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LARGE LIGHTWEIGHT DEPLOYABLE STRUCTURES FOR PLANETARY DEFENCE: SOLAR SAIL PROPULSION, SOLAR CONCENTRATOR PAYLOADS, LARGE-SCALE PHOTOVOLTAIC POWER

Patric Seefeldt(1,2), **Waldemar Bauer**(1,3), **Bernd Dachwald**(7), **Jan Thimo Grundmann**(1,4), **Marco Straubel**(8,9), **Maciej Sznajder**(1,5), **Norbert Tóth**(1,6), **Martin E. Zander**(8,10,11)
(1)DLR Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen
(2)+49-(0)421-24420-1609,
(3)+49-(0)421-24420-1197,
(4)+49-(0)421-24420-1107,
(5)+49-(0)421-24420-1623,
(6)+49-(0)421-24420-1186,
(7) Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Hohenstaufenallee 6, 52064 Aachen, Germany, +49-241-6009-52343 / -52854,
(8)DLR Institute of Composite Structures and Adaptive Systems – Composite Design, Lilienthalplatz 7, 38108 Braunschweig, Germany
(9)+49-(0)531-295-2383,
(10)+49-(0)531-295-2316,
(11) Technical University of Braunschweig, Institute of Adaptronics and Function Integration, Langer Kamp 6, 38106 Braunschweig, Germany, +49-(0)531 391-2684,

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ABSTRACT

Several studied planetary defence (PD) related mission types made use of very large spacecraft in order to target small solar system body (SSSB) Mission examples are solar sail propulsion, very large photovoltaic generators, and solar concentrator mirrors for SSSB deflection. In order to enable such mission scenarios large lightweight deployable structures are required.

The paper at hand provides an overview of the GOSSAMER solar sail technology developed by DLR since the 1990s. Boom and foil structures, including deployment mechanisms, with a focus on solar sail applications were developed. The technology was subject to extensive on ground qualification testing. The qualification included vibration testing, fast decompression, centrifuge tests and laboratory deployment. In addition metalized films were subject to degradation testing employing DLR's complex irradiation facility.

The technology appears to be suitable as a technology base for the development of other very large lightweight deployable structures. An outline of their potential for highly compressed deployable photovoltaic arrays and foil-based solar concentrator mirrors will be given.

Introduction

In order to enable planetary defence missions studied in the past very large spacecraft are required to target small solar system body (SSSB). The missions studied included solar sail propulsion, very large photovoltaic generators for solar-electric propulsion or electrically powered deflection mechanisms, and solar concentrator mirrors for SSSB deflection.

However, for Earth escape, the largest currently available launch vehicles are constrained to about 10 t payload mass per launch. The largest payload fairings have about 250 m^3 volume [1][2][3][4]. Requirements for higher initial velocity (c_3) would further constrain the payload. Docking of spacecraft on a common trajectory may be feasible but available technologies were developed for crewed spaceflight. This equipment is designed for large man-rated pressurized spacecraft and thus heavy, with or without fuel transfer options. Such scenarios may require Earth parking orbital phases, new escape stages with extended high-performance fuel storage, or a significant expansion of rendezvous navigation technologies to deep space beyond the Apollo-era low lunar orbit experience.

Planetary defence related missions of this size are only likely to be built upon discovery of a specific threat. Consequently, there is a strong motivation for single-launch spacecraft even in overall multiple-launch scenarios. Hence, for practical interplanetary missions, very large structures need to be very lightweight *and* deployable with a very high volumetric compression factor.

The GOSSAMER solar sail technology developed by DLR since the 1990s and subsequently extended to the framework of the DLR-ESTEC GOSSAMER Solar Sail Technology Roadmap could provide such deployable structures. An artist's impression is given in Figure 1.

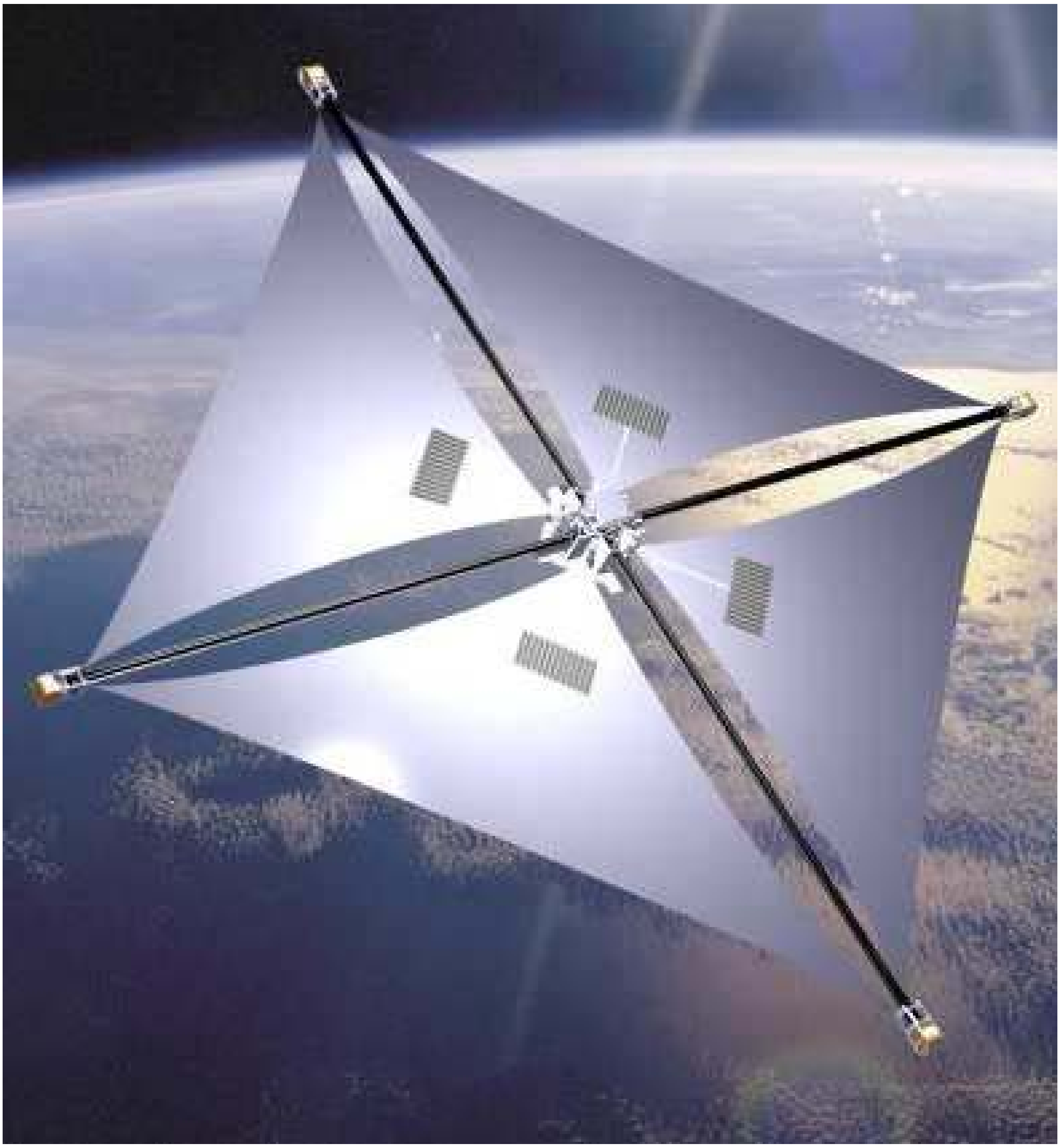


Figure 1: Artist's impression of the Gossamer-1 deployment demonstrator.

