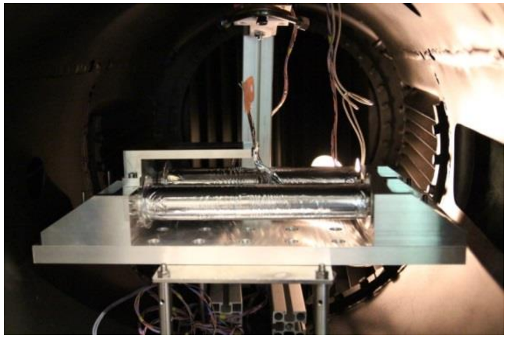
Membrane Verification on the example of DLR's Gossamer-1project



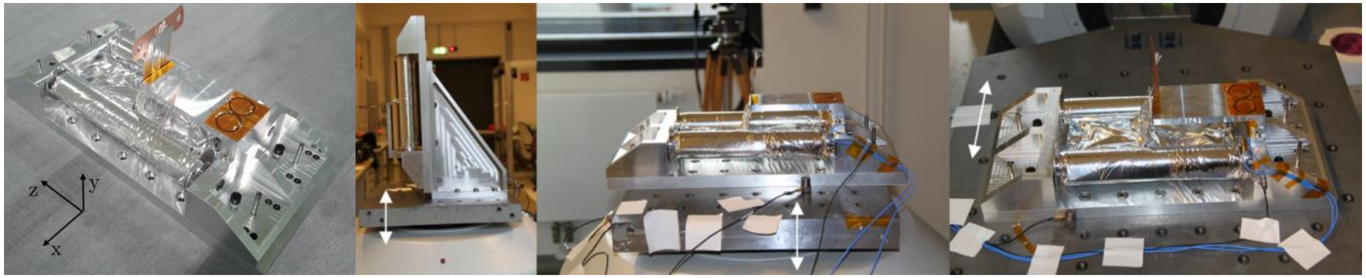
- Shaker
- Centrifuge
- Fast Decompression
- Deployment







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

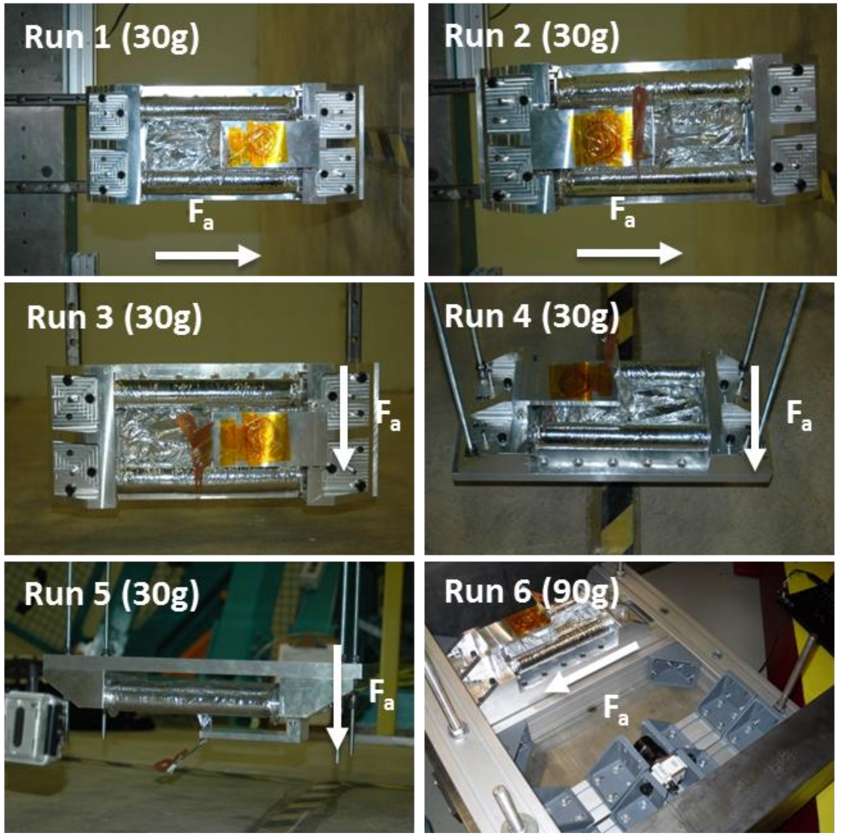
Axis	Peak Frequency	Peak Level	Overall level [g_{rms}]
X	100 Hz 120 Hz	7 g²/Hz 7 g²/Hz	19.89
Y	100 Hz 130 Hz	10 g²/Hz 10 g²/Hz	23.89
Z	190 Hz 215 Hz	7 g²/Hz 7 g²/Hz	28.53
duration		2 min per axis	