Boom and foil structures, including deployment mechanisms, with a focus on solar sail applications were developed and tested. The qualification included vibration testing, fast decompression, centrifuge tests, mechanical testing and laboratory deployment. In addition metalized films were subject to degradation testing employing DLR's Complex Irradiation Facility, CIF. The most important degradation factors can be simulated, i.e. flux of protons, electrons and a wide range of electromagnetic radiation, from 40 to 2500 nm. Films exposure can be made simultaneously with all working sources; hence, a wide range of degradation effects can be simulated.

Some interplanetary science missions benefiting from the unique capabilities of solar sail propulsion have been studied based on GOSSAMER technology. These include a multiple NEO rendezvous and fly-by scanario [5] and scenarios similar to near-Earth co-orbital [6] and high ecliptic inclination NEA targets [7]. The technology also appears to be suitable as a base for the development of other very large lightweight deployable structures. An outline of their potential for highly compressed deployable photovoltaic arrays and foil-based solar concentrator mirrors will be given.

DLR's Gossamer-1 Deployment Technology

Based on previous projects, DLR developed scalable deployment technology for GOSSAMER spacecraft structures. While a focus was on solar sailing and thin film photovoltaics the aim of the development is to provide scalable and reliable technology for deployable membrane structures for various space applications. The development is made within DLR's GOSSAMER-1 project, aiming for a first technology demonstration in space.

GOSSAMER-1 is a low cost technology demonstrator that is part of an intended three step technology development. Within this project, scalable deployment technologies including membranes, booms, photovoltaics and their corresponding mechanisms will be developed. Scalable means that GOSSAMER-1 is a technology demonstrator that will deploy a 5m×5m sail using technology that is suited to build GOSSAMER-2 with a 25m × 25m sail and GOSSAMER-3 with a 50m × 50m sail. One main difference from former European solar sail projects is the complete abandonment of any scientific payload. Scientific objectives would introduce a higher complexity and thereby introduce additional risk to a mission, which is solely focused on the development of deployment technology. Furthermore, linking of such a development to scientific objectives would increase mission cost. Both aspects were the cause for previous failures of solar sail projects.

The mission objective of GOSSAMER-1 is the demonstration of a successful and reliable deployment, not yet it's use as a solar sail or full scale solar power generator. Consequently, it is sufficient to demonstrate the deployment in Low Earth Orbit (LEO), and it is not required to launch into altitudes where solar photonic pressure dominates over atmospheric drag effects. The satellite will have a mass of about 30 kg and a very compact launch configuration shown in Figure 2. The Gossamer-1 is based on a crossed boom configuration with four sail segments. Four Boom and Sail Deployment Units (BSDUs) will deploy the booms and sail segments simultaneously. In contrast to other projects like JAXA's IKAROS [8][9] and NASA's NANOSAIL-D, one of the main requirements is that the deployment is fully controlled. That means the deployment process can be stopped and resumed at any time if required.

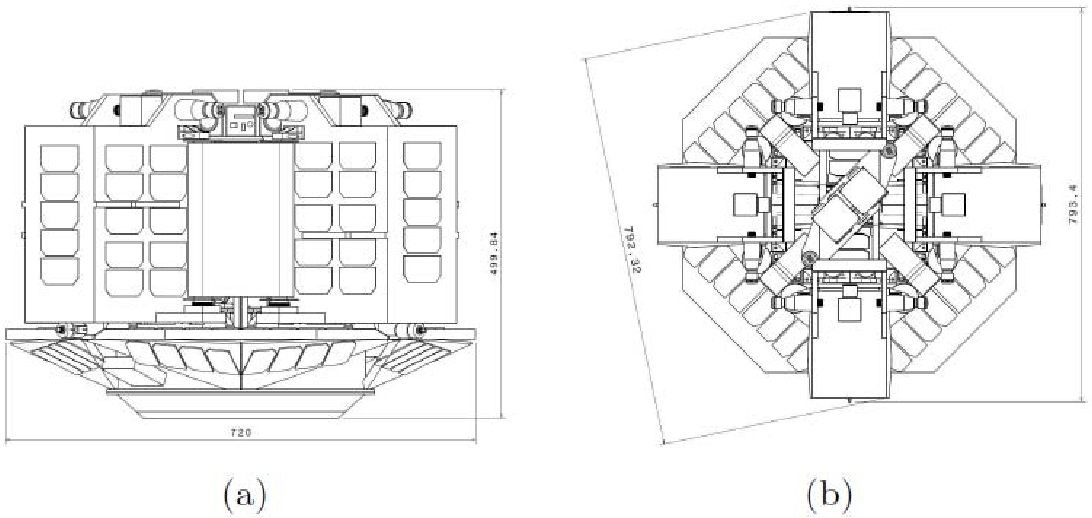


Figure 2: Gossamer-1 launch configuration, (a) – side view, (b) - top view (in plane of the sail).

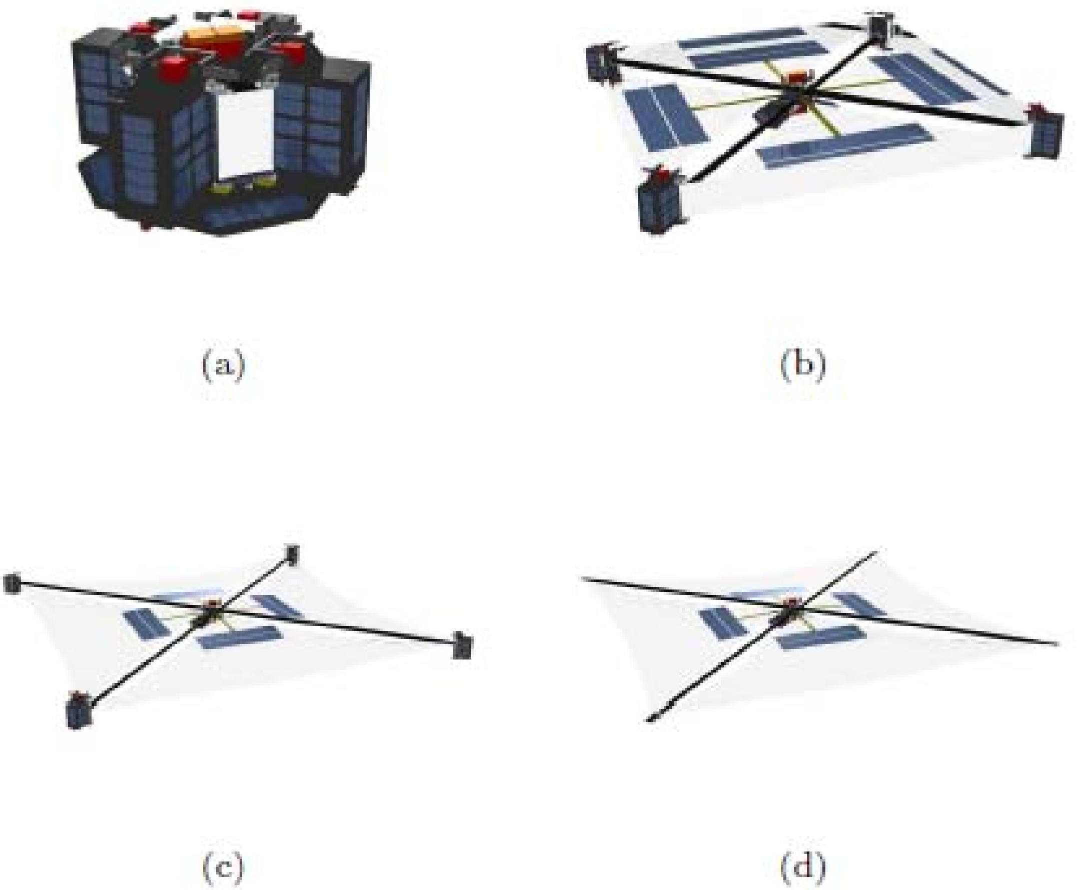


Figure 3: Gossamer-1 deployment process, (a)- launch configuration, (b) deployment, (c) deployed sail, (d) deployment mechanisms are jettisoned

Deployment process

The deployment is started via time tagged command to ensure that deployment starts in sunlight and just prior to the next downlink such that nominal deployment will be done a few minutes before ground contact. It is desired to start the deployment in sunlight in order to have good illumination for camera monitoring of the deployment. The deployment starts just prior to the next downlink in order to ensure that in case of non-nominal behaviour, the system status is quickly known via status downlink. By that, apart from autonomous on-board FDIR, ground commanded FDIR measures can also be considered and realized.