Verification - Centrifuge

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

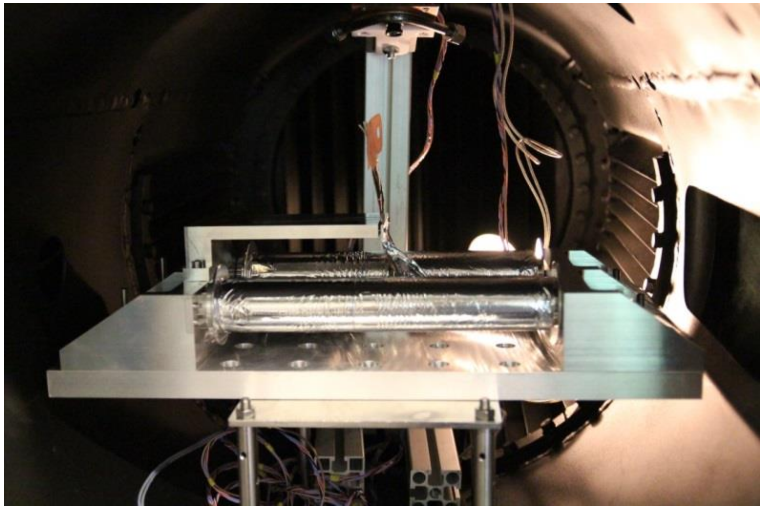
=>Centrifuge testing with very high g-levels

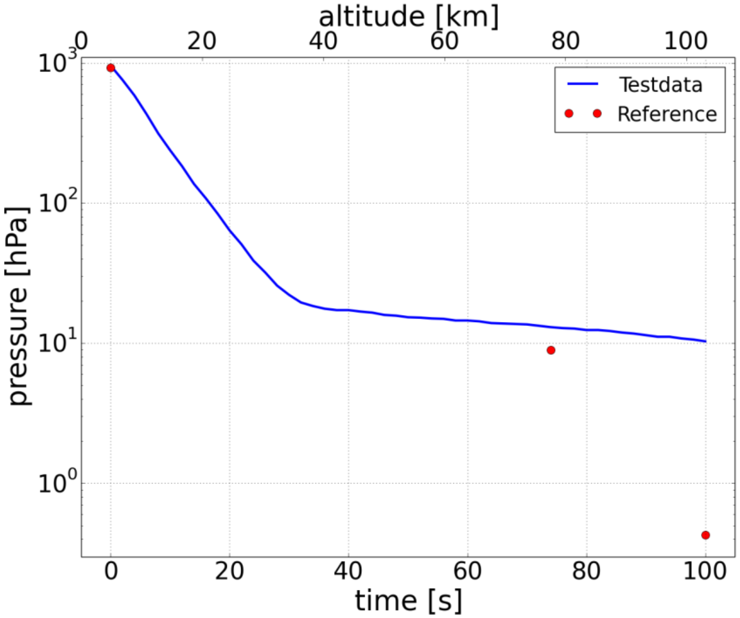
- 2σ standard deviation of the maximum vibration accelerations were covered (83.29g)



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

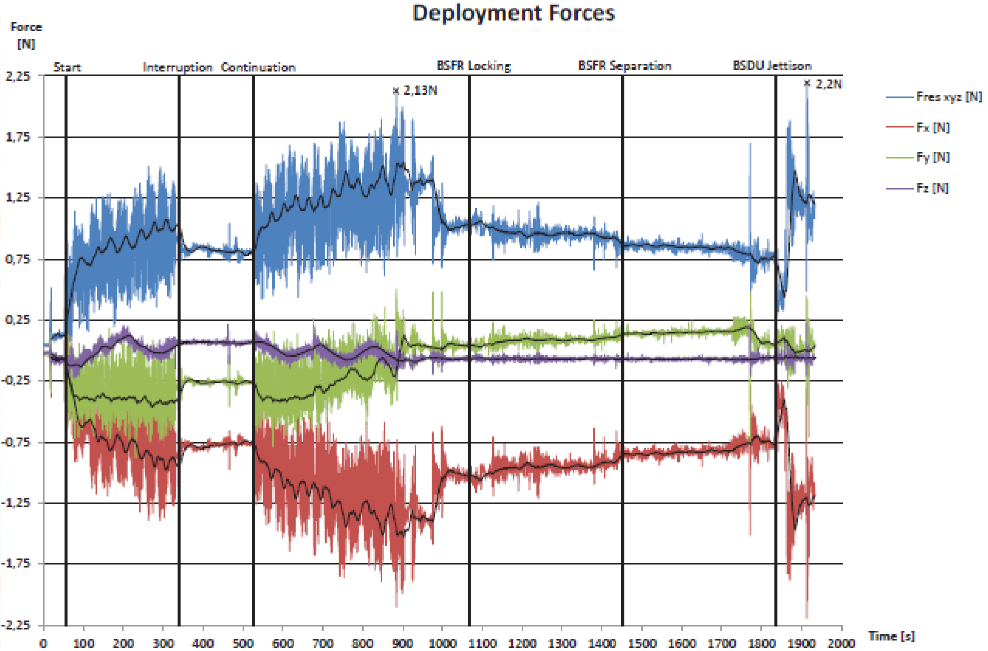
- Final laboratory deployment testing, including measurement of deployment forces

(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

[1] ESA, "Esa space debris website." http://www.esa.int/. Accessed: 11-12-2014.

[2] N. Wolff, P. Seefeldt, W. Bauer, *et al.*, "Alternative applications of solar sail technology," in *Advances in Solar Sailing* (M. Macdonald, ed.), Springer Praxis Book, 2014.

[3] M. Hillebrandt, S. Meyer, M. Zander, *et al.*, "The boom design of the de-orbit sail satellite," in *Proceedings of the European Conference on Spacecraft Structures, Materials and Environmental Testing*, 2013.

[4] L. Johnson, M. Whorton, A. Heaton, *et al.*, "Nano sail-d a solar sail demonstration mission," *Acta Astronautica*, vol. 68, pp. 571–575, 2010.

[5] M. Pfisterer, K. Schillo, and C. Valle, "The development of a propellantless space debris mitigation drag sail for leo orbits," in *Proceedings of the WMSCI*, 2011.

[6] G. Bonin, J. Hiemstra, T. Sears, and R. E. Zee, "The canx-7 drag sail demonstration mission: Enabling environmental stewardship for nano- and microsatellites," in *Proceedings of the 27th Annual AIAA/USU Conference on Small Satellites*, 2013.

[7] D. Agnolon, "Study overview of a solar sail demonstrator: Geosail," an esa technology reference study, DLR/ESA, 2008.

[8] I. Space Service Holdings, "Sunjammer webpage." www.sunjammermission.com. Accessed: 11-11-2014.

[9] Y. Tsuda, O. Mori, R. Funase, *et al.*, "Achievement of ikaros - japanese deep space solar sail demonstration mission," *Acta Astronautica*, vol. 82, no. 2, pp. 183 – 188, 2013. 7th {IAA} Symposium on Realistic Advanced Scientific Space MissionsAosta, Italy, July 2011.

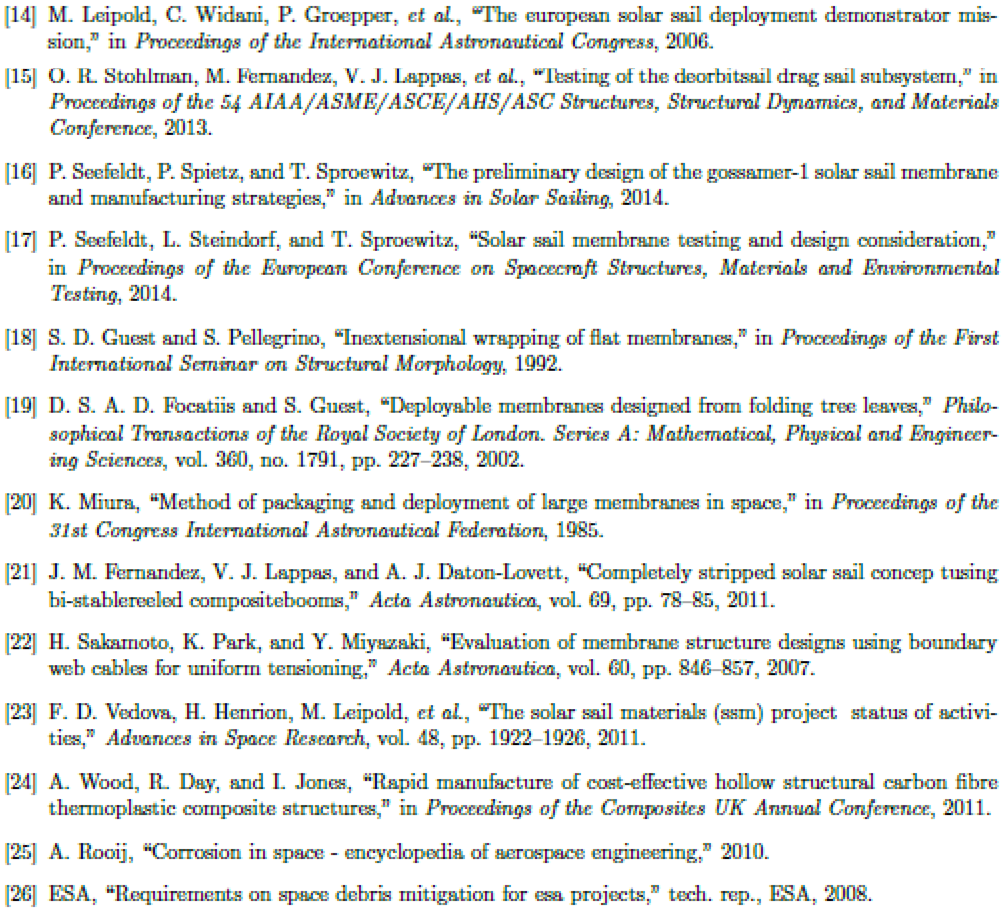
[10] R. E. Freeland, G. D. Bilyeu, G. R. Veal, *et al.*, "Large inflatable deployable antenna flight experiment results," in *Proceedings of the 48th Congress of the International Astronautical Federation*, 1997.

[11] J. Huang, "The development of inflatable array antennas," *AUTOMATIKA*, vol. 43, pp. 145–150, 2002.

[12] M. Pscherer, M. Guenthner, C. A. Kaufmann, *et al.*, "Thin-film silazane/alumina high emissivity double layer coatings for flexible cu(in,ga)se2 solar cells," *Solar Energy Materials and Solar Cells*, vol. 132, no. 0, pp. 296 – 302, 2015.

[13] H. Furuya, Y. Inoue, and T. Masuoka, "Deployment characteristics of rotationally skew fold membrane for spinning solar sail," in *Proceedings of the 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*, 2005.