When the deployment is started, the BSDU’s and SSM’s will be unlocked and the BSDU’s will start moving outwards, deploying the booms and the sails at the same time. At the end of the deployment it is possible to jettison the mechanisms. This jettison of BSDUs is one central part of the solar sail use case, to shed dead mass. This is in order to maximize sailcraft loading and thereby maximize characteristic acceleration, which can be reached with a solar sailcraft. After jettisoning the BSDUs the spacecraft is in sailcraft configuration. The deployment is illustrated in Figure 3. Communication between the BSDU’s and the CSCU will be via the On-board Wireless Communication System (OWCS).

Booms and Sails

The GOSSAMER-1 demonstrator is based on a crossed boom configuration. At the centre the Central Spacecraft Unit (CSCU) the interface for two crossed booms to the spacecraft is located.

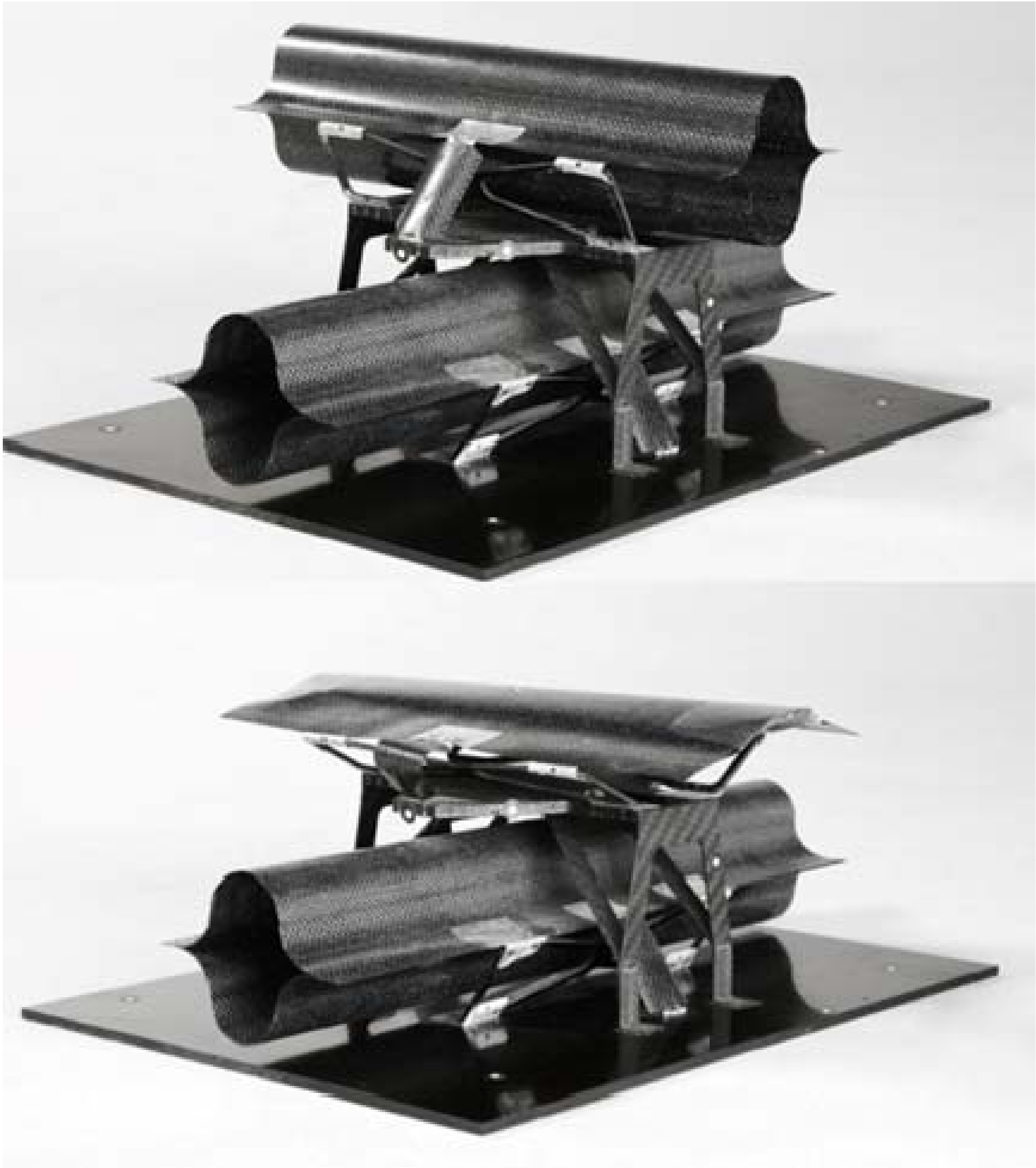


Figure 4: Flexible boom-spacecraft interface.

As explained four Boom and Sail Deployment Units (BSDUs) will deploy the booms and sail segments. The booms are stored inside those BSDUs as shown in the in Figure 5. Further description can be found in [10].

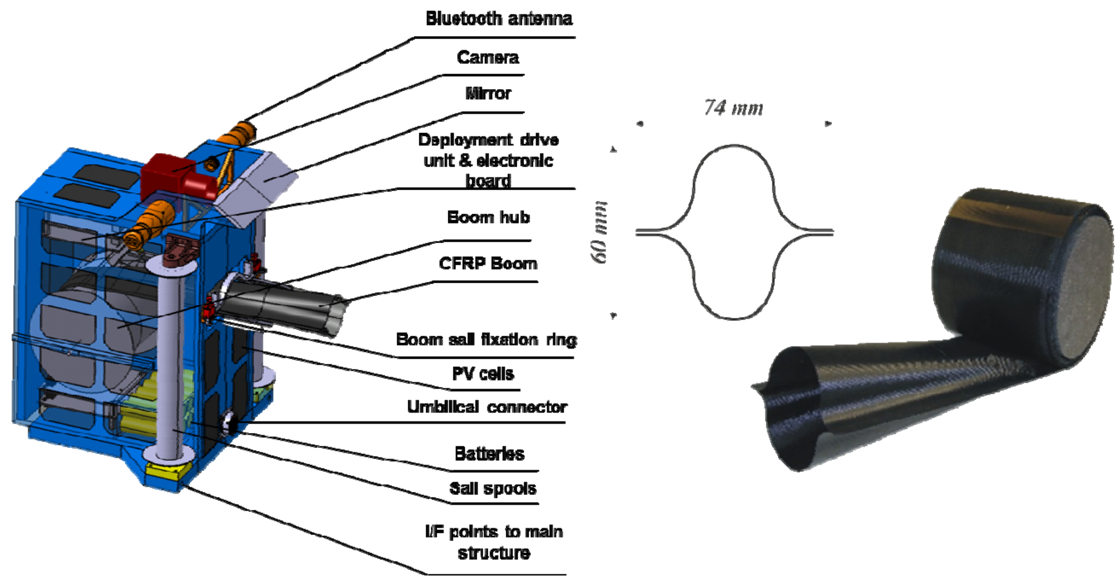


Figure 5: BSDU assembly (left), Cross section and partially coiled GOSSAMER-1 CFRP boom (right)

The sails are mounted on the outside of the BSDUs on spools. The design of the sail segments and the stowing strategy is shown in Figure 6. The triangular segments are zig-zag folded and coiled on two spools. The spools are mounted on two neighbouring BSDUs.