Bibliography



[14] M. Leipold, C. Widani, P. Groepper, *et al.*, "The european solar sail deployment demonstrator mission," in *Proceedings of the International Astronautical Congress*, 2006.

[15] O. R. Stohlman, M. Fernandez, V. J. Lappas, *et al.*, "Testing of the deorbitsail drag sail subsystem," in *Proceedings of the 54 AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2013.

[16] P. Seefeldt, P. Spietz, and T. Sproewitz, "The preliminary design of the gossamer-1 solar sail membrane and manufacturing strategies," in *Advances in Solar Sailing*, 2014.

[17] P. Seefeldt, L. Steindorf, and T. Sproewitz, "Solar sail membrane testing and design consideration," in *Proceedings of the European Conference on Spacecraft Structures, Materials and Environmental Testing*, 2014.

[18] S. D. Guest and S. Pellegrino, "Inextensional wrapping of flat membranes," in *Proceedings of the First International Seminar on Structural Morphology*, 1992.

[19] D. S. A. D. Focatiis and S. Guest, "Deployable membranes designed from folding tree leaves," *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, vol. 360, no. 1791, pp. 227–238, 2002.

[20] K. Miura, "Method of packaging and deployment of large membranes in space," in *Proceedings of the 31st Congress International Astronautical Federation*, 1985.

[21] J. M. Fernandez, V. J. Lappas, and A. J. Daton-Lovett, "Completely stripped solar sail concep tusing bi-stablereeled compositebooms," *Acta Astronautica*, vol. 69, pp. 78–85, 2011.

[22] H. Sakamoto, K. Park, and Y. Miyazaki, "Evaluation of membrane structure designs using boundary web cables for uniform tensioning," *Acta Astronautica*, vol. 60, pp. 846–857, 2007.

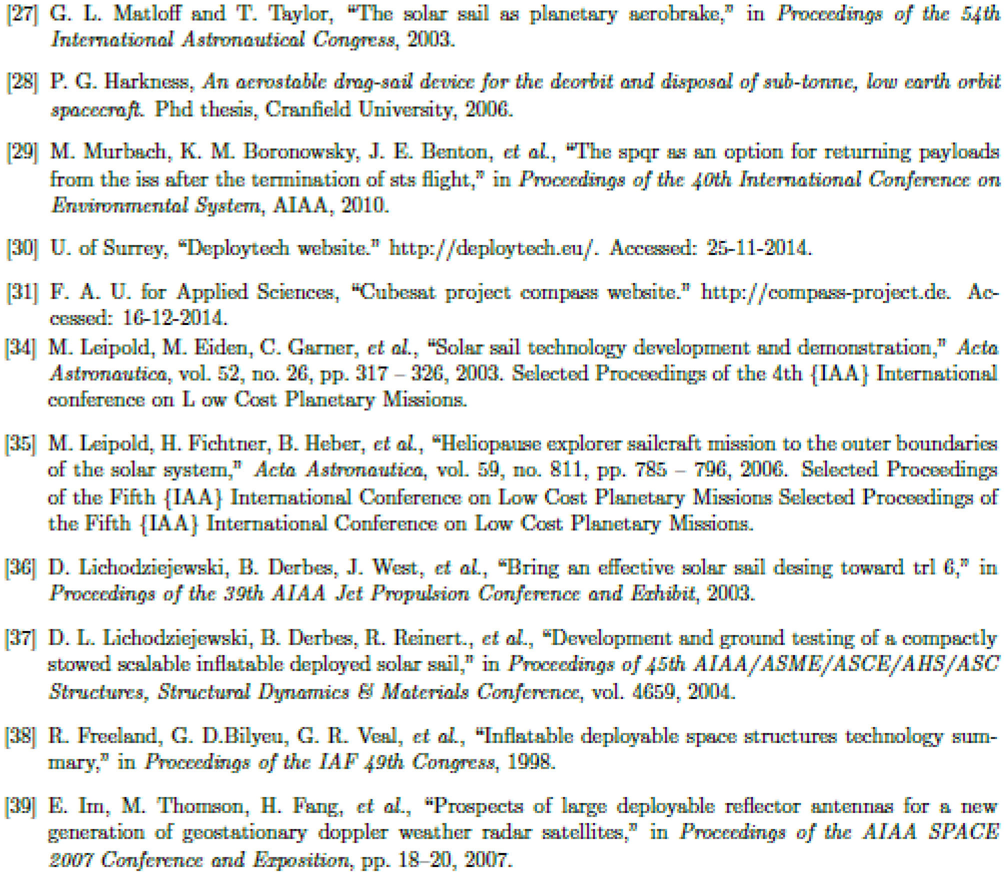
[23] F. D. Vedova, H. Henrion, M. Leipold, *et al.*, "The solar sail materials (ssm) project status of activities," *Advances in Space Research*, vol. 48, pp. 1922–1926, 2011.

[24] A. Wood, R. Day, and I. Jones, "Rapid manufacture of cost-effective hollow structural carbon fibre thermoplastic composite structures," in *Proceedings of the Composites UK Annual Conference*, 2011.

[25] A. Rooij, "Corrosion in space - encyclopedia of aerospace engineering," 2010.