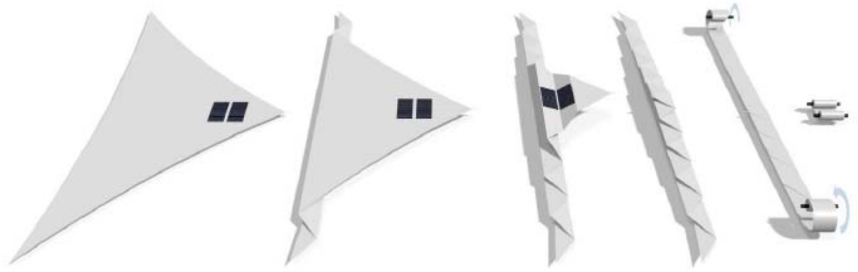


Figure 6: Gossamer-1 sail segments and stowing strategy (zig-zag folding and coiling on two spools)

During the deployment process, the BSDUs move away from the CSCU by uncoiling the booms and deploying four triangular sail segments that are spanned between the CSCU and the BSDUs. The thin film photovoltaics are located near the inner corner of the sail segments.

Throughout the deployment the process will be monitored with cameras. The data volume is limited by taking sequences of images consisting of patterns of a number of low resolution images always followed by one high resolution image. Data volume is decoupled from deployment speed by taking one image per 2.5 cm of deployment distance, as measured along the booms. In addition, reflective markers on the boom in combination with an optical sensor allow a length and deployment speed measurement. Strain-gauges are employed for force measurement.

Bus system

The GOSSAMER-1 spacecraft bus system consists of two segments: The first is the main bus system, which is on the CSCU, with the most important units:

- OBC
- S-Band Transceiver
- TC decoder / TM encoder
- PCDU.

The second bus segment is on the BSDU side. This bus segment is fully independent from the CSCU segment and has its own on-board computer and power subsystem.

These two segments are needed, because the deployment concept does not allow for wired communication and power exchange between the CSCU and BSDU, once separated. The CSCU segment will command and control the BSDU segment.
Therefore the communication between both segments uses a wireless implementation (Bluetooth). On the spacecraft, there is an On-Board Wireless Communication System (OWCS), which consists of one Master (CSCU) and four Slaves (BSDU) and has its own TM/TC structure and implementation.

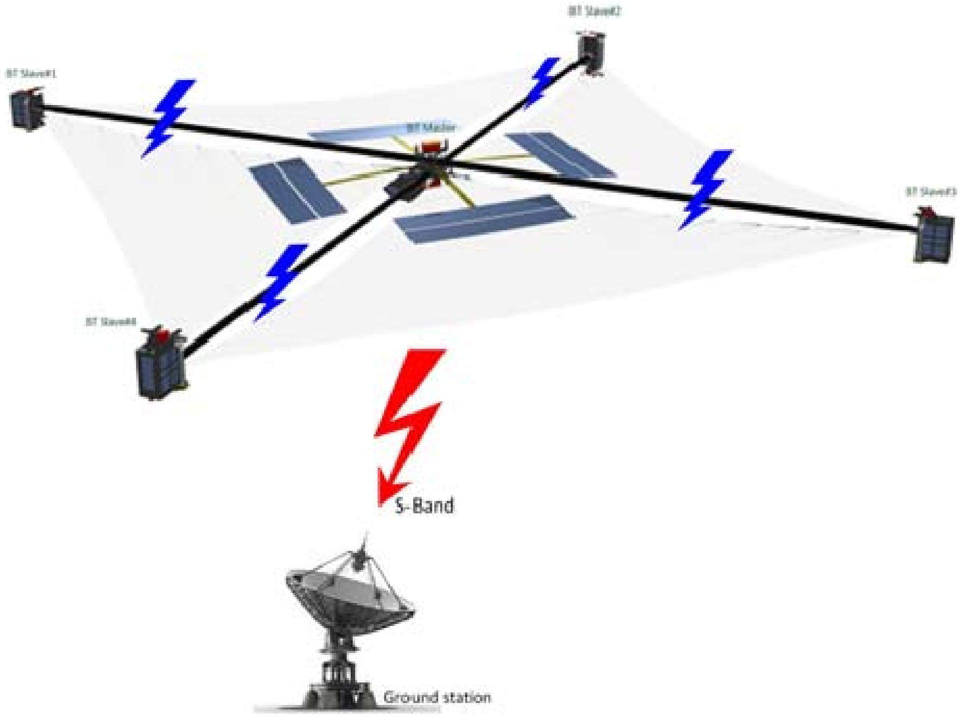


Figure 7: On-Board Wireless Communication System

Qualification testing

For the validation of deployable gossamer technology a series of tests was employed. This included shaker tests, centrifuge tests, fast decompression, mechanical tests and laboratory deployment tests. In a first step the testing was made on a component level. Currently a qualification model of the BSDU is built for environmental testing. In the past the sail package was subject of several tests explained in the next paragraphs. The deployment was made with an engineering model of the BSDU. For these tests a sail was built that represents all mechanical characteristics without integrating the thin-film solar cells. Instead Flex PCB dummies were used. In Figure 8 and Figure 9 give an impression of the testing processes.

Furthermore mechanical tests on boom component level and sub-assembly level were conducted. Here the mechanical capability regarding bending (buckling) and axial compression loads under different directions of loading, simulating solar sail and deployment loading of Gossamer-1, were investigated. Single boom specimens as well as booms mounted in their boom spacecraft interface, and equipped with a on board boom load sensor system, were mechanically characterized in the boom test stand of the “DLR Space Structures Lab @ Uni”, located in Braunschweig [11]. Figure 10 shows the schematic view of the boom test stand principle, measuring boom deflections mainly at the boom tip and on different points on a boom and interface, as well as the applied load. The external loads can be applied in all 3 axis as well as in a combination. With a hardware extension deflections in all 3 axis and rotations can be measured with an optical 3D measuring system. In the right image of Figure 10 a buckling boom after reaching a critical load is displayed. The acquired test results deliver data to validate FE models as well as specific values for a robust structural dimensioning.

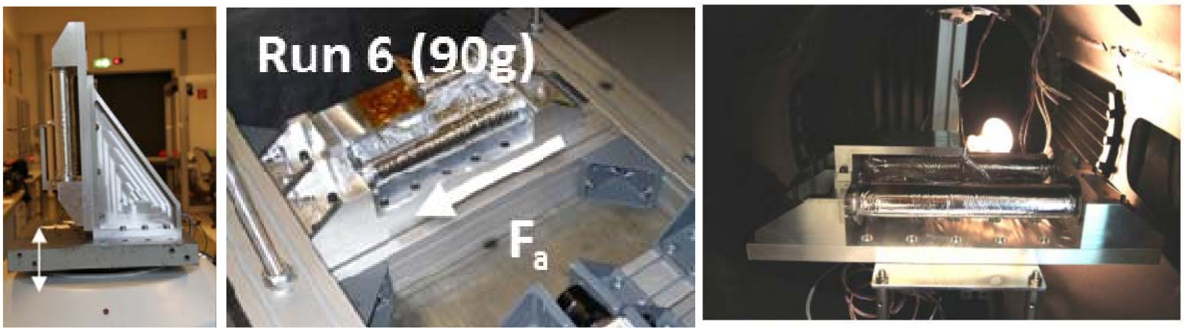
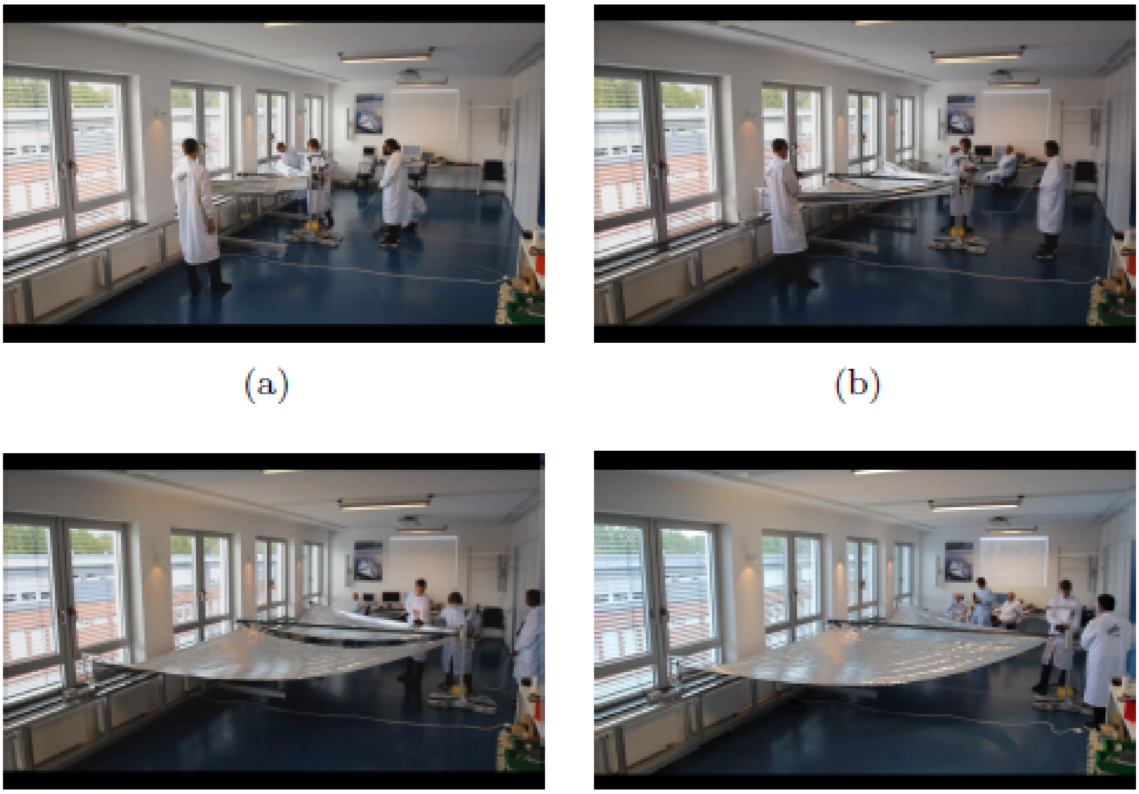


Figure 8: Qualification Testing of the Gossamer-1 sail package on a test adapter, vibration testing (left), centrifuge testing (middle), fast decompression (right)



(a) (b)

(c) (d)

Figure 9: Gossamer-1 laboratory deployment.

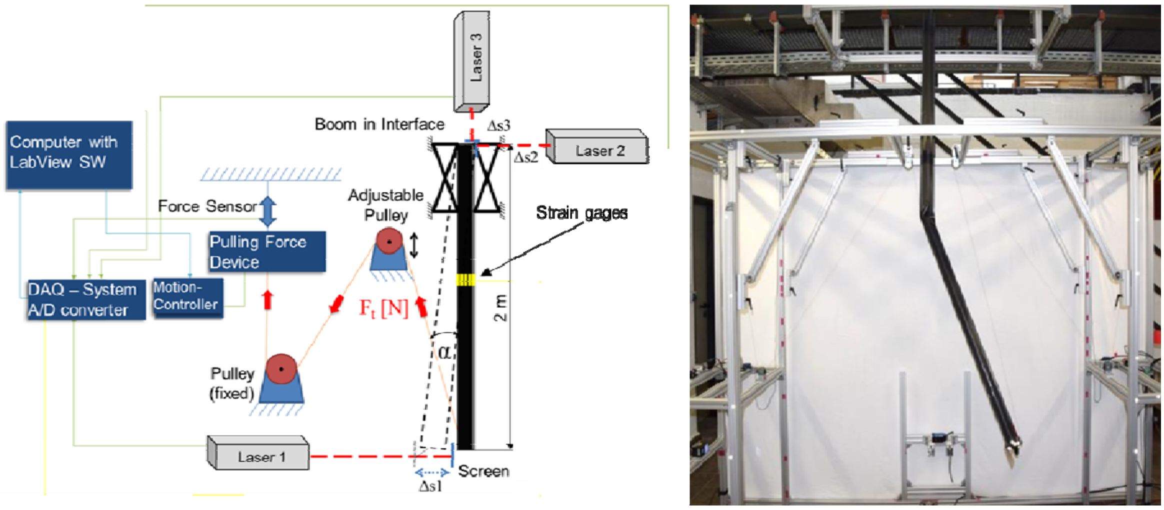


Figure 10: Schematic view of the boom test stand principle (left), a boom specimen buckling under external loading (right)

Degradation studies

Materials planned for space applications have to be evaluated for their behaviour under particle and electromagnetic radiation (EMR) [12]. It is known from many of these tests that particle and EMR can significantly degrade materials and, e.g. lead to changes in their mechanical behaviour or thermo-optical properties, e.g. [13].

These changes can cause early failures of satellite components or even failures of complete space missions [14].

DLR in Bremen conducts research in the degradation field of materials used in space industry. Both experimental and theoretical studies are focused on materials physical and thermo-optical properties change due to the aging factors that occur in space, i.e. high intensity particle- and electromagnetic- radiation.

Tests are performed in-situ by use of the Complex Irradiation Facility (CIF) which provides simultaneous irradiation with particles- or electromagnetic- sources. CIF is equipped with proton- and electron- gun and three light sources: Argon-source [15], deuterium-, and Xenon- lamp [16]. Post-aging tests are performed ex-situ. Specimens' thermo-optical properties (α_s – solar absorptance, ε – thermal emittance) or morphological changes of degraded materials can be studied.

Our latest degradation experiments were focused on thin Aluminum layers deposited under vacuum (VDA) on polyimide foils (VDA on Upilex-S). We studied morphological changes of the specimens' after the high intense proton bombardment. We have proved both experimentally and theoretically that the protons induce formation of small (~0.4 μm in diameter) bubbles filled with hydrogen molecular gas. Hydrogen is produced by recombination processes of incident protons and VDA free electrons [17].

Future studies will be focused on thin film photovoltaic, i.e. their efficiency- and electrical properties- change caused by the UV-light and protons exposure. Possibilities of their protection, e.g. by use of the SiO_x thin coatings, are considered and will be tested. Also we proceed with studies of polyimide base materials. New degradation effects are hypothesized, e.g. delamination of VDA and Upilex substrate caused by high proton fluxes or intense VUV light (< 100 nm). The effects will be investigated in the next irradiation campaign.

Outline of planetary defense applications

Throughout previous Planetary Defense Conferences and Workshops, small solar system body (SSSB) mitigation missions have been proposed which use or imply very large structures in space. Examples of direct use of very large structures include solar concentrator mirrors to heat SSSB surface areas to the point of volatiles emission and solar sails as a means of spacecraft propulsion. Directed energy methods often imply electrical power sources that significantly exceed the power generation levels so far achieved in space, presently of approaching 20 kW for the very largest geostationary communication satellites. Were much higher power levels to be achieved by photovoltaic generators this would require very large deployable solar panels.

Following the recent successful demonstration of sail effect by the Japanese mission IKAROS [8][9] a combination spacecraft is being proposed to studydistant SSSBs such as Jupiter Trojans using solar sail propulsion as well as electrical propulsion for which the majority of sail's area is covered with lightweight flexible thin fim photovoltaics. [18][19]

PRESENT SPACE APPLICATIONS OF LARGE DEPLOYABLE STRUCTURES

Large deployable structures are presently used in space for electric power generation and as primary reflectors for radio communication. However, these structures are mostly based on rigid panels or taut flexible surfaces supported by many or closely spaced rigid support elements.