[26] ESA, "Requirements on space debris mitigation for esa projects," tech. rep., ESA, 2008.

Bibliography



[27] G. L. Matloff and T. Taylor, "The solar sail as planetary aerobrake," in *Proceedings of the 54th International Astronautical Congress*, 2003.

[28] P. G. Harkness, *An aerostable drag-sail device for the deorbit and disposal of sub-tonne, low earth orbit spacecraft*. Phd thesis, Cranfield University, 2006.

[29] M. Murbach, K. M. Boronowsky, J. E. Benton, *et al.*, "The spqr as an option for returning payloads from the iss after the termination of sts flight," in *Proceedings of the 40th International Conference on Environmental System*, AIAA, 2010.

[30] U. of Surrey, "Deploytech website." http://deploytech.eu/. Accessed: 25-11-2014.

[31] F. A. U. for Applied Sciences, "Cubesat project compass website." http://compass-project.de. Accessed: 16-12-2014.

[34] M. Leipold, M. Eiden, C. Garner, *et al.*, "Solar sail technology development and demonstration," *Acta Astronautica*, vol. 52, no. 26, pp. 317 – 326, 2003. Selected Proceedings of the 4th {IAA} International conference on L ow Cost Planetary Missions.

[35] M. Leipold, H. Fichtner, B. Heber, *et al.*, "Heliopause explorer sailcraft mission to the outer boundaries of the solar system," *Acta Astronautica*, vol. 59, no. 811, pp. 785 – 796, 2006. Selected Proceedings of the Fifth {IAA} International Conference on Low Cost Planetary Missions Selected Proceedings of the Fifth {IAA} International Conference on Low Cost Planetary Missions.

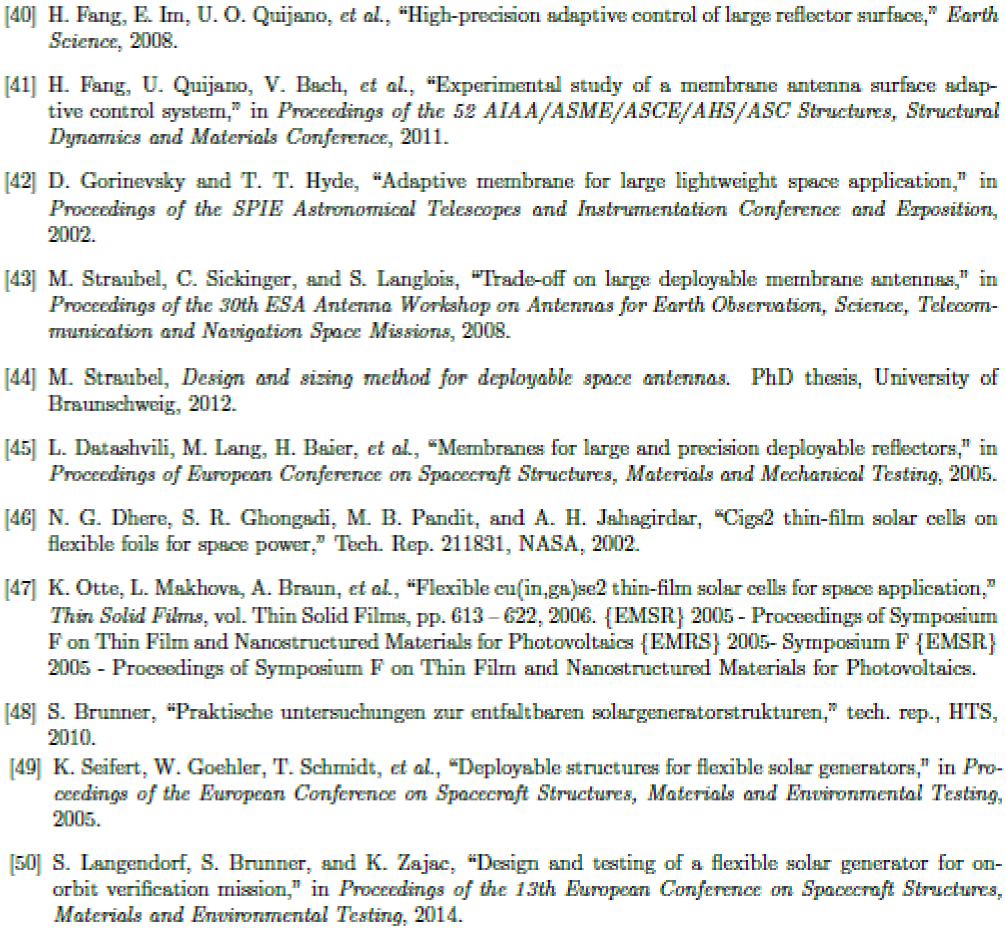
[36] D. Lichodziejewski, B. Derbes, J. West, *et al.*, "Bring an effective solar sail desing toward trl 6," in *Proceedings of the 39th AIAA Jet Propulsion Conference and Exhibit*, 2003.

[37] D. L. Lichodziejewski, B. Derbes, R. Reinert., *et al.*, "Development and ground testing of a compactly stowed scalable inflatable deployed solar sail," in *Proceedings of 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference*, vol. 4659, 2004.

[38] R. Freeland, G. D.Bilyeu, G. R. Veal, *et al.*, "Inflatable deployable space structures technology summary," in *Proceedings of the IAF 49th Congress*, 1998.

[39] E. Im, M. Thomson, H. Fang, *et al.*, "Prospects of large deployable reflector antennas for a new generation of geostationary doppler weather radar satellites," in *Proceedings of the AIAA SPACE 2007 Conference and Exposition*, pp. 18–20, 2007.

Bibliography



[40] H. Fang, E. Im, U. O. Quijano, *et al.*, "High-precision adaptive control of large reflector surface," *Earth Science*, 2008.

[41] H. Fang, U. Quijano, V. Bach, *et al.*, "Experimental study of a membrane antenna surface adaptive control system," in *Proceedings of the 52 AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, 2011.

[42] D. Gorinevsky and T. T. Hyde, "Adaptive membrane for large lightweight space application," in *Proceedings of the SPIE Astronomical Telescopes and Instrumentation Conference and Exposition*, 2002.

[43] M. Straubel, C. Sickinger, and S. Langlois, "Trade-off on large deployable membrane antennas," in *Proceedings of the 30th ESA Antenna Workshop on Antennas for Earth Observation, Science, Telecommunication and Navigation Space Missions*, 2008.

[44] M. Straubel, *Design and sizing method for deployable space antennas.* PhD thesis, University of Braunschweig, 2012.

[45] L. Datashvili, M. Lang, H. Baier, *et al.*, "Membranes for large and precision deployable reflectors," in *Proceedings of European Conference on Spacecraft Structures, Materials and Mechanical Testing*, 2005.

[46] N. G. Dhere, S. R. Ghongadi, M. B. Pandit, and A. H. Jahagirdar, "Cigs2 thin-film solar cells on flexible foils for space power," Tech. Rep. 211831, NASA, 2002.

[47] K. Otte, L. Makhova, A. Braun, *et al.*, "Flexible cu(in,ga)se2 thin-film solar cells for space application," *Thin Solid Films*, vol. Thin Solid Films, pp. 613 – 622, 2006. {EMSR} 2005 - Proceedings of Symposium F on Thin Film and Nanostructured Materials for Photovoltaics {EMRS} 2005- Symposium F {EMSR} 2005 - Proceedings of Symposium F on Thin Film and Nanostructured Materials for Photovoltaics.

[48] S. Brunner, "Praktische untersuchungen zur entfaltbaren solargeneratorstrukturen," tech. rep., HTS, 2010.

[49] K. Seifert, W. Goehler, T. Schmidt, *et al.*, "Deployable structures for flexible solar generators," in *Proceedings of the European Conference on Spacecraft Structures, Materials and Environmental Testing*, 2005.

[50] S. Langendorf, S. Brunner, and K. Zajac, "Design and testing of a flexible solar generator for on-orbit verification mission," in *Proceedings of the 13th European Conference on Spacecraft Structures, Materials and Environmental Testing*, 2014.

Bibliography

[51] K. Shimazaki, M. Imaizumi, and K. Kibe, "Sio2 and al2o3/sio2 coatings for increasing emissivity of cu(in, ga)se2 thin-film solar cells for space application," *Thin Solid Films*, vol. 516, pp. 2218–2224, 2008.

[52] M. Guenthner, M. Pscherer, C. Kaufmann, and G. Motz, "High emissivity coatings based on polysilazanes for flexible cu(in,ga)se2 thin-film solar cells," *Solar Energy Materials and Solar Cells*, vol. 123, no. 0, pp. 97 – 103, 2014.

[53] F. D. Vedover, D. de Wilde, C. Semprimoschnig, *et al.*, "The solar sail materials (ssm) project - results of activities," in *Advances in Solar Sailing*, 2014.

[54] M. Company, "3m adhesive transfer tapes with adhesive 100," tech. rep., 2006.

[55] H. GmbH, "Fabrikationsvorschrift /-protokol, kleben von polyimid folien," tech. rep., 2004.

[56] H. GmbH, "Fabrikationsvorschrift /-protokoll, kleben von dnnschichtsolarzellen," tech. rep., 2005.

[57] I. Jones and G. K. Stylios, *Joining Textiles: Principles and Applications (Woodhead Publishing Series in Textiles)*. Woodhead Publishing, 2013.

[58] S. Multek Corporation, "The red book," 2014.

[59] U. C. Ltd., "Upilex films - product catalog, www.ube.com," 2014.

[60] ASTM-D674-46, "Recommended practices for long-time creep or stress relaxation of plastics under tension or compression at different temperatures," 1973.

[61] DuPont, "Mylar polyester film, product information," 2014.

[62] T. D. Films, "Teonex pen film, product information," 2014.