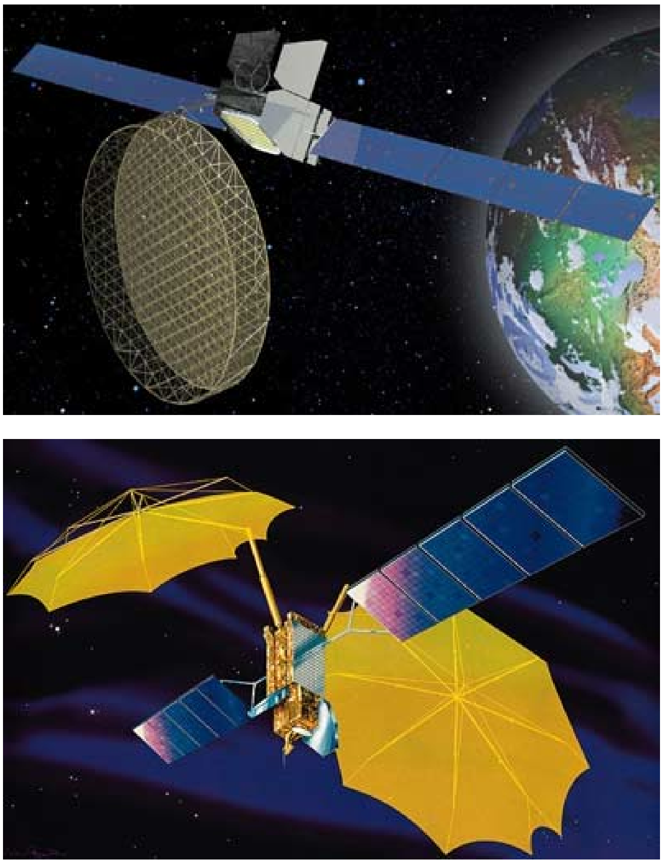


Figure 11: Large deployable antenna main reflectors on geosynchronous communication satellites for direct-to-satellite mobile phone systems – (top) Thuraya 2 and 3 design, 12.25 m antenna diameter (artists concept: Boeing BSS via Gunter's Space Page) – (top) Garuda-1 (ACeS-1) design, two times 12 m antenna diameter (Lockheed-Martin via Gunter's Space Page)

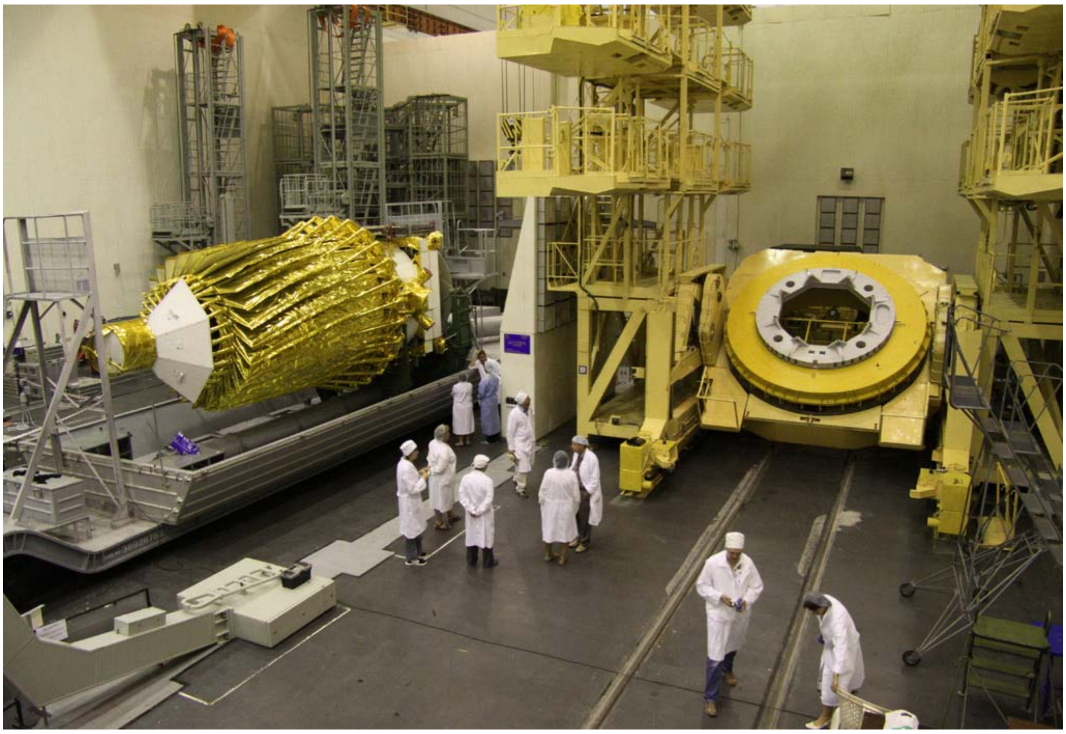


Figure 12: Spektr-R (RadioAstron) space-borne 10 m diameter radio telescope, undeployed (RIA Novosti archive, image #930415 / Oleg Urusov / CC-BY-SA 3.0)

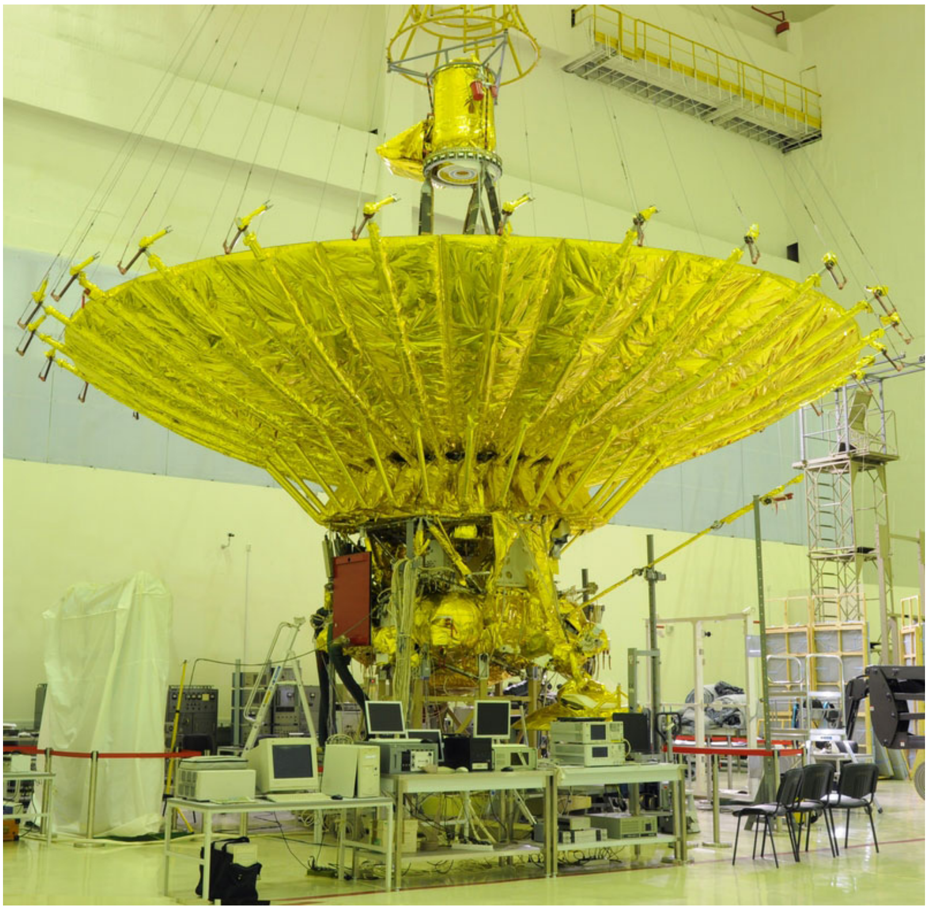


Figure 13: Spektr-R (RadioAstron) space-borne 10 m diameter radio telescope, deployed for final tests (NPO Lavochkin)