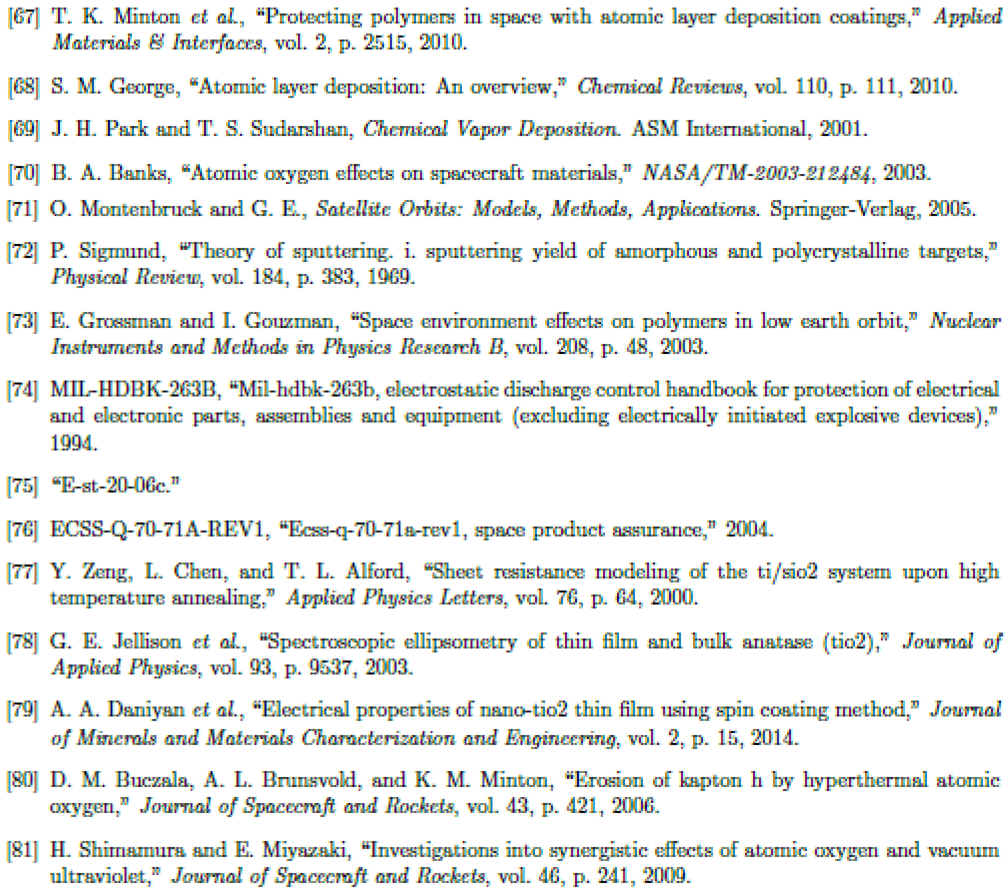
[63] U. C. Ltd., "Upilex films - data sheet, tcf-s-000, rev. a," 2002.

[64] de Groh *et al.*, "Nasa glenn research center's materials international space station experiment (misse 1-7)," *Proceedings of International Symposium on SM/MPAC&SEED Experiment*, 2008.

[65] I. Gouzman *et al.*, "Thin film oxide barrier layers: Protection of kapton from space environment by liquid phase deposition of titanium oxide," *Applied Materials & Interfaces*, vol. 2, p. 1835, 2010.

[66] E. M. Silverman, "Space environmental effects on spacecraft: Leo materials selection guide," *NASA Contractor Report*, vol. 4661, 1995.

Bibliography



[67] T. K. Minton *et al.*, "Protecting polymers in space with atomic layer deposition coatings," *Applied Materials & Interfaces*, vol. 2, p. 2515, 2010.

[68] S. M. George, "Atomic layer deposition: An overview," *Chemical Reviews*, vol. 110, p. 111, 2010.

[69] J. H. Park and T. S. Sudarshan, *Chemical Vapor Deposition*. ASM International, 2001.

[70] B. A. Banks, "Atomic oxygen effects on spacecraft materials," *NASA/TM-2003-212484*, 2003.

[71] O. Montenbruck and G. E., *Satellite Orbits: Models, Methods, Applications*. Springer-Verlag, 2005.

[72] P. Sigmund, "Theory of sputtering. i. sputtering yield of amorphous and polycrystalline targets," *Physical Review*, vol. 184, p. 383, 1969.

[73] E. Grossman and I. Gouzman, "Space environment effects on polymers in low earth orbit," *Nuclear Instruments and Methods in Physics Research B*, vol. 208, p. 48, 2003.

[74] MIL-HDBK-263B, "Mil-hdbk-263b, electrostatic discharge control handbook for protection of electrical and electronic parts, assemblies and equipment (excluding electrically initiated explosive devices)," 1994.

[75] "E-st-20-06c."

[76] ECSS-Q-70-71A-REV1, "Ecss-q-70-71a-rev1, space product assurance," 2004.

[77] Y. Zeng, L. Chen, and T. L. Alford, "Sheet resistance modeling of the ti/sio2 system upon high temperature annealing," *Applied Physics Letters*, vol. 76, p. 64, 2000.

[78] G. E. Jellison *et al.*, "Spectroscopic ellipsometry of thin film and bulk anatase (tio2)," *Journal of Applied Physics*, vol. 93, p. 9537, 2003.

[79] A. A. Daniyan *et al.*, "Electrical properties of nano-tio2 thin film using spin coating method," *Journal of Minerals and Materials Characterization and Engineering*, vol. 2, p. 15, 2014.

[80] D. M. Buczala, A. L. Brunsvold, and K. M. Minton, "Erosion of kapton h by hyperthermal atomic oxygen," *Journal of Spacecraft and Rockets*, vol. 43, p. 421, 2006.

[81] H. Shimamura and E. Miyazaki, "Investigations into synergistic effects of atomic oxygen and vacuum ultraviolet," *Journal of Spacecraft and Rockets*, vol. 46, p. 241, 2009.

Bibliography

[82] ONERA, 2014. SEMIRAMIS, http://www.onera.fr/en/desp/semiramis.

[83] ECSS-Q-ST-70-06C, "Ecss-q-st-70-06c, particle and uv radiation testing for space materials," 2008.

[84] ESA/ESTEC, 2014. STAR Facility, http://www.esa.int.

[85] M. Albano and A. Delfini, "Atomic oxygen facility description," 2014. Sapienza University of Rome, Astronautics Electric and Energetic Engineering Department.

[86] G. Technical University in Dresden, "Atomic oxygen exposure facility," 2014. Atomic Oxygen Exposure Facility, *https : //tu − dresden.de/die_tu_dresden/fakultaeten/fakultaet_maschinenwesen/ilr/rfs/forschung/lab/ausstattung en*.

[87] T. Renger *et al.*, "The complex irradiation facility at dlr-bremen," *Journal of Materials Science and Engineering A*, vol. 4, p. 1, 2014.

[88] ASTM-E490, "Standard solar constant and zero air mass solar spectral irradiance tables," 2014.

[89] M. Sznajder, T. Renger, A. Witzke, U. Geppert, and R. Thornagel, "Design and performance of a vacuum-uv simulator for material testing under space conditions," *Advances in Space Research*, vol. 52, p. 1993, 2013.

[90] H. Shimamura *et al.*, "Joint evaluation of space materials by cnes and jaxa," *Scientific Report*.

[91] R. Kitamura, L. Pilon, and M. Jonasz, "Optical constants of silica glass from extreme ultraviolet to far infrared at near room temperature," *Applied Optics*, vol. 46, p. 8118, 2007.

[92] R. T. Sanderson, *Chemical Bonds and Bond Energy*. Academic Press, 1971.

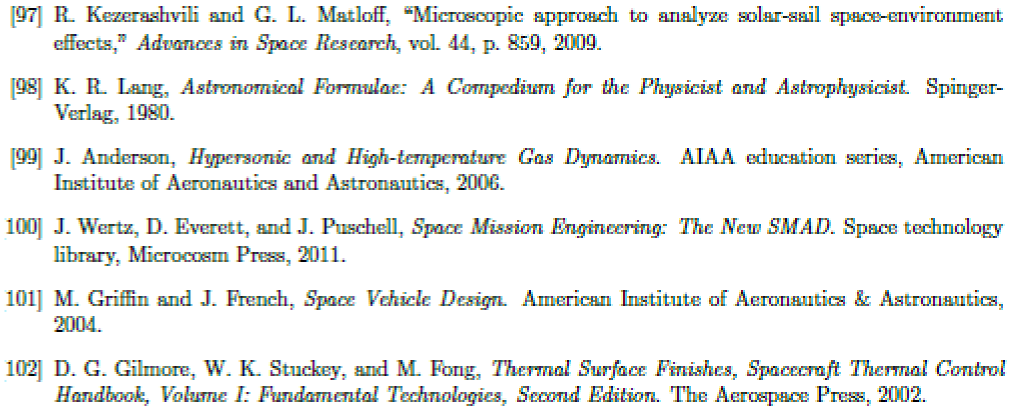
[93] R. T. Sanderson, *Polar Covalance*. Academic Press, 1983.

[94] B. A. Banks *et al.*, "Atomic oxygen erosion yield prediction for spacecraft polymers in low earth orbit," *NASA/TM-2009-215812*, 2009.

[95] A. D. Rakic, "Algorithm for the determination of intrinsic optical constants of metal films: Application to aluminum," *Applied Optics*, vol. 34, p. 4755, 1995.

[96] R. Kezerashvili and G. L. Matloff, "Solar radiation and the beryllium hollow-body sail: 2. diffusion, recombination and erosion processes," *Journal of British Interplanetary Society*, vol. 61, p. 169, 2008.

Bibliography



[97] R. Kezerashvili and G. L. Matloff, "Microscopic approach to analyze solar-sail space-environment effects," *Advances in Space Research*, vol. 44, p. 859, 2009.

[98] K. R. Lang, *Astronomical Formulae: A Compedium for the Physicist and Astrophysicist.* Spinger-Verlag, 1980.

[99] J. Anderson, *Hypersonic and High-temperature Gas Dynamics.* AIAA education series, American Institute of Aeronautics and Astronautics, 2006.

100] J. Wertz, D. Everett, and J. Puschell, *Space Mission Engineering: The New SMAD.* Space technology library, Microcosm Press, 2011.

101] M. Griffin and J. French, *Space Vehicle Design.* American Institute of Aeronautics & Astronautics, 2004.

102] D. G. Gilmore, W. K. Stuckey, and M. Fong, *Thermal Surface Finishes, Spacecraft Thermal Control Handbook, Volume I: Fundamental Technologies, Second Edition.* The Aerospace Press, 2002.