So far, only experimental structures have been created from largely flexible and/or thin film materials. One example of comparable size and intended application as the presently operational large antennae in geostationary orbit is the Inflatable Antenna Experiment which was flown on STS-77 and deployed from the subsatellite Spartan 207 in May 1996. It deployed a 14 m antenna reflector structure on three 28 m long inflatable struts. Due to the low orbital altitude of the Shuttle the jettisoned antenna decayed from orbit within days, demonstrating the final phases of dragsail application. The carrier spacecraft Spartan 207 was retrieved by the Shuttle ENDEAVOUR. [20]

The largest deployed structure in space is the ISS, dominated by eight large photovoltaic arrays. These are semi-flexible structures employing a pair of flexible blankets to support rigid bifacial photovoltaic cells to collect direct sunlight as well as Earth albedo. A mast between the blankets is used to extend and retract them. However, the ISS was not launched and deployed in one piece. It was assembled over many years from units delivered by several tens of dedicated large payload space launches delivering a mix of rigid and deployable structures ranging from experiments and minor replacement part to equipped pressurized laboratory modules.

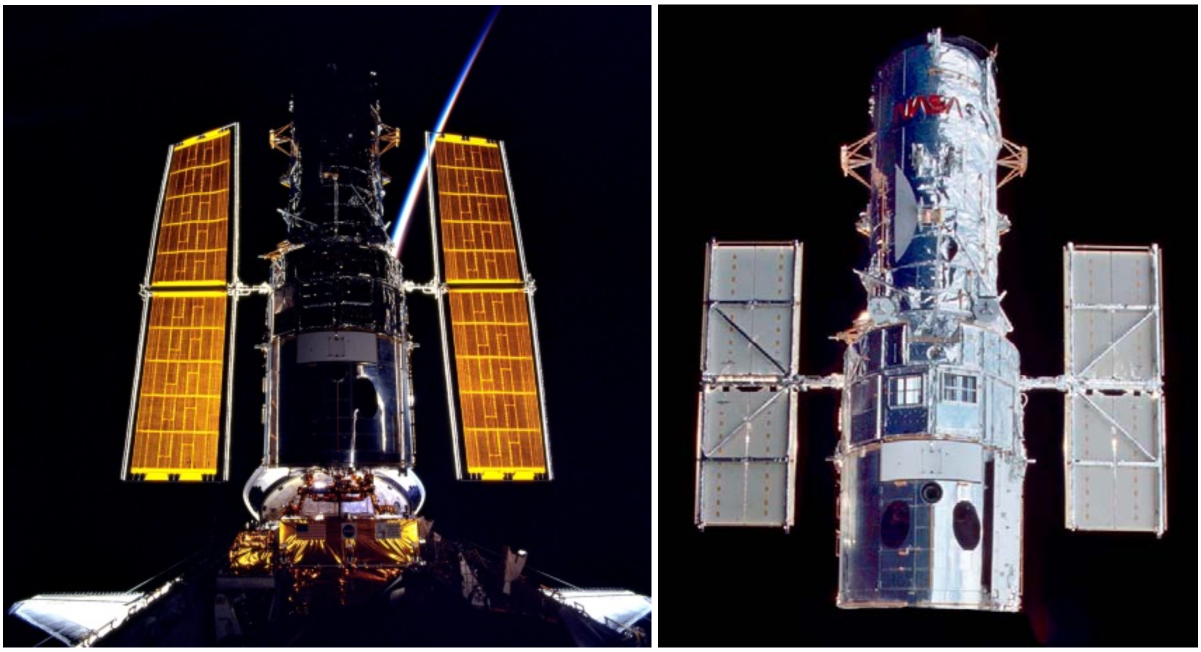


Figure 14: Hubble Space Telescope flexible photovoltaics (left) and rigid replacement (right) – (NASA / STS crews)

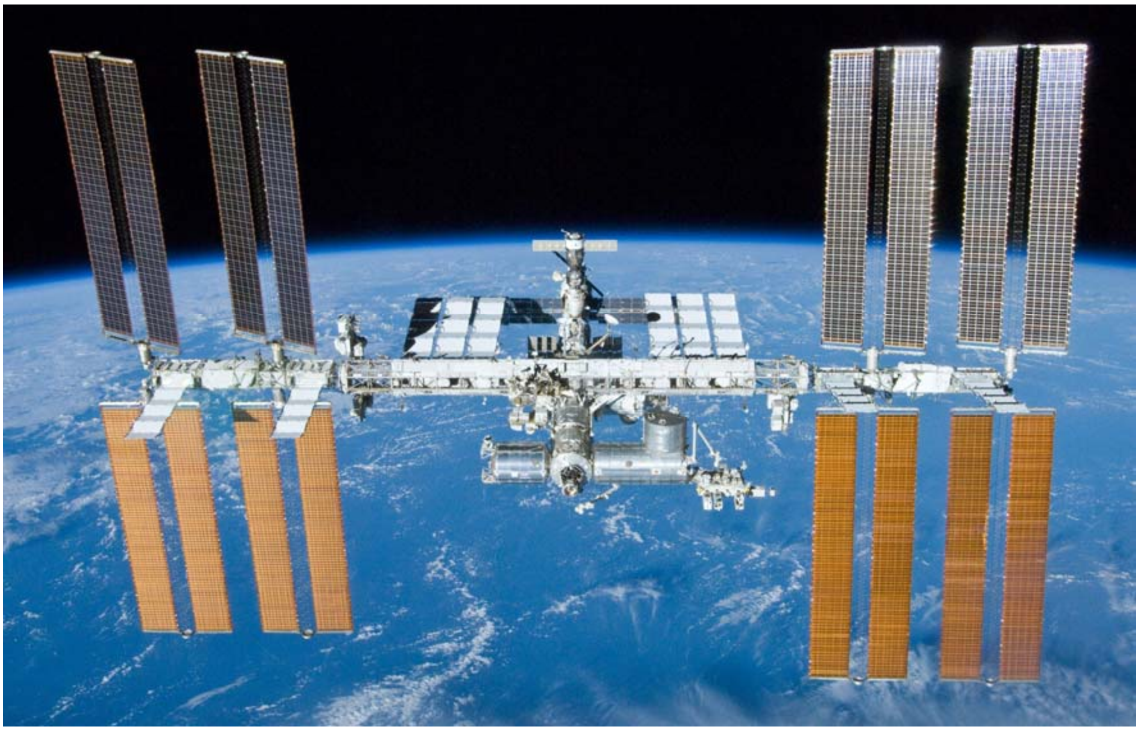


Figure 15: ISS large-scale photovoltaics (NASA/Crew of STS-132)

LARGE-SCALE PHOTOVOLTAIC POWER

Proposed mission scenarios requiring very high electrical power, sometimes projected almost 50 years into the future with correspondingly optimistic assumptions on the then available technologies, e.g. [21][22]. Most of these employ nuclear power generation. However, a rough estimate of the required photovoltaic area to achieve the same electrical power output is easily possible: presently used high-efficiency rigid triple-junction photovoltaic cells achieve about 340 W/m^2 at 1 AU and realistic operation temperatures. Thin-film photovoltaic cells achieve about 100 W/m^2 but at a much lower power-specific mass. This is equivalent to some $(55\ m)^2$ and about $(100\ m)^2$ per MW electrical power, respectively. This size is in the range of proposed solar sail missions.

Although MW-scale photovoltaic generators have not yet been designed in detail, preliminary studies indicate that thin-film photovoltaics on a solar sail like deployable structure can be significantly lighter than rigid photovoltaics for kW-scale power.

mission study	PDC / year	spacecraft mass, kg	electrical power	use	generator
B612 [21]	2004	20000	250 kW	VASIMIR 2.5 N	nuclear reactor
DEFT 2050 (D'Artagnon) [22]	2004	80000	1, 25, 50, 75, 100 MW	ablation laser	nuclear-electric
			50 MW	VASIMIR	
DAWN-based gravity tractor [23]	2009	1100 …2823	10 kW	DAWN ion propulsion	photovoltaic
Laser Bees [24]	2009	1000 …3400	6.7…100 kW	laser	photovoltaic/ concentrator
Multiple Gravity Tractor [25]	2011	1000	~10 kW	DAWN ion propulsion	photovoltaic
Ion Beam Sheperd [26]	2011	1000 …10000	10's …100's kW	ion propulsion	photovoltaic
Light-Touch2 [27]	2013	967	0.86 kW	laser	photovoltaic
DE-STARLITE [28]	2015	18500 …28790 (…70000)	105 …450 kW (…3 MW)	laser	photovoltaic
enhanced gravity tractor [29]	2015	4000 …	50 …300 kW	ion propulsion, solar sail augmented	photovoltaic
Ion Beam Sheperd [30]	2015	1200	10 kW	DAWN ion propulsion	photovoltaic

Figure 16: Planetary defense related mission studies with high power requirements, as presented at PDCs

SOLAR CONCENTRATOR AND SHIELD PAYLOADS

Solar concentrators were proposed relatively early as a method of asteroid deflection, e.g. [31][32]. However, for direct close-in application it is likely that their lifetime is limited by the dust released from the target object along with the intended vapour and volatiles. However, for small bodies and moderate deflection velocity they still seem useful. Contamination problems may be resolved by using multiple mirror approaches, e.g. a Cassegrain configuration, where only a smaller and cleanable mirror is required close to the target object. [32]

An alternative use of large surfaces redirecting sunlight is the modification of a target object's own non-gravitational forces, e.g. disabling the Yarkovsky effect through shadowing of the object. [33]

mission study	PDC / year	spacecraft mass, kg	reflector diameter, m	use	technology, shape
Athos Deflection [31]	2004	2000	170	single mirror concentrator	inflatable lens, one side transparent
PHA deflection [32]	2006	5000	630	single mirror concentrator	
Apohis Sunshield Flotilla [33]	2009	1200	50	square or hexagonal sunshield	flotilla of 12 to 16
Mirror Bees [24]	2009	20460	60	single mirror reflector in flotilla	Inflatable Antenna Experiment, 5 kg/m^2
		2730			ARISE (TRL4), 0.5 kg/m^2
		876			adaptive membrane (TRL2), 0.05 kg/^{2}

Figure 17: Planetary defense related mission studies using large deployables to re-direct sunlight, as presented at PDCs

SOLAR SAIL PROPULSION

Solar sail propulsion can propel small payloads to otherwise inaccessible heliocentric orbits. The spacecraft resulting from solar sail studies are of comparable geometric size to MW-scale photovoltaic and solar concentrator concepts. However, unlike those, (100 m)² scale solar sail proposals arrive at spacecraft of a few hundred kg launch mass and undeployed spacecraft volume suitable for secondary payload launches to e.g. GTO. [5][6][7][34][36][37][38].

mission study	PDC / year	spacecraft mass, kg	sail size, m	use	technology, shape
Apophis deflection [34]	2007	318	160 x 160	jettisonable propulsion module	square 4-boom sail
ballasted solar sail [39]	2013	200…700	200 x 200 … 400x 400	12.5 t tractor mass suspension	square, 1.2 µm reinforced film

Figure 18: Planetary defense related mission studies using solar sail propulsion, as presented at PDCs

SUMMARY OF PLANETARY DEFENCE APPLICATIONS

Solar concentrators arrive at masses similar to conventional interplanetary missions of the order of a few tons, and very high electrical power missions come in one or two orders of magnitude heavier, at 10s of tons if not clearly beyond then at best barely within present launch capability for very low Earth orbit.

It seems thus likely that the development of very large and lightweight deployable spacecraft structures will at first advance through low-cost small missions which – comparing within the same field of application – are solar sail propelled missions. [5][6][7] They appear suitable to reach otherwise inaccessible asteroids, for planetary science or target characterization in the context of a threat scenario. [5][37][38] Also, the only significant technology development they require beyond the already successfully ground-tested choice of deployment technologies is that of attitude control, where also several developed concepts await their chance to be built and tested.

It is likely that technologies also of use for solar concentrators will follow, due to the inherent similarity to radio communication and radioastronomy antenna reflectors. For these to become successful, especially in a multi-mirror scenario using a distant main reflector with long focal length, significant advances in shape control of a sail-like membrane are required. [32] With somewhat reduced shape tolerance requirements, solar concentrators could be useful for solar-thermodynamic power generation in space if such systems can be made more efficient overall than currently available photovoltaics.

Before solar sail like deployment technologies can be used to construct high kW-scale or even MW-scale photovoltaics in space, significant development of electrical distribution and harness concepts is necessary, followed by extensive testing. Due to the about one order of magnitude higher area mass of thin film photovoltaics compared to a bare sail foil, much higher masses need to be handled, although still much lighter than conventional rigid photovoltaics. The handling of sail-based power generators will thus likely benefit from shape control technologies to be developed for large foil antennae or solar concentrators. The most significant mass contribution may well come from the harness required to collect the current from the foil panel: On the ground, high kW to MW scale power is transported by high-voltage lines operating at 20 to several 100 kV. Photovoltaic cells are inherently low voltage, high current generators with operating voltages of order 0.5 V/junction. The solar panels of the ISS operating between 100 and less than 200 V already require careful management of plasma discharge risks. If it turned out that operating voltages can not be increased significantly, current handling capabilities in the kA range may be required to provide such high power levels. Required conductor cross-section increases in proportion to the current, and hence, harness mass as well.

Here again, the initial development impulse comes from a small solar system body related planetary sciene background. [18][19]

For small spacecraft projects such as GOSSAMER or MASCOT the majority of the project staff is colocated at DLR Bremen and nearby sites such as Braunschweig. Also, the Concurrent Engineering Facility (CEF) at DLR Bremen is regularly used for internal and external customers' studies of nearly all kinds of space projects. Engineers working in the ongoing projects at DLR Bremen frequently serve as experts of their fields in CEF studies. Through this intense exchange, we can easily access and apply our complete inventory of experience. The work on GOSSAMER-1, which itself is a very compact design already, has benefited from the experience gained on MASCOT in small spacecraft systems engineering and organically integrated design [40] and concurrent Assembly, Integration and Verification processes [41]. Stepwise development approaches like the GOSSAMER roadmap and the extension of already developed technologies, e.g. of the GOSSAMER deployment concept into photovoltaic power generation, are supported by Model-Based System Engineering approaches [42] which are extensively applied in the CEF and throughout projects at our site, not restricted to the use of specialized design facilities, cf. [43][44][45][46].

Conclusion

The development of technology for a controlled deployment of GOSSAMER spacecraft structures was presented. Based on the mission design and the subsequent requirements a satellite bus, auxiliary systems and the deployment technology itself was developed. The technology is on TRL four approaching level five with a qualification model for environmental testing currently being built.

First studies exploring the potential of GOSSAMER-like deployment technology for large-scale photovoltaic power generation are just beginning. The experience gained in other fast-paced and small spacecraft projects such as MASCOT is directly applied to the ongoing work on GOSSAMER technology.

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